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Sensitivity analysis of multi-angle extended elastic impedance (MEEI) to fluid content: A carbonate reservoir case study from an Iranian Oil field

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Abstract

The concept of Extended Elastic Impedance (EEI) has capability to estimate reservoir fluids. In general, AVO response for carbonate reservoirs is weaker than the clastic reservoirs. Therefore, it is difficult to discriminate fluid content in carbonate reservoirs using EEI. In this study, a novel method called Multi-angle Extended Elastic Impedance (MEEI) was used to discriminate fluid in a carbonate reservoir. Before MEEI analysis, a rock physics modelling was carried out using Xu-Payne model in a well within the filed. The modelling was carried out on Santonian-Campanian Ilam carbonate reservoir. The rock physics model was created to utilize petrophysical logs. Then Gassmann fluid substitution was applied to see fluid sensitivity of the reservoir. Three reservoir scenarios representing fully saturated water, oil and gas were modeled. The log data of density, P-and S-wave velocities were generated that relates to each fluid scenario. The log data were than used to create MEEI spectrum for three fluid scenarios. MEEI spectrum were created for dry conditions as well. The results illustrated that the trend of MEEI values is different in various fluid contents in the reservoir. Therefore, MEEI analysis was capable to estimate the fluid content of the reservoir.

Keywords: Rock physics, Fluid substitution, Multi angle Extended Elastic Impedance

Introduction

The direct effects of changes in petrophysical properties on elastic parameters provide the opportunity for qualitative and quantitative seismic reservoir characterization. The concept of Extended Elastic Impedance (EEI) has capability to estimate elastic properties such as density, S-impedance, Vp/Vs ratio, shear modulus and bulk modulus as well as petro-physical properties of reservoir such as clay volume, porosity and water saturation. EEI analysis by calculation of impedance values physically observed beyond the range of incident angles (imaginary angles not really recorded in the seismic gathers) is useful to delineate different fluid and lithology types. Each EEI log relates to various angle can be proportional to a reservoir property that is defined through the maximum value of cross correlation. In carbonate reservoirs, the cross correlation is very low. Therefore, the EEI inversion has not full capability to characterize the reservoir. In some carbonates the Multi-angle Extended Elastic Impedance (MEEI) analysis which considers the trend of EEI values with various incident angles is efficient to discriminate fluid in the reservoir (Zhen-Ming, 2008). Fluid substitution plays an important role in AVO analysis, gas injection, gas storage and interpreting the results of a 4D seismic analysis. Rock physics modeling and fluid substitution help to predict the quantity of fluids content in the reservoirs. The available models are usually valid for sandstone reservoirs and may not be directly useful for carbonate reservoirs. Therefore, creating a certain model to study carbonate reservoirs is necessary. In this study, to test the ability of MEEI analysis a carbonate reservoir from south west of Iran was selected. By using petrophysical data and core analysis and then by fluid substitution, different fluid scenarios were modelled. The necessary log data were generated according to fluid contents. The logs (V_p, V_s and density) resulted from rock physics modeling for each fluid scenario were used to build log parameter model and EEI spectrums. Then the EEI trend changes with various incident angles were plotted to establish the fluid-bearing patterns and effective criteria for discriminating the fluid content by MEEI analysis in target zone. The results confirm that MEEI analysis has capability to delineate hydrocarbon zones of a carbonate reservoir.

Theory and Method

Connolly (1999) defined EI as an angle-dependent weighted product of P-velocity, S-velocity and density. One of the problems of EI is that the values related to different angles are not scaled correctly. This is due to the variable dimensionality caused by changing incident angle. Withcombe et al. (2002) proposed that EI can be normalized by scaling as follows:

$$EI(\theta) = V_{p0}\rho_0\left[\left(\frac{V_p}{V_{p0}}\right)^{1+\tan^2\theta}\left(\frac{V_s}{V_{s0}}\right)^{-8K\sin^2\theta}\left(\frac{\rho}{\rho_0}\right)^{1+K\sin^2\theta}\right], \tag{1}$$

Where, V_{P0}, V_{S0} and ρ_0 are reference constants and K denotes the average of $(V_S/V_P)^2$.

Modification of elastic impedance (EI) definition beyond the range of physically meaningful incident angles is one of the efficient techniques of pre-stack AVO analysis. EEI is one of the linearized forms of the Aki and Richards (1980) AVO equation introduced by Shuey (1985), where $\sin^2(\theta)$ is replaced with $\tan(\chi)$ for extrapolation beyond physically observed range of theta as follows:

$$R(\theta) = A + B\,tan(\chi) \tag{2}$$

$$R(\theta) = A + B\sin^2\theta + \ C\,sin^2\theta\,tan^2\theta \tag{3}$$

Then,

$$R_{EEI}(\chi) = R(\theta)cos\,\chi = Acos\,\chi + Bsin\,\chi. \tag{4}$$

where (χ) Changes between -90° and 90° angles, which gives extension of EI for any combination of intercept and gradient. It is noticeable that EEI is equal to acoustic impedance at $\chi = 0$ and to gradient impedance (B) at $\chi = 90$.

EEI analysis provides a simple robust tool of deriving lithology and fluid information from pre-stack seismic data. It is sensitive to numerous elastic and petro-physical parameters such as density, water saturation and porosity in different chi values. The optimum angle for any parameter is selected through the maximum value of cross correlation of the desired parameter and EEI logs in different angles. In brief, the process involves four steps, choosing a target log and finding the optimum χ angle via the maximum cross correlation values, building the log parameter model, computing the EEI (χ) seismic reflection volume from the intercept and gradient sections and at the end, performing the inversion scheme (Mirzakhanian, et al., 2015). In carbonate reservoirs the cross correlation values of any elastic or petro-elastic logs with EEI values is not satisfactory so it is impossible to predict the reservoir fluid quality and quantity by EEI analysis. But it is proved that (Zhen-Ming, 2008) in some carbonate rocks the trend of EEI spectrum in reservoir layer could be used to determine the fluid content. To illustrate the ability of MEEI analysis, feasibility study can be performed by utilizing rock physics modeling (Xu and Payne, 2009 and Gassmann) and fluid substitution procedures. The significance of feasibility study is to perceive if there is any sensitivity to fluid content according to trend of EEI spectrum changes. In order to fluid substitution, the petrophysical, geological and core data are needed. Due to regional tectonics, formation weakness and the presence of clays may crate borehole instability, collapse and even washout. Therefore, the wireline logs and their petrophysical interpretations may be affected. Considering this fact, log correction is unavoidable which is performing by rock physics modeling. To perform rock physics modeling, the bulk modulus of fluids is estimated using well test data and engineering reports. Other parameter such as saturated bulk (K_{sat}) and shear moduli (μ_{sat}) at in-situ condition can be estimated from the wireline log data using Gassmann's equation (1951). Gassmann's equation relates the bulk modulus of a rock to its pore, frame, and fluid properties. Therefore, in order to estimate the saturated bulk modulus at a given reservoir condition, it is needed to estimate bulk modulus of frame, matrix and pore fluid. Frame bulk modulus can be derived from the laboratory measurement, empirical relationship, or wireline log data. K frame can be determined by Gassmann equation using wireline data (Mavko et al., 2009). Finally, the modeled logs are compared with the results of petrophysical tools such as sonic and density in zone of studied well. This comparison reveals that, when caliper value is low, the match between petrophysical logs and rock physics modeling increases and as caliper value is increases, this match decreases. The rock physics model is used to fluid substitution according to Gassmann's equation. The logs created in this stage will be used to build EEI spectrums for each reservoir scenarios in order to test the ability of MEEI analysis for fluid discrimination.

Case study

The case study in this paper is a carbonate oil field located in the south west of Iran with 4 production wells. This reservoir has already produced 40 million barrels of oil from Santonian - Campanian (Ilam) formation. The Ilam formation consists of up to 190 m of limestone with interbedded shale and some minor amounts of dolomite. The base of Ilam is another carbonate layer which is called as Sarvak formation. Sarvak consists of a 40 m oil column with some portion of gas solution. The depth of reservoir ranges between 2800 to 3000 m. One of the wells penetrating these Formations (well No.2) is chosen for the modelling purpose of this study. This is a well which penetrated brine column with some portion of heavy oil (about 50 m of the whole reservoir thickness). This well also is passing through a weak formation with lots of borehole instability and collapses (evidence from high Caliper log value). These environmental factors have, in turn, affected the measured logs as well as their interpretation in a way that some significant errors can be observed in the interpreted logs. Therefore, the petrophysics-rock physics workflow has been used on this well to correct elastic logs for the bad-hole effects. Therefore, different rock physics models (Kuster and Toksoz, 1974, Self-consistent, Differential effective medium model and Xu-Payne, 2009) are tested and compared against the measured logs for the intervals with low Caliper (no washouts). The comparison confirms that Xu-Payne (2009) model shows a better match with measured one compared with other models. This match reduces as the Caliper value increase. This is a clear indication of the borehole effects on the measured logs especially on elastic logs. Furthermore, Xu-Payne (2009) model parameters (like aspect ratio) are tuned based on the best match with measured sonic data in the intervals with very low Caliper reading (almost no wash outs). In this study, pore fluid properties are calculated using well test data and engineering reports. The mineral types and their volume fractions are taken from petrophysical interpretation. Frame bulk modulus which is an important input into Gassmann can be derived from the laboratory measurement, empirical relationship, or even wireline log data (Mavko et al., 2009). Here, we did not have access to the first two database to calculate frame properties, and therefore, the calibrated rock physics model is used to estimate rock frame properties. Then, Gassmann fluid substitution is used in order to model different saturation scenarios (100% water, 100% oil and 100% gases) for the studied formation. The properties of different hydrocarbon fluids were taken from other wells penetrated the reservoir. The final output of fluid substitution is saturated bulk modulus, shear modulus and density for either of the defined saturation scenarios. These logs were used to build EEI spectrums for each scenario (Fig. 1) to study the trend of EEI for each saturated fluid. The figure shows different trend of EEI for each condition in the modelled interval. The EEI values for each scenario and dry conditions were extracted from a certain depth (Fig. 2). The trend of EEI values shows that in hydrocarbon saturated condition especially gas, in negative values of Chi angles (-80 to -90) the amount of EEI is more than water bearing condition. In brine, EEI values are approximately less than 45000 (ft/s.g/cm^3) but for hydrocarbon saturation this value in negative angles. In positive chi angles (80 to 90) the relation is different. The amount of EEI in brine saturation is approximately more than 32000 (ft/s .g/cm^3) but in hydrocarbon saturated ones it is less than this value in positive angles (Fig. 2). There are also different values of EEI at neighbouring zero angles especially at 25 related to different fluid contents. But because of uncertainties involved in inversion process, sometimes it is difficult to recognise these differences in inverted seismic sections. According to the fact that the well was penetrated in water zone, the results of fully water saturated are closely matched to the petrophysical results. The results of this case study indicate that considering the pattern EEI trend was effective in fluid discrimination.

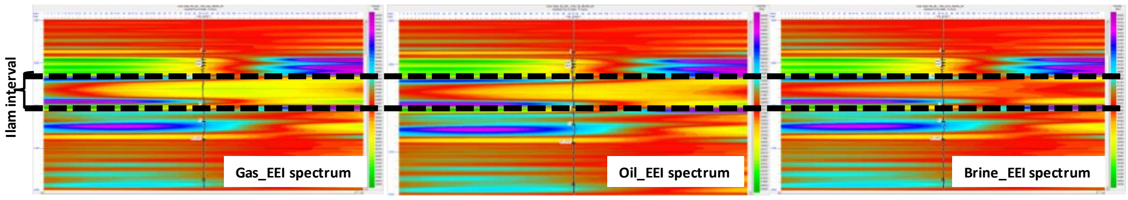

Figure 1. EEI spectrum for -90 and +90 degree for each scenario. Dashed box shows Ilam FM of the reservoir zone used for modelling.

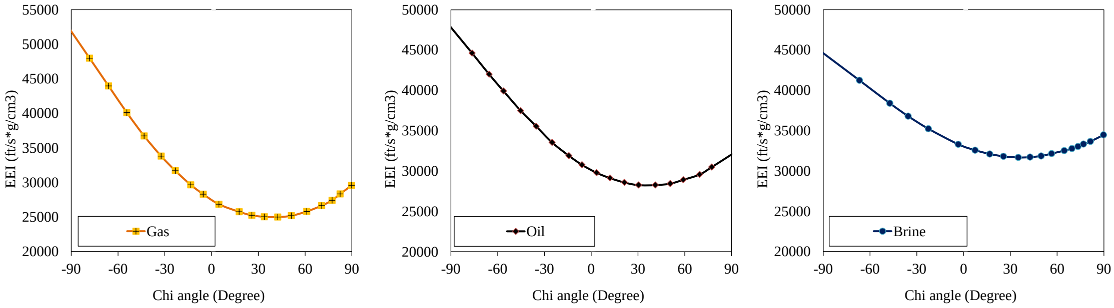

Figure 2. EEI values in different incident angles from -90 and +90 degrees with the different fluid types at a selected depth.

Conclusions

The trend changes of EEI with various incident angles called MEEI analysis can be liable to discriminate fluid content in carbonate reservoir. EEI analysis performed in this case study by Xu and White (1995) rock physics modelling and Gassmann fluid substitution. The results reveal that the trends of EEI values in various incident angles are different for each fluid saturation scenario. In hydrocarbon saturated conditions especially in gas saturation, in negative values of Chi angles the amount of EEI is more than the water bearing condition. While in positive chi angles the relation is different. The amount of EEI in brine saturated condition is more than hydrocarbon saturated ones. Also there are different values of EEI at neighbouring zero angles related to different fluids. Because of uncertainties involved in inversion process sometimes it is difficult to recognise these discriminations in seismic inverted sections. Therefore, it is recommended to take advantages of MEEI analysis to estimate fluid content in carbonate reservoir instead of EEI.

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