Mapping Sweet Spots in a Shale Reservoir through Simultaneous Inversion of 3D Seismic Data

Mukul Srivastava[1], Ajit Sahoo[1], Diya Mukherjee[1], Rudranath Mukherjee[1,2] and Ranjit Shaw[2]
[1] Reliance Industries Limited, [2] CGG Services India Pvt. Limited.
E-mail: ranjit.shaw@cgg.com

Keywords

Shale Reservoir, Sweet Spot, Simultaneous Inversion

Summary

In contrast to a conventional clastic or carbonate reservoir, where sweet spots for drilling are defined by petrophysical properties like porosity, volume of clay and water saturation, in a shale reservoir the same are characterized by geomechanical properties of the rock such as brittleness, elastic moduli, Young's modulus, Poisson's ratio and total organic carbon (TOC). An accurate description of the reservoir and appropriate mapping of the sweet spots are key for an optimized drilling campaign in shale gas reservoirs, The detailed mapping of sweet spots helps in proper planning of well location and completions. Traditionally, such programs are heavily dependent on well logs recorded at pilot wells. ,traditionally, post-stack seismic attributes are used to augment interpretations from the well logs to avoid zones of structural complexities, such as faults etc. Recently, rich information available in seismic gathers in the form of Amplitude Variation with Offset (AVO) has been used to achieve these objectives (Sena et al., 2011; Gabino et al., 2014). We present here the results of simultaneous inversion of multiple offset stacks from a 3D onshore survey over a shale block from the United States to demonstrate that geomechanical properties derived from inversion provide invaluable information to map sweet spots for further use in well planning and designing of hydraulic fractures.

Introduction

The search for unconventional reservoirs for oil and gas met with great success in the last decade in the form of exploration and development of shale gas and shale oil reservoirs. With the rapid growth in hydraulic fracturing, the challenges and complexities associated with the well placement and completions are better understood. Initially 3D seismic data over shale reservoirs played a very limited role in identifying the sweet spots which are different in character from conventional reservoirs. Sweet spots in shale reservoirs (Waters, 2011) are characterized mainly by the brittleness of the rock and the total organic carbon. Brittleness can be derived from other properties like Young's modulus and Poisson's ratio. On the other hand, TOC has a direct impact on the density of the rock. This shows that simultaneous AVA inversion plays a key role to play in characterizing these reservoirs. Typically P-impedance, S impedance and density can be directly derived from simultaneous inversion of multiple offset/angle stacks, which in turn, can be used to define the brittleness and TOC. In the present study over a shale block from the United States we integrated rich information available in 3D PreStack Time Migration (PSTM) gathers, seismic velocity, measured elastic and density logs from 3 wells, and two horizons interpreted from full stack seismic data. The inverted volumes of P-Impedance, Vp/Vs and density are further used to derive geomechanical properties including brittleness index and volume of carbonate and sand. Three different facies have been classified on the basis of these geomechanical properties along with TOC. Maximum probable facies and the associated probabilities have been derived within the target zone covering the shale layer. The result indicates that properties derived from seismic inversion can provide valuable information for planning of exploration and development wells.

Method

We have used a standard simultaneous inversion workflow in the present study. Multiple offset stacks were created from PSTM gathers. These stacks are integrated with well data and seismic velocity through simultaneous inversion to produce a model of the absolute elastic properties of the reservoir and surrounding rocks. These elastic properties are then used to derive relevant geomechanical properties based on a petro-elastic model derived from the well data. This workflow is shown in Figure 1. Key elements of this workflow are summarized below for the sake of continuity and outlined below:

- Data loading and quality check
- Data conditioning
- Petrophysics and Rock Physics
- Well Tie and Wavelets
- Low Frequency Modelling
- Simultaneous Inversion
- Derivation of geomechanical properties and facies
- Time to depth conversion
- Interpretation

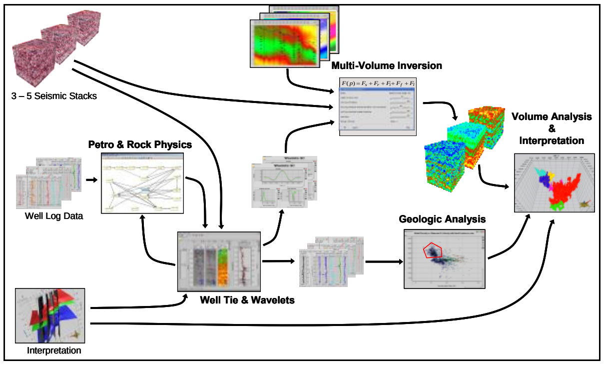

Figure 1: Standard workflow for simultaneous Inversion.

Data Conditioning

Since simultaneous inversion integrates multiple data sets with different sources, conditioning of each set of data is key to success of such studies. We outline below the basic conditioning of the different sets of data.

Seismic Gather

QC of PSTM gathers showed significant time misalignment at the target level which required to be corrected before generation of offset stacks for simultaneous inversion. Amplitude variation with offset (AVO) appeared to be reasonable with decreasing frequency content at the far offset. PSTM gathers were conditioned to align the major reflection events across offsets in the target zone to extract information up to ~60 degree angle of incidence. Seven offset stacks were generated to be used as input for simultaneous inversion. The frequency bandwidth varied widely across the different offset stacks.

Seismic Velocity

The interval velocities were found to be of good quality for use in the seismic inversion workflow after moderate lateral (median) filtering. Vertical filtering was applied to improve the data quality before calibration with well data. Good correlation with well velocity is observed. Conditioned interval velocities appear to be consistent with the structural setting of the area. Figure 2 shows the seismic velocities in section view after different stages of conditioning.

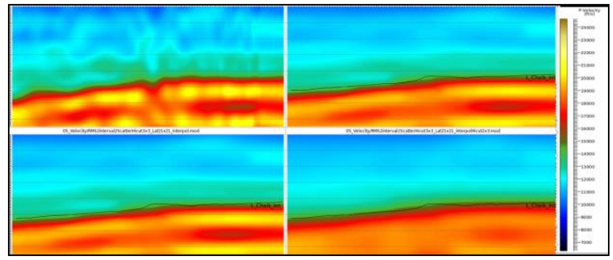

Figure 2: Section showing interval velocity from RMS velocity in a coarse grid (top left), interval velocity after application of median filter (top right), interpolation to seismic grid (bottom left) and high cut filter to (bottom right). Other two figures show intermediate steps.

Well Logs

Three wells were available for petrophysics and rock physics analysis. There were some sections where Density and P-Sonic logs were affected due to bad bore hole conditions and gaps were observed in Density and Neutron logs. Sections which exhibited these issues were corrected and patched with synthesized logs. Only one well among these three had shear data recorded, a rock physics model was used in generating the missing shear information in the other two wells.

Petrophysics and Rock Physics

The aim of a petrophysical analysis is to accurately compute the volumes of hydrocarbons (fluids), kerogen and minerals (lithology). These data are later used as inputs to the rock physics modeling. The petrophysical phase of the workflow is carried out to provide suitable input to the rock physics stage, as well as meaningful evaluation of the petrophysical properties of the reservoir rocks.

The objective of the rock physics modeling is to provide a consistent set of elastic logs at each well for wavelet estimation, thus providing a link between the petrophysical properties and the elastic properties of the rocks (Vp, Vs, Density). This link will allow the elastic properties of the rocks, determined through seismic inversion, to be interpreted in terms of reservoir properties. This link can only be achieved accurately for full bandwidth inversion results. The methodology applied was to construct a rock physics model that was consistent with the petrophysical analysis and the elastic properties of the rocks as given by the conditioned well log data. The parameters of the rock physics model were determined where the measured data were complete and considered to be of good quality. The model was then applied everywhere to generate synthetic elastic logs that were used to determine the quality of the data. Where necessary, the synthetic data were used to replace poor quality data and to supply data where they were not measured. An example of the rock physics modelling output is shown in Figure 3.

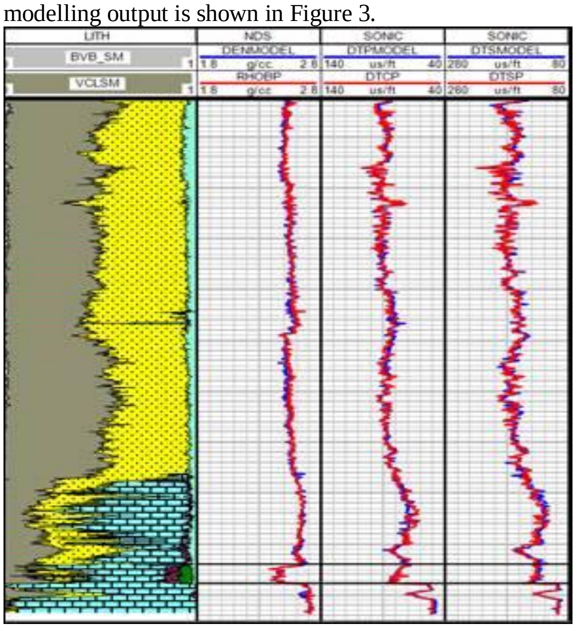

Figure 3: Comparison of measured logs (red) and modeled logs (blue) shown in last three tracks. The shear wave is shown in the last track.

Well Tie and Wavelets

AVO wavelets were extracted from well-seismic ties for each offset stack at the two well locations, which are within the seismic survey. The extractions were undertaken to cover the target zone bounded by top and base of the reservoir. The wavelets and well ties are of reasonable quality in the zone of interest. The conditioned logs show good to reasonable AVO match between the synthetic and seismic for key reflectors in the zone of interest.

Low Frequency Modeling

The low frequency elastic property models that contribute to the frequencies below the seismic bandwidth were built from a combination of seismic velocity, well log and rock physics information. A correct low frequency model will remove side lobes and provide absolute values for the elastic properties required for quantitative interpretation. Additionally, the low frequency model must be consistent with the geology and therefore often requires interpretation and iteration to achieve the desired results. For this particular study, the low frequency model was divided out into two part e.g. – Ultra-Low frequency & Mid-Low frequency.

The ultra-low frequencies (0-2 Hz) were derived from seismic velocities and transformed into the low frequency models of P-Impedance, Vp/Vs and density..

The mid low frequencies (2-12 Hz) were derived from the interpolation of well data. The final low frequency model was thus prepared by merging these two models, which were used as the inputs in the simultaneous inversion process. The final models are shown in Figure 4 below.

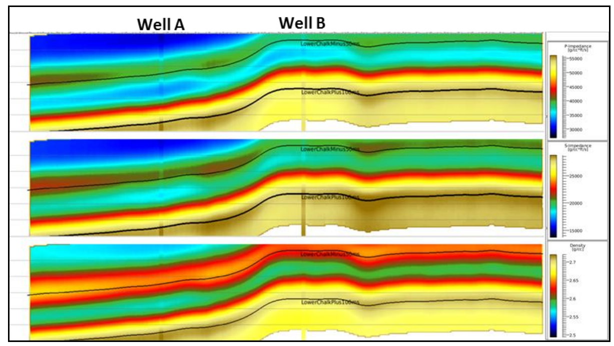

Figure 4: Section showing the Low Frequency models for P-impedance (top), Vp/Vs (middle) and density (bottom). Blue indicates lower value & golden-yellow indicates higher value.

Simultaneous Inversion & QC

Simultaneous multiple offset stack inversion combines the information from the low frequency model with the seismic reflectivity data to produce broadband elastic property models of the reservoir and surrounding rocks. The main results are models of P-impedance, Vp/Vs and density with frequency content up to about 40 Hz. Key aspects of this inversion were that the near stack and ultra-far stack was weighted down with respect to the other stacks. Also, correlation between inverted and wireline P-impedance and density logs are reasonable enough indicating a good quality inversion. Quality of inversion for Vp/Vs was comparatively poorer. The full bandwidth inverted results are shown in Figure 5.

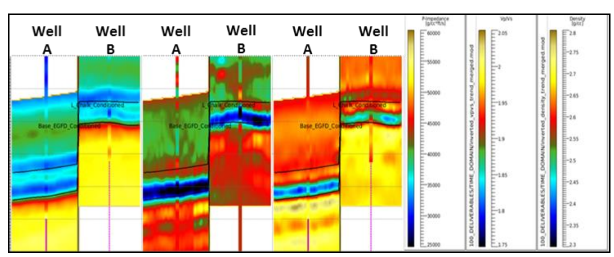

Figure 5: Inverted full bandwidth P-Impedance (left), Vp/Vs (middle) and density (right) around wells. Blue

indicates lower value & Golden-yellow indicates higher value.

QC of the inverted result within seismic bandwidth shows very good match for P-Impedance and Density whereas the match for inverted Vp/Vs was moderate. The comparison for both the wells is shown below in Figure 6.

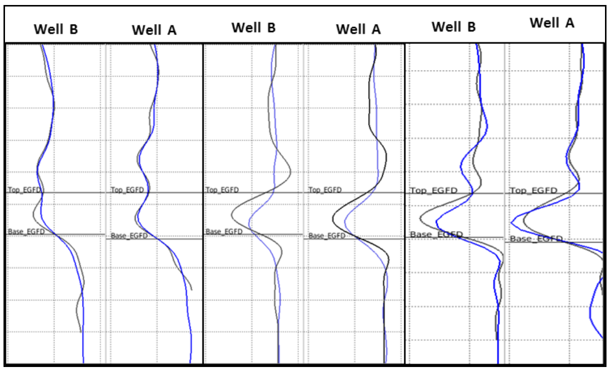

Figure 6: Inverted (Blue) and wireline (Black) P-Impedance, Vp/Vs & Density logs from left to right respectively.

Geomechanical Properties and Brittleness Index

The inverted elastic property volumes were thus used to compute the geo-mechanical property volumes such as Young's Modulus, Poisson's ratio etc.. Carbonate and sand volume show a positive correlation with P-impedance, facilitating its derivation from inverted P-impedance. Additionally, the volume of kerogen has also been derived from a linear relationship between P-impedance and kerogen observed in the well logs and cores. In this study Brittleness Index (BI) is defined in terms of Young's modulus € and Poisson's ratio (υ). Shales with higher E and lower υ tend to be more brittle (Rickman et al., 2008). Waters et al. (2011) defined BI as:

$$BI = 0.5 * [(E - E_{min}) / (E_{max} - E_{min}) + (\upsilon - \upsilon_{max}) / (\upsilon_{min} - \upsilon_{max})] \quad \ldots(1)$$

Where, E and υ are Young's modulus and Poisson's ratio at each depth location along a well path. E_{min} and E_{max} are the minimum and maximum vertical Young's modulus in the interval of interest; υ_{min} and υ_{max} are the minimum and maximum vertical Poisson's ratio in the interval of interest, respectively.

Facies Classification

Facies classification is required to interpret the inverted rock properties and derived geomechanical properties with the objective of mapping sweet spots characterized by regions of high brittleness and/or high volume of carbonates and sands and relatively high volume of TOC. However, It should be noted that at seismic frequencies, there is significant averaging of these properties, resulting in increasing the uncertainty in discriminating amongst these facies. Thus, these facies are always interpreted in terms of associated probabilities. The probability of occurrence of a particular facies at a location within the zone of inversion is derived under the framework of Bayesian inference (Avesth et al., 2005) which can be simply put as

P(Facies| Rock Property) α

P(Rock Property| Facies). P(Facies) … (2)

where, *P*(Facies) represents prior probability, the probability of occurrence of a facies before any additional knowledge or inference from results and analysis of inversion. (Rock property| Facies) represents the conditional probability of occurrence of a value of a specific rock property, e.g. P-impedance, given the facies. It is also called the likelihood function. *P*(Rock Property) represents the probability of occurrence of a particular rock property and is considered constant. Cross-plot analysis for facies classification is shown in Figure 7.

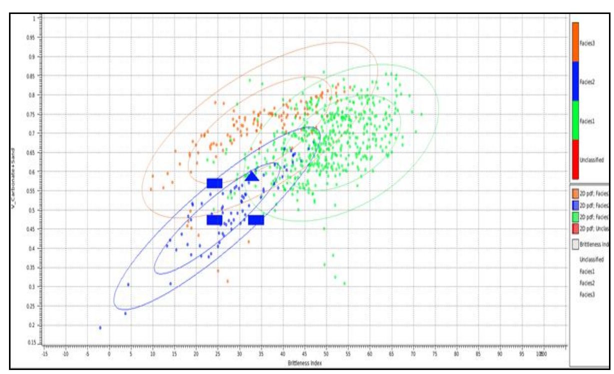

Figure 7: Cross plot of volume of carbonate and sands versus brittleness index coloured by facies. The pdfs corresponding to three different facies have been shown by different colors. Most brittle facies is represented by red.

Time to Depth Conversion

For interpretation of the results in terms of sweet spots to be used for designing trajectories for horizontal wells, the mechanical properties volumes in time are required to be converted into depth. Conditioned and scaled seismic interval velocity calibrated at wells has been used to convert time volumes to depth.

Interpretation

Interpretations were conducted using the full-bandwidth inversion results. These were interpreted in terms of brittleness index and volume of TOC. The brittleness Index, defined as an average of variation of Young's modulus and Poisson's ratio within the shale layer scaled to fall within the range 0-1 highlights the potential distribution of brittle zones. This brittleness index combined with the volume of TOC derived from P-impedance has been used for interpretation. High values of brittleness index along with high values of TOC indicate sweet spots for drilling and improving likelihood of inducing artificial fractures for fluid flow. In addition, the inversion results can be transformed to probability for each of the identified facies. Interpretation of probability of occurrence of facies is more intuitive and quantitative.

Figure 8 shows the mean probability of the most brittle facies in two sub-layers within the shale interval. The color scale has been selected to highlight large probabilities represented by warm color. This figure also asserts that probability of occurrence of rocks with higher brittleness index increases towards the lower part of the shale section.

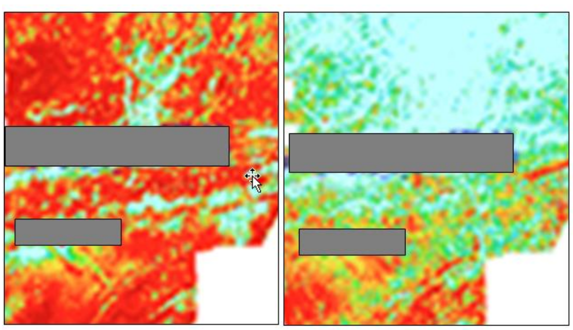

Figure 8: Mean of probability of occurrence of the most brittle facies (facies1) in two sub-layers from Base of the shale reservoir upwards. Warm colours (red)represent higher probability.

Conclusions

Simultaneous inversion of multiple offset stacks from 3D PSTM gather over a shale block from Unites States has clearly shown that this technology has great potential in mapping sweet spots for unconventional reservoirs like shale gas or shale oil. Proper data conditioning before inversion is required to invert reliable density from simultaneous inversion. Density plays a significant role in defining the total organic content which is a key component in determining the sweet spot.

Amplitude variation with offset (AVO) signature captured in PSTM gathers has been successfully used to derive elastic properties and density of shale. These properties, in turn, have been be used to derive geomechanical properties like brittleness index, volume of carbonates and sand that carry useful information for further well planning for exploration and development.

References

Avseth, P. Mukerji, T. and Mavko, G., 2005, Quantitative Seismic Interpretation, Cambridge University Press.

Casstillo, G., Voisey, S., Chesser, K., van de Covering, N., Bouziat, A., Oliver, G., Ly, C. V. and Kuo, L., 2014, Integrating surface seismic, microseismic, rock properties and mineralogy in the Haaynesville shale play: First Break, 32, 71-77.

Rickman, R., Mullen, M., Petre, E., Grieser B. and Kundert, D., 2008, A practical use of shale petrophysics for simulation design optimization: all shale plays are not clone of the Barnett Shale, SPE 115258.

Waters, G.A., Lewis, R.E. and Bentley, D.C., 2011, The effect of mechanical properties anisotropy in the generation of hydraulic fractures in organic shales, SPE 146776.

Sena, A., Castillo, G., Chesser, K., Voisey, S., Estrada, J., Carcuz, J., Carmona, E., and Hodgkins, P., 2011, Seismic Reservoir characterization in resource shale plays:Stress analysis and sweet spot discrimination, The Leading Edge, 30, 758-764.