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ORIGINAL PAPER

Well log-aided source rock potential, basin modeling, and seismic attributes: Petroleum geology case study of Pliocene discovery at South Mansoura Area (Nile Delta)

Ahmed M. Elatrash[1,2] · Mohammad A. Abdelwahhab[3] · Hamdalla A. Wanas[4] · Samir I. El-Naggar[5] · Hasan M. Elshayeb[1]

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Abstract

Confirming hydrocarbon charge in reservoir assessment is crucial for exploration and appraisal phases of oil and gas business. This paper addresses the source rock assessment and basin modeling, as well as seismic attributes, of Miocene-Pliocene sequences, shedding light on petroleum potential at South Mansoura Area. South Mansoura-1 well was chosen in performing the required investigation. It contains complete set of logs, enclosing gamma ray, resistivity, neutron, density, and sonic logs. Passey formula was used in calculating the TOC (total organic carbon) within the source rock intervals, employing resistivity and porosity logs. 1-D basin model was established to retrieve the burial history and maturation levels within the area. Various seismic attributes have been extracted for the Pliocene target, to confirm the hydrocarbon accumulation within the reservoir intervals. The results show a rather significant source-prone interval for Middle-Late Miocene Sidi Salem and a predominant source potential for Pliocene Kafr El Sheikh shales, capable of feeding reservoir intervals of Messinian Qawasim, Abu Madi, and Pliocene Kafr El Sheikh formations, due to the adequate generation level featuring the penetrated rocks. The shales of the penetrated units are in the main generation window for expelling hydrocarbons. Moreover, direct hydrocarbon indicator and seismic attribute analyses of Pliocene and Miocene Kafr El Sheikh and Abu Madi formations, respectively, confirm the hydrocarbon charging within the reservoir intervals. Accordingly, it is recommended to expand the investigations to reveal out the structural configuration controlling the area, and migration pathways revealed applying 2-D basin modeling approaches, so as to mark the best locations for drilling new development wells. Furthermore, the established 1-D basin model, performed in this study, could be effectively used as a baseline for future plays at the Nile Delta basin.

Keywords Source rock evaluation · Basin modeling · Petroleum geology · Miocene-Pliocene sequences · South Mansoura development lease · Onshore Nile Delta

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✉ Mohammad A. Abdelwahhab
geo.mohammad85@azhar.edu.eg;
abdelwahhabfulbright@gmail.com

1 Department of Geology, Faculty of Science, Menoufia University, Shebin El-Kom, Menoufia, Egypt

2 Exploration Department, Egyptian Natural Gas Holding Company (EGAS), Nasr City, Cairo, Egypt

3 Geology Department, Faculty of Science, Al-Azhar University, Nasr City, Cairo, Egypt

4 Department of Petroleum Geology & Sedimentology, Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Saudi Arabia

5 Alamein Petroleum Company, Maadi, Cairo, Egypt

Introduction

The Nile Delta province has been a focus of extensive combined approaches to outline the hydrocarbon potential and unprecedented discoveries in Nile Delta basin (Egypt). Few years ago, successful exploration campaigns have been operated within the Nile Delta. This may show that this province has started to disclose some of its hidden petroleum potential due to using the state-of-the-art techniques in exploration and development. Moreover, the use of various kinds of geophysical, geochemical, and geological modeling could increase the chances of success in revealing out the area's hydrocarbon potential (EGPC 1994) and also geothermal potential (AbdelHafeez et al. 2019), particularly upon combining approaches. About 60

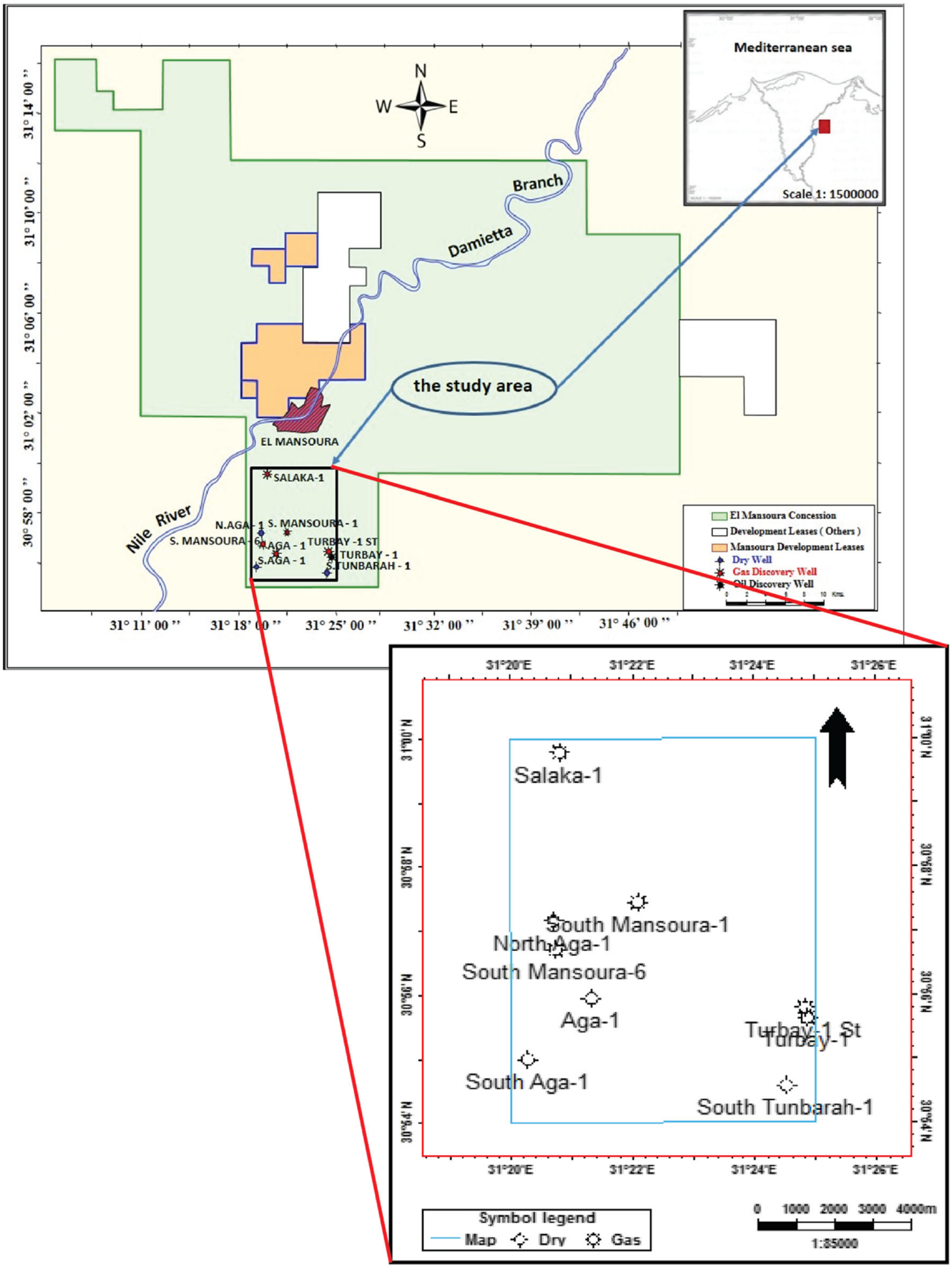


Fig. 1 Location map of the study area

Tcf gas reserves have been found within various intervals, from Oligocene to Plio-Pleistocene, in the Nile Delta basin till recent time (Nini et al. 2010). So that, many multinational companies started exploring for new discoveries in the Nile Delta (Hussein et al. 2019). The main aim of this paper is to run a workflow capable of investigating the petroleum potential, of Miocene-Pliocene sequences, in the study area, though combining TOC calculation, from well data, 1-D basin modeling, and seismic attribute analysis approaches.

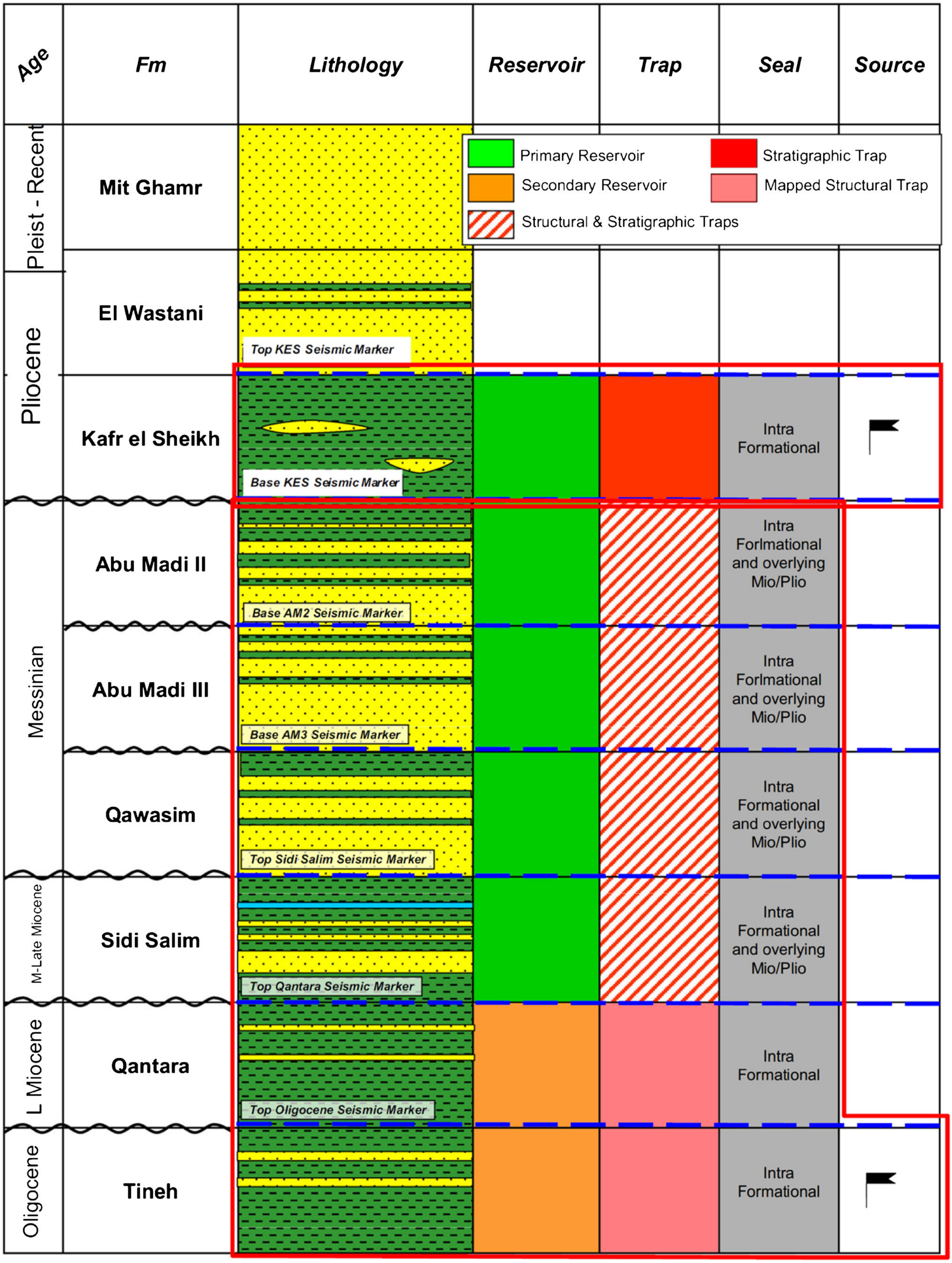
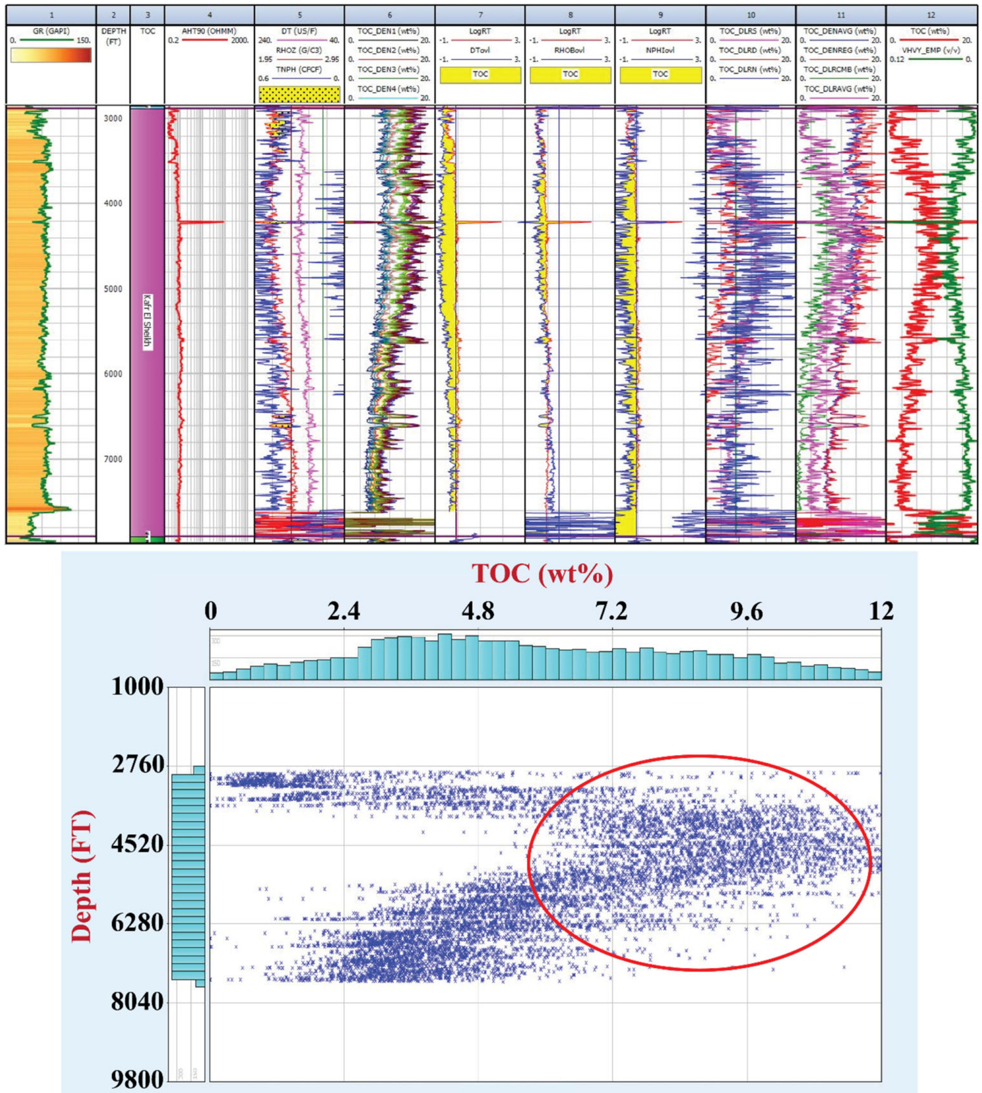


Fig. 2 The stratigraphic column of the study area (Abu El-Ata et al. 2019)

Fig. 3 Well log-based TOC calculation for Kafr El Sheikh formation



Geological setting

The Nile Delta province is located within plate margin of the East Mediterranean region. It occupies the northern margin of Africa, from arcs of Cretan and Cyprus formed by subduction zone to the Red Sea (EGPC 1994). The study area is located in the Nile Delta at approximately 6 km South of El Mansoura City (Elatrash et al. 2021) that occupies the central Damietta branch. The study area (Fig. 1) is approximately located between latitude 30 deg 54 min 00 s and 31 deg 00 min 00 s N and longitudes 31 deg 20 min 00 s and 31 deg 25 min 00 s E. It occupies the unstable shelf within the Delta. The petroleum potential lies within Neogene–Quaternary sequences (Abdel Halim 2001; Abd El-Gawad et al. 2019). The potential sequences of Neogene–Quaternary are divided into three main sedimentary successions: the Miocene, the Pliocene, and the Holocene (Kamel et al. 1998). In the study area, Miocene successions consist of shales and sandstones of Sidi Salim, Qawasim, and Abu Madi formations that underlie the Pliocene shales and minor sandstone beds of Kafr El Sheikh interval. El-Wastani, Mit-Ghamr, and Bilqas formations come over Kafr El Sheikh sediments (Fig. 2) (Leila et al. 2016; Leila and Moscariello 2017; Abu El-Ata et al. 2019; Hussein et al. 2019 ; Leila and Mohamed 2020).

Data and methods

The current investigation depends on the use of the available data of boreholes, South Mansoura-1 well, and post-stack time migrated seismic data. Complete set of well logs are employed, e.g. gamma ray, sonic, resistivity, density, and neutron logs. Passey formula was used in calculating the TOC (total organic carbon) within the source intervals, using

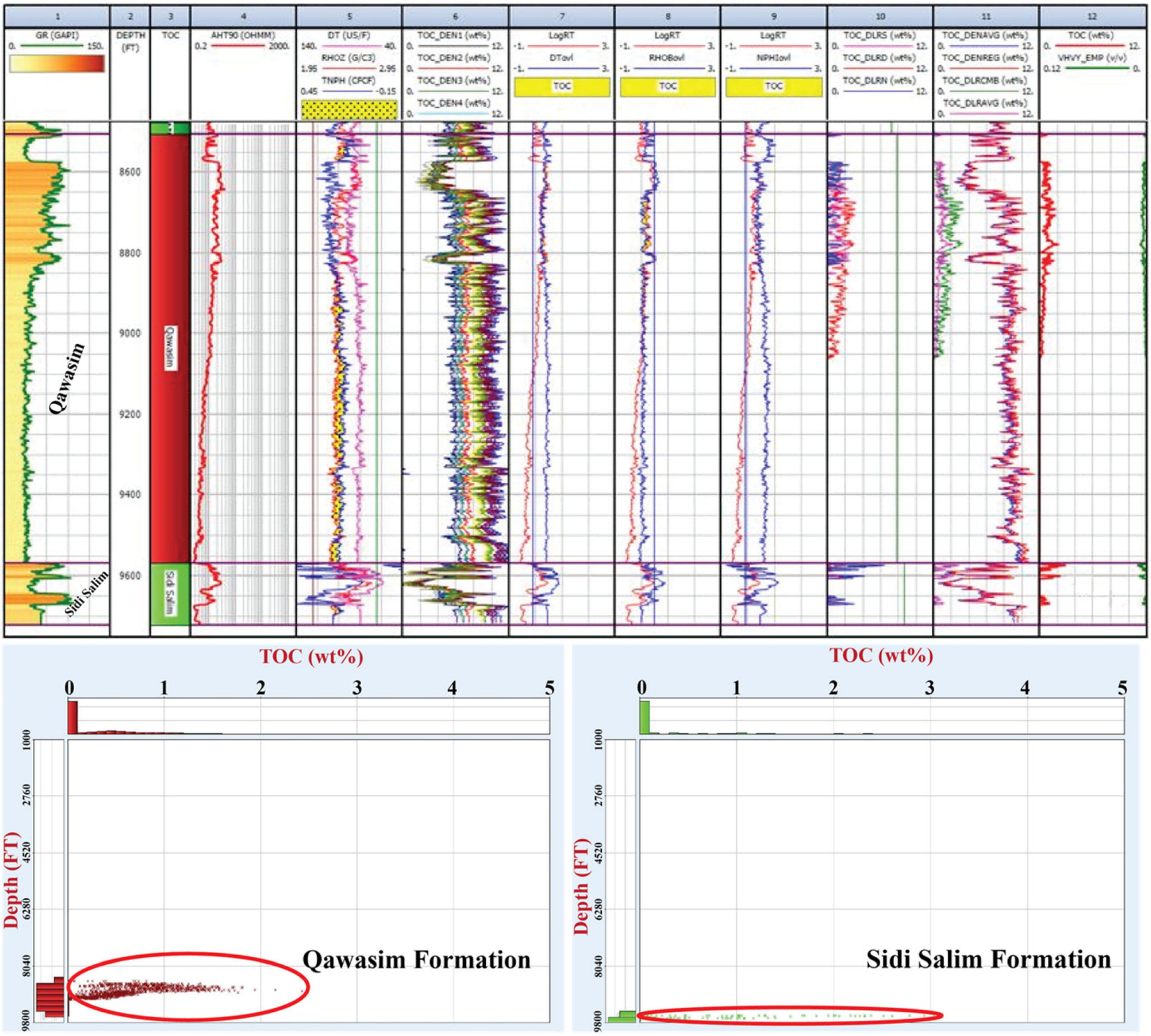


Fig. 4 Well log-based TOC calculation for Qawasim and Sidi Salim formations

resistivity and porosity logs' separation (Passey et al. 1990). 1-D basin model was established to retrieve the burial history and maturation levels within the area, using information of age, depth, lithology, TOC, and boundary conditions (Abdelwahhab and Raef 2020). Direct hydrocarbon indicator (DHI) and seismic attribute analyses, e.g. energy and RMS attributes, were conducted to shed light on the accumulation indication within the reservoir intervals. This work is an attempt to establish an evaluation approach (Abdelwahhab 2020b), combining various related disciplines, capable of setting a baseline for unfolding petroleum potential of an area, reasonably adjusted to appropriate language usage (Abdelwahhab 2020a).

Results and discussions

Source rock evaluation

Evaluation of source rocks, in terms of calculating the TOC content, of different intervals in the study area has been performed using well data of South Mansoura-1 well. TOC was calculated applying Δlog R technique of Passey (Passey et al. 1990), depending on resistivity-porosity logs separation, following the equations:

$$\Delta \log R = \log_{10}(R_{LLD}/R_{base}) + (\Delta t - \Delta t_{base})/164 \qquad (1)$$

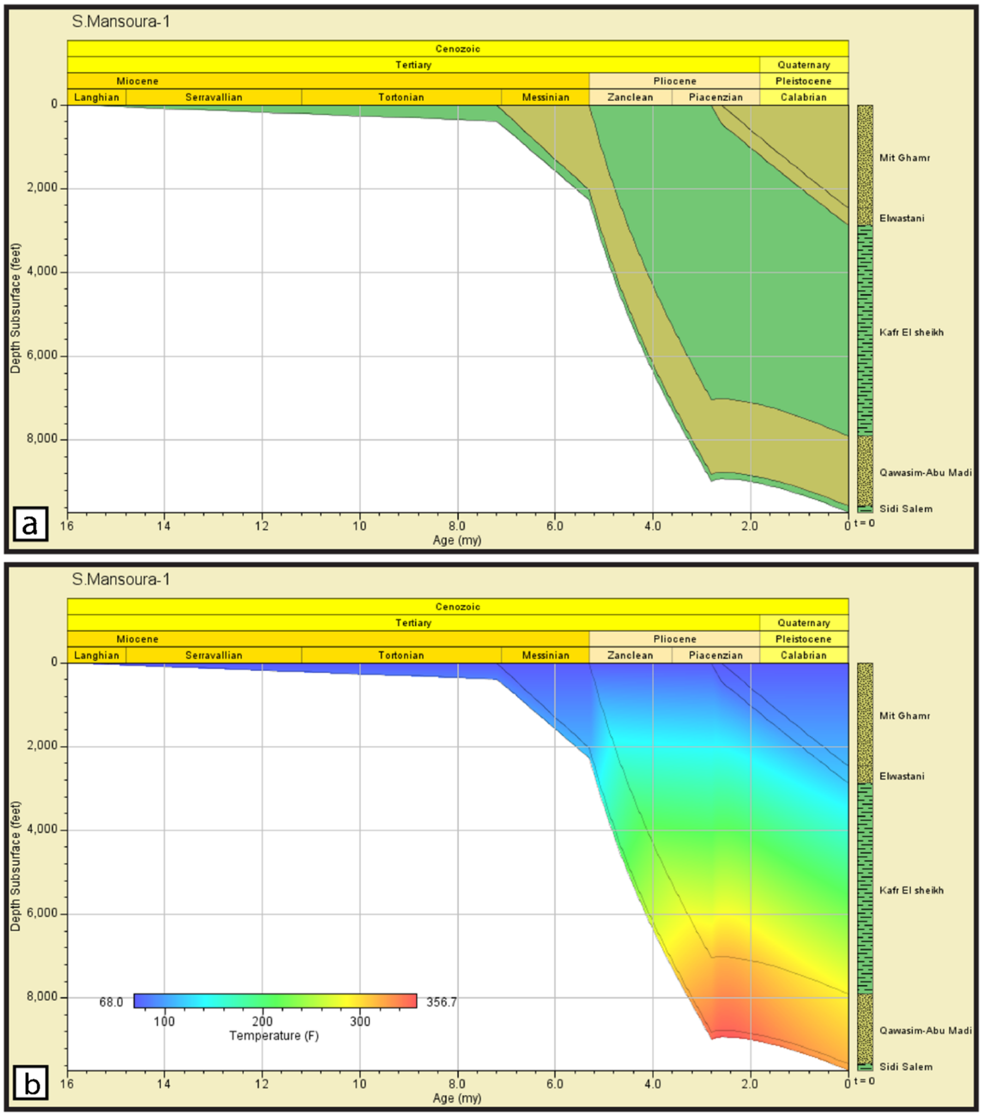


Fig. 5 Burial (**a**) and thermal (**b**) histories of the study area

$$TOC = 10^{(2.297-0.1688L_m)}\Delta \log R \quad (2)$$

where the deep resistivity is R_{LLD}; the resistivity baseline is R_{base}: the interval transit time is Δt; the sonic baseline is Δt_{base}; and the organic maturity level is L_m.

Figure 3 shows the analysis of well log-based TOC calculation and histogram of Kafr El Sheikh Formation. It shows values ranging from 5 to 10 wt%, proving an excellent source potential for Kafr El Sheikh Shales. Moreover, Fig. 4 shows analysis of TOC calculation and histogram of Qawasim Formation. It shows values ranging from 0 to 2 wt%, pointing to a rock far from being even a good source for hydrocarbons; however, it indicates fair source-prone for shale intervals. Furthermore, Fig. 4 also shows analysis of well log-based TOC calculation and histogram of Sidi Salim Formation. It shows values ranging from 0 to 3 wt%, indicating a good source for hydrocarbons attributed to Sidi Salim shale intervals.

Basin modeling

The history of burial and thermal maturation levels was simulated following Littke et al. (1993), Poelchau et al. (1997), Yalcin et al. (1997), Buker et al. (1999), Hantschel and Kauerauf (2009), and Dembicki Jr. (2017). The 1-D basin model input data for testing the thermal maturity of source intervals in this study were depth, age, lithology, TOC, and kinetics (Burnham and Sweeney 1989). Overlying EASY%Ro model of Sweeney and Burnham (1990), organic maturities of source rocks can be calculated. The modeling aims to determine depths and time of generation-expulsion for the selected well in this study.

Through retrieving the geohistory of the area, it is revealed that the temperature gradient increases with depth of burial. The burial, thermal, and maturation histories of the area, as well as the generation rates, are shown in Figs. 5 and 6. It is shown that a discrete four stages subsidence (Fig. 6a) has

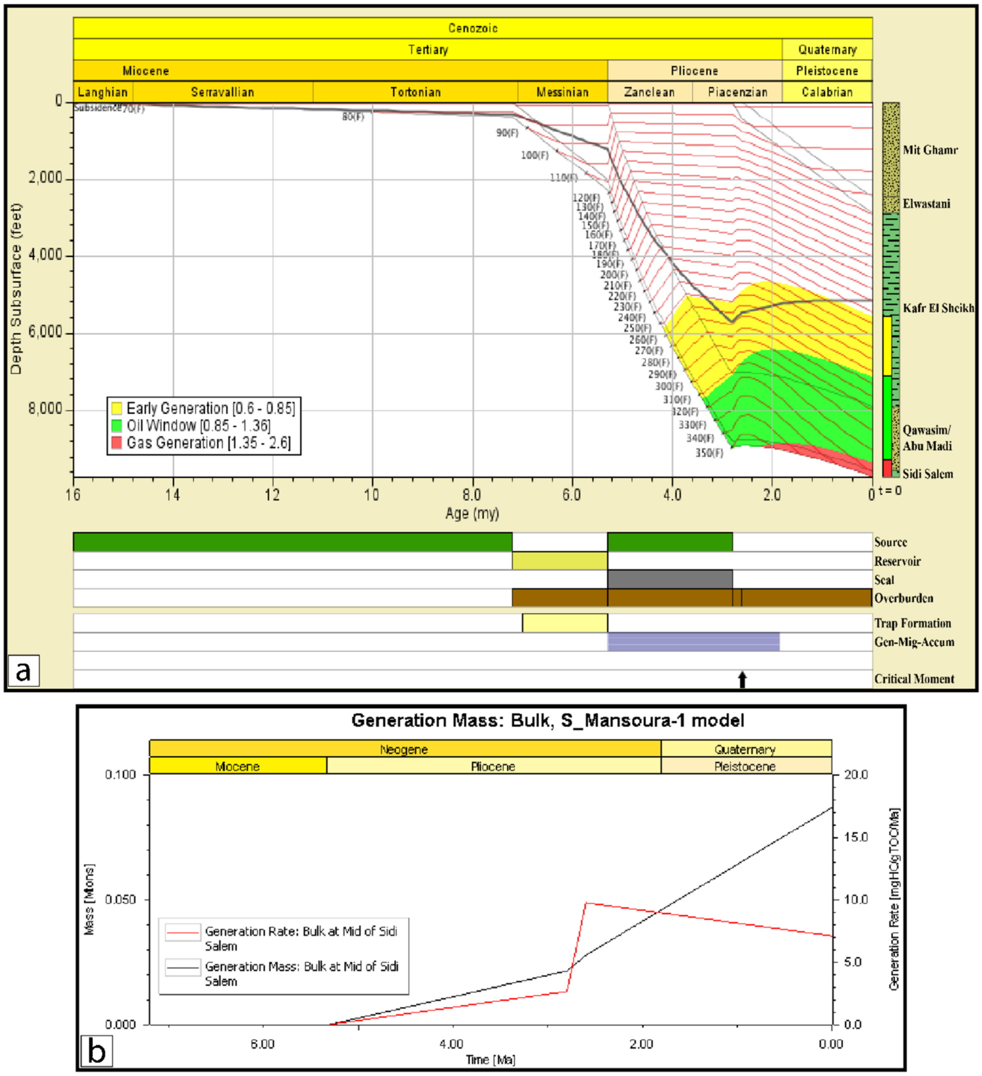


Fig. 6 1-D basin model, thermal maturation, of the study area. **a** Maturation levels (black curve indicates subsidence stages) and **b** generation rate

controlled the tectonic evolution of the area with two phases of rapid rate of subsidence, exactly during the Messinian and Zanclean ages. These phases of slow and rapid rates of subsidence led to the present-day thickness of the rock units in the study area. Using kinetics of Burnham (1989) and EASY%Ro model of Sweeney and Burnham (1990), stages of hydrocarbon generation were obtained. It is clear that Sidi Salem and Kafr El Sheikh shales, source intervals, have yet entered the onset of main generation (0.85–1.36 VRr), providing clues for the oil potential and the subsequent development phases in the area.

Seismic attributes

Energy attribute measures the reflectivity at a particular time window and therefore gives indication for the high amplitude reflection. A time-gate of −8,+16 ms has been evaluated and chosen for detecting the high amplitude anomalies present within the siliciclastic reservoirs of the Pliocene and Miocene intervals of the study area (Fig. 7c). It is obvious that the Pliocene Kafr El Sheikh and Miocene Abu Madi formations contain certain high energy gas-prone sandstone bodies within their reservoir intervals.

Moreover, root mean square (RMS) amplitude attribute (Fig. 7b) has been extracted and used to highlight the high amplitudes over traces; it is commonly known as direct hydrocarbon indicator (DHI). High RMS values are often related to lithological change, sand-bearing landward facies, bright spots, and particularly gas-filled sand zones, where low RMS values point to shale-prone and pro-delta facies. Figure 7 b shows a high RMS amplitude anomaly within Pliocene Kafr El Sheikh formation, indicating the gas-prone facies featuring the reservoir intervals.

Furthermore, the original amplitude attribute (Fig. 7a) shows an obvious bright spot, flat spot, and amplitude polarity reversal, over the gas-bearing reservoir interval of Pliocene Kafr El Sheikh Formation, confirming the accumulation and charging of hydrocarbons.

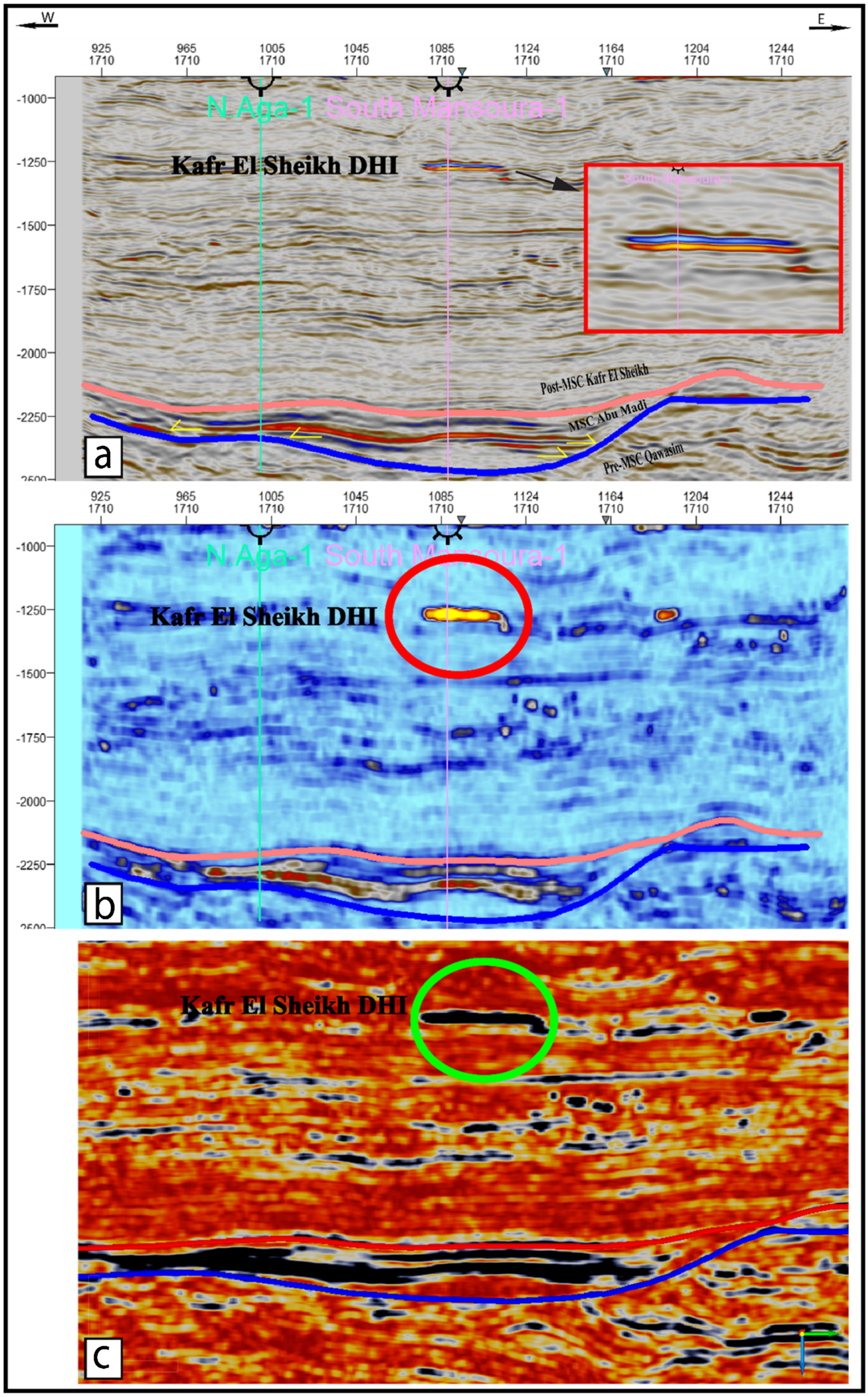


Fig. 7 DHI and seismic attributes of the Miocene-Pliocene reservoir intervals. **a** Original amplitude, **b** RMS amplitude, and **c** energy attribute

Once reservoir distributions, and hydrocarbon confirmation, are achieved, such promising condition would be thoroughly considered during further development plans in the area (Abd El-Hady et al. 2014).

Conclusions

Integrating source rock assessment and 1-D basin modeling, as well as seismic attribute analysis, led to better evaluation of the petroleum system, elements and processes, empowering the area of study. Moreover, the established 1-D basin model, performed in this study, could be effectively used as a baseline for all the Nile Delta plays. It has been obvious that the shales of Sidi Salem and Kafr El Sheikh formations do play a significant role in the formation of hydrocarbons in the area, as they are yet in the main generation stage of development. Moreover, DHI and seismic attribute analyses confirm the gas-prone facies of the reservoir intervals, confirming the hydrocarbon charge from the source intervals of Miocene-Pliocene formations. So, it is recommended to expand the investigations so as to reveal out the structural configuration controlling the area and migration pathways obtained from 2-D and 3-D basin modeling approaches, in order to mark the best locations for drilling new development wells.

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Declarations

Conflict of interest The authors declare no competing interests.

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