ISSN: 1687-1251

Egyptian Society of Applied Petrophysics

Journal of Applied Geophysics (Cairo)

Journal home page: https://jag.journals.ekb.eg/

Original Article

Hydrocarbon Evolution of Northeastern Sinai Peninsula, Egypt

Fatma H. Amin[1*], Adel R. Moustafa[2] and Ashraf A. Hassan[3]

[1] *General Petroleum Company, Nasr City, Cairo Governorate, Egypt.*
[2] *Ain Shams University, Faculty of science, Cairo, Egypt.*
[3] *Ex-chairmen, N. Bahariya Petroleum Company, Cairo, Egypt*

ARTICLE INFO

Keywords:

Hydrocarbon
Sinai Peninsula
EGPC
Egypt

Received: 17 May 2022;
Revised: 19 July 2022
Accepted: 17 August 2022
Published: 1 September, 2022.

ABSTRACT

Good hydrocarbon potentiality is reported in Northeastern Sinai, where good source and reservoir rocks are available, in addition to the structural traps related to the Late Cretaceous-Early Tertiary Syrian arc deformation. Proven working hydrocarbon system is evidenced by the discovery of gas in the fractured Cenomanian carbonate rocks of Sadot field at the northeastern part of this area. Although four wells were previously drilled in the area, the accuracy of seismic structural mapping, as well as the small net/gross sand are behind the failure of three of these wells. We recommend exploration of fractured Cretaceous (and Jurassic) carbonate reservoirs and mapping the fractures from good 3D seismic data, in order to increase the chance of success of future proposed wells.

* Corresponding author at: *General Petroleum Company, Nasr City, Cairo Governorate, Egypt*

1. Introduction

Northern Sinai is a semi region that was affected by the opening and closing of the Neo-Tethys Sea, since the Late Paleozoic-Early Mesozoic times. Excellent exposures of the large NE-SW oriented doubly plunging folds in Gebels Maghara, Halal and Yelleg as well as smaller folds to the south of the Sinai Hinge Belt (Shata, 1959; and Moustafa et al., 2014) represent the Syrian Arc structures previously dealt with by Krenkel (1925) and Said (1962) and summarized in a regional context by Moustafa (2020). Hydrocarbon exploration of similar structural closures in the offshore areas north of Sinai (East Mediterranean Basin, EGPC, 1994; Roberts and Peace, 2007), as well as in the northern Western Desert of Egypt (El Ayouty, 1990 and EGPC, 1992) led to the discovery of many oil and gas fields controlled by such NE-SW oriented anticlines.

The present study area lies at the northeastern portion of Sinai Peninsula, close to Sadot gas field, that was discovered in 1975. This area is 2600 km2 and is bounded to the north by the Mediterranean Sea, to the east by the eastern international border of Egypt, to the south by latitude 30º 51' N and to the west by longitude 33º 52' 30'' E (Fig. 1). The main objective of this study is to throw light on the hydrocarbon potentiality of this area, based on its vicinity to other hydrocarbon fields, both onshore and offshore.

2. Data and Methodology

The data used for this study include seismic and borehole data. The seismic data include 20 2D seismic lines of two surveys (1984 and 1986), with a total length equal to 55 km. Four wells drilled by the General Petroleum Company are also used (Raad-1, Misri-1, Jb 91/3 and Ja 90/2) and have composites, gamma-ray, caliber, resistivity, density, neutron and sonic logs.

The work methodology included the following steps:

1. Defining the stratigraphic column of the study area from the data of the four available boreholes.
2. Stratigraphic correlation of the e-logs of the four wells, in order to study the changes in thickness and facies of the different rock units.
3. Seismic mapping of two different horizons, through the use of Petrel software. These horizons are the near-top Jurassic and the near-top Senonian. Due to the lack of VSP logs and check shots in the used wells, comparison with an interpreted seismic section of Sadot field (EGPC 1994) helped to identify the stratigraphic intervals equivalent to the mapped seismic horizons.
4. Construction of time structure maps for the mapped seismic horizons.
5. Dry-hole analysis of the drilled wells.
6. Study of the hydrocarbon potentiality of the study area, based on the stratigraphic and structural data, as well as the results of the four wells and the comparison with other fields in the nearby areas.

3. Stratigraphy

The stratigraphic section of the study area based, on the 4 available wells, as well as a fifth (older) well named El Khabra-1 and drilled by Standard Oil Company in 1946, is shown in Fig. 2. The deepest penetrated section in these wells is Jurassic in age.

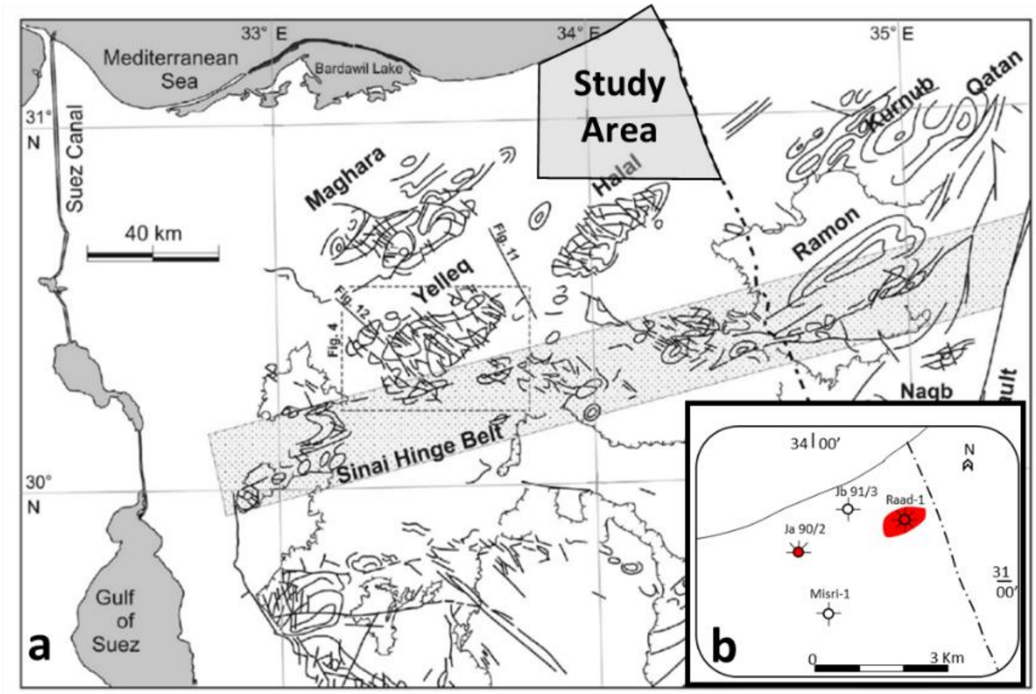

Fig. 1: a- Simplified structural form-line map of north Sinai after Khalil and Moustafa (1994) showing the location of the study area with respect to the Syrian Arc folds of northern Sinai and the nearby area. b- Location map showing the 4 boreholes used in the present study and their location relative to Sadot gas field.

The basal part of the Lower Jurassic was not reached by any of the used wells. The Lower Jurassic section includes, from base to top, the Mashabba, Rajabiah and Shusha formations. The Mashabba Formation consists mainly of compacted carbonates and some clastics, with net/gross sand equal to 16% (78/469 m) in Ja 90/2 well. The Rajabiah Formation consists of compacted and massive limestone, and rare clasticts. The Shusha Formation is an intercalation of clastics and non-clastics, where the shale increases to the north and the sand increases toward the south, with net/gross sand equal to 22% (169/764 m) in Misri-1 well and 5% (22/465 m) in Ja 90/2 well. These clastics are rich in the carbonaceous matter that contains coal seams, especially toward the south.

The Middle Jurassic section is represented by Bir Maghara and Safa formations. The Bir Maghara Formation consists mainly of limestone interbedded with some clastics. The thickness of Bir Maghara Formation increases northward and the net/gross sand is only 1% (4/364 m) in Jb 91/3 well. The Safa Formation varies in thickness and facies from north to south, where its content of carbonates and coal increases northward and the thickness of the clastics increases southward. The net/gross sand in the Safa Formation is 8% (29/384 m) in Misri-1 well and 3% (10/310 m) in Ja 90/2 well.

The Upper Jurassic is represented by the Masajid Formation, which varies in facies from north to south. It is dominantly made up of carbonates northward, but southwards the shale is dominant with rare sand. The net/gross sand in the Masajid Formation is equal to about 2% (7/372 m) in Misri-1 well.

The Cretaceous section unconformably overlies the Jurassic section. The Lower Cretaceous is represented by the Shaltut (Malha) Formation and Alamein Dolomite. The Malha Formation is mainly shale, with some interbedded limestone in the upper part, acting like source and reservoir rock (Abdel Aal and Lelek, 1994). The Alamein Dolomite consists mainly of dolomite, with limestone and shale interbeds.

The Upper Cretaceous includes Cenomanian, Turonian and Senonian rocks. The Cenomanian is represented by the Halal Formation, which is made up of highly fractured dolomitic limestone, that has been recorded as a gas reservoir in Raad-1 well and was also penetrated by Ja 90/2 and Jb 91/3 wells. The Turonian Wata Formation and the Senonian Matulla and Sudr formations are considered good hydrocarbon source and seal rocks, as penetrated by Raad-1 well (after El Kawa et al., 1988).

The Tertiary rocks are mainly carbonates and shale, with rare sandstone. The carbonate rocks increase toward the north, while the clastic sediments increase toward the south.

4. Structural Setting

Seismic mapping of the study area reveals that, the structures affecting the Mesozoic rocks are NE-SW oriented reverse faults dipping toward the NW direction. Each of these reverse faults has a NE-SW oriented, asymmetrical doubly plunging anticline in its hanging wall. These asymmetrical anticlines have steeper southeastern flanks close to the bounding reverse faults (Fig. 3). These reverse faults show normal slip at deeper stratigraphic levels (near top Jurassic and deeper) and reverse slip at shallow level (mostly top Cretaceous rocks). It is obvious that, the northernmost reverse faults in the mapped area have the largest throw (faults at the Jb 91/3 and Ja 90/2 wells). The anticlines in the hanging walls of these reverse faults also have the largest structural relief among the other folds. A NE-SW oriented syncline lies in the footwall of these large-throw reverse faults. Both anticlines in the hanging walls and synclines in the footwalls are genetically related to the reverse faults, representing fault-propagation folding.

Fig. 4 is a 2D seismic section, showing the structural style in the study area. This section extent from north to south at the eastern part of the study area. The section shows a fault dissecting the two Mesozoic horizons (the near top Jurassic and the near top Senonian horizons). The fault has normal slip at the near top Jurassic level and reverse slip at the near top Senonian level. The thickness of the stratigraphic section between the two horizons in the hanging wall is greater than that in the footwall. Flattening of the seismic section at the near top Senonian horizon (Fig. 4b) gets rid of the reverse slip and indicates that, the fault had larger magnitude of normal slip at the Jurassic level. This indicates positive structural inversion on this fault. For this reason, all the doubly plunging anticlines on the hanging walls of similar faults in the study area represent inversion anticlines. Fig. 4 indicates that, the area was subjected to extension during the Jurassic, Early Cretaceous and perhaps part of the Late Cretaceous time, leading to normal faulting and the area was subjected later to compression causing the positive structural inversion and leading to reactivation of the faults by reverse slip. This conclusion agrees with the studies on the Syrian arc structures of northern Sinai (Ayyad et al., 1998; Moustafa, 2010; Yousef et al., 2010; and Moustafa, 2020 among others).

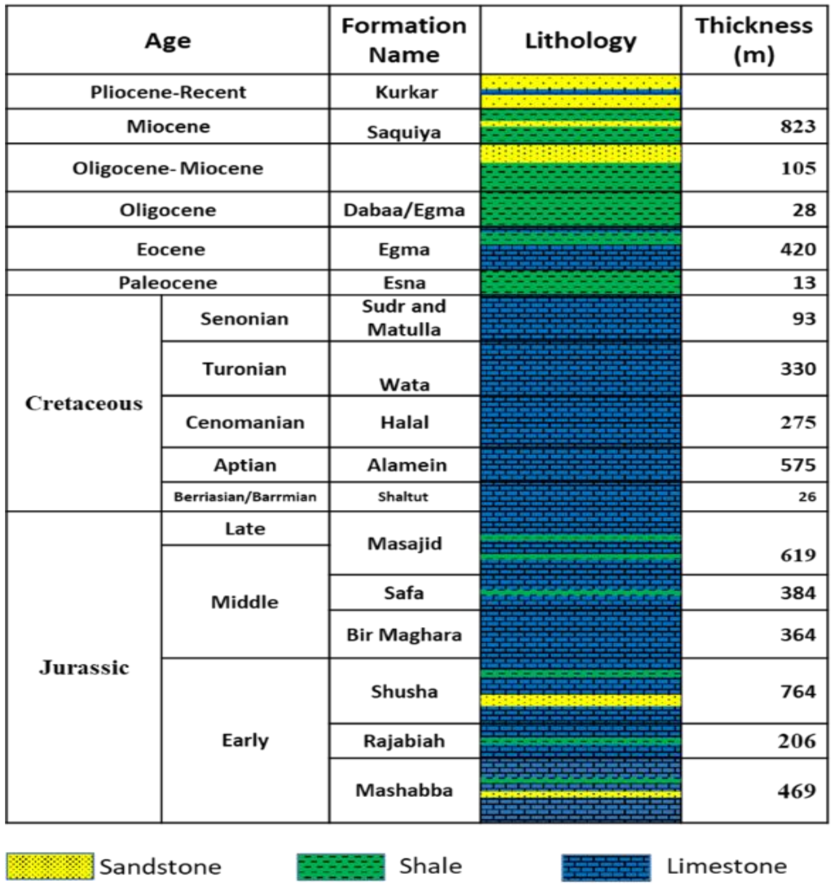

Fig. 2: Ideal Stratigraphic section of the study area based on the results of the available four boreholes.

5. Hydrocarbons potentiality

Four wells were already drilled in the study area, two of them are dry (Misri-1 and Jb 91/3), one was abandoned (Ja 90/2) and the last one (Raad-1) reported high gas reading in the Jurassic section and gas production from the Cenomanian carbonates as it is located within the Sadot gas field but was suspended due to high water saturation and the reservoir was classified as depleted reservoir.

In order to study the hydrocarbon potentiality of the area, we discuss first the different elements of the petroleum system of the area and then the dry hole analysis.

- *Petroleum System Elements of the Study Area*

The information of the petroleum system elements in the study area and their characteristics are based on the previous studies of the exploratory phases of the area including some of the available internal reports, e.g. Gondowana and Robertson (1989).

A. Reservoir Rocks

The reservoir rocks in Northeastern Sinai are represented mainly by sandstone and carbonates of different ages, including Jurassic and Cretaceous, while the Triassic section was not penetrated in the study area. The Jurassic sandstone reservoirs are present in the Mashabba, Bir Maghara, Shusha, Safa, and Masajid formations. These formations are mainly carbonates in the study area with little amounts of clastics (Fig. 5). The Jurassic limestone reservoirs in the study area are represented in the different Jurassic formations, including the Middle Jurassic Safa Formation in Misri-1 well, where these limestones show asphaltic materials and oil spots.

The Lower Cretaceous sandstone reservoir in the study area is represented by the Alamein Formation in Misri-1 and Jb 91/3 wells, with very low net/gross sand values, as shown in Fig. 5. It worth mentioning, that the name “Alamein Dolomite” should not be used for these rocks in the study area as their facies are different from the proper Alamein Dolomite of the Northern Western Desert, where it is composed mainly of dolomite. Exposed rocks of the same age are named the Risan Aneiza Formation at Gebel Maghara area. The Upper Cretaceous section is characterized by fine-crystalline carbonates of marine platform, that are interrupted by conglomerates at disconformities where the quality of the reservoir may be improved by karstification (EGPC, 1994), as these carbonates were locally exposed at the crests of anticlines in some areas in North Sinai. An Upper Cretaceous carbonate reservoir is present in the Cenomanian Halal Formation, as fractured dolomitic limestone, that has high gas reading in Raad-1 well and is gas-bearing and productive in Sadot field, to the northeast of the study area. Although Raad-1 well was drilled at the crest of a four-way dip closure in Sadot gas field, the analysis applied on the Cenomanian reservoir revealed that the water saturation is high with an average of 40% and is classified as a depleted reservoir. values of the Jurassic and Lower Cretaceous formations in the study area. It clearly shows that the net/gross sand values decrease toward the north. Also, they are relatively low except for the Mashaaba and Shusha formations, where the net/gross values are reasonable.

B. Source Rocks

The hydrocarbon source rocks of the study area exist in the Jurassic and Upper Cretaceous formations. The existence of coal seams in the Jurassic rocks of Gebel Maghara (Shusha and Safa formations; Al-Far, 1966) marks the Jurassic rocks as potential source rocks.

Geochemical analysis of the offshore and onshore wells in Northern Sinai shows that, the Jurassic source rocks are rich in organic matter and exist in the Shusha, Bir Maghara, Safa and Masajid formations and have more than 1.5 % TOC (internal report). The average TOC in the Jurassic is 2 % and the recorded TOC in Misri-1 well is 2.64 %. Also, the presence of coal in the Safa Formation proves its inclusion of organic matter (Alsharhan and Salah, 1996).

C. Seal and Cap Rocks

The seal/cap in the study area is represented vertically by the Jurassic shale and massive carbonate formations overlying the Lower Jurassic sandstone and Middle Jurassic carbonate reservoirs. The Cretaceous shales are also considered as a good cap for the Lower Cretaceous reservoirs. In addition, the Eocene

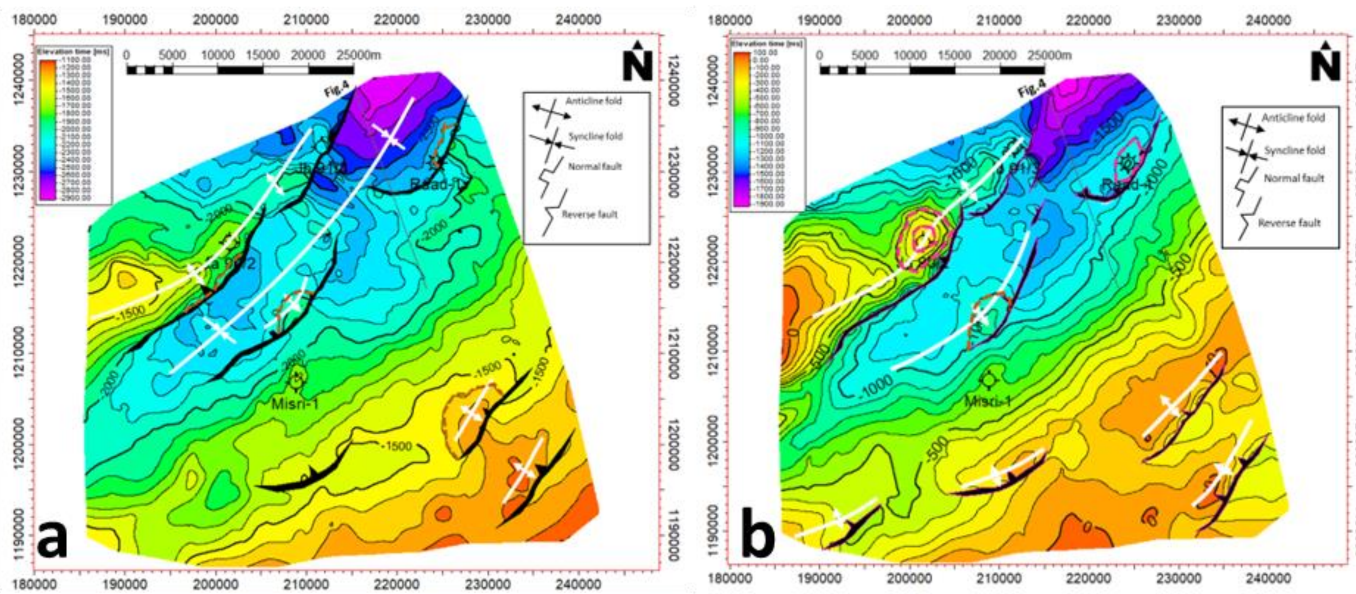

Fig. 3: a- Time structure maps of the Near-top Jurassic surface (deep seismic reflector) (a) and the Near-top Senonian? surface (shallow seismic reflector) (b).

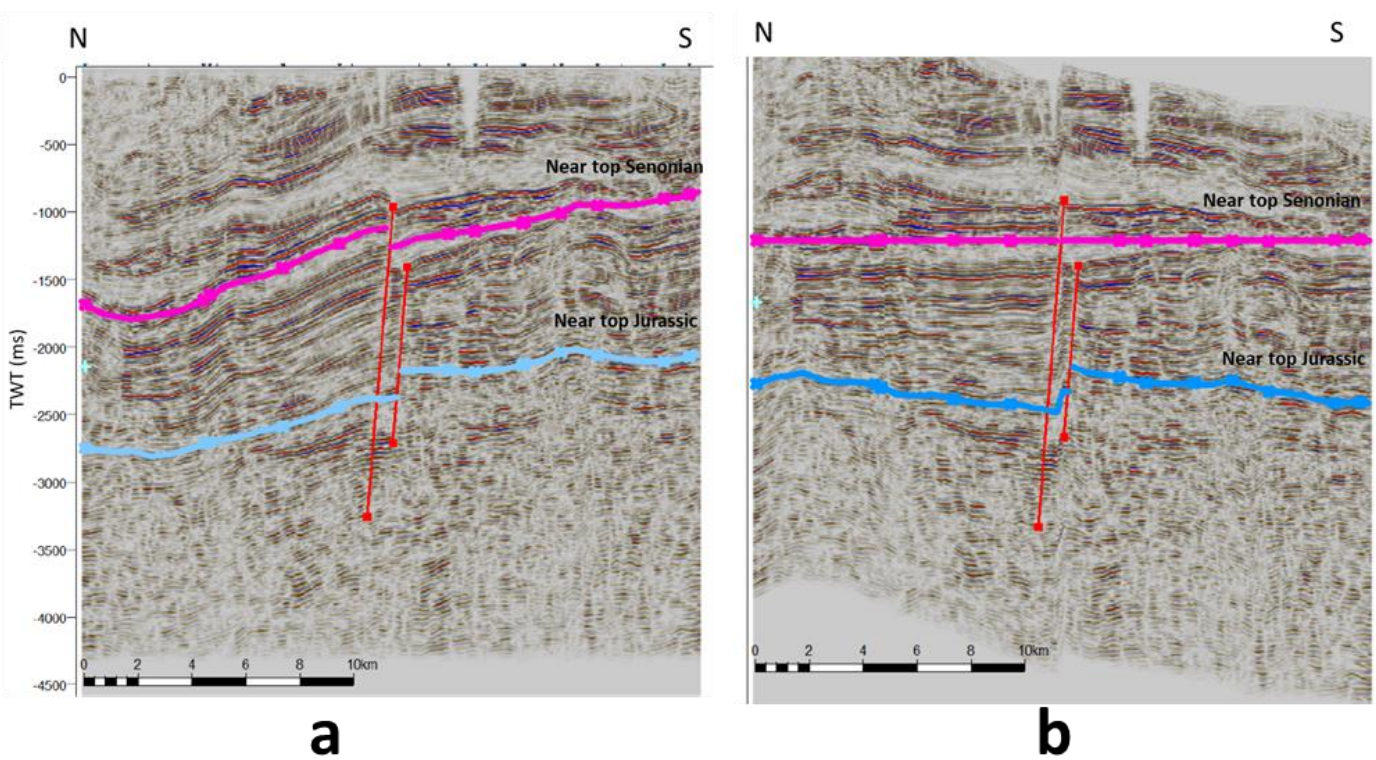

Fig. 4: a- 2D seismic section showing normal fault slip at near top Jurassic level and reverse slip at near top Senonian level, b- Same seismic section flattened at near top Senonian reflector showing the larger stratigraphic thickness in the hanging wall. See Fig. 3a for location.

Carbonates work as a cap for the underlying Upper Cretaceous reservoirs. These Eocene carbonates also lie unconformably above the Upper Cretaceous rocks.

Several three-way dip closures are represented by anticlines in the hanging walls of the NE-SW oriented reverse faults. Good fault juxtaposition will be necessary to laterally seal such three-way dip closures.

D. Trapping Mechanism

Structural traps in the study are represented by NE-SW oriented four-way and three-way dip closures. Reverse faults bound the southeastern flanks of these folds and can act as good lateral seals for the three-way closures, depending on good juxtaposition. At the deep seismic horizon (near top Jurassic, Fig. 3a), the four-way fold closure at the Ja 90/2 well seems to have a vertical closure of about 500 ms (from -1500 ms to -2000 ms). Also, at the Raad-1 well, a three-way fold closure exists at -2300 ms depth. Added, to the north of Misri-1well, another three-way fold closure exists at -2100 ms and is bounded by a NE-SW oriented reverse fault. Shallower four-way and three-way dip closures exist at the southeastern part of the study area at -1200 and 1100 ms (Fig. 3b). Other four-way and three-way fold closures are also mapped in the shallow seismic horizon (near top Senonian). A good example of such folds is at the Ja 90/2 well, where a four-way fold closure is obvious at -200 to -500 ms. Other folds are also clear at the shallow seismic horizon e.g. at Raad-1 well location, north of Misri-1 well, as well as at the southern and southeastern parts of the study area (Fig. 3b).

Despite the presence of structural traps, detailed geological data may also indicate the presence of stratigraphic and combination traps in the area.

- **Dry Hole Analysis**

  A. Structural Position (trap)

Although the four wells of the area were drilled through structural highs, the detailed seismic mapping of the present study indicates the following problems concerning the locations of three of these wells with respect to the mapped structures:

1. The Raad-1 well has a good structural position on both the deep and shallow seismic horizons (Fig. 3). It is located at the crest of a NE-SW oriented doubly plunging anticline lying on the hanging wall of a NW dipping normal fault.

2. The Misri-1 well is not in a good structural position, as shown by the structural maps of the deep and shallow horizons (Fig. 3). Both horizons show no closure at the Misri-1 well location.

3. The Ja 90/2 well was drilled at the crest of a four-way closure, affecting the shallow seismic horizon, but this well is located at the NE nose of a NE-SW oriented anticline affecting the deep seismic horizon (Fig. 3). This indicates that, at the deep seismic horizon the well is off the fold crest.

4. The Jb 91/3 well is also located away from the anticlinal crest at both the deep and shallow seismic horizons.

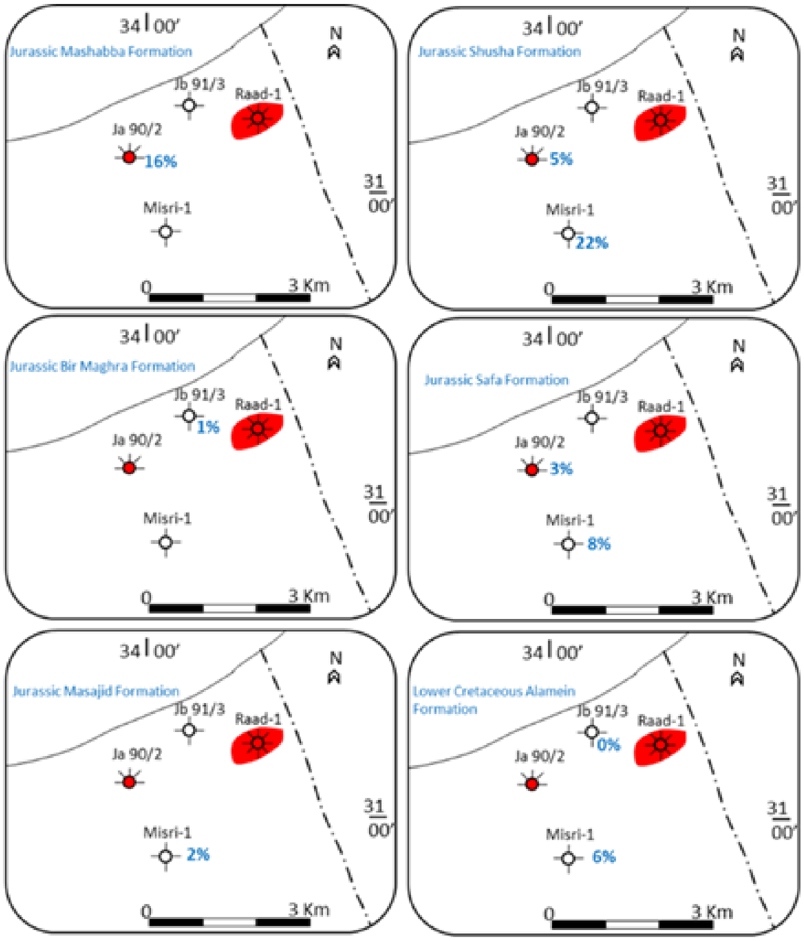

Fig. 5: Summary diagram showing the sand net/gross values of the different studied formations in the study area.

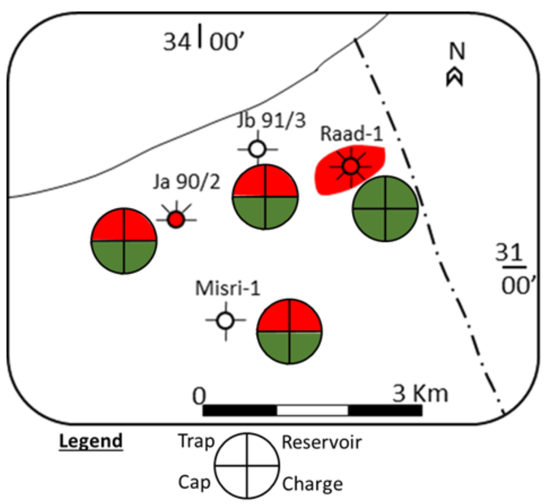

Fig. 6: Results of the dry hole analysis of the study area. See text for explanation.

B. Reservoir Rocks

The reservoirs penetrated by the four wells of the study area seem to be of bad quality. The Lower Jurassic reservoirs have very poor porosity and low net/gross sand values (Fig. 5). There is no data about the presence of fractures in the Upper Cretaceous limestone reservoirs, which may be a reservoir problem, except in Raad-1 well, which has a proven fractured carbonate reservoir, that includes gases. Also, these carbonate reservoirs are not porous in the other wells (as indicated from well-site descriptions, which needs to be supported by petrophysical analysis).

In Misri-1 well, the reservoir is represented by Middle Jurassic and Cenomanian rocks with very poor oil shows. In Jb 91/3 well, no good reservoirs were penetrated, due to the absence of Lower Cretaceous reservoirs and the Upper and Middle Jurassic sands are of bad quality. In Ja 90/2 well, the reservoir is represented by Cenomanian, and Middle and Lower Jurassic rocks. The Cenomanian section is made up of tight and massive dolomitic limestone with no porosity. The loss of returns in the Middle and Lower Jurassic section may refer to the presence of fractures. The Lower Jurassic sandstone is tight and contains very poor oil shows and has high water saturation.

C. Charge

The charge is proven in the study area due to the presence of gas in the Raad-1 and in the Sadot field.

D. Cap Rocks

The presence of a cap or seal rock is proven in the study area and is represented by the shales and carbonate rocks above the reservoirs.

Fig. 6 shows the results of the dry hole analysis. A circle is drawn at each well and is divided into four quadrants. These four quadrants represent the trap, reservoir, charge and cap. If any of these four elements of the hydrocarbon system is bad, its quadrant is represented by red color. If it is good, it is represented by green color.

6. Conclusions

Northeastern Sinai has good hydrocarbon potential, due to the validity of the four elements of the hydrocarbon system. The Jurassic rocks represent the potential source rock in the area, which is also a proven source rock in other areas in Northern Egypt (e.g. the northern Western Desert) as well as the Eastern

Potential traps in the area are represented by NE-SW oriented anticlinal traps (both four-way and three-way closures) bounded by northwest dipping reverse faults. The reservoirs are mainly carbonate reservoirs in the Jurassic and Cretaceous rocks. These carbonate reservoirs are expected to be fractured, such as those of Sadot gas field in the northeastern part of the study area. On the other hand, clastic reservoirs in the Jurassic and Lower Cretaceous rocks have low net/gross sand. Cap/seal rocks are represented by the shales and carbonates of the Jurassic and Cretaceous sections.

For successful hydrocarbon exploration of the area, it is recommended to have 3D seismic acquisition and special attribute extraction to map fractures in the Cretaceous rocks. Also, proposed exploratory wells need to have good suite of logs, especially the image logs, to map the fractures in the carbonate rocks, that can act as potential fractured reservoirs.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

7. References

Abdel Aal, A., Lelek, J.J., 1994. Structural deformation of the northern Sinai, Egypt and its implications on the hydrocarbon prospectivity of the Mesozoic. In: Proceedings of the Middle East Petroleum Geoscience Conference (GEO94, Bahrain), vol. 1, pp. 15-30.

Al-Far, D.A. 1966. Geology and coal deposits of Gebel El Maghara (north Sinai). Geological Survey of Egypt. Paper no. 37, 59.

Alsharhan, A.S and Salah, M.G, 1996. Geologic setting and hydrocarbon potential of north Sinai, Egypt, Vol. 44, No 4, 615-631 p.

Ayyad, M.H., Darwish, M., and Sehim, A., 1998. Introducing a new structural model for north Sinai with its significance to petroleum exploration: Proceedings of the 14th Petroleum Conference, Cairo, Egypt, Egyptian General Petroleum Corporation, Cairo, v. 1, p. 101–117.

EGPC, 1992. Western Desert oil and gas fields (A comprehensive overview): Egyptian General Petroleum Corporation, 431 p.

EGPC, 1994. Nile Delta and North Sinai fields, discoveries and hydrocarbon potentials (A comprehensive overview): Egyptian General Petroleum Corporation, 387 p.

El Ayouty, M.K., 1990. Petroleum Geology, In: Said, R. (editor) The Geology of Egypt: A.A. Balkema, Rotterdam, Chapter 27, p. 567-599.

El Kawa, S., Taha, T., and Nurmi, R., 1988. Analysis of subsurface fractures of Cenomanian carbonates in north Sinai, Egypt. Proceedings of 9th EGPC Exploration and Production Conference, v. 1, p. 372- 393.

Khalil, M.H. & Moustafa, A.R. 1994. Tectonic framework of northern Egypt and its bearing on hydrocarbon exploration. Proceedings of 12th Egyptian General Petroleum Corporation Petroleum Exploration and Production Conference (Cario), 1, 67-86.

Krenkel, E. 1925. Geologie Afrikas. Berlin: Verlag von Gebruder, 461 p.

Moustafa, A.R., 2010. Structural setting and tectonic evolution of north Sinai folds, Egypt, In: C. Homberg and M. Bachmann (eds.): Evolution of the Levant Margin and Western Arabia Platform since the Mesozoic: Geological Society of London Special Publication 341, p. 37-63.

Moustafa, A.R., 2020. Mesozoic-Cenozoic Deformation History of Egypt, In: Hamimi, Z., El-barkooky, A., Martínez-Frías, J., Fritz, H., Abd El-Rahman, Y.M. (eds.), The Geology of Egypt: Springer Nature Switzerland, Regional Geology Reviews, p. 253-294. DOI/10.1007/978-3-030-15265-9_7.

Moustafa, A.R., Salama, M.E., Khalil, S.M., and Fouda, H.G., 2014. Sinai Hinge Zone: A major crustal boundary in NE Africa: Journal of the Geological Society of London, v. 171, p. 239-254.

Roberts, G. and Peace, D., 2007. Hydrocarbon plays and prospectivity of the Levantine Basin, offshore Lebanon and Syria from modern seismic data: GeoArabia, v. 12, no. 3, p. 99-124.

Said, R. 1962. The geology of Egypt. Elsevier Pub. Co., Amsterdam, 377 p.

Shata, A. 1959. Structural development of the Sinai Peninsula (Egypt). Proceedings of the 20th International Geological Congress (Mexico, 1956), 225-249.

Yousef, M., Moustafa, A.R., and Shann, M., 2010. Structural setting and tectonic evolution of offshore north Sinai, Egypt: In: C. Homberg and M. Bachmann (eds.): Evolution of the Levant Margin and Western Arabia Platform since the Mesozoic, Geological Society of London Special Publication 341, p. 65-84.