Application of Rock Physics Modelling in Exploration Studies: A Case Study of Reservoir Quality Diagnostics of Fatehgarh Sandstones near Aishwariya Field, Barmer Basin, India

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Summary
The field of rock physics represents the link between qualitative geological parameters and quantitative geophysical measurements. With increasing use of quantitative seismic techniques to identify subtle traps and hydrocarbon prospect screening, rock physics studies are becoming more important in exploration workflow. We present a case-study, highlighting the application of rock-physics modelling in estimating reservoir quality from seismic inversion volume, in order to identify near-field hydrocarbon prospectivity in Fatehgarh formation near Aishwariya field in Barmer Basin. We interpreted the well-log based velocity-porosity trends, integrating the rock-texture information from petrographic studies. Heuristic rock physics modelling approach is used to model the observed trend. The models are then transferred in to seismic inversion attributes domain by using rock physics templates. We also demonstrate how these rock physics templates can help us to interpret the lithology variation from seismic inversion volume.

Introduction
The Barmer Basin, located in the Thar Desert of western Rajasthan, India, has attracted major hydrocarbon exploration and development activities in the last two decades. More than 200 exploratory and appraisal wells have been drilled, with 38 oil & gas discoveries made to date. The Upper Cretaceous (Ghaggar Hakra) – Paleocene (Fatehgarh) sandstones are the most prolific reservoirs in this basin (Dolson et. al, 2012), currently under production from 6 fields, including the Mangala, Bhagym and Aishwariya fields, with a ~6.4 Billion barrels of discovered HIIP. The current challenge is to add new resources that can replace the producing reserves, by bringing new prospects online.

Conventionally, hydrocarbon prospects were mostly defined and drilled based on ‘qualitative’ seismic interpretation. This mainly concentrated on mapping geological elements and/or recognizing stratigraphic patterns to define trap geometries from seismic reflection data. However, when exploring for new targets in a well explored basin like the Barmer Basin, quantitative seismic interpretation techniques are becoming more important to delineate subtle traps that are not easily revealed from conventional qualitative seismic interpretation, and for prospect evaluation and reservoir de-risking. These techniques, which include tools like post-stack amplitude analysis and acoustic and elastic impedance inversion, primarily try to extract seismic amplitude patterns. These amplitudes primarily represent contrasts in elastic properties between individual subsurface layers. Rock physics modelling studies, which established a ‘quantitative link’ between elastic properties to geological parameters, allow us to interpret the seismic amplitude patterns into reservoir quality diagnostics. The increased use of elastic seismic inversion coupled with rock physics modelling has brought a paradigm change in prospect mapping in the exploration studies.

In this study, we will demonstrate a case study on application of rock-physics modelling to help in converting elastic parameters from inversion data to reservoir parameters and seismic screening of hydrocarbon prospects. The elastic response of the producing Fatehgarh sand in Aishwariya field was analyzed and modelled using rock-physics templates. These rock-physics templates can be used for
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reservoir quality assessment away from the producing field from the seismic inversion data.

Area of interest: Geological background

The Aishwariya Field, discovered in March 2004, is currently the third largest field discovered in the Barmer Basin of Rajasthan, India (Figure 1). This is a simple tilted fault block footwall structure with the bounding fault system located to the west and northwest. The producing reservoirs are the Palaeocene Fatehgarh and Upper Cretaceous Ghaggar Hakra comprising of single to multistoried, incised fluvial channels having porosities varying from 17% to 33% and permeabilities of 200 md to 20 Darcy. Figure 2 shows a type log response of the reservoir interval from an Aishwariya well.

Data set and methodology

Eleven (11) wells from the Aishwariya field were selected for rock-physics modelling, based on the availability of shear sonic data. Standard petrophysical interpretation, calibrated with core data, was available for these wells. Petrographic observations from four (4) cored wells were also used to integrate the rock physics observations with the textural information.

The first step in rock-physics modelling is to make observations to relate the dependency of well-based elastic parameters with the petrophysical reservoir parameters like porosity ($\phi$), water saturation ($S_w$) and volume of shale ($V_{sh}$). There are multiple factors which control elastic properties of a rock, like, lithofacies (or mineralogy), porosity, fluids, formation pressure and rock texture like variations in clay content, sorting, packing, or cementation. The relative effect of some of the parameters may be dominant over the other parameters. Understanding the critical controls on the elastic properties is essential to constrain the modelling approach. This is mainly achieved by cross-plotting the petrophysical parameters with the sonic velocities and correlating the observed trends with rock fabric and lithofacies information obtained from petrographic studies. The observed trends in the sonic velocity-reservoir quality cross-plots were then modelled through a set of empirical or heuristic or theoretical effective medium models. These models quantitatively link the reservoir quality parameters with the elastic parameters. Finally, these well-based rock physics models, put into appropriate rock physics template, are applied to calibrate and interpret the amplitudes obtained from seismic inversion volumes. We will demonstrate the application of these rock-physics templates by estimating the reservoir quality of the undrilled areas from seismic inversion attributes.

Rock physics trends: Observations and integration with core data

Volume of shale content ($V_{sh}$) has a significant effect on the sonic velocities (P-wave $V_p$ and S-wave $V_s$) and porosity (Figure 3). Increasing $V_{sh}$ significantly decreases the total porosity; however, the corresponding decrease in velocities are relatively
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smaller. There is a consistently decreasing Vp-\( \phi \) trend with increasing Vsh from the sands (Vsh \( \geq 0.05 \)) plotting in upper right, and increasingly shalier rocks plot towards the shale trend (Vsh = 1.0) occurring in the lower left part of the plot.

Figure 3: Vp-\( \phi \) crossplot of Fatehgarh formation from 11 wells in Aishwariya field. The data is color coded with volume of shale (Vs), with increasing darker color indicating higher Vsh.

The sands (Vsh \( \geq 0.05 \)) show significant scatter in the velocity-porosity domain. The dominant trend is a curvilinear increasing horizontal trend with a relatively small increase in Vp (and Vs) with decreasing porosity (Figure 4). There is also a significant scatter in the vertical direction, with few data points having higher velocities for the same porosity values. The more horizontal vector trends are commonly associated with depositional textures and in this case, can be correlated in deteriorating sorting effect with the sands, as observed from the petrographic studies (Figure 5). The lower porosity sands in Well#6, occurring on the upper sections of the individual channels, have a larger spread in grain-size, indicating poorer sorting, compared to the higher porosity sands which have more uniform grain size distribution with a better sorting. Deteriorating sorting implies increasing volume of pore-filling (non-cementing) material which causes lower porosities. The stiffer vector trends in the Vp-\( \phi \) domain are commonly associated with diagenetic textures. Comparison between two wells (Well#5 and Well#6) suggest presence of higher quartz overgrowth cements in Well#6, resulting in significantly stiffer rock fabric (hence higher velocities) relative to Well#5, with no/slight change in porosities (Figure 6).

To understand the effect of fluids and their saturation, Gassmann modelling studies were carried on the Fatehgarh sands. The Fatehgarh reservoirs are saturated with relatively heavier oil (API 30 -32°), and they are fluid substituted with 100% brine saturation. Figure 7 compares the P-wave velocities before (with in-situ saturations) and after fluid substituting with 100% brine. The change in P-wave velocity is 1-2% and the effect of fluid is
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insignificant compared to the effects with other parameters, like lithology and rock fabric.

Figure 6: Effect of cementation on Vp-ϕ trends in sands (Vsh ≥ 0.05) from Well#6 and Well#5. Thin sections suggest Well#6 have higher average cement content compared to Well#5.

These observations suggest that lithofacies (changing Vsh) have marked effect in porosity compared to that in velocities, and there is a systematic decrease in velocity-porosity trends with increasing Vsh. For clean sands, the velocity-porosity trends are dominated by sorting effects, which was superimposed by a second order cementation trend. The effect of fluid saturation on sonic velocities is relatively negligible as indicated by Gassmann fluid substitution modeling. These Vp-phit trends with increasing Vsh. For clean sands, the velocity-porosity trends are dominated by sorting effects, which was superimposed by a second order cementation trend. The effect of fluid saturation on sonic velocities is relatively negligible as indicated by Gassmann fluid substitution modeling. These observations now can be modelled by different rock physics models to quantify the trends.

Rock-Physics Modeling

Avseth et al. (2005) describe three heuristic rock physics models that have been used to diagnose the rock texture of medium- to high-porosity sandstones: (a) the friable sand model; (b) the contact cement model; and (c) the constant cement model. The clean sand trends observed were modelled using constant and contact cement models as shown in Figure 8. The data from Aishwariya field fall above the friable sand model as the sands are cemented. The data can be bound with a constant cement line with 1% cement. The upper bound of the data is modelled using a combination of contact cement model (Dvorkin and Nur, 1996) and upper Hashin-Shtrikman bound. The upper bound is a good representation of diagenetic effect like increasing quartz cement, while the lower bound accurately describes the effect of sorting. The entire data can be explained with multiple constant cement lines, with varying cement content. It may be noted that the Constant Cement line 1, which captured the lowest trend in the Vp-ϕ domain, passes through almost the middle of the data cluster in the Vs-ϕ. This suggests that the contact models overestimate the shear wave velocity, but capture the velocity trend with porosity. Avseth and Skjei (2011) reported that the Dvorkin-Nur contact-cement model
often over predicts shear stiffness in cemented sandstones, related to non-uniform grain contacts and tangential slip at loose contacts that are not accounted in the contact theory.

Applications: Reservoir quality diagnostics from seismic inversion volume

Seismic Inversion volume provides us separate volumes of two different attributes, Acoustic Impedance (AI) and Vp/Vs ratio. To apply the rock-physics models in interpreting the seismic inversion volumes, we cross plot the well scale AI-versus-Vp/Vs data and compare with specific rock-physics models constructed. Figure 10 shows a Rock-Physics Template (RPT) including the clean sands and shaly sand models calibrated to Aishwariya wells and superimposed on top of that well-log data, to capture the target zone.
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that these provide “What-if scenarios” to extrapolate our models to understand undrilled areas. For example, the clean sand trends predict the AI and Vp/Vs response of similar sand with increasing diagenesis and reducing porosity or increasing Vsh with change in depositional environment.

To predict and analyze the lithology content and porosity along the Fatehgarh reservoir tops with a hanging 30 msec window, we derive the acoustic impedance, and VP/VS ratio, as shown in Figure 11, using the seismic inversion workflow. The rock physics templates, in Figure 10, help us to differentiate the different lithologies and assess reservoir quality away from the wells in undrilled areas. For example, the highlighted area (dotted) towards the south-east corner have low AI and Low Vp/Vs ratio indicating high quality reservoir sands with high porosity. However, the area to the left has similar acoustic impedances but higher Vp/Vs ratio. Based on the rock physics template in Figure 10, we interpret the lithology in this area to be higher in shale content. If we rely only on acoustic impedance cut-off to understand distribution of sand, we would erroneously interpret the south-western area to be sand rich. Through the application of the well-calibrated rock physics template, the reservoir lithology can be interpreted accurately for the undrilled locations.

reservoir quality in undrilled locations to identify near-field hydrocarbon prospects in Fatehgarh formation close to Aishwariya field in Barmer Basin.

The main conclusions of this study are as follows:
1. Vshale content has a systematic decreasing effect on velocity-porosity trends for the Aishwariya Fatehgarh formation
2. Sorting effect dominates clean sand trend; Cementation shows 2nd order trend
3. Fluid saturation variation effect relatively negligible on velocities
4. A combination of constant cement model, tied to contact cement model, accurately models elastic behavior of Fatehgarh sands; however constant cement models overestimate the shear velocities
5. Constant clay models accurately capture the effect of Vsh on elastic property variation
6. Well-calibrated rock-physics template should be used for interpreting seismic inversion volumes.

Conclusion

We presented a case-study highlighting the application of rock-physics modelling in estimating

References
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