Western Desert Petroleum System: New Exploration Opportunities and Challenges

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Abstract

The Western Desert province is one of Egypt's most productive hydrocarbon provinces, ranking second in terms of oil production after the Gulf of Suez province and second in terms of gas and condensate production after the Nile Delta. Over the last few decades, many discoveries and thousands of wells have been drilled to explore hydrocarbons in the organic-rich sedimentary basins of the Western Desert. This chapter aims to provide comprehensive studies on the Western Desert's total petroleum system, as well as the tectono-stratigraphic history control on petroleum system development across the basins. The dominant source rocks, conventional reservoirs, unconventional reservoirs, seals, and petroleum traps have all been thoroughly discussed in this chapter. This chapter also includes the major Western Desert sedimentary basins and their petroleum systems in detail. Furthermore, this chapter introduces new exploration opportunities as a means of achieving successful exploration and the discovery of new resources, such as stratigraphic traps, deeper targets, inversion structures and faulted traps, sequence stratigraphy application, and unconventional resources. Finally, the chapter discusses the challenges that could affect hydrocarbon exploration in the Western Desert, such as drilling, petroleum systems, and seismic imaging, as well as some mitigations.

Keywords

Western desert • Petroleum system • Unconventional resources • Conventional resources • Source rocks • Petroleum traps

1 Introduction

Understanding the petroleum system of hydrocarbon reservoirs in sedimentary basins is a critical factor in evaluating and simulating hydrocarbon reservoirs for better exploitation and development (Radwan et al., 2021a). Global energy consumption has increased significantly in the last few decades as a result of significant technological advancements and rising living standards. Thus, ongoing research developments in the energy sector aim to improve subsurface resource exploitation by increasing production (Radwan, 2022; Radwan et al., 2022). This can be accomplished by accurately modeling the characteristics of the petroleum system in subsurface basins in order to improve production efficiency and resource recovery (Radwan et al., 2021a). Furthermore, a better understanding of the petroleum system elements will lead to more discoveries and shed light on unconventional reservoirs, which will impact countries' economies and raise people's living standards. Northeast Africa sedimentary basins have been distinguished by their organic richness and multi-hydrocarbon-bearing reservoirs, including the Western Desert (WD), Nile delta, Gulf of Suez and Mediterranean sedimentary basins of Egypt. Intraplate rift basins, according to Guiraud et al. (2005) and Radwan et al. (2021a), are the most prolific hydrocarbon-bearing places in Northeast Africa. The Egyptian economy is heavily reliant on petroleum energy, and governments are focusing on attracting foreign and domestic companies to invest in Egyptian petroliferous basins. Egyptian oil and natural gas production is constantly expanding as a result of ongoing exploration and investment activities. According to BP's 2019 statistical report, Egyptian oil proved reserves reached 3.1 BBL in 2019, and natural gas proved reserves exceeded 75.5 TCF (Fig. 1). The daily production of oil, natural gas, and condensate is increasing year after year as a result of new discoveries in the three major petroleum provinces, which include WD, the Nile Delta, and the Gulf of Suez (Fig. 1).

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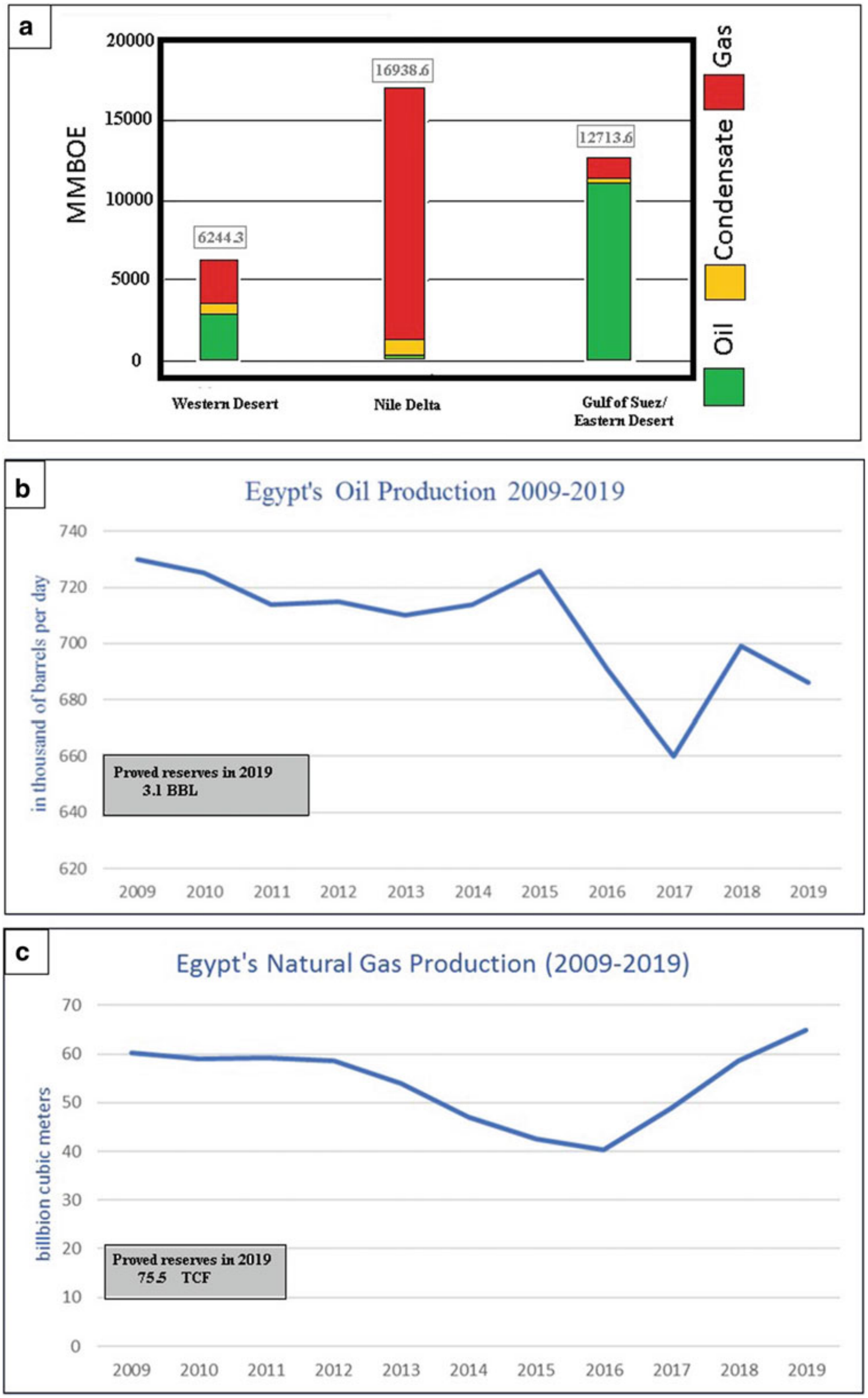

Fig. 1 Petroleum production sketch for Egyptian petroleum provinces, **a** summary of the discovered volume of fluids in Egyptian petroleum main provinces, updated to 2017 (Dolson, 2020); **b** Egypt's oil production from 2009 to 2019, with proven oil reserves until 2019; **c** Egypt's natural gas production from 2009 to 2019, with proven oil reserves through 2019 (BP Statistical Review of World Energy 2020)

The WD is Egypt's second most important petroliferous province in terms of oil, gas, and condensate production (Fig. 1). Over geological time, the WD sedimentary successions formed during complex tectonic regimes such as rifting, inversion, and deformation phases. The WD sedimentary succession is rich in reservoir intervals and organic-rich source rocks (e.g., Dolson et al., 2001a, 2001b; Katz, 1995; Leeder & Gawthorpe, 1987; Scherer et al., 2007). Rifting in WD begins in the Late Triassic, but the main rifting phase is mostly associated with the Middle Jurassic (Dolson et al., 2001a, 2001b; Garfunkel, 2004; Guiraud et al., 2005). These basins are formed by a southwestward thickening Paleozoic strata overlying the crystalline basement complex, which is followed by a northward thickening Mesozoic-Neogene sedimentary pile (Said, 1990; EGPC 1992). The north WD rift basins were formed during the Early Mesozoic continental breakup phase, following the opening of the Neo-Tethys Ocean (Bosworth et al., 2008; Garfunkel, 1998, 2004; Tassy et al., 2015). Throughout the Mesozoic, the WD coastal rift basins remained a broad shelf region near sea level.

They witnessed various transitions between continental and marine deposition, so facies changes are regular (Moretti et al., 2010; Said, 1990; Sultan & Halim, 1988). The North WD of Egypt (greater Western Desert basins) is a crucial component of Northern Africa's unstable shelf (Fig. 2). The North WD of Egypt has been subjected to various tectonic regimes since the Paleozoic Era, allowing the formation of multiple basins, sub-basins, ridges, platforms, and troughs. Most significant hydrocarbon accumulations have been encountered in Mesozoic rift basins of the WD. More than 3 (bnboe) were produced from the WD's overall reservoirs, with the Cretaceous and Jurassic reservoirs contributing significantly (IHS and WoodMac, online source). According to Dolson (2020), the estimated reserves of the WD as high as 5.6 billion barrels of oil equivalent (BBOE) recoverable to date, with additional reserves yet to be discovered that could reach 7 BBOE. This chapter will focus on the following: (1) the WD petroleum system, (2) the tectono-stratigraphic history control on petroleum system development, (3) exploration history of the WD hydrocarbons, (4) WD sedimentary basins and their petroleum system, (5) the development of innovative opportunities as a means of achieving successful exploration and the discovery of new resources, (6) challenges that could affect the hydrocarbon exploration in the WD.

2 General Lithostratigraphy of the Western Desert

The WD lithostratigraphy contains a variety of lithologies ranging from the Cambrian to more recent deposits that have been influenced by numerous tectonic events which have formed its current sedimentary succession (Fig. 3). The WD's sedimentary succession was influenced by transgressive/regressive cycles that constrained its evolution. The Paleozoic succession in WD is characterized by coarse and fine clastics, as well as minor carbonate rocks that overlie the basement rocks (Fig. 3). Four major regressive cycles distinguished the WD sedimentary succession, each terminated by a marine transgression (Sultan & Halim, 1988). The Middle to Late Jurassic non-marine clastics (Ras Qattara formation) represent the earliest cycle, and the deposition continued by the marine deposits of the Khatatba formation. The earliest cycle was ended by the maximum transgression surface represented by the Late Callovian carbonates of the Masajid formation. The post-Paleozoic sedimentary succession consists of alternating clastic and carbonate strata from four major depositional cycles: The Jurassic, Lower Cretaceous, Upper Cretaceous, and Paleogene (Fig. 3; Sultan & Halim, 1988). The syn-rift sediments originate from the Jurassic and Lower Cretaceous cycles, whereas the post-rift strata belong to the Upper Cretaceous and Paleogene (Said, 1990; Sultan & Halim, 1988). The Lower Jurassic fluvio-lacustrine siliciclastics of the Yakout and Ras Qattara formations overlie the Paleozoic sandstones unconformably in the Jurassic cycle (Said, 1990; EGPC, 1992. The Middle Jurassic sediments comprise the Khatatba formation's coastal and shallow marine strata, which are followed by the Masajid formation's marine carbonate that represents the maximum extent of the Jurassic transgressive phase (Sultan & Halim, 1988; El Hawat, 1997).

The second cycle started during the Early Cretaceous and was separated by an unconformity surface that separated the carbonates mentioned above from the marine clastics of the Alam El Bueib (AEB) formation, Dahab shale, and Alamein dolomite (Moretti et al., 2010). The sediments of the second cycle lie unconformably on the Masajid carbonates, and began with the shallow marine siliciclastics and carbonates of AEB formation and ended by the Dahab shale deposition.

The third sedimentary cycle spanned the Middle Albian to Paleogene epochs. The post-rift Upper Cretaceous cycle is characterized by continental to coastal siliciclastic facies at the base (Kharita and Bahariya formations) changing upward into marine carbonates (Abu Roash and Khoman formations) (Fig. 3). The fourth cycle is composed of marine clastics, such as the Apollonia, Dabaa, and Moghra formations, which are capped by the flat-lying Marmarica limestone (El-Din et al., 2001). The Upper Cretaceous cycle is terminated by a major unconformity that marks the base of the Paleogene sediments of the fourth cycle, which are dominated by marine carbonate at the base (Apollonia formation), followed by marine siliciclastics of the Dabaa and Moghra formations (Sultan & Halim, 1988; EGPC, 1992).

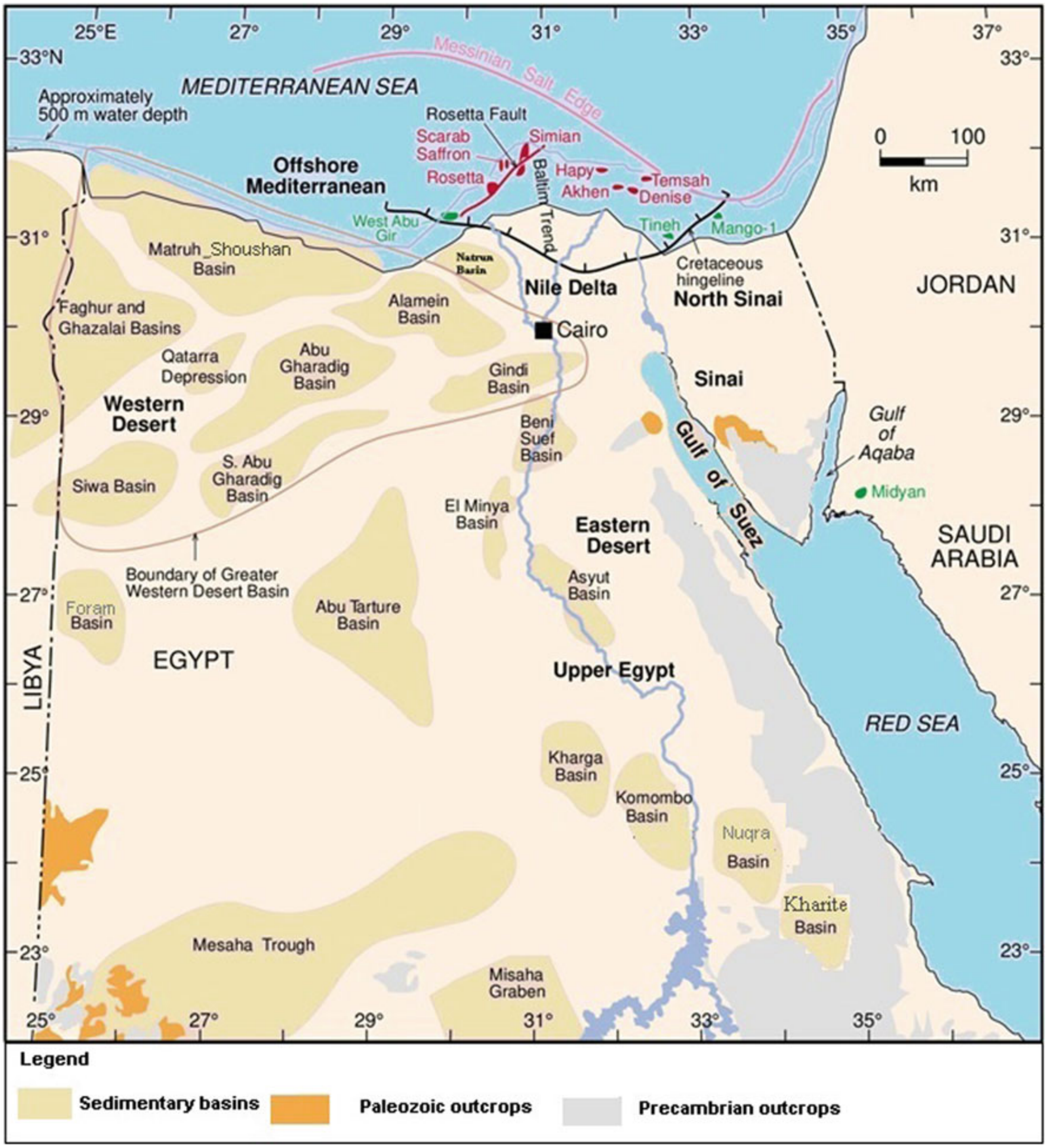

Fig. 2 Location map displays the main sedimentary basins of the WD, the basement rocks distribution and Paleozoic outcrops across Egypt (modified after Dolson et al., 2001a, 2001b)

3 Exploration History

Exploration efforts in the WD began in 1954, several decades after the exploration in the Gulf of Suez. The Sahara Petroleum Company conducted the exploration trial after signing an agreement with the Egyptian government at this time. The aforementioned company conducted geological and geophysical studies for four years, until 1958, and they also used aerial photography and surface mapping in their research. Later, in 1963, two foreign oil companies were awarded exploration contracts: one (Phillips Petroleum) was given rights to explore areas north of latitude 30°N, and the other (Amoco) was given rights to explore areas east of longitude 27°E and south of latitude 30°N. Both companies have used aeromagnetic surveys in their ongoing efforts for ten years.

Phillips Petroleum Company conducted geophysical studies in 1966, on the Alamein field using 2D seismic profiles, which resulted in the identification of an anticline related to the Late Cretaceous inversion structure. Subsequently, this petroleum company has drilled Alamein-1X exploratory well which is considered the first producing well in the WD. The

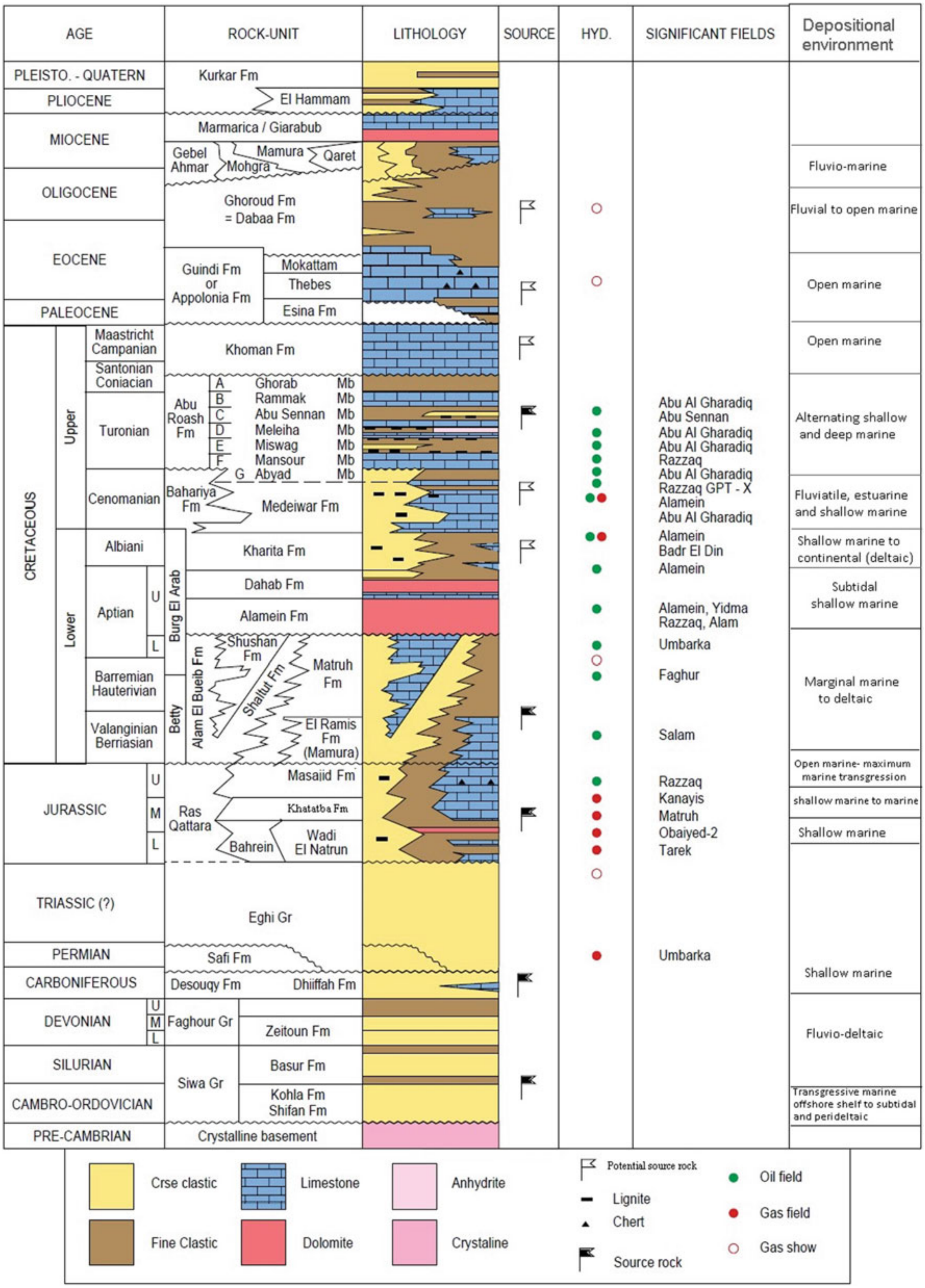

Fig. 3 General Lithostratigraphic column of the Western Desert display the dominant source rocks, reservoirs, and reservoir production in the significant fields from the Western Desert (modified from Schlumberger, 1984, 1995; EGPC, 1992)

initial oil production of Alamein-1× was approximately 8000 barrels of oil per day (BOPD), with a very good quality of 34.5°API gravity oil. The Aptian reservoir's dolomitic limestone exhibits very good petrophysical characteristics, with permeability ranging from 30 to 2250 md and fracture and vugs dominating as secondary porosity.

The Alamein discovery brought attention to the WD's petroleum potential, and several petroleum companies conducted additional studies and drilled exploratory wells to maximize production. Egyptian companies have been conducting exploration trials in WD since 1969 when the General Petroleum Company (GPC) began exploration activities in the Siwa area. The gigantic Abu Gharadig field was discovered in 1969 by the Amoco Petroleum Company, one of the most important hydrocarbon finds in Egypt. Following the exploration of the Abu Gharadig field, many large to small fields were discovered within the WD sedimentary basins providing rewarding discoveries, particularly the northern greater WD basins (Table 1).

The ongoing exploration activities in the WD were continued, and various companies were involved in the exploration activities; by 1985, approximately 20 fields had been discovered in the WD. In 1985, Phoenix Petroleum used the most advanced seismic techniques available at the time to explore previously unexplored areas, and they discovered oil and gas in the Jurassic sediments of the Salam field. Many exploration wells have been drilled across the WD basins in recent decades, with a focus on numerous localized "highs" within these rift basins, providing a variety of reservoir possibilities to date. The majority of petroleum fields have been discovered in Mesozoic basins that formed after the Permo-Triassic rifting of Neotethys. The estimated ultimate recovery (EUR) of some significant hydrocarbon fields in the WD is summarized in (Table 2).

4 Tectono-Stratigraphic History Control on Petroleum System

The geological framework of Egyptian lands has been dominated by major events (see Fig. 4). As a result, these episodes have influenced the hydrocarbon potentiality of each basin in

Table 1 Giant fields and significant discoveries examples located in the WD display the hydrocarbon type, exploratory well name, year, and reservoir ages

Fields	Discovery well name, year	Age	Hydrocarbon types	References
Abu Gharadig	Abu Gharadig-1,1969	Cretaceous	Oil and gas	Hegazy (1992)
Khaleda	Khaleda-1, 1971	Cretaceous	Oil and gas	Hegazy (1992)
Bed-2	Bed2-1, 1982	Cretaceous	Oil and gas	Hegazy (1992)
Bed-3	Bed3-1, 1987	Cretaceous	Oil and gas	Hegazy (1992)
Kanayes	Kanayes-5,1992	Jurassic	Oil and gas	IHS Energy Group (2006)
Obayeid	Obayeid-3, 1993	Jurassic	Oi and gas	IHS Energy Group (2006)
Qarun	El Sagha-3x,1995	Lower Cretaceous	Oil	Dolson et al. (2001a, 2021b)
Shams	Shams-2x, 1997	Jurassic	Oil and gas	IHS Energy Group (2006)

Table 2 Estimated ultimate recovery of significant fields that located in the WD display the operator company, EUR, year, and hydrocarbons field names. MMBOE is million barrels of oil equivalent

Fields	Company	Estimated ultimate recovery (EUR)	Year
Alamein	Phillips Petroleum Company	82 MMBOE	1966
Abu Gharadig	Pan American Oil Company/Amoco	320 MMBOE	1969
Meleiha	Wepco/Agiba	77 MMBOE	1972
Badr el Din complex (3 fields)	Shell Winning N.V	510 MMBOE	1982/83
GPAA	General Petroleum Company	190 MMBOE	1985
Obaiyed 1	Shell Egypt N.V	155 MMBOE	1992
Obaiyed 2	Shell Egypt N.V	270 MMBOE	1992
Qarun	Phoenix Resources Company	72 MMBOE	1994
Qasr	Khalda Petroleum Company/Apache	700 MMBOE	2003

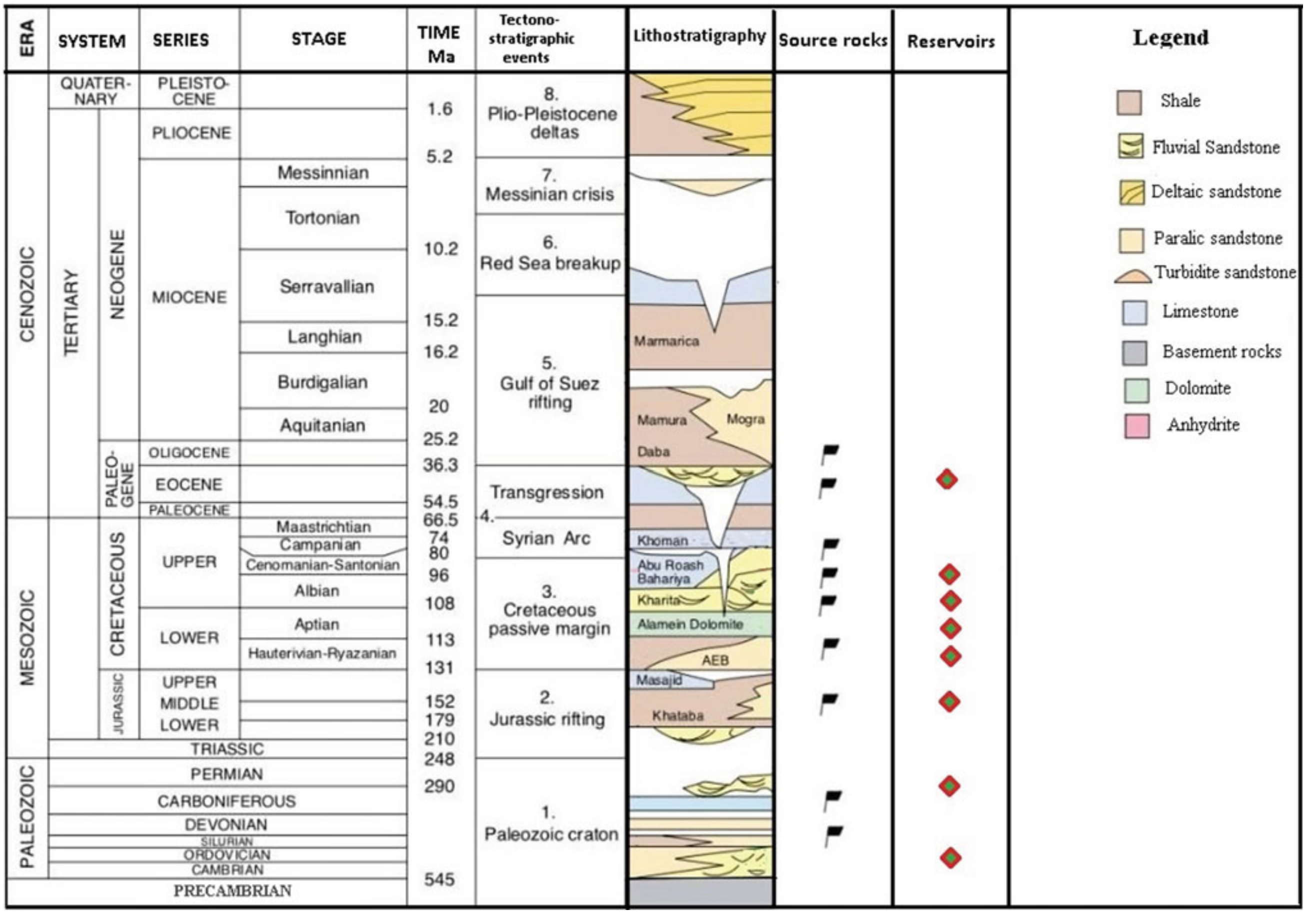

Fig. 4 General Tectonostratigraphic events of the Western Desert display the dominant source rocks, reservoirs (modified from Schlumberger, 1984; EGPC, 1992)

Egypt, where petroleum system elements were developed in relation to these tectno-stratigraphic frameworks.

4.1 Paleozoic Craton

During the Paleozoic Craton event, the WD was composed of a low relief alluvial plan dipping *N* along the (proto-Mediterranean) and *W* toward (cratonic sags, Libya), and it was dominated by shallow marine facies of carbonates and clastics in the north (Dolson et al., 1999). The southern area of the WD, on the other hand, was dominated by fluvial-alluvial lithofacies composed primarily of glauconitic sandstones and red shales. Furthermore, Silurian-age black shales were deposited in the WD, equivalent to an important source facies (Tenzuft Shales) in Libya (Dolson et al., 1999; Farooqui et al., 2012; Hegazy, 1992). The Paleozoic's main source rocks are organic-rich Carboniferous and Silurian deposits; however, the Paleozoic petroleum system is not fully understood. The maximum thickness of Paleozoic strata in the WD is 2500 m in the Siwa area, with a general thickness increase trend toward the north. Strong erosion events and onlap around pre-existing basement have affected the Paleozoic strata throughout Egypt during the Triassic and Jurassic rift, resulting in the absence of these strata along large areas of Egypt. Paleozoic sediments received little attention prior to the 2000s, in comparison to other Mesozoic facies. However, new Paleozoic discoveries (mainly Carboniferous) have drawn attention to Paleozoic deposits.

4.2 Jurassic Rifting

During Late Triassic through the Jurassic, several rift basins occurred across North Africa. These rift basins were formed during the Pangea breakup, which controlled the opening of the Neotethys (Dolson et al., 1999; Garfunkel, 2004; Stampfli et al., 2001). The Mesozoic rift basins affected the North WD areas, (e.g., Matruh-Shoushan, and Natrun) (Fig. 2). The Mesozoic rift basins of Northern WD are synchronous with other rift basins in Sinai-Levant, Algeria, and Libya forming a regional system that surrounds the Nubian Craton (Bosworth, 1994; Dolson et al., 1999; Guiraud et al., 2005; Morris & Tarling, 1996). On the other hand, three rift basins have been reported in the Southern WD, namely the Komombo, Nuqra, and Kharit basins, in addition to other basins below the greater WD sedimentary basins (Fig. 2), but these basins do not appear to be linked to the larger WD basins (Dolson et al., 1999).

Prosser (1993) discusses the Jurassic strata sedimentary record as a typical example of three-phase rifting development. Non-marine and shallow marine sediments were developed at Late Triassic and Early Jurassic, which thinned southward. More carbonate and marine shale were formed north of the Tethyan margin, while sandstones and red shales were noticed south of the Tethyan margin (Dolson et al., 1999). During this time, the organic-rich deposits of the Khatatba formation formed by onlapping on paleostructural highs from the early rifting phase. Later, by the Middle Jurassic, fault blocks had fully developed, resulting in the deposition of deep marine facies of the Masajid formation.

The most well-preserved syn-rift deposition occurred during the Middle Jurassic (Bathonian-Callovian) and was subsequently culminated during the period of the Early Cretaceous (Bosworth, 1994). As a result, the Middle Jurassic Khatatba formation sediments provide a complete stratigraphic record and are mostly home to highly productive hydrocarbon exploration targets (e.g., Keeley et al., 1990; Alsharhan & Abd El-Gawad, 2008; Shalaby et al., 2011). Masajid formation is considered as carbonate-prone with some local black marine shales, while Khatatba formation is dominated by marine shale and grading into carbonaceous shales and coal toward the south. Both Masajid and Khatatba formed proven source rocks within the WD petroleum system. These rift basins host the most significant hydrocarbon fields of the WD province (e.g., Alamein, Safir, Abu Sennan, Meleiha, Badr El-Din, Aghar, Razzak, Khalda, Qarun, Um Barka, Salam, and Tut).

4.3 Cretaceous Passive Margin

Eraly Cretaceous time has witnessed the development of mixed silisiclastic and carbonate systems across North Africa in response to thermal events associated with wide passive margin development (Dolson et al., 1999). During this period, the AEB formation was deposited overlying the Masajid formation, but some local unconformities were recorded and distinguished by lignite and carbonaceous shale prior to the deposition of this formation. According to Dolson et al. (1999), these deposits could indicate a local continuation of rift episodes during the Early Cretaceous. Extensional faulting have perhaps proceeded during the Early Cretaceous, and multiple unconformities were created locally as a result of horst block erosion. The AEB formation is characterized by mixed sandstone, shales, and carbonate, indicating sea level oscillations during deposition, and it is similar to the Nubia formation. The marine carbonate of AEB formation is organically rich and proven source rock. The aforementioned formation is overlain by a dolomite facies known as the Alamein Dolomite, which dates from the Aptian period and reflects sea level rise, implying regional level oscillations during this era. Aptian age transgression was discovered in the Komombo basin (Fig. 3), indicating that it influenced southern Egypt. According to Dolson et al. (1999), the Aptian age transgression is used as a useful flooding surface marker horizon by many authors throughout the WD. Thermal subsidence has been accompanied by continued southward transgressions, which regulate the deposition of significant widespread source and reservoir rocks (Kharita and Bahariya formations). The aforementioned sediments are synchronous to the Nubia (fluvial) and Raha (shallow marine) formations in the Gulf of Suez, and they are dominated by a mixture of sandstones, shales, siltstones, and carbonates.

4.4 Syrian Arc Deformation and Foreland Transgression

The Tethys closure between the African and European plates has formed a series of northeast-southwest trending folds that occurred during the Cenomanian to Turonian periods. These cretaceous folds have affected the entire area from Syria to the northern part of the WD (Moustafa & Khalil, 1990). The aforementioned folds, known as the "Syrian Arc," have caused regional uplift in many areas, resulting in some rift basin inversion across the Northern WD (Ayyad & Darwish, 1996; Guiraud & Bosworth, 1997; Shahar, 1994). According to structural deformation events on these evolving highs, unconformities developed throughout the inverted structural crests.

The Syrian Arc continued through Turonian to Santonian, where carbonates of the Abu Roash formation were deposited on the flanks of inverted structural crests. The Abu Roash carbonate facies deposits exhibit cyclicity and they are important productive traps of the WD petroleum system, that influenced by the Syrian Arc related structural trends (ceased by Early Campanian). As a result of the subduction of the African and European plates, wide foreland has developed in the Northern WD beginning in the Cenomanian (Dolson et al., 1999). According to Haq et al. (1988), the early Campanian witness significant sea level rise, which resulted in the deposition of source-rich carbonate and shales deposits of the Khoman formation in the WD and their equivalent in the Gulf of Suez (Brown Limestone). Moreover, the Campanian-Maastrichtian important sediments have not been affected by Cenozoic Era uplift and erosion. The Paleocene and Eocene periods are distinguished by continued transgression, which formed widespread shales and carbonates across Egypt including the WD, each with its different name. The Paleocene–Eocene sediments are considered top seals of the Cretaceous underlying reservoir, and they control the faults and folds structural geometries in some ways.

Other tectono-stratigraphic events have affected the sedimentary basins of Egypt of the Gulf of Suez, Nile Delta, and Mediterranean provinces, but with less significant control on the WD total petroleum system, these include (1) Gulf of Suez Rifting, (2) Red Sea Breakup, (3) Messinian Crisis, and (4) Plio-Pleistocene Delta Progradation.

5 Total Petroleum System in the Western Desert

The main hydrocarbons play that encountered in the northern WD basins are Cretaceous (mostly oil-prone), Jurassic (mostly gas-prone), and Paleozoic (mostly oil-prone) plays. The source rocks within the basins have mature and immature conditions with varying organic richness and are distributed in Paleozoic (Silurian and Carboniferous deposits), Jurassic (Khatatba, Masajid), Cretaceous (AEB, Alamein Dolomite, Kharita, Bahariya, Abu Roash, khoman), Eocene (Appolonia), and Oligocene (Dabaa) deposits. Immature conditions exist in shallower organic-rich areas (Khoman, Appolonia, Dabaa). In some basisns, the Kharita, Masajid, Alamein Dolomite, Abu Roash, and Bahariya formations have poor to fair source rock potential. However, the Jurassic Khatatba and AEB shales are the most common source rocks in most basins. The reservoirs are mainly porous sandstones that are distributed from the Paleozoic to Eocene, while the carbonates are restricted to the Jurassic Masajid, and Cretaceous Alamein dolomite and Eocene Apollonia carbonates. The trapping style is mainly structural with little contribution from combined and stratigraphic traps. The main seal rocks are the shales and carbonates across the sedimentary sequence from the Paleozoic to Miocene.

6 Western Desert Sedimentary Basins and Their Petroleum System

The sedimentary basins that are distributed across two-third of Egyptian lands (about 680,650 km^2) can be classified into two categories: the first is the greater WD sedimentary basins which are located Northern the WD and have been subjected to the same geological and tectonic events and they are linked together. These basins include Matruh, Matruh-Shoushan, Abu Gharadig, Natrun, Alamein, Faghour, Ghazali, Siwa, and Guindi basin. The second is the southern basins which include distributed basins in the middle and southern parts of the WD (Fig. 2). Over 10,600 wells have been drilled in the WD sedimentary basin, forming the current WD basin shapes and aiding in the discovery of numerous hydrocarbon fields. The following section will discuss some of these basins and some representative examples from their fields.

6.1 Northern or Greater WD Sedimentary Basins

6.1.1 Abu Gharadig Basin

The first significant discovery in the WD was the AG-1 well, which was drilled to Upper Cretaceous clastics in the Abu Gharadig field and yielded oil and gas. Despite the fact that the AG-1 well was discovered in 1969, oil production started in 1973 and gas production began in 1975. The basin is 330 km long and 50–75 km wide, and it is classified as an intracratonic rift basin with an *E-W* trend. The basin is defined as an asymmetrical sublatitudinal graben with flanks complicated by normal and strike-slip faults that form semi-graben structures, sometimes horsts, and buried linear inversion folds formed by wrenching dislocations during the Alpine tectonic epoch. The basin includes several oil and gas fields that reach more than 100 hydrocarbon fields. As a result of the Syrian Arc movement, the basin experienced inversion during the Late Cretaceous period (Abdel-Fattah et al., 2020; El Gazzar et al., 2016). As a result, an asymmetry anticline with a NE-SW orientation developed in the basin, which is bounded by inverted faults. Based on stratigraphic relationships and thickness changes, El Gazzar et al. (2016) concluded that the inversion began in the Santonian and continued to the Dabaa formation deposition period (Late Eocene). In terms of the petroleum system, the main reservoirs in the basin are hosted by sandstone facies of the Bahariya formation (Cenomanian) and the Abu Roash formation (Turonian). However, the carbonate facies of the Abu Roash *D*, *F*, and *G* members are also oil-bearing reservoirs in local areas within the basin (EGPC, 1992). According to EGPC (1992), the Bahariya formation sandstones have excellent porosity (up to 18–25%) and permeability (up to 500 mD). Locally, commercial hydrocarbon pools have been discovered in the Kharita (Albian) and Khoman formations. Oil and gas shows have also been reported from the sedimentary rocks of the AEB, Masajid, and Khatatba formations. In general, the hydrocarbon fields in the region are multipay and form producing trends along linear uplifts complicated by faults. The Abu Roash horizons yielded oil, while the Cenomanian Bahariya and Albian kharita reservoirs yielded mostly gas (EGPC, 1992). Other Jurassic and Early Cretaceous reservoir potentialities of the sandstone facies of the AEB, Khatatba, and Ras Qattara formations have recently been confirmed. The sediments of the Abu Roash (*E*, *F*, *G* Members) and the Bahariya formations contribute as source rocks in the basin. According to Lüning et al. (2004) and El Nady (2016), both formations are immature to mature source rocks with fair to good source potential for oil generation, which are still within the early stage of hydrocarbon generation till the present time. The Abu Roash “*F*” Member has oil-prone character (type I-II kerogen) with TOC values of 1.5–2.5 wt. % that reach to 6 wt. % or higher value at the central of the basin (EGPC, 1992; Lüning et al., 2004). The Abu Roash “*G*” Member has mixed Type II/III with marine and terrestrial origins with TOC values of 0.4–2.35 wt.% and has entered the early stage of hydrocarbon generation (Salama et al., 2021). The Bahariya formation has kerogen Type III of terrestrial origin and entered the early stage of hydrocarbon generation in Eocene time (Salama et al., 2021). On the other hand, the AEB, Masajid, and Khatatba formations are mature source rocks for generating both oil and gas. The AEB and Masajid formations entered the oil window between the Cretaceous and Miocene epochs and remain within oil and gas windows today, whereas the Khatatba formation entered the oil window between the Late Cretaceous and Eocene epochs (El Nady, 2016). The Khatatba formation sediments are a unique source rocks not only in the Abu Gharadig Basin, but all over the Northern WD sedimentary basins. For example, the TOC, Rock-Eval pyrolysis, and vitrinite reflectance in the northern area of the basin indicate mixed oil/gas-prone with fair to very good hydrocarbon generating potential in this mature source rock (1.0 to 5.36 wt.% TOC, S2 yields 2.29–15.18 mg HC/g rock, and HI 225 to 332 mg HC/g TOC) (El Diasty, 2015). In addition, other kerogen types exist, such as oil-prone (1.02–21.32 wt. % TOC, *S*2 yields 4.36–7.26 mg HC/g rock, and HI 368–687 mg HC/g TOC), and gas-prone (1.28–1.69 wt. % TOC, *S*2 yields 2.31–2.40 mg HC/g rock, and HI 142–180 mg HC/g TOC). The basin contains multi-seal rocks of shales and carbonates that range in age from the Middle Jurassic to the Oligocene. The large proportion of hydrocarbons discovered in the WD basins, including the Abu Gharadig Basin, were discovered through the drilling of structural traps, either as three- or four-way closure structures or as fault block structures. The dominant trapping mechanisms are structural traps formed by compressional tectonics associated with the Syrian Arc tectonic event and extensional tectonics associated with rifting. The basin traps include the tilted fault block trap, the horst fault block trap, and the horst fault block with three faults trap that accompanied the extensional tectonic regime. On the other hand, other traps like folds related to the basin bounding fault trap, inverted, folded and faulted within the basin trap, reverse fault trap, strike-slip trap, and flower structure trap that formed due to the compressional tectonic regime. The main petroleum system elements of the basin are summarized in (Fig. 5).

6.1.2 Matruh-Shoushan Basin

The Matruh-Shoushan Basin is a Mesozoic rift basin that experienced three stages of development, including (Pre-Syn-Post-rift) (Fig. 2) (Shalaby et al., 2014; El Nady, 2013). The Matruh-Shoushan Basin was influenced by the Syn-rift phase of the basin, which occurred from the Jurassic to the Middle Cretaceous when rapid subsidence occurred due to crust stretching and was accompanied by the highest heat flow (Metwalli & Pigott, 2005). Later, during the Post-rift phase, the basin experienced thermal cooling subsidence from the Albian to the Coniacian epochs (113–88 Ma). The basin contains numerous reservoirs and source

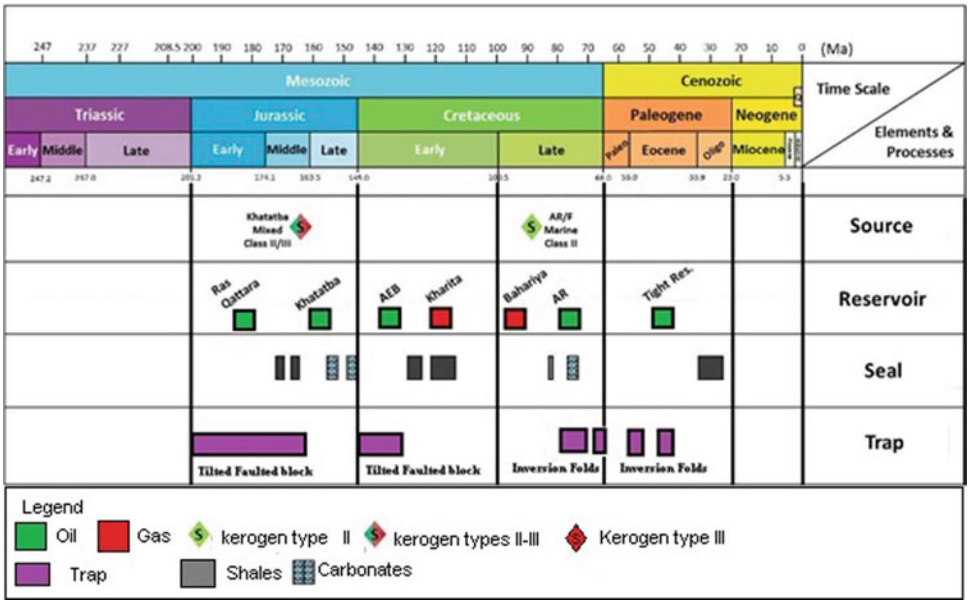

Fig. 5 Constructed petroleum system chart of Abu Gharadig basin. Legend is applied to all petroleum system charts in this chapter

rocks, and some horizons serve as both source and reservoir rocks. In terms of the petroleum system, the deltaic and shoreline facies of the Ras Qattara and Khatatba formations are recognized the source and reservoir rocks at the Jurassic depositional system level, while the inner carbonate platform of the Masajid formation is Seal rocks for the underling Khatatba (Shalaby et al., 2011). The TOC of Khatatba and Ras Qattara formations dark shale ranging from 1.8 to 46.9 wt. % and 2.23 to 53.71 wt. %, respectively (Shalaby et al., 2011). The source rock analysis indicated mixed kerogen types II-III as well as kerogen type III in both Khatatba and Ras Qattara formations (Fig. 6). TOC values and pyrolysis analysis of the aforementioned formations indicate excellent source rock quality, and petroleum system studies indicate that these dark shales have reached the final maturation stage of the hydrocarbons generation window in the Late Cretaceous. The Lower Cretaceous sediments have significant reservoirs and sources, which are represented by the deltaic to shoreline facies of the AEB formation, which has reservoir and source rock intervals capped by the shallow water peritidal dolostone of Alamein Dolomite. The TOC of AEB formation shales ranges from 1.85 to 2.40wt. % and is characterized by mixed kerogen types II-III (Younes, 2012). TOC values and pyrolysis analysis indicate good source rock quality, and petroleum system studies indicate that these shales have reached the mid maturation stage of the

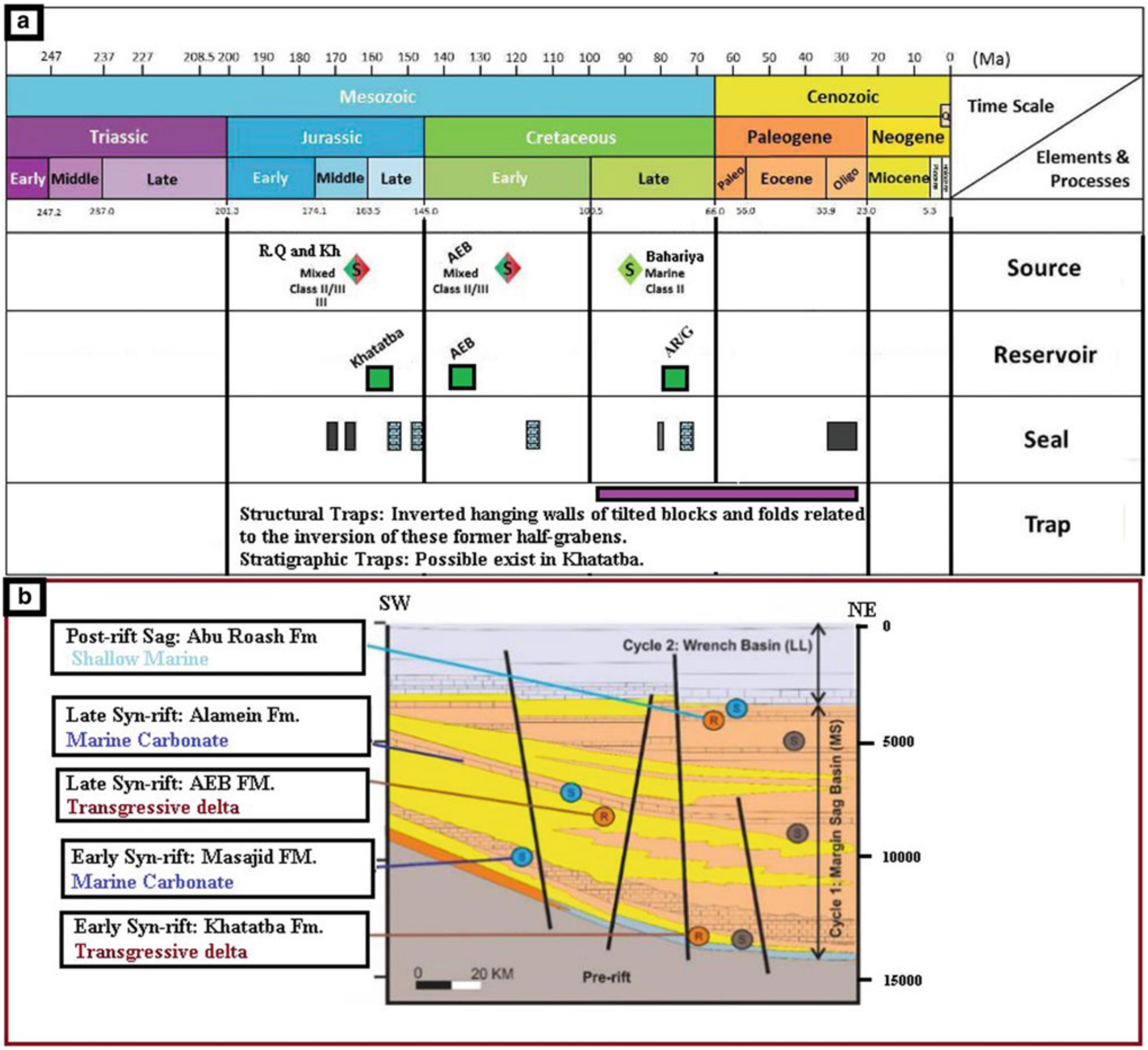

Fig. 6 **a** Constructed petroleum system chart of the Matruh-Shoushan basin, **b** schematic diagram showing the petroleum system types (PSTs) of the basin (adapted from Shalaby et al., 2014)

hydrocarbons generation window in the late Cretaceous. The shallow marine deposits of the Abu Roash formation, serve as a source and reservoir, while the upper carbonate of the Abu Roash Members serves as cap rock. The TOC of AR formation (AR/G Member) shales ranges from 1.10 to 1.50 wt. % and is characterized by mixed kerogen types II-III. TOC values and pyrolysis analysis indicate fair source rock quality, and petroleum system studies indicate that these shales have reached the mid maturation stage of the hydrocarbons generation window in the Late Cretaceous to Late Eocene. The Matruh-Shoushan basin produced both oil and gas fluids, and its hydrocarbon traps are dominant due to the structural type that formed during the Late Cretaceous period (Abdel-Fattah, 2015). Generally, the dominant trapping mechanism is structural traps formed by extensional and compressional tectonic regimes. The basin traps include the tilted fault block trap and the horst fault block trap that accompanied the extensional tectonic regime. On the other hand, other traps like inverted, folded and faulted within the basin trap, inverted and faulted trap that formed due to the compressional tectonic regime. The Khatatba formation, on the other hand, is stratigraphic due to facies change in these sediments. The reservoir characteristics of Khatatba Sandstones display measured permeability values range from 0.05 to 1000 mD and porosity values ranging from 1 to 17% (Cheng, 2020). The main petroleum system elements of the basin are illustrated in (Fig. 6).

6.1.3 Alamein Basin

The Alamein Basin was the source of the first hydrocarbon discovery in the WD, so it is an iconic basin, and it is known as the deeply buried basin. The Alamein basin is bounded on the Northeast by the Matruh-Shoushan basin, and it is separated from the Abu Gharadig basin by the Shareb-Sheiba high structural ridge (Fig. 2). The basin contains several oil-producing fields arranged in a belt of an ENE-WSW direction, including Razzak, Alamein, Horus, and others (Yousef et al., 2019). The basin is distinguished by an ideal inversion anticline that has been compartmentalized by several NW-SE trending faults (Abdine et al., 1993; Yousef et al., 2019). The basin includes a total of 33 hydrocarbon fields distributed across the basin. There are numerous reservoirs and source rocks in the basin, and some horizons serve as both source and reservoir rocks. From the petroleum system analysis in the basin, it has been inferred that the Jurassic rocks of the Khatatba formation are considered both source and reservoir rocks, and the expelled hydrocarbons migrated upwards to fill the Cretaceous reservoirs. The faults of the Alamein basin have a corridor nature, which aided oil drainage within the basin; however, it is unclear whether the formation of the dominant structural traps occurred prior to or concurrent with hydrocarbon migration. The Abu Roash formation's shales and tight carbonates acted as the basin's ultimate seal rocks, while the Masajid formation's inner carbonate platform serves as the basin's seal rocks for the underling Jurassic reservoirs. In terms of reservoirs, the basin is distinguished by numerous clastics sandstone reservoirs including Kharita, Bahariya, and AEB, as well as the dolomitic limestone of Alamein Dolomite and Abu Roash "*G*" Member (EGPC, 1992). In terms of hydrocarbons traps, Ayyad and Darwish (1996) argued that the structural traps are dominant in the cretaceous plays of the basin (ex. inverted hanging walls of tilted blocks, tilted blocks, three-way dip closures, and inverted anticlines of former half-grabens). In terms of source rock potentiality, Younes (2012) reported that the major matured source rock of the Khatatba formation contained mixed kerogen types II-III. According to Yousef et al. (2019), the AEB is still in its early stages of maturation. Moreover, the Abu Roash formation ("*F*" Member) has potential as source rock (Fig. 7). Furthermore, the Lower Cretaceous Kharita and Bahariya formations have some source rock potential in the basin and WD. The Eocene Apollonia formation has good source potential as well, but it is still immature in most basins (Moretti et al., 2010). The Abu Roash "*F*" sediments have TOC measurements ranging from 2 to 2.50 wt.% and are characterized by mixed kerogen types II-III. TOC values and pyrolysis analysis indicate that the source rock is of good quality (Moretti et al., 2010). The AEB shales have TOC measurements ranging from 1 to 2 wt.% and are characterized by mixed kerogen types II-III too. TOC values and pyrolysis analysis indicate that the source rock is of fair to good quality, with more lipid-rich material. The TOC measurements of the Khatatba shales range from 1 to 64 wt. % and are characterized by mixed kerogen types II-III. TOC values and pyrolysis analysis indicate that the source rock is of fair to excellent quality, with more lipid-rich material. Moretti et al. (2010) point to the Paleozoic sediments (e.g., Carboniferous, Devonian, and Silurian) as having source rock potential, although it is still not understood. According to petroleum system studies by Moretti et al. (2010), the migration of oil and gas in the basin begins in the Oligocene-Miocene epoch. The dominant trapping mechanism is structural traps formed by compressional and extensional tectonic regimes. The basin traps include folds related to the basin bounding fault trap, and (inverted, folded and faulted within the basin trap) that formed due to the compressional tectonic regime. Also, the basin traps include the tilted fault block trap that accompanied the extensional tectonic regime. The main petroleum system elements and burial history of the basin are illustrated in (Fig. 7).

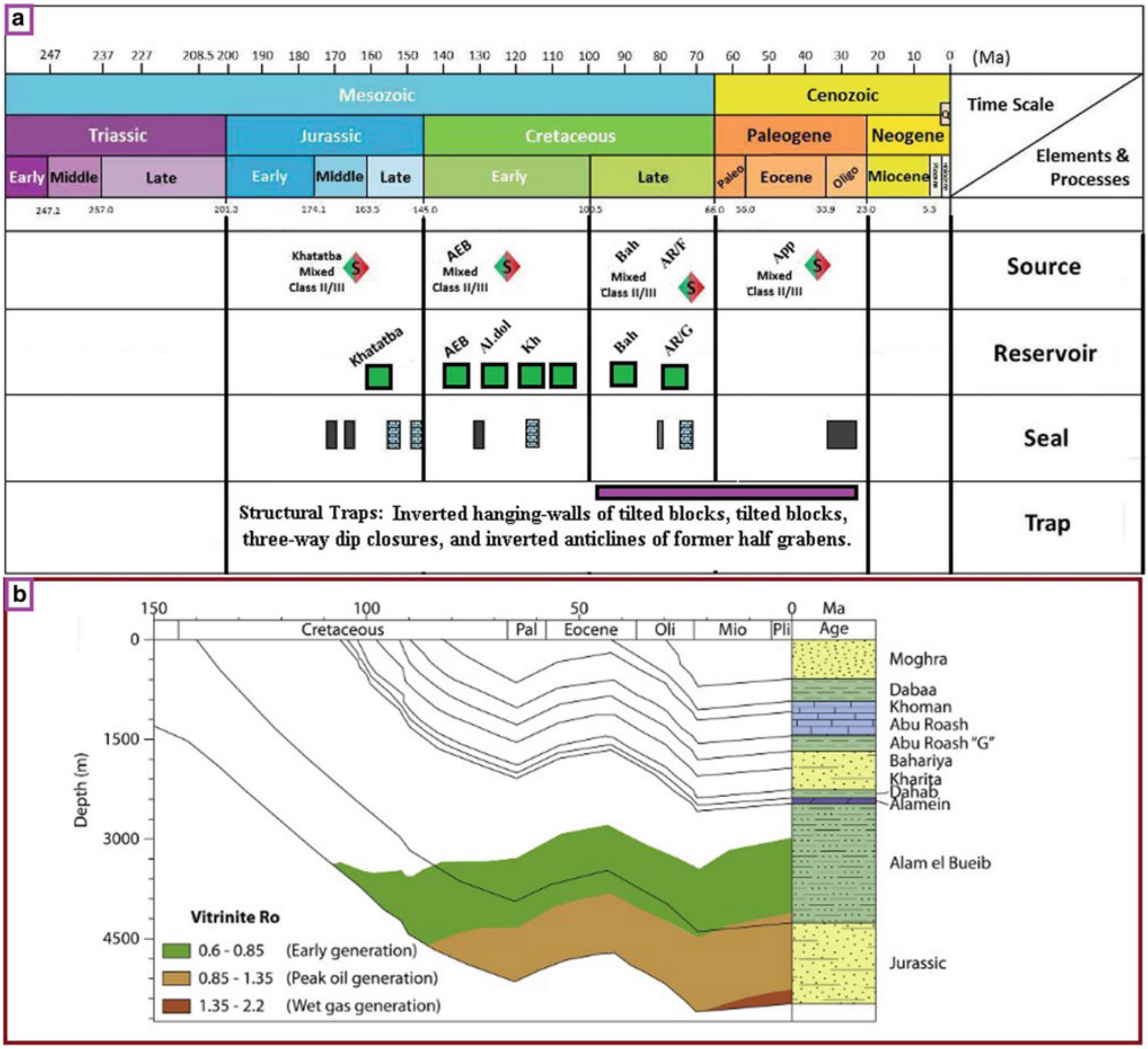

Fig. 7 **a** Constructed petroleum system chart of the Alamein basin, **b** burial history model of (PSTs) of the basin (after Yousef et al., 2019)

6.1.4 Faghur Basin

The basin is located near the borders of Libya in the western most of the WD rift system (Fig. 2). Although the hydrocarbons discoveries within the neighbor basins, the commercial discovery in Faghur basin commenced in 2006 (Bosworth & Tari, 2021; Bosworth et al., 2015a, 2015b). According to Bosworth et al. (2015a, 2015b), only the fluvial to estuarine Khatatba formation which deposited in the Late Jurassic first phase of rifting is the functioning source rock in the basin. The Khatatba was affected by extensional faults dip to the south that might reflect reactivation during the Hercynian according to Bosworth and Tari (2021). The TOC measurements of the Khatatba shales range from 0.1 to 80 wt.% (coals), with an average reading of 2.9 wt.%, and are characterized by mixed kerogen types II-III (Bosworth et al., 2015a, 2015b). The basin is affected by the inversion at the very Early Cretaceous while the deposition of AEB, forming inverted anticline and four-way dipping unfaulted closures. The Aptian–Cenomanian rifting was very important for the basin petroleum system as it brought the Khatatba source rocks below the oil generating window. Bosworth et al. (2015a, 2015b) reported that the hydrocarbons migration in the basin started after the Late Cimmerian inversion structure. Abu Roash formation was affected by younger inversion resulted in forming small folds. Later, renewed NE-SW extension influenced Campanian and Maastrichtian sedimentation. It can be inferred that both Late Cretaceous NW-SE shortening and NE-SW extension

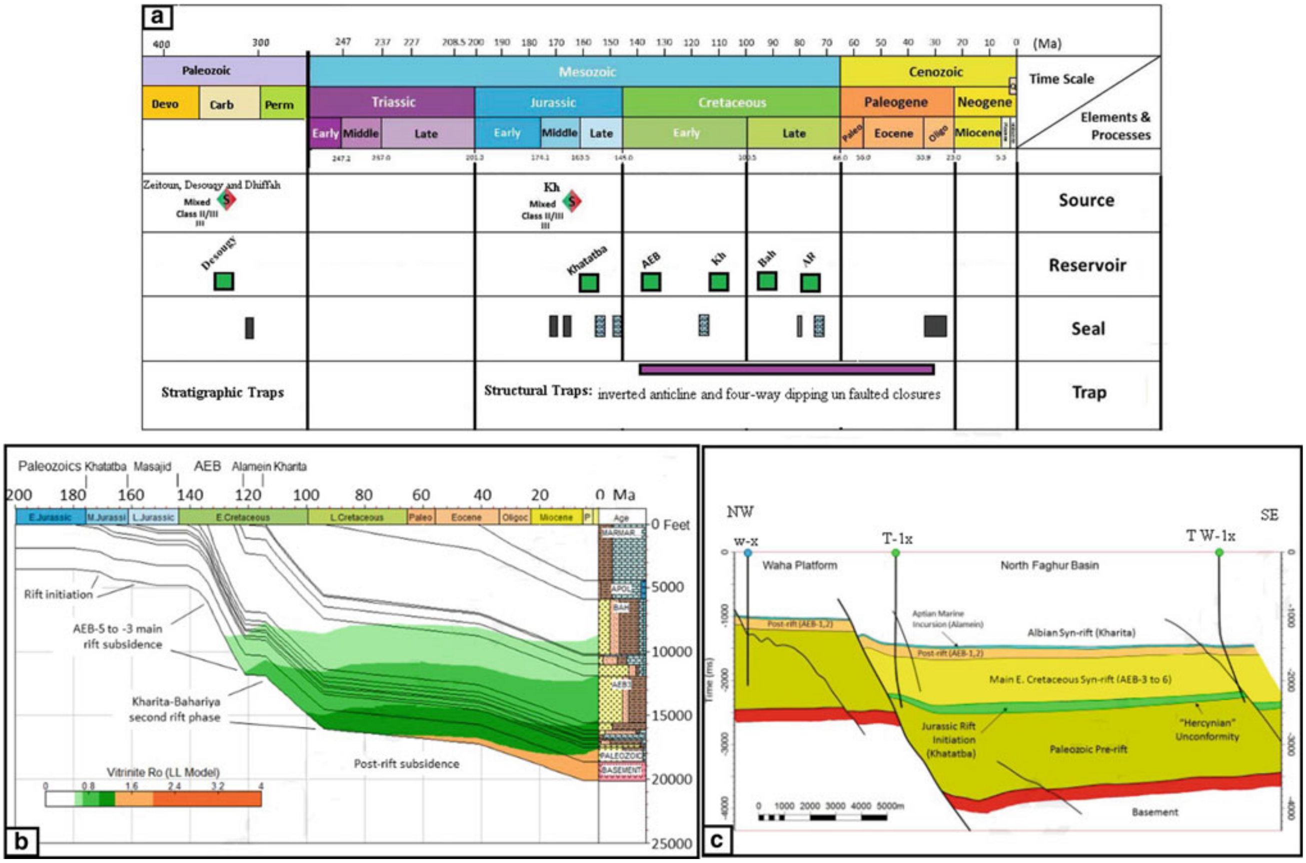

Fig. 8 **a** Constructed petroleum system chart of the Faghur basin, **b** burial history model of the basin, **c** representative cross section of the Faghur basin (after Bosworth & Tari, 2021)

influenced the basin, in turn, all these indicated the role of dominant structural traps in the Faghur basin. In terms of reserves, the porous sandstones in both pre and post-inversion time act as reservoirs, and the produced oil is characterized by variable wax content and a wide range of API gravities. Having fluvial sandstones interbedded with the actual source beds (Khatatba) also increases the robustness of the hydrocarbon system as vertical migration is not necessary in this case (source-reservoir). A recent study by Makled et al. (2018) and Abd el Gawad et al. (2019a, 2019b) studied the Paleozoic section in the Faghur basin and they inferred that Paleozoic Zeitoun, Desouqy, and Dhiffah are source rocks in the basin and they are characterized by kerogen type III and mixed type II/III (Fig. 8). Abd el Gawad et al. (2019a, 2019b) argued that the Paleozoic petroleum system mainly depends on stratigraphic traps that might form along the unconformity surfaces. The main petroleum system elements and burial history of the basin are illustrated in (Fig. 8).

6.1.5 Gindi Basin

The Late Cretaceous-Eocene basin is located 80 km southwest of Cairo and bisects the Nile in the easternmost part of the WD rift system, south of the Alamein Basin (Fig. 2). The surface area of the basin is about 9500 km^2 and the main famous hydrocarbon field is Qarun, which was discovered in 1994 by the El Sagha-1A wildcat well. Other oil and gas fields include a total of 27 fields distributed across the basin. For example, Silah, North Silah, Ain Assillen, N. Silah deep, southwest Qarun, Tersa, NE Tersa, Kahk, West Auberge, and SE Gindi fields. The basin was affected by the Jurassic-Early Cretaceous rifting phase, followed by right-lateral wrenching in the Late Cretaceous, and ended by reactivation of the NW-SE oriented fault (El Ghamry et al., 2020). The stratigraphic column of the Gindi Basin is the same as other basins in the northern WD, but it is less thick, ranging between 4 and 6 km, compared to 9 km of sedimentary thick in the Abu Gharadig Basin. The E-W and ENE fault trends are dominant in the Gindi Baisn and intersected by the youngest fault sets of the NW and NNW trends (EGPC, 1992). The Albian Kharita formation, together with the Aptian Dahab formation, has a very thick sedimentary succession of about 1000 m, while the Upper Cretaceous formations are composed of more than 1500 m of thick sediments (Mansour & Tahoun, 2018).

In terms of reserves, the porous sandstones in both pre and post-inversion times act as reservoirs, and the produced oil is characterized by variable wax content and a wide range of API gravities. The Albian Kharita formation, deposited in a fluvio-deltaic to marginal marine environment, and the Early-Middle Cenomanian Bahariya formation, deposited in oxic fluvio-deltaic, marginal to inner neritic environments, are the dominant reservoirs in the Gindi Basin since they are composed of sandstones with intercalated siltstones and shales. The sandstones of the Albian Kharita formation are occasionally medium to fine-grained, fair porous with traces of glauconite, while the Bahariya formation sandstones are characterized by being fine to medium-grained with dominant calcareous cement. The shallowing and deepening depositional trend has exerted significant vertical and lateral lithologic control over the Abu Roash formation in the Gindi Basin. It is divided into seven members from base to top (*G*–*A*) like in other northern WD basins. The "*B*, *D*, and *F*" members are mostly carbonate-dominant, while the "*A*, *C*, *E*, and *G*" members are mostly fine clastics, and these have produced hydrocarbons and have potential reserves in the basin.

According to Hammad et al. (2010), the fluvial to estuarine Khatatba, AEB, Kharita, Bahariya, and Abu Roash formations are the basin's source rocks. The TOC measurements of the Khatatba shales range from 1.29 to 4.64 wt. % and are characterized by mixed kerogen types II-III that are capable of producing oil and gas, with Tmax ranging between 433 and 444 °C, forming mature source rocks. The III kerogen type is detected in the AEB, Kharita, and Bahariya formations with gas generation potential. According to Hammad et al. (2010), the Abu Roash sample analysis is characterized by mixed kerogen types II-III that are capable of producing oil and gas, while some samples belong to Abu Roash "*F*" indicate a capability of generating oil with OI and HI values of 51–72 mg/g and 212–472 mg/g. According to Hammad et al. (2010)'s analysis of the AEB and Kharita formations, Tmax ranges between 417 and 436 °C, indicating an immature to marginally mature stage, as well as the Bahariya nad Abu Roash formation. The hydrocarbon expulsion started after the deposition of the Apollonia formation. El Ghamry et al. (2020) claimed that the Gindi's inversion resulted in the deposition of a remarkably thick succession of Appolonia carbonate, which acted as a seal rock, and these carbonates have contributed to enhancing the hydrocarbon trapping of Cretaceous source rocks. They refer to quick subsidence of the fault's downthrown side as a result of concurrent activity on the Gindi fault (basement structure), which resulted in hydrocarbon migration in an up-dip direction and the formation of hydrocarbon traps. The dominant trapping mechanism is structural traps formed by compressional and extensional tectonic regimes. The basin traps include folds related to the basin bounding fault trap and (inverted, folded and faulted within the basin trap, reverse fault trap) that formed due to the compressional tectonic regime. The basin traps include the tilted fault block trap and the horst fault block trap that accompanied the extensional tectonic regime. The main petroleum system elements and structural elements of the basin are illustrated in (Fig. 9).

6.2 Southern WD Sedimentary Basins

In general, the southern WD sedimentary basins have not gained the same importance and directed exploration activities as the greater WD sedimentary basins. Because of fewer exploration activities in the Upper Egypt and Red Sea regions, the Southern WD basins are poorly understood as a part of the Upper Egypt lands. The WD's southern basins include Kharit and Komombo, El Minya, Abu Tarure, Beni Suef, Assiut, Foram, and Kharga (Fig. 2). Non-marine lacustrine sediments were identified in Upper Egypt and Sudan by Schull (1988) and Taha (1992). According to the former researchers, additional Mesozoic rift basins are not physically connected to the greater WD rift basins. In 1990, geophysical and geological studies were conducted by Repsol Petroleum Company to determine the geological characteristics and boundaries of the Nuqra, Kharit, and Komombo basins that are located in the Southern WD. The first three basins are distinguished by their NW-SE orientation, which may be due to rifting associated with the breakup of the Afro-Arabian plates. Although the Nuqra basin is located geographically in the eastern desert, some authors consider it part of the WD sedimentary basins because it is structurally aligned with the Komombo Basin. In 1997, the Komombo-1 well in the Komombo basin was completed, and the results were interesting for both the government and investors, as oil was produced from Jurassic reservoirs (Dolson et al., 2001a, 2001b). Elmaadawy and El-Ashmony (2021) investigated the Foram basin, which is close to the Libyan border. They used magnetic, gravity, basin modeling, and seismic methods, as well they indicate that the basin structure trend is NE-SW, with a thickness of 1.8–5 km of Paleozoic sediments and the remaining represent the Mesozoic-Cenozoic sediments. As a result, Elmaadawy and El-Ashmony (2021) identified the basin as a Paleozoic basin with the Silurian Kohla formation as the main source rock. Elmaadawy and El-Ashmony (2021) basin modeling and petroleum system analysis revealed that hydrocarbon generation is quite low and cannot facilitate oil expulsion. Recently, new discoveries in southward basins (for example, Komombo and Beni Suef) in Cretaceous reservoirs have demonstrated that hydrocarbon systems exist within those smaller basins, implying that the WD will remain an attractive exploration target in the future. To conclude, more research is required to confirm the hydrocarbon potential of

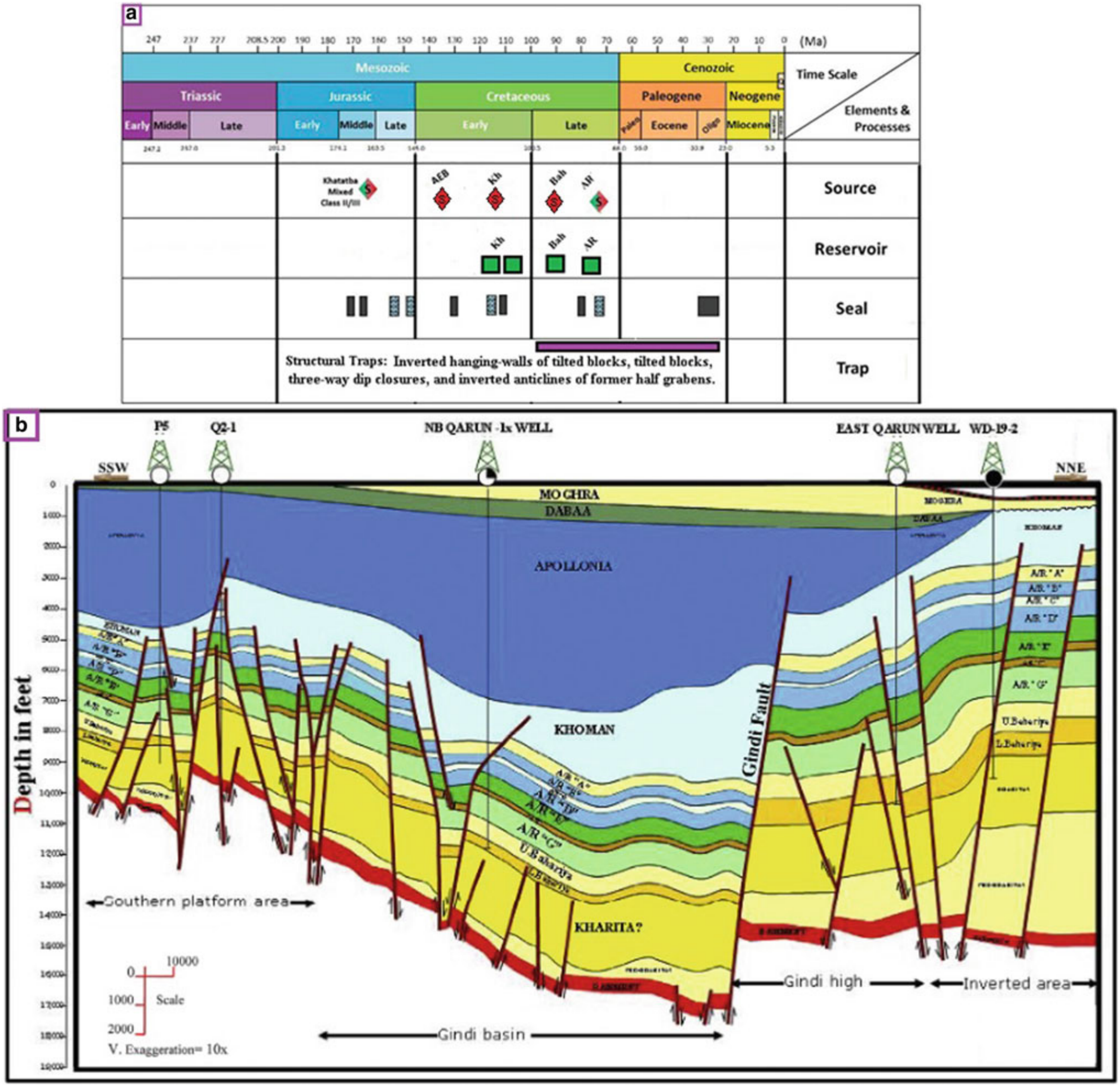

Fig. 9 **a** Constructed petroleum system chart of the Gindi Basin, **b** representative cross section of the Gindi Basin (after El Ghamry et al., 2020)

Upper Egypt basins, particularly the Southern WD basins, where additional studies can bring new ideas and exploration plans into Egypt's southern basins.

6.2.1 Beni Suef Basin

The Beni Suef basin is located south of the greater WD sedimentary basins and it belongs to the Southern WD basins (Fig. 2). The Beni Suef Basin bisects the present-day Nile Valley. The eastern side of the basin is located in the Eastern Desert, while the western side is located in the WD region. Although the hydrocarbon discoveries are within the neighboring Greater WD sedimentary basins, the commercial discovery in this basin commenced in 1997 by the Seagull Energy Corporation (Makky et al., 2014). The basin includes many fields, namely Yusif, Beni Suef, Lahun, Azhar, Gharibon, and Sobha. The stratigraphic column of the basin is similar to the neighboring Greater WD sedimentary basins, where basement rocks through the Jurassic clastics followed by the Cretaceous sequence, the Eocene carbonates, Oligocene shales, and topped by Late Tertiary to recent deposition (Makky et al., 2014). According to Makky et al. (2014), several source rocks exist in the basin. They report fair to good source rock in the Abu Roash (*E* member) with 0.51 to 3.66 wt.%. The Abu Roash "*F*" member had

TOC content ranging from 1.27 to 4.46 wt.%, indicating good to very good source rock characteristics. The Abu Roash "*G*" member had TOC content ranging from 0.51 to 1.15 wt.%, indicating fair to good source rock. TOC content in the Kharita formation ranged from 0.58 to 1.16 wt.%, indicating fair to good source rock, while TOC content in the Betty formation ranged from 0.39 to 1.16 wt.%, indicating fair to good source rock. The Rock-Eval pyrolysis that were analyzed by Makky et al. (2014), point to the Abu Roash (*F* member) as oil-prone source rock with excellent generation potential, while Abu Roash "*E*" member have the potential to generate mainly oil with some gas.

On the contrary, the Abu Roash (*G* member) and Betty formation have mixed oil/gas-prone source rocks. Mainly gas-prone source rock is assigned for the shales of the Kharita formation. Later, Abdel-Fattah et al. (2017) studied the TOC and Rock-Eval pyrolysis data and concluded three main source rock (kerogen) types, where the Abu Roach "*A*, *E*, and *F*" members indicate strongly oil-prone (kerogen type II). They found kerogen mixed type II/III belongs to shale-rich intervals within the Abu Roach "*A* & *G*" members and the AEB formation. The third source rock type by Abdel-Fattah et al. (2017) is gas-prone (kerogen type III) sediments and belongs to the Abu Roach "*E* & *G*" members, Kharita, and AEB formations. In terms of reservoir rocks, the main reservoirs in the Bani Suef basin are sandstone reservoirs. Both the Kharita and Bahariya formations have excellent sandstone reservoirs and represent the main reservoirs. The clastic sandstones of the Abu Roash "*A*, *E*, and *G*" members might act as additional resources in the basin. Anticline, half-anticline, fault block, and anticline faulted structure are the dominant trap types in the Bani Suef basin. The aforementioned reservoirs in the basin are sealed by the Lower Cretaceous and Upper Cretaceous shales of the Kharita and Bahariya formations, as well as the fine-grained limestones of the Abu Roash formation, which act as seals too. The Early to Late Cretaceous rifting tectonics resulted in forming migration pathways for accumulated hydrocarbons. The later developed faults and anticlines assist in the secondary migration of hydrocarbons. According to Abdel-Fattah et al. (2017), the Cretaceous source rocks commenced oil generation during the Late Cretaceous period. The dominant trapping mechanism is structural traps formed by extensional tectonic regimes. The basin traps include the tilted fault block trap, the horst fault block trap, and the horst fault block with three faults trap that accompanied the extensional tectonic regime.

6.2.2 Komombo Basin

The Komombo basin is an intracontinental rift basin that is located in South Egypt; it belongs to the Southern WD basins (Fig. 2) and it lies 65 km northwest of Aswan. The basin is defined by a normal fault that runs northwest to southeast, it is characterized by 70-km-long and 30-km-wide. This basin is a very significant basin in the petroleum system of the Southern Western Desert, where it is the most significant hydrocarbon resource in Upper Egypt to date. The basin includes two fields, namely Al Baraka and West Al Baraka fields. The stratigraphic column of the basin is about 4000 m of Cretaceous non-marine and shallow marine sequences (Abdeen et al., 2021; Hakimi et al., 2023; Ali et al., 2020). The formations in the Komombo basin are named from top to bottom: Dakhla, Qusier, Taref, Maghrabi, Sabaya, Abu Ballas, Six Hills, and Komombo formations (Fig. 10). Komombo formation is debated between authors, where El Nady et al. (2018) and Abdeen et al. 2021 add it in the stratigraphic column, while Selim (2016) and Ali et al. (2020) did not add this formation in their studies. Various sandstone layers are distributed across the stratigraphic column of the basin and can act as reservoirs (Fig. 10). The Albian/Cenomanian formations act as reservoirs deposited during the Albian/Cenomanian period and consist of shallow marine sandstone. As well, the Abu Ballas (Aptian) and Six Hills formations (Early Cretaceous) are reservoirs in the Al Baraka oilfield. In the flanks and depocenter of the basin, the Albian/Cenomanian thickness ranges from 137 to 411.5 m. Horst, graben, and half-graben are the dominant structures in the basin. The Albian/Cenomanian sandstones have good to very good reservoir quality. However, hydrocarbon saturation is restricted to some parts of the basin. The sandstone reservoirs in the basin are characterized by high amount of siliceous and argillaceous cement which control the reservoir tightness in some parts. According to Abdeen et al. (2021), the core data indicate poor to fair reservoir properties (average $\varnothing = 4.03\%$, FZI = 5.50 µm, and $k = 3.56$ md) in the siliceous sandstone samples. On the other hand, the argillaceous samples are characterized by tight to poor reservoir properties (average $\varnothing = 11.8\%$, FZI = 1.22 µm, and $k = 3.44$ md). The proven source rock belongs to the Early Cretaceous, represented by the Hauteriviane–Early Barremian and Neocomian sediments. Ali et al. (2018) studied the Hauterivian–Early Barremian source rock and found the TOC content ranged from 1 to 3.36 wt.%, which indicates good to very good source rock characteristics. The Hauterivian–Early Barremian formation is dominated by Type II/III kerogen based on Rock-Eval pyrolysis and indicates oil–gas-prone (Ali et al., 2018). The structural traps are dominant in the basin. The pre-Cretaceous and Cretaceous shales act as a seal rock across the Komombo basin. El Nady et al. (2018) studied the source rock characteristics of the Sabaya and Abu Ballas formations and concluded that kerogen type III and mixed type II/III are dominant, which indicates fair to excellent source rocks. They found the in Sabaya and Abu Ballas formations. El Nady et al. (2018)

considered the Six Hills formation as poor to fair source rock in Komombo basin. They found that the kerogen type III and IV is dominant in the Six Hills formation. They concluded that the shales of Komombo formation (*B* member) have fair to excellent source rock with kerogen type II and mixed type II/III. El Nady et al. (2018), studied Quseir and Taref formations and indicate poor to fair source rock, on the other hand, they indicate very good to excellent source rock in the Maghrabi formation (III and II/III kerogen type). The Campanian-Maastrichtian sediments.

Indicate fair to excellent source rocks (II and II/III kerogen type). Both oil and gas are mainly the potential products of the Cretaceous formations based on the thermally transformed organic matters within these formations. According to El Nady et al. (2018) work the upper cretaceous sediments are immature to marginally mature source rocks, except Maghrabi formation that entered the early stage of hydrocarbon generation. The Neocomian sediments are mature rocks based on thermal maturity ($R_0 = 1.25$), while sediments of the Sabaya and Abu Ballas formations are of marginally mature.

6.2.3 Nuqra Basin

The Nuqra basin is an intracontinental rift basin that is located in South Egypt. It belongs to the Southern WD basins. The basin is characterized by a NW-SW fault trend, but a younger fault set of NE-SW to the east of the Nile River (Abdeen et al., 2021). The basin includes two fields, namely Al Baraka and West Al Baraka fields. The stratigraphic column of the basin is about 2000 m. The formations in the Nuqra basin are named from bottom to top: Six Hills, Abu Ballas, Sabaya, Maghrabi, Quseir, and Duwi

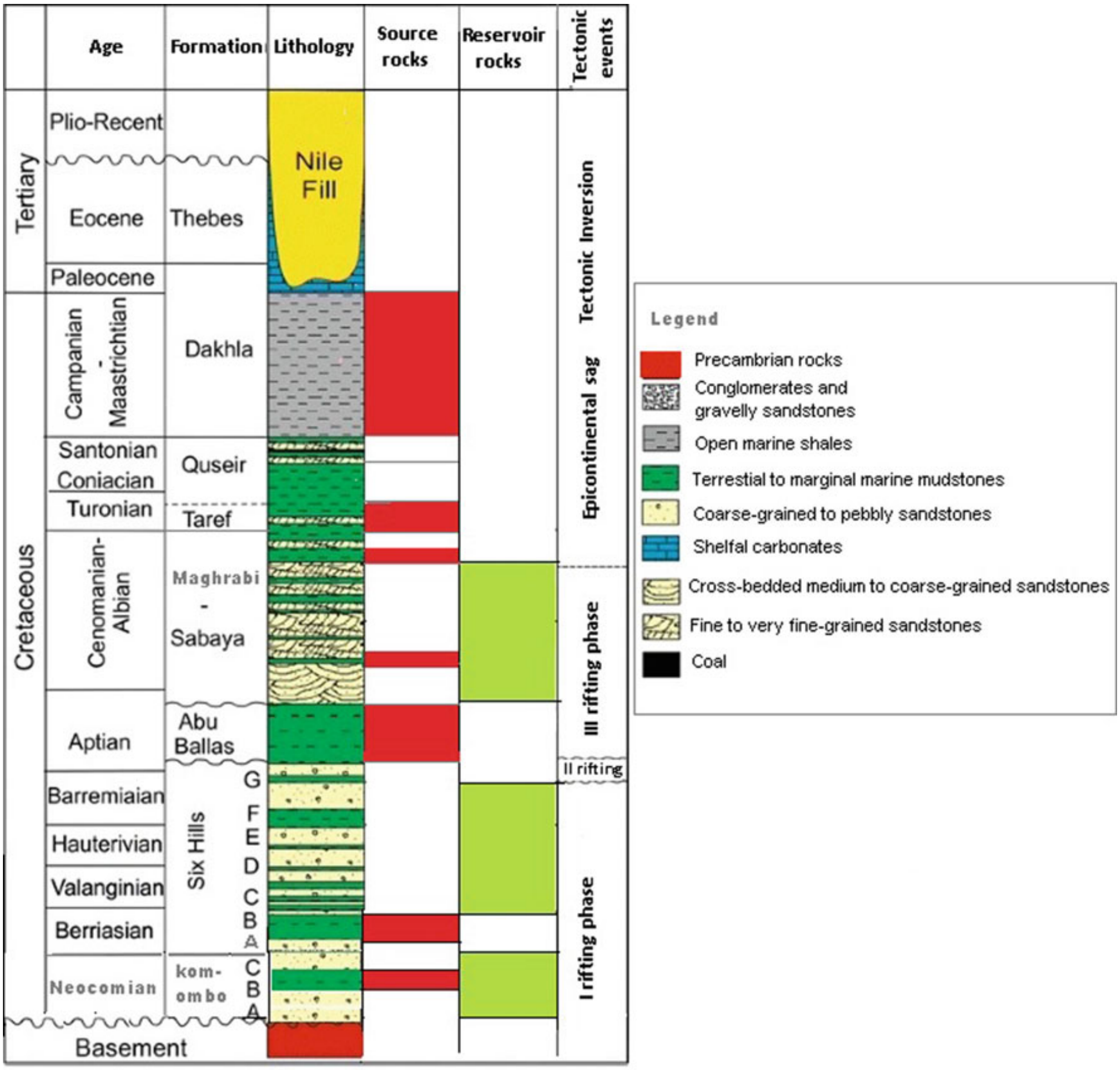

Fig. 10 **a** lithostratigraphic column of komombo basin (modified after El Nady et al., 2018)

formations. The aforementioned formation is of Late Jurassic, Cretaceous, and Paleocene succession. The Six Hills formation acts as the dominant reservoir deposited during the Early Cretaceous period and consists of porous sandstone. However, the water saturation is very high in these reservoirs, except in selected layers with low water saturation that might be prospective. The source rocks in this basin are from the Jurassic and Early Cretaceous periods, but the available information is not well documented. The structural traps are dominant in the basin. The pre-Cretaceous and Cretaceous shales act as a seal across the Nuqra basin. Further exploration is much needed in the Nuqra basin to better understand the petroleum geology and find economical quantities of hydrocarbon.

7 New Opportunities: Road to Successful Exploration and New Resources

Changes in exploration concepts and/or utilized technology are the most important factors in achieving significant development and increasing the extracted hydrocarbons from any basin (Dolson et al., 1999; Dolson, 2020; Radwan et al., 2021a). Moreover, governments can play a positive role in this by changing business terms in the energy sector, which may create trends and attract new companies to explore. In this regard, the Egyptian government has made ongoing efforts over the last several decades to facilitate the exploration agreement process and attract a number of new companies to work and explore in the WD sedimentary basins. The observed significant increase in WD petroleum reserves over the last two decades indicates a combination of evolving exploration concepts and technological advancement (ex. enhanced seismic imaging in particular deep horizons).

Although many discoveries have been made in the WD sedimentary basins over the last few decades, it is believed that the WD sedimentary basins have not yet revealed their maximum petroleum resources. Successive exploration and potential growth of WD basins can be achieved by employing an integrated approach that can deliver more refinement of the play, trap, or reservoirs. In order to achieve the maximum benefits, the former integrated studies should be supported with source, maturation and migration studies (Radwan et al., 2021a). According to Radwan et al. (2021a), source rock analysis is critical in both the exploration and development stages because it quantifies the expelled hydrocarbon volumes in each trend within a specific sedimentary basin to be traced in the basin or neighboring basins. Dolson et al. (1999) conducted statistical studies to predict potential unexplored fields in the WD, and they proposed about 30 new fields in the WD basins that have yet to be discovered. Dolson (2020) based their prediction on the assumption of new deeper objectives that must be traced within the WD's large distributed basins. According to the distribution of source rock facies across the WD basins and the calculation of the expected recoverable hydrocarbons, it can be assumed that approximately 7–10% of the expelled hydrocarbons have migrated toward the basin traps (Dolson et al., 1999). The estimated migrated hydrocarbons by (Dolson et al., 1999) are very large (47.4 BBOE) when compared to the actual produced (1.15BBO and 3.2 BBOE) from the various basins in the WD. As a result, the yet-to-find discovered hydrocarbons in the WD sedimentary basins are very likely to be discovered by additional petroleum studies and exploration efforts.

According to Dolson et al. (1999), new discoveries in the WD petroliferous basins may contain more than 11 BBOE of additional resources. Finding such hidden hydrocarbons, however, necessitates long-term planning as well as significant technological investments. In addition, new ideas and a willingness to pursue more difficult targets (ex. deeper reservoirs). In this section, I summarize some of the new opportunities that should be pursued in further exploration within the WD sedimentary basins.

7.1 Stratigraphic and Combined Trap Concept

Exploration for stratigraphic and combined petroleum reservoirs has made significant progress around the world (Radwan et al., 2021a). The petroleum exploration strategy in the WD was primarily based on structural analysis of comparable petroleum provinces in Egypt and around the world (EGPC, 1992). Stratigraphic traps in hydrocarbon exploration have received increased attention in the WD basins over the last two decades, with consideration in both the exploration and development phases. The exploration of stratigraphic traps began in the 1990s, when over 250 m of Jurassic rocks in Obaiyed Field displayed pinch-outs due to rapid lateral facies changes (Fig. 11). Furthermore, (Abd El Gawad et al., 2019a, 2019b) reported a Paleozoic stratigraphic trap in the Faghur basin in response to an angular unconformity.

Apache Corporation announced the discovery of a stratigraphic trap by the Riviera SW-1X (Riviera field, Abu Gharadig Basin), with oil (5800 barrels) and gas (2.8 MMcf) production from reservoirs 24 feet thick of Lower Bahariya sandstones. Another stratigraphic trap (1000 acres) was discovered while drilling Narmer-1X to the east of the Neilos oil field in the Faghur basin. The Narmer-1 × well encountered about 85 feet net pay of Paleozoic-aged sandstones, with daily oil (1200 bbl) and gas production (400 Mcf). The former examples of explored stratigraphic traps highlight the significance of these types of traps, which may add additional reserves to the total hydrocarbon reserves across the WD sedimentary basins. In this regard,

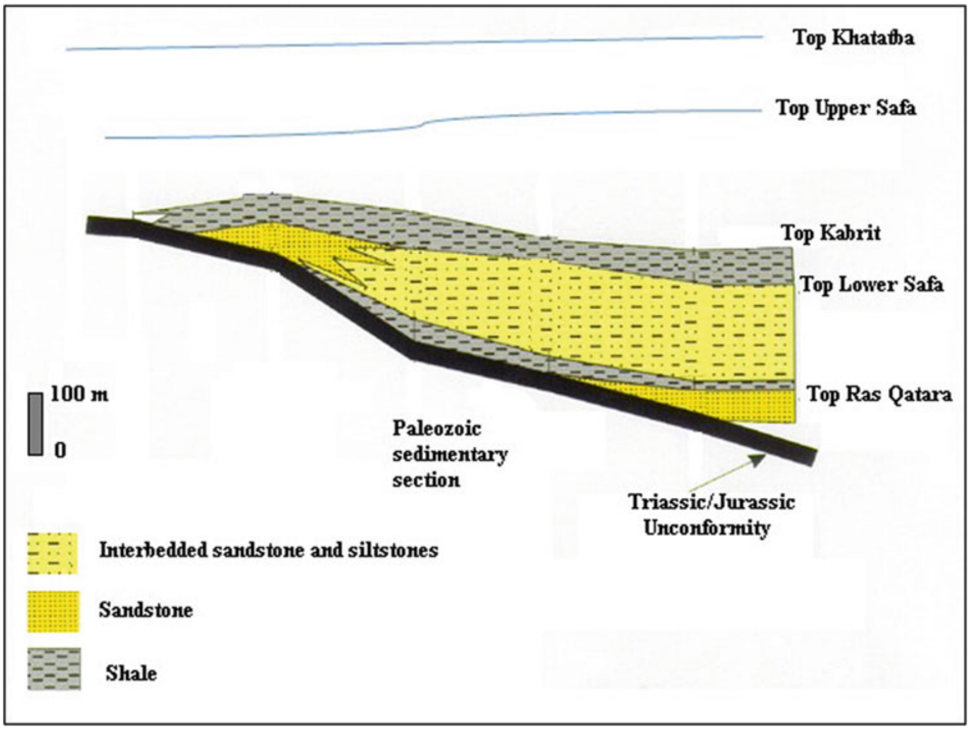

Fig. 11 Jurassic play of Obaiyed Field, Matru Basin, WD. (modified from Mahmoud & Barkooky, 1998)

hydrocarbon accumulations may exist in the WD's deeply buried Mesozoic (half-graben basins) and Paleozoic sediments. More emphasis should be placed on the heterogeneous reservoirs found in the WD sedimentary basins (ex. Khatatba, Bahariya, AEB, Abu Roash, and Paleozoic formations). When looking for stratigraphic elements in the WD basins, the following characteristics are especially important: facies change, pinched-out sandstone bodies facies, truncation or erosion at unconformities, isolated sand bodies (channel) and diagenetic traps. The former stratigraphic elements can form perfect stratigraphic petroleum traps in all WD sedimentary basins. For example, the Khatatba formation is composed of sandstone channels that thin away from the channel axis in some regions and are surrounded by floodplain mudstone; tracing the channel axis could be advantageous and bring thick isolated reservoirs in new wells rather than thin sandstone drilled far from the channel axis. At the same time, it is not necessary to find a pure stratigraphic trap on its own; it could be accompanied by other structural elements, resulting in combined stratigraphic-structural traps, such as the Gulf of Suez trapping style (Radwan et al., 2021a).

7.2 Deeper Targets Reservoirs

The deeper Paleozoic and Jurassic targets are the treasure of WD sedimentary basins, and while some petroleum companies have recently begun to explore deeper targets, additional resources are still under-exploration, and significant discoveries in these promising targets require extensive research. The OBA-A3 well was one of the wells drilled in 1996 to target deeper reservoirs in the Matruh Basin, and it produced Paleozoic oil. Later, as the importance of deeper targets becomes more widely recognized, Eni announces some new discoveries in the South West Meleiha Field (Faghur Basin). Aligning with Eni efforts to explore the WD's deep geological resources, particularly within the deeper Paleozoic and Jurassic sequences of the Faghur Basin.

Eni drilled several exploratory wells and announced new discoveries in the Faghur Basin; I will highlight some of the most recent new discoveries here. The SWM A-2X well (5090 m total depth) was drilled in the Faghur Basin and encountered an 18-m oil column of Carboniferous age sandstones, with an average production of 2300 BOPD. Later, the SWM B1-X well in the same basin made another discovery (7 km distance from SWM A2-X). The SWM B1-X well reached a total depth of 4523 m and encountered light oil (37° API) produced from deeper targets of Carboniferous sandstones with a thickness of 35 m and an average production rate of 5,130 BOPD. Another recent discovery was made while drilling the SWM-A-6X well (4815 total depths in meters), where a 130-ft oil column was discovered in the Dessouky formation (Carboniferous age) with an average production of 5000 BOPD.

In addition to Paleozoic source rocks, Khatatba source rocks appear to contribute significantly in the expulsion of oil to both syn-rift and deeper Paleozoic reservoirs (Devonian and Silurian). According to Boote et al. (1998), the Devonian and Silurian deposits are important source rocks in Libya, but these deposits are thinning from Libya to the WD. Recent petroleum discoveries by petroleum companies in deeper targets have also discovered hydrocarbons in the AEB formation at deeper levels, indicating the additional resources that can be gained through deeper target exploration across the WD sedimentary basins. Exploring deeper targets, on the other hand, presents several challenges in terms of exploration and drilling, which will be highlighted in the challenge section.

7.3 Structural Play: Inversion Structures and Faulted Traps and Their Accompanied Fluid Migration

Inversion events influenced the structural regime of most WD sedimentary basins, reinitiating faults and forming folds in response to the unique structural features of each basin. More attention should be paid not only to the effect of such inversion events on structure features, but also to the accompanying “Tertiary” hydrocarbon migration. Inversion structures are common in the WD sedimentary basins, such as the Razzak Field, Mubarak Field, and Kattaniya High (Bevan & Moustafa, 2012).

Fluid leakage or Tertiary migration in a faulted trap, according to Sales (1997) & Bevan and Moustafa (2012), can be caused by gouge failure spill point juxtaposition spill point, or filled to seal capacity, which is known as “Cryptic” spill points. Bevan and Moustafa (2012) provided an example from Kattaniya High in the WD, where inversion events affected hydrocarbon accumulations on the inverted hanging wall half-graben anticline, causing the AEB formation to “switch off” to a shallower depth and influencing hydrocarbon migration (Fig. 12). More research into such phenomena could lead to new discoveries and unexpected reservoirs, but this will be dependent primarily on the petroleum system study in new prospect basins, which must be analyzed due to the uniqueness of each field.

7.4 Applying Sequence Stratigraphy Concept

The study of the spatiotemporal evolution of sedimentary basins is critical for fully understanding the geological and sedimentation conditions that control reservoirs and can lead to the discovery of new reservoirs (Catuneanu, 2006; Slatt, 2006; Radwan et al., 2021a; Shehata et al., 2021). Radwan et al. (2021a) emphasize the significance of sequence stratigraphy in hydrocarbon exploration in half-graben rift basins, which are similar to the WD half-graben basins.

According to Posamentier and Vail (1988), it is critical to investigate the spatial and temporal rock relationships within a surface boundary of erosion or non-deposition, as well as their correlative conformities. Several sedimentary cycles and sequence boundaries are recorded in the WD sedimentary succession; applying recent advances in sequence stratigraphy and tracing the output of these models will contribute to a better understanding of depositional sequences, which will improve our understanding of reservoirs geometries and reservoir qualities at the pre-rift and syn-rift levels.

The use of sequence stratigraphy in WD sedimentary basins will lead to significant advances in predicting the lateral and vertical distribution of depositional sequences, including source, reservoir, and seal rocks. Furthermore, the sequence stratigraphy concept in hydrocarbons exploration can aid in the definition of component system tracts and facies, which will contribute significantly in the exploration and development of reservoirs, particularly clastic reservoirs. Using the sequence stratigraphy concept and the utility of correlating time-synchronous surfaces in heterogeneous clastics reservoirs of Cretaceous, Jurassic, and Paleozoic clastics deposits could lead to new discoveries and petroleum system geometries, specifically reservoir geometries.

7.5 Unconventional Resources

Recently, the development of unconventional resources has been one of the primary economic goals (Law & Curtis, 2002; Radwan et al., 2021b). Unconventional resources are becoming one of the ways to maintain domestic energy demand in Egypt and worldwide in order to replace declining conventional resources. The WD basins are not far from such unconventional resources and technology, and now some wells are already tested to discover and assess the predicted unconventional resources (Salah et al., 2017; Gomaa et al., 2019).

Unconventional resource evaluation necessitates the collection of a variety of integrated data, including geochemical, geomechanical, and petrophysical measurements. Because of the organic richness and widespread nature of Khatatba shales as the primary source of petroleum to conventional resources in the WD basins, it is of relative importance. The Apollonia and Khatatba formations are the most promising unconventional resource layers in the WD. In this regard, a series of horizontal and vertical wells were drilled in the WD to evaluate the Apollonia tight carbonate and Khatatba dark shales using multistage and one-stage hydraulic fracturing.

The open marine Apollonia Tight (Gas) Chalk formation, on the other hand, is spreading across the WD lands and is characterized by high porosity/low permeability soft chalky limestone. The Apollonia formation is divided into four

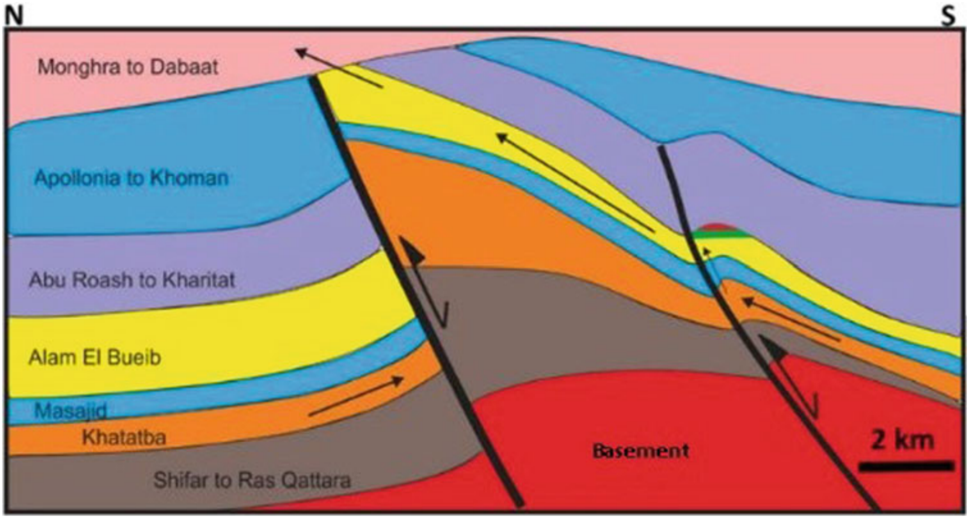

Fig. 12 Kattaniya high inversion structure and fault trap (after Bevan & Moustafa, 2012)

units: *A*, *B*, *C*, and *D*; the candidate's unconventional resources are massive chalky limestone (*A*) and glauconitic limestone (*C*). The Apollonia Tight Chalk and Khatatba formations in Egypt's Western Desert have been identified as potentially containing economically valuable gas accumulations. Salah and Ibrahim (2018) compared the Khatatba characteristics in the Matruh-Shoushan Basin to the well-known shale plays in the United States (Barnett and Marcellus) (Table 3). Accordingly, the WD Apollonia Tight Chalk and Khatatba formations have significant unconventional gas reserves, and developing these resources can help Egypt increase its natural resources. The tight sandstones in the southern WD should be evaluated economically for potential hydraulic fracturing for better hydrocarbon exploitation. More integrated work is required to better assess existing unconventional resources in the WD, as well as to improve exploration, characterization, and evaluation of WD sweet spots. More efforts are required to stimulate the unconventional gas industry, improve industry policy in the WD, and address development challenges.

7.6 Further Exploration in the Southern Western Desert Basins

More focus is needed to explore the hydrocarbon secrets of the southern WD sedimentary basins of Nuqra, Kharite, and Komombo basins. The exploration efforts in the Upper Egypt sedimentary basin during the last decades succeeded in presenting two commercial discoveries in the Komombo Basin, namely Al Barka and West El Barka oil fields. Petroleum companies were disappointed with high water saturation and low reservoir quality (tightness) in Nuqra and Komombo basin, however this because the less understanding of the structural setting and hydrocarbon system of these basins compared to other basins in the WD. The discoveries in Komombo basin indicate the potential of multi-pays across the sedimentary succession of these basins, therefore more structural, geophysical and geochemistry studies on the sedimentary succession of these basin studies has potential to bring new insights and better exploitation of these potential resources. According to El Nady et al. (2018), the source rocks of the Upper Cretaceous

Table 3 Comparisons of the Khatatba of the Matruh Shoushan basin with well-known shale plays (Barnett and Marcellus)

Shale plays	Khatatba	Barnett	Marcellus
Age	M. Jurassic	Mississippian	Devonian
Vertical depth (ft)	11,000–1300	6500–9000	4500–8000
Thickness (ft)	250–240	200–300	50–300
TOC (% wt.)	10-Feb	7-Mar	10-Mar
Vitrinite reflectance Ro	1.0–1.4	1.0–1.74	0.8–3
Pressure gradient (psi/ft)	0.55	0.45	0.4–0.6
Porosity (%)	12-Aug	10-Apr	6-Apr
Brittleness (%)	60–70	60–70	50–60
GIP (BCF/section)	100–200	100–300	70–150

formations range from immature to marginally mature, with the Maghrabi formation reaching only the early stages of oil generation. On the eastern side of the Komombo basin, there is a good chance of finding oil generated by the Abu Ballas, Dakhla, Maghrabi, Duwi, and Sabaya formations. Proven kerogen II source rock of up to 7wt. % TOC is exist in the Cretaceous sediments of Komombo Basin, the very good potential of source rocks to generate hydrocarbon shed the light for more exploration opportunities compared to the current minimal explored hydrocarbon traps. The presence of porous clastics throughout the startigraphic section of these rift basins, as well as the seal capacity in the upper interval of the Senonian-Paleocene, indicate the presence of potential reservoirs somewhere in these basins. Furthermore, the formation of rotated fault blocks by the Early Cretaceous extensional rift and mildly inverted structures by a long period of Late Cretaceous to post-Early Eocene Syrian Arc compression in South Egypt indicate the potential for forming structural hydrocarbon traps and the presence of good hydrocarbon system elements. These rift basins are formed structurally as NW-trending rift basins with asymmetric fault-bounded half-grabens trending (oblique) to the Red Sea trend as a result of the reactivation of a major by the Neocomian, the Precambrian Pan African tectonic zone had been replaced by the Neocomian extensional tectonic. According to recent drilling and seismic interpretations, Neocomian-Barremian maximum subsidence might be exist and the Kharite, Nuqra of the eastern Nile River.

Advanced production techniques such as horizontal drilling and hydraulic fracturing might be the best option to enhance the productivity in tight sandstone reservoirs. Applying this technique has raised the reserves from 0.6 to 5.23 MMBO in the Al Baraka field (Mostafa et al., 2021). The produced oil from the southern basins is 37°API with a wax content that is similar to the oil in the neighboring Sudanese rift basins. The main risk is the absence of one of the hydrocarbon petroleum elements in the Komombo, Nuqra, and Kharite sedimentary basins. In terms of exploration risks, basin exhumation caused erosion of the basin roof and brought the maturity level to 1200 feet in the Nuqra basin. Moustafa et al. (2002) argued that the basin roofing was milder in the Komombo basin, with a maturity level of 2100 feet in the Komombo basin. The mildness of the inversion tectonics in the Nuqra and Kharite basins provides a good opportunity for hydrocarbon preservation, but the time of basin exhumation remains a risk. Further exploration is much needed in the Nuqra basin to better understand the petroleum geology and find economical quantities of hydrocarbon.

8 Challenges for Hydrocarbon Exploration in WD Basins

Although the WD's Mesozoic basins offer a variety of rewarding exploration opportunities, they are difficult to obtain and represent a difficult exploration opportunity. In general, the WD basins are distinguished by a complex geological history that has influenced their depositional setting and petroleum system elements. The structural regime of most basins in the greater WD sedimentary basins has been influenced by the Syrian Arc event's deformation and inversion. Furthermore, below the Alamein Dolomite, the quality of seismic imaging is very low.

Despite the numerous benefits of exploration in WD (for example, multiple reservoirs, onshore drilling, various traps, low cost, and conventional resources), it appears that exploration will continue to be active in WD for many years to come. However, challenges are arising at various levels of exploration and drilling. In this section, I will discuss some of the difficulties associated with hydrocarbon exploration in the WD sedimentary basins.

8.1 Drilling Issues Challenges

Quite apart from the geological and geophysical modeling of planned exploration and development wells, drilling obstacles have emerged as a major issue during the exploration and development phases (Radwan et al., 2019; Radwan, 2021). Drilling success is typically achieved through improved pore pressure prediction and geomechanical analysis (Radwan et al., 2020, Radwan and Sen, 2021a, 2021b). Drilling issues can arise during drilling into the carbonate of the Masajid and Alamein formations, resulting in partial or total losses.

According to, the main cause of these losses was that the former carbonates was karstified during the Jurassic period in response to tectonic uplift (Keeley et al., 1990). The difficulty in predicting the geometry and patterns of such phenomena is that the vugs are localized.

While drilling these sections, some mitigations, such as underbalanced drilling and Pressurized Mud Cap Drilling (PMCD), can be considered. The current depletion of conventional resources adds additional risks for losses while drilling, resulting in a stuck pipe and lost money which is matched with the current depletion status in gulf of suez according to (Radwan and Sen, 2021a, 2021b; Kassem et al., 2021; Abdelghany et al., 2021).

8.2 Petroleum System Challenges

Much of the deeper production from the Paleozoic across the WD is attributed to charge from Khatatba (Jurassic) or (AEB) Cretaceous shales via fault juxtaposition with the Paleozoic, raising questions about the role of the oldest Carboniferous source rocks, which are sometimes unknown. A comprehensive study that confirms the Paleozoic petroleum system has yet to be completed. Poor seismic images of the deepest source rocks (Carboniferous), contributing to poorly studied source rock. More research into the geochemical characterization of deeper resources, as well as biomarker analysis, are required to confirm the petroleum system in the deeper targets.

8.3 Seismic Issues

The number of 3D and 4D seismic surveys conducted across the WD basins is very limited, and the few conducted 3D seismic surveys are local in extent. In terms of seismic quality, seismic images beneath the Alamein dolomite horizon are low resolution, and thus deeper Jurassic and AEB horizons are poorly imaged.

Furthermore, human insight is still required in seismic imaging. In order to provide a precise interpretation. Improved seismic imaging could aid in the discovery of additional structural and combined traps. The majority of the new discoveries are based on 3D seismic imaging, demonstrating the importance of precise seismic imaging in increasing the resources in the WD basins. Furthermore, the deep basin geometries were not adequately defined and are still being unraveled, implying that seismic image quality will improve across the WD sedimentary basins.

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