ORIGINAL ARTICLE

Static reservoir modeling using geostatistics method: a case study of the Sarvak Formation in an offshore oilfield

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Abstract

Static reservoir modeling for optimizing the strategies of hydrocarbon field developments using seismic data and well logs is the focus of this study. The static reservoir modeling is conducted to estimate reservoir properties of the Upper Sarvak formation in one of the offshore oil fields in the Persian Gulf. The Sarvak Formation with middle Cretaceous age is considered as one of the most important productive oil and gas reservoirs in the south and southwest Iran. In this study, we have used seven well logs and 3D seismic data in geostatistical methods for reservoir modeling. The petrophysical parameters such as effective porosity and permeability have been estimated, using the sequential Gaussian simulation method. The evaluation of petrophysical parameters in the reservoir layer shows that the mean effective porosity and permeability are 12.75% and 51.5 mD, respectively. The evaluation of petrophysical parameters from the reservoir characteristic viewpoint demonstrated that a zone called A2 has the best reservoir quality. The well-log validation with core data has been achieved by a cross-validation method. The correlation coefficients derived from the permeability and core data are 86% and 81% for wells w-01 and w-03, respectively, which show that the Sequence Gaussian Simulation is an acceptable method. The result of this study can provide useful information for the development of hydrocarbon exploration studies and reservoir simulation models in this oil field.

Keywords Static modeling · Geocellular network · Sequential gaussian simulation · Correlation coefficient · Cross-validation

Introduction

The increasing demand for hydrocarbon products has led to significant changes in the optimization of oil and gas exploration methods. Technological and computational advancements resulted in better assessment of the hydrocarbon reservoirs. According to geological complications, hydrocarbon exploration has become a significant challenge for the oil industry. As a result, modeling to optimize oil production and fulfilling the global consumption of hydrocarbons has become more challenging. Implementing integrated geological, geophysical, petrophysical, geostatistics, and reservoir engineering approach is crucial for reservoir characterization (Ma 2011; Osinowo et al. 2018; ArabAmeri et al. 2019). The simulation of hydrocarbon reservoirs aims to construct a model for improving reservoir estimation,

reservoir prediction, production increase, and decision-making for the development of oil fields (Tyson 2007). The static reservoir model is a demonstration of the reservoir network-based mathematics that uses various information from different sources such as seismic, core, and well logs data (Viste 2008; Cannon 2018). Reservoir modeling can provide information that can be used to improve production and reservoir performance (Johnston 2004; Yu et al. 2011). The reservoir property model can be generated by integrating seismic, and well-log, and geological information that has been used exclusively for oil and gas exploration and production studies (Aizebeokhai and Olayinka 2016; Sanuade et al. 2017). The static reservoir model uses geological and geophysical data to describe the geological architecture of a reservoir. The reservoir study involves examining the internal and external geometry of the reservoir and evaluating the reservoir properties such as effective porosity, permeability, and reservoir thickness (Cosentino 2001; Pyrcz and Deutsch 2014). Building high-precision reservoir geometry and geological structures are one of the primary stages in 3D reservoir modeling. This approach uses seismic data and

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well logs to design a geocellular network. This geocellular network calculates the reservoir properties in each cell using geostatistical methods (Nikravesh and Aminzadeh 2001). Geostatistics is one of the most efficient techniques used in reservoir characterization and simulation. Reservoir properties such as porosity and permeability have specific spatial correlations or spatial structure, and geostatistics apply to these types of variables (Dubrule 2003; Huysmans and Dassargues 2013). On the other side, due to the low intensity of static and dynamic reservoir data, researchers in the exploration basin have always been looking for a way to estimate the distribution of reservoir petrophysical parameters (Deutsch and Journel 1998). Generally, static modeling is utilized using deterministic methods such as Kriging, and stochastic methods such as Sequential Gaussian Simulation (SGS). The application of these methods requires sufficient knowledge of geostatistics and accurate adjustment of information (Dubrule 2003). We choose 3D static modeling technique as a tool for better understanding of the spatial distribution of discrete and continuous reservoir properties. The static model creates a framework for a geological structure that can be used to predict the performance and production of a hydrocarbon reservoir. The main problem in using these methods is to choose the exact type of spatial correlation. If the relationship is carefully selected, the desired result will be obtained. The carbonate Sarvak Formation in the Persian Gulf area is considered as a major hydrocarbon target in many offshore oilfields in the Persian Gulf (Ghazban 2007; Sharlandet al. 2001) and also onshore oilfields in the Zagros Basin (Motiei 1994; James and Wynd 1965). In this study, we have used the Petrel software as the 3D modeling package to illustrate the reservoir structure and petrophysical property models. The purpose of this study is to model the petrophysical properties of the upper Sarvak Formation in one of Persian Gulf offshore oilfields using geostatistical methods, e.g., sequential Gaussian simulation.

In this paper, we review the related geological setting of the study area and describe static reservoir model including a discussion on integration interpretation of seismic data and processing petrophysical properties using geostatistics method. Before the concluding section, we discuss and express the comment on the obtained result of the static model in the study area. Finally, the conclusion of the paper is presented.
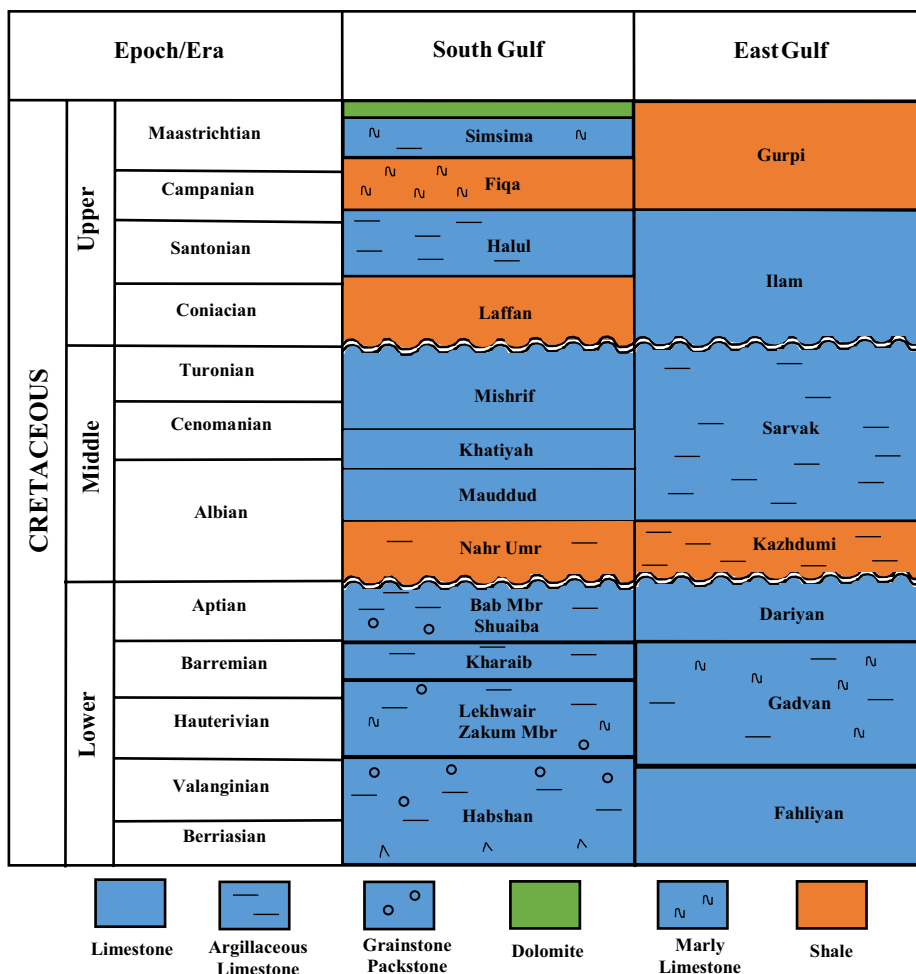
Geological setting

The study area is an Iranian offshore oilfield in the Persian Gulf. The Persian Gulf is known as the wealthiest hydrocarbon basin in the world (Ghazban 2007). The complex sedimentation process and tectonics in the Persian Gulf basin have caused large hydrocarbon fields (Murris 1980). The

Sarvak Formation is the unit strata as a carbonate part of the Bangestan Group. This formation is identified at its type section in the Sarvak strait located on the southern edge of the Bangestan Mountain (northwest of Behbahan City) in the Khuzestan Province (James and Wynd 1965). This formation in terms of stratigraphically is equivalent to Khatiyah, Mauddud, Ahmadi, and Mishrif Formations of the Persian Gulf area (Ghazban 2007). The sediments of this formation are deposited on the passive continental margin (Arabian plate) from the Albian to Turonian (James and Wynd 1965; Alavi 2004). Sarvak Formation, with Middle Cretaceous age (Albian to Turonian), is widely deposited in southern to southeastern Iran (Fig. 1). The lower boundary of the Sarvak Formation is overlain the Kazhdumi Formation with transitional contact. The upper contact is the Ilam formation, which is the Turonian unconformity, Fig. 1. (Motiei 1994). The unconformity in the upper boundary of the Sarvak Formation with the Middle Turonian age is widely present in the Zagros basin sediments and the Arabian platform (Razin et al. 2010; Sharland et al. 2001; Van Buchem et al. 1996). The Upper Sarvak reservoir (equivalent to Khatiyah Formation with the Cenomanian age) in the southern Persian Gulf mainly includes organic matter-rich mudstone and wackestone. In other parts of southern Iran, Sarvak is equivalent to the Mishirif Formation, and it has been deposited with Santonian–Thorin age. Mishirif is considered as an important hydrocarbon reservoir in the Persian Gulf (Farzadi 2006; Van Buchem et al. 1996). The lithology of Sarvak formation is typically limestone and dolomite. This formation includes two facies, shallow and deep. The lower part of the Sarvak Formation includes limestone and pelagic. The upper part consists of a massive limestone containing algae, echinoderms, and rudists (Taghavi et al. 2006; Ghazban 2007). The reservoir that we study in this field is the Khtiyah Formation. Seismic studies showed that the oilfield structure is affected by fault systems. These fault systems have two main fault trends, the Zagros (NW–SE) and the Arabian trend (N–S, NE–SW). Persian Gulf structures are dome shape anticlines with NE–SW to NNE–SSW trends with associated salt dome activities. In tectonic terms, the structure of the studied oilfield is one of several slopes formed on the sloping side of the eastern part of the Fars–Qatar arc and has a dome-shaped anticline structure affected by normal faults.

Methodology

In this study, all available data in this oilfield were collected, including geological and geophysical data. The seismic acquisition area of this field covers an approximate area of 97 km^2. These post-stack time-migrated seismic data were used with a sampling rate of 4 ms in the SEGY format. The structural interpretation of this study is performed using

Fig. 1 Cretaceous stratigraphy chart in the south and east of the Persian Gulf (modified Al-Husseini 2007)

Epoch/Era			South Gulf	East Gulf
CRETACEOUS	Upper	Maastrichtian	Simsima	Gurpi
		Campanian	Fiqa	
		Santonian	Halul	Ilam
		Coniacian	Laffan	
	Middle	Turonian	Mishrif	Sarvak
		Cenomanian	Khatiyah	
		Albian	Mauddud	
			Nahr Umr	Kazhdumi
	Lower	Aptian	Bab Mbr Shuaiba	Dariyan
		Barremian	Kharaib	Gadvan
		Hauterivian	Lekhwair Zakum Mbr	
		Valanginian	Habshan	Fahliyan
		Berriasian		

Legend:
- Limestone
- Argillaceous Limestone
- Grainstone Packstone
- Dolomite
- Marly Limestone
- Shale

seismic data. Petrophysical parameters were evaluated using well-log data from seven wells. Static modeling consists of two main parts. The first part of structural modeling is the process of making a skeleton or a 3D reservoir network. Structural modeling has been used for fault modeling, geocell networks, horizon picking, and layering after 3D interpretation of the seismic data (Avseth et al. 2005; Cannon 2018). The second part is petrophysical data analysis and static reservoir modeling. Petrophysical modeling is the process of filling the grid cells with the petrophysical properties for which a geocell must be made to fit the available data. In general, petrophysical modeling between two surfaces is performed using interpolation methods. Spatial interpolation is a method for making unknown data points (petrophysical properties such as effective porosity and permeability), which is derived from a set of known data points to estimate reservoir properties in the static model (Kelkar et al. 2002; Pyrcz and Deutsch 2014). Generally, the process of petrophysical data analysis consists of (1) upscaling the well log, (2) analyzing the data, (3) geocell modeling, and (4) petrophysical modeling. The main focus of this paper is on petrophysical modeling for effective porosity and permeability.

Core data have been used to evaluate the accuracy of petrophysical well data. The flowchart adopted in this article is shown in Fig. 2.

Seismic data interpretation

Seismic data interpretation is one of the most significant ways of imaging subsurface structures. One of the essential steps in interpreting seismic data is to establish the relationship between seismic reflections and stratigraphy of the studied area (Avseth et al. 2005). Correlating borehole data and seismic data helps us in identifying and correlating the seismic horizon with the formations. One of the important steps before modeling is the depth conversion of the seismic data as the seismic data are recorded in the time domain, whereas the well data are in depth domain (Abdel-Fattah and Tawfik 2015). For making synthetic seismogram, we have used the density and sonic logs of a vertical well (W-1) (Fig. 3). Constructing a synthetic seismogram should be performed before interpreting geophysical horizons. Corrections and depth assessments of the synthetic seismogram

Fig. 2 Flowchart adopted for this study
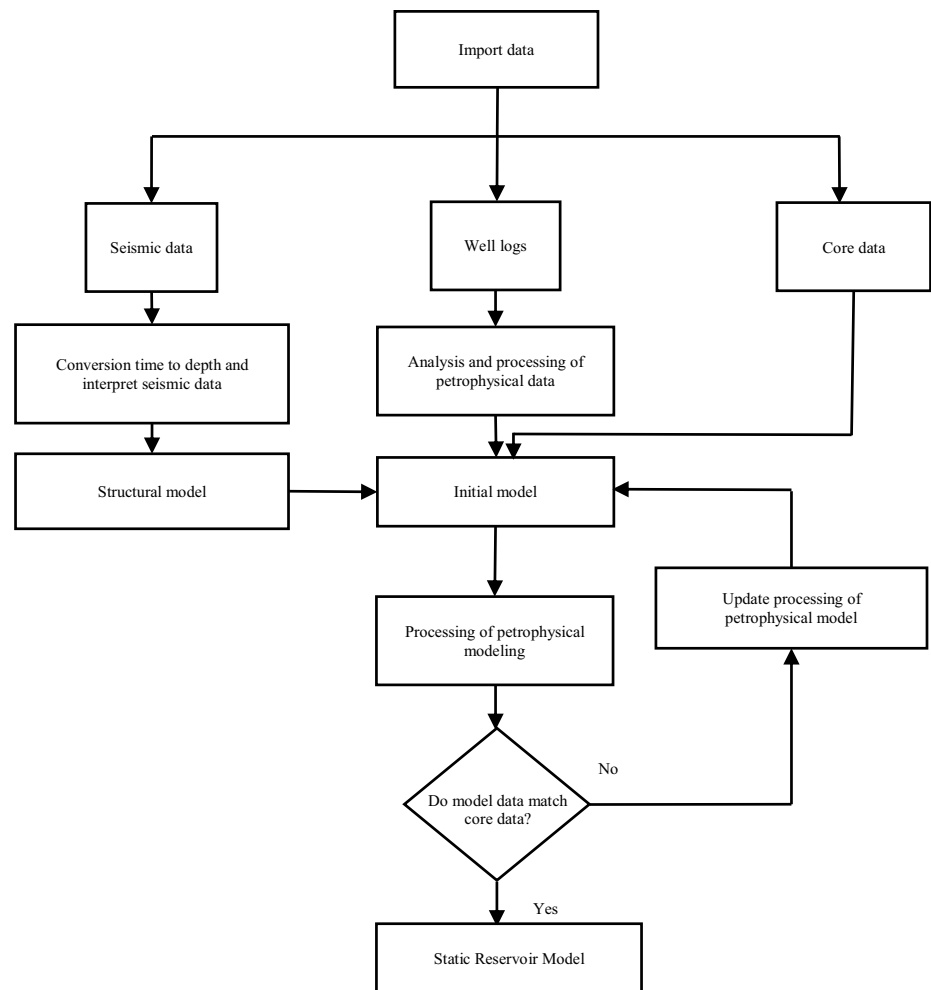
are performed based on well logs and check shot data. The first step in reservoir modeling is the interpretation of seismic data. The interpreter interprets seismic horizons using geological information and geophysical methods. There are many ways to interpret seismic data. One of these methods is to compare seismic traces with the synthetic seismogram at well locations (Dequirez 2006). First, in this method, we select the desired geological horizon at the well site and then connect the wells to each well by picking the horizon between the wells. Using this method, four reservoir surfaces, as well as faults in this reservoir layer, were picked. The map of these seismic events is shown in Fig. 4.

Structural modeling

The first step in constructing a static model is reservoir structural modeling. The structural reservoir model includes seismic interpretation of geological horizons and faults and constructing the geocellular network. This model forms a 3D geometric framework and determines the range of

petrophysical models (Cannon 2018). In this section, tectonic properties such as faults and fractures can be modeled using geological information. The reservoir network model consists of a 3D geocellular network. Each of these cells conveys a property of the petrophysical parameters. Geocellular networks include geocells in vertical or horizontal directions with vertical pillars (Caumon et al. 2004; Fremming et al. 2004). The pillars connect the top and bottom of the reservoir grids. Generally, these geocells model reservoir properties and structural orientations. Following data import and interpreting the seismic data, we can produce mapped surfaces. At this stage, the geocell networks are constructed to fit the dimensions of the reservoir. Network, as the mainframe of the model is used to integrate the structural data and petrophysical properties to generate the static reservoir model (Gringarten et al. 2008). It allows petrophysical parameters to be defined at the location of each well in the networks. In the next step, when the reservoir is divided into a geocellular network, it evaluates all the properties of each geocellular, such as the petrophysical properties, the distance, and dimensions of the geocellular in each cell. The

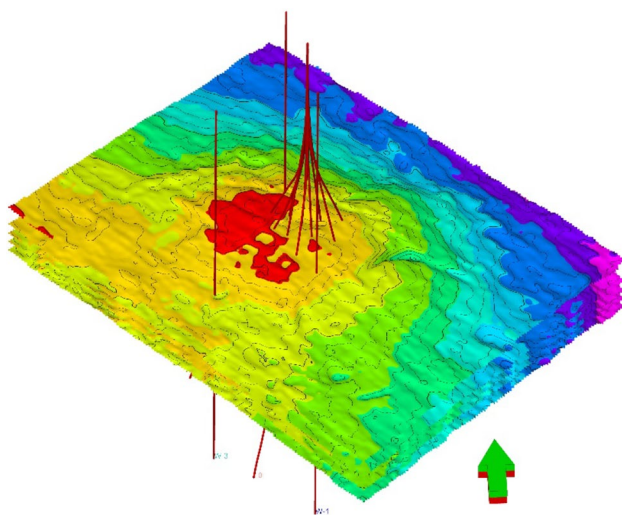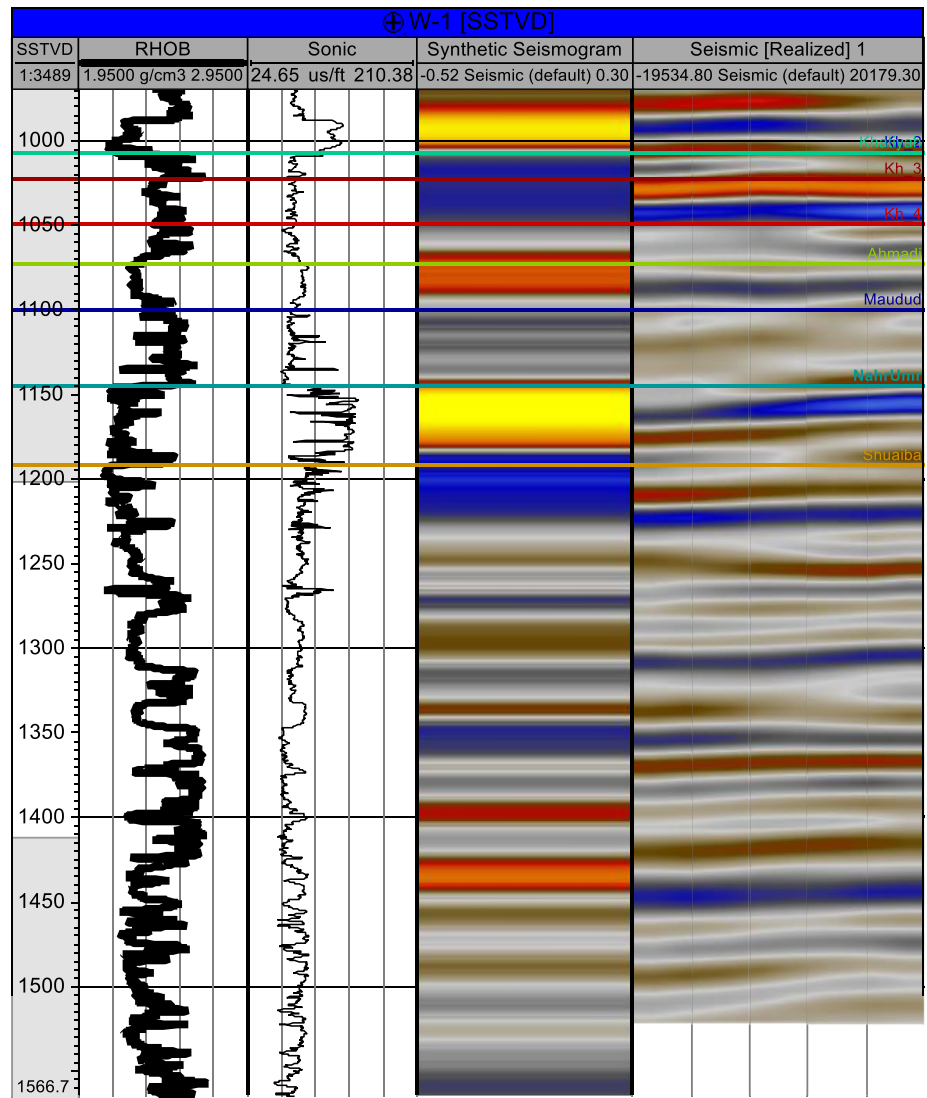**Fig. 3** Synthetic seismogram diagram for W-1 well

Fig. 4 Surface (depth domain) of the reservoir model

dimensions of each of these cells are useful in evaluating the model accuracy. In this study, the X- and Y-dimensions of the 100 * 100-m geocell with the 1-m thickness of the reservoir section and three meters in the non-reservoir section are considered. Geocellular gridding is a process to construct the skeletal frame of the model using the faults that include top, middle, and bottom skeleton grinding in the reservoir framework. The geocellular network is shown in Fig. 5.

Petrophysical data analysis

At this stage, the operations are prepared to import petrophysical data into the Petrel software. At this stage, the data obtained from the petrophysical logs, which are effective porosity and permeability, are upscaled. Resistivity, SP, neutron, sonic, and density logs were used for the identification and estimation of petrophysical properties, e.g., effective

Fig. 5 The Pillar gridding in the reservoir section
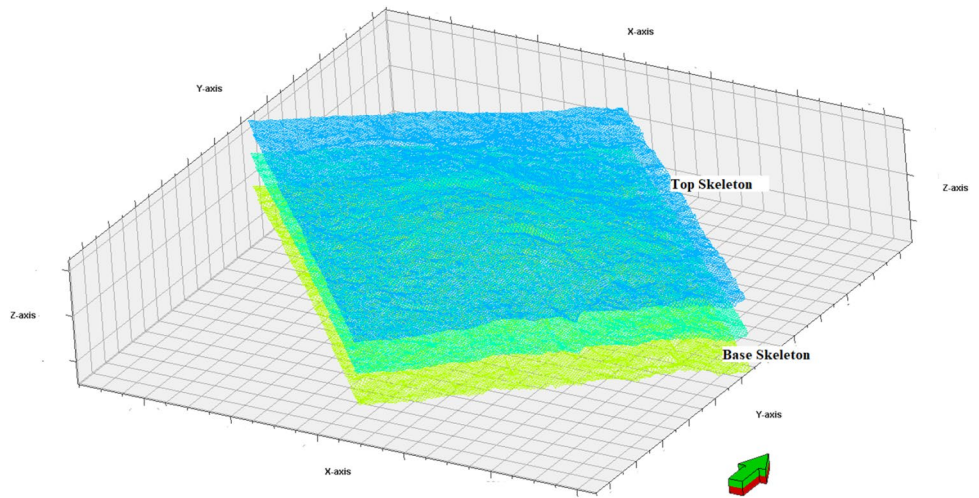
porosity and permeability. Also, the previously mentioned logs were used to generate the effective porosity and permeability of the reservoir. The seven well logs were correlated, and the reservoir framework was characterized in terms of the petrophysical parameters (Fig. 6). The purpose of upscaling is to place the geometrical location of the petrophysical properties in each geocell. The two basic requirements for upscaling are that the data have a normal distribution and no orientation in the input values (Dean 2007). In geostatistics, the spatial location of samples should always be quantitatively analyzed. On the other hand, it should be possible to correlate the different values of a quantity in the sampling frequency and orientation of the samples. This spatial relationship between the value of a quantity in the population of

samples taken from the spatial structure is expressed (Bahar and Kelkar 2000). In this step, the geocell input parameters designed in the reservoir network model are evaluated by the averaging method. In the modeling of petrophysical parameters using geostatistical methods, the existing data trends must be eliminated. The trend in data prevents the variogram from reaching a fixed ceiling. Normalization must be performed to eliminate the effect of the trend in the data. A normal distribution has a mean of zero and a standard deviation of one. After normalizing, the spatial structure of the data should be examined (Gringarten and Deutsch 1999). A variogram is one of the computational tools that can examine spatial data structures (Hasani pak 2007). The amount of nugget is obtained by evaluating the data in the
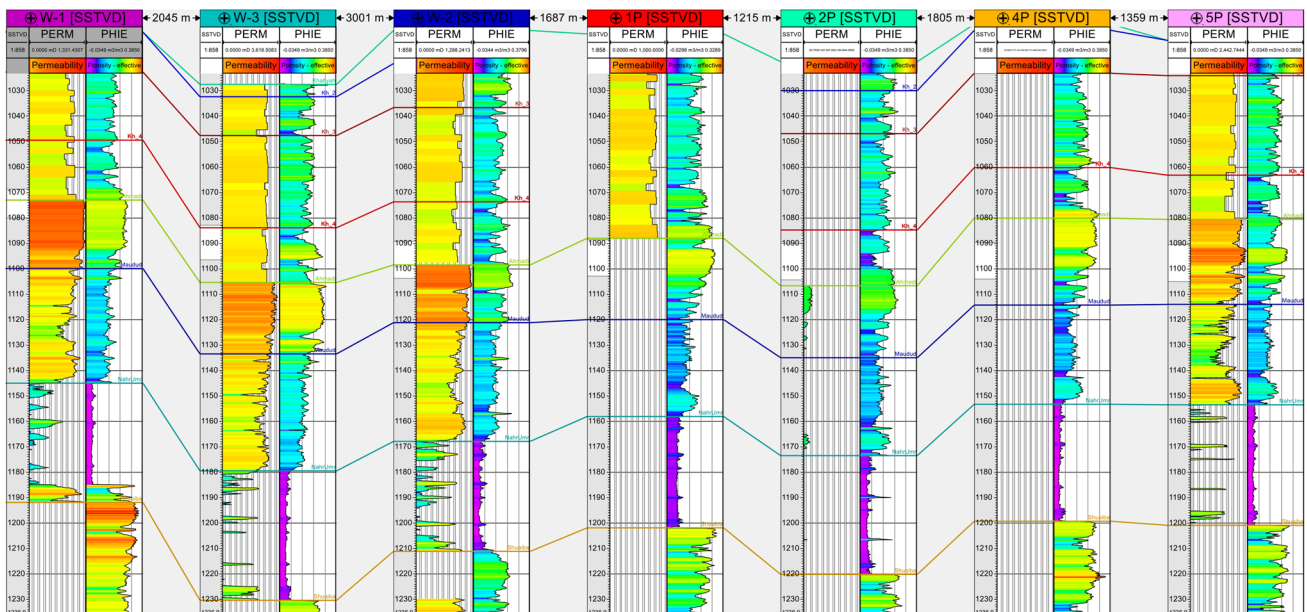

Fig. 6 Reservoir well correlation of the seven wells in the upper Sarvak Formation

variogram model. The nugget effect that is less than the horizontal distance from the sampling point is reduced or taken to zero. At this stage, the data are processed at the Variography stage, and the variograms are plotted in vertical (Fig. 7) and main directions (Fig. 8) using a spherical model for effective porosity and permeability in the reservoir area. Variography is the method of studying and describing the spatial variations of parameters. The basis for this is a technical variogram for analyzing the data variability versus the distance. Therefore, the reservoir properties are more similar for shorter distances than longer distances. Table 1 shows the results of the variogram for effective porosity and permeability. After the variogram operation, the reservoir properties can be modeled.
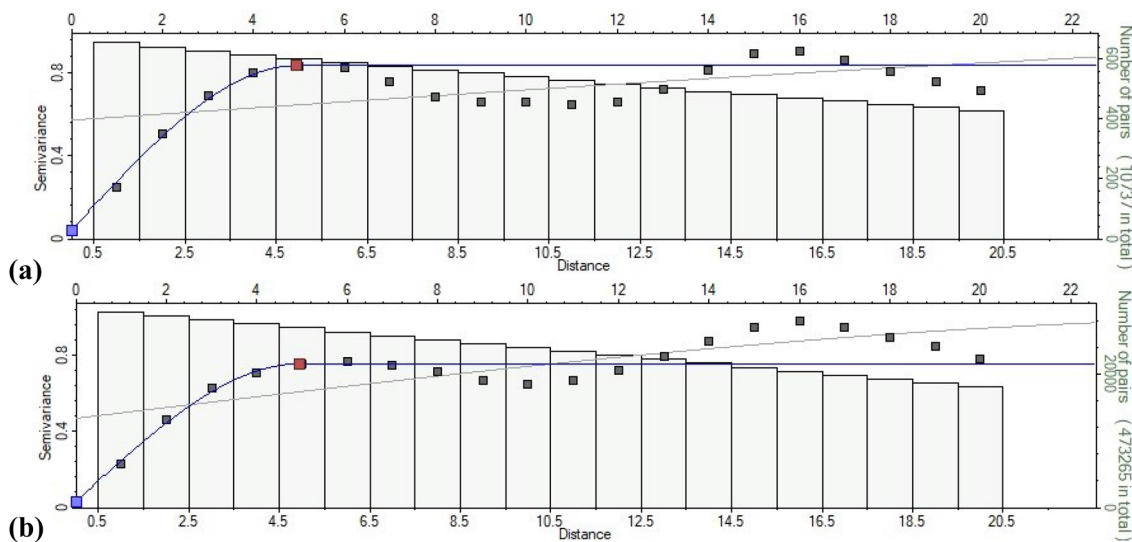

Fig. 7 Variography model in the vertical direction, **a** effective porosity data, **b** permeability data
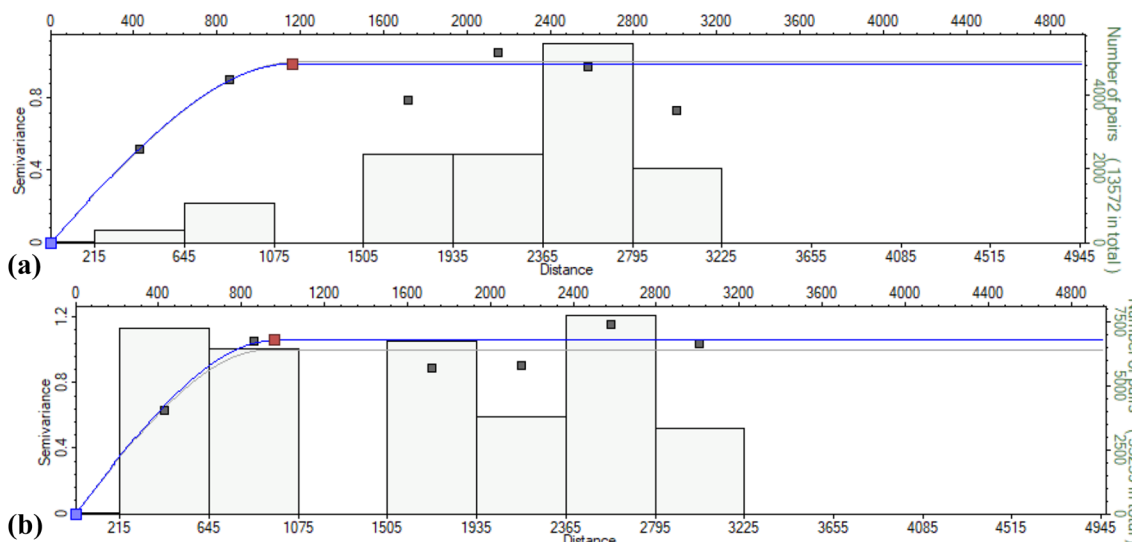

Fig. 8 Variography model in the main direction; **a** effective porosity data, **b** permeability data

Table 1 The results of variography and anisotropy of petrophysical properties	Main range	Vertical range	Nugget	Sill	Variogram model	Parameters
	943	4.5	0.05	1	Spherical	Effective porosity
	874	4.8	0.07	1	Spherical	Permeability

Static reservoir modeling

Modeling is one of the essential stages of studying a hydrocarbon reservoir. The static model includes a geocellular network that contains information such as stratigraphy and fault modeling which leads to the construction of structural models and petrophysical properties. A geocellular model (3D grid-based model) generally has thousands to millions of geocells, and for each cell, rock facies and petrophysical properties such as porosity, permeability, and water saturation can be specified (Pyrcz and Deutsch 2014). The static petrophysical model provides a complete classification of the reservoir parameters continuously in each cell of the 3D network (Dubois et al. 2003). There are various methods for reservoir simulation, each of which is based on its specific algorithms (Deutsch and Journel 1998). The sequential Gaussian simulation method is one of the best simulation methods for its reduced computational time. This simulation procedure consists of five principal steps: (1) select a random point to estimate in the unknown dataset, (2) apply the kriging method using the modeled dataset and variogram method, (3) select a random value for unknown points, (4) at this stage the simulated point is considered as the known point and will be used to simulate the next randomly chosen unknown point, (5) repeat steps 1 to 4, until there are no unknown points (Mata Lima 2005). Geostatistics simulation is one of the methods that can generate data compatible with a spatial variable. The most important result of the simulation is that it can create histograms and model spatial variability of the real data. Sequential Gaussian simulation is one of the methods that can be used to detect the

reservoir anisotropy and reflect such anisotropy in the generated models. Reservoir zoning is one of the most critical steps in reservoir evaluation. To evaluate reservoir parameters, according to past studies, the Sarvak Formation was divided into four separate sections. At this stage, static modeling can be performed using SGS method based on the variogram models. Figure 9 shows the distribution of permeability and effective porosity values in the static reservoir model. Based on the petrophysical evaluations carried out using the SGS method in the reservoir section, the mean effective porosity and permeability are calculated as 12.75% and 51.5 mD, respectively (Table 2). One of the methods to evaluate the accuracy of simulation results is to compare the modeled values with the original data (well data). The closer the simulation results are in the original data, the better the accuracy of the simulation calculations. The simulation results showed good agreement between simulation results and preliminary data (Fig. 10). The data obtained by sequential Gaussian simulation of effective porosity and permeability in cross-plot diagrams show a good correlation (Fig. 11). Based on the acceptable

Table 2 Permeability and effective porosity calculated in the reservoir interval

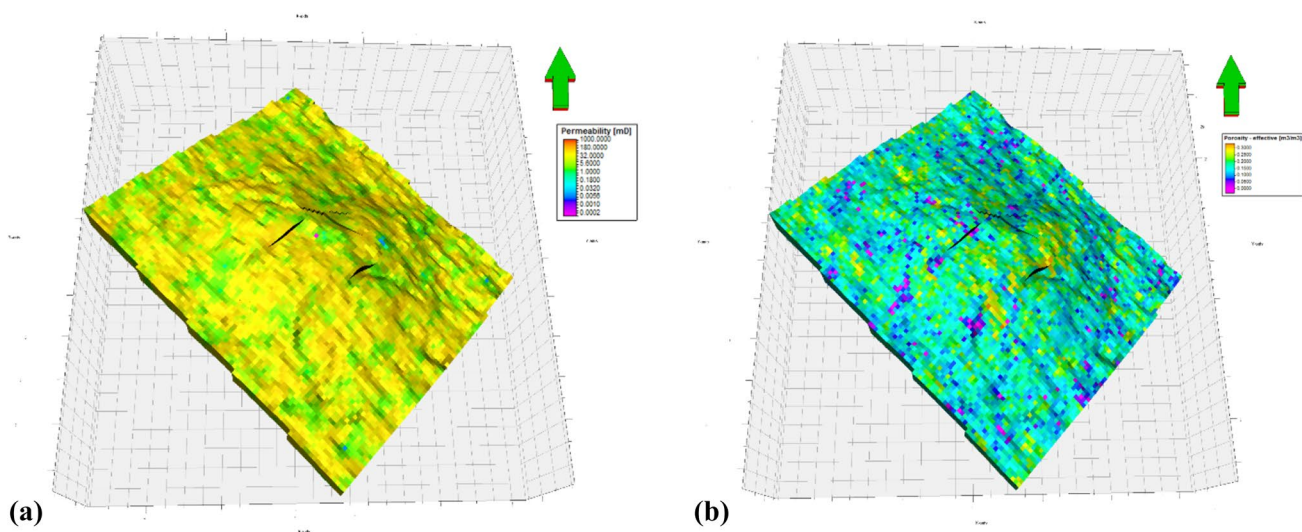| Zone	Thickness (m)	Permeability (mD)	Effective porosity (%)
A1	25	56	13.8
A2	27	72	17.6
A3	29	48	12.1
A4	35	30	7.5
Total	116	51.5	12.75

(a)   **(b)**

Fig. 9 Static models of the reservoir using SGS method; **a** permeability model **b** effective porosity model
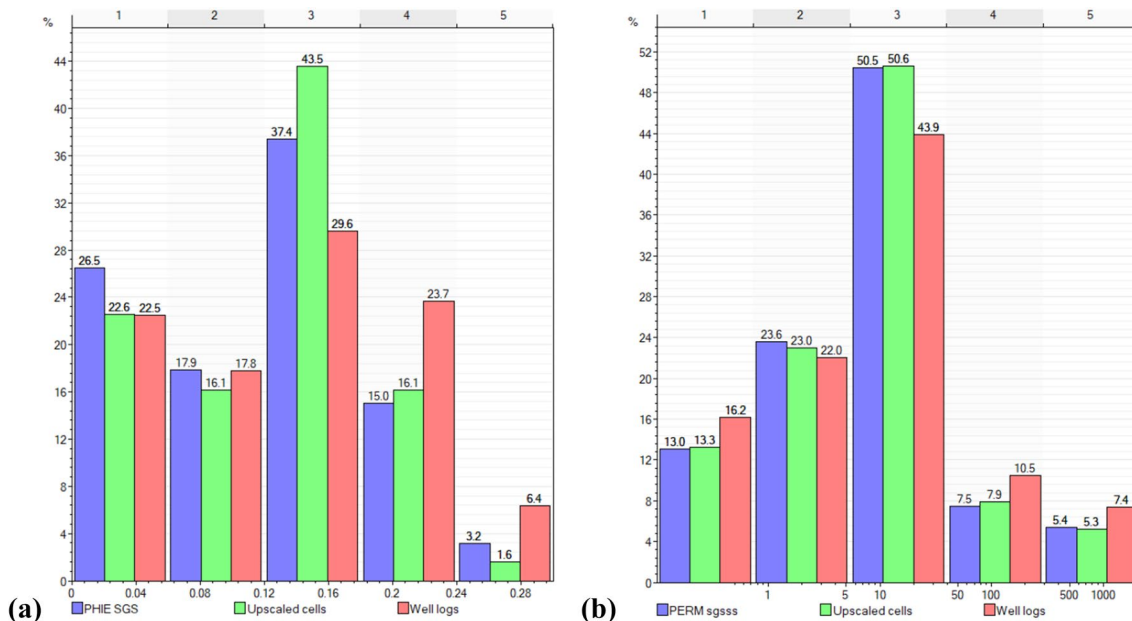
Fig. 10 The relation between porosity and permeability using well-log data
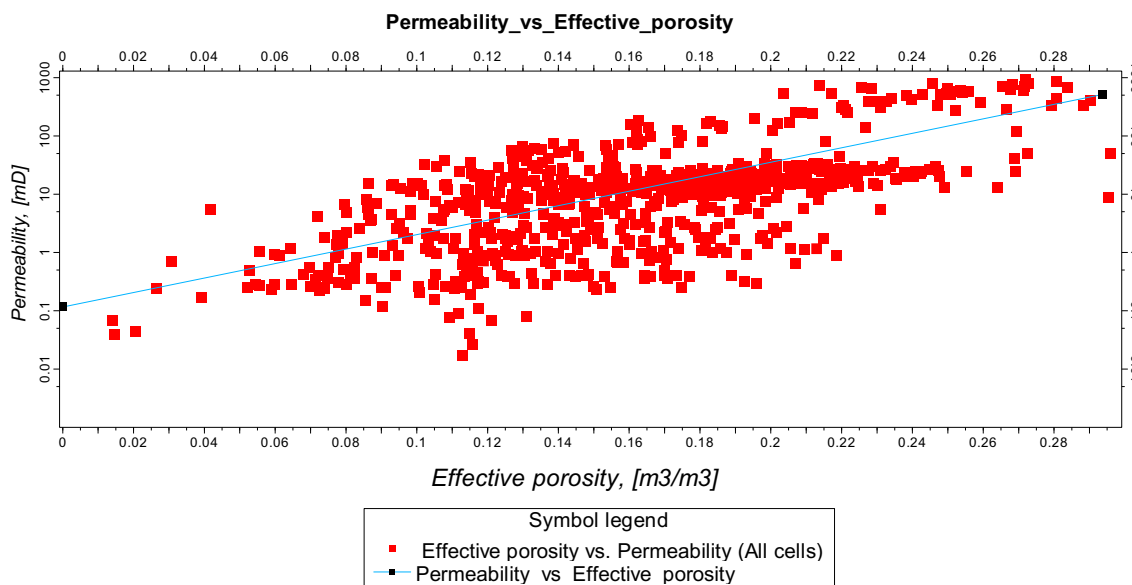

Fig. 11 Cross-validation results of estimated permeability, the correlation coefficient for w-01 well with a correlation coefficient of 0.86 (right) and for well w-03, the correlation coefficient is 0.81 (left)

results of this histogram, the accuracy of the simulation can be evaluated. Estimates of effective porosity and permeability in the entire reservoir due to the presence of effective porosity and low permeability in the reservoir indicate low-permeability layers such as anhydrite in the vicinity of the reservoir. According to the obtained results, the dominant permeability of this reservoir is modeled to be within the range of 0 to 100 ms of the seismic section interval (Fig. 11) and the range of 0 to 23% porosity is considered to be the dominant porosity in this reservoir (Fig. 12).
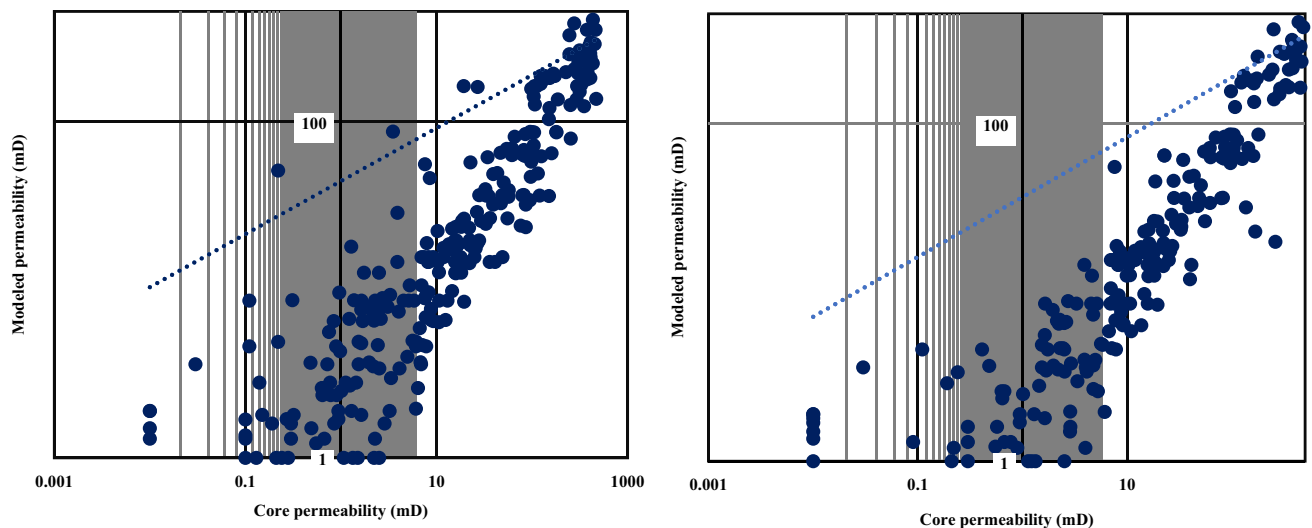
Fig. 12 Cross-validation results of estimated porosity of the well w-01 (right) and the well w-03 (left)

Validation of permeability values

Estimated permeability values should be verified according to its sensitivity and cross-validation employed. In the cross-validation, information from one of the wells is removed from the model, and, with the help of other wells, the permeability is estimated in the reservoir. Then the estimated permeability at the well location is compared with the true permeability, and the correlation coefficient is determined. The same procedure is repeated for wells w-01 and w-03. The correlation coefficient is between zero and one; the correlation coefficient closer one represents a more reliable result. The correlation coefficient for the two wells w-01 and w-03 is 86% and 81%, respectively (Fig. 11). The results of cross-validation of porosity for the two wells w-01 and w-03 show that the SGS method is able to generate reliable results in estimating petrophysical values, especially in complex geological structures (Fig. 12).

Discussion and results

Structural modeling with high accuracy is the first step in the 3D static modeling process of the reservoir. The seismic and well-log data are used to construct the reservoir model with the purpose of modeling the reservoir properties. Seismic studies in the field under review show that faults, similar to other oilfields in the Persian Gulf, are due to upward movements of the deep Hormuz salt (Kent 1979; Talbot and Alavi 1996). The structural model of this field consists of five main and four smaller faults in the upper Sarvak Formation. Interpretation of seismic data in this reservoir results in the interpretation of five major and four minor faults that

often extend northwest–southeast and northeast–southwest, northern–southern directions.

The upper Sarvak formation was influenced vertically and laterally by Salt diapirism movements related to Hormoz Salt Series and basement fault activities in the Persian Gulf (Van Buchem et al. 1996; Razin et al. 2010). Most of the hydrocarbon reservoirs of the Sarvak Formation in the Persian Gulf are naturally fractured. These fractures could be related to the tectonic activity of the area, which caused paleo high and regional discontinuities in the oil fields of the Persian Gulf. Most of the previous studies have shown that the effect of regional epeirogeny in the Turonian age caused dissolution and channel in carbonate ramp in the Persian Gulf (James and Wynd 1965; Burchette 1993). These channels and sedimentological facies in the upper part of the Sarvak Formation could increase permeability and porosity. Overall, porosity and permeability in carbonate rocks depend on the density of fractures and the presence of a channel in the reservoir rocks. The effective porosity and permeability diagrams showed increasing trend in the reservoir area, which can indicate the presence of fractures and channels in the reservoir. One of the important factors affecting the petrophysical properties of the reservoir is the presence of clay minerals in the sedimentary environment. Many studies have been done on the stratigraphy and reservoir facies of the Sarvak Formation in the Persian Gulf (James and Wynd 1965; Razin et al. 2010; Burchette 1993). The upper Sarvak Formation was deposited in the carbonate intra-shelf basin with bioclastic deposits such as wackestone, packstone, mudstone and claystone facies (Van Buchem et al. 1996; Alsharhan and Nairn 1997). Based on previous studies, it can be concluded that the accumulation of samples with low effective porosity and permeability indicates the
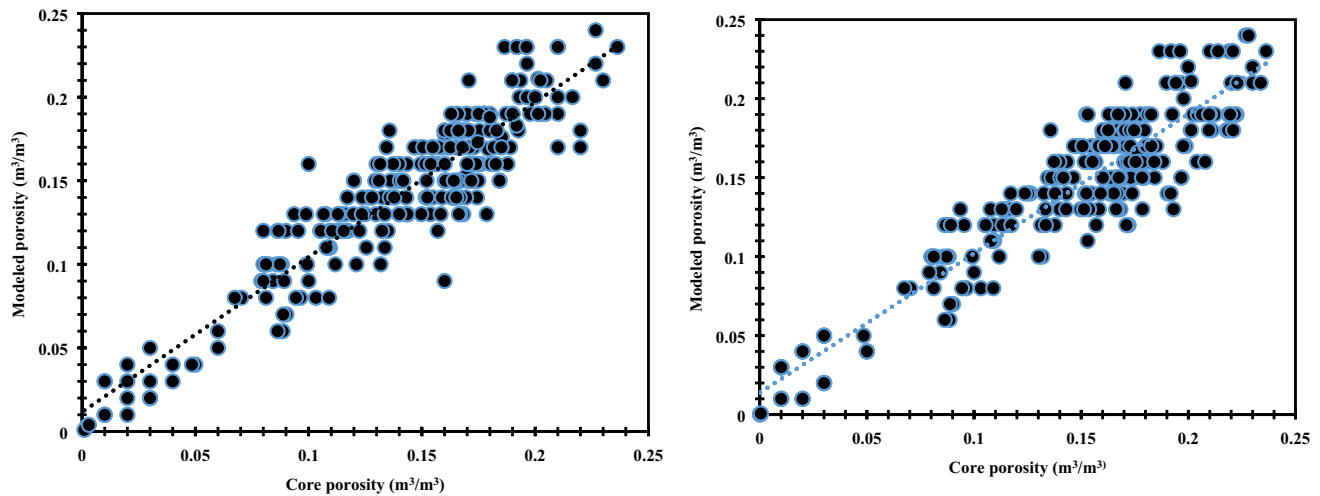
Fig. 13 Histogram derived from SGS model and petrophysical logs, **a** effective porosity, **b** permeability

presence of low-energy facies such as mudstone and claystone in the reservoir section; furthermore, high porosity and permeability values can be representative of the presence of channel or fracture. Based on a previous study (Yang et al. 2016) in this area along with the results of porosity and permeability cross-plots (Figs. 11, 12), it can be concluded that the carbonate reservoir is characterized by fractures and sedimentary facies similar to carbonate reservoirs in the region. According to these cross-plots, it can be inferred that the fracture density and sedimentation conditions in this region have increased the porosity and permeability values in the reservoir interval.

Most of the geostatistical methods are based on variogram modeling. One of the most important methods for anisotropy analysis of reservoir parameters is the variogram analysis. The variogram results were evaluated under a spherical model for two effective porosity and permeability parameters in the reservoir layer. After assessing the variogram for the petrophysical data, considering the anisotropy results, the Upper Sarvak Formation data are modeled using the sequential Gaussian simulation method. Changes in effective porosity and reservoir permeability values of the models can be investigated in 3D. The studied reservoir layer is divided into four zones based on previous studies. Petrophysical evaluation results in the reservoir zones are indicated in Fig. 9 and also in Table 2. The best evaluation of the reservoir area in the field can be identified by examining the average of the estimates obtained for each reservoir variable. Accordingly, the effective porosity and permeability of the A2 zone are 17.6% and 72 mD, respectively. This zone introduced as the main reservoir of this field. Zone A4 with effective porosity and permeability of 7.5% 30 mD, respectively, has the lowest reservoir quality compared to other reservoir zones. The calculated effective porosity and

permeability showed similar values compared to the Sequential Gaussian Simulation method. This comparison can be seen in the histogram in Fig. 13. Also, the evaluation of cross-validation results showed that the sequential Gaussian simulation method has relatively high efficiency in estimating petrophysical values. Static reservoir modeling using geostatistics methods in terms of the possibility of creating multiple realizations of the reservoir in which the heterogeneities and range of variations of the variables are well displayed. This is one of the most efficient ways to provide a reservoir property model.

Conclusion

In this study, static reservoir modeling for effective porosity and permeability is performed, using the Sequential Gaussian Simulation (SGS) method. Static reservoir modeling provides acceptable results using the geostatistics method in reservoirs that have a complex geological structure. Due to the high correlation obtained between core data and the results of the model, the SGS approach shows the superiority of this method in petrophysical modeling. The evaluated petrophysical parameters indicate that the reservoir effective porosity and permeability are 12.75% and 51.5 mD, respectively, which show that the geostatistical SGS method is a proper method for modeling petrophysical parameters. The comparison of the results using the SGS method with the core permeability data at wells W-01 and W-03 indicates the acceptable correlation coefficients of 86% and 81%, respectively. The accumulation of the samples with small permeability is interpreted as the presence of low-energy facies such as mudstone and claystone. On the other hand, trends of increasing permeability emphasize the possibility

of the presence of a channel or fractures in the reservoir. The results show that the static modeling can provide information for the development of methods for reservoir evaluation and subsurface geological studies.

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