Prospect evaluation and hydrocarbon potential assessment: the Lower Eocene Facha non-clastic reservoirs, Hakim Oil Field (NC74A), Sirte basin, Libya—a case study

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Abstract

Petrophysical assessment of Facha Formation based on log data of six wells A1, A3, A4, A5, A8 and A13 recorded over the entire reservoir interval was established. Hakim Oil Field produces from the Lower Eocene Facha reservoir, which is located at the western side of Sirte basin. Limestone, dolostone and dolomitic limestone are the main lithologies of the Facha reservoir. This lithology is defined by neutron porosity—density cross-plot. Noteworthy, limestone increases in the lowermost intervals of the reservoir. Structurally, the field is traversed by three northwest–southeast faults. The shale of the Upper Cretaceous Sirte Formation is thought to be the source rock of the Facha Formation, whereas the seals are the limestone and anhydrite of the Lower Eocene Gir Formation. In this study, the Facha reservoir's cutoff values were obtained from the cross-plots of the calculated shale volume, porosity and water saturation values accompanied with gamma ray log data and were set as 20%, 10% and 70%, respectively. Isoparametric maps for the thickness variation of net pay, average porosity, shale volume and water saturation were prepared, and the authors found out that the Facha Formation has promising reservoir characteristics in the area of study; a prospective region for oil accumulation trends is in the north and south of the study area.

Keywords Well log · Petrophysical parameter · Lower Eocene · Hakim Oil Field · Sirte basin · Libya

Introduction

The Sirte basin covers an area of about 600,000 km² with a sedimentary succession of about 7500 m (Hallet 2002). The basin has the largest petroleum reserves where it has about 36.7 BB of oil and 37.7 TCF of gas (Ahlbrandt 2001).

This study focuses around the Hakim Oil Field, where the main pay is the Facha reservoir. The Hakim Field located at the southwestern part of Sirte basin in concession NC-74A, approximately 580 km southeast of Tripoli, lies between latitudes of 28°40' and 29°00'N and longitudes of 17°21' and 18°00'E, (Fig. 1).

The first well was discovered and drilled in 1978 at the southwestern side of Sirte basin from the Upper Facha dolomite with 20 MM barrels of recoverable oil (Geological Review of Hakim 1981).

The lithology analysis included in this study depends on cross-plots by using logging data of six oil wells (A1, A3, A4, A5, A8 and A13). In addition, the petrophysical parameters are evaluated by estimating content of shale, storage capacity (porosity), water saturation and net pay thickness. The prospect evaluation of the study area is achieved by constructing isoparametric maps and estimating the prospective regions for hydrocarbon accumulations.

Geological and structural setting

The studied basin's tectonic features are represented from east to west by Maradah trough, Ajdabiya trough, Hameimat trough, Sarir trough, Zallah trough, Dur Al-Abd trough and finally Hun graben. They are separated by Amal platform, Rakk high, Zaltan platform, Al-Bayda platform and finally Waddan uplift (Fig. 2). These structural features have great

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Fig. 1 Location map of Hakim Field

effect on the migration of hydrocarbon from the troughs along the block basement faults to the platforms where most fields are situated.

Structural framework of the study area

It appears that the structural evolution of the study area (Hakim Field) was controlled by the regional tectonic activity that occurred on the western part of Sirte basin, where most of the area is divided by major NW to SE normal faulting pattern (Fig. 2). The fault-related anticline and syncline can be considered later as a potential trap for hydrocarbons in study area.

The Sirte basin formed due to the extension of crust during the Early Cretaceous–Tertiary leading to the subsidence and formation of the Sirte arch (Ahlbrandt 2001 and Van der Meer 1993). Four main phases of uplifting and subsidence are encountered within the basin as the following: (Abadi 2002).

- *Phase I* During Late Jurassic to the Early Cretaceous and represents the falling in the southeast of the studied basin over an E–W structural trend.
- *Phase II* Represents the major and rapid falling along the NW–SE structural trend during the Late Cretaceous time, when the main significant hydrocarbon source rocks deposited. In addition, a marginal marine was developed

south of the basin which continued from Cenomanian until the Coniacian.

- *Phase III* This phase, according to Guiraud and Bosworth 1997, represents the development of shallow marine in southern Libya during the Paleocene times with active subsidence affecting most of the troughs within Sirte basin. As a result of this subsidence, the basin was affected by a regression through the Lower Eocene causing deposition of evaporites of the Gir Formation south and west of the basin.
- *Phase IV* is concerning the Middle Eocene until the current day and was caused by sediments load and thermal relaxation within the basin. The Late Eocene was introduced by marine deposits due to a transgression event developed in the Lower Oligocene. In this period, subsidence was active along NW structure in the Ajdabiya trough. Regression event occurred in Post-Middle Miocene times due to rapid fall in the level of the Mediterranean, depositing continental facies.

These tectonic phases had an important effect on the lithostratigraphic units within the basin.

Lithostratigraphy

After the opening of the basin, sedimentary sequences varying from continental to near shore and marine

Fig. 2 Generalized tectonic map of the Sirte basin as located in the north-central Libya map (modified after Abadi 2002) showing the major structural elements and oil and gas fields. The dashed box

marks the Zallah trough area with its structural domains referred to in the text. Inset illustrates the Libya map

sediments were deposited. The sedimentary succession differentiated into four lithostratigraphic sequences by Barr and Weeger (1972) based on the available logging data of the drilled wells.

The Facha Formation is conformably overlain by the anhydrite and limestone of Gir Formation, whereas the lithology of the underlying formation varies from dolomite or anhydrite to limestone or marl (Fig. 3). It is predominately a tan, argillaceous, finely crystalline, massive, commonly vugular dolomite with minor amounts of anhydrite occasional limestone beds occurring within the formation, which consist of white to cream soft argillaceous calcilutite. The average thickness of Facha Formation is 308 feet (Barr and Weeger 1972).

Petroleum system

The structural conditions of the study area are represented by fold and fault systems which form the trapping pattern. In more detail, fault-related NW–SE anticlines is considered as a main hydrocarbon trap in the Hakim Field (Geological Review of Hakim 1981).

Source rocks

The published studies have concluded that the main source rock in the studied area is the Shale of Sirte Formation (Parsons et al. 1980; Gumati and Schamel 1988; Montgomery 1994; El-Alami et al. 1989; Ghori and Mohammed 1996;

Fig. 3 General stratigraphic column of Sirte basin. Modified after Aboglila and Elkhalti (2013)

Macgregor and Moody 1998; Ambrose 2000; Burwood 1997). The thickness of these Shale beds reaches up to 900 m in the troughs and produces oil at burial depths from 2700 to 3400 m (Futyan and Jawzi 1996).

Reservoirs

The tectonic events in the Sirte basin are of great effect on the reservoir distribution and quality. Most of the reservoirs from Precambrian to Eocene are charged along faults (Harding 1984).

The Tertiary carbonate reservoirs and the Pre-Tertiary clastic reservoirs contain 42 and 58% of the petroleum volume,

respectively (Harding 1984). These reservoir rocks of Facha Formation are characterized by high porosity and permeability. The low porosity could be compensated by joints and fractures.

Sealing

The reliable seals for the Facha Formation are represented by the anhydrite and limestone, which belongs to Gir Formation. The limestone texture ranges between fine to coarse crystalline, nodular and sub-banded (Barr and Weeger 1972).

Data and methodology

The reservoir hydrocarbon potential of the Facha Formation was assessed in six drilled wells (A1, A3, A4, A5, A8 and A13), depending on lithological and petrophysical analyses. The logging data cross-plot of the neutron porosity versus bulk density were utilized in this study, for lithological determination of the Facha Formation.

The logging data for the studied reservoir comprising true resistivity, neutron porosity and bulk density were collected and digitized. The authors utilized *schlumberger Interactive petrophysics software (v3.6)* in this study, for borehole environmental calibration and interpretation. The removal of the flush effect on shale section was applied.

The amount of shale content (V_{sh}) in a reservoir is the wet shale volume per unit reservoir volume. Determination of shale content is very important as the percentage of shale in the reservoir has a large impact on the log interpretation and hence reserves estimation and hydrocarbon production (Asquith 1982). The clay minerals affect reservoir porosity, water saturation and permeability. Shale content might be worked out utilizing an assortment of petrophysical records, for example, gamma ray, neutron porosity.

Archie's equation (Archie 1942) is the fundamental process for all S_w estimation. Water saturation (S_w) often specified from the resistivity logs and porosity.

Results and discussion

Lithological interpretation using cross-plots

Petrophysical analysis through conventional cross-plots is the key to relate two groups. Logs were carefully edited to compensate for washouts, cycle skipping, environmental

corrections and any other problems. Therefore, through this section, we will present the main cross-plots which are used for lithological analysis of the Facha reservoir.

Neutron porosity (ϕ_N) versus bulk density (ρ_b) cross-plot

Neutron porosity (ϕ_N) versus bulk density (ρ_b) cross-plot is a common technique and quick step to know the lithology. The lithology of Facha reservoir is considered as dolomitic limestone with anhydrite interbeds (high density) at the upper part of the reservoir as indicated by the blue dots. The lithology in all the studied wells varies from calcareous dolostone in A1 (Fig. 4), A5 and A13 (Fig. 5) wells with an increase in clay content in A1 and A5 wells, to limestone in A3 well with slightly increase in clay content (Fig. 6), to dolostone in A4 well with an increase in clay content (Fig. 7), and to dolomitic limestone in A8 well with less clay content (Fig. 8). The Facha reservoir in all wells includes few anhydrite interbeds.

It is noteworthy that the limestone increases within the lower interval of the Facha reservoir.

Litho-saturation log plot

The petrophysical characteristics deduced from the process of well log analysis are generally varied vertically through litho-saturation log plots and horizontally through isoparametric maps (El-Khadragy et al. 2017).

Gamma ray, density, acoustic, neutron porosity and true resistivity logs were adapted to evaluate the entire reservoir section. From the interpreted litho-saturation log plots, it is clear that the structural settings of the study area may play an important role in change of pay thickness of the Facha reservoir and its effective porosity, rather than change in lithology. A1 and A3 wells illustrate high and good hydrocarbon content (Fig. 9), whereas A5 and A13 wells, which

Fig. 4 Neutron porosity (ϕ_N) versus bulk density (ρ_b) cross-plot of A1 well

Fig. 5 Neutron porosity (ϕ_N) versus bulk density (ρ_b) cross-plot of A13 well

Fig. 6 Neutron porosity (ϕ_N) versus bulk density (ρ_b) cross-plot of A3 well

Fig. 7 Neutron porosity (ϕ_N) versus bulk density (ρ_b) cross-plot of A4 well

Fig. 8 Neutron porosity (ϕ_N) versus bulk density (ρ_b) cross-plot of A8 well

Fig. 9 Litho-saturation log plot of A1 well (as example), Facha reservoir

are located at low structure of the field, show a decrease in hydrocarbon content (Fig. 10).

The possible oil–water contact was defined on the log plot roughly within the Facha reservoir and above the highly water saturated interval for all the studied wells. The depth of this contact is dependent on the depth of the reservoir, determined at remarkably different total vertical depths sub-sea “TVDSS” for A1 and A13 wells (≈ 5670 ft and 5840 ft, respectively). It is noteworthy that the two litho-saturation log plots (Figs. 8, 9) are examples of wells located at high

structure and low structure (A1 and A13, respectively) (Fig. 11).

Determination of cutoff values

The effective porosity versus shale content and effective porosity versus effective water saturation cross-plots, derived from logging data, in conjunction with gamma ray log readings plotted on the z axis (Teama and Nabawy 2016; and El-Din et al. 2013) of the Facha reservoir were utilized

Fig. 10 Litho-saturation log plot of A13 well (as example), Facha reservoir

Fig. 11 Structure contour map of the Facha reservoir

in this study, to identify the total clean carbonate intervals from the shaly ones. The cutoff values of the shale content (V_{sh}) and the effective porosity were set at 20% and 10%, respectively (Fig. 12). On the other hand, the cutoff values of the effective water saturation and the effective porosity were set at 70% and 10%, respectively (Fig. 13).

In conclusion, most of the net pay productive reservoir intervals (porous intervals) are characterized by an effective porosity values greater than 10%, a shale content values less than 20% and a water saturation values less than 70%.

Fig. 12 Cross-plot of the shale content as a function in porosity accompanied with the gamma ray scale for cutoff determination

Fig. 13 Effective porosity–water saturation cross-plot accompanied with the gamma ray scale for cutoff determination

Table 1 Reservoir parameters of the Facha reservoir

Well name	Strata	Top depth (ft)	Bottom depth (ft)	Total thickness (ft)	Average porosity (%)	Average water saturation (%)	Average Shale content (%)	Net pay thickness (ft)
A1	Facha Formation (Lower Eocene)	6617	6940	323	15.9	48.8	11.5	48
A3		6572	6903	331	17.6	64.9	10.7	42
A4		6676	6856	180	15.3	74.9	11.3	32
A5		6706	7025	319	16.9	89.2	12.7	0
A8		6684	7014	330	17.3	62	9.9	53.5
A13		6775	7097	322	14	77.6	9.9	22.5

Formation evaluation

The petrophysical parameters of the studied reservoir have been driven from six wells (A1, A3, A4, A5, A8 and A13). The results are summarized in Table 1 and represented by

different maps of reservoir characteristics in the Hakim Oil Field.

The contour maps for the acquired results were prepared using *Petrel (2013) Schlumberger* software to reflect the general distribution throughout the Facha reservoir.

Fig. 14 Average shale content (V_{sh}) in the Facha reservoir in the study area

Contour map of shale content

By applying gamma ray and neutron–density records, the volume of shale was calculated. The shale volume ranges from 9.9 to 12.7% representing a clean reservoir. However, Fig. 14 shows that the shale content of the reservoir tends to increase relatively toward the northwestern part of the study area.

Water saturation contour map

According to the obtained results, the S_w values (Fig. 15) show that the water content within the reservoir decreases in both northeastern and southern parts of the area of investigation, where the A1 well has the minimum value of S_w with 48.8%. On the other hand, in the central and northwestern parts, the values increase, where they reached to a maximum value at A5 well with 89.2% of S_w , which means that the A5 well can be considered as a dry hole.

Fig. 15 Average water saturation (S_w) of the Facha reservoir in the study area

Fig. 16 Average porosity values (Φ) of the Facha reservoir in the study area

Contour map of average porosity

Porosity distribution of Facha reservoir is shown by Fig. 16. This map shows that the reservoir is characterized by its good porosity character. The minimum value reached at the central part of the study area, where it has a value of 14% at A13 well, whereas the rest of area shows good values of porosity, with a maximum value of 17% at A3 well at the eastern part of the study area.

Contour map of net pay thickness

The net reservoir thickness of Facha reservoir ranges from 96.50 ft at A1 well to 130.50 ft at A5 well and was calculated according to the cutoff values. However, the pay thickness ranges from 0 ft at A5 well to 53.5 ft at A8 well, which implies that the south and north of the study area have a tendency to have more amounts of recoverable hydrocarbons (Fig. 17).

Fig. 17 Average net pay thickness of the Facha reservoir in the study area

Conclusions

The study of petrophysical characteristics and evaluation of hydrocarbon potentiality of the Lower Eocene Facha reservoir were established based on geological information and the results obtained from well log analysis in Hakim Oil Field.

We concluded from cross-plot analysis that the lithology of the Facha reservoir varies from calcareous dolostone in A1, A5 and A13 wells with an increase in clay content in A1 and A5 wells, limestone in A3 well with slightly increase in clay content, dolostone in A4 well with an increase in clay content, and dolomitic limestone in A8 well with less clay content. The Facha reservoir in all wells includes few anhydrite interbeds with an increase in limestones in the lower parts.

The structural settings might play an important role in change of pay thickness and effective porosity, rather than change in facies.

The multi-well cross-plot of shale content versus effective porosity cross-plot and gamma ray scale, in addition to, water saturation versus effective porosity cross-plot accompanied also by gamma ray scale were used to define the different required cutoffs to discriminate between reservoir and non-reservoir intervals. The cutoff values of the effective pays were determined as 20% for shale content, 10% for porosity and 70% for water saturation.

Contour maps of water saturation, porosity and net pay thickness show that the Facha reservoir has good petrophysical properties, especially in south and north of the study area and is favorable for oil accumulation.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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