A static modeling approach to the Brown Limestone carbonate reservoir, Geisum Oilfield, Gulf of Suez, Egypt

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Abstract
The Gulf of Suez in Egypt contains more than 80 conventional oil fields with reservoirs from Precambrian up to Quaternary age. To date, these fields have all been conventional resources. This abstract will take part of the Gulf of Suez sequence within the fields of Petrogulf Misr Company and present a work process for unconventional resource assessment of the Brown Limestone formation within one of these areas. The Brown Limestone formation is a Late Cretaceous Pre-rift mega sequence succession and plays an important role in the conventional system of Gulf of Suez, Brown Limestone formation is not only as one of the important source rocks, but also a fractured carbonate reservoir in multiple fields especially is the southern Geisum oil field. However, this formation is characterized by uncertainty due to the complexity of reservoir architecture, various lithologies, lateral facies variations, and heterogeneous reservoir quality. These reservoir challenges, in turn, affect the effectiveness of further exploitation of this reservoir along the Gulf of Suez Basin. In this work, we conduct an integrated study using multidisciplinary datasets and techniques to determine the precise structural, petrophysical, and facies characteristics of the Brown Limestone Formation and predict their complex geometry in 3D space. The Brown Limestone formation is considered to be as a reservoir in the study area. The value of water saturation ranges from 15 to 45%, where the value of Effective Porosity ranges from 11 to 15% for the selected potential intervals in Brown Limestone due to the highly structural setting in the study area, so Reservoir thickness was used as the proxy for reservoir effectiveness where thicker reservoir had a higher chance of containing multiple intervals for good potential intervals.

Keywords Unconventional resources · Carbonate reservoir · Brown limestone formation · Reservoir characterization · Reservoir zonation

Introduction
The current research developments within the energy sector are seeking better exploitation of subsurface resources through enhancement of resource prediction and efficient production. Three dimensional (3D) modeling of hydrocarbon reservoirs is the key factor that controls hydrocarbon reservoir evaluation and simulation for better exploitation and successful development by using various available software, the modeling accuracy still presents a big challenge that has a great impact on the effective development of hydrocarbon reservoirs (Abdel-Fattah et al. 2018; Bryant and Flint 1993; Radwan 2022). The main advantage of 3D modeling approaches is the ability to model complex reservoirs with variable facies and reservoir heterogeneities using accurate parameters to get the integrated reservoir modeling. The ultimate goal of this approach was to provide a new set of potentially optimistic reservoir targets for modeling hydrocarbon accumulation and reservoir characteristics in
the heterogeneous Brown Limestone reservoir, using precise 3D modeling with low uncertainties. To overcome the associated facies changes and reservoir complexity of Brown Limestone in the subsurface of the Geisum oilfield, the reservoir architecture, petrophysical parameters, structural characteristics, and facies distribution must be understood and recognized. Simulation of complex reservoir property was used in this work to populate the grid cells of a 3D model with integrated constructed (structural modeling), discrete (facies modeling), and continuous properties (petrophysical modeling). Therefore, we utilized available data from 3D seismic reflection sections and wire line logs to define the main structural characteristics of the study area, recognize the distribution of the thickness/facies of the Brown Limestone formation, and evaluate its petrophysical perspective and therefore, volumetric assessment will be done over the sweet spot by extracting the inputs for volumes and chance of success for the calculation directly from the geological and chance maps.

Geological framework and overview

The Gulf of Suez rift is an extended graben shaped by Oligocene rifting as a northern continuation of the Red Sea (Radwan 2021a, 2021b). The studied Geisum oilfield is located in the Zeit province (NW-tilted fault blocks and SE dipping normal faults) as shown in (Fig. 1), and it is bounded to the north by latitudes 27° 34’ and 28° 37’ N and to the east by longitudes 33° 00’ and 33° 42’ E as shown in (Fig. 2); (EGPC 1996; Gaafar et al. 2009).

The Gulf of Suez stratigraphy can be divided into three main tectonic stratigraphic successions. Some authors describe these successions as lithostratigraphic units (Alsharhan, 2003; Radwan 2021a, 2021b; Said 1990). They include pre-rift (pre-Miocene) interval (e.g., Radwan 2021a), syn-rift (Oligocene–Miocene) interval (e.g., Kassem et al. 2021a, b; Radwan and Sen 2021; Shehata et al. 2021), and post-rift (post-Miocene) interval (e.g., Radwan 2020a; 2021a, 2021b, 2021c). The thickness, areal distribution, lithology, hydrocarbon importance, and

![Interpretation of major faults and shear zones in the Gulf of Suez area](image-url)

Fig. 1 Interpretation of major faults and shear zones in the Gulf of Suez area
Fig. 2 Location map of the studied area showing the positions of the 20 seismic lines and 4 wells
depositional environments of these units vary (e.g., Alsharhan, 2003; El-khawaga et al., 2021; Radwan et al. 2019a, 2019b).

In the Geisum oilfield, the sedimentary sequence ranges in age from Paleozoic to Recent (EGPC, 1996). The general stratigraphic section of the Geisum oilfield is shown in Fig. 3. According to EGPC 1996, the main reservoirs of the Geisum oilfield are Miocene clastic deposits (Rudeis and Nukhul Formations), pre-Miocene Cretaceous Nezzazat Group, and Nubia Formation. The studied deposits of the Brown Limestone formation are a Late Cretaceous Pre-rift mega sequence succession. It is composed of mainly fossiliferous limestone (cherty limestone), nummulitic with flint and thin interbeds of marl, from marine sublittoral depositional setting and plays an important role in the petroleum system of Gulf of Suez as a source rock. The cumulative source rock thickness varies considerably between wells, but seems to thicken towards the South West of the Geisum fields.

Methods and materials

The Petrogulf Misr Petroleum Company provided the datasets for the current study as part of an agreement with the Egyptian General Petroleum Corporation (EGPC). Twenty 3D seismic sections were represented by 9 NE–SW direction sections (inline seismic), 8 NW–SE direction sections (cross-line seismic), and 3 sections (randomly) as shown in Fig. 2. Digital well logs for the G-9, GA-1, GA-2, and GA-5 wells were also provided, which include caliper, gamma ray, resistivity, neutron, density, and sonic datasets. The interpretation of seismic data is an integral part of the hydrocarbon development strategy of the oil field. It performs a variety of tasks in 3D seismic interpretation, such as analyzing the parameters that govern reservoir architecture (John et al. 2010). Evaluation of sedimentological and well log analysis is the key for better reservoir discrimination and better reservoir quality prediction (Radwan 2021a; Qadri et al. 2021). The Brown Limestone formation petrographic studies and facies analysis were carried out on samples from G-9 well, based on the cumulative interval from 4771 to 4430 ft with total thickness 341 ft (104 m). The stratigraphic section of the Brown Limestone formation consists mainly of hard, highly argillaceous, cherty, Phosphatic limestone with thin interbeds of shale and marl and was deposited in a deep marine setting, according to cutting sample analysis, core samples, and well logging analysis as shown in Fig. 4.

Results and discussion

Depth structure contour map of the Brown Limestone formation

After completing the seismic interpretation process for all lines, the seismic to well tie was performed. The studied horizons were then selected on seismic sections, and the faults affecting them were interpreted as shown in Figs. 5 and 6. The preceding steps made it simple to create depth structure contour map of the Brown Limestone Formation. The reflection map as shown in Fig. 7 at the top of the Brown Limestone Formation shows strong spatial variability of the horizon in the study area, Geisum field structurally composed mainly of a series of NW–SE normal faults dissecting the field into several blocks. It revealed that the structure of south Geisum is a titled fault block trending northwest–southeast (three-way dip closures) at the main block. As shown in Fig. 7. The final structural modeling is in the creation of 3D structural grid surfaces, which comprise both the fault modeled pillar grids/models and the horizon surfaces. Structural cross sections reflect that the study area is a highly structure and affected by set of normal faults.

Isopach map of the Brown Limestone formation

The Brown Limestone Formation isopach map was created by subtracting the Matulla interval’s depth map from the Brown Limestone interval’s depth map (see stratigraphic position in Fig. 4. All of the wells investigated (G-9, GA-1, GA-2, and GA-5) penetrated the Brown Limestone Formation in this region. The Brown Limestone formation isopach map (Fig. 8) shows that the thickness of the Brown Limestone Formation increases in the south–west direction of the Geisum oilfield. However, the thickness decreases in the north eastern direction of the Geisum oilfield. The basin area is directed to the southwest part of the Geisum oilfield and has a maximum thickness of 200 ft (60.9 m), while the northern east part of the studied area has a minimum thickness of less than 20 ft (6.09 m) due to uplifting and post-depositional erosion.

Petrophysical parameters of the Brown Limestone formation

The petrophysical and hydrocarbon characteristics of the Brown Limestone formation were based mainly on well logging analysis of the four studied wells, which were distributed across the study area. The average values of the various derived petrophysical parameters of the examined wells of the Geisum oilfield are summarized in Table 1. The petrophysical data logs of selected well (G-9) from the Geisum oilfield are depicted in Fig. 9.

The Brown Limestone formation in the Geisum oilfield was encountered in the depth range 3999–4256 ft in G-9, 3841–3965 ft in GA-1, 3830–4198 ft in GA-2, and 3517–3609 ft in GA-5. The lateral and vertical changes in petrophysical properties were thought to be directly connected to lateral and vertical facies changes across the Brown Limestone reservoir. The petrophysical analyses of the wells under consideration showed good reservoir properties and
Fig. 3  Summary Stratigraphy of the Gulf of Suez (Al Sharhan and Salah 1995; Bosworth et al. 2014)
Fig. 4 Well correlation across A, B section showing the logs’ reaction and the divided zones through the Brown Limestone formation.

Fig. 5 Interpreted seismic section IL-1460 before and after interpretation passing through G-9 well shows the set of step fault block.

Fig. 6 Interpreted seismic section IL-1480 before and after interpretation passing through GA-2 and GA-5 wells shows the set of step fault block.
hydrocarbon fluid entrapment in the Brown Limestone formation. The litho-saturation cross-plot revealed a complex lithologic nature that varied between cherty, argillaceous limestone’s with shale intercalations at different levels. Relatively high GR due to organic matter, high resistivity, high density, and low neutron porosity logs were recorded against cherty carbonate lithology intercalated with shale zones. Along the shale zones, high GR, low resistivity, low density, and high neutron porosity values were observed. To distinguish the entire Brown Limestone Formation, it was divided into six zones: A, B, C, D, E, and F (see well correlations in Fig. 4) based on facies interpretation and log response. Oil was the fluid type in the Brown Limestone formation, and the majority of the source rocks in the Geisum oilfield were oil prone according to the type of kerogen (type I/II), (EGPC 1996).

According to the petrophysical investigation, the Brown Limestone had excellent reservoir characteristics and that it can store and transfer hydrocarbons. The statistical analyses showed a good range of total and effective porosity, as well as water saturation, implying that the Brown Limestone Formation’s reservoir quality was good. The value of water saturation ranges from 24.8 to 29.3%, where the value of effective porosity ranges from 11.8 to 12.8% for the selected potential intervals in Brown Limestone (A, C, E, and F) zones, the extreme lateral and vertical changes in lithology may be linked to the significant lateral and vertical changes in petrophysical properties of the Brown Limestone reservoir as shown in Fig. 9.

3D structural model

A precise structural model of the Brown Limestone formation was required for the explanation and knowledge of the structural pattern of the reservoir in a 3D outline. By optimizing the information from seismic data, the goal was to create a solid structural model using the available wells. The Geisum oilfield is a highly faulted, complex system that generates several fault blocks from four reservoirs, the 3D structural framework illustrates complex structures that affect the Geisum area, with normal faulting serving as the primary faulting system. According to the 3D structural model, normal faults with NW–SE trends represent the dominant fault system based on the structural style of South Geisum oilfield based on depth structural contour maps represented by tilted fault blocks bounded by a major normal fault these fault trended are trended in NW–SE direction (clysmic faults), in addition to a cross faults trended in NE–SW direction as shown in Fig. 10. At the uppermost Limestone of the Brown Limestone formation, the crest of the structure occurs at
3600 ft TVDSS in GA-5 well on top Brown Limestone formation in the Eastern area of the main part of the oilfield (present study), whereas the OWC is at 5300 ft TVDSS, giving average thickness of oil column of ~200 ft. Moreover, the model indicated that the horizon depths of the Brown Limestone formation reservoir were smallest in the northeast part of the Geisum oilfield and increased gradually toward the southwest of the basin.

**3D facies model**

The basic goal of reservoir description was to identify reservoir heterogeneities that affect the amount, position, accessibility, and movement of fluids across the reservoir. Because standard data collecting methods produce sparse sampling, 3D description at the appropriate resolution was generally problematic. In order to predict "geological, geophysical, and petrophysical properties between sampling points (e.g., wells and seismic lines) and define probable variabilities, geostatistical approaches were used (Radwan, 2022; Seifert and Jensen, 1999). To build the 3D facies model, the allocated values were loaded into Petrel™ software in a distinct code for the lithology distribution, and then dispersed in two directions (vertically and horizontally) across the grid cells to fill the full 3D grid between the wells (Abdel-Fattah et al. 2018; Godwill and Waburoko 2016; Jika et al. 2020; Okoli et al. 2021; Radwan 2022). In addition, the 3D facies model was applied using the stochastic sequential indicator simulation (SIS) method (Deutsch and Journel 1998; Radwan 2022; Remy et al. 2009). This algorithm is the most widely used for discrete or categorical variable data such as facies, whereby upscaled facies values and allocated variograms are the most important factors (Deutsch and Journel, 1998; Radwan, 2022).

When using stochastic modeling, SIS, a number of uncertainties can arise. In this simulation approach, a grid-node that has no simulated value (an unknown lithotype) is selected randomly and neighboring node points are identified and simulated with reference to the original conditioning dataset. Later, another grid-node is selected randomly, and the variable is simulated using the newly generated CDF (cumulative distribution function), which is now increased in size by one value. In this way, each node is simulated (Deutsch and Journel 1998; Seifert and Jensen, 1999; Radwan, 2022).

The initial stage in facies modeling is to create discrete facies that are upscaled as shown in (Fig. 9) to grid-based model cells (Radwan 2022). In terms of lithology, the Brown Limestone formation displayed various lithologies. The outcomes of the data analysis were employed for facies modeling. Based on the combined sedimentological and petrophysical analysis, the following were the proportions of the various lithologies as shown in Fig. 11. Brown Limestone formation is subdivided into 125 layers in order to capture the small scale vertical heterogeneity, the three dominated facies are cherty limestone, which is distributed towards the northwest and southeast of the modeled zones (A, B, C, D, E, and F), calcareous shale and argillaceous limestone which are concentrated in the zones (B and D). The interpreted facies of mixed carbonate/marl facies of the Brown Limestone formation consisted of different lithologies that have been deposited from lower intertidal to slightly deep subtidal in a fluctuating depositional regime. Cross section of the Brown Limestone formation reservoir as shown in Fig. 12 was generated in addition to the facies model to highlight the lateral and vertical facies changes. The rapid facies changes across the studied wells reflect the changes in depositional conditions.

**3D petrophysical model**

The interpreted petrophysical characteristics of the Techlog™ Program were upscaled and then modeled using standard procedures. In the process of petrophysical modeling, the SGS algorithm was the utilized statistical approach (Radwan 2022). Given the amount of available data, this approach is most likely the best fit in this case, where it had the advantages of simulating

| Well name | Gross interval | Net pay | Effective porosity | Water saturation | Hydrocarbon saturation |
|-----------|----------------|---------|--------------------|------------------|-----------------------|
|           | (ft)           | (ft)    | (%)                | (%)              | (%)                   |
| G-9       | 257            | 86      | 12.8               | 29.3             | 70.7                  |
| GA-1      | 140            | 47      | 12.5               | 27.7             | 72.3                  |
| GA-2      | 245            | 91      | 12.1               | 24.8             | 75.2                  |
| GA-5      | 92             | 38      | 11.8               | 28.3             | 71.7                  |

*1 ft = 0.3048 m
continuous variables such as porosity and water saturation. The parameter values of unsampled intervals were determined using the equations derived from data regression during SGS, and then all values were forced to satisfy the normal distribution by normal scoring.

The fundamental simulation parameters are illustrated in Figs. 13 and 14. In order to characterize the 3D distribution of these specific attributes within the Geisum oilfield, across sections were derived from these models (Figs. 13 and 14). The petrophysical model of the

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**Fig. 9** Quality control of the continuous petrophysical properties logs for effective porosity (PHIE) and water saturation (SWE); upscaled discrete log for facies (Facies-U), effective porosity (PHIE-U), and water saturation (SWE-U) in G-9 well
Brown Limestone reservoir upper zone showed high to intermediate porosity and water saturation values that generally increased in the northeast direction. The upper part of the Brown Limestone reservoir in the studied region had relatively intermediate water saturation values. In addition, the model showed relatively high values of water saturation and the values of effective porosity were decreasing in the southwest direction. These results explain the increase in effective porosity and hydrocarbon saturation in the upper zones (E and F) with slight increase in the lower zones (A and C). We deduced that the upper zones (E and F) had overall good to very good

Fig. 10  a Final adjusted faults in the fault model of the study area. Different colors indicate various faults. b 3D view of the modeled Brown Limestone horizon displaced by faults
Fig. 11  Facies proportions vs. layers of the Brown Limestone formation

Fig. 12  a Static model showing top view of the facies model of the Brown Limestone formation. b Cross section shows the facies model. The $X$ and $Y$ axes are measured in meters, whereas the $Z$-axis is measured in feet
reservoir quality (high porosity and low water saturations), especially in the intervals which have the cherty limestone facies; also, the lower zones (A and C) were of good quality reservoir. However, the zones (B and D) had poor reservoir quality (low porosity and high water saturations). Finally, according to the integrated 3D model, the most favorable sector for hydrocarbon accumulation and production through the Brown Limestone reservoir were located in the northeast sector of the South Geisum oilfield. Therefore, it is recommended that future development activities be concentrated on northeast area. Figure 15 displays the oil water contact at depth of 5300 ft TVDSS, providing a large column of oil in the Brown Limestone reservoir.
Volumetric calculations

For realistic resource estimation, volumetric calculations were employed in conjunction with geological reservoir models (Attia et al. 2015; El Khadragy et al. 2017; Radwan et al. 2022). We used the following formula to compute the volume of hydrocarbons:

\[
OOIP(\text{STB}) = 7758^a a^h\phi(1 - SW)/B_o
\]

where \( OOIP \) is original oil in place, \( a \) is study area in acres, \( h \) is net pay thickness in feet, \( \phi \) is porosity in %, \( SW \) is water saturation in % and \( B_o \) is the oil formation volume factor. The volumetric estimations of oil within the Brown Lime- stone reservoir were performed using a 3D grid-based geocellular model developed in this work (Table 2). The OOIP at the Geisum oilfield was assessed to be 17 million stock tank barrels (MSTB).

Conclusions

The present work dealt mainly with the interpretation of geological and geophysical data to evaluate the structure, lithofacies and petrophysical characters as well as the volumetric parameters of the Brown Limestone reservoir and their 3D distribution in the Geisum oilfield. The following were the main findings of this study.

- The contour lines of depth-structure contour maps showed the top and base of the Brown Limestone reservoir across the Geisum oilfield with a general deep topography to the southwest reaching maximum value of 7800 ft. However, the Brown Limestone contour lines displayed shallow topography to the northeast section of the region, which was mapped to minimum value of 3600 ft. The main faults that were delineated on the seismic sections showed Geisum Field is an elongated, NW, SE trending, SW dipping Pre-Miocene fault block. The structural style of Geisum field based on depth structural contour maps represented by SW tilted fault blocks bounded by a major normal fault with throw direction toward the northeast. The down dip side of area tilted fault blocks is bounded by major normal faults.

Table 2 Volumetric estimations of Brown Limestone reservoir

| Reservoir            | \( \text{Volume} \times 10^6 \text{ MCF}^* \) | \( \text{OOIP} \text{ MSTB}^{**} \) |
|----------------------|---------------------------------------------|----------------------------------|
|                      | Bulk volume | Pore volume                           |                                  |
| Brown Limestone      | 156,497     | 176.8                                 | 17                               |

\( MCF \) million cubic feet, \( MSTB \) million stock tank barrel
\( ^* 1 \text{ ft}^3 = 0.0283 \text{ m}^3 \)
\( ^{**} 1 \text{ barrel} = 0.0158 \text{ m} \)
fault dips toward the SW direction, these normal faults trends are clysmic orientated faults (NW–SW direction), in addition to NE–SW Trend fault (cross fault). The isopach map showed that in the southwest sections, the Brown Limestone formation thickness increased and reached maximum thickness of 250 ft, and decreased in the northeast portion of the region platform reaching minimum thickness of less than 20 ft.

- The 3D facies model indicates that the Brown Limestone formation is made up mainly a cherty limestone and thin interbeds of marl, from marine sub-littoral depositional setting and plays an important role in the petroleum system of the Gulf of Suez, the Brown Limestone formation is made up vertical heterogeneity, the three dominated facies are cherty limestone, which is distributed towards the northeast and southwest of the modeled Zones (A, C, E, and F), calcareous shale and argillaceous limestone which are concentrated in the zones (B and D).

- According to the petrophysical model, the Brown Limestone had excellent reservoir characteristics and that it can store and transfer hydrocarbons. The statistical analyses showed a good range of total and effective porosity, as well as water saturation, implying that the Brown Limestone formation's reservoir quality was good. The value of water saturation ranges from 15 to 45%, where the value of effective porosity ranges from 11 to 15% for the selected potential intervals in Brown Limestone (A, C, E and F) zones.

- To better exploit the Brown Limestone reservoir, the most favorable sectors in the Brown Limestone reservoir for accumulation and production of hydrocarbons are likely at the northeast part of the studied oilfield.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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