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Reservoir potential, net pay zone and 3D modeling of Cretaceous Pab Formation in Eastern Suleiman Range, Pakistan

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Abstract

The Eastern Suleiman Fold and Thrust Belt comprises of a thick cover of sedimentary sequences. Despite of presence of complete petroleum system source, reservoir and seal rocks less attention was paid by the exploration and production companies to prospect. An integrated approach is adopted to delineate reservoir potential and net pay zones in the clastic reservoirs of the Cretaceous age widely distributed in the area. Wireline logs and migrated seismic reflection data were used for field development and optimization. Petrophysical analysis reveals that Pab Sandstone of the Cretaceous age is acting as a reservoir rock, whereas the Ghazij Shales of the Eocene age are acting as a regional seal rock. A complete workflow is proposed for formation evaluation, and structural interpretation of the subsurface geology. Based on wireline logs it is interpreted that the thickness of the Pab Sandstone varies from 250 m to 350 m in the entire study area. The sandstone is massive with high porosity and intercalated layers of shales. Faulted anticlinal structures are present in the study area which are favorable for the accumulation of hydrocarbon. 3D structural models and various seismic attribute models were prepared to analyze the reservoir character of this clastic reservoir. Based on wireline logs and seismic data clean sand, shaly sand and shale are marked as dominant facies in the study area. However, clean sand facies are more favorable to act as potential net pay zone.

Keywords: *Cretaceous, Pab sandstone, Petrophysics, 3D structural modeling, Anticlinal structures*.

1. Introduction

Porosity, water saturation, volume of shale and facies model are the main petrophysical properties of a reservoir rock and have a vital impact on hydrocarbon reservoir evaluation and characterization. To evaluate hydrocarbon reserves, there is a need of accurate determination of porosity, water saturation, and volume of shale, facies and pore volume (Ahmed et al. 2017; Berg et al. 2017; Khalid et al. 2018a, b; Azeem et al. 2018). Petrophysical properties have a reasonable contribution to reservoir estimation, therefore it needs a serious attention. Reservoir characterization is the integraton of different data in order to describe the reservoir properties of interest in inter-well locations. Various petrophysical properties are used for reservoir modeling. Hydrocarbon reservoirs properties can be estimated by deterministic and probabilistic modeling. Petrophysical parameters can be derived from geophysical logs or core samples. Porosity can be obtained from sonic, neutron or bulk density log while resistivity logs are used for the calculation of water saturation.

The study area lies to the north of Sufaid Koh, on the eastern boundary of the Suleiman Range, with latitude 30°55'20.5" N and longitude 70°22'39.0" E nearly 80 km north of Dera Ghazi Khan City is shown in figure 1.

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Dhodak Field is producing hydrocarbon since 1970. The petroleum system in Dhodak Field is well established. It is one of the utmost prolific gas prone zone with the largest gas field, (Sui ~ 12 Tcf) trillian cubic feet per day in Pakistan from the Eocene carbonates. Mughal Kot Formation, Sember Formation as well as Guru Formation shales are common in Dhodak Field and these shales are rich in biological matter. The shale of these three formations act as a source rock in Dhodak field (Khan and Scarselli 2020). In Central Indus Basin shale of Sember Formation acts as a common source rock and contain type III kerogen, generating gas or condensate, but in some parts type II kerogen is also present. Pab Formation Sandstone (Cretaceous) age used as a reservoir in the study area. Seal rocks are existing for all reservoirs in this basin. The Shale of Ghazij Formation acts as a seal rock in Dhodak Field (Raza et al. 1989).

2. Geology and Tectonic Settings of Study Area

The different geodynamic changes in the Indus Basin are due transtensional transpressional forces that ocur through geological time. Due to these forces the Cambrian to Eocene age reservoir and source rocks of clastic and carbonate origins as well as various stratigraphic and structural traps traps are formed (Khan et al. 1986; Malik et al. 1988; Raza et al. 1989; Ahmed and Ali 1991; Bannert and Raza 1992; Ali et al. 1995;

Iqbal et al. 2008; Afzal et al. 2009; Baratian et al. 2018). Dues to these transpressional forces which occur from the east and the west directions may rose and as a result Suleiman Fold Belt in Teritary age is formed (Ali et al. 1995; Yazdi and sharifi teshnizi 2021). On the eastern side, the thickskinned tectonic structures on the surface are marked by the left lateral en echelon folds related with thrust faults, while on the western side the right lateral en echelon folds, and positive flower structures are present in the sub-surface. Hydrocarbon have been reported from positive flower structures and en echelon folds from the eastern side of Suleiman range (Ali et al. 1995; Bannert et al. 1995; Iqbal et al. 2008; Peresson and Daud 2009). In this area, the Suleiman Fore Deep acts as a kitchen for the anticlinal structures and has an enormous rate of uplifting in the Late Tertiary that give rise structures filled by hydrocarbon (Iqbal et.al. 2008; Yazdi et al. 2019).The rocks which are present in this basin are of Triassic to Tertiary age by (Hunting Survey Corporation 1960; Baker and Jackson 1964; Raza et al. 1989; Kazmi and Jan 1997 and Shah 2009; Otari and Dabiri 2015; Poorbehzadi et al. 2019; Mollai et al. 2019).

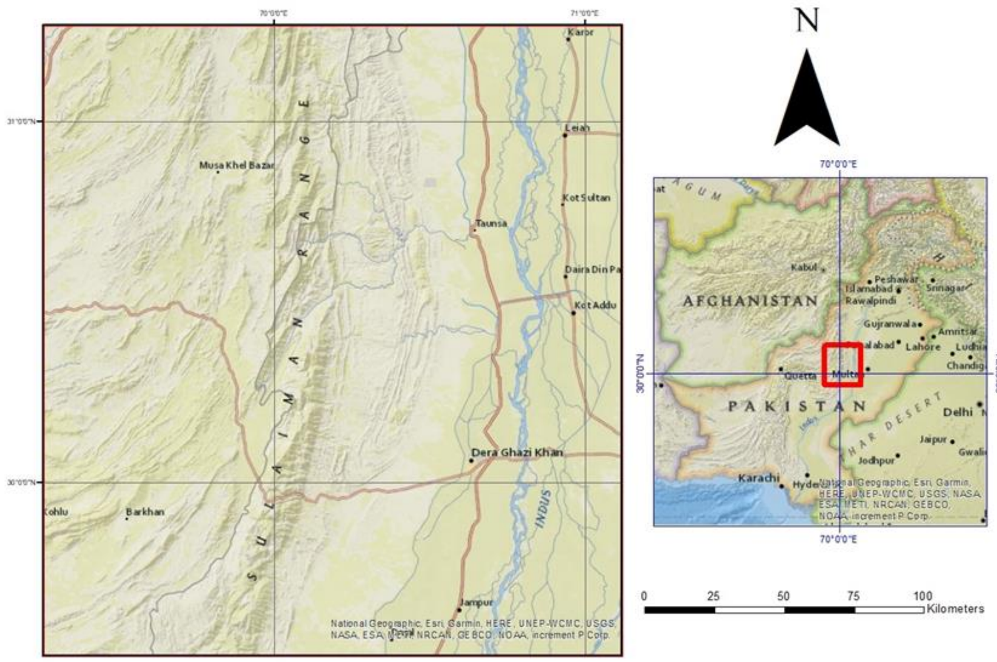

Fig 1. Location map of the study area (GSP 2003). Dhodak Field highlighted on google earth.

The older rocks are exposed in the hinterland, whereas in the foreland the younger rocks are present. About 5000-10000 meters thickness of sediments are present in the basin (Kemal et al. 1992) with almost 7000 meters thick sequence of Mesozoic and early Tertiary rocks are present (Raza et al. 1989). In the Suleiman Depression the Paleozoic rocks that cover the subsurface are not present but have been found and drilled in the adjacent areas of the Punjab Platform (Raza et al. 1989). The Precambrian to Permian rockas are expected to be present in the subsurface (Jadoon et al. 1994).

From the eastern side, the Zindapir Anticlinorium are delineated with Suleiman depression while Barthi Syncline found in the west. Zindapir Anticlinorium enclosed the area of approximately 6000 sq.km and the rocks of the Eoceane age were seen in the core of Dhodak, Afiband and Rodho anticlines. The proven reservoir rocks of Dhodak anticline of Late Cretaceous age are Pab Sandstone and Mughal Kot Formation while Lower Rani Kot Formation are of Paleocene age (Nazeer et al. 2013).

3. Petrophysical Parameters of Well Logs

Petrophysics is the knowledge that defines the rock, soil and fluid physical and chemical properties as well as its behavior. Some of the significant parameters which are important in the petrophysics for hydrocarbon exploration are water saturation, lithology, porosity, permeability and density.

Different wireline logs and the measuring parameters are used to study these properties. Petrophysical analysis of Dhodak-01, Dhodak-02, Dhodak-03 and Dhodak-05 wells were carried out by using available well logs. Hydrocarbons in a reservoir can be identified on the basis of various logs. Important logs are the gamma-ray (GR), sonic (DT), neutron porosity (NPHI), bulk density (RHOB), self-potential (SP), and Resistivity. If we identify hydrocarbon in a reservoir there is some criteria for that i.e. low values of spontaneous potential and gamma-ray logs and high values of neutron porosity and resistivity logs. A workflow was established for the petrophysical analysis in the study area. The workflow is presented in the figure 2.

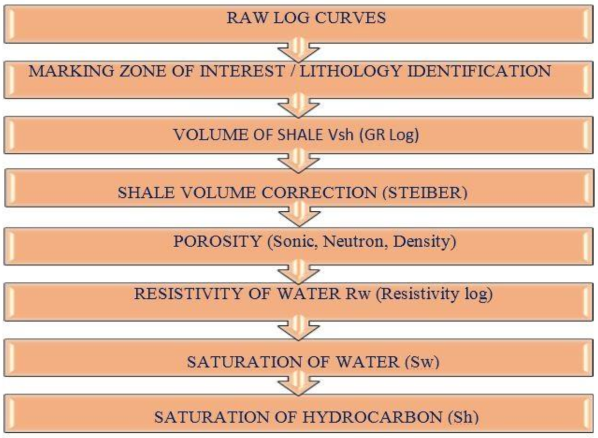

Fig 2. Workflow for the petrophysical analysis carried out in this study area

3.1. Volume of Shale calculation

Shale volume is calculated via Gamma-ray log, having a unit is API, scale is from 0 to 150, and run in first track. For quantitative estimation of shale volume, radioactive minerals other than shales are not present.

"Shale index" I_{GR}, is calculated as (Asquith and Krygowski 2004).

$$V_{sh} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \times 100$$

Where,

$GR_{\log}$ = Gamma-ray value

$GR_{\min}$ =Gamma deflection is minimum (clean beds)

$GR_{\max}$ = Gamma deflection is maximum (shaly beds)

3.2. Effective Porosity Calculation

To calculate effective porosity, we have to correct shale influence from total porosity (Woodhouse and Warner 2004).

$$\phi_{eff} = \phi_t \times \langle 1 - V_{sh} \rangle$$

Where;

$\phi_{e\,ff}$ = Porosity effective

ϕ_t = Total Porosity

3.3. Calculation of Water Saturation

During well analysis, Archie and Indonesian equations play the key role to calculate water saturation (Archie 1952).

$$(S_w)^n = \frac{a}{\phi_m} \times \frac{R_w}{R_t}$$

Archie Equation

Where;

R_W =Formation water resistivity

n = Saturation exponent

a = Lithology co-efficient

ϕ = Fraction porosity

m = Factor of cementation (constant value 1)

R_t = True resistivity (obtained from LLD).

(m, n, and a) came from the core analysis. Value used for (m, n and a) are; (n = 2), (m = 2), and (a = 1)

3.4. Calculation of Hydrocarbon

Saturation of hydrocarbon were computed from formula as shown under;

$$S_{hc} = (1 - S_w)$$

Here

S_{hc} = Hydrocarbon saturation

S_w = Water saturation

4. Seismic Interpretation

It is defined as, the study to get the key information of the subsurface geology from the processed seismic data. Through the examination of seismic records the reasonable models, structures of the subsurface and estimation about hydrocarbon are generated (Hardage and Remington 1999). For the oil and gas prospects the seismic data interpretation is the key activity. Seismic interpretation suggests and helps to calculate the hydrocarbon potential.

In interpretation, a significant role is to identify different horizons and reflectors on the basis of geological formations. The seismic reflectors are acknowledged through stratigraphic information. On the seismic section, the faults and the horizons are pointed out. After then these sections are interpreted and select the best location for drilling (Humayun et al. 1991).

Six seismic lines are used for the interpretation of research work in which one line is the strike line and five are the dip lines which are shown in figure 3A.

For seismic interpretation we have chosen the seismic line 795-SK-07. We have to pick three reflectors i.e. Lower Ranikot Formation, Mughal Kot Formation and Pab Sandstone on a seismic section shown in figure 3B. Two faults i.e. F1and F2 are present on a section. The faults F1and F2 are marked on a line 795-SK-07. The seismic section which are interpreted shows anticlinal pop up structure in the research area that is surrounded by thrust/reverse faults.

4.1. Time Contour Map

It displays the horizontal and the vertical changes with respect to time. On Pab Sandstone the time contour is created which is shown in figure 3C. Time difference is declared through the color bar that ranges from 1.580-1.940 seconds. Red to orange color 1.580-1.640 second shows the shallowest part and greenish color that ranges from 1.66-1.780 second is the deeper part as compared to red and orange one.

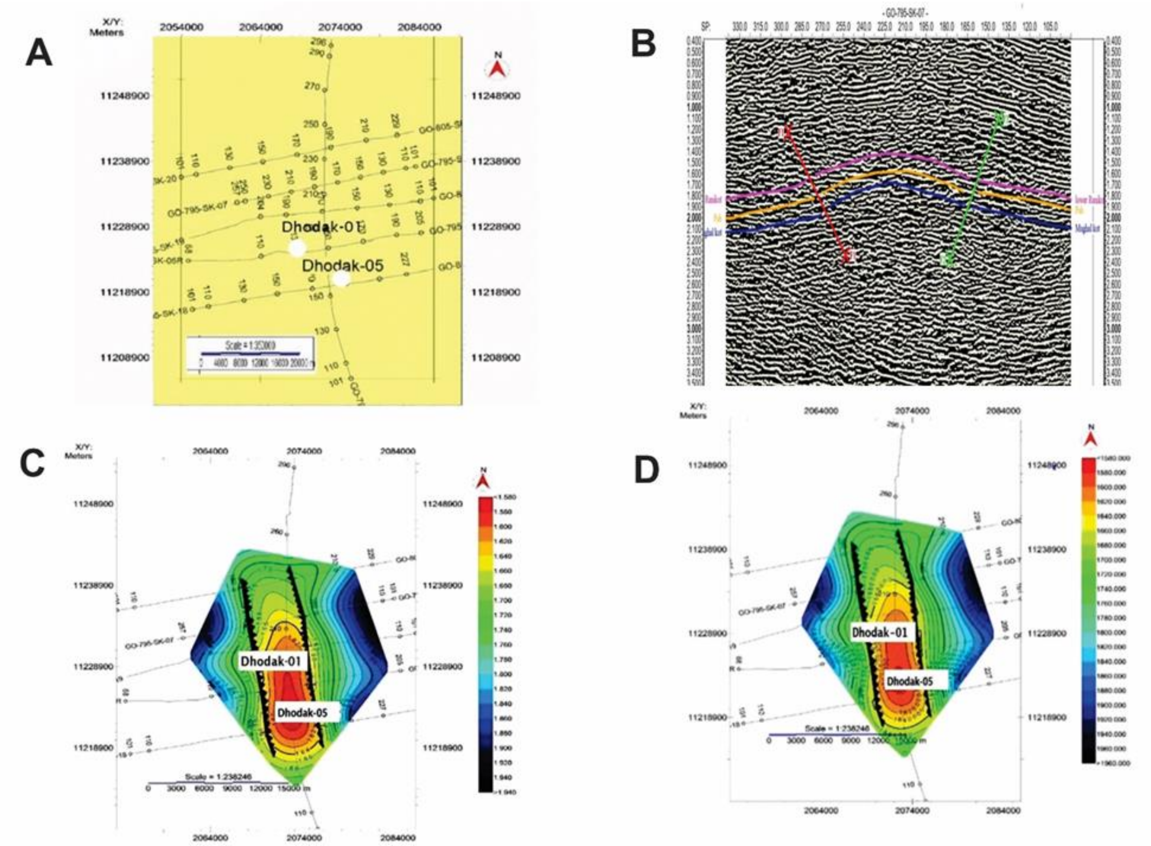

Fig 3. (A) Base map of Dhodak Field (Central Indus Basin). (B) Interpreted seismic section of line 795-Sk-07 having Mughal Kot Formation, Pab Sandstone and Lower Rani Kot Formation are marked. In this section, anticlinal pop up structure are present which are formed between the faults F1 and F2. (C) Time contour map of Pab Sandstone along with the fault polygons. In this map two faults, are shown F1 and F2. Anticlinal pop up structure is present between these two faults which show in red and orange colors. (D) Depth contour map of Pab Sandstone along with fault polygons. In this map two faults, are shown F1 and F2. Anticlinal pop up structure are present between these two faults which shows in red and orange colors.

While blue and dark blue color 1.800-1.94 second shows comparatively deepest portion. Therefore from the figure 3C, it is clear that structure formed by the fault polygons after contouring is an anticlinal pop-up structure surrounded by reverse/thrust faults. Orange and red color that ranges from 1.580-1.640 second have highest peak point and it is the utmost promising area for hydrocarbon exploration**.**

4.2. Depth Contour Map

It is prepared by the mean of well point velocities. This map indicates the horizontal changes with respect to depth. The depth and the time contour maps are same because equal horizontal variation has been done in both. The depth contour map of Pab Sandstone displayed in figure 3D. Color bar ranges from top 1580 meter to bottom 1960 meter. Red to yellow color ranges from 1580-1660 meter shows the shallowest part while the green color 1680-1780 meter is showing a deeper part. While blue to dark blue color 1800-1960 meter represents the deepest part. Figure 3D shows that red to yellow color from 1580-1660 meter shows the highest peak, the structure that is formed in that zone is anticlinal pop up, which represents the most promising region for hydrocarbon.

5. Discussion

5.1. Reservoir Modeling

In view of the necessity of dynamic simulation process and to arrive at a final well and production behavior, it was necessary to build a reservoir model that represented as closely as possible the sub-surface reality of Dhodak field that have been encountered by most wells. The model of Dhodak for the entire Dhodak field in Pab sandstone was built by integrating relevant sub-surface data and interpretation presented in the preceding sections. The seismic structural interpretation, lithological descriptions and facies interpretation, porosity, volume of shale and water saturation from log analysis were used to build the reservoir model. The PETREL Schlumberger software was used in building the reservoir model. The structural and property model of the reservoir are briefly described as follows.

For geological modeling, data preparation is the basic step. The steps used for geological modeling are

- Well heads
- Well logs
- Well tops

5.2. Property Modeling

5.2.1. Facies Modeling

It is an important step in property modeling that shows the difference in variation in term of facies. The facies log was then up scaled into grid and after then facies are modeled by applying stochastic method (Haldorsen and Damsleth 1990). The technique that is used for facies modeling is Sequential Indicator Simulation (SIS) that arrange the sand bodies in all intervals as well as to settle litho facies in the reservoir. 3D model of facies was prepared on Pab Sandstone of Cretaceous age and having lithology sandstone, shale, sandy shale, and shaly sand. The lithology percentage of sandstone, shale, sandy shale (siltstone) and shaly sand is 35.2%, 2%, 6%, and 56.8% respectively in the 3D model of facies in figure 4A. The percentage of shaly sand is higher than other facies in the model. It also allows easy modeling of facies environment where facies volume proportion vary vertically, laterally or both. Figure 4B shows the histogram model of facies.

5.3. Petrophysical Model

5.3.1. Porosity model

Porosity is an essential property of an oil reservoir that determines the capacity of oil it can contain. The porosity model is based on porosity logs generated from the petrophysical interpretation of 4 wells. The well logs were scaled up using the method of arithmetic averaging. The porosity was distributed in the model using Sequential Gaussian simulation method. This attribute is controlled by the distribution of Lithofacies in the reservoir. The porosity model was built on the porosity logs formed from the petrophysical interpretation of Dhodak-01, Dhodak-02, Dhodak-03, and Dhodak-05 wells. The porosity distribution is mostly between 4.2%-10% with an average porosity of 7.5% within the 3D model. Figure 4C shows that the porosity in the well drilled in Dhodak Fields are in the range of 7-9% which shows in the green color in a 3D model. Figure 4D shows histogram distribution of porosity.

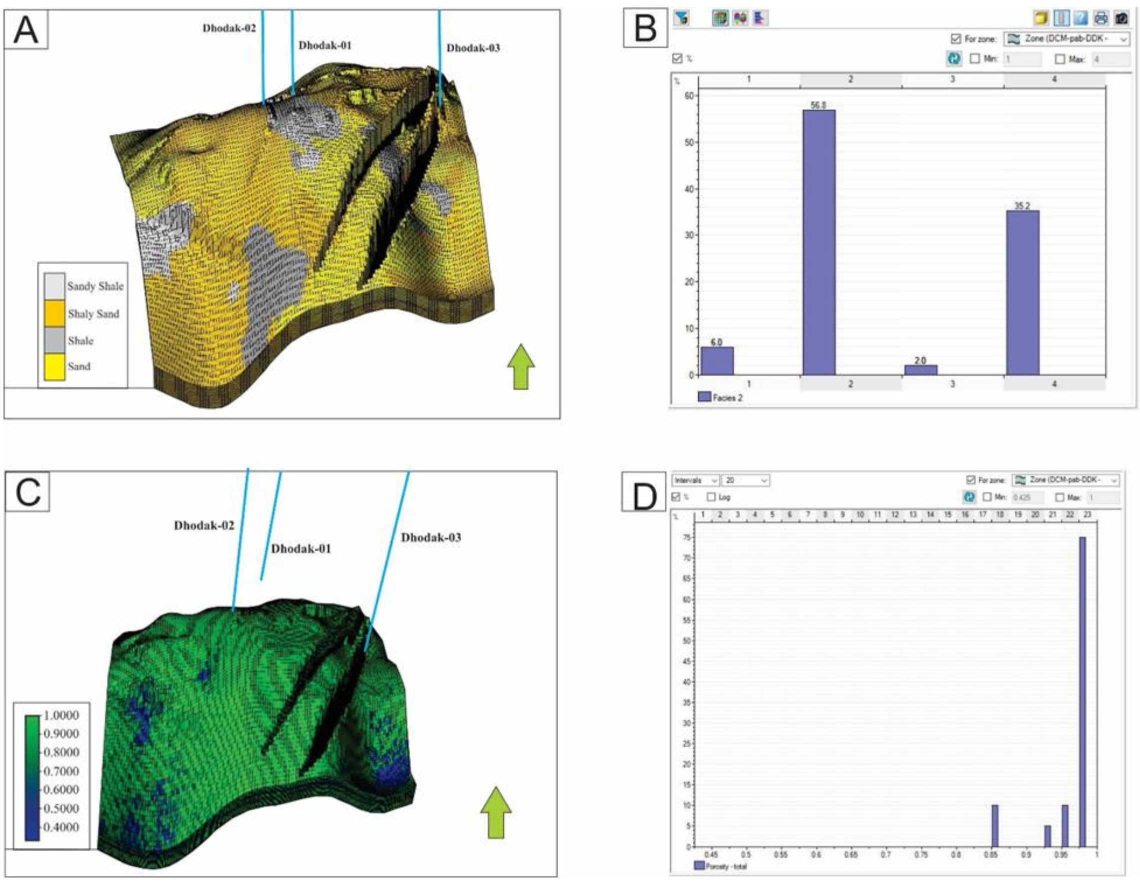

Fig 4. (A) 3D model representing different facies distribution in the Dhodak Field, where percentage of shaly sand is up to 56.8% higher than other facies present in the field. In the facies model, two faults are present which are oriented along the north south direction. (B) Histogram of facies distribution in model. (C) 3D model representing porosity of Pab Sandstone of Dhodak Field in which average porosity value in the study area is up to 7.5%. The green color in this mode representing good porosity zones. The 3D model also shows two faults in Dhodak Field which are oriented along the north-south direction. (D) Histogram of Porosity distribution.

5.3.2. Water Saturation model

Even though saturation is not important as porosity, saturation distribution model helps to identify potential high water area. Saturation is the fraction of oil, water, and gas found in a given pore space. This is expressed as a volume/volume percent of saturation units. Typical saturation analysis does not show 100% fluid saturations due to the volume expansion and fluid loss associated with bringing a subsurface core with typical higher temperatures and pressures to the surface with lower temperatures and pressures. To determine the quality of hydrocarbons accumulated in a porous rock formation, it's necessary to determine the fluid saturation (oil, water and gas) of the rock material. This study modeled the water saturation of Dhodak field which is shown in figure 5A. Sequential Gaussian Simulation (SGS) algorithm was applied to distribute water saturation in each zone (Esfahani and Asghari 2013). The wells are drilled in the study area where water saturation is between 35-55% except Dhodak-01 well, where water saturation is too much less. 3D model of water saturation as shown in figure 5A.Overall water saturation is high in Dhodak Field due to the presence of shale layers between sand layers. Quality control of the water saturation was conducted by displaying the histogram figure 5B.

5.3.3. Volume of Shale model

Gamma-ray is used to compute volume of shale. Zones are modeled using the "Sequential Gaussian Simulator (SGS)" algorithm after biasing it with facies for both oil and gas reservoir (Esfahani and Asghari 2013). Knowledge of the volume of shale is essential because it helps to compute formation porosity, fluid type, and globally the rock quality (Haldorsen and Damsleth 1990). In this 3D model, different zone shows the percentage of shale volume in the study area. In our study area volume of shale is up to 18-27% in proportion as shown in figure 5C. The zone of interest where wells were drilled is having a volume of shale up to 18%. The 3D model also shows that the volume of shale is normal in overall Dhodak Field. Histogram distribution of volume of shale is shows in figure 5D.

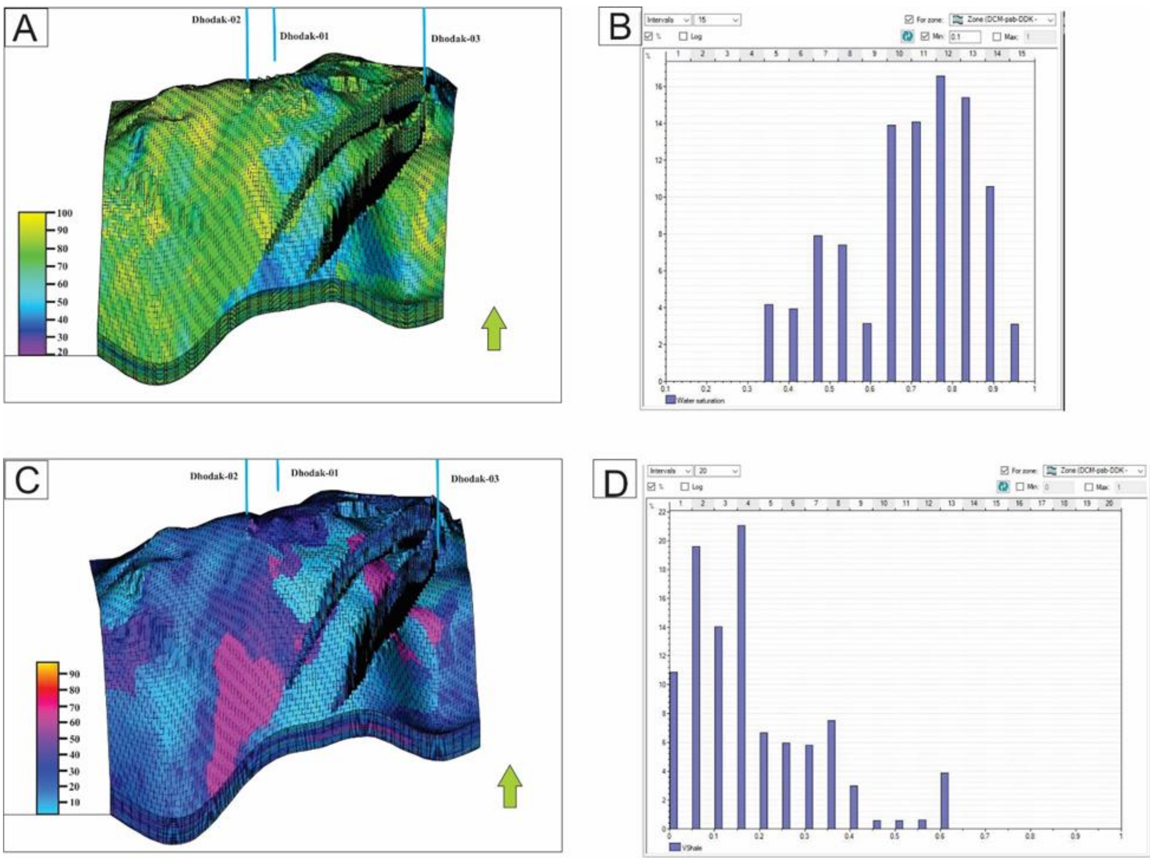

Fig 5 (A) 3D model showing water saturation in Pab Sandstone in the Dhodak Field. Color bar represents the distribution of water saturation in the field, blue to light blue color in the model represents 35-55% of water where wells were drilled. The 3D model shows that overall water saturation is high in Dhodak Field. Two faults are also present in this model that are oriented along the north-south direction. (B) Histogram of water saturation distribution. (C) 3D model representing the distribution of volume of shale in Pab Sandstone. The average volume of shale in the study area is up to 18%. Light blue color in the model represents a low volume of shale. Mostly wells were drilled in the area where the volume of shale is up-to 18-27%. The model also represents low volume of shale in overall Dhodak Field. (D) Histogram of volume of shale distribution

6. Conclusions and Recommendations

The present research work in Dhodak area reveals the existence of hydrocarbon potential which is present in the structural traps. Time and depth contour maps were prepared and from the results, it is clear that anticlinal pop up structure is present in the Dhodak Field. From the research, it is clear that Sember Formation shale are used as a source whereas Pab Sandstone of Cretaceous age is acting as a reservoir rock. Well interpretation discloses that the reservoir of Late Cretaceous are the best reservoirs for hydrocarbon potential. The 3D study discloses that the research area is being so old, still demonstrate positive signs of the presence of hydrocarbon reserves. Pab reservoir is most favorable because of its better porosity values, low values of shale, moderate water saturation values and high hydrocarbon saturation. 3D model has provided better results for petrophysical and property modeling. 3D static modeling of the Dhodak Field has provided better results of the spatial distribution of discrete as well as continuous properties in the field. Core data may be acquired for core-log calibration which can improve prediction of petrophysical parameters and facies. 3D seismic data may be utilized and integrated with other datasets for geo body extraction, improved structural interpretation and attributes analysis for inversion of seismic data and prediction of reservoir characters. Image logs (FMI etc.) can be employed and integrated with seismic and well logs data for facies and fracture analysis. This model might be discussed with reservoir engineer for proper interpretation in future drilling, but more parallel/horizontal deep wells should be drilled to increase optimization of the reservoir.

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