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# Exploring carbonate reservoirs potential, north Egypt

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**Abstract:** Carbonate reservoirs contain a significant portion of the world's oil reserves. The Middle East is home to many of these reservoirs. Carbonate reservoirs can be found in a few very large oil fields, including Egypt's Zohr field, the largest conventional gas field in Egypt. In this article, we present a couple of successful tertiary carbonate reservoirs that are bearing hydrocarbon in the Egyptian Western Desert and Gulf of Suez provinces, they are distributed across Egypt's subsurface, and they are characterized by heterogeneous porosity and permeability. These heterogeneities are caused by the wide spectrum of tectonostratigraphic environments in which carbonates are deposited and by subsequent diagenetic alteration of the original rock fabric. The structural analysis of the study areas based on the interpretation of both geophysical and geological data, in JD, Abu Sennan, and the North Amer areas in the Western Desert and offshore Gulf of Suez respectively showed that tectonostratigraphic history during tertiary time affected a great extent carbonate reservoir quality. Major fault trends formed secondary fracture porosity possibly allowing hydrothermal solutions to pass through the reservoirs and form secondary vuggy porosity. These characteristics are considered important factors of promising carbonate reservoirs. In this study, several carbonate reservoirs have been outlined. The study workflow helped us better identify carbonate prospects with high fractured density.

**Key words:** carbonate reservoirs, Egypt, Western Desert, Gulf of Suez, fractures

## 1. Introduction

The development of novel techniques and concepts is the current emphasis of carbonate exploration activities, and the discovery of fresh plays in carbonate rocks is leading to a rise in oil and gas discoveries across the globe. Due to variations in pore-size distribution, pore connectivity, fracturing, and dolomitization level, carbonate reservoir quality fluctuates frequently (*Bust et al., 2009*). Due to the variability of the carbonate characteristics, fracture

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distribution, wettability effect, complex mineralogy, and digenetic evolution estimating prospective pay is challenging, particularly in exploratory locations (*Dou et al., 2011*).

Most experts estimate that between 50 and 60 percent of the world's "conventional" petroleum is stored in carbonate rocks. Many sizable carbonate reserves are anticipated to have a production lifetime of more than 50 years. Therefore, it is no wonder that the petroleum industry advocates for the advancement of research into carbonate rocks and depositional systems. The petroleum industry occasionally views carbonate oil reserves with trepidation since it can be challenging to anticipate the quality of and ensure high recovery factors from this rock family. The complex and heterogeneous nature of carbonate rock porosity, which frequently results in wide variations in permeability for any given porosity, and the structuring of carbonate successions as typically vertically heterogeneous but laterally permanent strata pose particular issues.

Techniques for evaluation that work in sandstone reservoirs can occasionally fall short in carbonate reservoirs. These variances make evaluating reservoirs and recovering hydrocarbons more difficult. However, academics are striving to find solutions to these issues because of the economic importance of oil production from carbonate reservoirs, particularly giant and supergiant sources in the Middle East. About 60% of the world's oil reserves are found in carbonate reservoirs, and there is significant potential for finding new gas deposits, notably in the Middle East.

Predicting reservoir quality at inter-well scales and in un-cored wells, identifying problematic high permeability layers, deciding how much permeability to allocate to fractures and connected vuggy systems, and populating reservoir models with representative physical parameters are all significant problems that frequently arise in the description of carbonate reservoirs.

Conventional core plugs are rarely representative of large rock volumes because porosity in carbonate rocks typically exhibits as diverse and heterogeneous. There are still significant issues with the scale compatibility of the various datasets for measured physical parameters that are used to describe carbonate reservoirs. After being discovered and exploited, many of the greatest carbonate reservoirs in the world are now displaying signs of maturity, including pore pressure support, water or gas breakthroughs, and stranded resources.

This study's ultimate goal was to examine Tertiary reservoirs in Egypt such as the JD field, Abu Sennan field, and the North Amer offshore field in the Western Desert and offshore the Gulf of Suez (Fig. 1), respectively, highlighting the productive hydrocarbon-bearing carbonates and outlining the key success variables that will influence the Tertiary Reservoirs in the Northern Western Desert of Egypt and Offshore Gulf of Suez. Through the study, an integrated formation evaluation tries to pinpoint potential pay zones using wireline and mud log data with an emphasis on identifying and analysing a geometrical seismic attribute (variance) was performed to help identify minor and major faults and fracture patterns. The study results helped to better identify carbonate prospects with high fractured density regionally in the Egyptian Western Desert and Gulf of Suez basins.

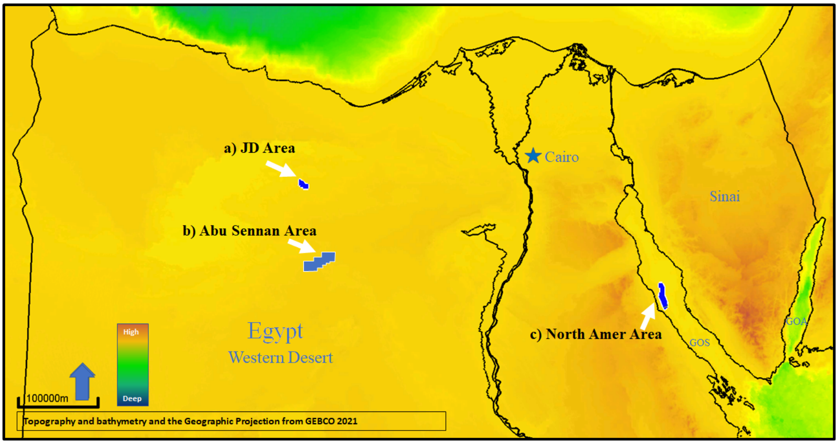


Fig. 1. Topography and bathymetry of the study areas, geographic projection from *GEBCO (2023)*.

## 2. Geological settings of Tertiary carbonates

Egypt is located in the north-eastern corner of Africa, where it is bordered by the Mediterranean Sea to the north, Libya to the west, Sudan to the south, and the Red Sea and Israel to the east. The country has a long and complex geological history, which has resulted in a diverse range of tectonic and stratigraphic units. The tectonostratigraphy of Egypt (*Hantar, 1990*) can be divided into three main stages. First, The Pre-rift stage of Egypt's tectonic history occurred during the Paleozoic and Mesozoic eras. During this time, Egypt was part of the North African craton, a stable continental mass. The craton was covered by a shallow sea, in which carbonate deposits accumulated. Secondly, the Rift stage of Egypt's tectonic history began in the Jurassic and continued into the Cretaceous era. During this time, the African plate began to rift apart, forming the Red Sea and the Gulf of Suez. The rifting caused the formation of several basins, in which thick sequences of sediments, including carbonates, were deposited. Lastly, the Post-rift stage of Egypt's tectonic history began in the Late Cretaceous and continues to the present day. During this time, the Red Sea and the Gulf of Suez continued to widen, and the Arabian Plate began to move northward. This movement led to the formation of the Alpine fold belt, which includes the mountains of the Sinai Peninsula.

The tectonostratigraphy of Egypt has had a significant impact on the distribution of carbonate deposits in the country. Carbonate deposits are found in both the pre-rift and rift stages of Egypt's tectonic history. Pre-rift carbonate deposits are found in the Paleozoic and Mesozoic eras. These deposits are typically thick and high-quality, making them ideal for hydrocarbon exploration and production. Rift carbonate deposits are found in the Jurassic and Cretaceous eras. These deposits are also typically thick and high-quality, but they can be more difficult to explore and produce hydrocarbons from due to the complex tectonic structure of the rift basins.

The tectonostratigraphy of Egypt has also had a significant impact on the hydrocarbon potential of the country. Hydrocarbon reservoirs are found in both the pre-rift and rift stages of Egypt's tectonic history. Pre-rift hydrocarbon reservoirs are typically found in sandstone and carbonate formations. These reservoirs are often large and contain significant volumes of oil and gas. Rift hydrocarbon reservoirs are found in sandstone, carbonate, and shale formations. These reservoirs can be more difficult to explore and produce hydrocarbons from due to the complex tectonic structure of the rift basins.

Several carbonate reservoirs in Egypt are currently producing hydrocarbons. Some of the most important examples include:

- Abu Gharadig field: The Abu Gharadig field is located in the Western Desert of Egypt. It is one of the largest oil fields in Egypt, and it produces oil from a pre-rift carbonate reservoir.

- North Amer Offshore field: The Alam El Yunis field is located in the Gulf of Suez. It is a giant gas field that produces gas from a rift carbonate reservoir.

The sedimentary section in Egypt ranges from the Lower Paleozoic to recent. Four major sedimentary cycles occurred with maximum Southward transgression in Carboniferous, Upper Jurassic, Middle and Late Cretaceous, Middle Miocene, and Pliocene times (*Beghoul et al., 1995*). A generalized stratigraphic column of both the Western Desert and Gulf of Suez provinces is shown in Fig. 2.

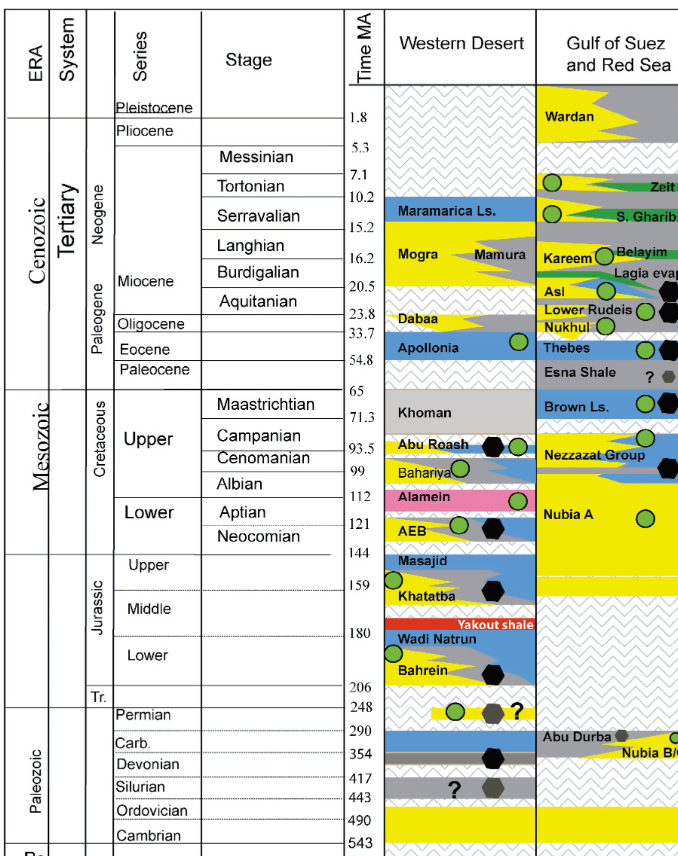


Fig. 2. Generalized stratigraphic column of the Northern Western Desert and Gulf of Suez basins (*Dolson et al., 2014*).

Carbonate tertiary reservoirs are widely distributed across the Egyptian Northern Western Desert and Offshore Gulf of Suez (Figs. 3 and 4), especially in the Eocene time, where thick carbonates are deposited in the basinal areas and thin deposits in the structural highs.

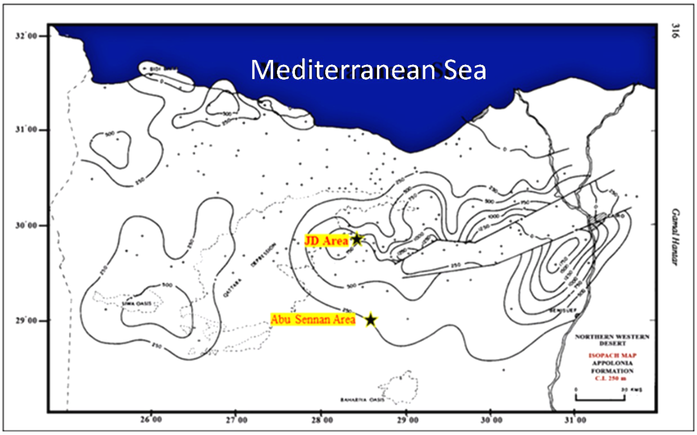


Fig. 3. Distribution and thickness of Apollonia formation (tertiary time) across Egypt (*Hantar, 1990*).

Apollonia Formation which is the Eocene equivalent Formation in the Western Desert represents a Paleocene to Middle Eocene time, which comprises white, light dark, or earthy nummulitic limestone and minor shale beds (*Hantar, 1990*). Apollonia Formation thickness and distribution are represented in Fig. 3. The type section is at the slopes south of the town of Apollonia (Libya). The type section is 250 m. in thickness and is comprised of enormous siliceous limestone with various cherty groups. Over the largest part of the North Western Desert, the Formation overlies unconformably Khoman chalk. A significant hiatus covers the whole Paleocene and some of the time the Early Eocene exists in most sections. Apollonia Formation, is especially thick in the Gindi Basin 1788 m., while it is absent over the Kattaniya High, West of the Northern Delta, Matruh, and Sidi Barani regions (*Hantar, 1990*).

For the offshore Gulf of Suez Province, Figure 4 is a thermal maturation map generated from regional geothermal gradient maps from (*Alsharhan, 2003*) and extends east and west to incorporated onshore basins, all of which have undergone some uplift and Late Tertiary erosion. This map

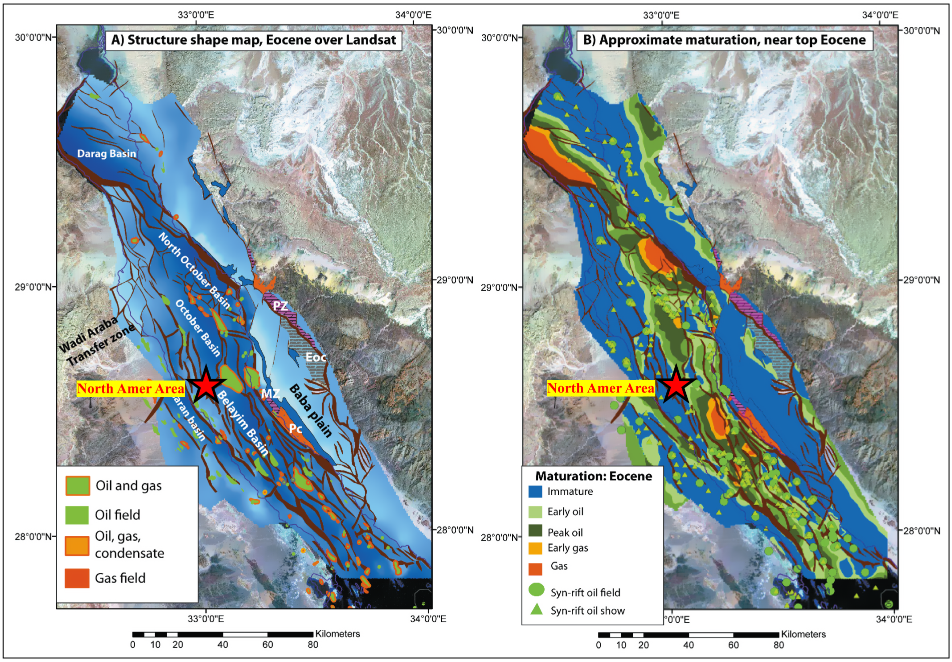


Fig. 4. Gulf of Suez Regional Eocene (tertiary time) structure. A) Thermal Maturation map overlaying the hydrocarbon fields. B) Approximate maturation near the top Eocene (modified after *Dolson et al., 2014*).

shows general trends of maturation near the top of the Eocene but is limited in quality by only regional structural grids and a general lack of many burial history wells. However, the patterns shown fit well with oil-shows data, particularly the distribution of heavier, early migration phase hydrocarbons near the edges of these kitchens. Many of the Gulf of Suez fields have a complex charging system, which is located on high blocks charged from deep grabens or lateral migration from Miocene kitchens. The kitchens themselves, however, are almost completely unexplored, and as such offer significant deep water turbidite trap potential within syn-rift strata.

## 3. Material and methods

The workflow performed in this study (Fig. 5) integrated the formation evaluation, and borehole images focusing on fracture identification, moreover, the structural mapping was performed using a combination of seismic features, including edge detection, coherence, and minimum curvature to spot fractures.

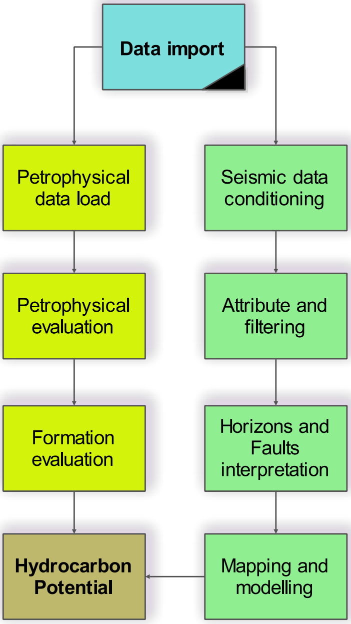


Fig. 5. The general framework of the undertaken workflow in this study.

Geological data for three wells (Well-J, Well-X, and NAO-3/5A) and multiple sets of the 3D and 2D seismic surveys covering the entire Eastern Northern-Eastern part of the Western Desert were merged by Egypt Upstream Gateway project activities and 3D seismic survey covering the North Amer Offshore field. This integration permitted a regional study that addresses the play potential and how existing fields are interconnected. The Western Desert merged volume included applying contemporary technologies in image enhancement, bandwidth extension, and data matching to the numerous legacy volumes. Leveraging the datasets' signal processing enhanced the seismic data's bandwidth and resolution. Then, merging the datasets and correctly matching the phase, amplitude, bandwidth, and reference datum during the imaging step made available a contiguous volume of seismic data for interpretation.

3D seismic attributes are very useful for locating faults and fracture zones that fall below seismic resolution. Evidence from geometrical seismic attribute (variance) in our case, is utilized to guide minor and major faults and fracture patterns, and may then be compared to the results of traditional interpretation, providing quality control on any human mistake that can come from the conventional interpretation of seismic reflectivity.

The performed workflow started with an integrated formation evaluation that aimed to identify possible promising zones based on wireline and mud logs for the sparkly distributed used wells in the basins of interest. It then moved on to integrating borehole images with a focus on fracture identification and analysis. Structural mapping was completed using a combination of seismic features, including edge detection, coherence, and minimum curvature to spot fractures.

Borehole image interpretation revealed the absence of fractures in the Apollonian reservoir in the Egyptian Western Desert and Offshore Gulf of Suez; laminated carbonate is detected from borehole images. Triple combo logs indicate the presence of the gas effect, with a large crossover between neutron and density; gas always has a low hydrogen index, resulting in low neutron porosity, and gas has a low density, resulting in low bulk density.

This work focuses on evaluating Tertiary reservoirs across Egypt highlights the successful hydrocarbon-bearing carbonates and defines the main critical success factors that will affect the tertiary reservoirs across the Egyptian Northern western desert and Offshore Gulf of Suez.

## 4. Case studies

Three case studies were selected to represent the tertiary carbonate reservoirs in Egypt in the shape of Thebes formation of Eocene time in the Western Desert (Apollonia) and the Gulf of Suez (Thebes). Tertiary reservoirs are fractured and diagenetic with some of the original rock fabric. It is highly influenced by post-depositional processes such as multiple phases of dolomitization, dissolution, cementation, compaction, and fracturing.

### 4.1. Case study 1 and 2 (Western Desert)

Hydrocarbon exploration efforts in Egypt's Western Desert have been concentrated on Cretaceous formations like the Abu Roash and Bahariya reservoirs. Recent exploration activities have focused on the Apollonia carbonate and other shallow prospects. While drilling this possible reservoir gas shows were observed. Fractures are seen to have been caused by tectonic buckling, which was created by the late cretaceous anticlinal structure, where the crest extension caused the fractures as illustrated through the seismic line from in JD Field (Fig. 6).

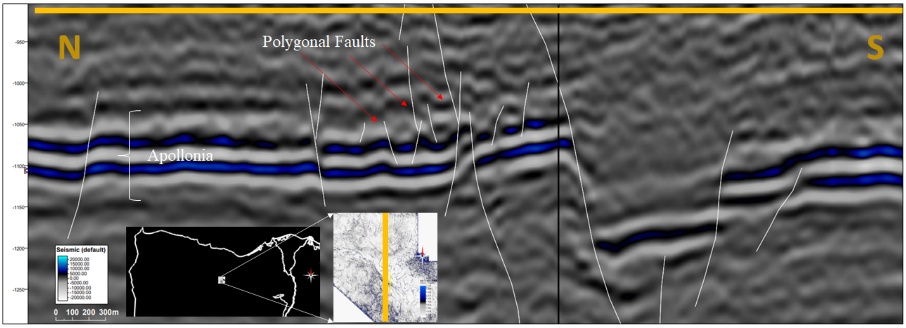


Fig. 6. Seismic line through Well-J which displays fractures and polygonal faults affecting Apollonia formation in JD Field.

Apollonia JD area is a tight gas chalk field located in the North-east Abu El Gharadig Basin in the Western Desert of Egypt (see Fig. 1). The Apollonia formation of the Paleocene-Mid Eocene age is a pelagic chalk with high porosity and low permeability. It is composed of alternative broad massive limestones with narrow marly streaks and some thinner members predominated by shales, marls, and thin limestone streaks that make up the Eocene Apollonia. Apollonia formation is overlain by Dabaa shale, which is considered to be an excellent top seal and all the wells encountered a good amount of thickness and quality of this shale. The Apollonia reservoir is one of Egypt's unconventional highly porous and low permeability gas opportunities.

The first Commercial discovery of the Apollonia formation in the JD field, tested at 4.8 mmcf/d, was in 2008 by Shell, with the first gas from vertical wells in 2012 with high porosity (15–40%), the detailed image analysis shows that the formation is highly fractured and has some secondary vuggy porosities (Fig. 7a). Apollonia has a high impedance response in the seismic data as the top unit is soft kick and Apollonia is hard to kick. The formation is highly fractured due to its stiffness and as a result, the formation becomes a good reservoir rock for hydrocarbon accumulation (Fig. 7b). The petrophysical interpretation for this well suggests the presence of low water saturation from 30% to 40% in the reservoir zone, the effective porosity from 18 to 24%, and the lithology computed as mostly limestone with the absence of dolomite.

Seismic attributes play an important role in hydrocarbon exploration and production because they bring additional information about the litho-

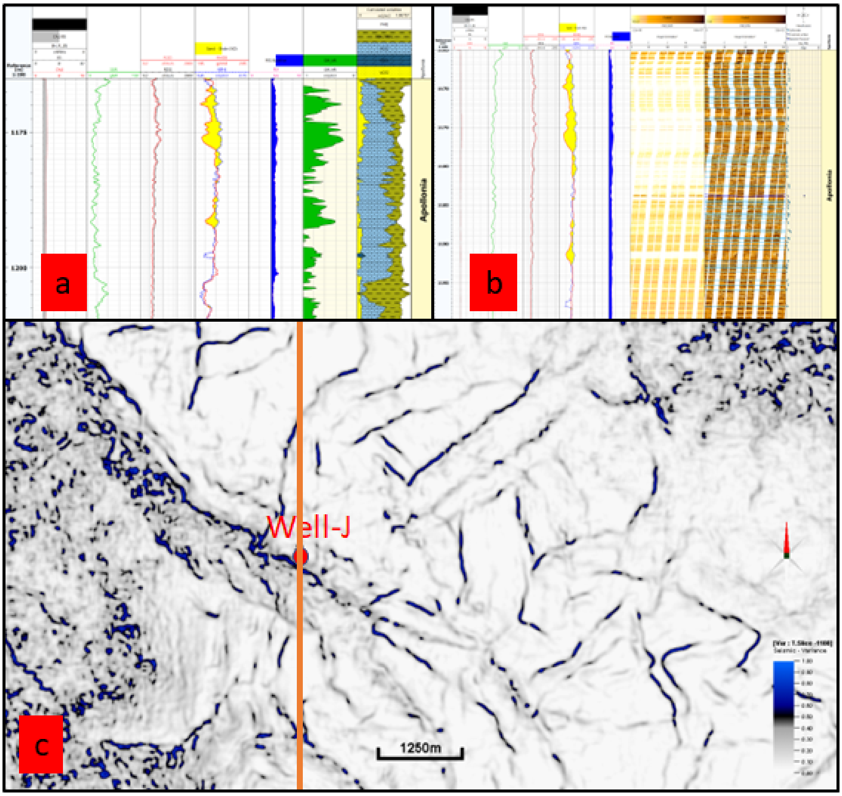


Fig. 7. (a) Well-J is an example of the Apollonia reservoir, a Petrophysical interpretation layout with triple combo tracks, photoelectric factor, water saturation, and lithology. (b) Detailed fracture analysis for the example well, well logging layout showing triple combo logs with processed borehole images (static and dynamic image). The last track is a tadpole track with a true dip of a formation. (c) Variance map on the top of Apollonia formation in JD field showing the polygonal faults and minor fractures affecting Apollonia reservoir.

logical and petrophysical changes in the subsurface along the main seismic reflectors. Borehole images are commonly used to evaluate carbonates, particularly for qualitative and quantitative studies of fractured and vuggy carbonate. Detailed seismic attribute analysis was conducted on the top Apollonia, especially variance attributes which showed good results for detecting the fracture network in the faulted areas (Fig. 6c).

The Late Cretaceous compressional forces that affected North Egypt formed a series of structural highs (Figs. 8a and 8b, from the Abu Sannan field). These structures rejuvenated in the Eocene time and the Apollonia

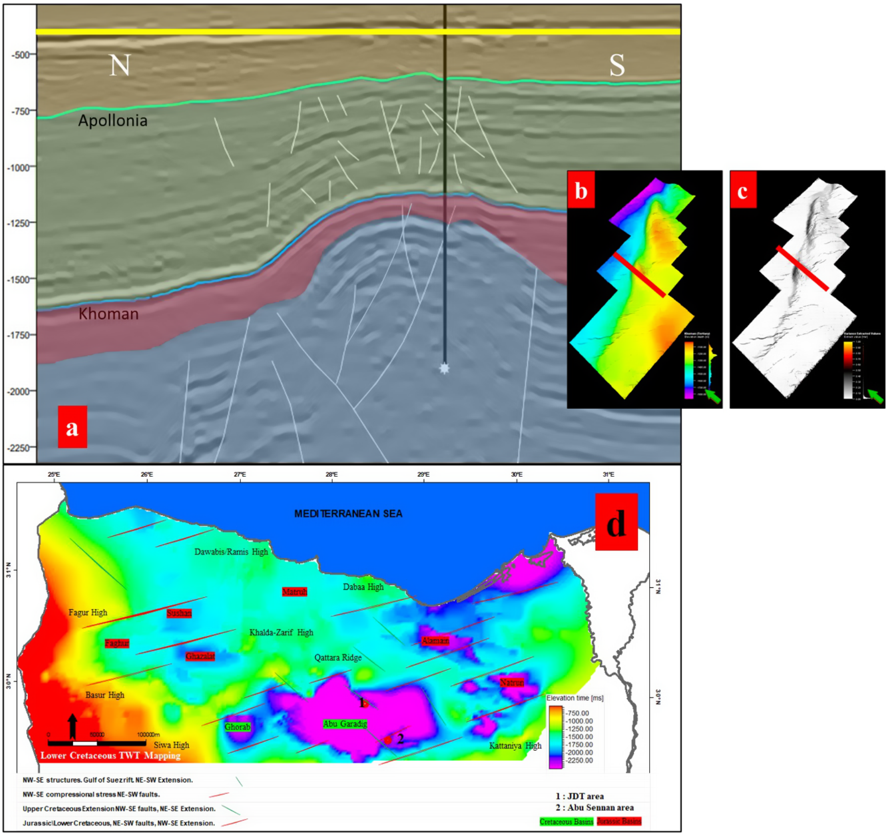


Fig. 8. (a) N–S Seismic line through the inverted structure in the Abu Sannan area passing through the Well-X. (b) and (c) structural subsurface mapping for Upper Cretaceous in SWS (d) Lower Cretaceous Mapping across the western desert.

was dramatically affected by them; the carbonates became thinner in the crestal areas and fracture intensity increased subsequently.

### 4.2. Case study-3 (Gulf of Suez)

The Gulf of Suez Basin is Egypt's oldest and most productive province. It encompasses more than 80 fields producing oil from Precambrian to Tertiary reservoirs. The case study area posted in Figure 1 is located in the central part of the gulf. The Gulf of Suez formed during Oligo-Miocene rifting and represents a northern extension of the Red Sea rift (*Purser and Philobbos, 1993; Purser et al., 1990*) because of the divergence between the African plate and the Arabian plate, which led to forming a series of extensional faults trending NW–SE to NNW–SSE.

The lithostratigraphy of The Gulf of Suez Basin starts with the clastics of the Nubia Formation, which are overlain by the Matulla, Duwi, and Sudr formations. These units are topped by the Esna Shale Formation (Palaeocene) and then the Thebes Formation (Eocene, case study). The Miocene stratigraphy comprises Nukhul, Rudeis, Kareem, Belayim, South Gharib, and Zeit formations from base to top (see Fig. 2).

The case study reservoir is Thebes formation of the Eocene age, it is composed mainly of cherty limestone, and deposited in a shallow marine environment. Thebes formation is highly affected by the gulf rifting and is widely distributed across the gulf (Fig. 4a). According to the maturity map (Fig. 4b), the Thebes formation is mainly oil-prone to some gas generation in the depocenter areas. The present work aims to perform a geophysical assessment using well-log and seismic data of the limestone of the Thebes Formation in the North Amer field that is located in the West-Central part of the Gulf of Suez. It is about 2 km offshore from the Western coast of the Gulf of Suez. It occupies the up-dip portions of large NW tilted fault blocks which are bounded from the West direction by a major fault that has a great throw towards the SW. The field belongs to the central half-graben of the Suez Rift, which is characterized by the NE direction of the dip.

Based on the available wells in North Amer Field, the Eocene Thebes Formation is mainly composed of limestones. The limestone of the Thebes Formation was deposited during the Tethyan major transgression over the northeast of Africa in the Eocene times. This limestone characterizes a potential source rock with TOC equal to 3.2% of type I/ II kerogens; however, the generated hydrocarbon has low API gravity, high sulfur content, and high hydrogen index and low oxygen index values (*Alsharhan, 2003*). The fractured limestones of the Thebes Formation provide around 1.1% of oil production in the Gulf of Suez Basin with 13% average porosity, and net pay thickness varies between 15 and 17 m (Fig. 9a). The study area is highly affected by rift faults which are oriented NW/SE direction, and the Thebes formation has an intensive fracture and vuggy porosities (Fig. 9b).

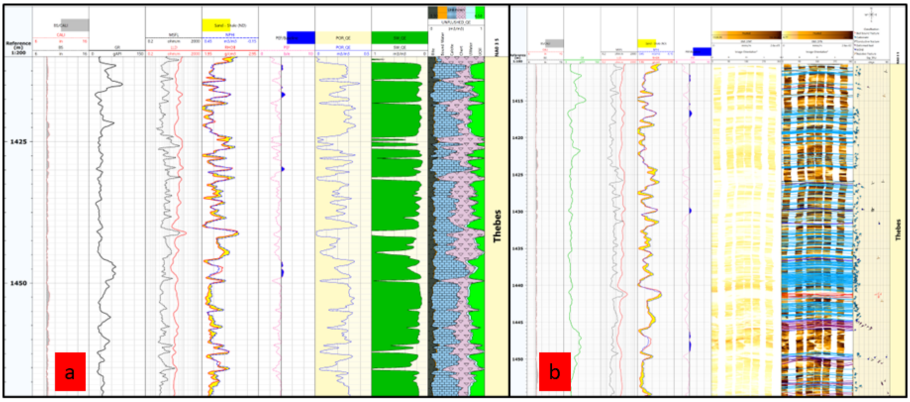


Fig. 9. (a) Composite log of NAO 3/5 well through the Thebes formation, Petrophysical Interpretation layout with mineral modeling results include effective porosity, water saturation, and lithology tracks. (b) Image interpretation of NAO 3/5 well through the Thebes formation, well logging layout showing triple combo logs with processed borehole images (static and dynamic image). The last track is the tadpole track with a true dip of a formation.

The petrophysical interpretation of NAO 3-5 was challenging due to the presence of the huge amount of chert bands, these chert bands are always filled with silica which could have a great effect on grain density, so mineral modelling was used for petrophysical evaluation of Thebes limestone. This mineral modelling is based on optimizing simultaneous equations described by one or more interpretation models. The different lithologies which were used in mineral modelling are calcite, chert, and clay. High effective porosity and low water saturation were detected at the top of Thebes associated with the presence of fracture with oil and gas shows suggesting a very good potential zone at the top of Thebes reservoir.

As a result, the fracture density increases beside the main faults and decreases away from these faults. The well NAO 3/5 was drilled beside one of the rift faults and heated many fracture sets as shown in (Figs. 10a and 10b), enhancing the reservoir porosities.

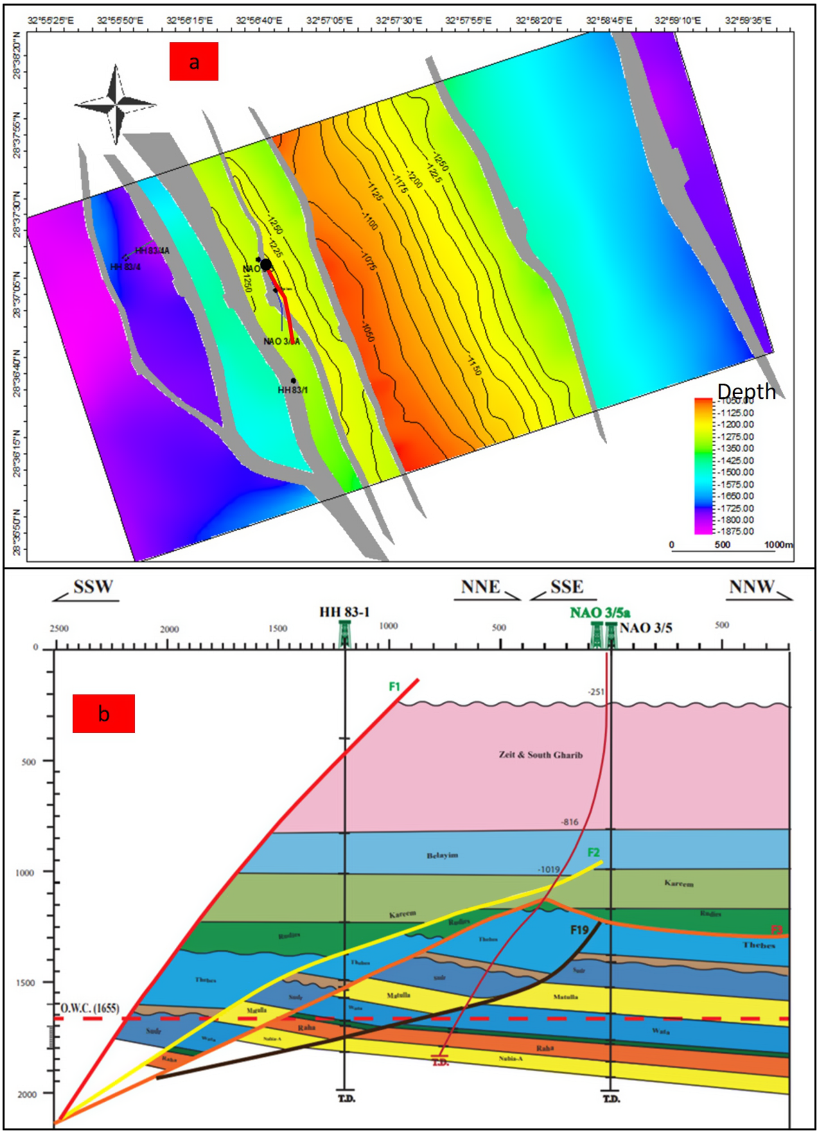


Fig. 10. (a) Depth structure map on top of Thebes. (b) Geological cross-section passing through HH and NAO wells in the study area.

## 5. Discussion

Our study of Tertiary/Carbonate reservoirs in the Egyptian basins (Northern Egyptian Western Desert) meets *Osman et al. (2022)* and *Burchette (2012)* conclusions about the Carbonate reservoirs. Carbonate reservoirs near fractured zones have high hydrocarbon potential. Fractures can significantly increase the permeability and porosity of carbonate rocks, providing pathways for hydrocarbon migration and accumulation. Additionally, fractures can create secondary porosity and storage space for hydrocarbons.

Fractured carbonate reservoirs can be found in a variety of geological settings, including faulted and folded regions, rift basins, and carbonate platforms. Some of the world's largest and most prolific oil and gas fields are fractured carbonate reservoirs, such as the Ghawar field in Saudi Arabia and the Permian Basin in the United States.

In the Egyptian Western Desert, carbonate reservoirs are productive in several fields from the Tertiary reservoirs, and they are thought to play a significant role in hydrocarbon production such as JD and Abu Sennan oil fields. The North Amer offshore oil field in the Gulf of Suez includes a producing carbonate reservoir.

It is important to note that the hydrocarbon potential of any reservoir will vary depending on several factors, such as the reservoir quality, the presence of hydrocarbons, and the trapping mechanisms. However, the carbonate reservoirs near the fractured zones in the Egyptian Western Desert and the North Amer offshore oil field are generally considered to have high hydrocarbon potential.

## 6. Conclusions and recommendations

The tectonostratigraphy of Egypt has had a significant impact on the distribution of carbonate deposits and hydrocarbon reservoirs in the country. Carbonate deposits are found in both the pre-rift and rift stages of Egypt's tectonic history. Hydrocarbon reservoirs are also found in both the pre-rift and rift stages of Egypt's tectonic history.

Some of the most important carbonate reservoirs in Egypt include the Abu Gharadig field and the North Amer Offshore field. These reservoirs are currently producing significant volumes of oil and gas.

Egypt has a significant potential for further hydrocarbon exploration and production, particularly in the rift basins. The country's government is encouraging investment in the oil and gas sector, and several international companies are currently exploring hydrocarbons in Egypt.

The integrated methodology described in this work offered vital information on the Tertiary reservoir's quality and prospectivity across Egypt, which could be summarized as follows:

- Due to the late stage of dolomitization which destroyed matrix intercrystalline porosity in the Tertiary reservoirs, it was important to find wells with significant secondary porosities reflected by fractures and vugs.
- The well-logging method for predicting fractures and vugs corresponds well to fractures and vugs detected in borehole images. This method may be used as a substitute choice to discover the highest potential wells by defining the fractures and vugs for each well.
- The Variance attribute was found to match the porosity types seen in the well-logging technique and borehole images. As a consequence, it was used to identify high fracture areas and those with touching vugs.
- It is highly recommended to acquire more core data in the studied wells, especially the Tertiary reservoirs, also it is recommended to drill identified prospects for future production of oil in the study area.

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