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3D static reservoir modeling by geostatistical techniques used for reservoir characterization and data integration

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Abstract To remove some of the ambiguities in a heterogeneous oil reservoir, a three dimensional model of the reservoir would be constructed by application of newly introduced methods. The aim of this study is to define an accurate and efficient model of a complex reservoir in southwest of Iran and accurately derive the geological and geometrical properties of the reservoir for well location proposal. Seismic data in addition to well logs were used for that purpose. A corner point grid was used in this study, and a generic global scale-up method was combined with previous result for reservoir simulation. The final model pointed out the heterogeneous characterization of the reservoir and proved the advantage of combining these methods in constructing accurate and efficient reservoir models. According to these models, it is concluded that the reservoir has different productive zones in different members that was not cleared in the previous models.

Keywords Reservoir modeling · Grid adaptation · Global scale-up · Reservoir zonation · Time–depth conversion · Depth map

Introduction

Understanding subsurface structure is an essential task in any reservoir characterization study (Al Bulushi et al. 2012). Various technologies are used to understand a prospective reservoir and provide information at many different scales (Chen and Durlofsky 2006). Most often, geologic interpretation based on seismic information is used to interpolate or extrapolate the measured data in sparse well locations in order to yield complete reservoir descriptions. Reservoir characterization and modeling obtained by this information are keys to match the production profile and well planning in oil fields (Aarnes 2004). However, reservoir modeling has become a crucial step in field development, as it provides a venue to integrate and reconcile all available data and geologic concepts (Branets et al. 2009).

One of the key challenges in reservoir modeling is accurate representation of reservoir geometry, including the structural framework and detailed stratigraphic layers (Novak et al. 2014). The structural frameworks delineate major compartments of a reservoir and often provide the first-order controls on in-place fluid volumes and fluid movement during production. Thus, it is important to model the structural frameworks as accurate as possible.

To construct a model, it is necessary to use geostatistic methods. These are considered as the study of phenomena variation using collection of numerical techniques to describe the spatial continuity by a model in a petroleum reservoir (Cornish and King 1988). A typical study in reservoir modeling contains classification and zonation of the reservoir, followed by structural construction and petrophysical models. Finally, 3D geo-model grid, water saturation, porosity, and permeability distributions map are made (Nikravesh and Aminzadeh 2001; Harris and Weber 2006). However, despite decades of advances in grid generation across many disciplines, grid generation for practical reservoir modeling and simulation remains a daunting task. Specific challenges in grid generation for

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reservoir simulation arise from the complex structure of subsurface reservoir (Du and Gunzburger 2002).

Ma et al. (2014) introduced a new data integration method for a single-well reservoir simulation. They applied this new integration strategy on a single well on a reservoir with different carbonate, from Foraminiferal grainstone to micritized packstone and dolomitized packstone. Finally, they built an accurate geological reservoir model with anisotropy by integrating petrophysical and pressure transient data with their new integration strategy. However, in this study, we are going to improve this strategy to a multiple well algorithm and apply that on a carbonate reservoir with more and less same petrology.

Integration strategy improvement from single to multiple well

Detailed petrophysical reservoir characterization, which is critical to reservoir management, consists of data acquisition, data processing, and data distribution in space, or modeling. Data typically include lithology, porosity (φ), water saturation (S_w), zone thickness (h), and permeability (k).

Permeability is the most difficult to characterize. This is especially true in carbonates, due to the heterogeneous pore structure caused by depositional environments and diagenesis, such as dolomitization, compaction, cementation, and fracturing (Ayan et al. 2001).

Unlike other reservoir petrophysical properties, permeability is directional. Thus, any geological reservoir model should be validated by comparisons with dynamic data from production logs, downhole pressure tests, and injection–falloff tests (Kuchuk 1994). Later it could be used in a single-well reservoir simulation to predict well performance, infer in situ reservoir scale reservoir conditions, relative permeability, and capillary pressure (Kuchuk et al. 2000).

In the methodology introduced by Ma et al. (2014), petrophysical properties derived from open hole logs and wireline formation testing (WFT) were calibrated with core analysis data before being distributed in space to build a geological model. The established model can be verified from borehole fluid flow profiles measured by a production log even though layers with no flow or low flow due to skin, low permeability, or low pressure may not be detectable by a production log. The Eq. (1) shows integration strategy used for single-well simulation (Ma et al. 2014):

$$\left(\sum_{i}^{n} k_i h_i\right)_{Core-Logs-falloff} = \left(\sum_{i=1}^{n} k_i h_i\right),$$

$$\left(\sum_{i=1}^{n} k_i h_i\right)_{PTA} = (k_{avg} H)_{WFT} \tag{1}$$

where H is the total reservoir thickness, h the individual layer thickness, n the total number of reservoir layers.

Indices I is the specific number of reservoir layer and avg is the average of all layers.

The following summarizes details of the methodology for single-well data integration, reservoir characterization, reservoir modeling, and well-performance prediction (Fig. 1).

Together with other geological information, the core data and open hole logs pretests are integrated for a foot-by-foot formation evaluation and reservoir characterization. Next, a layered, single-well geological model is generated from the detailed formation evaluation and reservoir characterization. Wireline formation testing (WFT) and vertical interference testing (VIT) data could be analyzed to quantify vertical and horizontal permeabilities of the layers selected for the VIT (Kuchuk et al. 2010). The geological model should be updated with the vertical and
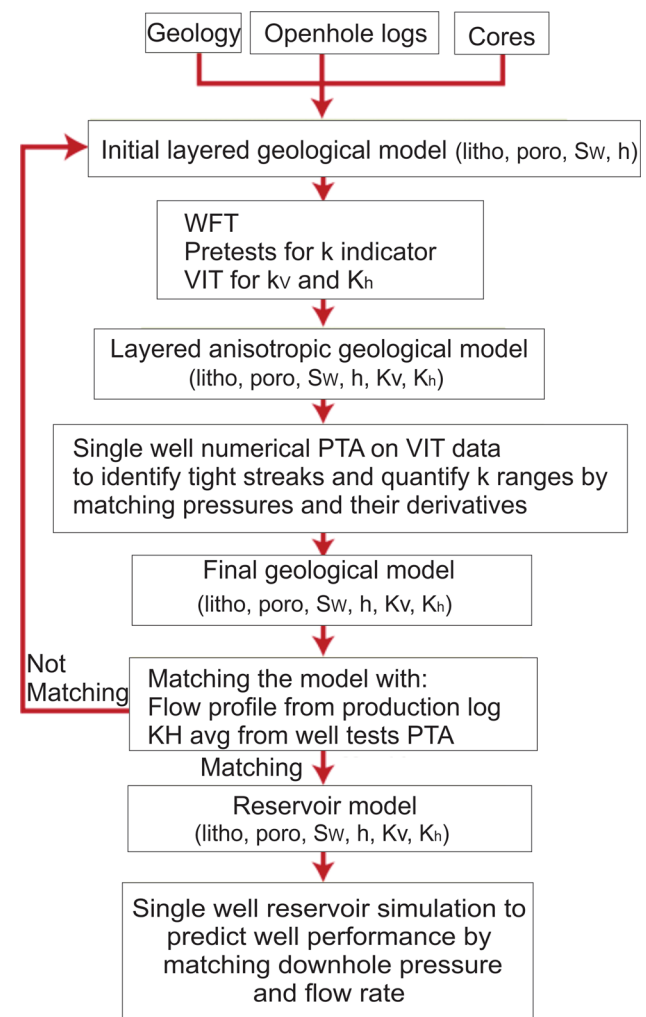

Fig. 1 Reservoir characterization and modeling strategy for single-well simulation (Ma et al. 2014)

horizontal permeability determined from analyses of all VITs. This layered anisotropic geological model is fine tuned by integrating geological features and the range of permeability obtained from performing a single-well numerical pressure transient analysis (PTA) with the pressure and pressure derivatives as the history-matching parameters for each VIT (Zeybek et al. 2002). Finally a geological reservoir model is established by iteratively validating the fine-tuned geological model with $\sum kh$ (Eq. 1) from a production log and the total $K_{avg}H$ (Eq. 1) from downhole pressure buildup and falloff tests.

Improving this single-well strategy, that was successfully applied on carbonate reservoir in Saudi Arabia, to a multiple well simulation strategy, could result in a more accurate geological reservoir model. Figure 2 shows the flowchart of a typical study and types of data that are used through a conventional reservoir characterization and modeling.

Now, the aim is to introduce the strategy of Ma et al. (2014) to the conventional strategy that produces a new

reservoir characterization method in a multiple well simulation. In this improvement, the single-well simulation method is considered as an element in the conventional simulation flowchart, but in a right place. The new strategy should not only reduce the uncertainty in the input data, but also should increase accuracy of the final model. Therefore, each single-well simulation flowchart should be performed to the end. Then the reservoir parameters will be evaluated by well test data. Now, these data from a single well are used as primary input for multiple well simulation. This strategy will suppress any noise in the data, while increase the computation time and gives in hand a set of primary results acting as input for multiple well simulation.

The simplified strategy of multiple simulation well that contains the single-well simulation as engine in its heart is shown in Fig. 3. To test the efficacy of this new methodology, a complete seismic and well data from an oilfield in southwest of Iran were used for reservoir characterization and modeling.

Fig. 2 Schematic flow chart of the petroleum reservoir modeling steps (Soleimani and Nazari 2012)
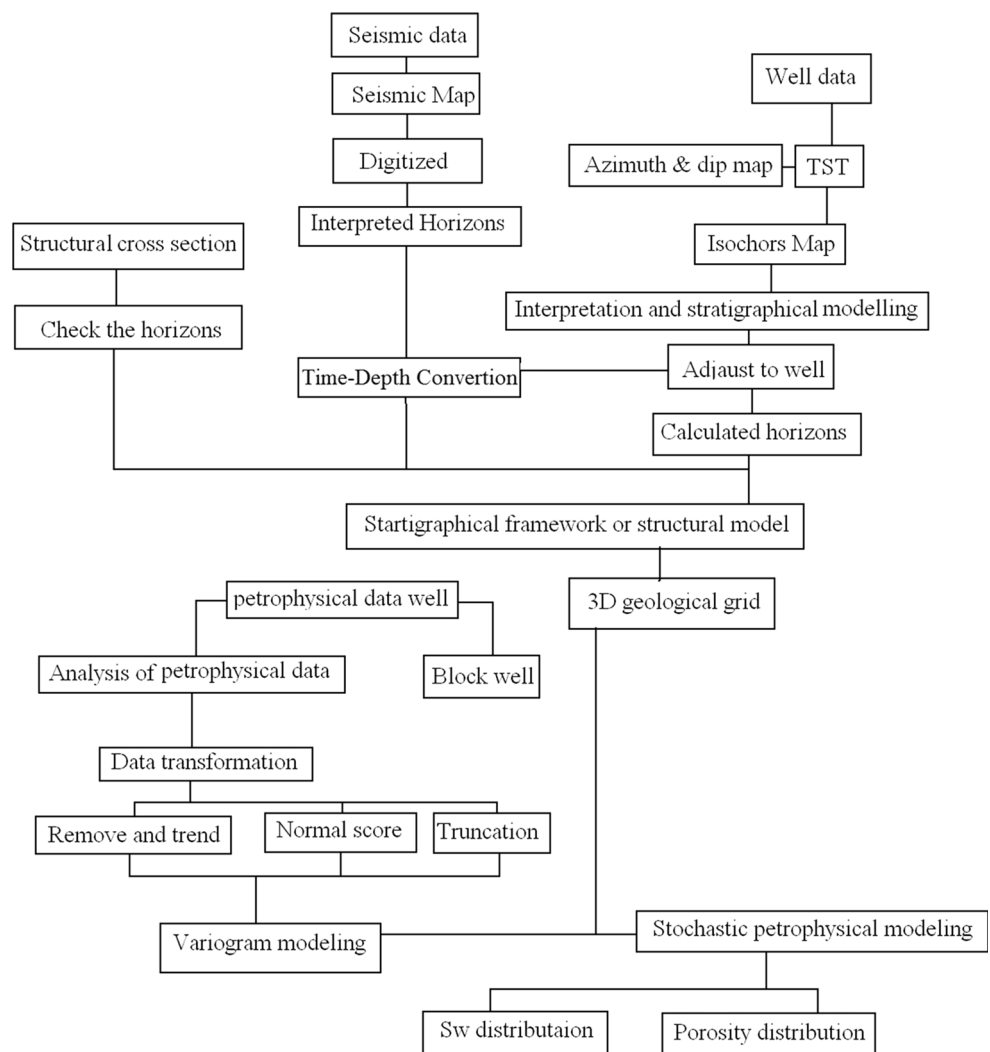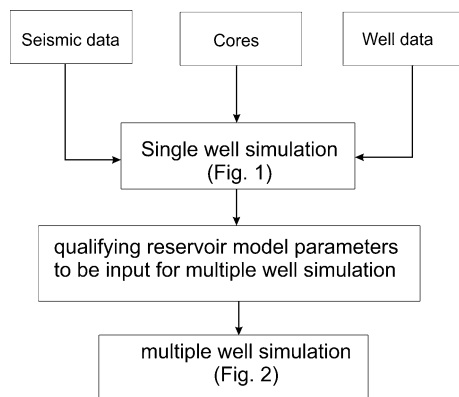
Fig. 3 The simplified flowchart of the newly introduced strategy used in this study

The study area

The Zagros hydrocarbon province is located in the north and northwestern border of the Arabian Plate (Fig. 4). Conditions for hydrocarbon accumulation occurred on the Arabian plate to the southwest of the Zagros mountain range. The crucial potential occurrence of Silurian source rock and the relationship of this Silurian shale source to gas resources in the Zagros area are proved in geochemical studies (Soleimani and Hashemi 2011). In most of the reservoir of this region, Carbonate rocks dominate the reservoirs of the Mesozoic stable platform history of the Zagros. The differential deformation during various Alpine orogenic pulses on these carbonates has resulted in different fracture systems, which usually have a large impact on the reservoir quality of these structures. The Sarvak formation, which contains bright brown to brown limestone, is the main reservoir in most of the oil fields in the Zagros area.

Many of the exposed anticlines in the easternmost part of the Zagros basin either never contained oil, or late migration allowed the oil to escape. Presumably the Zagros orogeny destroyed a number of pre-existing accumulations, either fully or partially. There are many indications in northeastern Iraq and southeastern Iran of the dissipation of light components from Late Cretaceous time onwards, that resulted in development of heavy oil deposits in the Sarvak formation and bitumen-impregnated reef limestone as well as water-laid bitumen pebbles in some Paleocene, Eocene, and Pliocene conglomerates (Soleimani and Nazari 2012).

Regional setting and stratigraphy

The youngest group in the area, Fars Group, consists of Aghajari and Gachsaran formations, Asmari, Pabdeh, and Gourpi formations, the middle group (Bangestan Group) consists of Ilam, Lafan, Sarvak, and Kazhdumi formations, and the oldest group (Khami Group) consists of Darian,


Fig. 4 Field location map (Emami 2008)

Gadvan, and Fahliyan formations. Thickness of the Aghajari, Gachsaran, and Asmari formations increased from south toward the north along the field of study, while the others are almost constant. Pabdeh, Gurpi, Lafan, Sarvak, and Darian are overlaying disconformable with each other. The Sarvak Formation with age of Albian–Turonian is equivalent to Mauddud (Albian–Cenomanian), Ahmadi (Cenomanian), Rumaila (Cenomanian–Turonian), and Mishrif (Turonian) formations in Iraq. Figure 5 shows the stratigraphy correlation between wells in the study area.

Seismic interpretation

Seismic interpretation is considered as the first step in building a 3D structural modeling of a reservoir. Seismic interpretation provides essential sub-regional information as well as some structural elements to be included in construction of the reservoir model. Interpretation results have been used to extrapolate geological and petrophysical well information. Time structure maps have been generated for top of Sarvak formation. Figure 6 ensembles processing flow applied on all seven seismic lines by help of well data. This figure shows a sample of the seismic line with picked horizon, the iso-frequency component section time map and the velocity model used for time–depth conversion. To correlate wells with seismic section, synthetic seismograms from five wells were made. Synthetic seismogram of well was tied to seismic section based on the best visual match of package reflection events between the synthetic seismogram and the actual seismic sections.

Fig. 5 **a** Well locations and seismic line used for this study. **b** The stratigraphical relation of the formation in the wells. True depths (*TD*) are in meters. Sarvak (*Sv*) is the reservoir formation in this study
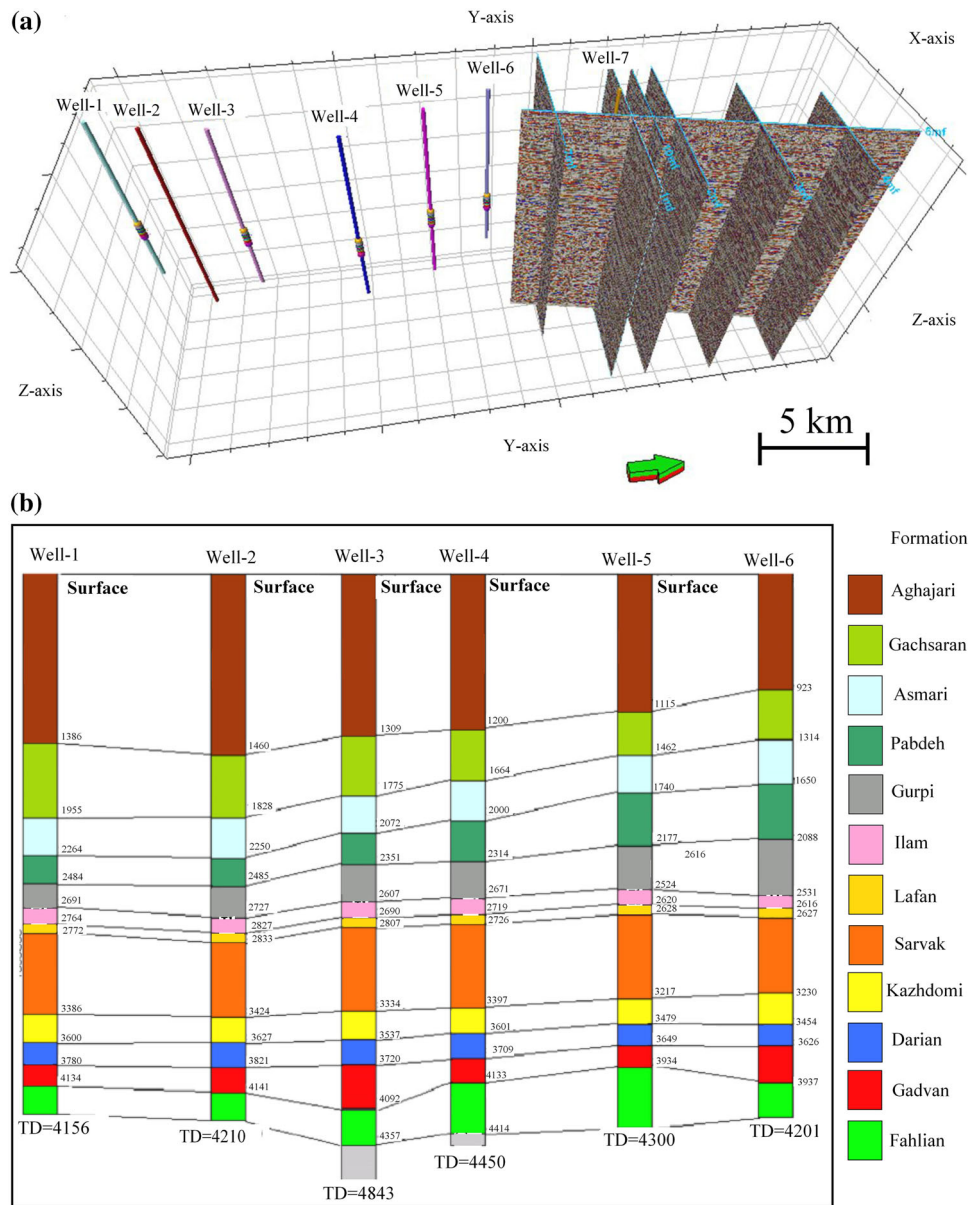
Velocity analysis

Different approaches can be used in generation of different velocity models such as stacking, RMS, migration, and well velocity (Gadallah 1994). As there was no stacking, RMS and migration velocity available to be calibrated by the velocity information obtained from the wells, a velocity field had to be constructed only from well velocities. As mentioned, well velocities in different wells are almost similar.

The well time–depth table data, shown in Fig. 7a, were used for depth conversion in this field. The velocity value in this field will vary both laterally and vertically. However, it is not the case here, because all wells in the study area are aligned almost on a straight line, following the crest of the

anticline, covering the whole length of the studying field (Fig. 7b). Then after, all the seismic time maps were converted to depth maps for input into the Geo-Model.

Reservoir characterization

One primary goal of reservoir characterization is to identify the most significant vertical and lateral heterogeneities within the reservoir and incorporate this information into a three-dimensional geologic model for reservoir simulation (Durlofsky et al. 1997). The reservoir characterization process integrates multiple datasets to provide a description of the static and dynamic properties of a reservoir, especially those that control fluid flow (Emre 2005; Coll et al.
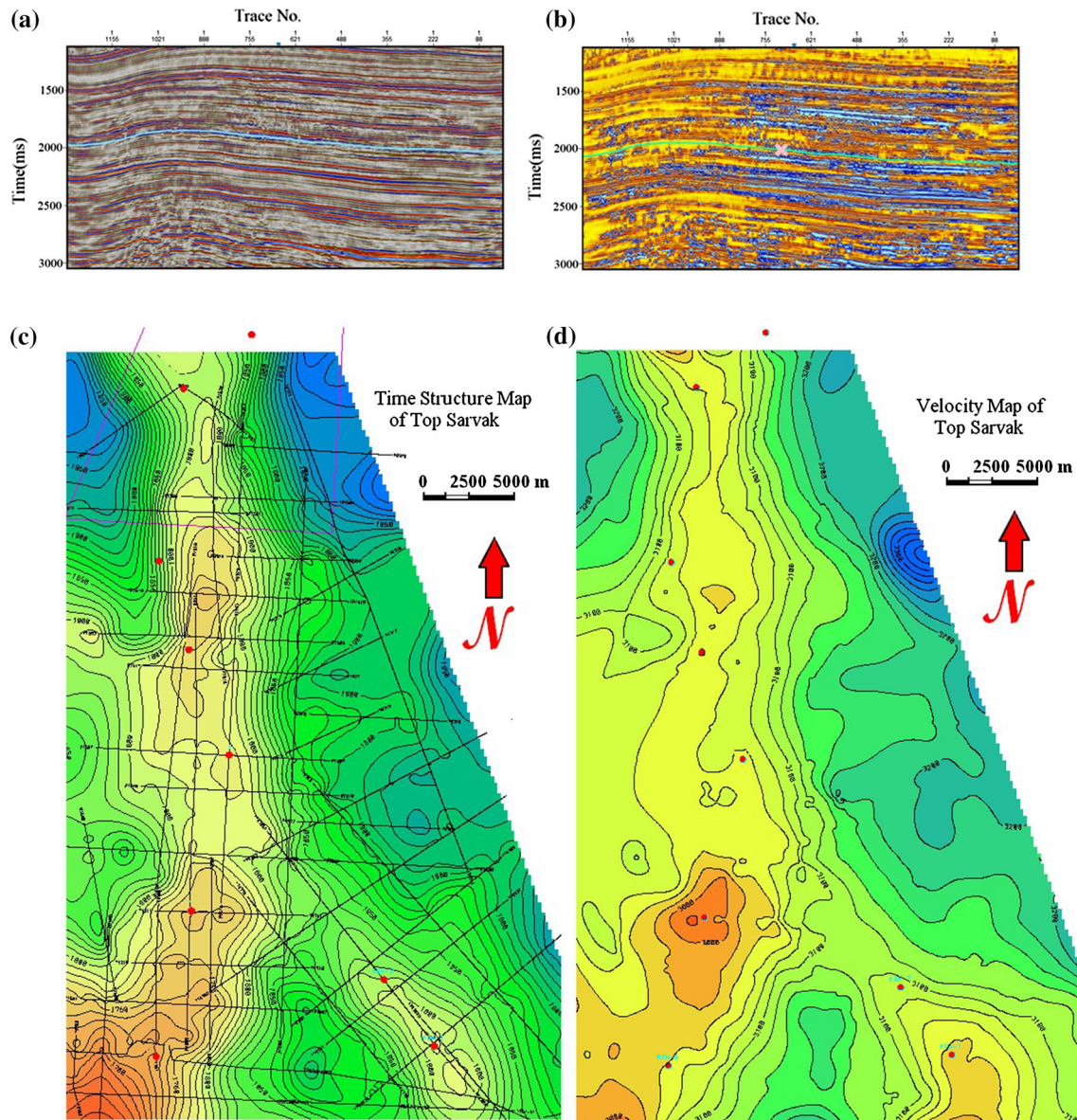
Fig. 6 a Seismic section of the study area used for horizon picking; **b** iso-frequency component of the same section used for validation of the horizon picking; **c** time map obtained by horizon picking of all seismic lines and **d** velocity map used for time–depth conversion

2001). In turn, the reservoir description is used to construct a geological model, which is then used for visualization, flow simulation to predict reservoir performance, and for other applications. Although a very detailed geological model may be useful for visualization or computing volumetric of original oil in place, it usually must be simplified or generalized for use as a model for flow simulation (Bahar and Kelkar 2000).

Reservoir zonation of the Sarvak formation

In this study, a new reservoir zonation has been made using new methods of reservoir analysis that integrates petrographic, sequence stratigraphic, and petrophysical data. It is obvious that prior to any reservoir simulation, each formation should be divided into different zones and subzones of reservoir and non-reservoir quality. In this study, target formation, the Sarvak formation, has been divided into 20 zones, gathered into four groups based on the core data. First group has identical mineralogical composition with more than 70 % of calcite, clay mineral between 0 and 20 %, and with dolomite up to 15 %.

Second group composition, petrography, and petrophysical characteristics are identical. The main lithologies are limestone, argillitic limestone, shaly limestone, and
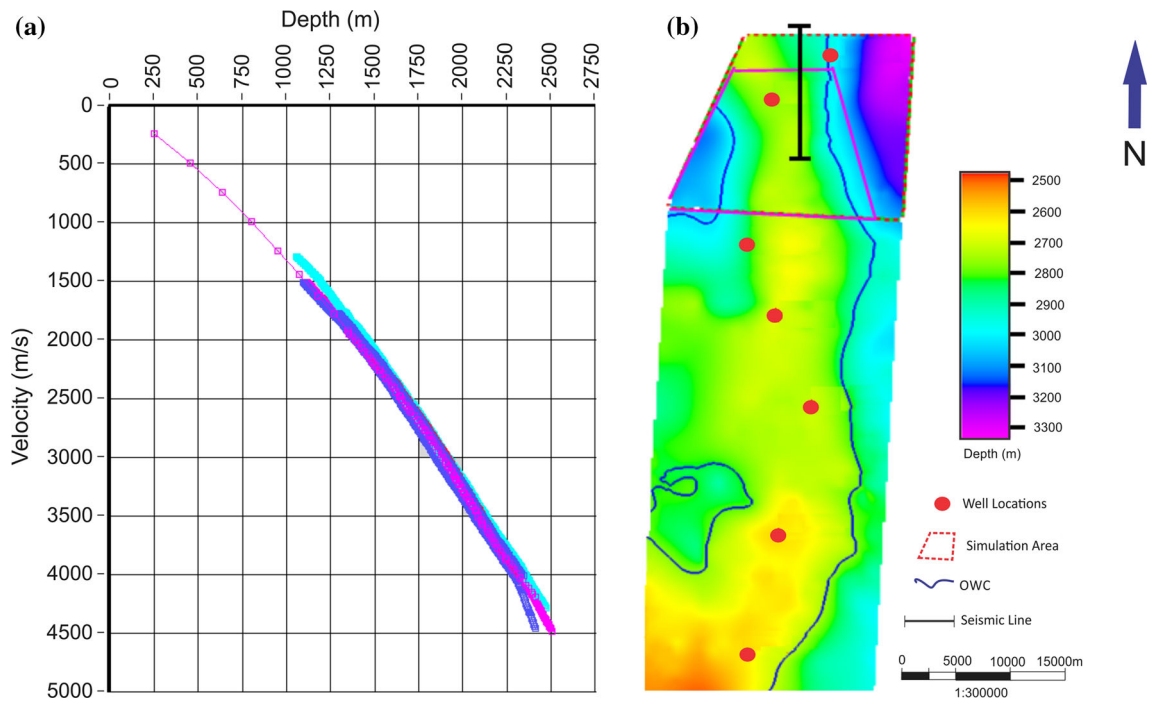
Fig. 7 a Comprehensive time–depth curve of the mapping area and **b** depth map and well location on the depth structure map close to Sarvak

shale. Based on the reservoir properties, it may act as a barrier or baffle to the vertical flows in the field, except in fractured zones.

Third group consists mainly of limestone, argillitic limestone, and tight clean limestone. The rocks are composed of calcite, clay minerals, and dolomite crystals.

Fourth group is non-reservoirs to poor reservoirs in the Sarvak formation. This zone consists mostly of calcite, clay minerals, and crystalline dolomite. The amount of clay minerals and dolomite is less than 20 %.

Geo-cellular modeling

Informed field development decisions must be based on a comprehensive understanding of the reservoir, including its static attributes and dynamic response. This knowledge is best encapsulated in a 3D geological model (Christie and Blunt 2001).

The 3D static connectivity of a reservoir can be assessed through a simple visualization and various connectivity tools. Major decision must be made in the presence of significant uncertainty. Stochastic modeling provides a way of estimating uncertainty of different reservoir properties. The geological model forms the basis for a dynamic simulation model which will, as far as possible, include the available geological data and insights from reservoir dynamic data. The seismic interpretations of the tops of horizons were imported to map the reservoir horizons and generate the structural framework.

Petrophysical study is the estimation of petrophysical properties such as porosity and permeability. It applies statistical and geostatistical techniques to well log data. After 3D seismic interpretation in the previous step, 3D Geo-cellular modeling will be revised. The output model should honor any heterogeneity in the reservoir (Wang and Kovscek 2002).

Upscaling involves making a coarse grid model in a way that honors the fine grid model properties. Geo-cellular modeling can be carried out either deterministically or stochastically. If only a quick and simple model is needed, advanced techniques such as stochastic facies modeling and stochastic petrophysics modeling may not be appropriate. Instead, a wide range of deterministic modeling methods can be applied to create a 3D property model (Chen and Wu 2008).

Stochastic modeling allows producing a variety of multiple realizations which all fit the basic data and field information. The range of possible outcomes can be assessed and, through ranking, the most appropriate models for reservoir prediction can be chosen. Stochastic modeling can also incorporate a wide range of information and data. The ability to integrate field data (such as petrophysical data and seismic data) is as important as multiple realizations for honoring heterogeneity (Holden and Nielson 2000).

Gaussian co-simulation and geostatistical techniques

Stochastic simulations are increasingly used to represent and characterize the spatial structure and uncertainty of

rock and soil properties (Larocque et al. 2005). Due to the potential presence of scale dependencies, simulations of the total variables can represent a mixture of spatial components operating at different scales, which may be better interpreted separately. While coregionalization analysis and factorial kriging provide means to characterize and estimate scale-specific components of variation, no methods are available that allow a proper representation of their spatial structure and an assessment of their spatial uncertainty. In this study, the conditional Gaussian co-simulation of regionalized components and regionalized factors is used. This study was used to reduce the correlation between components for different structures and avoid any bias on the sum of simulated components. Simulations obtained with this method adequately represent both the specific features of, and the uncertainty associated with, each scale of variation (Oliver 2003).

After defining and then reducing uncertainty in the variables by Gaussian co-simulation technique, geostatistical tools are used to analyze reservoir properties, such as porosity, permeability, and water saturation. Straight forward geostatistical estimation includes five steps: loading data and clean-up, statistical univariate analysis, semivariogram calculation and modeling, estimation, and visualization or mapping (Russell and Hampson 2008). In addition, geostatistic technique can produce measures of uncertainty by generating multiple realizations (Heinemann and Heinemann 2003; Han et al. 2014).

The most important application of geostatistical techniques is data integration. In a reservoir characterization study, there are huge amounts of data that come from various sources at various scales with different degrees of reliability. The problem in geo-modeling is to use and cross validate all of the information relevant to the final goal of the reservoir model (Barker and Thibeau 1997). Well blocking is one of the more important methods of overcoming the variety of scales of data (Alabert and Modot 1992).

Heterogeneity modeling is another important application of geostatistical tools, which is required in petrophysical modeling (Russell 2004). After heterogeneity modeling, petrophysical modeling has to be carried out. This will create a numerical model of reservoir such that each cell is assigned to a specific petrophysical property such as porosity, permeability, and water saturation.

However, before any simulation, the project boundary should be defined. Exact specification of the project boundary has been shown in Fig. 7b. Interpreted horizons are those for which there are sufficient data to describe the surface. The horizon can be a seismic reflector where there is seismic survey interpretation or an easily identified horizon in a stratigraphic sequence where there are many well penetrations. Calculated horizons are generated by mathematical operations on enclosing interpreted horizons and isochores.

Available data for interpreted horizons include seismic interpretation result in depth domain and horizon tops at well locations. Interpreted horizons and structure framework were generated with all the seven horizons and the related well tops data. All horizons were smoothed and corrected so that they were conditioned to the well tops. Figure 8 shows the input data for interpreted horizon modeling.
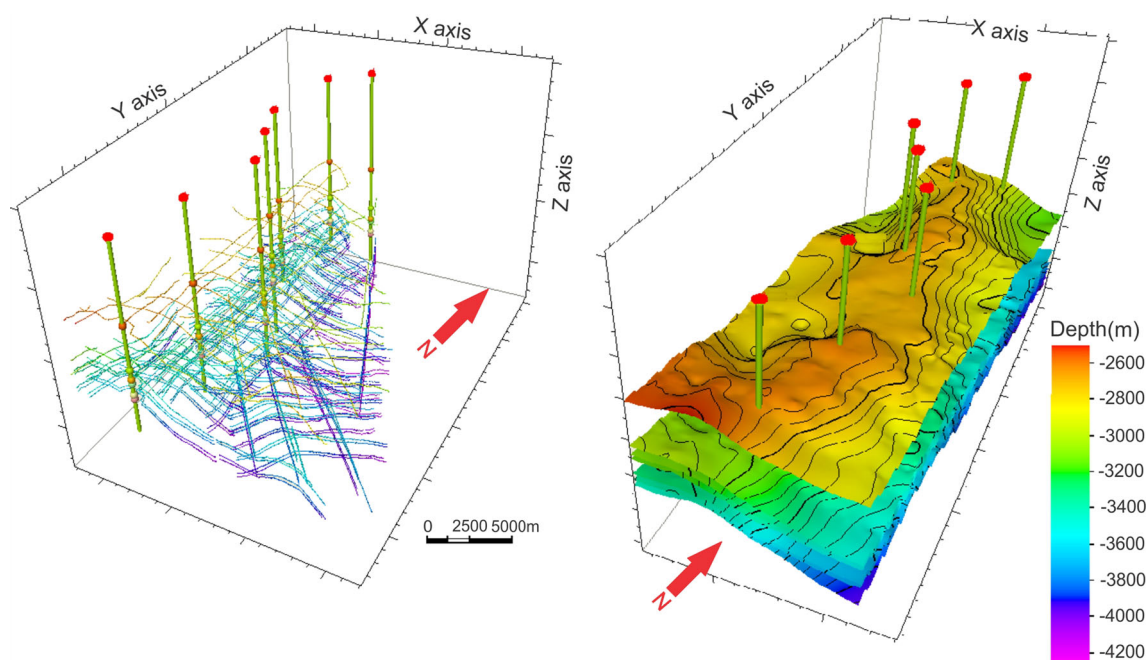

Fig. 8 Input data for interpreted horizon modeling and result

Zonation modeling/stratigraphic modeling

A reservoir characteristic reflects sedimentary processes, digenetic evolution, and mechanical stress. These three types of events produce different types of heterogeneities in the reservoir (Bahar 1997).

Zonation is a part of heterogeneity modeling in which the heterogeneity in the vertical direction is modeled by creating fine layers in vertical direction (Huysmans and Dassargues 2013). As it is not possible to create these fine surfaces from seismic sections, due to the limited seismic resolution, well data should be considered as the main
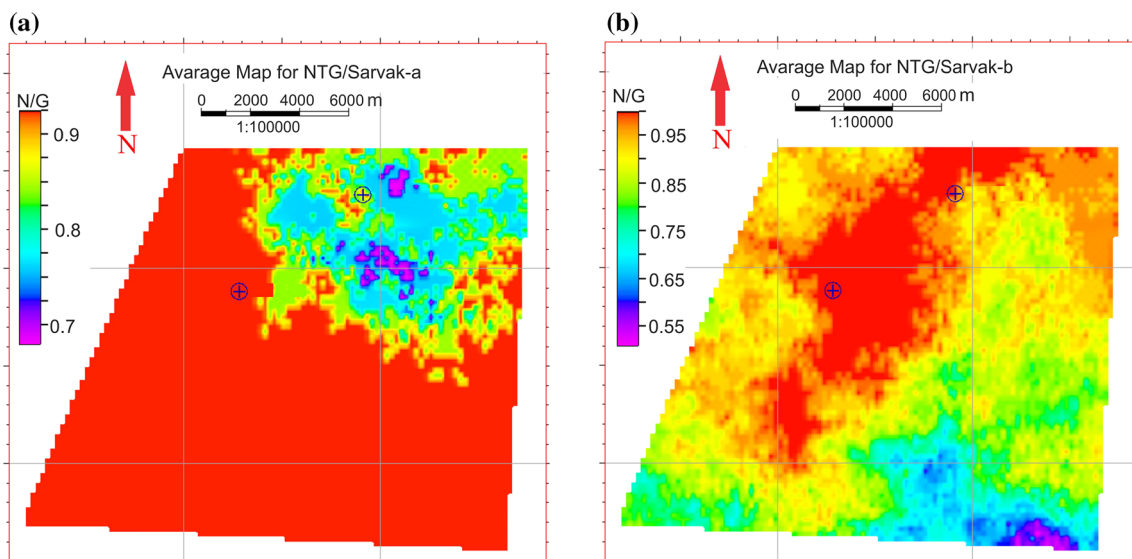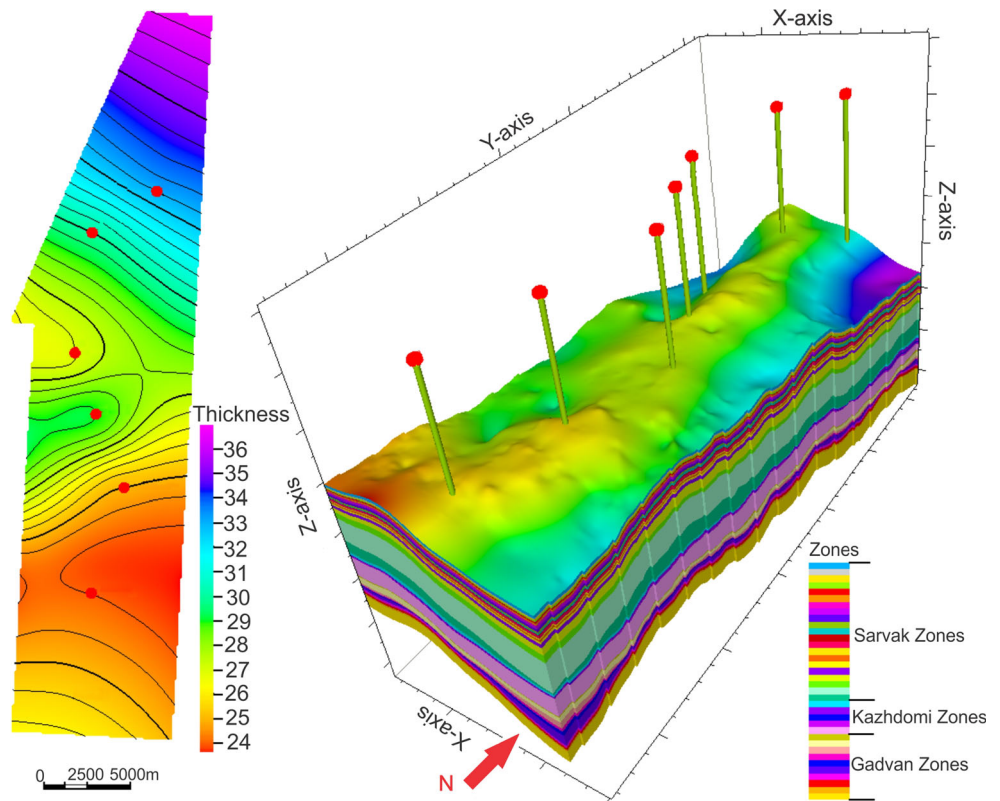

Fig. 9 Zonation modeling and result

Fig. 10 Average map of NTG for two selected zone of Sarvak for simulation area defined in Fig. 5

input data for zonation modeling. Zones are identified and described well by well. Results are depths of each zone in each well (Dumitrescu and Lines 2008).

Stratigraphic modeling should accompany vertical zonation as a support in geological point of view. It is a process of building stratigraphic framework for a reservoir by amalgamating seismic interpreted horizons generated by horizon mapping with geologically modeled isochores. Whether they are either generated by isochore mapping or calculated directly from well data. Isochore maps describe the average or integral properties of a stratigraphic zone. For all the isochore maps used in this study, a radius of 5,000 m was used for well correction in order to honor the

thickness of zones at the well locations. This value was obtained by a variography analysis, which defines validity range of well data.

To generate calculated horizons, the top and bottom interpreted horizons should be used in conjunction with isochore maps. The calculated horizons should be generated with the same resolution as the interpreted horizons. Isochores were corrected proportionally between the top and the bottom of each stratigraphic zone. Resulting output gives thickness of different zones while honoring input data. Figure 9 shows the zonal isochore thickness map and the zonation modeling result. These data were used also to produce average map of net to gross (NTG), porosity,
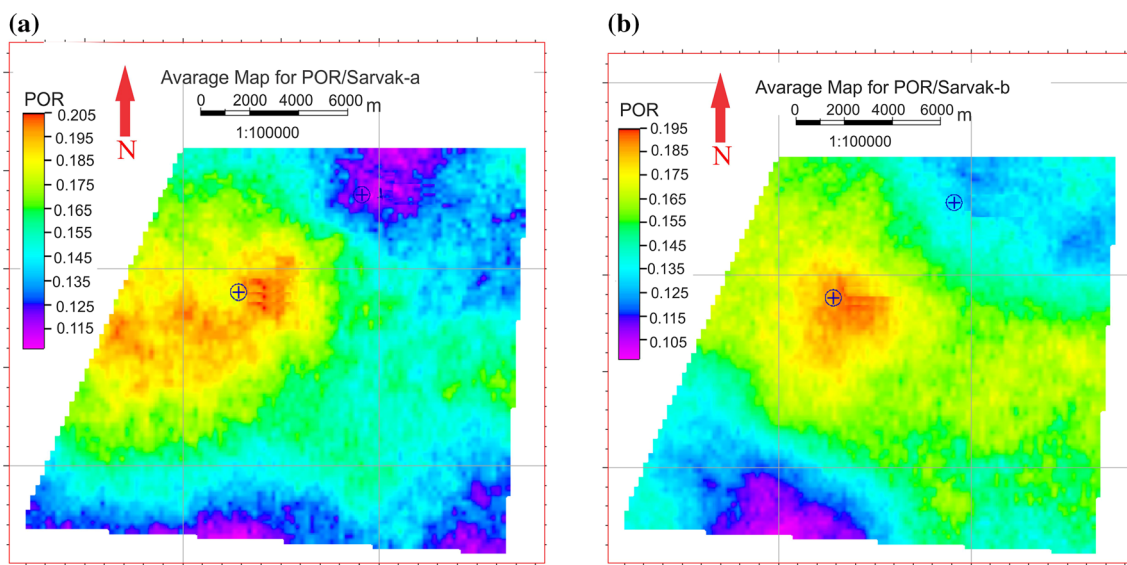

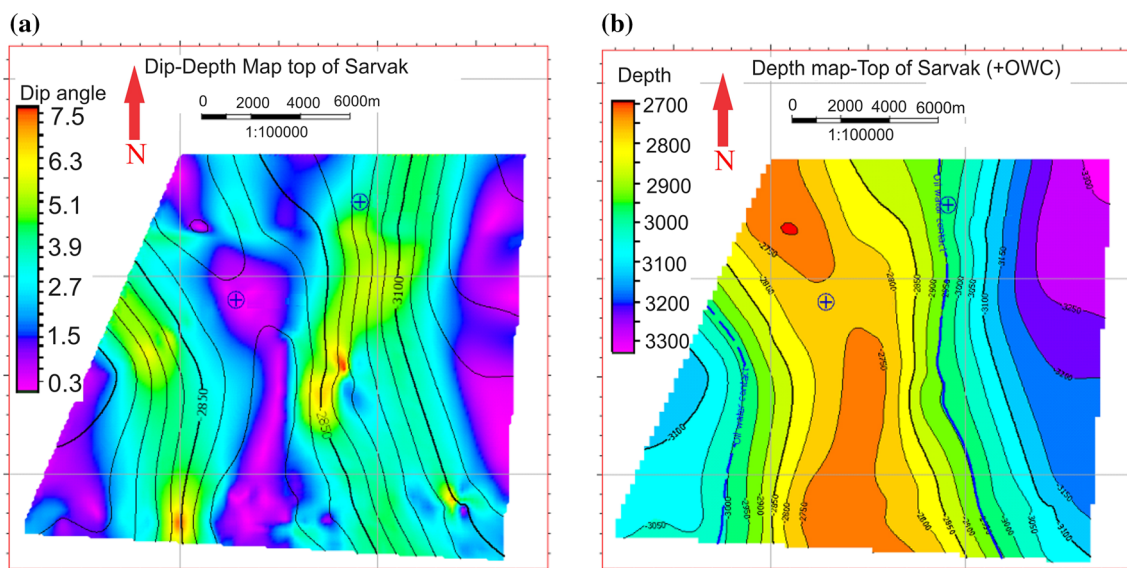Fig. 11 Average map of porosity for two selected zone of Sarvak for the simulation area

Fig. 12 a Dip depth map of top of Sarvak and b depth map of top of Sarvak

depth, and dip–depth map of the Sarvak formation that are shown in Figs. 10, 11 and 12.

A 3D modeling grid

A corner point grid was used in this study; this is a very flexible grid in which the horizontal distance between the cells corners may vary. The pillars are straight lines but may be dipping. Two alternative vertical resolutions can be chosen for layering (Leite and Vidal 2011). Cells may have a constant thickness; that is, all cells have the same z-increment. An initial reference surface is specified, and the cell layers are built upwards or downwards from this reference surface, (Chew 1989; Durlofsky 2005). The

alternative is to specify a constant number of layers (Balch et al. 1999). Two reference surfaces and the number of layers between them are specified, so all the cell ends along one pillar have the same z-increment. This increment may differ from pillar to pillar. The method of constant number of layers was used to model the reservoir formations, resulting in cells with an approximate average thickness of 1 m. The horizontal resolution remained at 200 × 200 m. This size was obtained by testing different sizes and comparing computation time with accuracy of the results. Finally, this cell size showed up accurate results in reasonable time. All zones were constructed using this specification for 3D grid. The resulting 3D grid contained 106 columns, 138 rows, and 358 layers. The total number of cells is about 5,236,824 in the 36 zones. Result of porosity modeling is shown in Fig. 13. It varies slowly in horizontal direction. Result of permeability modeling is also shown in Fig. 14.
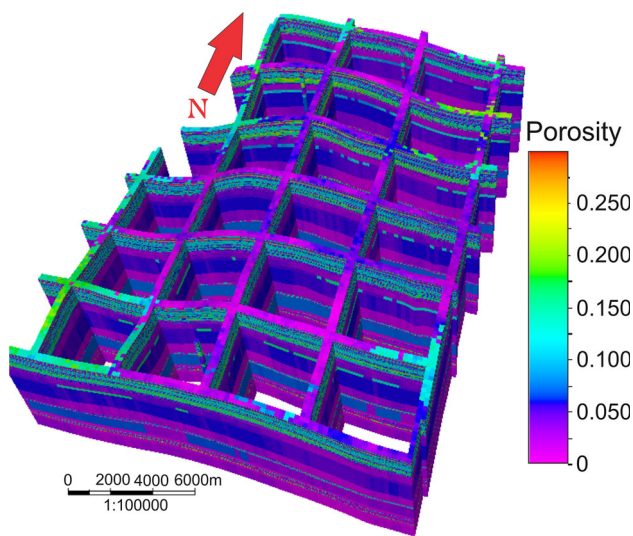
Conclusion

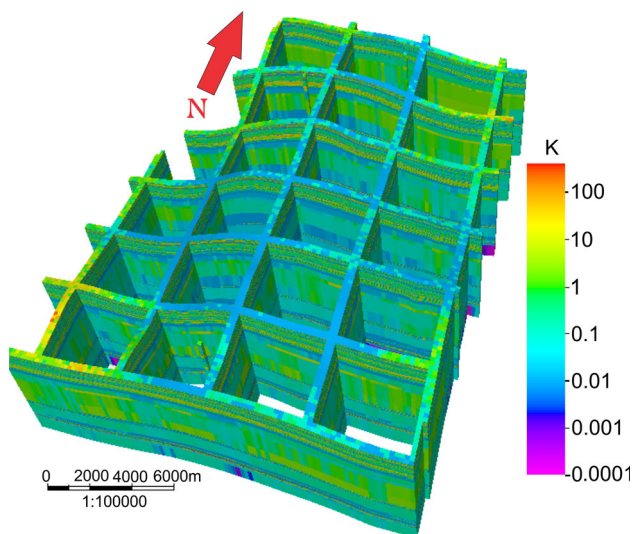Sensitivity studies of several hydrocarbon reservoirs have shown the importance of property modeling both facies heterogeneities and petrophysical properties, in order to capture the true reservoir characteristics that influence the flow pattern of hydrocarbons. Reasonable structure modeling procedure is adopted to ensure the reliable structure model. Porosity model in this study has been built by combining a newly introduced single-well simulation method and conventional multiple well simulation method. The newly introduced simulation method uses the advantage of single-well simulation in case of reducing the uncertainty in the input data. Another advantage of this new method is that the simulating engine performs well especially in carbonate reservoir. Using sequential Gaussian co-simulation based on data analysis and porosity log also used to qualify data for further simulation. Finally, permeability model has been built by co-simulated with porosity model. The final model showed the heterogeneity of the reservoir that was the aim of this study. This model shows slowly variation of porosity in horizontal direction. Permeability modeling also shows that this parameter varies also like as the porosity. Dip–depth amp also showed the structure of the reservoir that was controlled by stratigraphical parameters.

Fig. 13 Porosity model of the study area

Fig. 14 Permeability model of the study area

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