Reservoir characterization of Kamalapuram and Nannilam sands Using Elastic Attributes in Tiruvarur Field of Cauvery Basin

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Summary
Tiruvarur field is one of the prolific Hydrocarbon producing fields of Cauvery Basin by hosting oil & gas from both Paleocene Kamalapuram and Upper Cretaceous Nannilam reservoirs. Reservoir characterization of these two major Paleocene (PS) and Nannilam sand (NS) is carried out by Pre-stack inversion and subsequently converted Lame’s elastic parameters, \( \lambda \rho \) (Lambda-Rho) and \( \mu \rho \) (Mu-Rho). Feasibility study of seismic inversion on log and seismic scale clearly discriminates fluid and lithology. (Hydrocarbon sands have \( \frac{V_p}{V_s} = 1.55-1.7 \), Brine sands have \( \frac{V_p}{V_s} = 1.7-1.9 \) and shales \( \frac{V_p}{V_s} > 1.9 \)). Geobodies bodies are captured from the polygon filter between \( V_p/V_s \) and P-impedance. The geometries of captured facies “bodies” are consistent with well control and geological information. The presence of additional Geobodies might be valuable in future for play extension and field growth.

Introduction
Reservoir characterization has gained critical significance in recent times as the days of easy oil are over and facies heterogeneity is witnessed during play extension and field growth. Seismic inversion for acoustic impedance has been widely practiced in the E&P industry for reservoir characterization as it is a good lithological discriminator. Where reservoirs cannot be delineated by P-impedance alone, \( V_p/V_s \) is used for both fluid discrimination and litho variations (Aki and Richards, 1980). Since the sensitivity of P-wave velocity (Vp) to fluid changes is higher than that of S-wave velocity (Vs); thus change in \( V_p/V_s \) ratio in a reservoir would indicate different fluid saturation.

\[
V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad \text{and} \quad V_s = \sqrt{\frac{\mu}{\rho}}
\]

Where \( V_p \) and \( V_s \) are compressional and shear wave velocities, \( \lambda \) is Lame’s coefficient (Incompressibility), \( \mu \) is shear’s modulus (rigidity) and \( \rho \) is bulk density.

Prestack seismic inversion’s output is used to calculate the Poisson’s ratio. It is a diagnostic lithologic indicator (Avseth Per et al., 2005) and measures the longitudinal change of material when it is affected by lateral compression or tension. The Poisson ratio of various rocks lies between 0 and 0.5; below ~0.25 represents sandstone and greater than ~0.3 represents shale.

\[
\sigma = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}
\]

The basic impedances of both compressional and shear wave derived from seismic Inversion has been used for the estimation of Lame’s Parameters; \( \mu \rho \) (Mu-Rho) measures rigidity of rock where high rigidity discriminates sandstone from shale. Another Lame’ parameter; \( \lambda \rho \) (Lambda-Rho) measures incompressibility of rock, where for a given lithology, gas sand is having lower \( \lambda \rho \) than that of water bearing sand (Goodway et al, 1997).

\[
Z_s^2 = (\rho V_s)^2 = \mu \rho \\
Z_p^2 = (\rho V_p)^2 = (\lambda + 2\mu)\rho \\
Z_p^2 = (\lambda \rho + 2\mu \rho) \\
Z_p^2 = (\lambda \rho + 2Z_s^2)
\]

Hence \( \lambda \rho = (Z_p^2 - 2Z_s^2) \) and \( \mu \rho = Z_s^2 \)
Reservoir characterization of Kamalapuram and Nannilam sands Using Elastic Attributes in Tiruvarur Field of Cauvery Basin

Geology and Location of the study area

Cauvery basin lies along south-east coast of India which is a pericratonic rift basin evolved during Late Jurassic along with other East-coast basins of India. The basin has attained a passive margin setup after Cretaceous and hosts huge sediments ranging from Jurassic to Recent. The rifting and drifting along with the interaction of cross-trends (NE-SW rift trends and NW-SE Dharwarian cross-trends) have configured the basin into several sub-basins separated by intervening horsts (Fig. 1). Late Jurassic to Albian synrift shales of Andimadam formation are the established mature source rocks in this basin. Hydrocarbons have been established in several reservoirs ranging in age from Proterozoic fractured basement to Oligocene Neravy sands.

Figure 1: Tectonic map of Cauvery basin (left) and prospect map showing study area of Tiruvarur field along the flanks of Karaikal high (right).

Tiruvarur field lies the north-eastern part of Nagapattinam sub-basin along the southwestern flanks of Karaikal ridge of Cauvery basin (Fig.1). The field was discovered in 1990s and is still producing commercial volumes of oil and gas from several sands of Nannilam Formation of upper Cretaceous age and from one sand in Kamalapuram Formation of Paleocene age. Entrapment is mainly strati-structural and structural. The major Paleocene sand (henceforth referred as PS) has a variable sand thickness of 10-80m while the other major Nannilam Pay sand (hereby referred as NS) has 20-100m thickness. Present study is focused to delineate the reservoir distribution of these two major sands for their field extension by the application of different elastic parameters derived Pre-stack inversion study.

Methodology

The following workflow is adopted to carry out the Prestack seismic inversion for the present study (Fig.2).

A. Log conditioning and Rock Physics Modelling:

Total 34 wells have been drilled in the field. All drilled wells have at least a basic log suit to support Petrophysical evaluation. Shear sonic logs are available in four wells and by using these logs Rock Physics Modelling (RPM) was carried out for six wells for the present study.

B. Feasibility study:

Post stack seismic inversion does not support interpretation in the field where the reservoirs’ sandstones and shales cannot be distinguished from P- impedance alone. So, Prestack seismic inversion was attempted to bring out different facies distribution. Feasibility of Pre-stack inversion was
carried out and able to achieve the desired discrimination through cross-plot between P-impedance and Vp/Vs at log and seismic scale. Cross plot depicts three clusters of data; it separates the lithology and pore-fluids. Hydrocarbon bearing sands (red polygon) show low values of Vp/Vs (1.55-1.7) and P-impedance (6000-10000 m/s²/g) while brine sands are having relatively moderate Vp/Vs (1.7-1.9) with overlap of P-impedance (blue polygon) range. Shales are bearing high values of Vp/Vs (>1.9) with wide range of P-impedance (Fig. 3).

**C. Conditioning of Seismic data:**

In a Pre-stack approach, Conditioning of CDP Gathers is essential for quantitative interpretation of inversion end results. At the outset mute was applied to remove faulty data from the set of gathers by setting the amplitude for this data to zero. Then Seismic Super Gathers were created to enhance the signal to noise ratio. Multiples are bad because inversion will treat them as primaries; Parabolic Radon filter was used in a very sophisticated way to reduce the multiples. Subsequently Trim Statics was applied to fix migration move out problems and align the events on gathers and finally generated angle gathers (5°-36°) is appropriate range for inversion) inversion study (Fig.4).

**D. Well-to-Seismic Tie and Structural framework:**

The well to seismic tie is a crucial step in Seismic interpretation (a.o. White and Simm 2003) and estimation of exact wavelet is core part of seismic inversion because it facilitates the proper identification of impedances boundaries. Average statistical wavelet was used in inversion. Structural model has been prepared by mapping faults, the top envelope surfaces of Paleocene, K/T and G-1 (Turonian top) and levels close to pay top and bottom of PS (Paleocene sand) and NS (Nannilam Sand) (Fig. 5).

**E. Low Frequency Model:**

The seismic data is band limited or relative (~10-40Hz) due to the absence of low frequency (below ~10 Hz). So, inverted physical property (acoustic impedance, shear impedance and density etc) would
Reservoir characterization of Kamalapuram and Nannilam sands Using Elastic Attributes in Tiruvarur Field of Cauvery Basin

also be bandlimited or relative. But Interpreters need absolute impedance, density for quantitative interpretation like porosity, saturation etc. therefore, Low frequency modelling is an important part model based seismic inversion. These low obtained from seismic velocity and well data. In addition, this process enhances the resolution of the inversion output and helps to propagate the elastic properties of well logs. Low Frequency model (LFM) was generated using horizons, well log data by using the inverse square distance technique to populate the data. Fig. 6 depicts modeled P-impedance consistent with log P-impedance.

Figure 6: Low Frequency Model of P-Impedance.

Analysis of Inversion Results and Reservoir Characterization

Paleocene Kamalapuram sands are known as the channel fills in K/T canyon cut while Nannilam sands are mostly deposited as slope fans, slumps, debris flows and as channels.

The generated Vp/Vs volume has found to be in good match with well data especially for the major Paleocene (PS) and Nannilam sands (NS) (Fig. 7a). Using polygon filter (ranges of Vp/Vs <2.0 for Brine and Hydrocarbon sands) in the cross-plot between P-impedance vs Vp/Vs, extracted geobodies are effectively explaining the drilled wells in both Nannilam and Paleocene sands (Fig. 7b).

Figure 7: (a) Vp/Vs and (b) Geobodies extracted from polygon filter in Vp/Vs vs P-impedance shows the prominent geobodies for NS and PS in both sections and are matching with well data. Wells A & B are hydrocarbon producers from both NS & PS sands while Well D is hydrocarbon producer from NS sand.

In addition to the vertical sections, stratal slices extracted for Paleocene sand (Fig. 8a) and upper Nannilam sand (Fig. 8b) from Geobody volume to visualizes areal extension of facies. This supports the presence of low Vp/Vs sands in the main producing field (central area) and validating the geological model of sand dispersal. Sand provenance is from NW (adjacent Karaikal high).

Geobodies for PS sand (15ms below from PS sand top) shows the distribution of better reservoir facies PS (Fig. 9a), while it also gave presence of two additional sand bodies at west and southern areas (shown by circles in fig. 9a). Extracted Geobodies for Nannilam sand (25ms below from NS sand top);
justifies all producing wells in the central part (Fig. 9b). The wells D & E drilled further east are in separate fault block and are hydrocarbon producers from NS sand. The results are justifying these wells along with an additional sand body is present in the adjacent fault block (shown in circle in fig. 9b).

An effective fluid indicator can be found on cross plot of poisson’s ratio and Vp/Vs in the area. Hydrocarbon zones possess low poisson’s ration (< 0.25) as compared to brine sands. Shalier zones bearing relatively higher poisson’s ratio (> 0.3) than sands. Sweetspots can be established by using the relationship between Poisson’s ration and Vp/Vs subsequently brine and shale zones can also be identified. The selected polygon on the cross plot captures hydrocarbon zone (red) and brine zone (blue) at well-A and Well-B (Fig. 10).

The impedance logs and volumes were converted to Lame’s parameter to estimate other geophysical parameter which also discriminates fluid and lithologies. Fig.11 shows that hydrocarbon bearing sands possess high \( \mu \rho \) because of sand’s rigidity and low \( \lambda \rho \) because of less incompressibility of fluid content within the sandstone (Waffa El-shahat,2014). The selected polygon on the cross plot captures hydrocarbon zone (red) at well-R (Fig. 13). The results confirmed that this process may also be used to charactherize the reservoirs and to separate hydrocarbon bearing sands form water bearing sands and shales.

Conclusions
This study is an integrated work to characterize the Paleocene and Nannilam sands through elastic attributes

Since the well logs can differentiate the hydrocarbon zones from surrounding geology. So the Prestack seismic inversion is also a useful product for interpretation as expected.

The attributes of Acoustic impedance, Shear Impedance, Vp/Vs, Geobodies, Poisson’s Ratio and Lambda-Mu-Rho are good tools to discriminate lithology and fluid content within reservoir.

Geobodies bodies are captured from the polygon filter between Vp/Vs and P-impedance. The geometries of captured facies “bodies” are consistent with well control and geological information. The presence of additional Geobodies might be valuable in future for play extension and field growth

It is recommended to record shear-wave (DSI) at more no of wells to increase the level of confidence in reservoir characterization.
Reservoir characterization of Kamalapuram and Nannilam sands Using Elastic Attributes in Tiruvarur Field of Cauvery Basin

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