



3D geological modeling of the Upper Cretaceous reservoirs in GPT oil field, Abu Sennan area, Western Desert, Egypt

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Received: 10 May 2019 / Accepted: 19 September 2019 / Published online: 25 September 2019
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Abstract

This study aims to construct 3D geological model using the integration of seismic data with well log data for reservoir characterization and development of the hydrocarbon potentialities of the Upper Cretaceous reservoirs of GPT oil field. 2D seismic data were used to construct the input interpreted horizon grids and fault polygons. The horizon which cut across the wells was used to perform a comprehensive petrophysical analysis. Structural and property modeling was distributed within the constructed 3D grid using different algorithms. The workflow of the 3D geological model comprises mainly the structural and property modeling. The structural model includes fault framework, pillar girding, skeleton girding, horizon modeling and zonation and layering modeling processes. It shows system of different oriented major and minor faults trending in NE–SW direction. The property modeling process was performed to populate the reservoir facies and petrophysical properties (volume of shale (V_{sh}), fluid saturations (S_w and S_h), total and effective porosities (Φ_t and Φ_e), net to gross thickness and permeability) as extracted from the available petrophysical analysis of wells inside the structural model. The model represents a detailed zonation and layering configuration for the Khoman, Abu Roash and Bahariya formations. The 3D geological model helps in the field development and evaluates the hydrocarbon potentialities and optimizes production of the study area. It can be also used to predict reservoir shape and size, lateral continuity and degree of interconnectivity of the reservoir, as well as its internal heterogeneity.

Keywords Geological model · Petrophysical analysis · Upper Cretaceous · Seismic interpretation · Western Desert · Egypt

Introduction

Abu Gharadig Basin is one of the most prolific basins in the northern part of the Egyptian Western Desert. It is attracted the attention of geologists and geophysicists for oil and gas exploration. This is due to the huge subsurface sedimentary section which exists in the basin which includes considerable reservoir rocks within the members of the Upper Cenomanian to Maastrichtian (i.e., Khoman, Abu Roash formations), Lower Cenomanian (i.e., Bahariya Formation) and the Albian (i.e., Kharita Formation). In addition, potential

source rocks have been encountered within the Khatatba Formation and Abu Roash “F” member (El-Shaarawy et al. 1994).

GPT oil field (General Petroleum T oil field) is located at the southeast of Abu Gharadig Basin which includes Abu Sennan highs (Fig. 1). It lies about 200 km west to the Nile Delta and 15 km to the southeast of Abu Gharadig oil field. It covers an area of about 54 km² and is located between latitudes 29°36′ and 29°39′N and longitudes 28°36′ and 28°42′E.

Methodology

The geological model comprises mainly the structural and property modeling. Well log and seismic data were used to construct the structural model for GPT oil field including the fault framework, horizon modeling and zonation and layering modeling. The property modeling was performed to populate the reservoir facies and petrophysical properties

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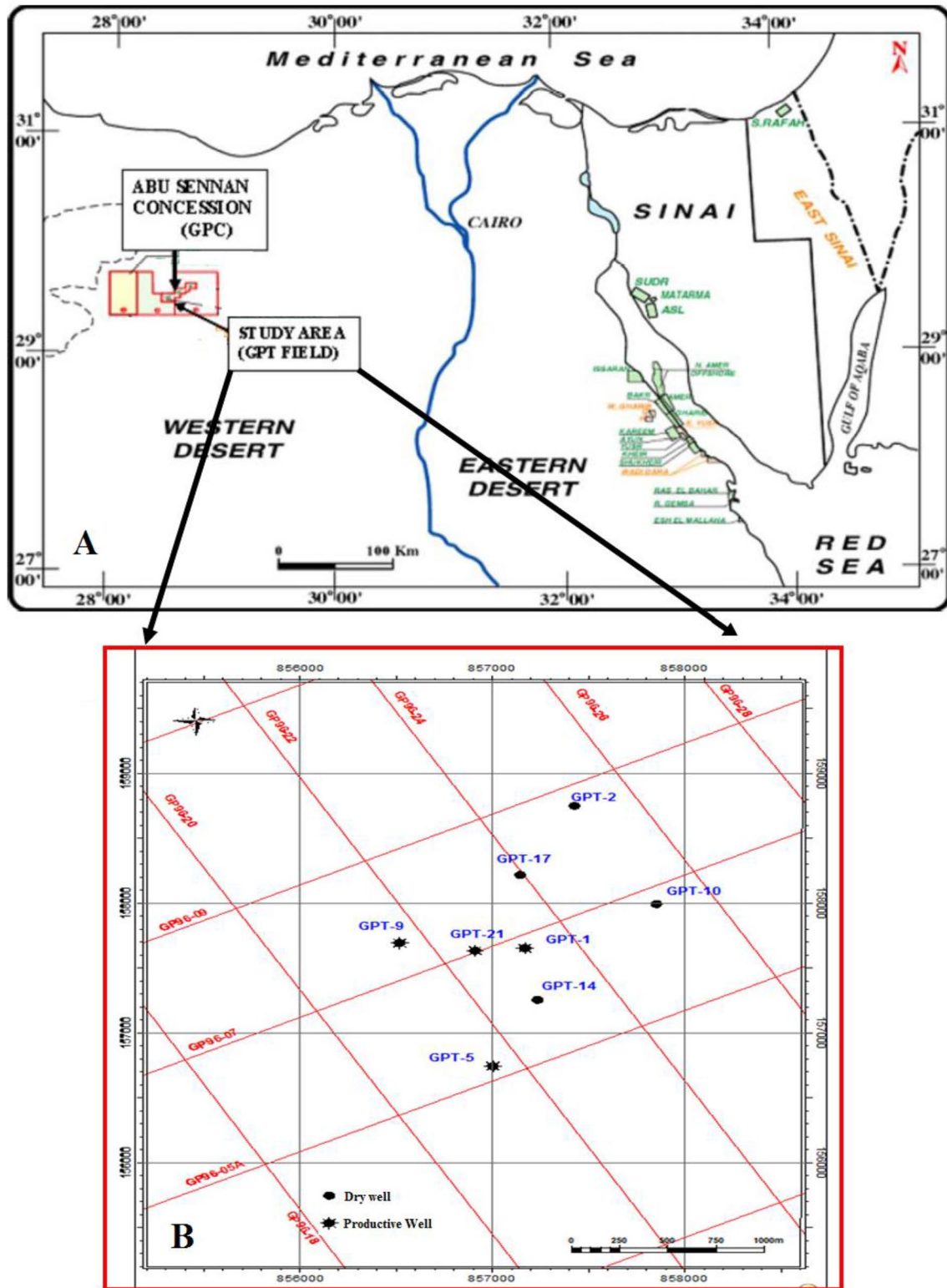


Fig. 1 a Location map of the study area. b Shot point and base map of the studied wells

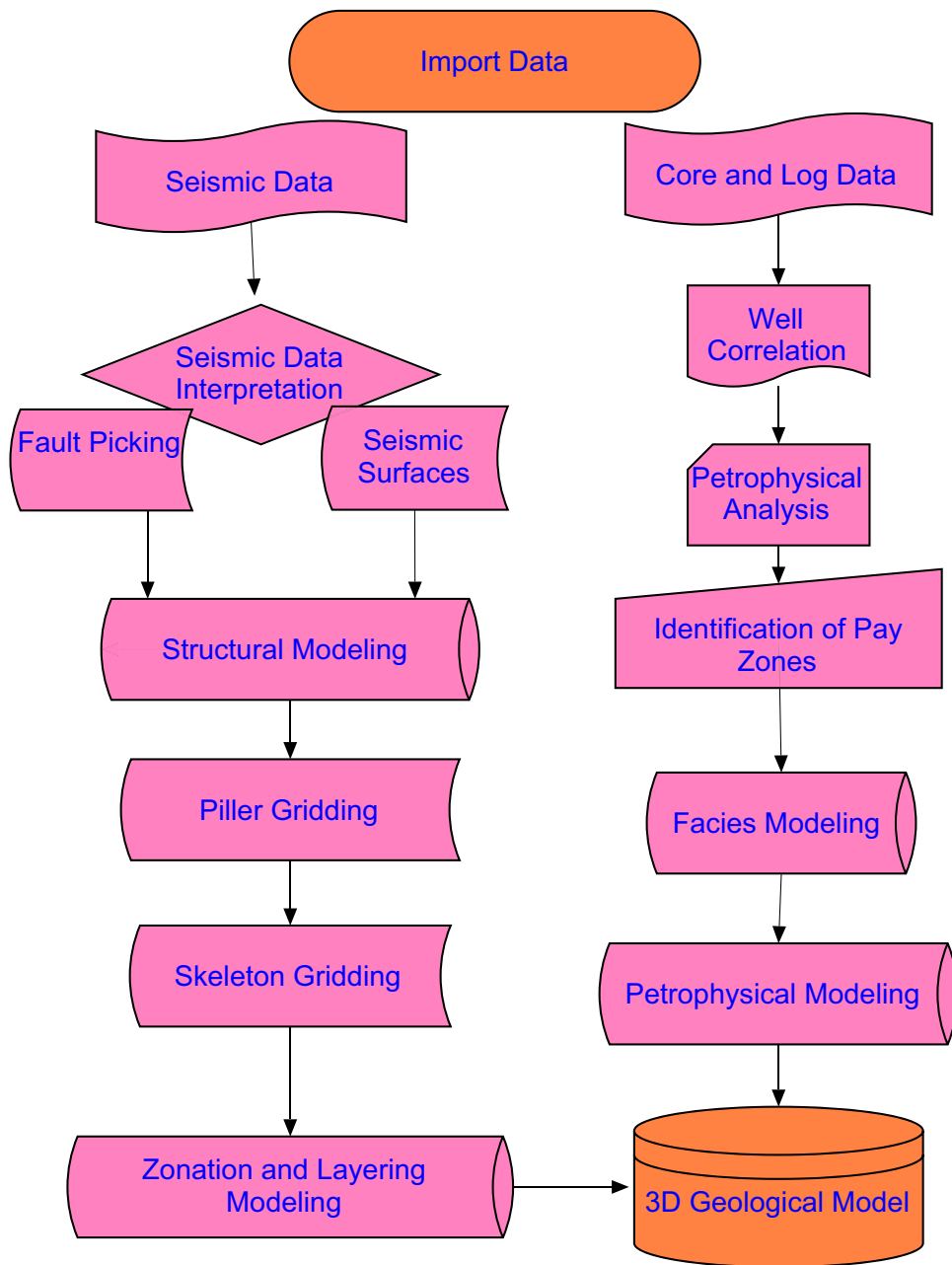
such as effective porosity, permeability and water saturation inside the structural model.

Cutting’s description, cores, well log data, formation tops were integrated to construct both the petrophysical and facies models. The structural map for the Upper Cretaceous rocks in GPT filed is constructed. Facies modeling was done by using of the sequential Gaussian simulation (SGS) method. And the petrophysical model of the porosity, effective porosity, permeability and water saturation is obtained. The flow-chart for the 3D geological model is shown in Fig. 2. The final geological model will be helpful for better development of the undrilled areas as well as for volumetric assessment of hydrocarbon reserves (Abu-Hashish and Said 2016).

Lithostratigraphy

Abu Gharadig Basin comprises rock units ranging from Cambrian to Recent resting on the basement rocks. The target formations in that area are the Khoman, Abu Roash and Bahariya formations (Fig. 3). The Lower Cretaceous (Albian) Kharita Formation is composed of sandstone interbedded with shales and siltstone. The Upper Cretaceous (Cenomanian) Bahariya Formation consists mainly of sandstone, with thin streaks of shales and limestone (Kandil 2003). The sandstones are the main gas and/or condensate pay zone. The Abu Roash Formation is subdivided into

Fig. 2 Flowchart of the 3D geological modeling



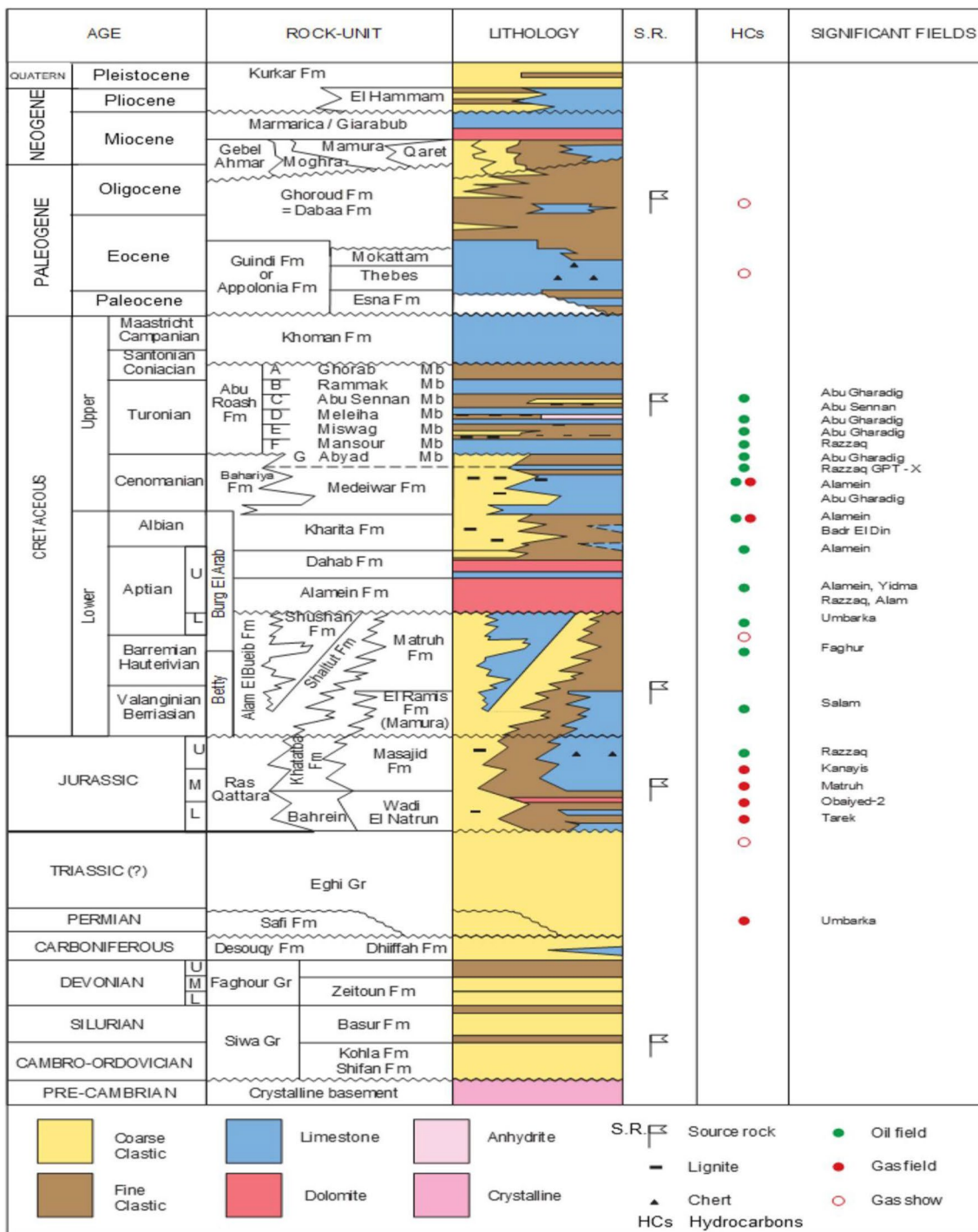


Fig. 3 General lithostratigraphic column of the North Western Desert Modified by Abdelmaksoud et al. (2019) after Schlumberger (1995)

several members which are termed alphabetically from A to G (Norton 1967). The members C, E and G are made up of calcareous sandstone with argillaceous intercalations, while the members A, B, D and F are composed mainly of limestone with argillaceous intercalations. The Khoman Formation is Santonian to Maastrichtian in age and is composed mainly of chalky limestone and shale. It is subdivided into

two members: “A” and “B.” Khoman “A” consists mainly of chalky limestone, whereas Khoman “B” consists of shale with limestone streaks. Khoman “B” is absent in the over high areas.

A well correlation chart was constructed in (NE–SW) direction passing through the wells: GPT-10, GPT-14 and GPT-5 and shows that the upper formations (Moghra,

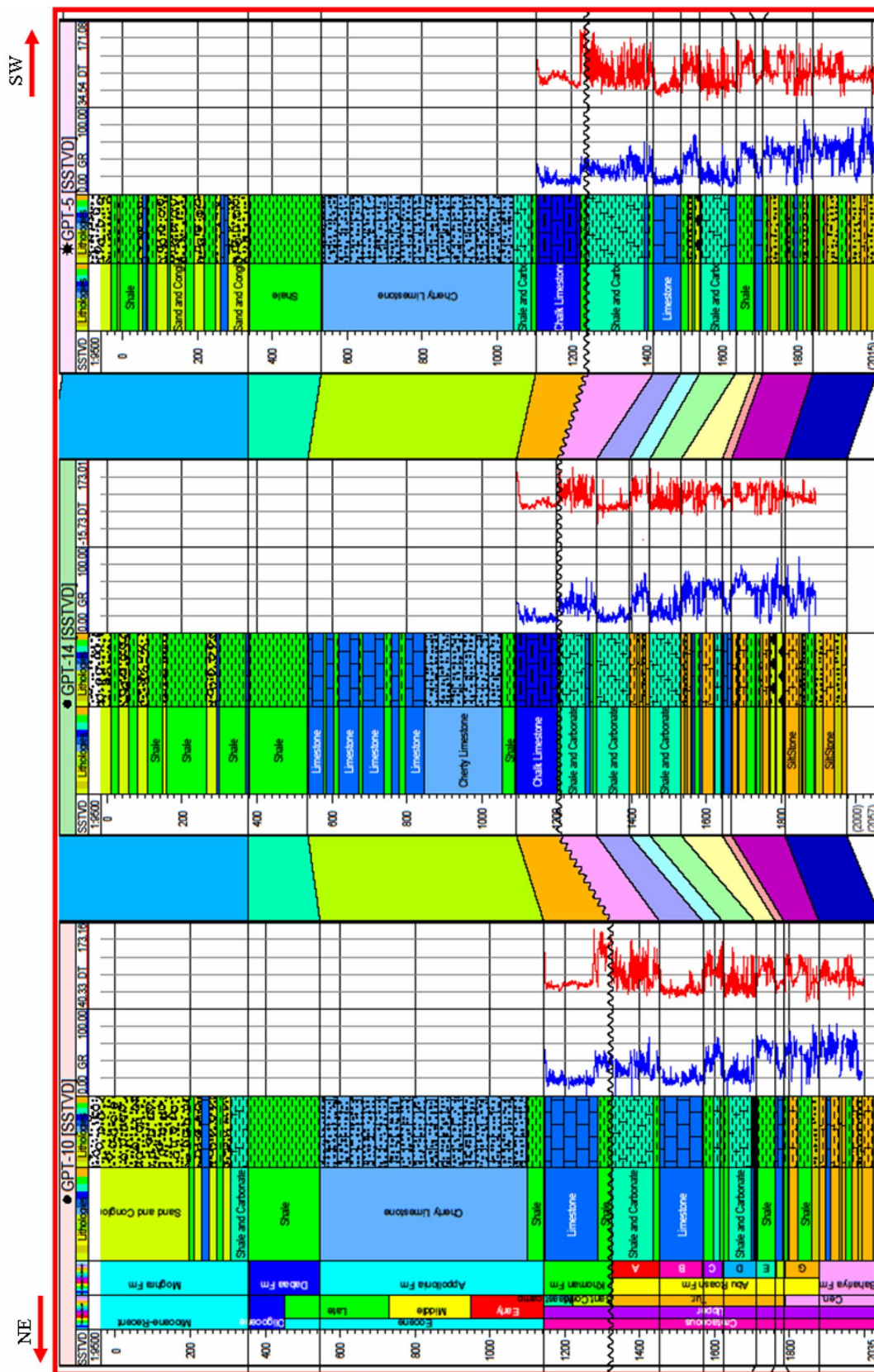


Fig. 4 Geologic cross section along the profile (NE-SW)

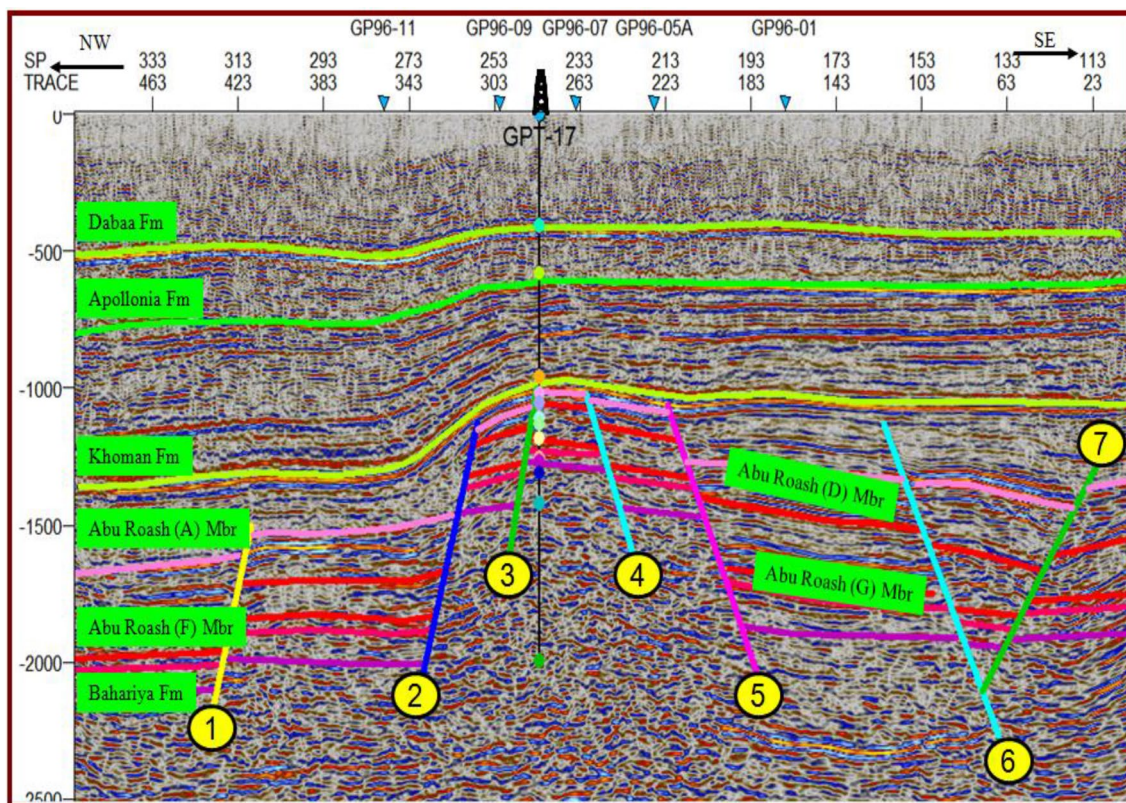


Fig. 5 NW–SE interpreted seismic section GP96

Dabaa and Apollonia) reveal the same thickness and gradual increase in the northeast and southwest directions (Fig. 4). However, three deeper formations (Khoman, Abu Roash and Bahariya) are thickening toward the southwest direction. This pattern of facies variation may be due to the depositional environment conditions as well as structural and tectonic settings.

Seismic data interpretation

Detection of the seismic surfaces and fault picking are the main two steps in the seismic data interpretation. During these processes, the seismic horizons and the structural and stratigraphic features could be recognized (Bacon et al. 2005). The eight seismic reflectors (tops of Dabaa, Apollonia, Khoman, Abu Roash (A, D, F and G members) and Bahariya formations) are picked out in ten seismic sections after being tied to each other. The seismic sections have been selected to highlight the structural pattern of the area.

Seismic sections run in northwest–southeast and northeast–southwest directions (Fig. 1). The interpretation of the seismic sections shows that the reflector sequences of these lines are strong with gradual dipping and thinning in a northeast–southwest direction. The main faults appear to

be in two sites: northeast–southwest main faults and northwest–southeast minor faults. Khoman reflectors appear strong and continuous, dissected with few numbers of the normal faults giving rise to a form of horst structures. For the other reflectors (Abu Roash and Bahariya formations), there are main and minor faults that affect the area forming the horst, step faults and half graben block area. The main normal faults and the structural closures of the Cretaceous levels are observed (Fig. 5).

TWT and depth structure contour maps were constructed for the top of Abu Roash (A, D, F, G members) and Bahariya formations, which indicate the asymmetrical faulted anticline trending in a northeast–southwest direction. Also, it shows that the area is affected by several parallel faults that have the trends of northeast–southwest forming horst and step faults. These normal fault elements are mostly dissected the northeast–southwest mid-basin arch of the Syrian Arc System. Moreover, most of these faults are throwing northward toward Abu Gharadig Basin forming synthetic faults, while the other fault group is throwing toward the Sitra platform forming antithetic faults (Figs. 6, 7, 8, 9).

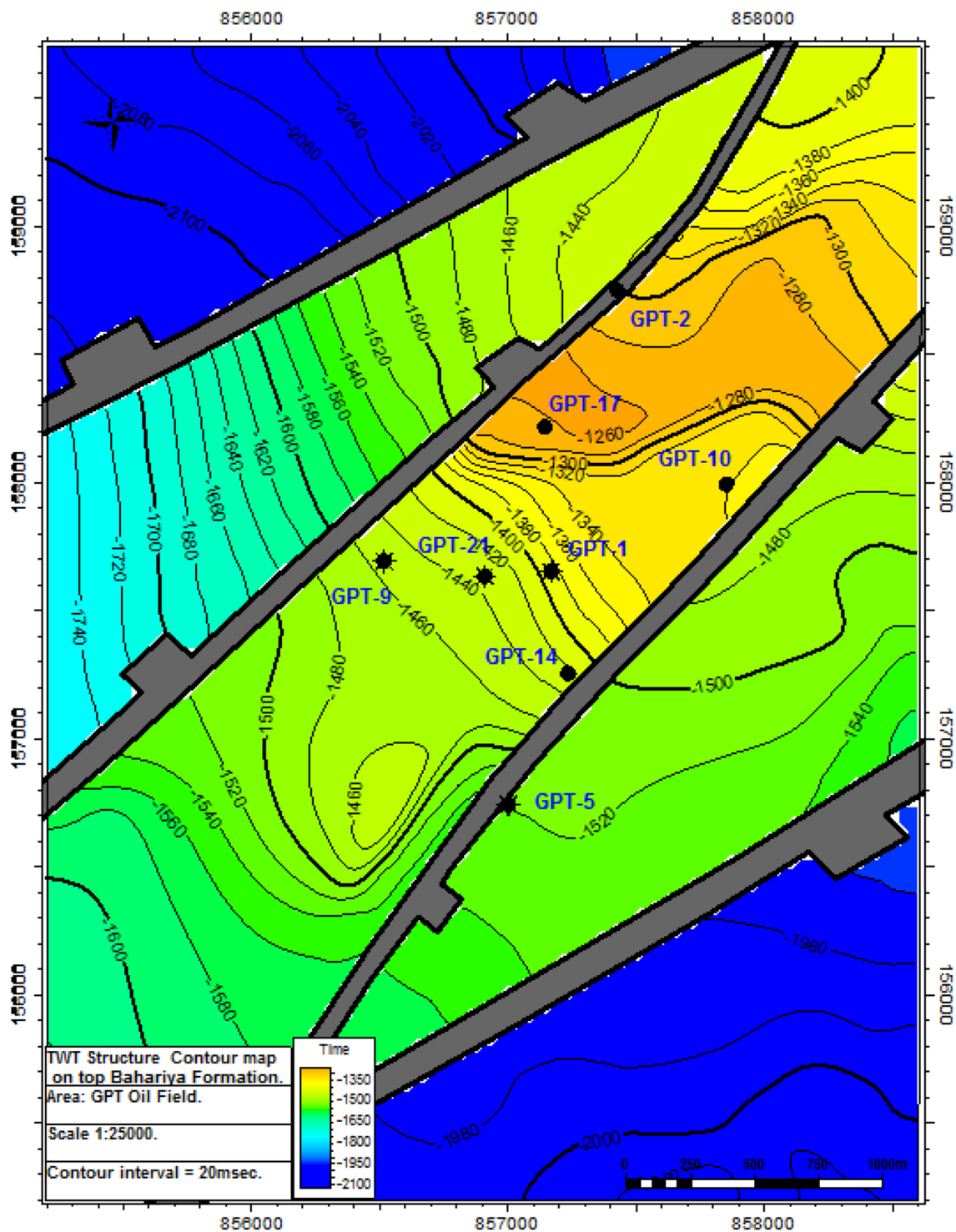


Fig. 6 TWT structure contour map of top Bahariya Formation

Petrophysical analysis

In order to construct the 3D geostatic model, a comprehensive petrophysical analysis was performed as it gives a full description of the main properties of the reservoir pore

system, permeability and saturation (Krygowski 2003). Environmental corrections that aimed to minimize the effect of variable hole size and acquisition conditions, especially the mud properties such as mud weight and salinity, were done. Volume of shale, porosity and net-to-gross ratio were

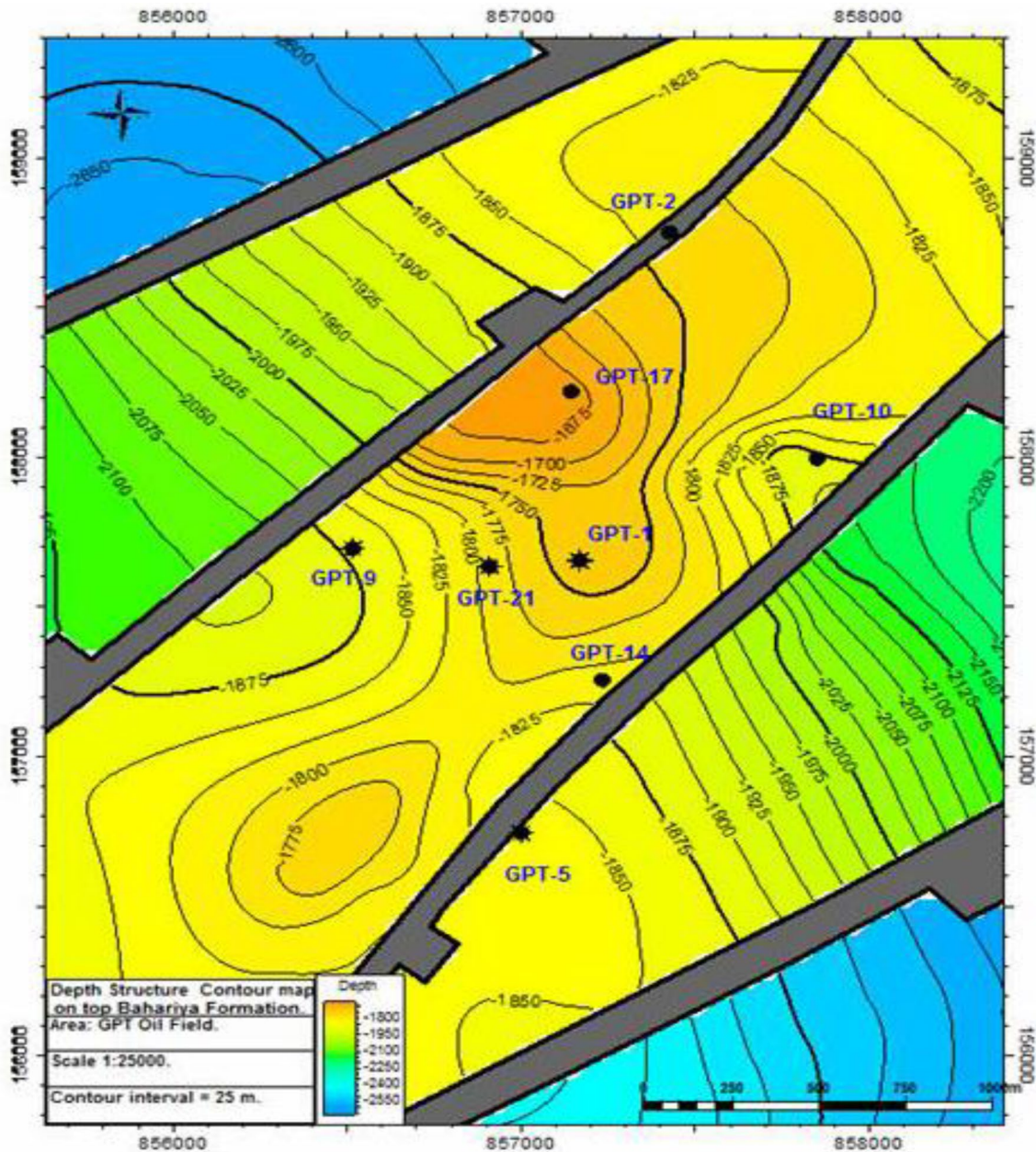


Fig. 7 Depth structure contour map of top of the Bahariya Formation

estimated. Because of the presence of shale Indonesian, formula (Eq. 1) was used to calculate the water saturation S_w (Poupon and Leveaux 1971):

$$\frac{1}{\sqrt{R_t}} = \left(\sqrt{\frac{\Phi^m}{aR_w}} + \frac{V_{cl}^{(1-V_{cl}/2)}}{\sqrt{R_{cl}}} \right) S_w^n \quad (1)$$

where Φ = porosity, R_t = true resistivity, R_w = formation water resistivity, V_{cl} = shale volume, R_{cl} = resistivity against shale, a = tortuosity factor.

The results of the petrophysical analysis in three wells in GPT oil field are tabulated in Table 1. The petrophysical properties of both Khoman and Abu Roash formations in GPT-1 well is presented in Fig. 10.

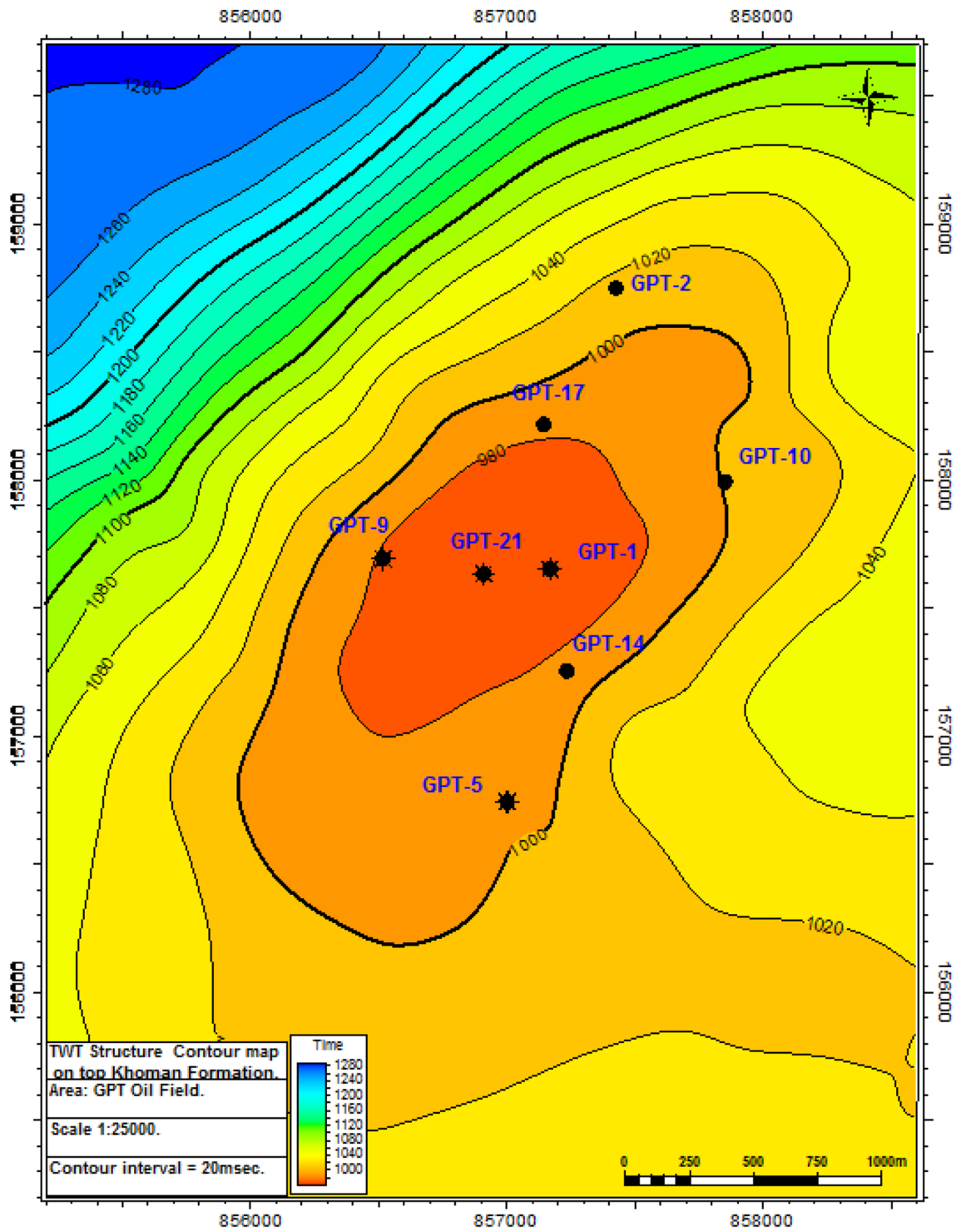


Fig. 8 TWT structure contour map of top Khoman Formation

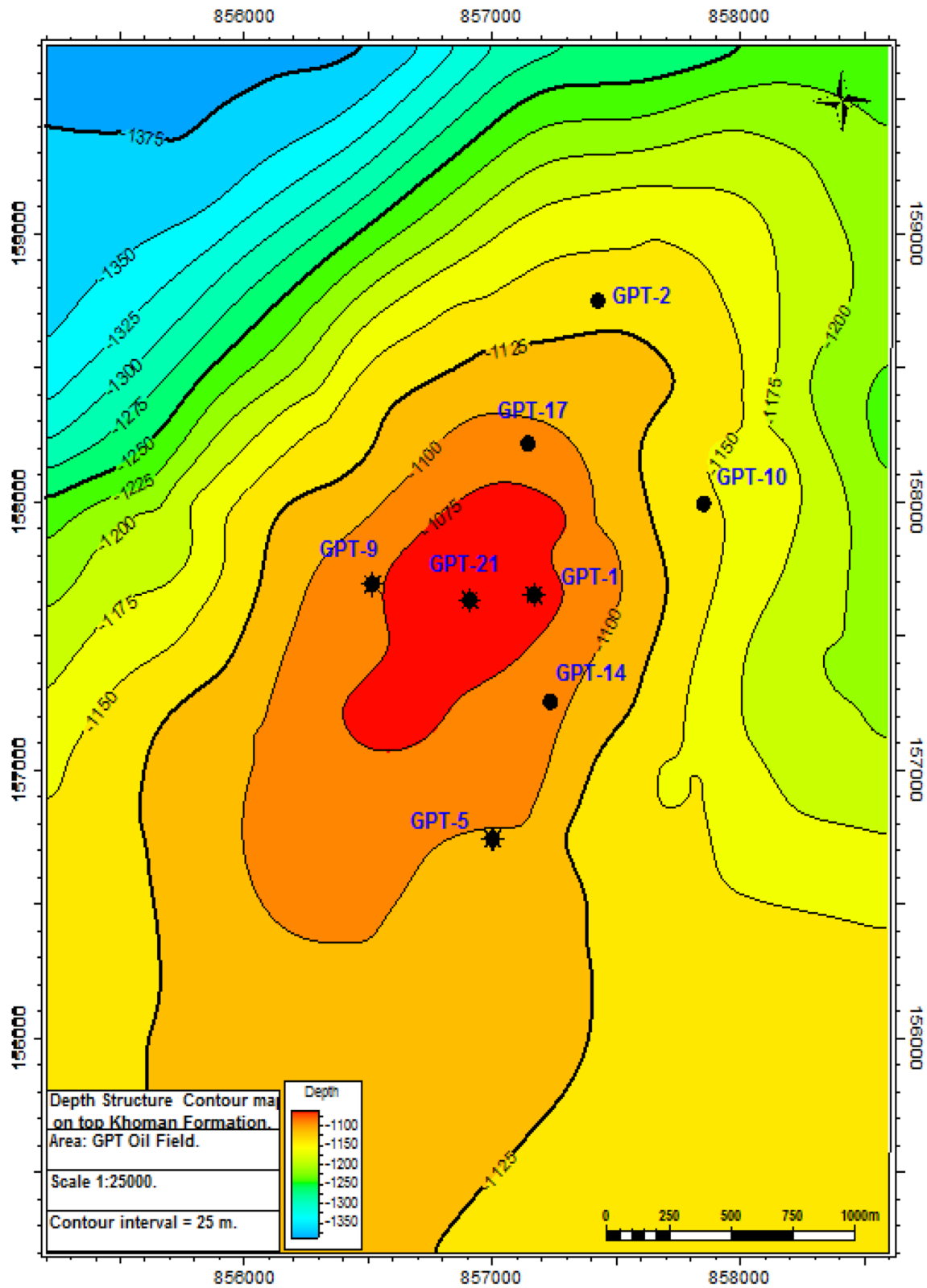


Fig. 9 Depth structure contour map of top of the Khoman Formation

Table 1 Petrophysical properties in GPT oil field

Parameters	Wells		GPT-1	GPT-14	GPT-17	
	Formation	Member				
Volume of shale (V_{sh}) %	Khoman		15	19	15	
	Abu Roash	B	12	6	20	
		D	18	20	18	
		E	11	16	16	
		F	18	14	19	
		G	14	21	16	
	Bahariya		17	13	18	
	Total porosity (Φ_{iT}) %	Khoman		20	18	13
		Abu Roash	B	16	13	10
			D	26	19	13
E			25	21	22	
F			21	18	18	
G			28	21	24	
Bahariya			25	23	21	
Effective porosity (Φ_{ie}) %		Khoman		15	16	12
		Abu Roash	B	13	12	8
			D	22	18	11
	E		22	20	21	
	F		17	17	16	
	G		20	20	22	
	Bahariya		21	23	21	
	Water saturation (S_w) %	Khoman		23	30	41
		Abu Roash	B	27	19	23
			D	25	23	13
E			16	18	12	
F			3	6	6	
G			16	18	17	
Bahariya			9	8	13	
Hydrocarbon saturation (S_h) %		Khoman		77	70	59
		Abu Roash	B	74	81	77
			D	75	77	87
	E		84	82	88	
	F		97	94	94	
	G		84	82	83	
	Bahariya		91	92	87	
	Gross thickness	Khoman		23.80	36.60	37.20
		Abu Roash	B	6.70	2.00	2.10
			D	3.70	3.00	6.20
E			6.4	8.20	6.40	
F			10.00	17.70	16.80	
G			13.8	10.90	14.20	
Bahariya			19.8	16.1	32.9	
Net thickness		Khoman		15.80	25.25	5.95
		Abu Roash	B	2.95	0.60	1.60
			D	2.50	1.35	1.80
	E		4.35	4.45	3.85	
	F		3.90	16.80	4.85	
	G		8.05	4.65	9.7	
	Bahariya		15.3	16.10	28.80	

Table 1 (continued)

Parameters	Wells		GPT-1	GPT-14	GPT-17
	Formation	Member			
Gross/net thickness	Khoman		0.66	0.69	0.16
	Abu Roash	B	0.44	0.30	0.76
		D	0.68	0.45	0.29
		E	1.41	1.23	1.24
		F	0.39	0.95	0.29
		G	1.747	1.321	1.364
	Bahariya		2.371	2.00	0.91

3D geological modeling

The 3D geological model mainly includes the structural framework of the area (faults and surfaces) in addition to zonation and layering of Khoman, Abu Roash (A, B, C, D, E, F and G members) and Bahariya formations, while the property model includes the population of the shale volume, porosity, permeability, net to gross thickness and fluid saturation as extracted from the available petrophysical analysis.

Geostatistical techniques have been used for modeling of the different geological properties which are helpful to estimate the values of the geological properties at the undrilled locations (Deutsch 2002). These variables include petrophysical properties such as shale volume, porosity, permeability and fluid saturation. Seismic information such as acoustic values or geological attribute as the thickness of the sand or shale is also used to describe the reservoirs. The GPT oil field is about (54 km²), and due to the presence of relatively thin layers and zones we subdivided the model into different small xyz cells (25 × 25 × 5 m). It was noted that the pay zones in GPT field are separated by some intervals which have relatively poor reservoir properties, so we decide to subdivide the model according to the stratigraphic settings not the geographic settings. A 3D geological model using multiple parameters (e.g., shale volume, porosity, facies, fluid saturation, net to gross thickness and permeability) was created using Petrel software.

Structural framework

Structural modeling is the first and the most important step in building a 3D geological model. It was mainly performed in two parallel ways: construction of maps for structural configuration of the formation tops and detecting the sets of faults running across the reservoir. The geometry definition process is used to define the geometry of the structural framework by specifying its coverage, defining the xyz resolution. The default x and y coverage and resolution are taken from the seismic, e.g., the same coverage and orientation as

the seismic survey. This model is finely layered and has relatively small xyz cell dimensions (25 × 25 × 5 m). A coarsening factor can be used to create a geometry that honors the input grid extents but with multiples of the grid increments (Fig. 11). The 2D seismic survey was used to interpret the sticks or boundary faults in the GPT oil field (four main faults). Then, the fault model was built in time domain and converted to depth domain using the velocity model. The 2D seismic survey was used to interpret the sticks or boundary faults in the GPT oil field (four main faults). Then, the fault model was built in time domain and converted to depth domain using the velocity model (Fig. 12).

Property model

The step of the property model includes the process of filling the grid cells with discrete or continuous properties (Schlumberger 2010). The target is to use all geological information available to build a realistic property model. Property modeling is split into three separate processes: geometrical, facies and petrophysical. The next step will be the analysis of data and scale-up well logs as it helps to assign the values of the well log data to the 3D grid cells in the model; every cell will hold one value only so the well log values will be averaged and scaled up to help in the distribution of the reservoir properties among the wells (Fig. 13).

Facies modeling

For better understanding of the sedimentology, it is required to realize high-resolution stratigraphic correlations (Wescott 1993). Facies analysis is very important and helpful to guide the decisions concerning the proper modeling technique (Henriquez et al. 1990; Hirst et al. 1993). Facies modeling techniques can be divided into interactive, deterministic and stochastic methods where the stochastic methods are often used in conditions where sparse data are available. These methods produce a possible result and can be used to produce multiple equally probable realizations (Petrel 2009). It

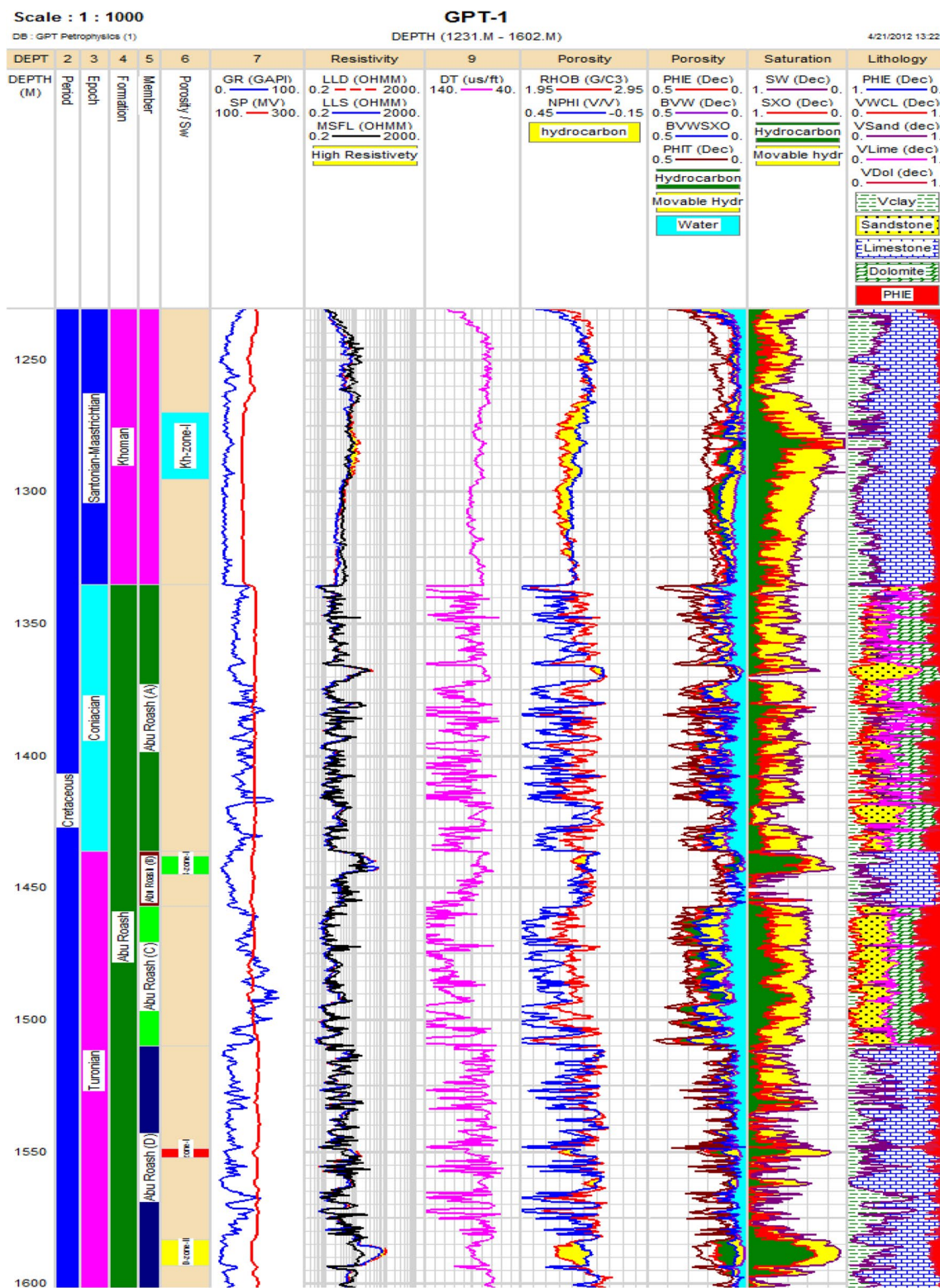


Fig. 10 Lithosaturatation cross-plot of Khoman Formation and Abu Roash Formation (A, B, C and D members) in GPT-1 well

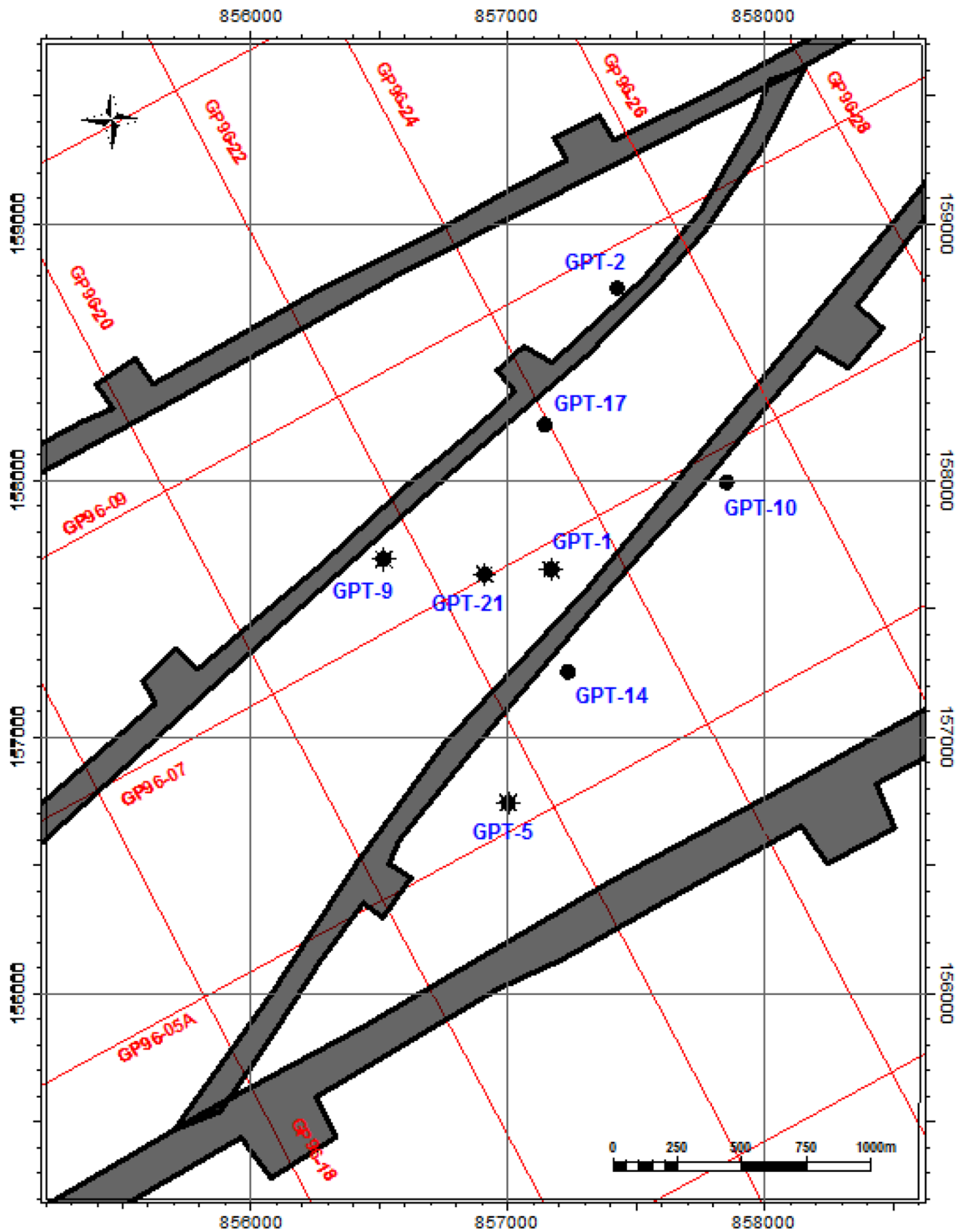


Fig. 11 Base map showing the modeled faults in the study area (top Abu Roash D member)

involves creating a series of equally probable realizations, or models, of a random variable. Each model, or stochastic image, depends on the assumptions that have gone into the

simulation procedure. The most popular type of simulation is called conditional simulation, which honors the hard data values at measured locations (Srivastava 1994).

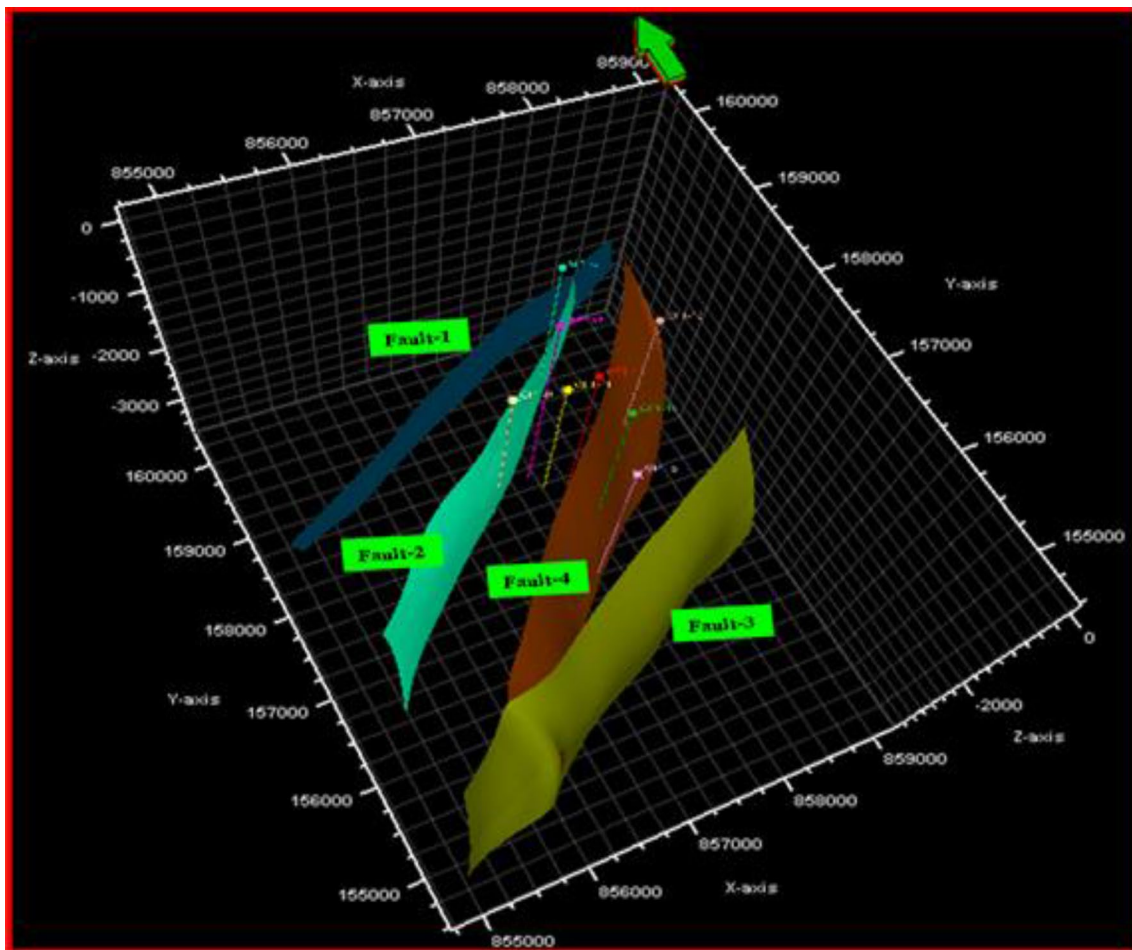


Fig. 12 3D view of the final fault model in the study area

Although there are several algorithms used to perform stochastic simulation, the most common is called sequential indicator simulation (SIS) and sequential Gaussian simulation (SGS). SIS allows a stochastic distribution of the property, using the pre-defined histogram. It is used to produce random facies but with rugged fuzzy boundaries between the different facies as it visits each cell in the model in a random order and assigns it the facies value that has the highest probability of existing in that location. The probability of a facies prevailing at a given location is known as the indicator transform for that facies and is determined from aerial and vertical geologic trend information, spatial statistics that define the degree of correlation with nearby points, and facies values both original and modeled in nearby model cells (Deutsch 2002). We use SIS to construct the three-dimensional facies modeling in GPT oil field which makes a random distribution of the facies with rugged fuzzy boundaries between the different facies (Fig. 14). Facies type described in the study area was given a numerical code (0–11), and facies logs were created from

the lithology descriptions. Recall that the model vertical resolution is high in the other geologic zones as shown in Table 2.

Common facies environments are carbonates, shale, siltstone and sandstone. The target is to build a 3D facies model containing the reservoir architecture with flow units and barriers. The facies model was constructed for the different reservoir zones within the Khoman, Abu Roash (A, B, C, D, E, F and G members) and Bahariya formations.

The main lithology of the GPT oil field reservoir (sandstone, shale, siltstone and limestone) was modeled to produce 3D geological models. In order to construct facies models, the following inputs are required: (a) discrete facies logs from the wells, (b) facies probability maps that characterize the general aerial distribution of each facies, (c) vertical proportion curves that quantify the vertical trends exhibited by each facies, (d) vertical and horizontal variograms that establish quantitative measures of spatial correlation between cells in each of the vertical and major and minor horizontal directions. Volume of shale, porosity,

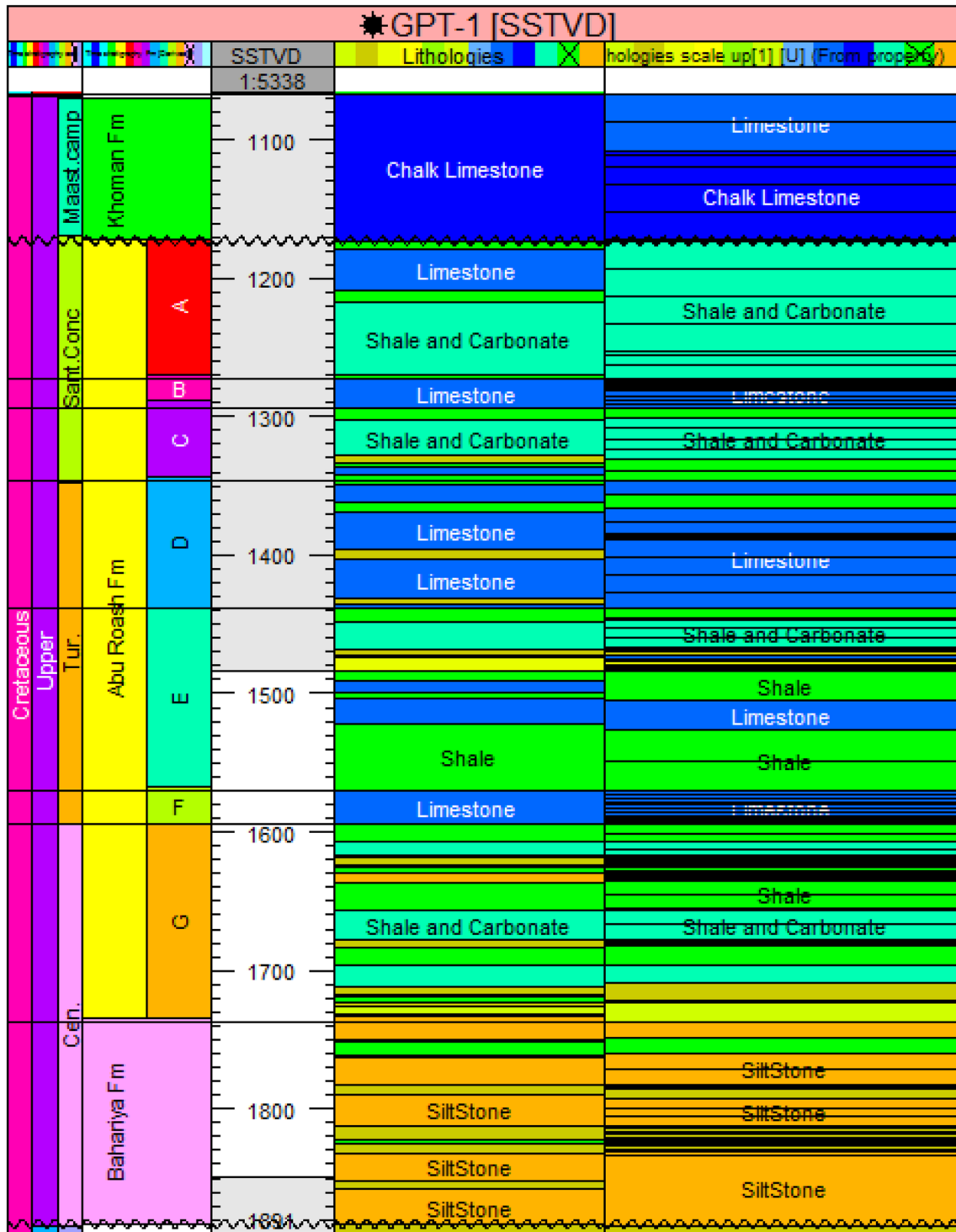


Fig. 13 Scale-up logs for facies modeling in GPT-1 well

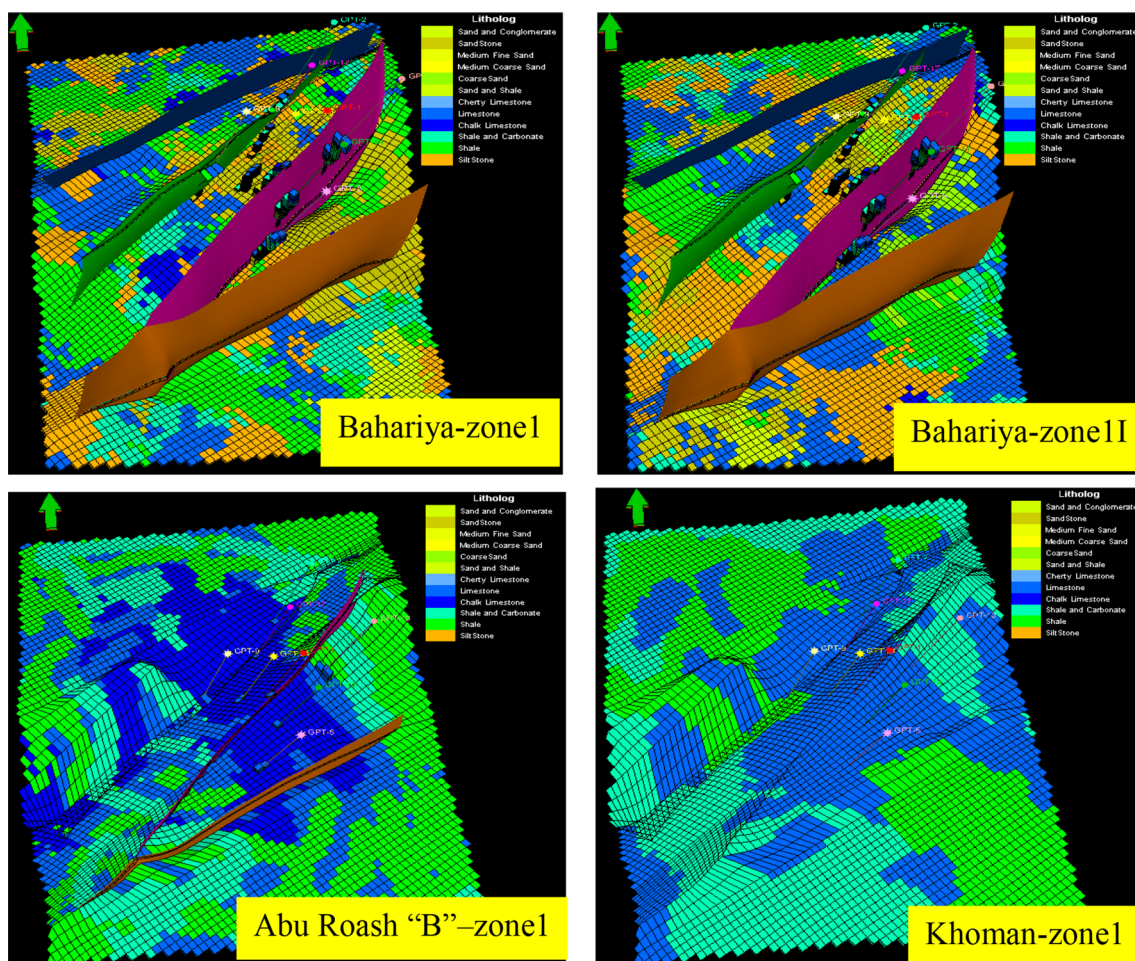


Fig. 14 Facies model example for the different pay zones

permeability, water and hydrocarbon saturation and net to gross value control the distribution of the facies.

Petrophysical model

The petrophysical evaluation data have been used to populate the reservoir properties in the finalized structural model, which include evaluation of shale volume, effective porosities, fluid saturations and permeability (Petrel 2009). Effective porosity, shale volume, fluid saturation, net to gross thickness and permeability models for the area represent the distribution of these properties within the reservoir. These models are used to analyze the distribution of reservoir quality within the formation.

Effective porosity model


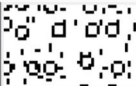









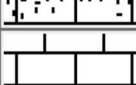



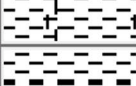

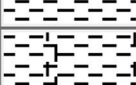
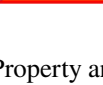
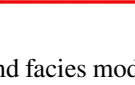
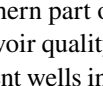
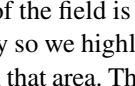
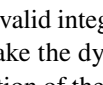
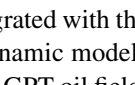
The main factor controlling the effective porosity is the facies; it is modeled separately for each rock unit. The model of both the effective porosity and facies is relatively similar. Effective porosity was populated into the model for the

Khoman, Abu Roash (A, B, C, D, E, F and G members) and Bahariya formations. The porosity log curves were scaled up honoring the new fine layering approach using the arithmetic computation (Fig. 15). Sequential Gaussian simulation algorithm method was used for Khoman, Abu Roash (A, B, C, D, E, F and G members) and Bahariya formations (Fig. 16). The effective porosity model shows several variations ranging from 2 to 35% and are related to color from red to green; this may be due to changes in facies. The effective porosity of the studied formations is highest in the central parts of the study area and decreases considerably in the south which led to the recommendation of further drilling in the central parts.

Permeability and water saturation models

In addition to populating grid cells with facies and porosity, as discussed above, the workflow process involves populating the grid cells with permeability and water saturation. Their log curves were controlled by the porosity and facies.

Table 2 Lithological code description in GPT oil field

Code	Name	Parent	Color	Pattern
0	Sand and conglomerate			
1	SandStone			
2	Medium fine sand			
3	Medium coarse sand			
4	CoarseSand			
5	Sand and shale			
6	Cherty limestone			
7	Limestone			
8	Chalk limestone			
9	Shale and carbonate			
10	Shale			
11	SiltStone			

These log curves for all wells were scaled up honoring the new fine layering approach using the arithmetic computation. SGS algorithm was used for the Khoman, Abu Roash (A, B, C, D, E, F and G members) and Bahariya formations (Fig. 17). The permeability increases toward the central part of the field and decreases to the north and south directions, while the water saturation shows several variations from increasing and decreasing. It decreases toward the south and the center of the study area (Fig. 18).

Conclusions

The constructed 3D geostatic model for GPT oil field shows that the main faults in the area appear in the north–east–southwest direction while the main faults are found in

the northwest–southeast direction. Property and facies modeling indicates that the central northern part of the field is a promising area having a good reservoir quality so we highly recommend to drill more development wells in that area. The constructed 3D geological model is valid integrated with the production data and flow rate to make the dynamic models in order to enhance the total production of the GPT oil field. The constructed model built a better understanding of the heterogeneity and variability of geological condition as well as the hydrocarbon distribution within the Upper Cretaceous reservoirs in GPT oil field. The Khoman and Abu Roash G sand and Bahariya reservoirs are very promising because of their good to very good porosity values, low water saturation, high hydrocarbon saturation (S_h), good permeability and moderate net to gross value.

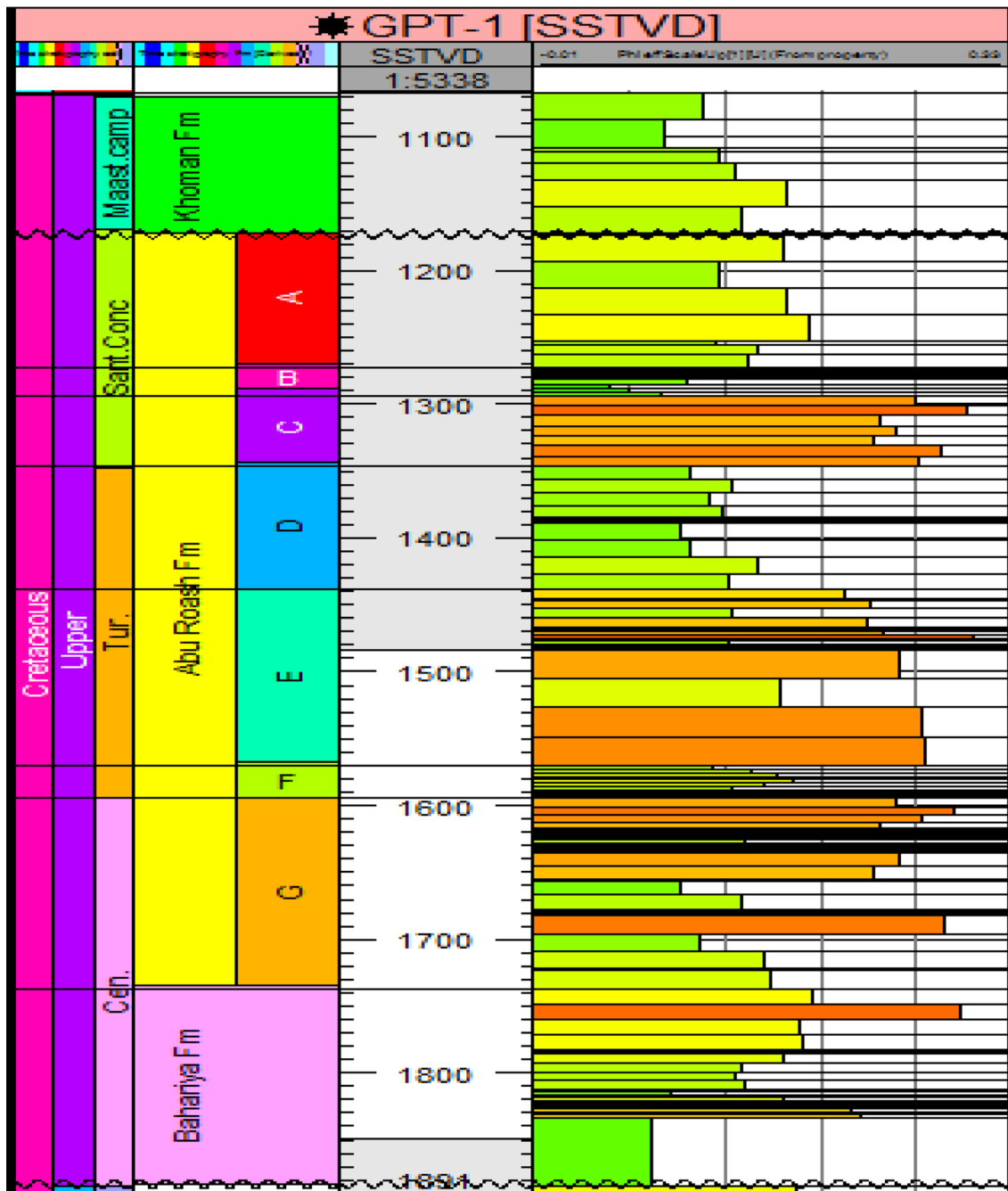


Fig. 15 Scale-up logs for the effective porosity modeling in GPT-1 well

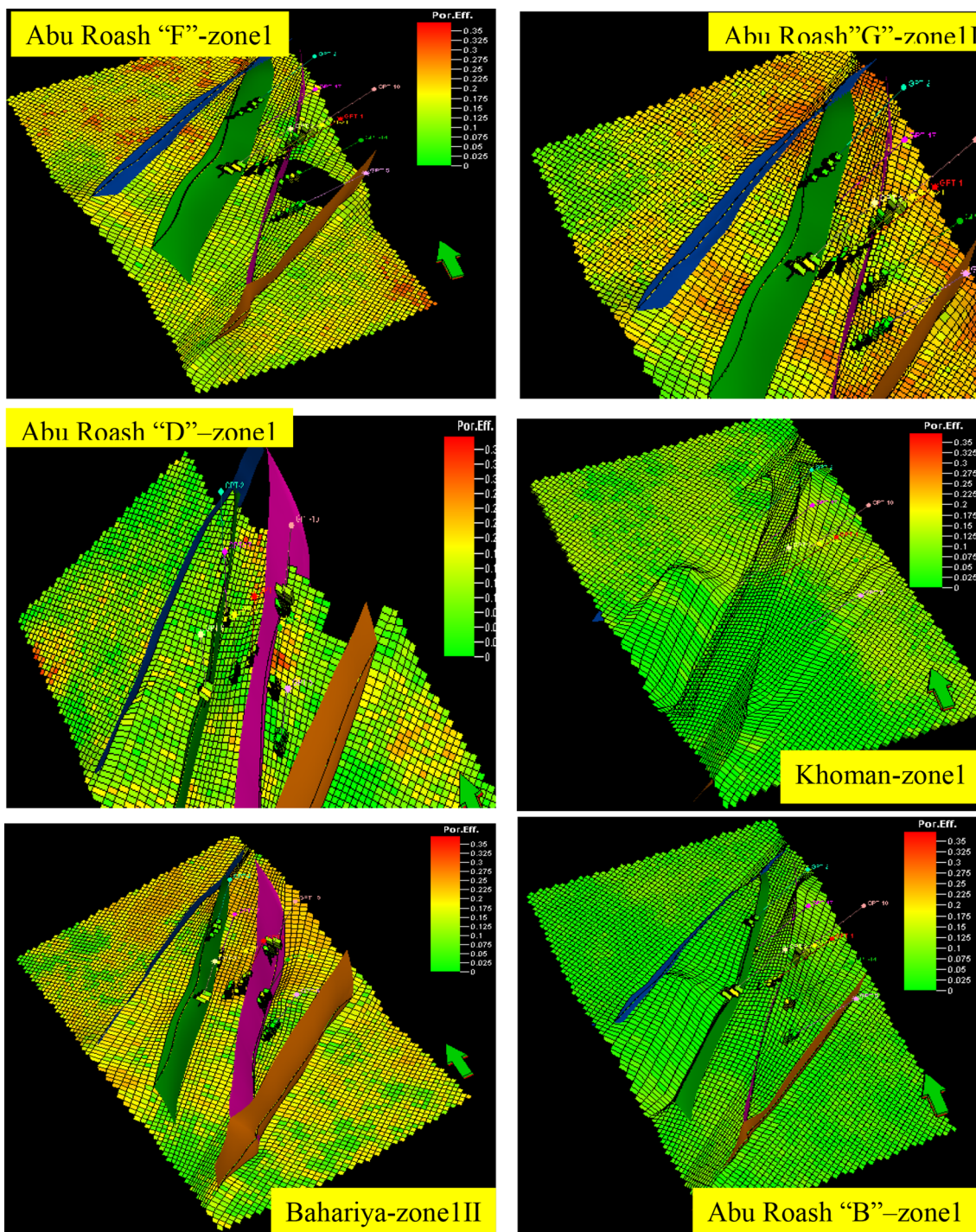


Fig. 16 Effective porosity model example for the some pay zones

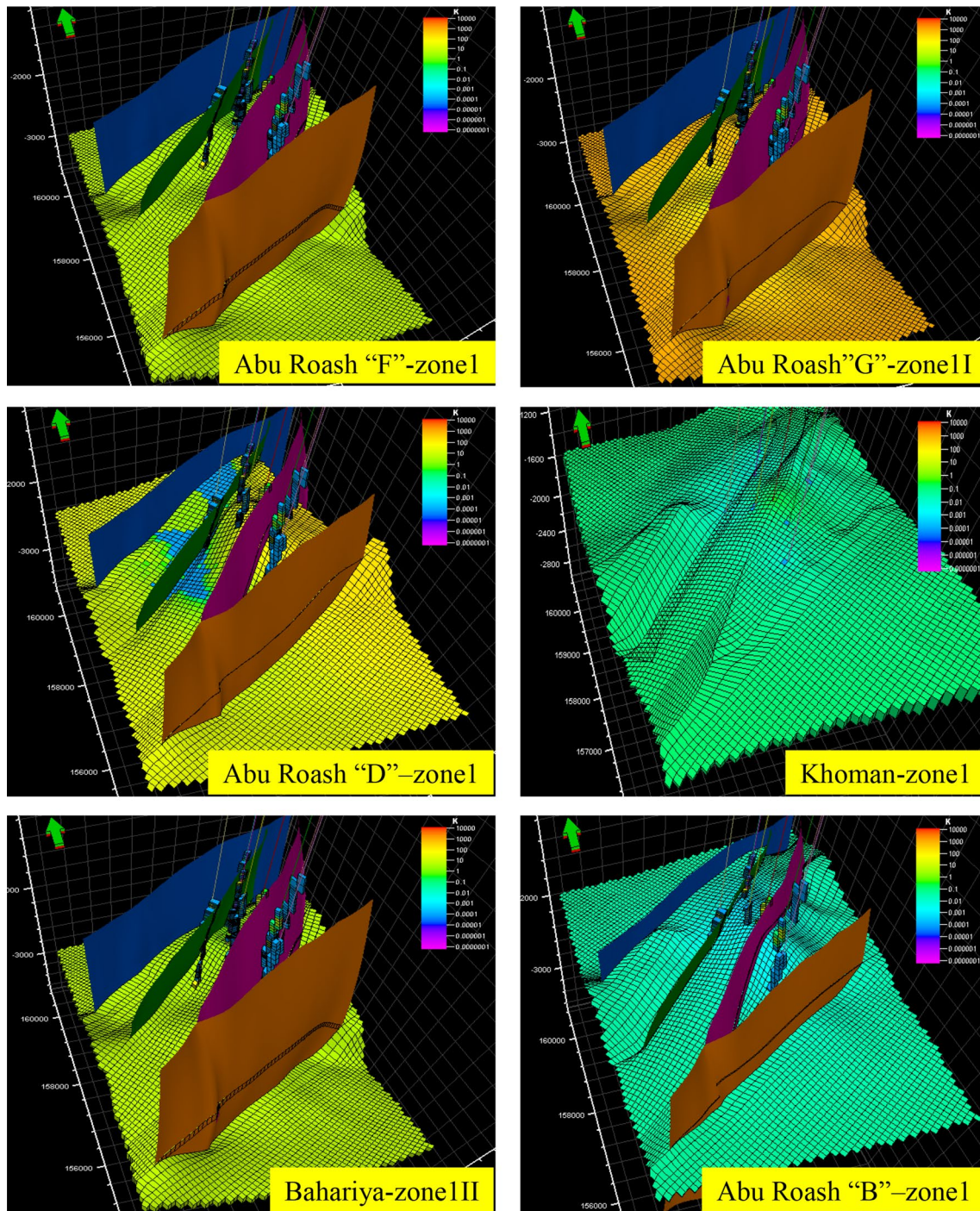


Fig. 17 Permeability model example for the different pay zones

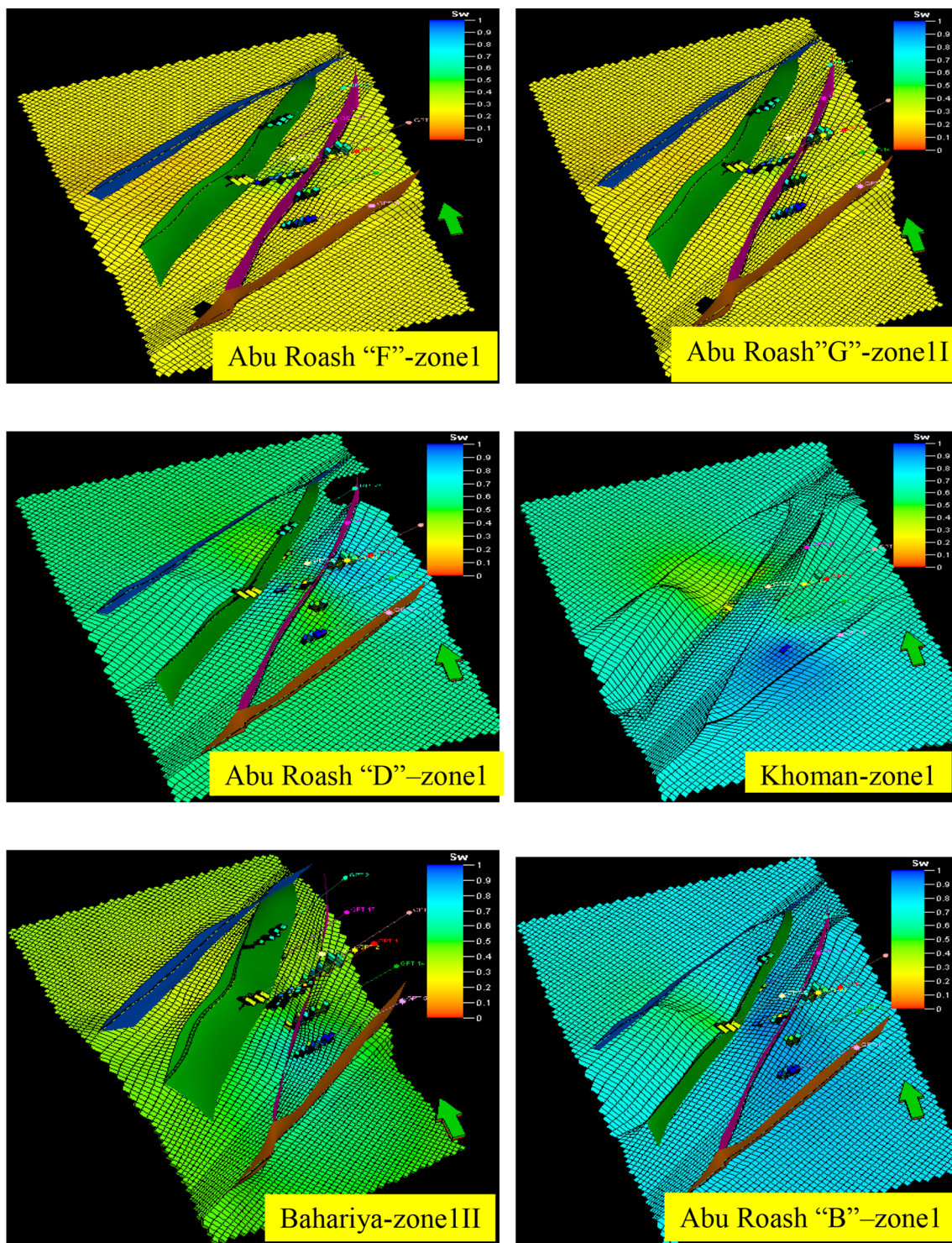


Fig. 18 Water saturation model example for the different pay zones

Acknowledgements The authors wish to express their thanks and gratitude to the EGPC (Egyptian General petroleum Corporation) and GPC (General Petroleum Company) for permission and release of the data for this research.

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