Introduction

Interpretation of reservoir properties using rock physics templates (RPTs) has long been an interest to geoscientists and geological engineers, moving them toward important findings. Application of RPTs for quantitative seismic interpretation dates back to more than a decade ago. Obtained from lithology and fluid trends, an RPT indicates variation of a particular seismic property with depth or time. Avseth and Ødegaard (2004) were the first to describe the use of rock and fluid properties to build RPTs for lithology identification and pore-fluid interpretation of well log and seismic data. Recently, Russell (2015) discussed several new approaches for linking RPT to the seismic reservoir characterization. As of present, RPT has turned into an integral part of quantitative interpretation of seismic data, with its good applicability frequently confirmed by geophysicists (e.g., Florez and Kuzmin, 2015). A common practice to reduce the risks and uncertainties engaged during hydrocarbon exploration activities is to assess the prospect using various methods. This highlights the usefulness of making templates for quantitative seismic interpretation (e.g., extended elastic impedance (EEI) templates). The capability of EEI for estimating elastic and petrophysical properties of a reservoir has been reported previously (Whitcombe et al., 2002). However, only limited research works have been focused on obtaining patterns for interpretation of EEI results. Zhen-Ming et al. (2008) obtained fluid patterns for the detection of brine and gas by considering EEI trends over target layers and could successfully verify their results against known well data. Florez and Kuzmin (2015) presented the RPT in the EEI domain as a tool for interpreting and modelling the results of Model-based inversion and amplitude versus offset (AVO) analysis. Later on, Sharifi and Mirzakhanian (2019) extended the concept of EEI to what they called the full-angle EEI (FEEI). Beginning with an introduction into the theory of EEI, the present work uses the fluid substitution modeling to propose a novel EEI template for discriminating different fluids based on well log and seismic data. A case study is then analyzed to verify the proposed methodology.

Theory and method

In terms of theory, the proposed template is based on extended elastic impedance and fluid substitution modelling. Connolly (1999) introduced elastic impedance (EI) as a generalization of acoustic impedance for non-normal incidence angles, extending the advantages of inversion to AVO data. He then used the two-term Zoeppritz linearizations using the commonly used AVO parameters (e.g., A, B, and C parameters) to derive the generalization. Then, Whitcombe et al. (2002) applied some modifications to the Connolly’s formulation to develop a new concept called extended elastic impedance (EEI), as follows:

$$ EEI(\chi) = \bar{V}_p \bar{\rho} \left[ \frac{V_p}{\bar{V}_p} p_1 \frac{V_s}{\bar{V}_s} q_1 \left( \frac{\rho}{\bar{\rho}} \right)^1 \right] $$

(1)

where $p = \cos \chi + \sin \chi$, $q = -8K \sin \chi$, $r = \cos \chi - 4K \sin \chi$, and $\bar{V}_p$, $\bar{V}_s$, and $\bar{\rho}$ are the corresponding (constant) average values of P-wave velocity, S-wave velocity, and density, respectively. Also, $V_p$, $V_s$, and $\rho$ are the values of the P-wave velocity, S-wave velocity, and density, respectively, while $\chi$ (or Chi) denotes intercept-gradient coordinate rotation angle.

In order to generate templates in the EEI domain, different fluid scenarios were developed in a process called fluid substitution modelling by changing the pore fluid content (e.g., brine, oil, and gas). The fluid substitution modelling can be done through different rock physical techniques based on theoretical, empirical, or hybrid models. Among others, Xu and Payne (2009) proposed a hybrid rock physics model based on the model that was originally proposed by Kuster and Toksoz (1974) for a differential effective medium (DEM) to account for the effect of fractures and more porosity types. After modelling different fluid scenarios, the obtained results have been subjected to EEI analysis to build fluid patterns. In this stage, FEEI analysis (Sharifi and Mirzakhanian, 2019) has been conducted to identify different EEI trends corresponding to different fluid types. Then, EEI templates were presented for the full spectrum of $\chi$ angles (-90° to +90°). FEEI analysis considers the variation of EEI versus full spectrum of $\chi$ angles continuously for each fluid scenario (here for oil), as follows:
$FEEI_{oil}(\chi, EEI) = f(EEI), \text{ for } \chi = -90^\circ \rightarrow +90^\circ.$ \hspace{1cm} (2)

where $FEEI_{oil}(\chi, EEI)$ is a two-element vector with $\chi$ and EEI as its elements, EEI is calculated from Equation (1), and $f(EEI)$ denotes a function of EEI for $\chi$ angles from $-90^\circ$ to $+90^\circ$. In the same way, the values of $FEEI_{brine}$ and $FEEI_{gas}$ were calculated via Equation (2) under brine- and gas-saturated conditions, respectively.

Case study

The case study is a carbonate oilfield hosting several production wells in the southwest of Iran. The field is producing oil from Sarvak Formation (L2), the second major oil-bearing reservoir in Iran. As a part of Zagros Basin deposited during the Middle Cretaceous, this formation is mainly composed of carbonate sequences sealed by two shale formations, namely Laffan (L1) and Kazdumi (L3) formations, on the top and base, respectively. In the study area, Sarvak Formation is composed of about 670 m of medium-bedded massive limestone containing chert nodules interbedded with shale at 2850 m below the mean sea level. A suite of well log curves, such as gamma ray, $V_p$, $V_s$, density, resistivity, and neutron porosity, were available for formation evaluation at five wells (the Wells F-10, D-5, T-5, M-3, and M-5). Check-shot data was also provided for time-depth conversion.

Continuing with this research, different fluid scenarios were developed by performing rock physics and fluid-substitution modelling along studied intervals of the Wells F-10 and D-5. The rock physics modelling was done based on the approach proposed by Xu and Payne (2009), wherein Voigt-Reuss-Hill model was used to determine effective modulus of the minerals (mainly calcite with minor amounts of clay). Subsequently, pore space characteristics (e.g., pore shape and aspect ratio) were determined from well log data and then verified qualitatively based on thin-section studies. Dry (frame) bulk modulus was estimated assuming DEM using the mineral and matrix properties and pore types. Then Gassmann’s (1951) equation was used, only with fluid-substitution modelling, to estimate elastic parameters under different scenarios (e.g. brine, gas, and oil) in saturated condition.

The results of rock physics modelling ($V_p$, $V_s$, and density) were converted to EEI trends for each fluid type. Then, the results were presented for the full range of $\chi$ angles from $-90^\circ$ to $+90^\circ$ using Equation (2), representing a fluid trend (Figure 1). Accordingly, the EEI values for different saturation scenarios exhibited clearly distinctive trends (Figure 1a), making them suitable for discriminating different fluid types. Figure 1b shows different fluid zones and corresponding EEI templates. In order to prove the capability of the proposed template, it was verified at a blind well (Well T-5) – i.e. not considered in the development of the model. In this regard, EEI values were calculated based on the blind well data (the points shown on Figure 1b), confirming the appropriateness of the templates. Looking into the template, it is evident that the positive $\chi$ angles followed an opposite trend to that of the negative $\chi$ angles. Moreover, the fluid type discrimination was not possible in the region corresponding to $\chi$ angles between -50° and -60°.

![Figure 1](image-url) EEI template: a) the template on which the increasing trends of saturation and density are indicated with arrows, and b) fluid discrimination with the use of the EEI template, demonstrating different zones in Sarvak Formation (resampled to 4 ms).
After discriminating different fluid types using EEI template based on the well log data, the next step was to detect fluid types on seismic data, for which purpose a real 3D seismic dataset containing angle gathers (5° to 40°) of migrated prestack data was selected. The seismic survey had covered an area of about 295 km² with an identical inline and cross line interval of 25 m. The sample rate for the data acquisition was 4 ms with a fold coverage of 70.

According to Figure 1, depending on the EEI templates, two different χ angles (-90° and +60°) were chosen to perform the EEI inversion for detecting the fluid type. Next, the seismic data was inverted to obtain a cube of EEI. A low-frequency model (LFM) was built based on well log data and interpreted horizons for each χ angle, before proceeding to wavelet extraction. Next, the AVO intercept and gradient sections were calculated through AVO analysis. Then, EEI reflectivity sections were obtained at certain χ angles. Finally, using the corresponding LFM and wavelet, EEI section was built by applying a Model-based inversion to the related EEI reflectivity series followed by scaling the results (Hampson et al., 2005). In order to confirm the capability of the proposed method, the result were verified at a blind well (Well T-5) (i.e. not considered for developing the model). Figure 2 shows the inverted EEI section along an arbitrary line cutting through Wells F-10 and D-5 at χ = +60°. On this figure, the black curve denotes the water saturation upon resampling to 4 ms alongside the results at the blind well (Well T-5). Similarly, Figure 3 shows the results at χ = -90°.

**Figure 2** Model-based inverted section based on the EEI reflectivity at χ = +60° in Sarvak Formation (L2). Arrows show the oil saturated layer with an EEI value of about 8000 m/s.g/cm³ according to the EEI template. Here the Well T-5 is a blind well and the black curves indicate water saturation upon resampling to 4 ms.

**Figure 3** Model-based inversion performed on EEI reflectivity series at χ = -90°. The oil-bearing column has lower EEI values than the brine-filled portion, being in agreement with the EEI template at negative χ angles. The black curves indicate water saturation upon resampling to 4 ms.
After doing EEI inversion, the results were interpreted based on the EEI template. With respect to the obtained EEI section at the positive $\chi$ angles of $+60^\circ$, the results showed that water-saturated zones exhibited EEI values beyond 8500 m/s.g/cm$^3$ while hydrocarbon-saturated ones showed lower EEI values. On Figure 3, based on the results of EEI section study, the hydrocarbon points are shown with arrows, being in agreement with the water saturation log data. At the EEI section corresponding to $\chi$ angle of $-90^\circ$, the results exhibit some opposite trend, meaning that the hydrocarbon zone has a higher EEI value than the water-saturated zones. This finding was confirmed by available geological reports. Despite its advantages, the EEI template analysis may end up deviating from actual values due to the adverse impacts of anisotropy, sonic error, and noise on the well log data, etc. Therefore, one should recalculate and verify EEI template for the specific reservoir in question before interpreting the EEI inversion results. Also, the EEI inversion cannot act beyond the conventional uncertainties associated with the seismic data and modelling procedures. AVO gradient is sensitive to noise, multiples and attenuation, all of which introduce particular errors into the data. LFM, wavelet estimation, and inversion algorithms are sources of modelling error in this method.

Conclusions

In this research a new template-based methodology for fluid detection on well log and seismic data was presented and verified on a case study. As conventional inversion method may render insufficient for fluid type detection, the EEI templates were introduced as an alternative for different types of fluid. In the proposed methodology, the full spectrum of $\chi$ angles was considered and fluid types were discriminated based on EEI values at certain $\chi$ angles. Therefore, a big advantage of the EEI template is that it considers more than one window to increase the accuracy fluid type detection. Good accuracy of this method was successfully confirmed by analysis at a blind well. The methodology proposed in this work can be applied to virtually any reservoir following a preliminary feasibly study. It is worth mentioning that the effectiveness of the proposed EEI template-based methodology is directly dependent on the accuracy of rock physics analysis and fluid-substitution modelling. The noise on real seismic data, wavelet estimation errors, and uncertainty of the log data represent the limiting factors for this method.

References


