



Seismic inversion as a reliable technique to anticipating of porosity and facies delineation, a case study on Asmari Formation in Hendijan field, southwest part of Iran

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Abstract

Porosity and facies are two main properties of rock which control the reservoir quality and have significant role in petroleum exploration and production. Well and seismic data are the most prevalent information for reservoir characterization. Well information such as logs prepare adequate vertical resolution but leave a large distance between the wells. In comparison, three-dimensional seismic data can prepare more detailed reservoir characterization in the inter-well space. Generally, seismic data are an efficient tool for identification of reservoir structure; however, such data usable in reservoir characterization. Therefore, these two types of information were incorporated in order to obtain reservoir properties including porosity and facies in the study area. Using Multimin algorithm, petrophysical analysis was carried out for estimation of reservoir porosity. Then, an accurate post-stack inversion was accomplished to obtain the acoustic impedance volume. The results showed that the Ghar sandstone is characterized by a lower acoustic impedance compared to the high acoustic impedance Asmari Formation. Because of a relationship between acoustic impedance and reservoir properties (i.e., porosity), porosity cube calculation was performed by artificial neural network method which is a popular approach for parameter estimation in petroleum exploration. The consequences showed a good agreement between log based and seismic inversion-derived porosity. The inversion results and well logs cross-plots analyses illustrated that the Ghar member considered as a high quality zone with porosity 22 to 32 percent and the Asmari dolomite shows a low quality interval characters with porosity 1 to 6 percent. The findings of this study can help for better understanding of reservoir quality (especially porous Ghar member delineation) by lithology discrimination in the analysis of identification reservoirs and finding productive well location in Hendijan field.

Keywords Seismic inversion · Reservoir characterization · Asmari formation · Hendijan field · Persian Gulf Basin

Introduction

In heterogeneous reservoirs, the precise determination of porosity and facies plays a significant role in drilling uncertainties reduction and improving hydrocarbon recoveries. Also, it is important in well placement and production prediction. Core information considered as the most trustworthy estimation of reservoir properties including porosity,

permeability, water saturation and facies in reservoir study but these measurements are expensive and limit (Abdulaziz 2019). The reservoir characterization and petrophysical evaluation are principal issues in the investigation of oil and gas resources for identification of new productive intervals (Ramadhan et al. 2019) and accurate estimation of reservoir quality. The formation evaluation based on well logs and core information provides principal characters such as lithology of reservoir rock (mineral volume), effective porosity (PHIE) and total porosity (PHIT), water saturation (Sw) (Mukerji et al. 2001; Kumar et al. 2018), net to gross thickness (N/G), identification of pay and non-pay zones and other properties which are crucial for analysis of reservoirs. Along with the well information, seismic data provide beneficial information from subsurface and have important impacts in reservoir study. In last years, mapping of acoustic impedance (AI) that obtained by seismic inversion plays an

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important role in prediction of spatial reservoir properties. Seismic inversion is an inexpensive, fast and efficient technique especially for examining inter-well space as well as regions that the hydrocarbon wells are far apart each other. Seismic inversion attempts to transform seismic amplitude into acoustic impedance for extract information relevant to spatial reservoir static and dynamic parameters including porosity, permeability and saturation (Soubotcheva 2006; Gogoi and Chatterjee 2019). Seismic inversion results have been widely used to the prediction of lithofacies, elastic and petrophysical properties (Singha and Chatterjee 2014; Kumar et al. 2016). The advantages of acoustic impedance information over seismic amplitude are described by many studies (Duboz et al. 1998; Latimer et al. 2000; Yilmaz 2001; Pendrel 2006). Generally, two types of inversion in exploration geophysics have been introduced: pre-stack inversion that used mainly for fluid indication and post-stack inversion utilized as a rock indicator by reservoir geophysicists. Therefore, seismic inversion is an efficient tool in forecasting of porosity and facies delineation in hydrocarbon explorations and development plan in oil and gas industry. Porosity and facies of reservoir can be delineated via several methods such as utilizing samples of core by laboratory analysis, from wireline logs, based on microscopic studies and also velocities of reservoir interval on trace and mathematical modeling. Various methodologies have been proposed in order to petrophysical parameters anticipation from elastic properties (Figueiredo et al. 2018; Babasafari et al. 2021). Such methodologies including empirical equations, geostatistical techniques, neural network algorithm and also seismic inversion attributes (Lang and Grana 2018; Babasafari et al. 2021). The artificial neural network (ANN) is an efficient tool developed to carry out complex pattern identification and they have been established for pattern quantification as well as extraction characters used in geological and geophysical application (Iturraran-Viveros and Parra 2014). The ANN approach works as a learning process from input data then trains it to construct pattern and, finally, forecast objective by output model. This approach was efficiently applied to forecast reservoir lithofacies based on well logs (Saggaf and Nebrija 2003a; Qi et al 2007), extracting logs value on missing zone (Saggaf and Nebrija 2003b), as well as predict porosity from seismic information (El-Sebakhy et al. 2012). There are several advantages that have made the neural network a popular method in hydrocarbon exploration such as applicability for noisy data and capability of this method for extraction of nonlinear relation between imported and exported information. The present research aims to predict porosity using both well logs (petrophysical evaluation) and seismic data (based on AI attribute derived from post-stack inversion and using ANN algorithm) and also predict facies using cross-plot analysis of well logs against acoustic impedance. The inversion derived acoustic

impedance, calibrated with well log derived acoustic impedance, hence, the estimated facies from well logs cross-plot is applicable to inter-well space within reservoir. The previous research works calculated porosity using inversion result incorporate with ANN method, whereas, in this study, in addition to porosity, the reservoir facies has been identified based on well logs cross-plot against acoustic impedance information. The Oligo-Miocene-aged Asmari Formation hosts the significant portion of recoverable oil of Iran (Ghazban 2007; Daraei et al. 2017). This formation deposited in a shallow-marine carbonate ramp, and locally, the siliclastic Ahwaz member in Dezful Embayment and evaporate Kalhur member in southwest of Lurestan deposited on it. In Hendijan field, the Asmari Formation is divided into two major lithologies including the upper siliclastic part named as the Ghar member which is characterized by high reservoir quality and the lower carbonate part considered as the dense dolomitic reservoir rock. The current study had been accomplished in several steps. At the first step, the petrophysical evaluation (on the basis for well logs) was carried out in order to acquire the reservoir properties (i.e., porosity). The calculated porosity (well log porosity) was correlated with core porosity. Then, using a three-dimensional seismic data, post-stack seismic inversion was performed to extract acoustic impedance attribute. At the next, porosity volume is constructed utilizing artificial neural network method. Finally, based on well logs and also post-stack inversion consequences, the facies discrimination within Asmari Formation was conducted on.

Geological setting

The Hendijan field is an offshore field which is located on the northwest part of the Persian Gulf Basin and southern part of the Dezful Embayment (Fig. 1). The geological and structural evidence such as significant thickness and facies variation in the Permian and Triassic strata, occasionally accompanied by the presence of syn-depositional normal faults (e.g., Sepehr and Cosgrove 2004) and volcanic activity (basalt, diabase and intermediate) in Sanandaj-Sirjan zone (Stocklin 1974; Berberian and King 1981), suggest that the Zagros zone is considered as sector of a passive continental margin of the Neo-tethys Ocean by this time. The passive margin persisted until the Early Cretaceous, when convergence between Arabia and Eurasia led to the transition of passive margin to an active margin setting ophiolites emplaced in the Late Cretaceous (e.g., Takin 1972; Agard et al. 2005; Frizon de Lamotte et al. 2011) and foreland basin development during the Santonian to Maastrichtian (e.g., Piryaei et al. 2011; Hassanpour et al. 2021). Actually, the Zagros Fold Thrust Belt (ZFTB) is situated on the northeast sector of the Arabian Shield, as

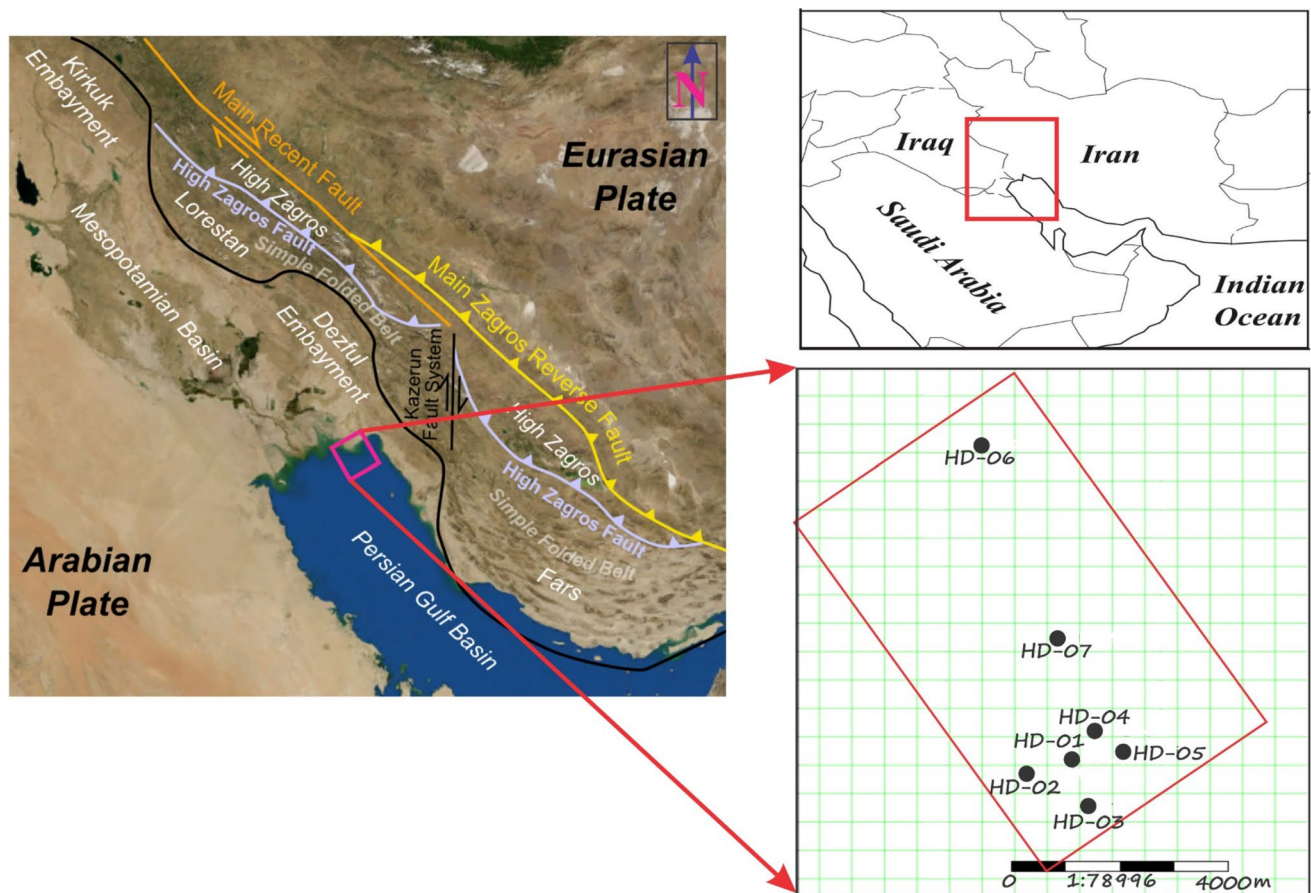


Fig. 1 Situation of study area within the northwest part of Persian Gulf basin

well as separated into zones with NW–SE trends which strikes parallel to plate margin which is divided by well-known Mountain Front Fault (Jafarzadeh and Hosseini-Barzi 2008). The most prolific reservoir in southwest part of Iran is the Oligo-Miocene-aged Asmari Formation that is one of the well-known resources of the world. In the studied area, the Asmari Formation was formed during Rupelian (Early Oligocene) to Burdigalian (Early Miocene) in a NW–SE trending narrow foredeep basin in late Cretaceous on the NE part of the Arabian Shield. During late Cretaceous to Eocene, this basin is filled by Amiran flysch deposits in the internal part, as well as Gurpi and Pabdeh Formations formed in the central and southern part. The final phase of closure of the Neo-Tethys caused subsidence of basin during the Asmari Formation deposition. Hence, the Asmari basin probably indicates the early phase of a foreland basin (Horbury et al. 2004; Soleimani et al. 2020) that is best matured in the Dezful Embayment. In the Hendijan field, the Asmari Formation (Fig. 2) overlay dolomitic Jahrum Formation and underlay by evaporitic Gachsaran Formation. The source and cap-rock of

the Asmari reservoir are the Kazdumi and the Gachsaran Formations, respectively. Based on the Iranian Offshore Oil Company (IOOC) classification, the Asmari Formation is divided into two main parts: the upper siliciclastic part named as the Ahwaz sandstone that equals to Ghar Formation in Kuwait (Alsharhan and Narin 1997) shows shallow-water facies and subdivided into six zones and the lower carbonate part named as the Asmari dolomite which is subdivided into four intervals consists of open marine facies.

Petrographic analysis (Fig. 3) (approximately 60 thin sections and 200 studied results of the thin sections samples) indicated that the Ghar member composed mainly of rounded to sub-rounded coarse grained quartz arenite as well as angular medium grained quartz-wack with porosity ranges from 2 to 32 percent with carbonate cement that deposited in a fluvial/deltaic system, while the Asmari reservoir is formed by skeletal wackstone to skeletal grainstone and dolomitized mudstone. The porosity values of this interval vary from 1 to 25 percent and deposited from lagoon and tidal flat to proximal open marine.

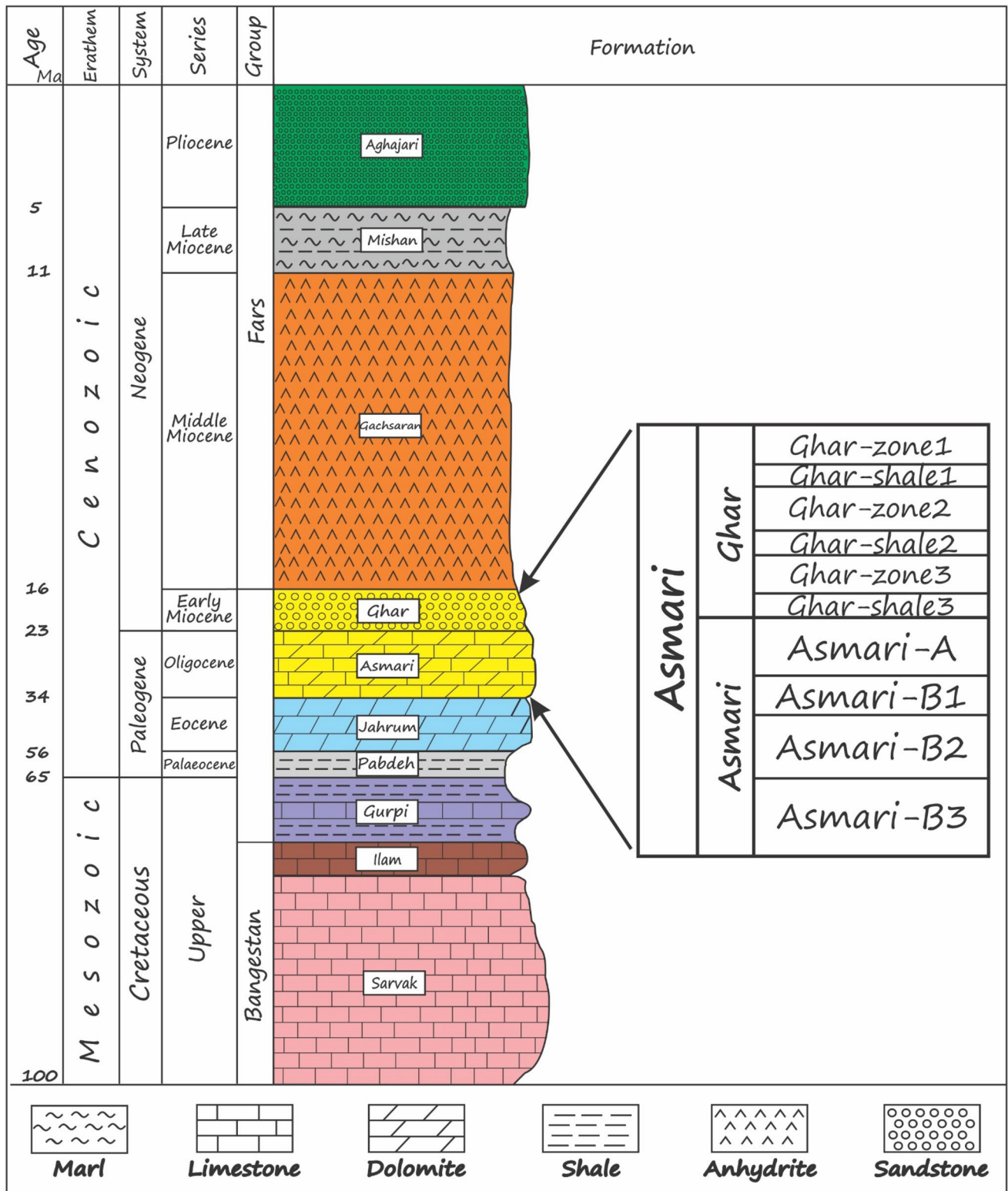


Fig. 2 The stratigraphic column of the northwest part of the Persian Gulf Basin. This column is defined based on the IOOC well information, drilling cuttings and geological evidence

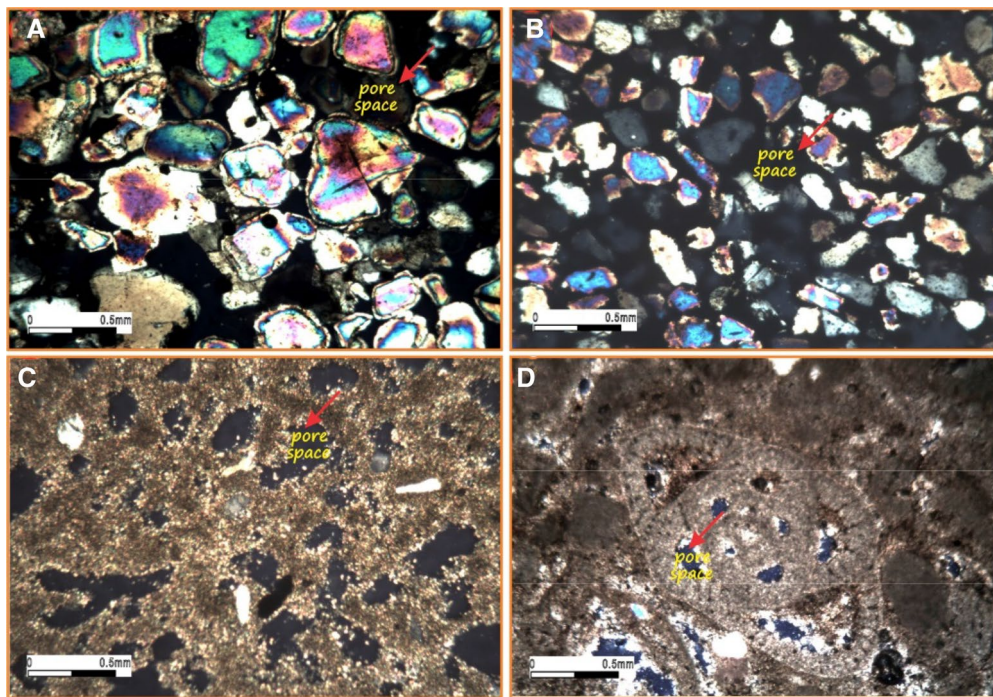


Fig. 3 Petro-facies and micro-facies of the Ghar and Asmari members across the research area. **A** Fluvial/deltaic quartz arenite **B** Fluvial/deltaic quartz wack. **C** Lagoonal skeletal wackstone with moldic

and vuggy porosity. **D** Lagoonal margin skeletal packstone to grainstone with interparticle and moldic porosity

Database and methods

The present study is based on seven wells with full suite of conventional well logs including Gamma Ray (GR), Density (RHOB), Compressional Sonic (DT), Induction log (IND), Microlaterolog (MLL), Laterolog deep (LLD) as well as Neutron Porosity (NPHI) along with a cube of post-stack seismic data covering a region approximately 400 km² containing 1000 In-lines and 600 X-lines utilized for post-stack inversion over Hendijan field acquired by IOOC. Direct sedimentological information consisting of thin section as well as core slabs analysis of both Ghar and Asmari members were available from seven wells. Before utilizing wireline logs, we carried out some conditional steps such as despiking and depth shifting. The advantage of the present study is access to high-quality 3D seismic data for inversion study. Because of this, the porosity delineation is more reliable than other research works. Also, the disadvantage of this research is inaccessibility to pre-stack seismic information for lithology discrimination. The most important limitation of this study is the low number of wells that have core measurements (such as porosity) in order to check predicted porosity with measured porosity in well location for calibration. This study aims to determine the reservoir porosity and facies. For this purpose, we employed a workflow (Fig. 4) that consists of several steps. The workflow starts with porosity calculation from petrophysical logs.

Next, using seismic data, inversion procedures including data conditioning, well tie, wavelet estimation, building of low frequency initial model and acoustic impedance inversion were carried out. Using ANN method, we calculated reservoir porosity for inter-well area. Afterward by cross-plots of acoustic impedance against well logs, we discriminated reservoir facies. Generally, current study consists of several stages showed in Fig. 4.

Results and discussion

Porosity estimation from wireline logs

As an important tool in reservoir quality study, several research works have been carried out in order to porosity estimation based on well logs (Chork et al. 1994; Aifa et al. 2014; Anyiam et al. 2017; Davies et al. 2018; Senosy et al. 2020; Atif Iqbal and Rezaee 2020; Kurah et al. 2021). Seven wells with full suite of logs including Gamma ray, Density, Compressional sonic, Neutron as well as Resistivity were employed for formation evaluation analysis especially porosity calculation over the Asmari Formation. Petrophysical evaluation of Asmari Formation showed that the siliclastic Ghar reservoir characterizes by good quality in comparison with the Asmari reservoir. Evaluation of the petrophysical characteristics from the wells of the Hendijan

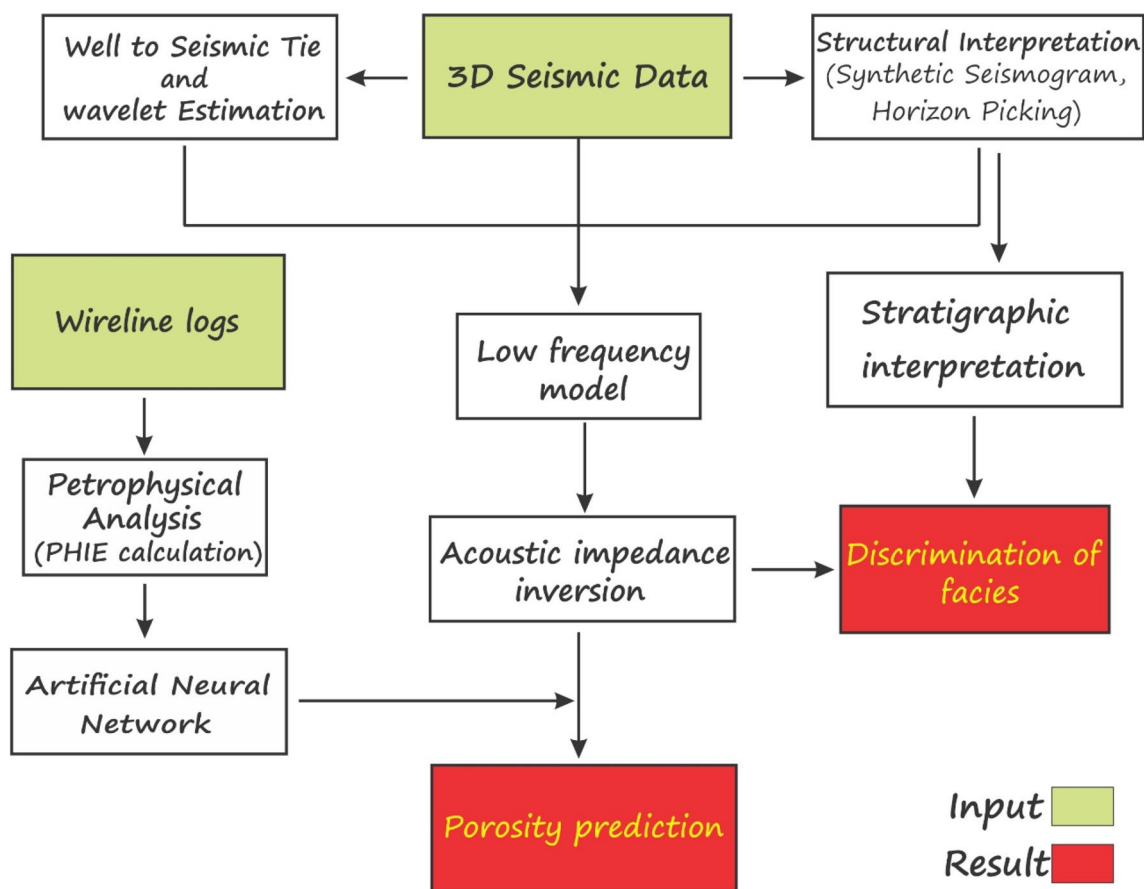


Fig. 4 Methods used in this study. The research starts with calculating of porosity by well logs. Then, post-stack seismic inversion accomplished in order to AI cube estimation. Next, using ANN algo-

rithm, porosity cube was extracted. Eventually, using well log cross-plots versus acoustic impedance, facies estimation was carried out

field illustrated effective porosity ranging from 1 to 33 percent and permeability of about 0.05 to 5500 mD in the Ghar member. Porosity and permeability variation in the Asamari member varies between 1 to 25 percent and 0.01 to 60 mD, respectively. Effective porosity is computed by MultimIn algorithm using the density and neutron logs. This method is introduced to prepare an integrated petrophysical analysis with utilizing geologic data, core information and well log measurements. This approach is a fundamental part of the geology application in order to provide optimum formation evaluation results. MultimIn (summarize of multi-mineral) is a module in Geolog software which utilizes stochastic parameters such as a Monte Carlo simulation. Unlike the step by step Deterministic approach, in the MultimIn method, whole unknown parameters (i.e., porosity, water saturation and shale volume) are calculated simultaneously (Chabock et al. 2017) and each parameters are separate each other. The acquired values were calibrated with core porosity samples (black dots in Fig. 5) and showed acceptable correlation. The consequences of petrophysical evaluation are illustrated in Fig. 5.

Post-stack seismic inversion

In order to post-stack inversion in the Hendijan field, seven wells along with a seismic cube have been established. Because of blind test analysis, we removed one well from dataset. We created synthetic seismograms over six wells in present research based on density and sonic logs. A synthetic seismogram is the consequences of forward modeling the seismic response for an input earth model, which is described in terms of 1D, 2D or 3D changes in physical characters. The term synthetic seismogram in hydrocarbon exploration is created by convolving the reflectivity series derived from compressional sonic and density well logs (to generate impedance profile) with the seismic-derived wavelet at the target interval in order to tie well log to the reflection event acquired by seismic. The accuracy of the match between synthetic seismogram strongly depends on logs and seismic data quality and estimated wavelet parameters. The goal of wireline logs calibration in time domain attempts to: 1) transforming logs domain from depth to time 2) make velocity logs which correlates with velocity of seismic data

3) generates acoustic impedance which utilizing in low-frequency model building. Check-shots information from two wells were used for transformation of density and sonic logs from depth to time domain. Well to seismic tying percent can enhance by shifting, stretching or squeezing of logs. Visual well to seismic ties are characterized by correlation between logs with the seismic amplitude at the well location. Well log-derived (product of sonic and density logs) synthetic trace (blue trace in Fig. 6) shows good agreement (up to 80 percent) with seismic-derived composite trace (red trace in Fig. 6). The time window of analysis was about 100 ms within the Asmari Formation. Troughs and peaks in both synthetic and composite trace are compatible each other. Because of prevent in changes of original well logs, the stretch and squeeze procedure were ignored. The results is displayed in Fig. 6.

After performing well tie, we extracted optimum wavelets for seismic inversion as well as computed synthetic trace via convolving the estimated wavelets with the reflectivity series obtained by wireline logs. The wavelet extraction (Fig. 7) procedure was carried out in order to recognition of seismic

character of various geological events. For all wells, optimum wavelets were estimated with 150 ms length within the Asmari Formation. For better consequences, we used 10 In-lines and X-lines around of well position. For all wells, we selected the wavelet with the best fit as well as checked the real seismic data with constructed synthetic seismogram at well location. The estimated wavelets were similar in both phase and amplitude.

Thereafter, we constructed an accurate initial model that controls the inversion results because of builds a template of seismic inversion. Low frequency initial model known as the background model was constructed by well logs as well as horizons for compensating the low frequency component which has missed on the real seismic trace. Finally, the post-stack seismic inversion was carried out using the estimated well-based wavelet (minimum phase) as well as the low frequency initial model. The acoustic impedance results passing through a well are illustrated in Fig. 8. Acoustic impedance is an important rock attribute which can be calculated in two ways. One is from inversion method, which uses acoustic impedance acquired from seismic data,

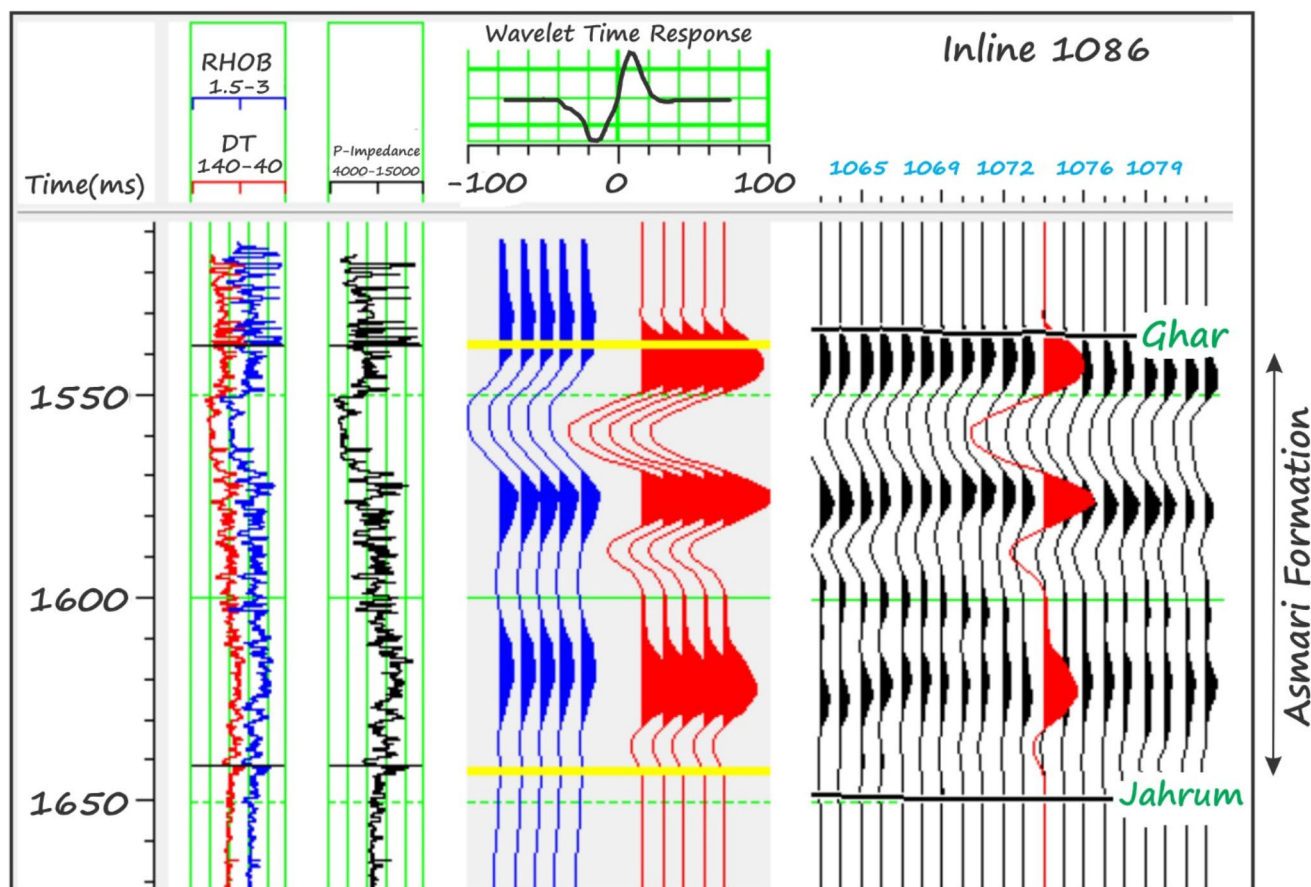


Fig. 6 Well to seismic tying and synthetic seismogram generation. Good match (peaks and troughs) between well logs (compressional sonic and density)-derived synthetic trace (blue trace) and seismic-

derived composite trace (red trace) within the Asmari Formation. The minimum phase well-based wavelet utilized for synthetic seismogram creation is illustrated in top of the figure

Fig. 7 Wavelet used for post-stack seismic inversion

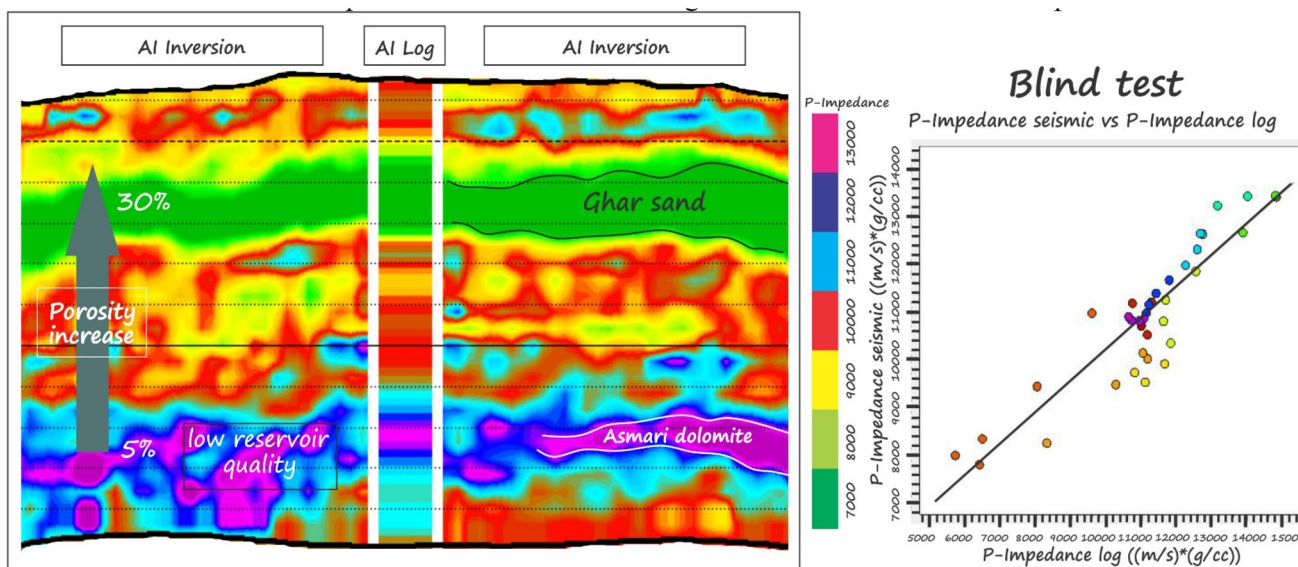
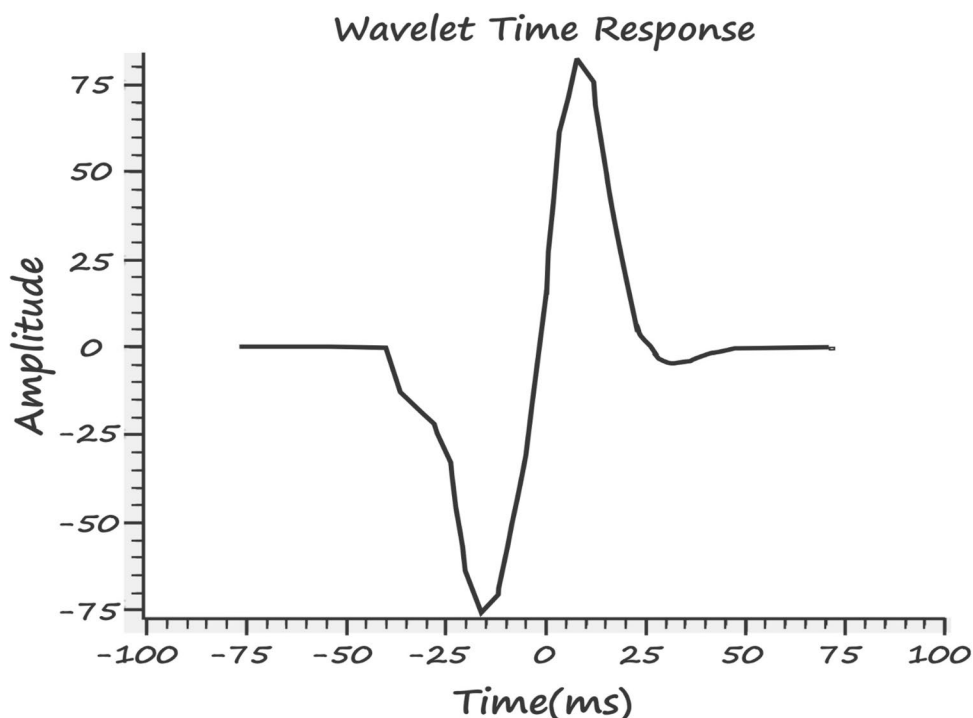


Fig. 8 Good match between well logs-derived AI with seismic inversion extracted AI (left) and Good correlation coefficient (up to 0.8) between seismic inversion and blind well (right)

and the other is forward modeling utilizing well logging information (Bagheri et al. 2021). Acoustic Impedance is the multiplication of compressional sonic velocity (DT) and medium density (RHOB). Generally, rocks with lower density value (lower seismic velocity as well) tend to show higher porosity that can be storage of fluids (including oil and gas) which is important for hydrocarbon resource exploration. The accurate way to assessment of the post-stack

inversion consequences is to compare the results with well logs-derived acoustic impedance on well location. Morozov and Jinfeng utilized wireline log calibration for improving the generation of acoustic impedance from seismic information (Morozov and Ma 2009). As illustrated in Fig. 8, the acoustic impedance of seismic demonstrates acceptable matches with the well logs-derived acoustic impedance. We used a blind well test for validation of inversion results. For

this purpose, we selected a well as a blind well that was not involved in the seismic inversion procedure. This analysis revealed a high correlation between the acoustic impedance of inversion and the acoustic impedance derived from well logs with correlation coefficient up to 0.8.

The wireline logs and cross-plot analysis revealed a valid correlation among porosity and acoustic impedance. As a result, we utilized acoustic impedance to anticipate porosity distribution at inter-well region. The constructed seismic-derived porosity cube illustrated an acceptable correlation with sand and dolomite lithology within the Ghar-Asmari reservoirs.

Porosity prediction by neural network

In present study, we established neural network technique for estimation of porosity from AI attribute at inter-well space. In last years, utilizing of neural network has widely been increased in petroleum industry for characterization of hydrocarbon reservoir, field development optimization and desirable design of stimulation treatment. Post-stack seismic inversion has been conducted to acquired information about the P-impedance prepares accurate understanding about reservoir parameters, because of its relationships with reservoir properties such as porosity (Fig. 9). As a result, we used extracted AI cube to predict porosity in inter-well area of the study. The consequences showed that the siliciclastic Ghar member has high value of porosity as well as the dense dolomite of Asmari member characterized by low quality interval with high amount of acoustic impedance and low value of porosity. The result of porosity estimation is illustrated in Fig. 10.

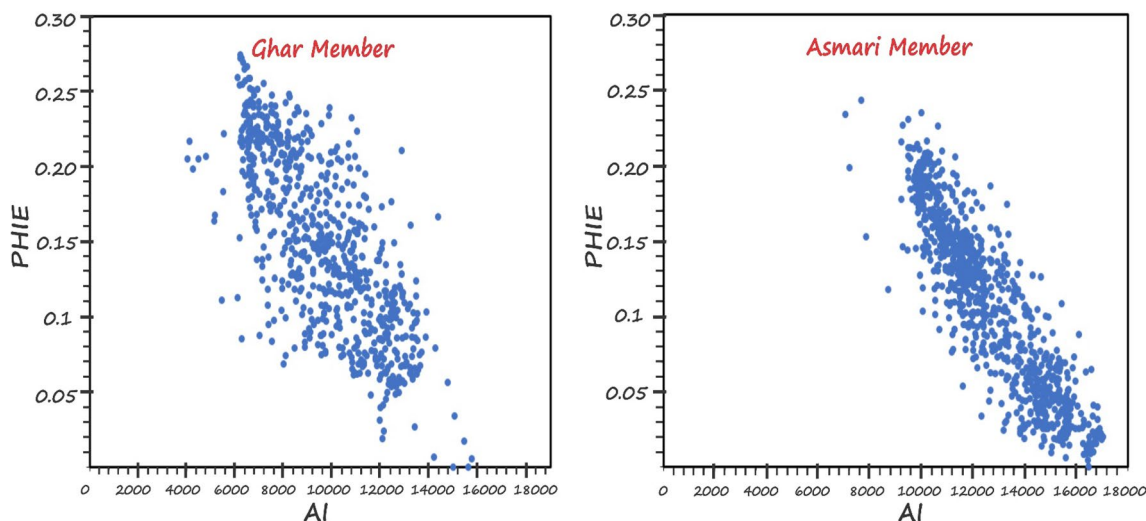


Fig. 9 The results of PHIE against AI at well location in Ghar and Asmari Formation. Because of relation between PHIE and AI attribute (inverse relation), it could be used as an efficient parameter in

Facies discrimination using seismic inversion

Acoustic impedance is an efficient attribute in prediction of the lateral facies changes which help in delineating the sand and dolomite lithology of Ghar and Asmari members (Fig. 8). In this cross section, green colors indicate low acoustic impedance (5000–7500 m/s*g/cc) reservoir interval which corresponds to high porosity (about 30%), whereas the purple color is associated with high acoustic impedance (about 15,000 m/s*g/cc) considered as the low quality interval which corresponds to low porosity (about 5%). In this study, we utilized wireline logs cross-plots for lithology discrimination in reservoir characterization. We utilized well logs including Gamma ray, Density, Compressional sonic as well as Porosity against the AI log to identify their relationships. Based on quantitative studies, we performed possibility of sand/dolomite delineation by acoustic impedance attribute extracted from post-stack seismic inversion. Using established cross-plots, we are able to forecast the rock properties which reveal acceptable correlation with acoustic impedance to discrimination sand and dolomite lithology. Hence, delineation of sand/dolomite lithology based on acoustic impedance is an effective way to understanding the spatial changes of reservoir lithology as well as reducing of risk in discovering, development and production in the Hendijan field. The porosity against acoustic impedance cross-plots showed inverse relationship which indicated that the low acoustic impedance zones are considered as the Ghar sand while dense dolomite of the Asmari determined by high value of acoustic impedance. The acoustic impedance is product of sonic velocity and density for an interval and because of high value of pore space in porous

porosity prediction in inter-well area due to AI cube extracted from post-stack inversion

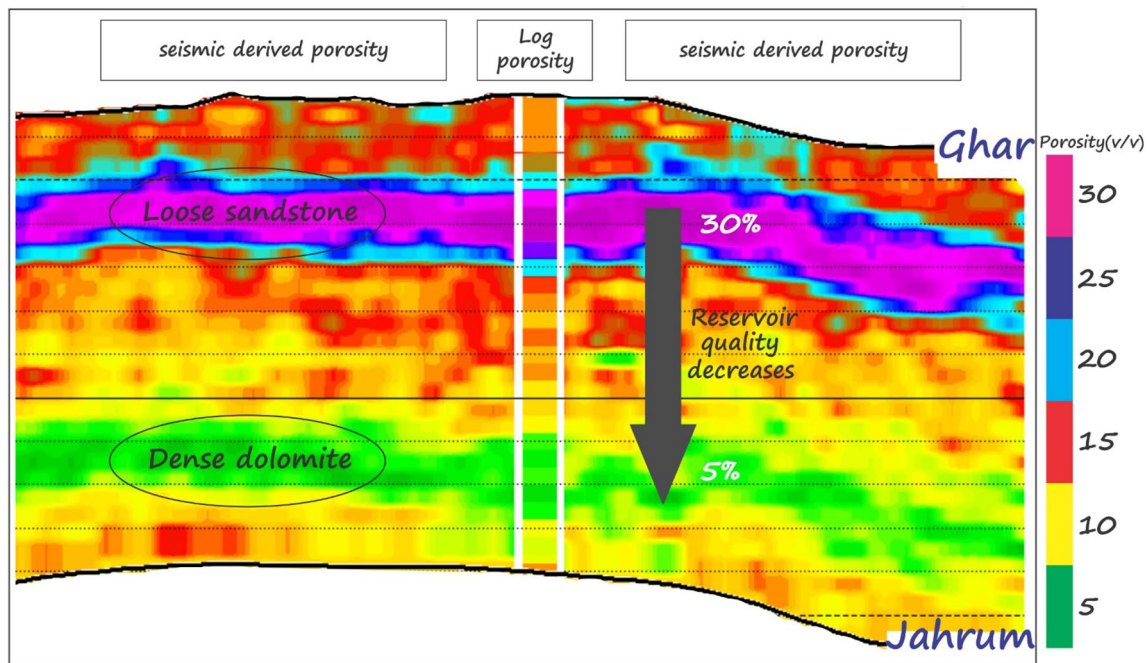


Fig. 10 Predicted porosity using ANN technique within the Asmari Formation

targets, the velocity is lower than tight and cemented zones, therefore, the acoustic impedance in unconsolidated and non-cemented zones is lower than the other parts of reservoirs. The cross-plot of compressional sonic versus acoustic impedance revealed inverse relationship. As a result, delineation of lithology between sand and dolomite is expected. Low acoustic impedance and high compressional sonic values are typically pointed out sand lithology, whereas dolomite lithology identified by low compressional sonic as well as high acoustic impedance. Clear direct relationship is illustrated in Density against acoustic impedance cross-plots. This is a lithology delineation cross-plot suggesting where low density associated with low acoustic impedance is considered as sand lithology while the high density value as well as high acoustic impedance corresponding to dolomite lithology. Generally, dense carbonate sediments have acoustic impedance value more than the porous siliciclastics. On the other hand, acoustic impedance has a reverse relationship with Gamma ray amount. It is obviously indicated that the sand lithology has low acoustic impedance associated by high Gamma ray value than carbonate lithology which corresponds by high acoustic impedance value (Fig. 11).

Summary and conclusion

A detailed seismic inversion analysis along with petrophysical results has been carried out in order to porosity and facies identification in the inter-well spaces of the Asmari

Formation, the Hendijan field. The Oligo-Miocene-aged Asmari Formation composed of both siliciclastic (on top) and carbonate (at bottom) lithologies. On the basis for seismic inversion result evaluation, it is founded to be a good component for porosity prediction and facies discrimination. Integrating seismic inversion result with neural network was utilized in prediction of porosity in the inter-well space. The main remarks of this study explained as follows:

- The siliciclastic Ghar interval is identified by high porosity and low acoustic impedance, whereas the carbonate Asmari interval illustrated low porosity and high acoustic impedance over the Hendijan field.
- The relationships between DT, RHOB, GR, PHIE with acoustic impedance confirmed that the acoustic impedance is an efficient tool for facies discrimination.
- The higher porosity (22–32%), compressional sonic (100–125 $\mu\text{s}/\text{ft}$) and gamma ray (15–35 API) along with low density (2–2.35 g/cc) of the Ghar sand facies are associated with low acoustic impedance value (5000–7000 m/s*g/cc), while the low porosity (1–6%), compressional sonic (45–55 $\mu\text{s}/\text{ft}$), gamma ray (10–20 API) and high value of density (2.7–2.85 g/cc) with high acoustic impedance (14,500–17,500 m/s*g/cc) are considered as the Asmari dolomite facies.

Therefore, post-stack seismic inversion result (AI) provided effective understanding in reservoir characterization

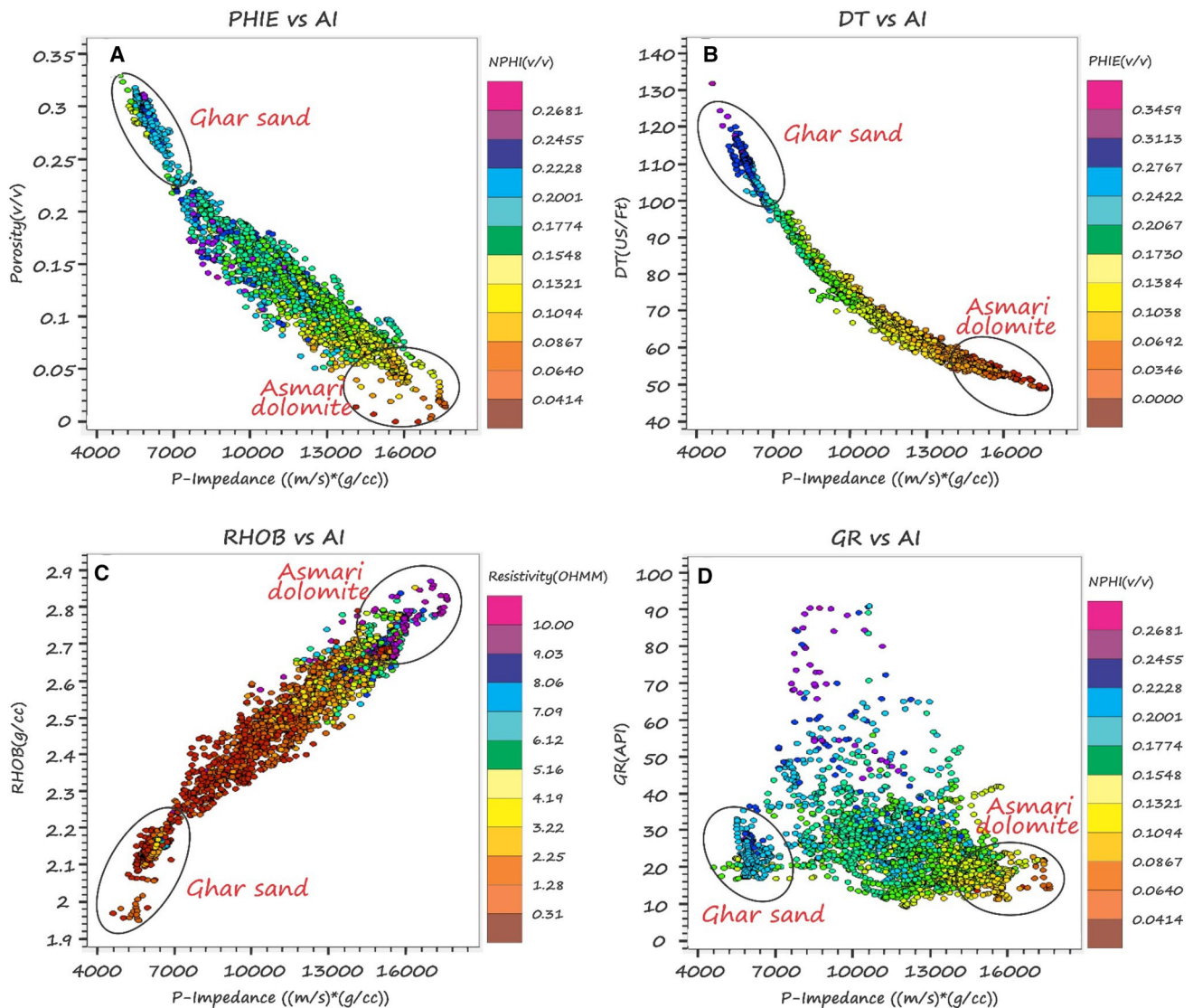


Fig. 11 Distribution of sand/dolomite utilizing AI against well logs. The results showed good separation between reservoir facies in Ghar-Asmari Formation

especially when integrated with well logs. The output of this research provides beneficial information which is usable in oil exploration and development in the Hendijan field or on other Persian Gulf Basin hydrocarbon fields.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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