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Sand Body Delineation and Reservoir Characterization using Multiple Seismic Attributes: Simultaneous Partial Stack Inversion & Spectral Decomposition

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Summary

Aishwariya is the third largest discovery till date in CairnRajasthan block. Development drilling in the field commenced in early 2013. One of the key challenges in this field has been its structural and stratigraphic understanding. The main reservoir unit in Aishwariya is the Fatehgarh Formation, consisting of inter-bedded sands and shales. The Fatehgarh Formation has been divided into two members namely lower and upper Fatehgarh which were deposited in a fluvial-lacustrine environment. In this paper, focus is set on chasing prolific lower-most Fatehgarh sand using combination of structural and multi-attribute seismic work flow. The latest drilling results indicate a combination of stratigraphic thinning and complex fault pattern in the field. 3D PSTM seismic data is available in this area which was acquired in 2004-05. Seismic data quality at the field varies from to good" over the majority of the structure and to "poor to very poor" at the crest adjacent to the main bounding faults (MBF). This poses main challenge in development well placement, reservoir characterization and production monitoring in the major part of the field.

Moreover, it was difficult to undertake even basic horizon interpretation within the specified development zone of interest. Henceforth, it was essential to delineate the lithology to map the stratigraphic reservoirs in the zone of interest. The objective of this study was to delineate fairways of lower Fatehgarh prolific sands so as to optimally place our development wells.

Keywords: *Feasibility Studies, Main Bounding fault, Partial Angle Stack, Simultaneous Inversion, Spectral Decomposition, Structural Interpretation*

Introduction

The Aishwariya field is located in the northern part of the Barmer Basin, Rajasthan (Figure 1), and is one of several large rotated fault block structures formed during late Cretaceous to early Paleocene rift initiation in the basin. Structurally, the field is a relatively simple fault block footwall high, with a major block bounding fault system to the west and north-west. Initial faults have a distinct NE-SW orientation, and may be basement structure related. These are cut by later more North-South extensional faults which now carry most of the block bounding displacement.

Methodology

Structural Interpretation

The key horizons interpreted in the field based on Well to Seismic correlation are Top Barmer Hill, Upper Fatehgarh, Lower Fatehgarh and Base Fatehgarh. Drilling of crestal wells in the field came with a surprise with missing basal sand in some of the wells not exactly correlatable at field level at seismic scale (Figure 2). Seismic dataset also provide us with some clues in Base Fatehgarh reflector discontinuity at crestal level indicating possible faults antithetic to Main Bounding Fault. This possibly could have created structural high and non-deposition of lowermost Fatehgarh sands. In subsequent sections various seismic attributes are discussed and their relationship with lower Fatehgarh sand body delineation.

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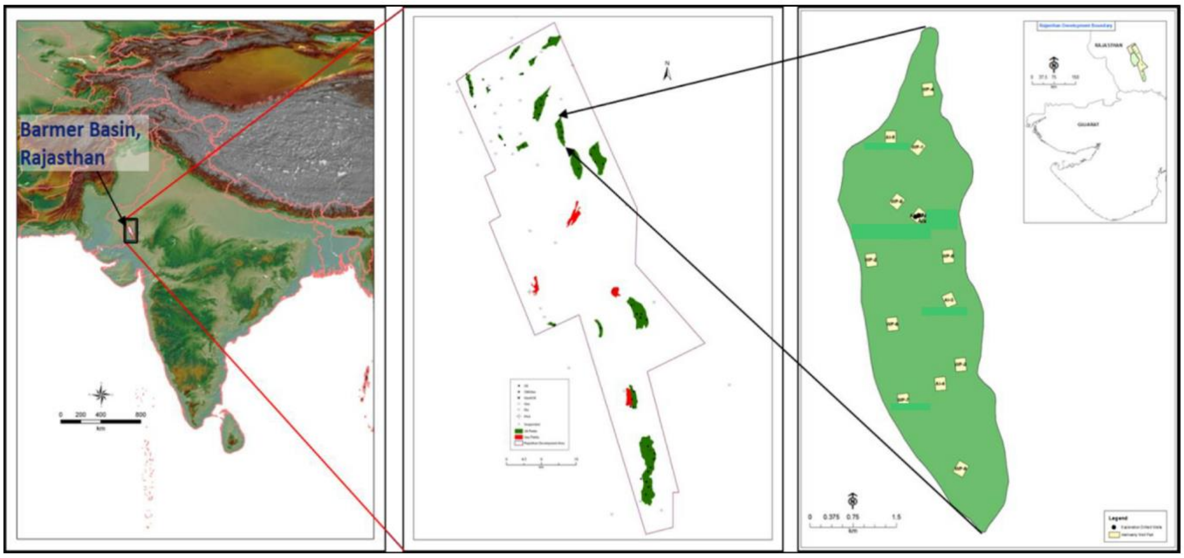


Figure 1: Location map of Barmer Basin and Aishwariya Field

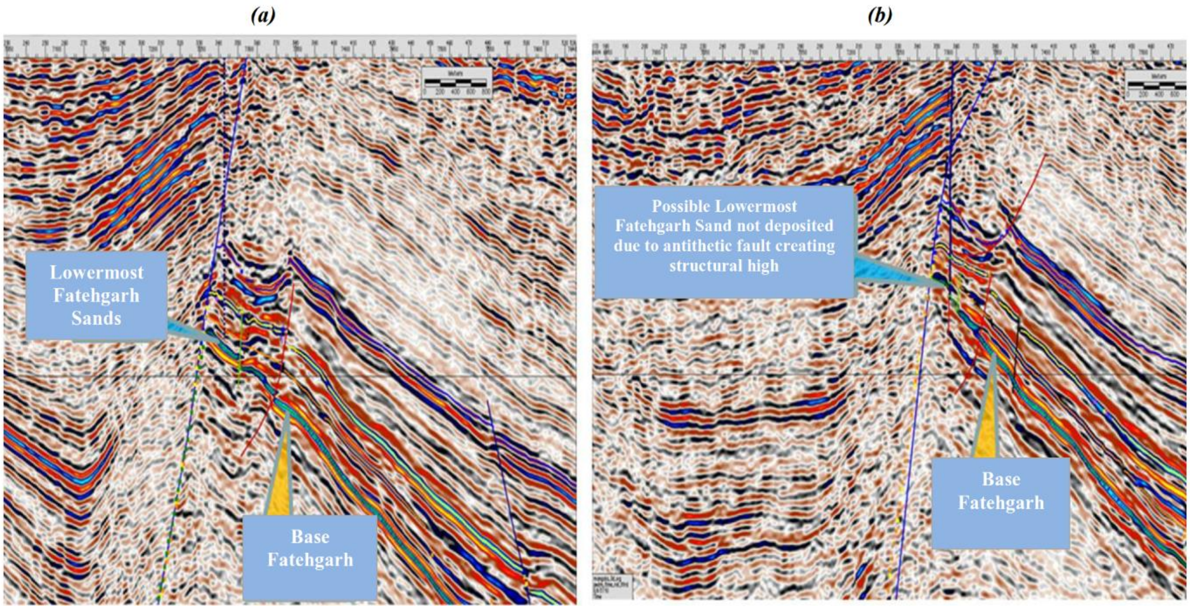


Figure 2: (a) Seismic section near A-22 base Fatehgarh continuity indicating lowermost Fatehgarh deposition; (b) Seismic section near A-18 base Fatehgarh discontinuity and dimming of amplitude; possible non deposition of lowermost Fatehgarh sands at crest.

Spectral Decomposition

This signal analysis technology has been used successfully in 3-D seismic surveys to delineate stratigraphic settings such as channel sands and structural settings involving complex fault systems (Partyka et al., 1999). The concept behind spectral decomposition is that a reflection from a thin bed has a characteristic expression in the frequency domain that is indicative of the temporal bed thickness.

The amplitude spectrum interference pattern from a tuned reflection defines the relationship between acoustic properties of the individual beds that comprise the reflection (Gochioco et al., 1991). Amplitude spectra delineate thin bed variability via spectral notching patterns, which are related to local rock mass variability (Sinha et al., 2004). Likewise, phase spectra respond to lateral discontinuities via local phase instability. Together, the amplitude and phase related interference phenomena allow the seismic interpreter to quickly and efficiently quantify and map local rock mass variability within large 3D surveys (Liu et al, 2011).

This is carried out by capturing the seismic response at each frequency subset; essentially, a -capture" of the seismic image for each of these intervals can be input into an animated sequence from lower frequencies to higher frequencies, thus revealing spatial changes in Stratigraphic thickness otherwise impossible to ascertain from the full frequency dataset. Spectral decomposition reveals details that no single frequency attribute can match (Chakraborty et al, 1995).

Feasibility Studies & Facies Prediction

Tuning cube was created using the CWT (Continuous Wavelet Transform) method using Morlet wavelet (Sinha et al., 2005). The various horizons were viewed at different frequencies and the responses were studied (Figure 3). These responses were compared with the amplitude maps to see the difference in illumination of different features. The well logs were studied to understand the levels at which sand responses may be expected and accordingly the various time shifts were applied to the identified horizons.

Simultaneous Inversion

Seismic inversion is a technique that combines surface-acquired seismic data and well log data to develop a model of subsurface layers and their thickness, density, and P- and S-wave velocities. It is an integration tool for the construction of seismic-scale reservoir models that are

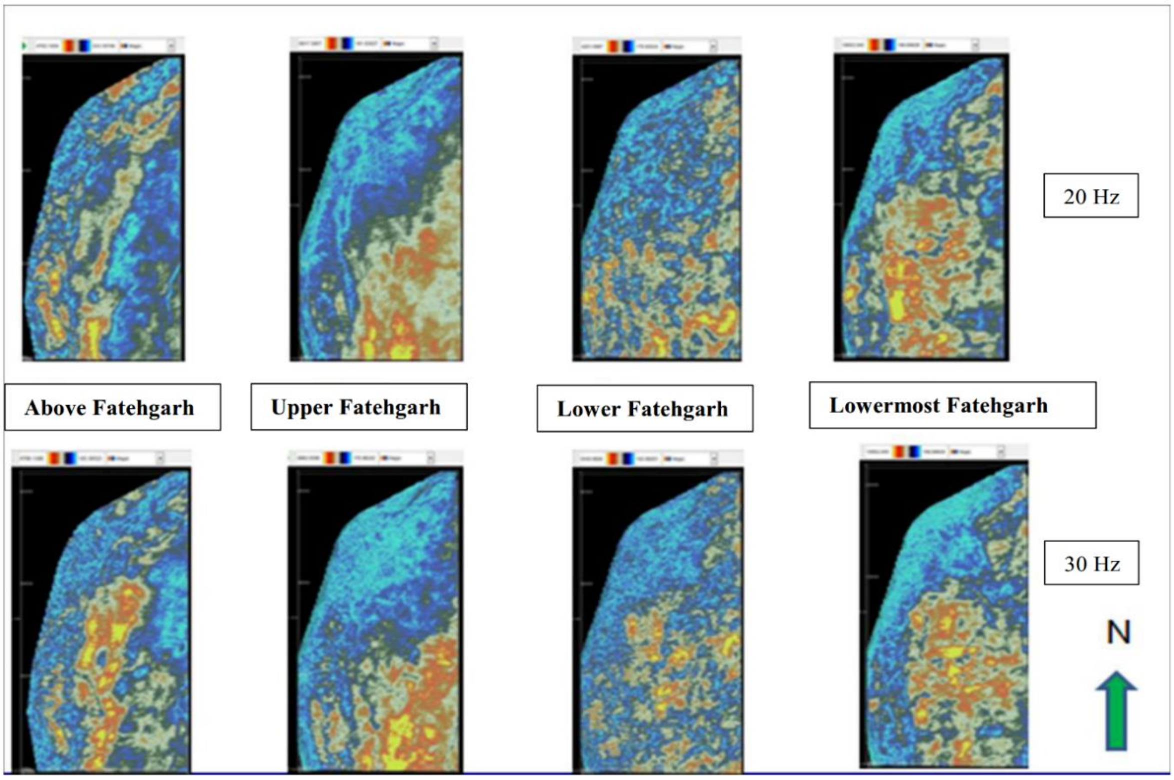


Figure 3: Frequency slices at the various horizon levels

consistent with rock physics knowledge, well data and seismic amplitude information. Seismic inversion provides a means to estimate rock properties from seismic data. To guide and constrain the interpolation of reservoir properties during simultaneous inversion, a prior low frequency model was generated by laterally extrapolating filtered well log data, using seismic horizons and interval velocities as constraints (Basha et al., 2012). Then the inversion was executed, which produced three outputs: acoustic impedance, shear impedance, and density.

A Rock physics study was undertaken to integrate seismic, petrophysical and geological data. The study included depth trends of different acoustic & elastic properties within the zone of interest to underpin which seismic inversion attribute best replicates the reservoir character. The corrected well data and the structure surfaces, obtained from seismic interpretation, were used to build a low frequency model of elastic parameters in the zone of interest. As a result of the 3D seismic data processing, three partial angle stacks in the range of incidence angles of 5^0–45^0 were produced namely Near, Mid and Far angle stacks.

After that, well-ties were performed and wavelets were estimated for each of three angle stacks. The final wavelets are shown in Figure 6. The comparison of inversion results with well data within the seismic frequency band indicated a high precision in the elastic parameters recovery (Yakovlev et al., 2010).

Inversion Feasibility Studies

The expected contrast in elastic properties between the Fatehgarh reservoir sands and inter-bedded shale helps to understand their seismic responses as a function of depth. Figure 4 shows the velocity and density trends with depth. The average density of reservoir sandstone and non- reservoir shale in Fatehgarh is nearly 2.2 g/cc and 2.55 g/cc respectively whereas the average velocities of the same lithologies are roughly 3200m/s and 3700m/s respectively. It indicates that density is a good discriminator whereas velocity is a moderate discriminator of the lithology in the Fatehgarh Formation. Partial angle stacks have limited angle information ranges from 5^0-45^0 only. Hence, it was not advisable to go ahead for inversion based on density.

Various cross plots have been derived to understand the best possible lithology discriminator. Cross-plot 5(a) below suggests that P-impedance and S-impedance has some linear trend for sand and shale, however, there is not any clear separation between the two. Hence, we derived few more attributes like Vp/VS, Lambda-Rho, Mhu-Rho etc. Cross-plot 5(b) shows good separation of lithologies.

Wavelet Extraction & Well Correlation

Initial studies suggested that the seismic is of a zero phase character. Available corridor stack were used to understand the phase character of the seismic. It was not possible to determine a single wavelet throughout the zone of interest for all three partial angle stacks. Hence, it was decided to go ahead with a deterministically derived wavelet for near, mid and far datasets which are almost consistent throughout the field (Figure 6).

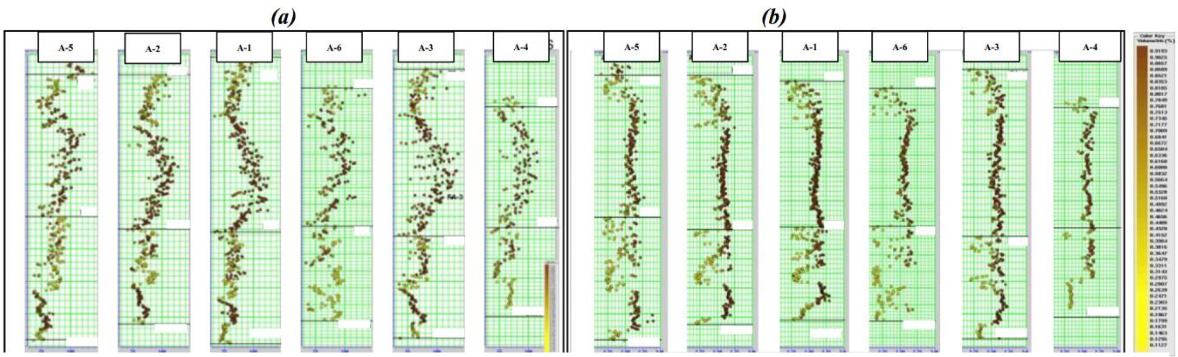


Figure 4: (a) Vp depth trends; (b) Density depth trends (Color Scale Vsh)

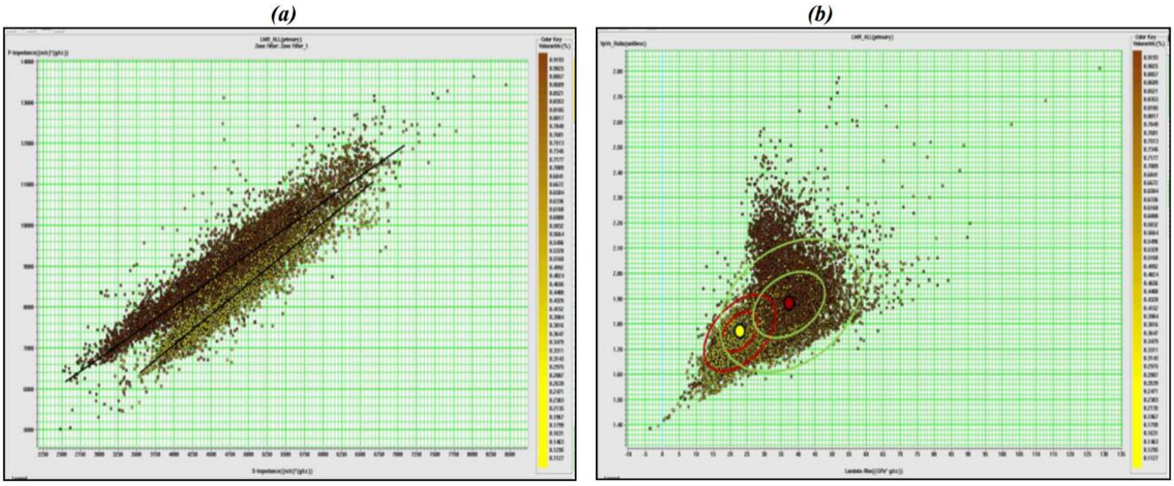


Figure 5: Cross plots (a) P-impedance vs S-impedance; (b) Vp/VS vs Lambda-Rho (Color Scale Vsh)

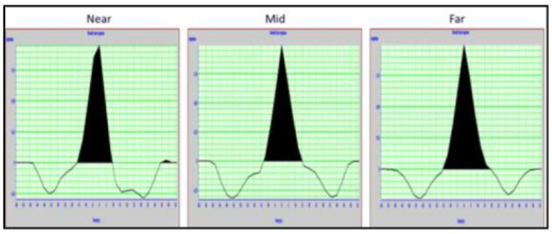


Figure 6: Deterministically Extracted Wavelets

Observations and Results

It is observed that at different frequencies various morphological features are highlighted which are not evident from the amplitude maps. There is no response in the northern crest side in both the maps which is due to loss of frequencies and amplitude in that region. The flanks and southern parts respond well to spectral decomposition as the data quality of the seismic in this area is good with dominant frequencies as high as 25-35 Hz.

It is observed that at 20 Hz some illumination is observed just adjacent to well A-4. By shifting up from the Base Fatehgarh by 12ms we are at the lowermost Fatehgarh level where around 17 m sand package is present as seen from well log of A-4 (Figure 7). This value correlates with λ/8 which is normally considered the limit of detectability (Widess, 1973).

Hence, at A-4 these may be detectable but not resolvable. Same observation can be made around A-13 when shifting down by 24ms from the lower Fatehgarh which too coincides with lowermost Fatehgarh level. From the well log it is observed that we are again at the sand level. Also, this level at A-4 comes out to be at lowermost Fatehgarh and we observe the illumination which correlates with our previous result. It is also observed that highlighted feature around A-3 splits into two as frequency is increased.

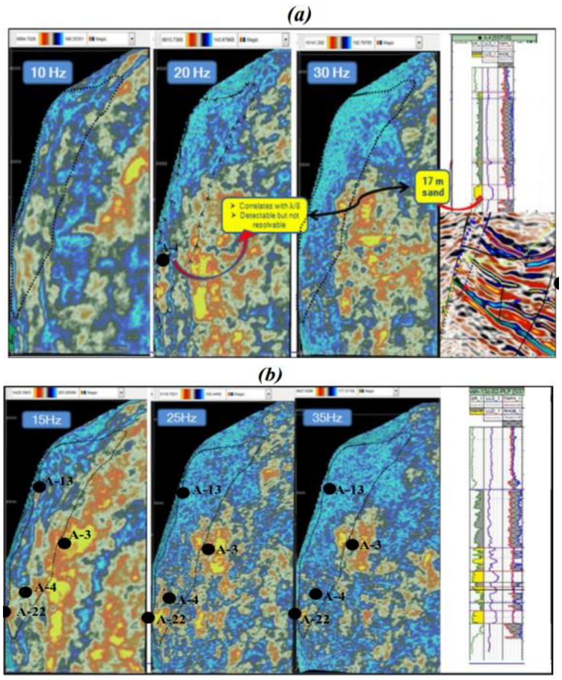


Figure 7: (a) Frequency slices by shifting Base Fatehgarh up by 12 ms; (b) Frequency slices by shifting lower Fatehgarh down by 24 ms

Moreover, as we go down the width of this feature increases. The trend is N-S which is also the geological trend in this area and this level is expected to have a channelized environment. Hence these features may be channels or channel systems. If the same shift is applied at 25 Hz (represent thicker parts than 35 Hz), again same kind of features are illuminated but their position is shifted in space (figure 8a). If we try to superimpose these on top of one another it is observed that the 25 Hz feature lies towards the center of the 35 Hz feature which is very logical as the center of the channels are thicker (figure 8b). The inversion results show a good match with the log data.

When the map of mean values of Vp/Vs and Lambda-Rho were extracted and compared with results from spectral decomposition at the lowermost Fatehgarh level the same type of signatures were observed which gives us an idea that thicker basal sands may be present south of A-4 and west of A-3 wells (figure 9). The results were validated after drilling of A-22 well south of A-4 well, where we encountered 20m of good quality lowermost Fatehgarh sand.

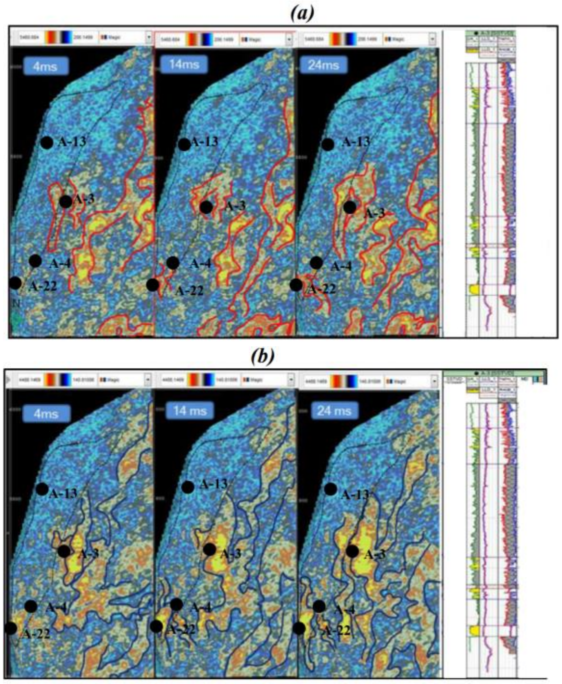


Figure 8: (a) Lower Fatehgarh shifted down by 4ms, 14ms and 24 ms at 35 Hz; (b) Lower Fatehgarh shifted down by 4ms, 14ms and 24 ms at 25 Hz

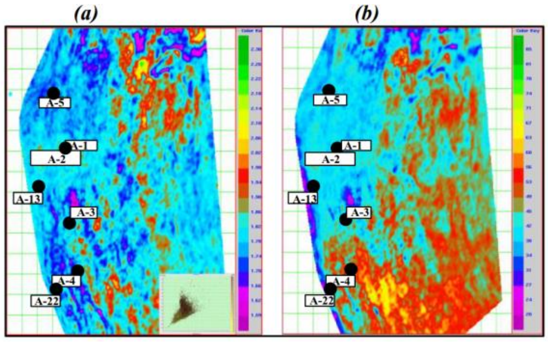
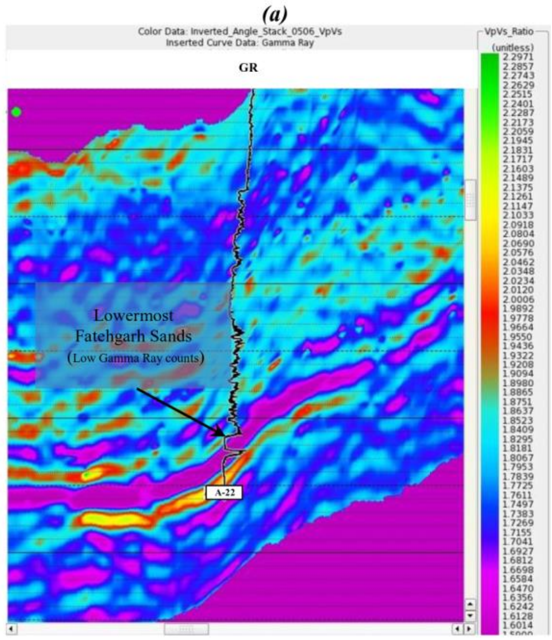


Figure 9: Mean Value of (a) Vp/Vs and (b) Lambda-Rho at lowermost Fatehgarh level

Correlation with well data

Inversion and spectral decomposition studies have shown clear indication of sand fairways in lower Fatehgarh formation particularly at Lowermost Fatehgarh level. The same has been drilled and we got gross reservoir thickness of around 20 m at Lowermost Fatehgarh level. The figure 10 shows comparison of both the results (predicted and measured), which is very well matches with structural interpretation.



(b)

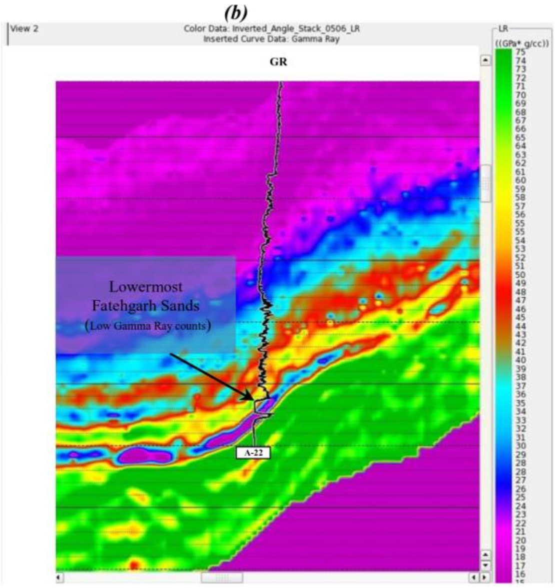


Figure 10: Comparison of Predicted & Measured values of (a) Vp/Vs & (b) LR.

Conclusion

Spectral Decomposition and Simultaneous Inversion complement each other. Each individual study helped in demarcating sand fairways in the field particularly in southern part where we have good seismic amplitude information and frequency to deal with. Integration of quantitative and qualitative interpretation helped a lot in optimization of well placement. Rock physics and QI studies together with structural interpretation solved the objective of selecting optimal well locations. Moreover, recently drilled development well (in southern part) shows encouraging results and shows how multiple seismic attribute analysis can help in minimizing uncertainties during development phase.

Acknowledgement

The authors thank key subsurface professionals at Cairn India who contributed to this work, particularly Ananthakrishnan B., Peter Hansen and Sanjay Kumar for supporting our work. The authors also acknowledge the full support of the Bhagyam Aishwariya subsurface team, and RJ/ON/90-1 Field Joint Venture partners, Oil and NaturalGas Corporation to carry out studies. We thank the management of Cairn India for their encouragement & permission to publish the work.

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