Subsurface geology and geochemical evaluation of the Middle Jurassic-Lower Cretaceous organic-rich intervals, West Kalabsha area, Western Desert, Egypt

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Abstract
The West Kalabsha (WKAL) area is a western extreme exploratory area of the Faghur Basin in the Western Desert of Egypt. The study of four wells (WKAL; A-1 X, K-1 X, P-1X, and C-1 X), interpreted with twenty seismic lines, shows that the area is dissected by a series of normal faults with an irregular, E–W strike direction. The general trend of the throw is toward the south–southeast. The most prospective area for hydrocarbon (HC) migration is toward the north (upthrown side) of an E-W striking normal fault north of the WKAL-K-1 X and A-1 X wells. The WKAL-P-1 X and WKAL-K-1 X wells in the Faghur Basin were selected for both geochemical evaluation of possible source rock intervals and burial history modelling within the basin. Integration of the wire-line logs with geochemical analysis identified six organic matter-rich intervals (OMRIs) within the Middle Jurassic-Lower Cretaceous sequence. Four intervals are in the Alam El-Bueib-3C (AEB-3C) member with a cumulative vertical thickness of 530ft. The other OMRIs are 110ft in thickness recorded within the AEB-6 (10ft) and Upper Safa (100ft) members. The studied organic matter (OM) reveals type III, IIIC, and IV kerogens (mainly gas-prone) with a terrestrial origin. They have reached a maturity level consistent with the late oil window. The expulsion threshold depth detected in the WKAL-P-1 X well is 12000ft in the AEB-3C member, whereas the active source depth limit (ASDL) is 15000ft in the Safa Member. The present study suggests a paleo-geothermal gradient range between 1.13°F/100ft and 1.39°F/100ft with an estimated regional erosion of 5500 to 7000ft of strata mainly between the Paleozoic-Jurassic and Cretaceous-Tertiary boundaries. The present-day geothermal gradient based on bottom-hole temperatures shows a geothermal gradient of 1.4°F/100ft (WKAL-P-1 X), that increases to the north to 1.65°F/100ft (WKAL-K-1 X). Burial history modelling reveals that sedimentary strata entered the mature oil zone in the Early Cretaceous (110–115Ma) at depths of 7500–8000ft in the deepest part of WKAL-P-1 X and WKAL-K-1 X wells (Paleozoic strata). Maturation continued to present, resulting in Jurassic and Lower Cretaceous strata currently falling into the late oil window.

Keywords Subsurface geology · Organic geochemistry · Burial history · Organic-rich intervals · Expulsion threshold depth · Active source depth limit

Introduction

The Western Desert (WD) is an important oil- and gas-producing area in Egypt. Most of the production comes from a series of NE-ENE half grabens representing Early Mesozoic Tethyan basins that extend across the central and western parts of Egypt (Moustafa 2020). These basins (Kattaniya, Mubarak, Alamein, Razzaq, Matruh, and Shushan) attribute their initiation to convergence between the Afro-Arabian and Eurasian plates (Fig. 1a). The West Kalabsha area and Faghur Basin are south and southwestern extensions of the Shushan Basin in the northern WD (Bosworth et al. 2015). The West Kalabsha area is located...
between latitudes 30° 15' N, 30° 39' N, and longitudes 25° 40" E, 26° 04" E of the Faghur Basin, north WD of Egypt (Fig. 1). The first exploratory Faghur-1X well was drilled by the Khalda Petroleum Company in 1989, and it encountered oil pay in the Alam El Bueib (AEB) Formation (Bosworth et al. 2015). From 2010 to the recent, many of the WKAL wells were drilled in the northern part of the Faghur Basin.

The WKAL area is divided into several exploration and development blocks which are named alphabetically from A to P according to Khalda Petroleum Company (2015). In the present study, the four studied wells in the WKAL area are A-1 X, K-1 X, P-1X, and C-1 X (Fig. 1b). The argillaceous sandstone units of the Middle Jurassic Lower Safa Member of the Khatatba Formation and the Lower Cretaceous AEB members are the main reservoirs in the studied area. A drill stem test (DST) taken in the study area revealed an average producing rate of 2.95 million cubic feet (MCF) of gas and 1660 barrels of oil per day (BOPD) from the Lower Safa and 15MCF of gas and 2900 BOPD from the Early Cretaceous AEB Formation (Energy Egypt 2018).

The Faghur Basin is a continental rift basin that contains multiple organic-rich shales and carbonates in its stratigraphic sequence. The main source rocks in the WD basins are the organic-rich shales and carbonates of the Abu Roash-F member carbonates (Upper Cretaceous), AEB member shales (Lower Cretaceous), Khatatba formation shales (Middle Jurassic), Desouky formation shale (Carboniferous), and Zeitoun formation shale (Devonian) (Fig. 2) (Keeley et al. 1990; EGPC 1992; Schlumberger 1995; Maky and El Sayed 2007; Bakr 2009; Abd El Gawad et al. 2019a; Abd El Gawad et al. 2019b).

This paper discusses the impact of subsurface structural geology that affected the WKAL area to reconstruct the general tectonic evolution and deduce its role in the hydrocarbon migration pathway, and implications for future exploration. Geochemical analysis along with measured vitrinite reflectance of the Middle Jurassic and Lower Cretaceous source
rocks from two wells was conducted to provide an understanding of the organic-rich intervals (OMRIs). Specifically, this study examines the lithologic character associated with favorable geochemical parameters of quantity, quality, and maturity of organic matter within the studied wells. The prediction of the expulsion threshold, active source rock limits depth, evaluation of geothermal gradients, and the extent of erosion were made to better understand the study area’s petroleum exploration potential. These data were incorporated into basin models to document the timing of hydrocarbon generation and migration.

**General geologic setting**

**Stratigraphy**

The stratigraphic succession in the Western Desert of Egypt ranges from the Paleozoic to Recent (Said 1990; Schlumberger 1995). El Sherief et al. (2020) simplified the sedimentary sequence in the Western Desert into a lower siliciclastic dominated sequence that ranges from the Cambrian to the pre-Cenomanian, a carbonate-dominated sequence from the Cenomanian to Eocene and the
upper siliciclastic dominated sequence from the Oligocene to Recent. The oldest Paleozoic strata rest unconformably on the Precambrian basement, which is rarely encountered except in the deepest drilled wells. Gravity and magnetic data in the Western Desert are used to establish the depth to the basement in these basins (Saada and El-Khadragy 2015; Saada et al. 2022). The generalized stratigraphic column of the Faghur Basin is illustrated (Fig. 2).

The Paleozoic contains pre-rift strata of the Desouky formation. Most of the sedimentary sequences in the continental rift basins begin with fluvial sandstones (Lower Jurassic Ras Qattara Formation). A major unconformity separates the Paleozoic and the Mesozoic (Abd El Gawad et al. 2016). The initiation of Jurassic rifting resulted in the syn-rift sediments of the Khatatba Formation that can be divided into two members: the lower Safa argillaceous sandstones and the Zahra shale and carbonate alternations. These packages represent marginal marine to shallow marine depositional settings respectively (Taha 1992; Moustafa 2008). The pre-rift Desouky and syn-rift Ras Qattara, Khatatba, and Masajid Formations represent the oldest basal major depositional cycle (Taha and Halim 1992). The second major depositional cycle includes the Lower Cretaceous AEB Formation, which has been subdivided into six members (Fig. 2). The lower AEB-5 and AEB-6 are composed of argillaceous sediments alternating with carbonates. These are overlain by marine shales of the AEB-4 and a fluvial sandstone succession separated by a marine shale of the AEB-3C (Fagelnour et al. 2018). The AEB-3C is overlain by alternating shale, sandstone, and carbonates of AEB-1 and AEB-2 followed upward by the limestones and dolomites of the Alamein formation. This major depositional cycle ended with the regional shale and siltstone deposition of the Dahab Formation. The third major depositional cycle initiated with the deposition of the thick fluvial Khairta formation sediments (end of the Early Cretaceous) which are composed of fine to coarse sandstones intercalated with siltstones. A major unconformity marks the transition of the Late Cretaceous into the Baharyia Formation, which was deposited on a shallow marine shelf; it consists of alternating sandstone, siltstone, shale, and carbonates. Increased water depth followed by deposition of the Abu Roash Formation limestones and shales. By the end of the Late Cretaceous, the chalky limestone of the Khoman Formation was deposited, suggesting water depths greater than 300m depth (Leeder 2011). This major depositional cycle ended with the deposition of the cherty-limestone of the Apollonia Formation (Paleocene-Middle Eocene). A conglomeratic unconformity surface separates the Apollonia Formation from the underlying Khoman Formation. The fourth cycle consists of the Dabaa and Moghra limestones and shale intercalations, which are topped by limestone of the Marmarica Formation (Fig. 2).

Structure

The WD is affected by four Mesozoic-Cenozoic deformation events that are responsible for the major aspects of fault trends (Moustafa 2020). These events were either subsequent or synchronous, resulting in the overlap of events. They are from the oldest to the youngest as follows: a) Tethyan rifting (Late Triassic–Early Cretaceous) responsible for the opening of NE-SW-oriented rifts, b) Cretaceous rifting (Early Cretaceous–Early Eocene) responsible for the opening of WNW-ESE oriented rifts, c) Tethyan convergence (Late Cretaceous–Recent) responsible for basin inversion of NE and ENE oriented rifts, and d) the Gulf of Suez and the Red Sea rifting (Late Oligocene–Recent) responsible for NE-SW-oriented extension (Moustafa 2008).

The above-mentioned deformational events affected the WD basins that appear bounded by generally normal faults of E-W, ENE-WSW, and NE-SW strike orientation. The Faghur Basin is characterized by a NE- to ENE-oriented half-graben geometry with general NNW tilting of sedimentary blocks toward the major listric faults that occupied the northwestern sides of the basin (Moustafa 2020). Tectonic activity in the area is mainly related to N-S major extension stresses during Jurassic rifting. The combined phases of extension and inversion in the WD controlled the geometry of fault trends and the direction of dipping sedimentary strata in each basin (Fagelnour et al. 2019). The geometric trends of structures in each area differ from one basin to another. These structures have an essential role in establishing the migration pathways emanating from pre-inversion source rocks (Bosworth and Tari 2021).

Available data and analytical methods

Subsurface geology

The dataset includes twenty 2D seismic lines, plus supporting data from four wells (wireline logs, mud logs, and check-shots). The locations of the seismic lines (in-lines and cross-lines) and wells (WKAL-K-1 X, WKAL-A-1 X, WKAL-C-1 X, and WKAL-P-1 X) are presented in Fig. 1b. Seismic lines were depth-converted before interpretation (Al-Chalabi 1997). A structural model was created using the depth maps and several zones have been correlated using well tops to constrain interpretation (Fagelnour et al. 2018). The lithological interpretation of each well was performed using wireline and mud logs (Rider 2002). The Schlumberger Petrel software has been used for seismic interpretation, lithology interpretation, and modelling (Schlumberger 2009; 2011).
Organic geochemistry and petrography

Geochemical analysis in the present study involved TOC and Rock-Eval pyrolysis on samples from the WKAL P-1X well. Thirty-nine drilling ditch samples were studied from five members of the AEB 3C (1100ft; 19 samples), AEB-4 (20ft; 3 samples), AEB-6 (50ft; 5 samples), Zahra (10ft; 2 samples), and U. Safa (100ft; 10 samples) as summarized in Table 1. Samples were powdered to < 200 microns in a glass beaker and then treated with dilute HCl to remove calcium carbonate. Samples were then washed with distilled water and dried, then ignited at 1200°C in a Leco crucible in an oxidizing environment. A C230 Instrument was used for organic carbon determination of TOC. Rock-Eval 6 was used to measure volatile HC (S1), residual HC (S2), and (CO2) amounts during pyrolysis (S3) by progressive pyrolysis stages. Tmax was obtained from the peak of the S2 curve.

Sixteen vitrinite reflectance (Ro) from the WKAL-K-1 X well was measured on a polished surface of telinite and collotelinite from different depths (Table 2). The preparation of polished block samples and measurements of random Ro reflectance data were carried out according to ISO7404/2 (2009) and ISO 7404/5 (2009). The Ro values were used to establish a maturity profile, geothermal gradient, and burial history.

The Ro_cal values were obtained from the Rock-Eval parameters (Ro_cal = (0.0317*Tmax)-13.224; Lohr and Hackley 2021) and used in the WKAL-P-1 X well to give additional information on the maturity and burial history that is valid and coincide with the true Ro in case samples did not exceed the overmature maturity stage (Wust et al. 2012; Lohr and Hackley 2021).

Analyses were conducted under standard conditions at the Stratochem Services (SCS) geochemistry labs. Further parameters and indices from the geochemical analysis are calculated to interpret the quantity, quality, maturity, OMRI, depositional setting, geothermal gradient, eroded thickness, and burial history.

The burial history models of two studied wells (WKAL- P-1 X and WKAL-K-1 X) were illustrated using the 2D PetroMod software by the Easy% Ro method of Sweeney and Burnham (1990). The construction used a combination of data of the composite stratigraphic thickness driven by logs, types of lithology, thermal maturity, and absolute age for each formation.

Results and discussion

Subsurface geology and entrapment style

The Early Jurassic rifting in the north WD created the accommodation space for basin fill, resulting in the deposition of thick fluvial and marine sediments in the WKAL area and Faghur Basin. Like the majority of rift basins, the WKAL area shows a series of normal faulting as a result of the extension. The interpreted NW-SE seismic line (Fig. 3) shows a pattern of normal step-faults affecting the Paleozoic, Upper Jurassic (Masajid Fm), and Lower Cretaceous (AEB-2 and Alamein Fm) sedimentary sequences. The Jurassic and Lower Cretaceous rocks thicken and dip toward the major faults bounding the basin to the north. Major normal faults are dipping south to southeast, with minor faults dipping to the north. The faults that dip to the north represent anti-faults that may indicate later inversion that affected the area associated with drag along many of the fault planes (faults number 2, 3, 4, and 6) as shown in Fig. 3. These faults dissect the study area into a sense of tilted faulted blocks, making step-faults and horst and graben structures. Some of these blocks are characterized by folded structures as a result of drape folding; they appear as monoclines in the younger post-rift strata. These monocline-like structures are also attributed to the inversion tectonism that occurred by the end of the Cretaceous (Guiraud and Bosworth 1997; Guiraud et al. 2001; Bevan and Moustafa 2012).

These folded and faulted blocks characterize most petroleum traps in the Jurassic and Lower Cretaceous section of the WKAL area and Faghur Basin (Fig. 4), and they have a throw ranging from 500 to 1500ft to the south and southeast directions. Migration of hydrocarbons occurred vertically along faults and also along updip pathways to the shallower sandstone reservoirs (Makled et al. 2020).

Five main lithologies were interpreted from wireline and mud logs: sandstone, shale, siltstone, limestone, and dolomite. The succession from Jurassic to Lower Cretaceous is presented and the lithology of each unit is shown in the geological cross-section of Fig. 5. The sandstones of both Alam El Bueib and Lower Khatahba formations (L. Safa Mbr) are the main reservoirs. The low permeability shales act as seals where the AEB-3E sandstone is capped by the AEB-3D shale; the Lower Safa sandstone reservoir is capped by shales of the Upper Safa. Normal faults play an important role in juxtaposing impermeable AEB-3C shales in the vicinity of the permeable sandstones of the Alam El Bueib units, which provide a lateral seal for migrating hydrocarbons. Intercalated sands and shales (i.e., AEB-3C, AEB-6, and U. Safa shales) allow some local charge to some sandstone reservoirs; others are sourced by migration pathways from the older Paleozoic-effective source rocks to the shallower sandstone reservoirs (L. Safa and AEB).

Structure contour maps of the main reservoirs (Lower Safa; Middle Jurassic) were constructed to realize the optimal shallow sites for further development (Fig. 4). These sites are on the upthrown-side blocks associated with fault number 6 that
Table 1  Summary of the Rock-eval pyrolysis analysis and its measured indices of samples penetrated five members of WKAL-P1-X well; Ro_{cal} = (0.0317 * Tmax) - 13.224 (Lohr and Hackley 2021)

| Age          | Members | Depth interval (ft) | Thickness (ft) | Total number of samples | Values (TOC (wt.% of rock), S₁ (mg HC/g rock), S₂ (mg HC/g rock), S₃ (mg CO₂/g rock), S₂/S₃ GP=S₁+S₂, HI (mg HC/g rock), OI (mg CO₂/g rock), RHP=S₁+S₂/TOC, PI=S₁/(S₁+S₂)*100, OSI=S₁/TOC*100, Vitrinite Reflectance (Ro_{cal}, %), Tmax (°C)) |
|--------------|---------|---------------------|----------------|-------------------------|---------------------------------------------------------------------------------|
| Early Cretaceous | AEB-3C  | 11760-13550         | 740            | 19                      | Min. 0.51 0.07 0.26 0.49 0.24 0.35 46 22 61.40 0.06 4.36 0.60 436                      |
|               |         |                     |                |                         | Max. 2.75 0.11 5.15 1.15 8.58 5.27 187 193 158.82 0.26 15.79 1.01 449               |
|               |         |                     |                |                         | Average 0.99 0.09 0.98 0.84 1.38 1.06 88 102 98.40 0.11 9.95 0.77 441            |
|               | AEB-4   | 14240-14260         | 20             | 3                       | Min. 0.75 0.08 0.53 0.69 0.70 0.61 64 83 73.49 0.12 9.64 0.79 442               |
|               |         |                     |                |                         | Max. 0.92 0.10 0.64 0.85 0.77 0.73 71 101 84 0.16 13.33 0.98 448               |
|               |         |                     |                |                         | Average 0.83 0.09 0.57 0.77 0.74 0.66 68 92 78.95 0.14 10.92 0.86 444         |
|               | AEB-6   | 14470-14520         | 50             | 5                       | Min. 0.67 0.08 0.40 0.63 0.25 0.38 40 44 56.72 0.08 7.75 0.69 439               |
|               |         |                     |                |                         | Max. 1.42 0.11 1.21 1.08 1.92 1.32 85 161 92.96 0.29 16.42 0.98 448            |
|               |         |                     |                |                         | Average 0.91 0.10 0.61 0.79 0.84 0.70 63 97 73.95 0.17 11.45 0.88 445          |
|               |         |                     |                |                         | Min. 0.62 0.08 0.28 0.78 0.36 0.36 45 126 58.06 0.22 12.90 0.66 438             |
|               |         |                     |                |                         | Max. 0.62 0.09 0.32 0.84 0.38 0.41 52 135 66.13 0.22 14.52 0.72 440            |
|               |         |                     |                |                         | Average 0.62 0.09 0.30 0.81 0.37 0.39 48 131 62.10 0.22 13.71 0.69 439         |
| Middle Jurassic | Zahra  | 14770-14780         | 10             | 2                       | Min. 0.62 0.08 0.28 0.78 0.36 0.36 45 126 58.06 0.22 12.90 0.66 438             |
|               |         |                     |                |                         | Max. 0.62 0.09 0.32 0.84 0.38 0.41 52 135 66.13 0.22 14.52 0.72 440            |
|               |         |                     |                |                         | Average 0.62 0.09 0.30 0.81 0.37 0.39 48 131 62.10 0.22 13.71 0.69 439         |
|               | Upper   | 14790-14970         | 180            | 10                      | Min. 0.58 0.09 0.25 0.75 0.33 0.34 43 43 56.76 0.05 4.53 0.72 440               |
|               | Safa    |                     |                |                         | Max. 3.31 0.15 3.07 2.39 2.16 3.22 93 166 97.28 0.26 15.52 1.36 460             |
|               |         |                     |                |                         | Average 1.37 0.11 1.02 1.22 0.80 1.13 66 102 75.77 0.14 9.93 1.10 452           |
runs from the west to east direction northern of the WKAL A-1 X and WKAL K-1 X wells (Figs. 1 and 4).

**Evaluation of OM-bearing intervals**

In the present study, the authors discuss the geochemical requirements for oil system production at a regional scale and the recognition of the local sweet spots throughout the wells.

**OM richness**

The quantity of the OM in source rock is fundamental for hydrocarbon generation (Tissot and Welte 1984; Espitalie et al. 1997). Therefore, the determined total organic carbon (TOC) provides a priority quantitative of involved OM in a sample (Hazra et al. 2017; Atta-Peters et al. 2015; Singh and Kumar 2018; Deaf et al. 2021). Traditionally, the TOC analysis is measured randomly throughout the formations that are thought to be rich in organic carbon. Further Rock-Eval analysis techniques are required for samples with a TOC value higher than 0.5wt%. Katz and Lin (2014) mentioned that the source rocks should possess TOC>1wt%.

| Sample no. | Depth (ft) | Ro % |
|------------|------------|------|
| 1          | 5510       | 0.37 |
| 2          | 7010       | 0.66 |
| 3          | 8350       | 0.69 |
| 4          | 8750       | 0.69 |
| 5          | 8950       | 0.72 |
| 6          | 9180       | 0.76 |
| 7          | 9620       | 0.75 |
| 8          | 10060      | 0.73 |
| 9          | 10670      | 0.68 |
| 10         | 11200      | 0.82 |
| 11         | 11700      | 0.79 |
| 12         | 12300      | 0.9  |
| 13         | 12660      | 0.91 |
| 14         | 13180      | 1.02 |
| 15         | 13420      | 1.14 |
| 16         | 13600      | 1.06 |

**Fig. 3** NW–SE structural pattern interpretation of a seismic line across wells WKAL-K-1 X and WKAL-P-1 X in the WKAL area.
and often greater than 2wt%. In this study, TOC of the investigated formations have values from 0.51 to 2.75wt%, with an average of 0.99wt% (AEB-3C), (0.75–0.92wt%), with an average of 0.83wt% (AEB-4), (0.67–1.42wt%), with an average of 0.91wt% (AEB-6), 0.62wt% (Zahra), and (0.58–3.31wt%) with an average of 1.38wt% (U. Safa) (Table 1). The Middle Jurassic Upper Safa Member has the richest TOC content, suggesting that it is a good source rock. Other investigated members contain limited TOC amounts between 0.5 and 1.0wt% (Peter and Cassa, 1994; Fowler et al. 2005; Deaf et al. 2022).

To assess the sample hydrocarbon staining or contamination during this study, the OSI parameters (S1/TOC) according to Smith (1994) and a cross-plot diagram of the free volatile HC (S1) against TOC of Jarvie et al. (2001) are used. The OSI parameter shows very low values of AEB-3C (9.95), AEB-4 (10.92), AEB-6 (11.45), Zahra (13.71), and U. Safa (9.93). Such data indicates
indigenous HC (Table 1). Plotted samples of investigated members on the Jarvie diagram also indicate indigenous organic matter (Fig. 6a).

Based on the TOC, the S1 and S2 of the investigated members reveal a wide variety of poor (TOC < 0.5, S1 < 0.5, and S2 < 2.5), moderate (TOC and S1 range between (0.5–1) and S2 (2.5–5) and good source quantities (TOC and S1 (1–2, 2–4, > 4) and S2 (5–10, 10–20, > 20)) according to Peters and Cassa (1994).

The relationship between the generative potential HC (S2) and TOC (Fig. 6b) shows that most of the samples with very good potential are restricted to the AEB-3C and U. Safa samples. Samples with fair potential are represented by all the other members besides AEB-4 and Zahra (Fig. 6b). Accordingly, the AEB-4 and Zahra are the lowest OM-bearing members in the studied well, while AEB-3C and U. Safa are the highest OM-bearing members.

**Kerogen types**

OM quality is investigated using the hydrogen index (HI). These values range from type IV HI<50 (48mg HC/g TOC, Zahra members), to type III kerogen (gas-prone) with HI between 50 and 200 (88mg HC/g TOC, AEB-3C; 68mg HC/g TOC, AEB-6; 63mg HC/g TOC, AEB-4, and 66mg HC/g TOC, U. Safa) (Table. 1). The kerogen quality can also be assessed based on the ratios of S2/S3 which indicate that the AEB-3C Member has an S2/S3 ratio between 1 and 5 (1.38); other members have an S2/S3 values less than 1 typical of type IV kerogen characterized AEB-4 (0.74), AEB-6 (0.84), Zahra (0.37), and U. Safa (0.80).

By plotting the studied members on the van Krevelen modified diagram (Vega-Ortiz et al. 2020) (Fig. 7a) and pseudo van Krevelen types diagram (Fig. 7b), the majority of OM belong to kerogen types III and IV of terrestrial
The kerogen type IV is an indication of a considerable alteration and oxidation of preserved OM.

Other diagrams used to confirm the types and productivity of OM-bearing samples include the HC generative potential S2 versus the TOC (Langford and Blanc-Valleron 1990; Delgado et al. 2018) (Fig. 8), which shows that the OM is mainly type III kerogen half that of the samples lay within the area belonging to type IV kerogen as characterized by the previous Fig. 7a and b); these are interpreted to be type III mature samples that were subjected to oxidation. The potential of the present samples is largely limited to a gas source.

Confirmation of kerogen types and their depositional environments can be made using the work of Walter (2006); (Fig. 9). The author gives an illustrated view of kerogen according to HI that matched with H/C ratios. The plotted samples on this diagram show three ranges of data: kerogen types IV of HI < 60mg HC/g TOC (equivalent to H/C ratio < 0.5), type III of HI of 90–120mg HC/g TOC (equivalent to H/C ratio range from 0.7 to 1), and type IIIC of HI of 120–300mg HC/g TOC (equivalent to H/C ratio of 1 to 1.2); (Fig. 9). The depositional setting of these types is suggested by Walters (2006) to be within a marine coastal plain and delta with an admixture potential of gas-prone (type III) and
coal-oil prone (type IIIC), with oxidized inert (type IV) of primarily biotic input of vascular land plants and algal origin.

The HI versus Tmax diagram discriminates one obvious zone of maturity of the oil window zone. All the samples occupying the area below the line concern type III of the per-hydrous character of OM rich in hydrogen (algal coal oil-prone type) according to Khatibi et al. (2018) (Fig. 10a).

Level of maturity

The maximum temperature of S2 peak (Tmax), calculated vitrinite reflectance \( R_{\text{cal}} = (0.0317 \times \text{Tmax}) - 13.224 \) (Lohr and Hackly, 2021), and production index (PI) are used in this study to identify the thermal maturity level by taking into account the limiting factors affecting the observed reflectance of kinetic maturity. These factors include the type of OM, temperature, time, and mineral matrix effect of sedimentary sequence with human factors of misidentification (presence of solid bitumen with vitrinite), multiple populations (presence of recycling vitrinite), and insufficient measurements, which also may alter data (Wust et al. 2012; Katz and Lin 2021; Lohr and Hackley 2021). Tmax averages range from 441°C related to AEB-3C member to higher average values of 452°C in the U. Safa member (Table 1). \( R_{\text{cal}} \) calculated values are between 0.77 and 1.1 for the same investigated members. These values indicate a maturity level within the mature-oil stage (Hunt 2000; Hazra et al. 2019).

In the PI against the Tmax diagram (Fig. 10b), the results are consistent. Additionally, half of the present samples lay above the line of 0.1 (PI), indicating a high-level conversion (thermal conversion of a carbonaceous substance to liquid) (Ghori and Haines 2007; Delgado et al. 2018). From the previous diagrams, the more mature samples are related to the deepest and oldest Middle Jurassic Upper Safa Member which is within the late mature oil-window maturity level. The chart of the semi-quantitative HC expulsion of investigated samples that belong to the effective source rock is illustrated to determine the source rock index (SRI; Fig. 11). The SRI reflects the actual percentages of expelled HC in comparison to the amounts that potentially are expelled for optimal source rocks. Samples show that the parts of U. Safa, AEB-3, and AEB-6 express medium and good quality source rocks, whereas most samples represent poor to non-HC source rocks. Within the same members, there are intervals rich in OM and intervals poor in OM.

OM-rich and OM-poor intervals

From the above-mentioned geochemical discussion, it is necessary to conclude that not all the members contain sufficient organic matter to be an effective source rock when thermal maturity is considered. The detection of the OMRIs in the studied well is done using an adapted quantity, quality, and maturity parameter that was suggested by Edress et al. (2012) in three continuous steps (Fig. 12). Six OMRIs are detected in the present study, belonging to AEB-3, AEB-6, and U. Safa members. The thickness of these rich intervals comprised 330, 90, 100, and 10ft from the top to bottom concerned AEB-3C (19.72% of their entire thickness), 10ft of AEB-6, and 100ft of U. Safa members. These zones are considered the effective source rocks in the WKAL-P-1 X well, based on their OM richness and maturity.

However, the lithologies interpreted from the wire-line and mud logging interpretation postulate the first two zones of the AEB-3C (depth intervals of 11760–12090ft and 12400–12500ft) are dominated by sandstones rather than mudstone and carbonate-prone source rocks (Fig. 12). The
other four OMRI, two in AEB-3C, one in AEB-6, and one in U. Safa Member, are interpreted as effective source rock-prone lithologies.

**Geothermal gradient and estimated eroded thickness**

Suggate (1998) spotlights two vital facts based on the relationships between Ro and burial depth. The first is that the measured Ro values from ditch cuttings samples at a certain depth do not coincide with the present-day proposal Ro at this depth (i.e., Ro exhibits a higher value than to greater burial depth than the depth in which samples are gathered). The second fact is that the relationship between Ro and burial depth is not linear, but is logarithmic (dog-leg shape). Dow (1977) suggested the latter phenomena of the multiple thermal maturity effects may be related to a much slower sedimentation rate between sedimentary
strata of different ages. Also, he mentioned that intrusive rock may cause a profound effect on changing the maturity profile within a basin. Suggate (1998) made a standard chart to determine the presumed maximum burial depth of the sedimentary sequence of any borehole plus ancient geothermal gradient (Fig. 13). While Suggate made a drawing relationship by hand, in the present study, the authors suggest the Chi-square exponential fit is a suitable correlation coefficient to make the Suggate dog-leg relationship between the present Ro versus the burial depth in the studied well (using Origin Pro-Software v.9); then, the Chi-square exponential fit curve was hand drawn to match the ancient geothermal gradient. After matching, the author was able to estimate the ancient burial of the investigated well to be higher than the present depth; this suggests the vertical thickness of missing (eroded) strata.

Katz and Pheifer (1984) noted that these would be a minimum estimate.

By applying the above-mentioned methods to sixteen measured Ro samples from WKAL-K-1 X well and thirty-nine calculated vitrinite reflectance (Lohr and Hackley 2021) samples from WKAL-P-1 X well, the Chi-square exponential fit curve of the WAKAL-K-1 X samples matches with a geothermal gradient of 1.39°F/100ft, while the fit line of the WAK-P-1 X matches with a geothermal gradient of 1.11°F/100ft (Fig. 13). The later differences between the geothermal gradient of the two wells show a slight increase from the south well (WKAL-P-1 X) toward the north well (WKAL-K-1 X). To confirm these notable
changes in the geothermal gradient in the study area, the authors used another procedure based on recent bottom-hole temperature to assign the geothermal gradient of the investigated wells. They postulate a geothermal gradient of 1.65°F/100ft and 1.44°F/100ft for the WKAL-K-1 X well and for WKAL-P-1 X well, respectively. The latter methods show a minor increase in geothermal with 0.26–0.33°F/100ft higher than the ancient geothermal gradient from Suggate Chart (Fig. 13). The increase in the geothermal gradient may be attributed either to an unknown magmatic intrusive located to the north of the study area or simply by a shallowing of the basement bathymetry toward the north. Seismic data do not detect any igneous intrusive in the north; it also does not image the basement. To confirm this argument, an additional geophysical study of magnetic and gravity is needed.

The Suggate model reveals that the studied well should be in the past buried to a position deeper than the present-day depth, with an additional of 5500–7000ft that may consider the amounts of erosion (Fig. 13b). This eroded thickness may be reflected within the unconformity surfaces between stratigraphic units in the area under investigation (Katz and Pheifer 1982) (Fig. 2).

Fig. 13 a) Linear correlation exponential fit relationship (Chi-square exponential decay first order) between the Ro against burial depth of investigated WKAL-P-1 X and WKAL-K-1 X wells. b) Matching of studied wells maturity curves on the standard Suggate burial chart for deep sedimentary basins (Suggate 1998)

Fig. 14 Cross plot of relative hydrocarbon potential ((RHP) versus depth to detect the Expulsion threshold depth and active source rock depth limit (ASDL) of the WKAL-P-1 X well (Pang et al. 2019)
Expulsion threshold depth and ASDL depths

To give the most acceptable depths of the hydrocarbon threshold expulsion and active source rock depth limit (ASDL), the author used the relative hydrocarbon potential (RHP) = ((S1 + S2)/TOC) peak curve related to the burial depth (Pang et al. 2019). The threshold maximum curve by the author fit the expulsion threshold depth, where the retreat of the RHP curve is an indication of ASDL (Fig. 14). Here the depth of 12000ft is considered the expulsion threshold depth at the WKAL-P-1 X well, where lies within the depths limits of the AEB-2C Member, where the depth of 15000ft is illustrated as a depth of ASDL that lies within the depths limits of the Safa member (Fig. 14).

Burial history modelling

Burial history models for two according to Easy% Ro (Sweeney and Burnham 1990) wells were used to distinguish the burial history in the study area from the south (WKAL-P-1 X) to the north (WKAL-K-1 X) wells (Fig. 15a and b). The burial model reveals that deposition began in the Paleozoic (340Ma ago) (Carboniferous) and continued to the recent with a sedimentary succession of more than 15000ft. The early oil stage of the investigated wells strata was initiated in the Early Cretaceous time (≈110–115Ma) until the Recent. The lower third part and lower half of the WKAL-P-1 X and WKAL-K-1 X wells in respective order are within the mature oil stage (from Paleozoic to Lower-Cretaceous
Dahab Formation in WKAL-P-1 X well, and possibly to the younger Kharita Formation in the WKAL-K-1 X well) (Fig. 15a). The lithological units within the oil maturity stages of the studied wells can be differentiated into three maturity levels. The first level is of mature early oil zones extending from Kharita to AEB-3C. The second portion of the mature main-oil zone level extends from AFB-3C, AEB-4 through the Zahra members. The lower portion of the late-oil mature zone level is restricted to the deepest and oldest Safa and Paleozoic. From Fig. 15a and b), the Kharita Formation at the WKAL-P-1 X well is still within the immature stage (Fig. 15b), whereas this zone to the north WKAL-K-1 X well enters the early oil stage of maturation (Fig. 15a). This may be related to an increase in the thermal effect due to the slight increase in the geothermal gradient in the study area to the north. Generally, the burial history reveals the oldest Paleozoic strata within the studied area entered an early oil zone from \( \approx 110 \) to 115Ma, reaching the main oil-zone \( \approx 75–80 \)Ma, and late-oil zone at \( \approx 25 \)Ma till the Recent.

**Conclusion**

Subsurface data, including 2D twenty seismic lines with four wells in the west Kalabsha area, are used to illustrate the lithological and structural patterns of the studied area. Seismic cross-section suggests a series of irregular E-W strike direction normal step faults with a general throw of (500–1500ft) toward the S and SE directions, and these faults dissect the area laterally forming separated blocks bounded by fault planes of irregular trending E-W strike direction. A normal and reverse drag along fault planes are recorded in the seismic cross-section and can be attributed to later Late Cretaceous inversion tectonism that affects the basin. This pattern of structure favored the development of oil migration pathways toward the N and NW. Geochemical characterization of thirty-nine samples of AEB-3C, AEB-4, AEB-6, Zahra, and Upper Safa members of Middle Jurassic-Late Cretaceous age differentiate six mature OMRI's in the studied WKAL-P-1 X well. The first two OM-rich intervals are recorded within the AEB-3C member at depth intervals 11760–12090ft and 12410–12500ft and display both reservoirs and source rock characteristics. The 3rd and 4th intervals consist of pure mudstone source rocks within the same AEB-3C member and attain a thickness of 110ft. The above-mentioned OMRI's have a cumulative thickness of 530ft, comprising 19.72% of the entire thickness of AEB-3C members. The 5th and 6th OMRI's are within the AEB-6 and U. Safa members with a vertical thickness of 110ft. These six OMRI's are considered the main effective source rocks within the studied well and their vicinity area. While the AEB-4 and Zahra members are considered poor intervals within the studied well, Chi-square exponential fit of \( \text{Ro}_{\text{cal}} \) and RHP against depth applied by the authors to distinguish both the expulsion threshold and ASDL depths within the WKAL-P-1 X well suggest burial depths of 12000ft and 15000ft, respectively. The 12000ft expulsion threshold depth coincides with the main oil stage of maturation in burial history of the AEB-C Member. The present study reveals a slight increase in the geothermal gradient in the study area from the south to the north as confirmed by two methods (Suggata chart and bottom-hole temperatures). The gradient increases toward the north led the younger Lower Cretaceous Kharita Formation to enter the early oil mature stage in the north, while still immature in the south. The burial history diagram reveals that the deposition of strata in the basin initiated from 340Ma.

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**Declarations**

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**Competing interests** The authors declare no competing interests.

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References

Abd El Gawad EA, Fathy M, Abd El Dayem KH (2016) Integrated characterization of Desouky reservoir Rock in Faghrur - Siwa Basin, Western-Desert, Egypt. Int J Innov Sci Eng Technol (IJISET) 3:2348–7968

Abd El Gawad EA, Ghaniem MF, Makled WA (2019a) Source rock evaluation of subsurface Devonian–Carboniferous succession based on palyno-organic facies analysis in Faghrur Basin, North Western Desert of Egypt: a division of the North Africa Paleozoic Basins. Arab J Geo Sci 12:655. https://doi.org/10.1007/s12517-019-4802-5

Abd El Gawad EA, Ghaniem MF, Lotfy MM, Mousa DA, Temraz MG, Shehata AM (2019b) Burial and thermal history simulation of the subsurface Paleozoic source rocks in Faghrur basin, north Western Desert, Egypt: Implication for hydrocarbon generation and expulsion history. Egypt J Pet 28(3):261–271, ISSN 1110-0621. https://doi.org/10.1016/j.ejpe.2019.06.001

Al-Chalabi M (1997) Time-depth relationships for multilayer depth conversion. Geophys Prospect 45:715–720

Atta-Peters D, Achaegakwo CA, Garrey P (2015) Palynofacies, organic geochemical analyses and hydrocarbon potential of the Takoradi 11-1 Well, Saltpond basin, Ghana. Petroleum and Coal 57(5):478–499

Bakr MMY (2009) Molecular organic geochemistry of crude oil from Shushan and Abu Ghuradig Basins, Western Desert, Egypt. J King Abdulaziz Univ Earth Sci 20:97–125

Bevan TG, Moustafa AR (2012) Inverted rift-basins of northern Egypt. In: Phanerozoic Rift Systems and Sedimentary Basins. Elsevier, pp. 483-507

Bosworth W, Drummond M, Abrams M, Thompson M (2015) Jurassic rift initiation source rock in the Western Desert, Egypt – relevance to exploration in other continental rift systems. in: Petroleum Systems in “Rift” Basins, 34th Annual GCSSEPM Foundation Perkins Rosen Research Conference, 13–16 December 2015, Houston, https://doi.org/10.5724/gcs.15.34.0615

Bosworth W, Tari G (2021) Hydrocarbon accumulation in basins with multiple phases of extension and inversion: examples from the Western Desert (Egypt) and the western Black Sea. Solid Earth 12:59–77. https://doi.org/10.5194/se-12-59-2021

Deaf AS, El Soughier MI, Gentzis T, Makled WA (2021) Hydrocarbon source rock potential of the Lower Eocene carbonates from the Western Desert of Egypt – relevance to exploration in other continental rift systems. in: Petroleum Systems in “Rift” Basins, 34th Annual GCSSEPM Foundation Perkins Rosen Research Conference, 13–16 December 2015, Houston, https://doi.org/10.5724/gcs.15.34.0615

Deaf AS, Omran AA, El-Arab ESZ, Maky ABI (2022) Integrated organic geochemical/petrographic and well logging analyses to evaluate the hydrocarbon source rock potential of the Middle Jurassic upper Khatatba Formation in Matruh Basin, northwestern Egypt Marine and Petroleum Geology 2021,132, 105235

Delgado L, Batezelli A, Luna J (2018) Petroleum geochemical characterization of Albian Oligocene sequences in the Campos Basin: case study: Eastern Marlim oil field, offshore, Brazil. J S Am Earth Sci 88:715–735

Dow WG (1977) Kerogen studies and geological interpretations. J Geochem Explor 7:79–99

Edress NAA, Darwish S, Ismail A (2021) Geochemical characterization of the source rock intervals, Beni-Suef Basin, West Nile Valley, Egypt. Open Geosci 13(1):1536–1551. https://doi.org/10.1515/geo-2020-0306

EGPC Egyptian General Petroleum Corporation (1992) Western Desert, oil and gas fields. In: EGPC 11th Petroleum Exploration and Production Conference, Cairo, Egypt (a comprehensive overview): Al-Ahram Commercial Presses, Cairo, 431 p

El Shereif MA, Elbdestawy MA, Abdeldayem AL, Mohamed SA (2020) Source Rock Evaluation of Some Mesozoic and Paleozoic Rocks, Faghur Basin, Neith Field, North Western Desert, Egypt. DJS. 42(2): 45 – 57

Energy Egypt (2018) Eni announces second oil discovery at Faghrur Basin in Egypt’s Western Desert. Energy Egypt Newsletter. https://energyegypt.net/eni-announces-second-oil-discovery-at-faghrur-basinin-egypts-western-desert/1

Espitalie JM, Laporte JL, Madec M, Marquis F, Laplot P, Paulet J (1997) Rapid method for source rock characterization, and for determination of their petroleum potential and degree of evolution. Rev de l’Inst Francais du Petrole et Ann des Comb Liq 32:23–24

Fagelnour MS, Metwalli FI, Shendi EH (2018) Structural and facies modeling of the Lower Cretaceous Alum El Bueib reservoirs in the Shushan Basin, Western Desert, Egypt. Arab J Geo Sci 11(9):1–24

Fagelnour MS, Gamil I, El Toukhy M, Gharieb A, Saad H (2019) Source rock potentiality, basin modeling, and oil to source correlation in Northern Shushan Basin, Western Desert, Egypt. Offshore Mediterranean Conference

Fowler M, Snowdon L, Stasiuk V (2005) Applying petroleum geochemistry to hydrocarbon exploration and exploitation. AAPG, Geologists Short Course Notes, June 18–19, Calgary, Alberta, 224 pp

Guiraud R, Bosworth W (1997) Senonian basin inversion and rejuvenation of rifting in Africa and Arabia: synthesis and implications to plate-scale tectonics. Tectonophysics 282:39–82

Guiraud R., Issawi B. , Bosworth W (2001) Phanerozoic history of Egypt and surrounding areas, in: Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins, edited by: Ziegler PA, Cavazza W, Robertson AHF, Crasquin- Soleau S, Mémoires du Muséum national d’Histoire naturelle de Paris, 186, 469–509, 2001

Ghori KAR, Haines PW (2007) Paleozoic Petroleum Systems of the Canning Basin, Western Australia: A review. Search and Discovery Article, 10120

Hazra B, Dutta S, Kumar S (2017) TOC calculation of organic matter rich sediments using Rock-Eval pyrolysis: Critical consideration and insights Inter. J Coal Geol 169:106–115

Hazra B, Wood DA, Mani D, Singh PK, Singh AK (2017) TOC calculation of organic matter rich sediments using Rock-Eval pyrolysis: Critical consideration and insights Inter. J Coal Geol 169:106–115

Hunt JM (2000) Petroleum geochemistry and geology, 2nd Eds. W. H. Freeman and Company, 743 P

ISO-7404/2 (2009) Methods for petrographic analysis of bituminous coal and anthracite-part 2: methods of preparing coal sampling International organization for standardization. Geneva Switzerland, pp.1-12

ISO 7404/5 (2009) Methods for the petrographic analysis of bituminous coal and anthracite. part 5: method of determining microscopically the reflectance of Vitrinite. International Organization for Standardization, Geneva, Switzerland, pp. 1-14

Jarvie DM, Morelos A, Han Z (2001) Detection of pay zones and pay quality. Gulf of Mexico: application of geochemical techniques. Gulf Coast Assoc Geol Soc Trans 51:151–160

Katz BJ, Lin F (2021) Consideration of the limitations of thermal maturity with respect to vitrinite reflectance, Tmax, and other proxies. AAPG 105(4):695–720

Katz BJ, Lin F (2014) Lacustrine basin unconventional resource plays: key differences. Mar Pet Geol 56:255–265

Katz BJ, Pheifer RN (1982) Characteristics of Cretaceous organic matter in the Atlantic. In Watkins, J. S., and Drake, C. L. (Eds.), Studies in Continental Margin Geology: Tulsa (AAPG), Mem. 34:617-628., 1986. Organic geochemical characteristics of Atlantic Ocean
Khalda Petrorroleum Company (2015) Tectonic and geologic setting of the Kalasha area. Internal reports (unpublished), 1-70
Khatibi S, Ostadhassan M, Tuschel D, Gentzis T, Carvajal-Ortiz H (2018) Evaluating molecular evolution of kerogen by raman spectroscopy: correlation with optical microscopy and rock-eval pyrolysis. Energies 11(1406):1–19
Keeley ML, Dungworth G, Floyd CS, Forbes GA, King C, Garva RM, Shaw D (1990) The Jurassic System in Northern Egypt: I. Regional stratigraphy and implications for hydrocarbon prospectivity. J Pet Geol 13:397–420
Langford FF, Blanc-Valleron MM (1990) Interpreting Rock-Eval Pyrolysis data using graphs of pyrolizable hydrocarbons vs. total organic carbon. AAPG 74:799-804
Leeder MR (2011) Sedimentology and sedimentary basins: from turbulence to tectonics 2nd Edition, Kindle Edition, Wiley-Blackwell, 1328 p
Lohr CD, Hackley PC (2021) Relating Tmax and hydrogen index to vitinite and solid bitumen reflectance in hydrous pyrolysis residues: comparisons to natural thermal indices. Int J Coal Geol 242:103768
Makled WA, Abd El Moneim A, Mostafa TF, El Sawy MZ, Mousa DA, Ragab MO (2020) Petroleum play of the Lower Cretaceous Alam El Blueib Formation in the El Noor-1X well in the north Western Desert (Egypt): a sequence stratigraphic framework. Mar Pet Geol 116:104287
Maky ABF, El Sayed SM (2007) Source rock characteristics of some Upper Cretaceous rock units, Abu Gharadig basin, north Western Desert, Egypt, and relevance to petroleum generation: Sedimentology of Egypt, 15: 121-138
Moustafa AR (2008) Mesozoic-Cenozoic basin evolution in the Northern Western Desert of Egypt”, 3rd Symposium on the Sedimentary Basins of Libya (The Geology of East Libya), 3: 29-46.
Moustafa AR (2020) Mesozoic-Cenozoic basin evolution in the Northern Western Desert of Egypt”, 3rd Symposium on the Sedimentary Basins of Libya (The Geology of East Libya), 3: 29-46.
Moustafa AR (2020) Mesozoic-Cenozoic deformation history of Egypt. In: Hamimi Z., El-Barooky A., Martínez Frías J., Fritz H., Abd El-Rahman Y. (eds) The Geology of Egypt. Regional Geology Reviews. Springer, Cham. https://doi.org/10.1007/978-3-030-15265-9_7.
Pang X, Jia C, Zhang K, Li M, Wang Y, Peng J (2019) The depth limit for the Formation and occurrence of fossil fuel resources. Earth Syst Sci Data Discuss 72:1–26. https://doi.org/10.5194/essd-2019-72
Peters KE, Cassa MR (1994) Applied source rock geochemistry. In: Magoon L. B., Dow, W. G., (Eds.) The petroleum system from source to trap. AAPG, 93-120
Rider MH (2002) The geological interpretation of well logs, 2nd edition, Whittles Publishing, 280 p
Saada SA, El-Khadrady AA (2015) An integrated study of gravity and magnetic data on West El-Minya Area, Western Desert Egypt. J American Sci 11(12):169–184
Saada SA, Eldosouky AM, Kamel M, El Khadrady A, Abdelrahman K, Fnais MS (2022) Micku K (2022) Understanding the structural framework controlling the sedimentary basins from the integration of gravity and magnetic data: a case study from the east of the Qattara Depression area, Egypt. J King Saud Univ Sci 34:101808
Said R (1990) The geology of Egypt. Balkema-Rotterdam-Brookfield
Singh AK, Kumar A (2018) Petrographic and geochemical study of Gurha Lignites, Bikaner Basin, Rajasthan, India: implications for thermal maturity, hydrocarbon generation potential and paleodepositional. Environ J Geol Soc India 92:27–35
Smith JT (1994) Petroleum system logic as an exploration tool in frontier settings. In: Magoon LP, Dow WG, editors. The petroleum system from source to trap. Vol. 60. AAPG Mem; 1994. p. 25–49
Suggate PR (1998) Relations between depth of burial, vitrinite reflectance and geothermal gradient. J Pet Geol 21(1):5–32
Sweeney JJ, Burnham AK (1990) Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. AAPG 74:1559–1570
Schlumberger (1995) Well evaluation conference, Egypt. EGPC Report Schlumberger (2009) Information Solutions, Petrel geology course. Schlumberger
Schlumberger (2011) Information Solutions, Petrel Geophysics course. Schlumberger
Taha MA (1992) Mesozoic rift basins in Egypt: their southern extension and impact on future exploration. Proceedings of the 11th Petroleum Exploration and Production Conference, Cairo, 1988. The Egyptian General Petroleum Corporation, 2: 1-19
Taha MA, Halim MA (1992) The impact of sequence stratigraphic synthesis on the petroleum exploration in the Western Desert. Proceedings of the 11th Petroleum Exploration and Production Conference, Cairo, 1988. The Egyptian General Petroleum Corporation, 2: 39-55
Tissot BP, Welte DH (1984) Petroleum formation and occurrence. 2nd ed. Heidelberg: Springer-Verlag, 699 p
Vega-Ortiz C, Beti DR, Setoyama E, Mc-Lennan JD, Ring TA, Levey R, Martinez-Romero N (2020) Source rock evaluation in the Tamaulipas Basin, Mexico. J Am Earth Sci 100:102552
Walters C (2006) The origin of petroleum In: practical advances in petroleum processing. https://doi.org/10.1007/978-0-387-25789-1_2, 79-101
Wust K, Hackley P, Nassichuk B, Willment N, Brezovski R (2012) Vitrinite reflectance versus pyrolysis Tmax data: assessing thermal maturity in shale plays with spectral reflectance to the Duvernay shale play of Western Canadian sedimentary basin. Soc Pet Eng J 167031:1–11

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