Provenance study of potential Oligocene reservoirs in Nile Delta and offshore Mediterranean

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Abstract
This study aims to investigate the provenance of the Oligocene sandstones exposed at Gebel Qatrani Formation at the Fayum Province and analogues subsurface Oligocene sandstone intervals cored from 2.7 to 5.12 km at the Nile Delta. The analysis and quantification of heavy mineral assemblages revealed that the two sites maintain similar heavy mineral suites but with variable concentrations and different patterns. The provenance reliable heavy mineral indices indicate that the exposed Oligocene sandstones at Gebel Qatrani Formation are much more mature than those of the Oligocene sandstone intervals at the Nile Delta. The lower and the upper members of Qatrani Formation display heavy mineral contents indicating more maturation than the middle member which reflects an influx of less mature sandstone. The middle member may reflect a tectonic reconfiguration of the hinterland during its deposition. The reliable heavy mineral indicators of the Oligocene sandstones at the Nile delta maintain their higher values at different depths along the entire wells indicating a significant rejuvenation of the source area and hence sand supply from a source(s) that was not far distant. In contrast, Habbar-1 well sand samples (cored from 3.8 to 4.5 km) display the highest pyroxene values along with considerable contents of amphibole, mica, sillimanite, and kyanite indicating transport from a shorter distant source including a metamorphic one. Thirty seismic cross sections are interpreted and used to construct isopach maps which revealed the diagenetic effect of the heavy mineral suits with depth. That will subsequently affect the reserving characteristics of Oligocene sand intervals. Moreover, according to the estimated petrophysical parameters, the Oligocene intervals in Habbar-1 and Port Fouad Marine Deep-1 wells are very promising.

Keywords Provenance · Oligocene · Potential reservoirs · Nile Delta · Offshore Mediterranean

Introduction
The Oligocene sandstones in the northern parts of Egypt are one of the most important economic assets due to their great hydrocarbon potentialities. The recent huge emerging field discoveries in the offshore Mediterranean have turned all eyes to this province. The importance of the Oligocene sedimentary rocks is represented in either being source rocks producing natural gases or acting like reservoirs in the Nile Delta. Many reservoir levels were embedded in the Dabaa Formation that represents the Oligocene Epoch in the eastern offshore area of Nile Delta, Egypt; these reservoir levels are distributed between Rupelian (Lower Oligocene) and Chattian (Upper Oligocene) (Ahmed and Khaled 2017).

In 2019, Eni revealed the under-evaluation gas discovery in the Eastern Egyptian Mediterranean. Nour-1 well found 33 m of gross sandstone pay with good petrophysical properties and an estimated gas column of 90 m in the Tineh Formation of the Oligocene Epoch. The well has not been tested; however, an intense and accurate data acquisition has been carried out. In June 2021, another futuristic expansion has been done by Eni in the Western Desert which reflects the great hydrocarbon potentialities (natural gas especially). Moreover, the Oligocene strata are an important piece in the jigsaw puzzle of the Nile history. Over a century now, the debate continued about the path and timing of the Nile River course. One opinion believed that the current course was not connected until Miocene or even more recent (Shukri 1950; Said 1990; Macgregor 2012), while the other suggests that...
the course of nowadays was established since the Lower Oligocene (Berry and Whiteman 1968; McDougall et al. 1975; Burke and Wells 1989; Williams et al. 2000; Craig et al. 2010; Fielding 2016, 2017, 2018; Garzanti et al. 2018). It has been reported the progradation of the Nile Delta toward the north at the same timing of the receding of the Tethys Ocean resulting from the accumulation of sediments in the current offshore position since Oligocene (Gardosh et al. 2009; Craig et al. 2011). The claimed progradation theory of the Nile Delta ensures the relationship between the exposed Oligocene strata and their correllative intervals in the offshore Nile Delta and the Mediterranean. The same pattern was thought to have existed according to Salem (1976) resulting from northerly flowing drainages.

Provenance study is one of the most effective tools that could aid in dealing with such issues, as the application of provenance studies in the oil industry provides critical aids in the exploration and production life cycle. For exploration, it enhances our knowledge of the reservoir distribution and quality (Scott et al. 2014). In the same context, reservoir characteristics of the sandstone bodies rely strongly on the composition of these bodies and, therefore, their provenance (Barwis et al. 1990; Bloch 1991; Lima and De Ros 2002).

In another context, applying the provenance-based correlation technique depends mainly on the changes of the sediments source or the transportation journey. The mineralogical and geochemical composition of the sediments reflects these changes. Meanwhile, using provenance-based techniques is such a sensitive tool because of the large number of factors that could affect the mineralogical and geochemical composition of the sediments which will lead to wrong interpretations. Hydrodynamic processes that act through (transport, deposition, and diagenesis during burial) are believed to be the most affecting factors in the provenance interpretation bias (Morton and Sylvester 2012; Scott et al. 2014).

For that, studying the provenance of the Oligocene strata in the northern Egypt is considered an important key to puzzling out the debate of the Nile River course, in addition to being a significant tool in mapping out the potential Oligocene reservoirs through identifying the possible fairway directions. In order to fulfill the expectations of the current study, the Oligocene samples of two localities were used to study their heavy mineral content. The first one represents the exposed Oligocene sandstones of the Gebel Qatran Formation in the Fayum area, and the second is the ditch samples from seven wells representing the Oligocene sandstone intervals in both onshore and offshore Nile Delta and the offshore Mediterranean. Moreover, the Oligocene intervals were interpreted in thirty seismic lines to create depth contour and isopach maps of the Oligocene interval to understand the distribution of Oligocene depth. The data of heavy mineral analysis in both surface and subsurface locations along with the seismic data should illustrate a reliable scenario for futuristic exploration development.

**Location of study areas**

**Surface area**

The surface study area is conducted on Gebel Qatran which is located northwest of the Fayum Province. The Fayum area occupies one of the spectacular depressions in the Eocene limestone plateau of the Western Desert of Egypt. The Gebel Qatrani escarpment represents the best exposure of the Oligocene sediments in Egypt (Said 1962). The surface study area lies between latitudes 29° 38' N and 29° 39' 30" N, and longitudes 30° 35' 30" E and 30° 39' 30" E within the Fayum Province (Fig. 1).

**Subsurface area**

The subsurface study area lies in the Nile Delta Basin. The onshore Nile Delta and its offshore extend to about 33° 30' N. About 70% of the basin lies offshore, in water depths down to 2800 m. Depth to the basement is typically up to 9 or 10 km (Said 1990). The basin overlies the passive margin of northeastern Africa; an important hinge line crosses the basin in its onshore sector and marks the transition from thick normal continental crust in the south to extended continental crust under both the northern onshore Delta and (probably) the entire offshore sector of the basin. In the west, the Nile Delta Basin overlies the eastern extension of the Northern Egypt Basin, whereas in the east, it overlies part of the Syrian Arc province. The selected subsurface study area lies between latitudes 30° N and 33° N, and longitudes 30° E and 33° E. The selected onshore wells are represented by Qallin-I, Tarif-2A, San El-Hagar-1, and the Rommana-I wells. On the other hand, the offshore wells are Boughaz-1, Port Fouad Marine Deep-1, and Habbar-1 (Fig. 2).

**Geologic settings**

Gebel Qatran Formation is bounded by two unconformity boundaries. The lower boundary separates it from the underlying 77 m of Upper Eocene sandstone, sandy mudstone, limestone, and carbonaceous shale “Qasr El-Sagha Formation” (El-Araby and El-Barkooky 2000). The upper unconformity surface separates Gebel Qatran Formation from the overlying basalt of Widan El-Faras (Vondra 1974). Gingerich (1993) defines this unconformity as the Rupelian-Chattian boundary. Basaltic sheets of Widan El-Faras vary in thickness from 2 to 25 m, the variation which was thought to be controlled by the number, the thickness, and
the topographic irregularities of its lower contact (El-Araby and El-Barkooky 2000). Bown and Kraus (1988) described Gebel Qatrani Formation as variegated alluvial rocks that show an evident geochemical and mechanical alteration recorded by the existence of ancient paleosol. They divided Gebel Qatrani Formation into three members (Fig. 3). The lower part is dominated by coarse, multistory, multilateral sand bodies that record deposition by meandering streams under essentially quiescent tectonic conditions.

The lower member of Gebel Qatrani Formation is characterized by the presence of gravelly, friable, sandstones containing silicified wood fragments. Petrified trees are recorded in the basal part of the Formation, with variable sizes (Fig. 4a). The E–W, NE–SW, and ENE–WSW alignment of these trees indicates the transport directions. Moreover, the lower part is characterized by the existence of the large scale, tabular-planar cross-bedded sandstone with azimuths that range from 210 to 316° and magnitudes varying from 20 to 30° (Fig. 4b). The middle member is characterized by variegated sandstones, mudstones, conglomerates, and channel fill sandstones. Rhizoliths and bioturbation dominate the upper member. Furthermore, the upper member is characterized by the presence of the paleocurrents with directions that range from 220 to 330° with magnitude ranging from 20 to 40° (Fig. 4c). Unlike the usual fining upward cycles that are recorded in both lower and upper members, sediments of the middle member show coarsening upward cycles (Fig. 4d) which reflect the deposition under relatively active tectonic settings or climatic change. The upper member contains both a greater proportion of fine sandstone and mudstone and more discontinuous sand bodies; these attributes point to deposition in a more active tectonic setting, under the influence of an encroaching marine strandline. Nearshore marine conditions prevailed in some areas of deposition of the upper part of the Gebel Qatrani Formation, but this advance was both minor and short-lived and was followed first by a return to alluvial deposition and then by regional erosion (Bown and Kraus 1988; El-Araby and El-Barkooky 2000).

Unlike the fluvial dominated sediments of Gebel Qatrani, the Oligocene sediments in Nile Delta province are represented by the Dabaa Formation which mainly composed of shales of open marine facies with intercalations of siltstone and often with sandstones and limestones. The deposition of the Dabaa Formation was thought to have taken place in an inner shelf to littoral setting, which changed to estuarine toward its top in various areas. Southward, the Dabaa grades laterally into the littoral to deltaic deposits of the Gebel Qatrani Formation, Fayum area (Hantar 1990; Issawi et al., 1999).

In the center of onshore Nile Delta, the lithology is mainly shale, whereas in the northwestern offshore area of Sinai, the sediments become more clayey facies that

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**Fig. 1** Landsat image showing the surface study area, Fayum, Egypt
changes into sandy facies with intercalations of limestone in the onshore area of Sinai. On the other hand, in the area to the east and northeast of the Nile Delta, the Dabaa Formation is either missed or represented by a thick continental, unfossiliferous sandy succession that rests unconformably on the Cretaceous strata and separates the underlying Cretaceous–Early Tertiary carbonate rocks from the overlying marine Qantara sediments (Ouda and Obaidalla 1995). According to Ouda and Obaidalla (1995), the Dabaa Formation is ranging from Early to Middle Oligocene and Qantara Formation represents Late Oligocene to Early Miocene. As Dabaa Formation Qantara is not encountered in the northern Delta and northwestern offshore area, its sediments are composed mainly of shales and claystone with common limestone and sandstone interbeds.
The structural evolution of the Nile Delta is largely contemporaneous with the breakup of the African Plate Margin consequent to the opening of the Red Sea and the northward transition of the Arabian Peninsula. The northern part of the Nile Delta is characterized by a series of major tectonic features with different orientations. Some of them are active during the deposition of the Tertiary section while others flatten with depth, become horizontal, and die on top of the Rosetta Formation affecting only through the Kafr El-Sheikh Formation (Said 1975). The Nile Delta is characterized by an asymmetric fold, overthrust faults, and diapirs. It dates back to the Syrian Arc System having an arcuate trend from northeast to southwest through the northern part of the Nile Delta to the Western Desert of Egypt (Said 1975).

Abdel Aal et al. (1994) stated that six major structural trends delineate the present Nile Delta and affect the distribution of sediments in the Nile Delta Basin. These trends are the E–W Neogene Hinge Zone, the NE Rosetta fault trend, the NW Temsah structural trend, the Pelusium shear zone, the NW Red Sea-Gulf of Suez fault trend, and the minor NS Baltim fault trend. The Mesozoic succession represents a rifted passive margin, formed at the opening of the Neo-Tethys Ocean in the Late Triassic to Early Jurassic (Abdel Aal et al. 1994). The Late Cretaceous to Early Tertiary dextral transpression generated the northeast–southwest trending structures of the Syrian Arc System.

**Materials and methods**

Fourteen samples were selected to study the heavy mineral content of the three members of Gebel Qatrani Formation. Moreover, ten thin sections were prepared for the petrographic investigation of the sandstones of Gebel Qatrani Formation. The thin sections have been described qualitatively in terms of texture and composition. Twenty-eight ditch samples were selected from the six wells (onshore and offshore) to represent the subsurface Oligocene sandstone
intervals in the Nile Delta. The depth intervals were defined according to the biostratigraphic framework done by Obaidalla (1993) and the Belayim Petroleum Company. Choosing the study wells was a precise procedure as we have been limited to wells that penetrate the Oligocene section, taking into account the geographic extent as we aim at covering the Oligocene interval distributed within the subsurface study area (onshore and offshore).

Heavy mineral separation

One hundred grams of each sample of Gebel Qatrani sandstones and 10–25 g of the ditch samples of the studied wells were subjected to the procedures of disaggregation to semi-consolidated sediments to get grain liberation. Organic matter and carbonate were removed. The sediments were sieved mechanically using standard sieves in steel. The analysis of heavy minerals was carried out in a definite grain size range (64–125 microns) because heavy minerals of this size can be obtained from sandstones of all grain sizes and thus eliminate the effects of grain size availability (Morton 1985; Knox et al. 2011). The ditch samples of the studied wells were weighed and went through the same procedure. The separation of heavy minerals is maintained by using the high-density liquid (bromoform) with specific gravities of 2.8. Three hundred grains are counted in each slide using the “line counting” method.

Seismic and well log data

Three digital and compositional logs along with thirty seismic lines are used in the current study. Two onshore wells (Qallin-1, San EL-Hagar-1) were provided by the Information Center, and the offshore well (Port Fouad Marine Deep-1) was provided by Belayim Petroleum Company. The available thirty seismic lines are distributed as follows: twenty seismic lines within the Port Fouad Marine Deep-1 block, four onshore seismic lines within the San El-Hagar-1 block, and six onshore seismic lines within the Qallin-1 block (Fig. 5).

The evaluation and interpretation of this data have been established by Petrel Software Version 2017.4. Petrel is a seismic interpretation and modeling software developed by Schlumberger Company. It was designed for working with seismic and well data from the interpretation to the dynamic modeling and with several functionalities, developed directly for the analysis of the reservoirs. The main target is to use the interpreted seismic cross sections with the studied heavy mineral suits identified in Oligocene sandstone horizons to attain a comprehensive perspective about the different dispersion patterns of these sediments, their provenance, and the potential Oligocene plays in the Nile Delta and the offshore Mediterranean. Such perspective is maintained by creating synthetic seismograms depending on the sonic and density logs (Fig. 6a, b). The created synthetic seismograms are then used to perform
the seismic to well tie process. The interpretation process includes the interpretation of the Oligocene interval by picking both Oligocene and Eocene horizons in all seismic cross sections (Fig. 7). It also includes the interpretation of Pliocene and Miocene horizons along with some structural features (Fig. 8). The next step is to construct the two-way time surfaces through mapping the picked time. After that, the average velocity is used for the time to depth conversion process allowing the construction of depth and thickness maps.

Some petrophysical parameters were calculated for the available logs (Port Fouad Marine Deep-1, Habbar-1, Qal-lin-1, and San El-Hager-1). The studied Oligocene interval is encountered at intervals of 3506–4999.7, 3828.5–4523.2, 3810–3976, and 2886–3780 m, respectively.

The Schlumberger software interactive petrophysics (IP) v3.6 is used for interpretation and evaluation of the available log sets. A complete set of log data has been used, including gamma ray (GR), caliper (Cal), shallow resistivity (LLS), deep resistivity (LLD), sonic (DT), density (RHOB), and neutron (NPHI) (Radwan et al. 2021, 2022a, b; Abdelmak-soud and Radwan 2022; Abdelwahhab et al. 2022).

Values of shale volume were computed applying single-log method (GR and LLD), whereas combination of NPHI- RHOB logs was used in the calculation of porosity values (effective porosity $\Phi_e$ and total porosity $\Phi_t$). Since the Dabaa Formation consists mainly of shales, the water saturation is calculated using the Indonesian equation (Poupon and Leveaux 1971), as it is one of best models to estimate SW in shaly rocks.

Values of property cutoff were obtained from the internal reports of PETROPEL CO. The used cutoffs were as follows: 70% for shale content ($V_{sh}$), 10% for effective porosity ($\Phi_e$), and 50% for water saturation ($Sw$). The average values of $R_w$, $m$, and $n$, calculated in this study, were 0.0552 $\Omega$ m (at formation temperature), 1.89, and 2, respectively.

**Results**

**Petrographic description**

The petrographic investigation showed that the sandstones of Gebel Qatrani Formation are mainly quartzose,
as quartz volume % ranges between 97.3 and 99.3%, feldspars vary between 0.25 and 1%, and lithic fragment content forms 0.5 to 1.5%. Percentages of the previously mentioned components are listed in Table 1 and represented in Fig. 9. The textural framework of lower member is ranging from moderately to poorly sorted, sub-angular to sub-rounded, medium- to fine-grained Qz-sandstones (Fig. 10a, b). The sandstones of the middle member vary from poorly sorted in its lower part to moderately to well-sorted in its upper part. It shows sub-angular to well-rounded coarse- to fine-grained Qz-sandstones (Fig. 10c, d). The upper member exhibits Qz-sandstones of poorly to moderately sorted, angular to well-rounded, and fine- to coarse-grained (Fig. 10e, f).

**Heavy mineral analysis**

**Surface Oligocene sandstones**

The location of the studied heavy mineral samples (referred as H) is shown within the lithostratigraphic columnar (Fig. 3). The identified transparent heavy mineral assemblage in the Oligocene sandstones of Gebel Qatrani Formation is arranged in decreasing order of abundance within the three members as follows:

Lower member: sphene > rutile > tourmaline > zircon > kyanite > pyroxene (enstatite) > garnet > mica > epidote > monazite > amphibole (tremolite)
Middle member: sphene > rutile > zircon > tourmaline > epidote > mica > pyroxene (enstatite) > garnet > monazite
Upper member: sphene > zircon > rutile > tourmaline > kyanite > pyroxene (enstatite) > garnet > mica > monazite > epidote

The examined heavy minerals (under the binuclear microscope) display several dissolution features such as hacksaw terminations, ragged edges, and pits which indicate the modification of the heavy minerals possibly during burial diagenesis or due to the transportation effect. The weight of the heavy minerals fraction is fairly constant through the three members of Gebel Qatrani Formation, with a slight decrease in the middle member. The heavy fraction weight represents 0.37 g of sand samples in the lower member, 0.28 g in the middle member, and 0.36 g of the upper member. The identified non-opaque heavies investigated in Gebel Qatrani Formation include abundance of 40–75% of ultra-stable minerals (zircon, tourmaline, and rutile) and 18.5–78.5% of moderately stable minerals (kyanite, and sphene along with trace amounts of garnet, and monazite). Unstable heavy minerals (0–37.7.8%) are represented by epidote, pyroxene, mica, and amphibole (Fig. 11). The frequencies of the recorded transparent heavy minerals in Gebel Qatrani Formation are listed in Table 2 and represented in Fig. 12.
Heavy mineral indices Although the heavy minerals are reliable indicators of sediment provenance, many other factors could mislead the deduction of such relation. Processes that act during the different stages of sedimentary cycles affect the abundance of heavy mineral assemblages (Morton and Hallsworth 1994). Hydraulic and diagenesis are the most two effective factors in the abundance of heavy minerals content, as the mechanical abrasion effect can be safely ignored. Hydraulic behavior of heavy mineral grains depends on the shape, size, and density of grains; thus, we can rely on the fact that mineral grains with the same hydraulic properties have the same behavior. Accordingly, prismatic grains tend to behave differently from those of platy or bladed habits. Thus, the best provenance results will be obtained by comparing proportions of heavy minerals with similar habits (Morton and Hallsworth 1994).

In the current study, some heavy mineral indices were calculated to reduce the misleading provenance evaluation concluded from the usual dependency of heavy mineral abundance. The different indices applied in this study are demonstrated in Table 3.

Traditionally, counting 200 to 300 transparent heavy mineral grains is good to know the mineral suit characterization. But there are significant errors with this method, especially the small amount represented mineral species. Thus, each ratio is calculated depending on a separate count in order...
to avoid the errors of calculating indices from the normal ratios. The minimum count should be 100 grains for each heavy mineral pair and 200 grains are meant to perfectly represent the heavy mineral species according to Morton and Hallsworth (1994).

The zircon–tourmaline–rutile index is calculated for the transparent heavy mineral assemblage in order to indicate the mineralogical “maturity” of the heavy mineral assemblages of sandstones (Hubert 1962). Since rutile and zircon are highly stable minerals, rutile:zircon index (RZi) is a reliable provenance index that can indicate recycling of sediment. Strong variations in RZi values may exhibit variation in metamorphic:plutonic source rocks. The monazite:zircon index (MZi) is a reliable provenance indicator as both minerals are highly stable. Monazite is a component of both igneous and metamorphic rocks (Knox et al. 2011). The garnet:zircon index (GZi) is a reliable provenance indicator as both minerals are highly stable (Andrew C Morton and Hallsworth 1994).

The transparent heavy mineral volume percentage in each sample is defined as the transparent heavy mineral concentration index (tHMCi) (Garzanti et al. 2018).

A stratigraphic plot of the studied heavy mineral indices for the Oligocene sandstone of Gebel Qatrani is shown in Fig. 13. ZTR index values show marked variation along the Oligocene sandstone of Gebel Qatrani. The values exhibit low concentration (19%) at the basal part of the lower member and along the boundary between the middle and upper members (23–37%). The higher values of the ZTR index are recorded within the lower member (46–70%), the basal part of the middle members (55–65%), and at the top of the upper member (68–69%). Variation in ZTR index shows a slight decrease (5%) along the boundary between the lower and middle members and quite an increase (14%) along the boundary between the middle and upper members (Table 4; Fig. 13). RZi values fall into three groups, one with moderate to extremely high values, where RZi values show a gradual upward increase from 48 to 75% within the lower member. The second group shows fairly stable high values (60–65%) within the middle member. The third group exhibits low RZi values (40–44%) within the upper member. The boundaries between the lower, middle, and upper members show an abrupt decrease in the RZi values (12% between the lower and middle members and 20% between the middle and upper members). The tHMC index values show moderate values (20–39%) across the Oligocene sandstone of Gebel Qatrani Formation but at the boundary between the middle and upper members (Table 4). Along this boundary, the tHMC index shows higher values with an abrupt decrease from 60 to 54%.

GZi is not recorded at the boundary between the middle and upper members as well as at the top of the upper member of Gebel Qatrani Formation. It shows marked variation within the remainder of Gebel Qatrani Formation with values ranging between 13 and 29%. MZi exhibits only some values within the lower (9 and 13%), middle (17%), and upper (9 and 11%) members.

### Subsurface Oligocene sand intervals

The studied (offshore and onshore) wells are arranged in ascending order according to depth.

#### Offshore wells

a) Port Fouad Marine Deep-1 (PMFD-1)

PMFD-1 is an offshore well located southeast of the Mediterranean (Fig. 2). The Oligocene interval in this well

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**Table 1** Main petrographic parameters recorded in Oligocene sandstones of Gebel Qatrani Formation, Fayum (Qz, quartz; F, feldspars; L, lithic fragments)

| Levels   | Ratios   |
|----------|----------|
| Upper    | 97.75 0.75 1.5 |
|          | 97.75 1 1.25 |
|          | 98.25 0.75 1.5 |
|          | 98 0.75 1.5 |
| Middle   | 98 0.5 1.5  |
|          | 99 0.25 0.75 |
|          | 99 0.25 0.75 |
|          | 98.5 0.5 1 |
| Lower    | 98.5 0.5 1  |
|          | 99.25 0.25 0.5 |
|          | 99.25 0.25 0.5 |
|          | 98.5 0.5 1 |

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**Fig. 9** Ternary diagram showing the composition of Gebel Qatrani Formation sandstones. Qz, quartz; F, feldspar; L, lithic grains
starts at 4200 m and ends at the total depth of the interpreted section at 5244 m. Three samples were obtained to represent the Oligocene at the depth interval from 5113 to 4912 m. The weight of the heavy fraction shows an overall increase downward with depth from 0.37 g at 4912 m to 0.61 g at 5113 m. The transparent heavy mineral assemblage encountered in the Oligocene sands of Pour Fouad Marine Deep-1 well is mica > sphene > epidote > zircon, tourmaline, rutile > pyroxene (enstatite) > monazite (Table 5).

Ultra-stable heavy minerals (zircon, tourmaline, and rutile) represent 12.27%. The moderately stable group (monazite and sphene) displays 33.82%, while the unstable group (pyroxene, epidote, and mica) represents 60.78%.

Generally, transparent heavy minerals represent 30%, while opaques represent 70% of the total heavy fraction identified in PFMDep-1. The heavy mineral grains are sub-rounded to well-rounded. Ultra-stable minerals like rutile grains show perfect rounded outlines. The grain size decreases with depth within the examined interval (Fig. 14d). Mica and rutile display decrease with depth.

b) Habbar-1

Habbar-1 well is located west to Port Fouad Marine Deep-1 on the Mediterranean offshore (Fig. 2). The Oligocene interval starts from 3852 to 4536 m. Five samples were acquired to represent the depth interval 3852–4443 m.

The weight of the heavy mineral fraction represents an overall decrease downward along with depth. It varies from...
0.61 g at depth 3582 m to 0.33 g at depth 4443 m. This is followed by a slight increase occurred at 4443 m.

The most various transparent heavy mineral assemblage is identified in Oligocene sands of Habbar-1 samples. It holds mica > pyroxene (enstatite, hypersthene) > sphene > zircon, tourmaline, rutile > amphibole (tremolite, hornblende) > sillimanite > epidote > kyanite > monazite > garnet.

Ultra-stable heavy minerals (zircon, tourmaline, and rutile) represent 12.27%. The moderately stable group (monazite, garnet, kyanite, and sphene) exhibits 33.82%. The unstable group (pyroxene, sillimanite, epidote, mica, and amphibole) represents 60.78%. The transparent heavy minerals represent 81.4%, while the opaques display 18.6% of the total heavy fraction identified in Habbar-1. Transparent heavy minerals of Oligocene sands in Habbar-1 are generally of larger grain size compared to the previously studied samples (Fig. 14e, f). The identified transparent heavy mineral assemblage is long prismatic, well-angulated grains at depth interval 3852–4362 m. It exhibits sub-rounded grains at 4443 m (Fig. 15). This well holds high values of pyroxene (10–31%) along with amphiboles (2–10%), sillimanite (2–8%), and kyanite (1–7%). Amphiboles and kyanite show decrease with depth; however, pyroxene and sillimanite exhibit variable distribution patterns.

iii) Boughaz-1

Boughaz-1 is an offshore well located south/southeastward of PFMD-1 well. In this well, the Oligocene interval starts from 2345 to 3100 m. Five samples were gained to represent the interval at the depth interval 3081–3470 m. Transparent heavy mineral assemblage encountered in Oligocene sands of Boughaz-1 well is represented by mica > epidote > zircon, tourmaline, rutile > sphene > pyroxene (enstatite) > monazite > kyanite > amphibole (tremolite).

The weight of the heavy fraction shows an overall decrease downward with depth from 0.16 g at 3081 m to depth interval 3852–4362 m. It exhibits sub-rounded grains at 4443 m (Fig. 15). This well holds high values of pyroxene (10–31%) along with amphiboles (2–10%), sillimanite (2–8%), and kyanite (1–7%). Amphiboles and kyanite show decrease with depth; however, pyroxene and sillimanite exhibit variable distribution patterns.
Table 2 Heavy minerals of Gebel Qatrani Formation, Fayum

| Lithostratigraphy | Sample | Transparent heavy mineral assemblages’ frequencies % | Within H. fraction | H. fraction weight (g) | H. ratio |
|-------------------|--------|------------------------------------------------------|--------------------|------------------------|----------|
|                   |        | ZTR | Mo | G   | Ky | Sp | Ep | Pr | Am | Mi | Opaques % | Trans. % | W (F and VF) | W (HMLS) |
| Gebel Qatrani Formation |        |     |    |     |    |    |    |    |    |    |            |          |              |          |
| Upper member       | Q88    | 20.13 | 1.01 | 0  | 2.68 | 2.01 | 0  | 3.69 | 0  | 0  | 70  | 30        | 42.93  | 0.27        | 0.01     |
|                    | Q87    | 16.56 | 0   | 0.66 | 3.31 | 3.31 | 0  | 0.00 | 0  | 0  | 76  | 24        | 61.83  | 0.35        | 0.01     |
|                    | Q86    | 14.06 | 0   | 0.96 | 3.19 | 3.83 | 0  | 1.92 | 0  | 1.92 | 74  | 26        | 47.16  | 0.20        | 0.00     |
|                    | Q83    | 20.19 | 0.93 | 0.62 | 1.55 | 24.84 | 1.24 | 3.73 | 0  | 0.93 | 46  | 54        | 35.04  | 0.62        | 0.02     |
| Average            |        | 17.73 | 0.48 | 0.56 | 2.69 | 8.50 | 0.31 | 2.33 | 0  | 0.71 | 67  | 46.74     | 0.36   | 0.01        |          |
| Middle member      | Q78    | 14.18 | 0   | 0.71 | 0.71 | 29.08 | 11.35 | 4.96 | 0  | 0.00 | 39  | 61        | 15.39  | 0.42        | 0.03     |
|                    | Q75    | 7.237 | 0   | 0   | 1.32 | 2.63 | 0.66 | 0.66 | 0  | 8.55 | 79  | 21        | 15.85  | 0.32        | 0.02     |
|                    | Q67    | 13.21 | 0.71 | 1.43 | 3.57 | 2.50 | 0  | 2.14 | 0  | 0.36 | 76  | 24        | 18.41  | 0.32        | 0.02     |
|                    | Q64    | 12.87 | 0   | 0   | 4.68 | 0    | 0  | 0.58 | 1.75 | 0  | 80  | 20        | 15.85  | 0.05        | 0.00     |
| Average            |        | 11.88 | 0.18 | 0.53 | 2.57 | 8.55 | 3   | 2.09 | 0  | 2.67 | 69  | 16.38     | 0.28   | 0.02        |          |
| Lower member       | Q43    | 18.21 | 0   | 0   | 0.66 | 6.62 | 0  | 0.66 | 0  | 0  | 74  | 26        | 32.49  | 0.21        | 0.01     |
|                    | Q42    | 11.96 | 0   | 1.00 | 2.33 | 5.32 | 0  | 1.33 | 0  | 0  | 78  | 22        | 8.50   | 0.14        | 0.02     |
|                    | Q33    | 12.05 | 0.33 | 1.30 | 3.26 | 6.51 | 0  | 2.28 | 0.33 | 0.33 | 74  | 26        | 103.54 | 0.57        | 0.01     |
|                    | Q24    | 14.64 | 0.62 | 1.25 | 1.25 | 2.18 | 0  | 2.18 | 1.56 | 76  | 24  | 61.87     | 0.36   | 0.01        |          |
|                    | Q14    | 15.54 | 0   | 1.69 | 1.69 | 4.73 | 1.35 | 3.38 | 0  | 0  | 72  | 28        | 76.08  | 0.01        | 0.00     |
|                    | Q1     | 7.333 | 0   | 0   | 2    | 28.33 | 0  | 1.00 | 0  | 0  | 61  | 39        | 37.68  | 0.92        | 0.02     |
| Average            |        | 13.29 | 0.16 | 0.87 | 1.86 | 8.95 | 0.23 | 1.81 | 0.05 | 0.31 | 72  | 28        | 53.36  | 0.37        | 0.01     |
| Total average      |        | 14.16 | 0.26 | 0.69 | 2.30 | 8.71 | 1.04 | 2.04 | 0.02 | 1.10 | 70  | 30        | 40.90  | 0.34        | 0.01     |
0.07 g at 3260 m. It exhibits 0.17 and 0.36 g at depths 3414 and 3470 m, respectively.

Ultra-stable heavy minerals (zircon, tourmaline, and rutile) represent 12.85% of the total heavy fraction. The moderately stable group (monazite, kyanite, and sphene) displays 4.81%, while the unstable group (pyroxene, epidote, mica, and amphibole) demonstrates 82.4%.

Generally, the identified transparent heavy minerals signify 48%, while the opaques represent 52% of the total heavy fraction identified in Boughaz-1. The heavy mineral grains of Boughaz-1 are sub-rounded to well-rounded (Fig. 14c).

Zircon, tourmaline, and rutile grains are a relatively smaller size than those identified in Tarif-2A, while some unusual large, prismatic flakes of mica (muscovite) and pyroxene (enstatite) grains are recorded at 3414 m depth. Rutile may show a decrease with depth while tourmaline exhibits increase.

| Table 3  | Heavy mineral indices used in the study |
|---------|----------------------------------------|
| Index   | Indexed minerals                      | Formula                           | Reference                       |
| ZTRi    | Zircon, tourmaline, rutile             | 100 x (ZTR / total THM)           | Hubert (1962)                   |
| RZi     | Rutile:zircon                          | 100 x rutile / rutile + zircon    | Morton and Hallsworth (1994)    |
| MZi     | Monazite:zircon                        | 100 x monazite / monazite + zircon | Morton and Hallsworth (1994)    |
| STi     | Staurolite:tourmaline                  | 100 x staurolite / staurolite + tourmaline | Morton and Hallsworth (1994) |
| GZi     | Garnet:zircon                          | 100 x garnet count / garnet + tourmaline | Morton and Hallsworth (1994)    |
| tHMCi   | Transparent HM concentration           | Volume of transparent HM in sample | Garzanti et al. (2018)          |
Fig. 13 Stratigraphic plot of heavy mineral indices for the Oligocene section, Gebel Qatrani, Fayum

Table 4 Heavy mineral indices of Oligocene sandstones of Gebel Qatrani, Fayum

| Lithostratigraphy | Sample | Indices                          | Rzi count | Mzi count | Gzi count | ZTRi count | tHMCi count |
|-------------------|--------|----------------------------------|-----------|-----------|-----------|------------|-------------|
| Gebel Qatrani Formation | Q88    | 40                               | 200       | 9.09      | 200       | 0          | 200         | 68.18       | 298         | 0.29       | 298        |
|                   | Q87    | 42.9                             | 200       | 0         | 200       | 16.7       | 200         | 69.44       | 302         | 0.23       | 302        |
|                   | Q86    | 41.7                             | 200       | 0         | 200       | 13         | 200         | 54.32       | 313         | 0.25       | 313        |
|                   | Q83    | 44.4                             | 200       | 10.71     | 200       | 16.7       | 200         | 37.36       | 322         | 0.54       | 322        |
| Upper member      | Q78    | 64.5                             | 200       | 0         | 200       | 18.2       | 200         | 23.26       | 282         | 0.60       | 282        |
|                   | Q75    | 60                               | 200       | 0         | 200       | 200        | 200         | 34.38       | 304         | 0.21       | 304        |
|                   | Q67    | 63                               | 200       | 16.67     | 200       | 16.7       | 200         | 37.36       | 322         | 0.54       | 322        |
|                   | Q64    | 62.5                             | 200       | 0         | 200       | 200        | 200         | 34.38       | 304         | 0.21       | 304        |
|                   | Q43    | 75                               | 200       | 0         | 200       | 0          | 200         | 69.62       | 302         | 0.26       | 302        |
|                   | Q42    | 75                               | 200       | 0         | 200       | 17.6       | 200         | 54.55       | 301         | 0.21       | 301        |
|                   | Q33    | 64.3                             | 200       | 9.09      | 200       | 20         | 200         | 45.68       | 307         | 0.26       | 307        |
|                   | Q24    | 54.8                             | 200       | 12.5      | 200       | 20         | 200         | 61.84       | 321         | 0.23       | 321        |
|                   | Q14    | 48.4                             | 200       | 0         | 200       | 25         | 200         | 54.76       | 296         | 0.28       | 296        |
|                   | Q1     | 64.3                             | 200       | 0         | 200       | 0          | 200         | 18.97       | 300         | 0.38       | 300        |
**Onshore wells**

a) Tarif-2A

Generally, transparent heavy minerals represent 72%, while the opaques represent 28% of the heavy fraction examined in Tarif-2A samples.

Ultra-stable heavy minerals are represented by zircon, tourmaline, and rutile which forms about 7.53%. The moderately stable group (monazite, sphene, and staurolite) represents 18.7%, while the unstable group (pyroxene, epidote, and mica) displays 73.8% (Table 5).

Generally, the grains of the heavy fraction embedded in the Oligocene sand horizons of Tarif-2A well range from sub-rounded to angular. On the other hand, epidotes show smaller size than zircon, tourmaline, rutile, pyroxene, and mica with sub-rounded outlines.

Some zircon, tourmaline, and rutile grains are prismatic with angular bipyramidal terminations, while other rutiles show well-rounded outlines. Monazite and sphene show sub-rounded to well-rounded outline grains. Staurolite exhibits sub-angular grains while pyroxenes (enstatite) display relatively long, prismatic grains, and at some intervals, it exhibits smaller size. Epidote grains are rounded in outlines. The identified muscovite and biotite are of flaky habit with long, prismatic grains (Fig. 14a).

Oligocene interval ranges from 3695 to 4710 m. Six samples were obtained to represent the depth interval 3635–4140 m.

The transparent heavy mineral assemblage is represented by mica > sphene > epidote > pyroxene (enstatite) > zircon, tourmaline, rutile > staurolite > monazite.

The weight of the heavy fraction shows an overall increase downward with depth from 1.35 g at 3635 m to 3.02 g at 4108 m. It exhibits 1.37 and 0.82 g at depths 4131 and 4140 m, respectively. The weight of the fine and very fine heavy fraction in this well exhibits variable values ranging from 0.17 to 1.46 g with the highest value found at depth 3834 m. The middle interval of this well (4108–4131 m) shows a similar weight (0.63 g) of the heavy fraction.

b) San El-Hagar-1 well

San El-Hager-1 well is located east of Tarif-2A onshore of the Nile Delta. The Oligocene interval starts from 2890 to 3700 m. Eight samples were attained to represent the depth interval 2764–3630 m.

The weight of the fine and very fine heavy fraction in this well exhibits variable values ranging from 0.22 to 0.8 g with the highest value at depth 2910 m. The middle interval of this well (2940–3570 m) shows a similar weight (0.48 g) of the heavy fraction (Table 5). The weight of the fine and very fine heavy fraction in this well exhibits a similar distribution pattern with variable values ranging from 1.07 to 4.31 g with the highest value at depth 2910 m. The middle interval of this well (2940–3570 m) shows approximately similar weight (1.56–2.13 g) of the heavy fraction.

The identified transparent heavy mineral assemblage identified is mica > epidote > sphene > rutile > zircon > pyroxene (enstatite) > tourmaline > staurolite > monazite > garnet. Generally, transparent heavy minerals represent 57.56%, while opaques display 42.44% of the heavy fraction examined in San El-Hager-1 samples.

Ultra-stable heavy minerals (zircon, tourmaline, and rutile) represent 15.42%. The moderately stable group (monazite, garnet, sphene, and staurolite) exhibits 15.64%, while the unstable group (pyroxene, epidote, and mica) represents 68.94%. It appears that rutile, pyroxene, and sphene contents decrease with depth, while tourmaline shows decrease. Zircon is the most abundant in ZTR group. The same optical properties were identified as

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### Table 5

Heavy mineral assemblage identified in the Oligocene sandstone intervals, Nile Delta

| Lithostratigraphy | Sampled Location | Depth (m) | Transparent heavy mineral assemblages frequencies (%) | Within H. fraction weight (g) |
|-------------------|------------------|----------|------------------------------------------------------|-------------------------------|
| **Daba Formation** |                  |          |                                                     |                               |
| **Arramoun-1**    |                  |          |                                                     |                               |
| A1 3000           | 3.03             | 2.45     | 1.58                                               | 0.89                           |
| A2 3000           | 2.45             | 2.00     | 1.62                                               | 0.90                           |
| A3 3000           | 2.00             | 1.58     | 1.25                                               | 0.71                           |
| A4 3000           | 1.58             | 1.25     | 1.04                                               | 0.63                           |
| A5 3000           | 1.25             | 1.04     | 0.89                                               | 0.56                           |
| A6 3000           | 1.04             | 0.89     | 0.82                                               | 0.56                           |
| Average           |                  |          |                                                     |                               |
| **San Faraj 1**   |                  |          |                                                     |                               |
| S1 2500           | 2.56             | 2.00     | 1.58                                               | 0.89                           |
| S2 2500           | 2.00             | 1.58     | 1.25                                               | 0.71                           |
| S3 2500           | 1.58             | 1.25     | 1.04                                               | 0.63                           |
| S4 2500           | 1.25             | 1.04     | 0.89                                               | 0.56                           |
| Average           |                  |          |                                                     |                               |
| **San Faraj 2**   |                  |          |                                                     |                               |
| T1 3000           | 3.03             | 2.45     | 1.58                                               | 0.89                           |
| T2 3000           | 2.45             | 2.00     | 1.62                                               | 0.90                           |
| T3 3000           | 2.00             | 1.58     | 1.25                                               | 0.71                           |
| T4 3000           | 1.58             | 1.25     | 1.04                                               | 0.63                           |
| T5 3000           | 1.25             | 1.04     | 0.89                                               | 0.56                           |
| Average           |                  |          |                                                     |                               |
| **San El-Hagar-1**|                  |          |                                                     |                               |
| B1 3000           | 3.20             | 2.00     | 1.58                                               | 0.89                           |
| B2 3000           | 2.00             | 1.58     | 1.25                                               | 0.71                           |
| B3 3000           | 1.58             | 1.25     | 1.04                                               | 0.63                           |
| B4 3000           | 1.25             | 1.04     | 0.89                                               | 0.56                           |
| Average           |                  |          |                                                     |                               |
| **Onshore wells** |                  |          |                                                     |                               |
| A1 3000           | 3.03             | 2.45     | 1.58                                               | 0.89                           |
| A2 3000           | 2.45             | 2.00     | 1.62                                               | 0.90                           |
| A3 3000           | 2.00             | 1.58     | 1.25                                               | 0.71                           |
| A4 3000           | 1.58             | 1.25     | 1.04                                               | 0.63                           |
| A5 3000           | 1.25             | 1.04     | 0.89                                               | 0.56                           |
| Average           |                  |          |                                                     |                               |
| **San Faraj 1**   |                  |          |                                                     |                               |
| S1 2500           | 2.56             | 2.00     | 1.58                                               | 0.89                           |
| S2 2500           | 2.00             | 1.58     | 1.25                                               | 0.71                           |
| S3 2500           | 1.58             | 1.25     | 1.04                                               | 0.63                           |
| S4 2500           | 1.25             | 1.04     | 0.89                                               | 0.56                           |
| Average           |                  |          |                                                     |                               |
| **San Faraj 2**   |                  |          |                                                     |                               |
| T1 3000           | 3.03             | 2.45     | 1.58                                               | 0.89                           |
| T2 3000           | 2.45             | 2.00     | 1.62                                               | 0.90                           |
| T3 3000           | 2.00             | 1.58     | 1.25                                               | 0.71                           |
| T4 3000           | 1.58             | 1.25     | 1.04                                               | 0.63                           |
| T5 3000           | 1.25             | 1.04     | 0.89                                               | 0.56                           |
| Average           |                  |          |                                                     |                               |
| **San El-Hagar-1**|                  |          |                                                     |                               |
| B1 3000           | 3.20             | 2.00     | 1.58                                               | 0.89                           |
| B2 3000           | 2.00             | 1.58     | 1.25                                               | 0.71                           |
| B3 3000           | 1.58             | 1.25     | 1.04                                               | 0.63                           |
| B4 3000           | 1.25             | 1.04     | 0.89                                               | 0.56                           |
| Average           |                  |          |                                                     |                               |
those of Trif-2A heavy mineral assemblage. The grain outlines of transparent heavy minerals are mainly sub-rounded to rounded. Unlike Tarif-2A, micas at San El-Hager-1 are rounded and show a remarkable decrease in grain size. Pyroxenes (enstatite) are relatively smaller in size than those of Tarif-2A. Epidote grains at San El-Hager-1 are similar to those in Tarif-2A (Fig. 14b).

iii) Rommana-1

This well is located eastward of San El-Hager-1 and is the nearest one to the Mediterranean shoreline (Fig. 2). Oligocene interval in Rommana-1 starts from 2710 to 3500 m. The available data represents a depth horizon of 2810 m. One sample surely is not an indication of the behavior of heavy mineral assemblage in this location, but it will give aid in the interpretation of the heavy mineral behavior in the area by comparing the identified assemblage in the other wells.

Transparent heavy mineral assemblage encountered in Oligocene sands of Rommana-1 is epidote > sphene > mica > zircon, tourmaline, and rutile.

The weight of heavy minerals is 0.23 g while the weight of the fine and very fine fraction is 1.26 g. The transparent heavy mineral grains identified are well rounded and have a relatively smaller size than the previous grains of the two wells (Tarif-2A and San El-Hager-1). The absence of pyroxenes is another distinguishing feature. The recorded heavy mineral assemblage in the studies wells is illustrated in Fig. 16.

Heavy mineral indices

In general, the values of Rzi and ZTR indices show marked variation through the Oligocene sandstones of onshore and offshore wells. In all wells, the higher values of Rzi correspond to lower values of ZTRi but San El-Hagar-1 (Table 6).
RZi values fall into three groups; one with low values (7.5–16.7%) occurs in PFMD-1 offshore well. The second group shows fairly stable moderate values (23–45%) that occur mostly within the Habbar-1 and within the lower and upper parts of Tarif-2 well. The third group exhibits the higher RZi values (50–100%) occurring mostly within the middle interval (3414–3201 m) of Boughaz-1 offshore, Tarif-2 onshore wells, and the lower and upper parts of San El-Hager-1 onshore well.

Fig. 15 Photomicrographs show a Large grains of kyanite (Ky) and muscovite (M) recorded in Habbar-1 well, offshore, Nile Delta Oligocene interval 3852 m. b Large grains of muscovite (M) recorded in Habbar-1 well, offshore, Nile Delta Oligocene interval 4283 m. c Large zircon (Z) recorded in Habbar-1 well, offshore, Nile Delta Oligocene interval 4283 m. d Large grains of kyanite (Ky) and pyroxene (Pr) recorded in Habbar-1 well, offshore, Nile Delta Oligocene interval 4363 m. e Zircon (Z), sphene (Sp), pyroxene (Pr), and muscovite (M) recorded in Habbar-1 well, offshore, Nile Delta Oligocene interval 4283 m. f Large grains of zircon (Z), pyroxene (Pr), and muscovite (M) flakes recorded in Habbar-1 well, offshore, Nile Delta Oligocene interval 4283 m. g Large grains of zircon (Z), pyroxene (Pr), sillimanite (S), and muscovite (M) flakes recorded in Habbar-1 well, offshore, Nile Delta Oligocene interval 4363 m.
Likewise, the RZi and the ZTRi values indicate marked variation through three groups with low (3–10%), moderate (10–15%), and fairly higher (15–25%) values. In general, the lower values of ZTRi correspond to the higher values of ZRi in all wells except San El-Hager-1 well. The lower part of San El-Hager-1 well displays the higher values (13–23%) of ZTRi and moderately to fairly high values (44–53%) of ZRi.

MZi values indicate a strong variation through the samples of the five wells. The lower values (3–12%) of MZi are recorded within the basal intervals of Habbar-1 and Boughaz-1 wells and through the entire of San El-Hager-1 well (Table 6). The moderate values (29–38%) of MZi are recorded within the basal, middle, and upper intervals of PFMD-1, Habbar-1, and Tarif-2 wells, respectively. The highest values (40–67%) of MZi are recorded within the upper interval of PFMD-1 and middle intervals of Habbar-1 and Boughaz-1 wells. Data for the GZi within both the offshore and onshore wells are very limited because of the scarcity of garnet in the sandstones of the studied wells in the Nile Delta. Very restricted values of GZi (9, 43, and 45%) were recorded in Habbar-1 and San El-Hager-1 wells (Table 6). tHMCi values signify a strong variation through the samples of the five wells. The lower values (0.21–0.33%) of tHMCi are displayed within the PFMD-1 and Rommana-1 wells. The moderate values (0.44–0.64%) of tHMCi are recorded within the entire San El-Hager-1 well. The highest values (0.70–0.94%) of tHMCi are recorded within the entire of Habbar-1 and Tarif-2 wells (Fig. 17).

**Subsurface mapping**

The mapping procedure is a fundamental step in the current study, as we mainly focused on mapping the Oligocene strata in the Nile Delta (onshore and offshore) to discuss (regionally) the provenance analysis results with the distribution and depth of Oligocene sedimentary rocks.

**Scanning electron microscope**

Based on the optical properties examined by both polarizing light microscope and binocular microscope, some samples were selected to be examined by scanning electron microscope for studying the burial effect on the heavy mineral assemblage identified in the Nile Delta. These samples belong to the offshore wells in Nile Delta (Boughaz-1, Port Fouad Marine Deep-1, and Habbar-1). The depth intervals are shown in Table 7.

A remarkable variation is observed among the heavy minerals in these intervals within the three wells. The size reduction and the increase of roundness of the heavy mineral assemblage are observed in Boughaz-1 well for two samples scanned at depth intervals of 3414 m (Fig. 18a) and 3470 m (Fig. 18b). Since the samples of Pour Fouad Marin Deep-1 well are the deepest, the heavy mineral assemblage has a remarkably increased percentage of corroded, deeply etched, and even skeletal grains. These features are observed in depths 4912 m (Fig. 18c) and 5113 m (Fig. 18d). In contrast, the investigated heavy minerals of Habbar-1 well showed that the heavy mineral grains are clean, with larger size (compared to the other two wells) and smooth prismatic habit at depth interval 4443 m (Figs. 18e, f).
### Table 6 Heavy mineral indices of Oligocene sand intervals in Nile Delta

| Lithostratigraphy | Sample | Depth | RZi | count | MZi | count | GZi | count | ZTRi | count | tHMCi | count |
|-------------------|--------|-------|-----|-------|-----|-------|-----|-------|------|-------|-------|-------|
| **Rommana-1**     | R1     | 2810  | 0   | 200   | 0   | 200   | 0   | 200   | 13.24| 318   | 0.21  | 318   |
|                   | S1     | 2764  | 55.56| 200   | 11.11| 200   | 25  | 200   | 16.77| 316   | -0.61 | 316   |
|                   | S2     | 2855  | 64.29| 200   | 0    | 200   | 0   | 200   | 6.20 | 308   | 0.78  | 308   |
|                   | S3     | 2910  | 41.18| 200   | 0    | 200   | 0   | 200   | 12.15| 323   | 0.56  | 323   |
|                   | S4     | 2940  | 44.44| 200   | 0    | 200   | 0   | 200   | 19.74| 307   | 0.49  | 307   |
|                   | S5     | 2970  | 50   | 200   | 9.09 | 200   | 0   | 200   | 12.69| 306   | 0.64  | 306   |
|                   | S6     | 3570  | 52.94| 200   | 11.11| 200   | 0   | 200   | 16.57| 316   | 0.57  | 316   |
|                   | S7     | 3600  | 53.33| 200   | 0    | 200   | 0   | 200   | 23.18| 311   | 0.48  | 311   |
|                   | S8     | 3630  | 43.75| 200   | 0    | 200   | 0   | 200   | 22.06| 306   | 0.44  | 306   |
| **San El-Hagar-1**| T1     | 3635  | 33.33| 200   | 0    | 200   | 0   | 200   | 5.75 | 379   | 0.66  | 379   |
|                   | T2     | 3660  | 60   | 200   | 33.33| 200   | 0   | 200   | 3.64 | 306   | 0.71  | 306   |
|                   | T3     | 3834  | 45.45| 200   | 0    | 200   | 0   | 200   | 8.15 | 323   | 0.56  | 323   |
|                   | T4     | 4108  | 66.67| 200   | 0    | 200   | 0   | 200   | 7.05 | 308   | 0.73  | 308   |
|                   | T5     | 4131  | 60   | 200   | 0    | 200   | 0   | 200   | 2.60 | 340   | 0.9   | 340   |
|                   | T6     | 4140  | 33.33| 200   | 0    | 200   | 0   | 200   | 18.02| 300   | 0.74  | 300   |
| **Tarif-2A**      | B1     | 3081  | 47.62| 200   | 0    | 200   | 0   | 200   | 24.80| 344   | 36    | 344   |
|                   | B2     | 3201  | 75   | 200   | 0    | 200   | 0   | 200   | 12.35| 311   | 0.26  | 311   |
|                   | B3     | 3260  | 75   | 200   | 50   | 200   | 0   | 200   | 4.13 | 323   | 0.74  | 323   |
|                   | B4     | 3414  | 100  | 200   | 0    | 200   | 0   | 200   | 7.25 | 314   | 0.43  | 314   |
|                   | B5     | 3470  | 9.09 | 200   | 4.76 | 200   | 0   | 200   | 15.73| 304   | 0.58  | 304   |
| **Boughaz-1**     | H1     | 3852  | 20   | 200   | 0    | 200   | 0   | 200   | 42.86| 308   | 0.81  | 308   |
|                   | H2     | 4283  | 38.46| 200   | 0    | 200   | 0   | 200   | 7.80 | 308   | 0.7   | 308   |
|                   | H3     | 4362  | 23.08| 200   | 28.57| 200   | 0   | 200   | 9.30 | 320   | 0.94  | 320   |
|                   | H4     | 4363  | 45.45| 200   | 40   | 200   | 0   | 200   | 7.12 | 329   | 0.89  | 329   |
|                   | H5     | 4443  | 34.78| 200   | 11.76| 200   | 0   | 200   | 14.35| 313   | 0.71  | 313   |
| **Habbar-1**      | P1     | 4912  | 75   | 200   | 66.67| 200   | 0   | 200   | 6.00 | 300   | 0.33  | 300   |
|                   | P2     | 5004  | 16.67| 200   | 37.5 | 200   | 0   | 200   | 8.91 | 314   | 0.32  | 314   |
|                   | P3     | 5113  | 16.67| 200   | 37.5 | 200   | 0   | 200   | 13.24| 288   | 0.23  | 288   |

**Fig. 17** Vertical variation of the heavy mineral indices of the Oligocene sand intervals, Nile Delta, Egypt

![Graph](image)
Two-way time mapping

The applied method to generate two-way time (TWT) surfaces in the present work is accomplished by the (editing surface) process; the workflow requires inputting the interpreted horizon and a boundary that delineates the mapping area (Fig. 19). The outcome is the TWT surface of the interpreted horizon within the delineated area.

The generated TWT surfaces of the onshore surveys have a TWT range (1250–6000 ms), while the generated surfaces of the same horizons in the offshore survey have a TWT range (3700–6200 ms).

After the generation of TWT surfaces, the next step is to convert these surfaces from time to depth to be capable of constructing depth contour maps and using them in the construction of the thickness maps. Time to depth conversion is accomplished through applying the formula (Depth = TWT surface × Velocity (m/s)); the outcome of this procedure is depth contour surface.

Thickness mapping

The generation of Oligocene thickness (isopach) maps is done through using the (make thickness map) command on the generated depth surface (Oligocene); then, the Eocene (i.e., Bottom Oligocene horizon) is defined as the base surface. The same procedure is applied on both off- and onshore-generated depth surfaces from the previous step. The generated isopach maps represent the thickness difference between the inputs (Oligocene and Eocene) which represent the thickness of the Oligocene interval in the Nile Delta. The thickness of the Oligocene interval in the onshore Nile Delta ranges from 500 to 4000 m (Fig. 20).

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**Table 7** The depth intervals of Boughaz-1, Pour Fouad Marine Deep-1, and Habbar-1

|        | Boughaz-1 | PFMDeep-1 | Habbar-1 |
|--------|-----------|-----------|----------|
| 3414 m | 4912 m    | 3852 m    |
| 3470 m | 5113 m    | 4443 m    |

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**Fig. 18** SEM images of a zircon (Z) and corroded, etched mica (Mi) recorded in Boughaz-1 well at depth interval 3414 m. b Corroded zircon (Z) and epidote (Ep) recorded in Boughaz-1 well at depth interval 3470 m. c Zircon (Z), rutile (R), and heavily corroded mica (Mi) and epidote (Ep) recorded in Port Fouad Marine Deep-1 well at depth interval 4912 m. d Heavily corroded and skeletal mica (Mi) and epidote (Ep) recorded in Port Fouad Marine Deep-1 well at depth interval 4912 m. e Fresh zircon (Z), pyroxene (Pr), and mica flake (Mi) recorded in Habbar-1 well at depth interval 4443 m. f Fresh kyanite (Ky) grain recorded in Habbar-1 well at depth interval 3852 m.
hand, the Oligocene interval in offshore ranges from 1000 to 2400 m (Fig. 21).

**Well log analysis and petrophysical parameters**

The calculated parameter of shale, used in this study, is shown in Table 8. The highest values in the constructed cross plots of bulk density, sonic transit time, neutron, and deep resistivity against gamma ray (Fig. 22) demonstrate the different characteristics of Oligocene shale. The Dabaa Formation shales have moderate bulk density (ranging from 2.13 to 2.67 g/cm³), high sonic transit time (ranging from 107 to 130 μs/ft), high neutron porosity values in the range of 38–46%, and low resistivity values (ranging from 0.32 to 1.185 Ω m). On the other hand, the lowest values represent the characteristics of sandstones embedded within the Dabaa Formation. It has moderate bulk density (ranging from 2.12 to 2.46 g/cm³), moderate to high sonic transit time (ranging from 98 to 116 μs/ft), moderate to high neutron porosity values in the range of (22–49%), and a wide range of resistivity values (0.67–7.9 Ω m).

The estimated petrophysical parameters of the logged Oligocene interval in the studied wells are demonstrated in Table 9. The net reservoir thickness attains the maximum values in Habbar-I well 153.9 m with a net pay 89.31 m; it also has the highest effective porosity value (22.8%), while the minimum values were recorded in San El-Hager-I well with a net reservoir thickness 17.3 m.

Among the studied wells, the most promising intervals are found in Habbar-I (Fig. 23) and Port Fouad Marine Deep-I wells. The Oligocene interval in Qallin-I and San El-Hager-I wells shows low values of reservoir characteristics compared to the two other wells (Table 9).

**Discussion**

**Provenance insights**

Although that this study is an attempt to identify successive changes in sand provenance during the Oligocene in both Gebel Qatrani and Nile Delta, the data are too limited to identify specific source rocks. It is, however, possible to
assess the possibility of local recycling of older sands by comparing compositional ranges as defined by heavy mineral indices.

Said (1962) and Salem (1976) believed that the transportation pattern of Oligocene sediments in the Fayum Province was a northward-flowing pattern. They supported their opinion by the absence of Red Sea igneous and metamorphic rock fragments in the Oligocene and Lower Miocene gravels while they are present in the Pleistocene gravels. They suggested that the Red Sea Hills were not uncovered until...
the end of the Lower Miocene or were excluded from the catchment area of the Oligocene–Lower Miocene “Ur-Nil” by some barriers. They constructed this conclusion on the absence of igneous and metamorphic rock fragments in the Oligocene and Lower Miocene gravels while they are present in the Pleistocene gravels.

This opinion was already criticized by Bown and Kraus (1988) who believed that the west-northwestward Oligocene streams are flowing in the same direction since depositions of Dir Abu-Lifa member of Qasr El-Sagha Formation. Two reasonable evidences enrich the opinion of Bown and Kraus

Table 8 The estimated shale parameters of the Dabaa Formation in the studied wells

| Well          | Parameter | ρsh (g/cm³) | ΦNsh (%) | Δtsh (μs/ft) | Rsh (Ω m) |
|---------------|-----------|-------------|----------|--------------|-----------|
| San El-Hager-1| 2.308     | -           | 130      | 0.3178       |
| Qallin-1      | 2.135     | 46.023      | 134      | 0.9833       |
| Habbar-1      | 2.52      | 35.5        | 107      | 0.9892       |
| PFMD-1        | 2.67      | 38.8        | 114      | 1.185        |

Table 9 Average petrophysical parameters of the Dabaa Formation in the studied wells

| Well          | Top         | Bottom      | GT     | NRT     | NPT     | N/G   | Øe   | Vsh  | SW    | Snc  |
|---------------|-------------|-------------|--------|---------|---------|-------|------|------|-------|------|
|               | m          | m           | m      | m       | m       | %     | %    | %    | %     | %    |
| San El-Hager-1| 2879.6     | 3780        | 894    | 17.3    | 0       | _     | _    | _    | _     | _    |
| Qallin-1      | 3810       | 3976        | 166    | 112     | 1.98    | 0.679 | 18.9 | 60.5 | 90    | 10   |
| Habbar-1      | 3828.5     | 4523        | 644.7  | 153.9   | 89.31   | 0.239 | 22.8 | 61   | 89    | 11   |
| PFMD-1        | 3506       | 4999.7      | 1491   | 149     | 46.33   | 0.092 | 19.2 | 84   | 79.5  | 19.5 |
| Total or Avg. | 3195.7     | 432.2       | 137.62 | 1.01    | 20.3    | 68.5  | 86.16667 | 13.5 |

Fig. 22 Cross-plots of gamma ray values vs. bulk density, apparent neutron porosity, deep resistivity and sonic transit time values used for estimating the different parameters of shale lithology (Habbar-1 well as an example)
first one is based on the large planner cross-bedding recorded in the lower member of Gebel Qatrani. The azimuth readings range from 210 to 316° with a magnitude varying from 20 to 30°. These paleocurrent directions prove that the lower part of the Gebel Qatrani Formation was deposited by west, southwest, and northwest streams, while in the upper member, the paleocurrent directions range from 220 to 330° with a magnitude ranging from 20 to 40°. The second evidence is the lineup of the petrified trees recorded in the basal part of Gebel Qatrani Formation which is measured by El-Araby and El-Barkooky (2000) to be trending E–W, NE–SW, and ENE–WSW, the trend which is believed to be the directions of paleorivers. Within the same context, the contour map which demonstrates the maturation trend indicated by ZTRi along with transparent heavy mineral distribution (Figs. 24 and 25) showed a decrease in the volume percentage of transparent heavy minerals toward the northwest trend. These data are confirmed by our results that demonstrate the decrease in the transparent heavy mineral percentages in the northwest trend.

The transparent heavy mineral concentration index tHMCi of Oligocene sandstones of Gebel Qatrani Formation is found to be ranged from 0.2 to 0.6%. Approximately, the tHMCi values within the entire formation were found between 0.2 and 0.4%. These values which define the transparent heavy mineral suites at Gebel Qatrani Formation are described as very poor according to the classification of Garzanti et al. (2018).

The maturation trend of Gebel Qatrani sandstones is E–W, NE–SW, and ENE–WSW which is in the same
direction of the measured large planar cross-bedding of the lower member of Gebel Qatrani in this study.

The calculated ZTRi demonstrated a distinct variation between the three members of Gebel Qatrani Formation. Generally, it shows a remarkable gradual increase within the lower and upper members but a gradual decrease within the middle member. Along the entire formation, the values of ZTRi show a negative correlation with the percentages of pyroxene (Table 6). The lower and the upper members of Qatrani Formation display high ZTRi and low pyroxene contents indicating more maturation than the middle member which reflects an influx of less mature sand. The middle member may reflect a tectonic reconfiguration of the hinterland during its deposition. This may be signified by the abrupt changes in ZTRi and the high pyroxene values along the boundaries between the middle and upper members (Tables 2 and 4) and (Figs. 12 and 13).

Although monazite is absent in almost all samples (9 samples) of the Qatrani Formation, the other five samples (represent the three members) show quite similar values of MZi. In contrast to the MZi, the RZi and GZi values show distinct variation along the three members of Gebel Qatrani, indicating strong support for a difference in provenance between the three members.

### Nile Delta

Provenance reconstruction of the Oligocene sedimentary rocks in the Nile Delta was a matter of debate over the last half-century. The history of the Nile drainage is very important to understand and interpret the provenance of the Oligocene strata in Egypt. The established controversy is set between two opinions. The first opinion proposed that the connection between the Ethiopian plateau and the Mediterranean was not established until the earliest Late Messinian (Chumakov, 1968; Issawi and McCauley 1992; Said 1993). The other opinion adopted by Berry and Whiteman (1968), McDougall et al. (1975), Burke and Wells (1989), Williams et al. (2000), Craig et al. (2010), and Abdelkareem et al. (2012) proposed that the connection was established since Oligocene.

The first attempt of using heavy minerals to distinguish between the Nile tributaries was accomplished by Shukri (1951). Based on the identified heavy minerals (pyroxene mainly) variation, he concluded that the Nile did not bring any sediments to Egypt during Pliocene and Plio-Pleistocene times. According to this, Atbara and Blue Nile sediments reached Egypt in more recent times. On the other
hand, Fielding et al. (2017) used multitechnique provenance studies to conclude that the uplift of the Red Sea Hills was associated with the uplift of the Ethiopian plateau and the eruption of continental flood basalts. They also stated that the provenance signature of zircons analyzed from Oligocene sediments is contemporaneous with those of Ethiopian highlands. They referred to the contribution of the older Phanerozoic craton and the Red Sea Hills in both Oligocene and modern Nile sediments. In the same context, Fielding et al. (2018) concluded that the Nile drainage has been extended from Ethiopian highlands to nowadays Nile Delta since Oligocene times. They reasoned their assumption by the constancy of the provenance signature of Nile Delta since Oligocene to the present with input of Ethiopian volcanics preserved within the Nile Delta succession. The earliest records of the delta are preserved onshore in Egypt near Fayum and have been dated as Eocene (38–35 Ma) (Salem 1976; Underwood et al. 2013). The delta began to pro-grade north as the Tethys Ocean receded, depositing in its current offshore location from the Oligocene (Fielding et al. 2018).

According to these assumptions, the Oligocene sandstones of Gebel Qatrani Formation in the Fayum Province should be enriched with the same heavy mineral signature of the Oligocene sand intervals of the Dabaa Formation in the Nile Delta as it is the proposed pathway of sediments. Moreover, the Oligocene sand interval suits of the Nile Delta should show much more maturation level when compared to their age equivalent of Gebel Qatrani Formation, because of the transportation path and burial depth effect as the Oligocene sand intervals of the Nile Delta are buried on more than 2 km at least.

Our data showed that the heavy mineral suits of Gebel Qatrani Formation are much more mature than those of the Oligocene sand intervals of the Nile Delta. The ZTR index of Gebel Qatrani Formation ranges from 18.97 to 69.62%, while in the Nile Delta, it varies from between 2.6 and 24.8%. Although the Oligocene sand intervals in the Nile Delta are buried at least under 2 km, the heavy mineral suits in the Nile Delta are more enriched than those of Gebel Qatrani sandstones. The heavy fraction ratio of Gebel Qatrani sandstones is 0.011 in the lower member and 0.017 in the middle member and 0.008 in the upper, while in Oligocene sands of Nile Delta, it starts with 0.17 at Boughaz-1 and Rommana-1, 0.26 at Habbar-1, and 0.4 at San El-Hager-1 and Pour Fouad Marine Deep-1 and attains the maximum value at Tarif-2A well with 0.6.

Fig. 25 Contour map illustrates heavy minerals’ ratio recorded within Oligocene sands in Northern Egypt (Fayum and Nile Delta)
The assumption proposed by Fielding et al. (2017) and depends basically on the existence of the same provenance signature of the Cenozoic flood basalts which was dated to be contemporaneous with the uplift of the Red Sea Hills and Ethiopian highlands. They also attributed the identified signature of Cenozoic basalts to the Ethiopian highlands exclusively. According to Fielding et al. (2017), the Ethiopian uplift is estimated to be timed at Oligocene which led to the initiation of flow in the Blue Nile. This fact opposes the idea of derivation of sediments from Ethiopian province to the Offshore Mediterranean either volumetrically or in timing. This fact might result in a misleading interpretation, as at the same timing (Oligocene), Northeast Africa generally — Egypt by necessity — witnessed basaltic eruptions accompanying the rift of the Red Sea Hills which was documented by Said (1990). Oligocene times also witnessed the rift opening in the Gulf of Suez, creating local pathways from rift shoulders (Dolson et al. 2014). Continental flood basalt (CFB) signature of those basalts that erupted in Egypt may have been contributed with the recorded signature of the consequent sediments.

In the study accomplished by Fielding et al. (2018), they reported that the Phanerozoic craton of the Red Sea Hills was a major source that supplied the Nile Delta sediments since at least 30 Ma, which agrees with their previous conclusion that the modern Nile trunk contains significant detritus derived from erosion of Phanerozoic cover (Fielding et al. 2017). But in these studies, they did not report a clear percentage of contribution which makes some questions matter of debate like the original signature provenance of these sediments in the Nile Delta sediments, does it completely originate from the Phanerozoic cover? or even if they were the main source? and what is the real percentage of the Cenozoic flood basalts in these sediments. Answering such questions makes the vision more clear in interpreting the provenance of these sediments, especially in Macgregor (2012) when he studied the sedimentary rates from source to sink that reached a different conclusion. Our data agree with Macgregor (2012) in his conclusion that Red Sea rift shoulders, which supply about half of the clastic sediment contribution to the system, are suggested to have first risen at 30 Ma, more or less contemporaneously with the Afar Plume, triggering the formation of the Nile system as represented by a sharp change from carbonates to clastics in the Nile Delta. The rise of these rift shoulders and other contemporaneous African swells led to a change in river patterns across Africa and caused systems that originally drained to the Niger to switch northwards to create the current Nile system. Sudanese and Eritrean rivers flowing down the Red Sea rift shoulder eventually connected with the “Giff” system of Issawi and McCauley (1992) and thereafter with a series of incised valleys in the Western Desert (Dolson et al. 2002). Moreover, the interpreted 30 seismic cross sections show no incision of the Nile River in the Oligocene sediments in both onshore and offshore surveys.

In contrast to the sandstones of the Gebel Qatrani Formation, the Oligocene sediments in the Nile Delta possess more mud and silt content and poor to moderately poor ZTRi-dominated assemblages. The THMCi values at the Oligocene sandstones of the Nile Delta show similar low values but slightly higher than those of the Gebel Qatrani Formation with the almost values range between 0.5 and 0.9% indicating poor transparent heavy mineral suites. The ZTR index of the Nile Delta varies between 2.6 and 24.8%, while in the Gebel Qatrani Formation, it ranges from 18.97 to 69.62%.

These data indicate that the sandstones of Gebel Qatrani Formation are much more mature than those of the Oligocene sand intervals of the Nile Delta.

Oligocene sandstones of the Nile Delta display a wide range of RZi, ZTRi, and MZi values. They also possess an extremely high content of mica along with significant pyroxene values (Tables 5 and 6). The sands are thus physically immature, indicating a lack of homogenization and hence a short transport distance. A cross-plot of pyroxene and zircon values (Fig. 26) shows very limited range for both minerals at all sand samples of the Nile Delta, but both Habbar-1 and Tarif-2A wells exhibit a wide range of values. These two wells share the interval between 3635 and 4300 m at which similar values of pyroxene and ZRi were recorded at the two wells. In contrast, Tarif-2A well comprises more content of pyroxene and mica than the other San El-Hager-1 of the onshore sands. On the other hand, the sands of Habbar-1 well display the highest pyroxene values along with considerable contents of amphibole, mica, sillimanite, and kyanite indicating transport from a shorter distant source including a metamorphic one.

Recent studies by Fielding et al. (2018) and Garzanti et al. (2018) have shown that the entire succession of the Nile Delta was deposited by a long drainage system connected with the Ethiopian volcanic highlands similar to the modern Nile since the lower Oligocene.

Garzanti et al. (2018) showed that with increasing burial depth in Nile Delta sands cored from up to 8.5 km thick, the non-resistant and medium-resistant heavy mineral concentration decreases considerably, transparent heavy minerals represent progressively lower percentages of the heavy fraction, and the resistant and very resistant heavy minerals zircon, tourmaline, rutile, apatite, monazite, and Cr-spinel relatively increase at the expense mainly of amphibole, pyroxene, and epidote. However, this is not the case along the Oligocene sandstones (cored from 2.7 to 5.12 km) of the Nile delta, where the sharp increase of tHMCi, ZRi, ZTRi, MZi, pyroxene, and mica values was recorded at different depths along the entire wells. This sharp increase in heavy mineral indices is the result of significant rejuvenation of the source area. This interpretation...
is supported by the lack of close grouping of individual sample compositions (Fig. 27), which indicates a lack of sand mixing and hence supply from a source(s) that was not far distant.

**Provenance and oil industry**

Reservoir characteristics of sand bodies rely strongly on the composition of these sand bodies and, therefore, their provenance (Barwis 1990; Bloch 1991; Dias Lima and De Ros 2002). Another application for provenance study is prospecting the futuristic play directions based on identifying the possible fairways of the sand bodies. Macgregor (2012) studied the development of the Nile drainage system and ended up with the existence of structurally controlled Nile cone geometry during the Oligo-Miocene. Such geometry affected the deep-water reservoir deposition in Levantine Basin. Moreover, the high reservoir potentiality in the deep waters of Herodotus Basin is reinforced by the high sedimentation rates of a westerly flowing river during the Oligo-Miocene times. Our data agree with this opinion as the contour map of the heavy fraction ratio shows a remarkable decrease in the heavy mineral content toward north, northeast directions.

One of the most common biases in the previous studies was ignoring the diagenesis effect resulting from the burial depth on interpreting the heavy mineral results. Dealing with heavy mineral analysis data ignoring this fact surely leads to misunderstanding of the probable provenance. Although we could not calculate the burial depth effect on the heavy mineral suits in the present study, we took into consideration the burial depth as a vital controlling parameter in discussing the obtained results in Nile Delta (Garzanti et al. 2018). The Oligocene sediments in Nile Delta are distributed within different depth intervals. The depth difference has an evident effect on the variations recorded within the heavy mineral suits in the Oligocene sand intervals of the Nile Delta which surely would affect the reservoir characterization either in a good or a bad way. Within the studied depth intervals in each well, the effect of burial depth is shown by the increase of maturation level of heavy mineral suits. The maturation level is indicated by the increase of ZTR index level along with the decrease in heavy mineral weight and transparent heavy minerals frequency as shown in the graphs of these parameters versus depth. This standardized behavior reinforces the truth of the diagenesis effect resulting from burial depth, which subsequently will the decision about interpreting the provenance of these sediments (Kahneman 2011).

Garzanti et al. (2018) studied the provenance of the whole Cenozoic succession of the Nile Delta to determine the diagenetic effect on these sediments. The study planned to detect such an effect. This study is one of the fundamental substrates which have been used in reasoning the claimed Ethiopian provenance of the whole Cenozoic succession of the Nile Delta. Surely, it is an axiom fact that the burial depth must be taken into consideration in interpreting the provenance of sediments. But to reach the right conclusion of the diagenetic effect on some sediments, we must take into consideration the geographic extent of the studied stratigraphic units and the effect on each interval within the unit to study the differential effect of diagenesis, which was not completely fulfilled in the study as they generalized the result of the analyzed five cored samples from Oligocene interval on the whole unit in Nile Delta. In the current study, the geographical distribution was taken into account by choosing wells distributed on- and offshore the Nile Delta to reflect the distribution of the Oligocene sediments and to identify the trends of the possible fairways of the potential reservoirs. The calculated mineralogic indices of Oligocene sands in the Nile Delta give a clear indication that heavy mineral suits can be used to indicate the reservoir characterization of different sand horizons. Each depth interval has distinctive features that
separate it from the others. By observing the variations in the depth interval (3300 to 3700 m), the behavior of mineralologic indices is nearly the same in both San El-Hager-1 and Tarif-2A wells. Likewise, the depth interval (3700 to 4400 m) Tarif-2A and Habbar-1 wells also show similar behavior. The ZTR index demonstrates a perfect model of heavy mineral diagenesis with depth. In PFMDeep-1 well, ZTR index values are less than those of San El-Hagar-1 well which seems for the first while a wrongly indicating parameter, but, taking into consideration the reduction of the whole heavy mineral assemblage of PFMDeep-1 due to great burial depth (4912 to 5113 m) makes sense. This result is reinforced by SEM images that indicate the dissolution effect. The mineralologic indices recorded within sands of the Boughaz-1 well show a different behavior at depth interval (3280 to 3500 m). The same odd behavior is repeated in ZTR, RZ, MZ, GZ, and tHMC indices. This behavior indicates that a type locality change affects the heavy mineral suite of Boughaz-1 Oligocene sands as the same depth interval in San El-Hager-1 well shows the normal behavior. Normally, the strong variations in the RZ index indicate changes in provenance source. In the present work, the calculated values show a variation, but it may be controlled either by the geographic distribution and different fairways of Oligocene sands in the Nile Delta or by the different diagenetic features of each depth interval of these samples.

It has been reported by Belayim Petroleum Company that the interpreted Oligocene interval consists mainly of shale with siltstone and sandstone strikes in PFM DEEP1 well. Sand intervals were described to be loose, fine to very fine, and sub-angular to sub-rounded with occasionally rounded grains. Most of these sandstones are enriched with quartz and variable quantities of detrital clays, lithic fragments, feldspars, carbonaceous debris, micas, opaques, and heavy minerals. Sandstones inhibit point and concavo-convex contacts. It has also been reported that the Oligocene interval has been affected by both shallow-moderate and moderate-deep burial diagenesis. Our data do match in a way or another to the described features as SEM images of the selected samples show size reduction and increase of roundness of the heavy mineral assemblage is observed in Boughaz-1 well between the two samples scanned at depth intervals (3414 m and 3470 m); another distinct variation is observed at Port Fouad Marin Deep-1 well, where the heavy mineral assemblage has a remarkably increased percentage
of corroded, deeply etched, and even skeletal grains; these features are clearly observed in depths (4912 m and 5004 m).

As discussed, the burial depth has a strong impact on heavy mineral suits. The available seismic and well data reinforced the obtained results of the heavy mineral analysis. The generated depth contour maps show clear discrimination between Oligocene intervals in both onshore and offshore. The Oligocene interval penetrated by PFMD-1 is deeper than its onshore equivalent. The offshore interval has depth values starting from 4700 m, while the onshore interval depth values start from 2000 m. The effect of burial depth could be observed in many parameters. The first one is the diagenetic features of the heavy mineral suits recorded within the offshore; deeper Oligocene intervals are intensively remarked compared to those of shallower depths. The second is the total reduction in the heavy mineral ratio of the offshore deeper interval.

The constructed thickness maps show that the onshore Oligocene interval is thicker than its offshore equivalent as the first one ranges from 500 to 4000 m, while the offshore ranges from 1000 to 2400 m. The wide range in the onshore interval gives room to multiple variations which observed in the mineralogic indices of the onshore wells (San El-Hager-1 and Tarif-2A); such variations could be misleading if they are interpreted without considering this perspective. On the other hand, the great depth of the offshore interval has a strong impact even though it is thinner.

Habbar-1 well is an exceptional state reflecting another possible fairway in the Nile Delta during Oligocene. The recorded heavy mineral suits represent an exceptional state compared to the heavy mineral suits studied within the different Oligocene intervals either onshore or offshore Nile Delta. It also represents an abnormal case study even when compared to the heavy mineral suits recorded within Gebel Qatrani Formation in Fayum.

Habbar-1 well is very important as it has been reported by Dolson et al. (2014) to get residual gas and fluid inclinations, which may enrich our conclusions in predicting the Oligocene potentialities in Northern Egypt. Although the Oligocene interval in Habbar-1 well begins from 3852 to 4536 m, and the samples submitted for heavy mineral analysis starts from 3852 to 4443 m, it contains the largest and the most various transparent HM assemblage (mica, pyroxene, sphene, ZTR, amphibole, sillimanite, epidote, kyanite, monazite, garnet). Transparent heavy mineral concentration (tHMC = 0.81) is the largest percentage recorded in the current study. Heavy minerals ratio represents 11.7% of the weighted fine and very fine fraction, indicating the increase of the light fraction compared to any other sample in the Nile Delta. The transparent heavy mineral suite of Habbar-1 well included the greatest recorded frequency abundance of pyroxene and mica with an average of 19.14 and 24.5, respectively. While the ZTR index shows the normal overall increase affected by the burial depth, the RZ index shows an overall decrease. The depth interval 4363 m in Habbar-1 well has distinctive characteristics, as the recorded values of RZ, GZ, Mz, and tHMC indices have different values from the expected normal behavior. These variations indicate a special intrastratal effect begins at this depth. All these pieces of evidence are a clear indication that the Oligocene sand intervals in this location had another provenance. Or it was locally affected by some igneous activity at earlier times which act as the main supplier to these sediments during Oligocene.

### Concluding remarks

The heavy mineral analysis gave discrimination between the three members of Gebel Qatrani Formation. The maturation levels represented in the calculated ZTR index show an overall upward increase in Gebel Qatrani Formation indicating the west–northwest maturation trend which is the same direction of the paleocurrents. The field observations and the heavy mineral analysis ensure that Gebel Qatrani Formation was deposited by E–W, NE–SW, and ENE–WSW flowing streams.

The middle member of Gebel Qatrani Formation has remarkable characteristics that differentiate it from both the lower and upper members. These changes may be due to local tectonics or the climatic conditions change that caused the abnormal recorded coarsening upward cycles.

The morphologic features of the heavy mineral suits in Gebel Qatrani Formation ensure that they were derived from proximal igneous and metamorphic rocks along with the contribution of the older recycled sediments (represented by Phanerozoic craton). The most proximal source is indicated by the existence of high rates of moderately and unstable heavy minerals, while the existence of the ultra-stable heavy minerals (that show dissolution features) indicates the contribution of the older recycled sediments.

Oligocene witnessed the major rifting phase; the rifting phase caused the uplift of Red Sea shoulders accompanied by high erosional rates created a northwest and westerly transportation direction of clastics transportation influx into Fayum basin.

Heavy mineral analysis showed remarkable discrimination between the Oligocene sandstones of Gebel Qatrani Formation and their age equivalent of the Nile Delta. The enrichment of heavy mineral content in the Nile Delta accompanied by an intense decrease in the ZTR index values compared to their age equivalent of Gebel Qatrani Formation suggests that Oligocene sands of Nile Delta were directly derived from proximate igneous and metamorphic sources that are closer to them than those of Gebel Qatrani. The calculated ZTR index shows east and northeast maturation trends reinforcing that the Oligocene sands of the Nile Delta were deposited with a flowing regime different from the sandstones of Gebel Qatrani Formation. Red Sea Hills
are the most proximal source. Thus, it represents the most possible source.

The absence of any incision in the interpreted seismic cross sections reinforces that the connection between Ethiopian highlands and the Mediterranean was not established during Oligocene. The variations in heavy mineral suites and enrichment ensure this as well.

The remarkable variation in heavy mineral suites in either assemblage or morphologic features shown by SEM images ensures that the Oligocene sand intervals embedded within Habbar-1 well were surely derived from different sources.

The obtained results of the heavy mineral analysis are reliable and dependable indicators to the reservoir characterization interpretations, taking into consideration the other diagenetic processes which may limit or enhance the reservoir potentiality.

The integration between the interpreted seismic data and heavy mineral analysis indicates that the eastern offshore Mediterranean in both north and eastwards to Port Fouad Marine Deep-1 well is the best trend for reservoir development. These trends are supposed to have a good quantity of sands with enhanced reservoir characterization.

The Oligocene interval in Habbar-1 and Port Fouad Marine Deep-1 wells showed very promising reservoir intervals with a total net reservoir thickness 302.9 m and net pay thickness 135.64 m. Moreover, the interval exhibits good reservoir quality with average effective porosity 21%.

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Declarations

Conflict of interest The authors declare no competing interests.

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References

Abdel Aal A, Price RJ, Vaitil JD, Shrawley JA (1994) Tectonic evolution of the Nile Delta, its impact on sedimentation and hydrocarbon potential. EGPC 12:19–34

Abdelkareem M, Ghoneim E, El-Baz F, Askalany M (2012) New insight on paleoriver development in the Nile basin of the eastern Sahara. J Afr Earth Sci 62(1):35–40

Abdelmaksoud A, Radwan AA (2022) Integrating 3D seismic interpretation, well log analysis and static modelling for characterizing the Late Miocene reservoir, Ngatoro area, New Zealand. Geomech Geophysics Geo-Energy Geo-Resources 8(2):1–31. https://doi.org/10.1007/s40948-022-00364-8

Abdelwahhab MA, Radwan AA, Mahmoud H, Mansour A (2022) Geophysical 3Dstatic reservoir and basin modeling of a Jurassic estuarine system (JG-Oilfield, Abu Ghurag basin, Egypt). J Asian Earth Sci 225:105067. https://doi.org/10.1016/j.jseaes.2021.105067

Ahmed K, Khaleed M (2017) Petrophysical evolution of east Mediterranean Oligocene reservoirs east Mediterranean offshore area. Geologic setting of East Mediterranean offshore area, Nile Delta. March 2018

Barwis JH, McPherson JG, Studlick JRJ (1990) Flood-tidal delta reservoirs, medora-Dickinson trend, North Dakota. In Sandstone petroleum reservoirs. Springer Verlag, Berlin, pp. 389–412.

Berry L, Whiteman AJ (1968) The Nile in the Sudan. Geogr J 134(1):1–33

Bloch S (1991) Empirical prediction of porosity and permeability in sandstones. AAPG Bull 75(7):1145–1160

Bown TM, Kraus MJ (1988) Geology and paleoenvironment of the Oligocene Jebel Qatrani Formation and adjacent rocks, Fayum Depression, Egypt. US Geol Surv Prof Pap 1452. https://doi.org/10.3133/pp1452

Burke K, Wells GL (1989) Trans-African drainage system of the Sahara: was it the Nile? Geology 17(8):743–747

Chumakov, I.S., 1968. Pliocene ingress in the Nile Valley according to new data. In:Butzer, K.W., Hansen, C.L. (Eds.), Desert and River in Nubia, Geomorphicology andPrehistoric Environments at the Aswan Reservoir. The University of Wisconsin Press, Madison, pp. 521–522.

Craig J, Grigo D, Rebora A, Serafini G, Tebaldi E (2010) From Neoproterozoic to Early Cenozoic: exploring the potential of older and deeper hydrocarbon plays across North Africa and the Middle East. Geol Soc London Pet Geol Conf Series 7(1):673–705

Craig T, Jackson J, Priestley K, McKenzie D (2011) Earthquake distribution patterns in Africa: their relationship to variations in lithospheric and geological structure, and their rheological implications. Geophys J Int 185:403–434

Dolson JC, Boucher PJ, Dodd T, Ismail J (2002) Petroleum potential of an emerging giant gas province, Nile Delta and Mediterranean Sea off Egypt. Oil Gas J 100(20):32

Dolson JC, Atta M, Blanchard D, Sehaim A, Villinski J, Loutit T, & Romine K (2014). Egypt’s future petroleum resources: a revised look into the 21st century. In: Marlow, Lisa Marie, Christopher G, St C. Kendall, and Lyndon A. Yose, (eds). Petroleum systems of the Tethyan region. Tulsa: American Association of Petroleum Geologists, 2014, P43-178

El-Araby A, El-Barkooky AN (2000) Stratigraphic architecture and facies evolution of the Oligocene gebel qatrani, Gebel Qatrani, North Fayum. In: Egypt 5th International Conference on the Geology of the Arab World. Cairo University, Cairo, pp 1175–1208

Fielding L (2016) A multi-technique provenance study of the Oligocene: recent Nile cone sediments and River Nile hinterland. Lancaster University, Lancaster
Fielding L, Najman Y, Millar I, Butterworth P, Ando S, Padoan M, Barfod D, Kneller B (2017) A detrital record of the Nile River and its catchment. J Geol Soc 174:301–317

Fielding L, Najman Y, Millar I, Butterworth P, Garzanti E, Vezzoli G, Barfod D, Kneller B (2018) The initiation and evolution of the Nile River. Earth Planet Sci Lett 489:166–178

Gardosh, Michael A., Yehezkel Druckman, and Binyamin Buchbinder. “The Late Tertiary deep-water siliciclastic system of the Levant Margin—An emerging play offshore Israel.” American Association of Petroleum Geologists Search and Discovery Article 10211 (2009)

Garzanti E, Andò S, Limonta M, Fielding L, Najman Y (2018) Diagenetic control on mineralogical suites in sand, silt, and mud (Cenozoic Nile Delta): implications for provenance reconstructions. Earth Sci Rev 185(April):122–139. https://doi.org/10.1016/j.earscirev.2018.05.010

Gingerich PD (1993) Oligocene age of the Gebel Qatrani Formation, Fayum. J Hum Evol 24(3):207–218

Hantar, G., 1990. North western desert. In: Said, R. (Ed.), Geology of Egypt. AA BalkemaPublishers, Rotterdam, Netherlands, pp. 293–327.

Hubert JF (1962) A zircon-tourmaline-rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones. J Sediment Res 32(3):440–450

Issawi, B., McCauley, J.F., 1992. The Cenozoic rivers of Egypt: the Nile problem. In:Friedman, R.F., Adams, B. (Eds.), The Followers of Horus, Studies Dedicated toMichael Allen Hoffman1944–1990, Oxbow Monograph. Vol. 20. pp. 121–138.

Issawi, B., El Hinnawi, M., Francis, M., & Mazhar, A. (1999). The Nile problem. In:Friedman, R.F., Adams, B. (Eds.), The Followers of Horus, Studies Dedicated toMichael Allen Hoffman1944–1990, Oxbow Monograph. Vol. 20. pp. 121–138.

Kahmane D (2011) Thinking, fast and slow. Penguin, London, p 499

Knox RW, Soliman MF, Essa MA (2011) Heavy mineral stratigraphy of Palaeozoic and Mesozoic sandstones of southwestern Sinai, Egypt: a reassessment. GeoArabia 16(3):31–64

Lima RD, De Ros LF (2002) The role of depositional setting and diagenesis on the reservoir quality of Devonian sandstones from the Solimões Basin, Brazil. Amazon Mar Pet Geol 19(9):1047–1071

Macgregor DS (2012) The development of the Nile drainage system: integration of onshore and offshore evidence. Pet Geosci 18(4):417–431

McDougall I, Morton WH, Williams MAJ (1975) Age and rates of denudation of Trap Series basalts at Blue Nile Gorge, Ethiopia. Nature 254(5497):207–209

Morton AC (1985) Heavy minerals in provenance studies. In: In Provenance of arenites. Springer, Berlin, pp 249–277

Morton AC, Hallsworth C (1994) Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. Sediment Geol 90(3–4):241–256

Morton AC, Sylvester P (2012) Value of heavy minerals in sediments and sedimentary rocks for provenance, transport history and stratigraphic correlation. Quantitative Mineralogy and Microanalysis of Sediments and Sedimentary Rocks. Mineral Assoc Canada Short Course Series 42:133–165

Obaida N (1993). Biostratigraphic studies on the Late Tertiary succession of the Nile Delta. Ph.D thesis. Assiut University. 558p.

Ouda K, Obaida N (1995) The geologic evolution of the Nile Delta area during the Oligocene-Miocene. Egypt J Geol 39:77–111

Poupon, André, and J. A. C. Q. U. E. S. Leveaux. “Evaluation of water saturation in shaly formations.” SPWLA 12th Annual logging symposium. OnePetro, 1971

Radwan AA, Nabawy BS, Abdelmaksoud A, Lashin A (2021) Integrated sedimentological and petrophysical characterization for clastic reservoirs: a case study from New Zealand. J Nat Gas Sci Eng 88:103797. https://doi.org/10.1016/j.jngse.2021.103797

Radwan AA, Abdelwahhab MA, Nabawy BS, Mahfouz KH, Ahmed MS (2022a) Facies analysis-constrained geophysical 3D-static reservoir modeling of Cenomanian units in the Aghar Oilfield (Western Desert, Egypt): insights into paleoenvironment and petroleum geology of fluvial-marine systems. Mar Pet Geol 136:105436. https://doi.org/10.1016/j.marpetgeo.2021.105436

Radwan AA, Nabawy BS, Shihata M, Leila M (2022b) Seismic interpretation, reservoir characterization, gas origin and entrapment of the Miocene-Pliocene Mangaa C sandstone, Karewa Field, North Taranaki Basin, New Zealand. Mar Pet Geol 135:105420. https://doi.org/10.1016/j.marpetgeo.2021.105420

Said R (1962). The geology of Egypt. Elsevier Pub. New York , 377p.

Said R (1975) The geologic evolution of the River Nile. Problems in Prehistory: North Africa and the Levant, Africa, pp 7–44

Said R. (1990), Cenozoic. In: R. Said (ed.): The geology of Egypt. Balkema, Rotterdam, 451-486.

Said R (1993) The Nile River: geology, hydrology and utilization, New York

Salem R (1976) Evolution of Eocene-Miocene sedimentation patterns in parts of northern Egypt. AAPG Bull 60(1):34–64

Scott, R. A., Smyth, H. R., Morton, A. C., & Richardson, N. (2014). Sediment provenance studies in hydrocarbon exploration and production. Geological Society of London, Volume 386.

Shukri NM (1950) The mineralogy of some Nile sediments. J Geol Soc 106(1–4):466–467

Shukri NM (1951) Mineral analysis tables of some Nile sediments. J Geol Soc 106(1–4):466–467

Underwood CJ, King C, Steurbaut E (2013) Eocene initiation of Nile drainage due to East African uplift. Palaeogeogr Palaeoclimatol Palaeoecol 392:138–145

Vondra CF (1974) Upper Eocene transitional and near-shore marine Qar el Sagha Formation. Fayûm Depression, Egypt

Williams MAJ, Adamson D, Cock B, McEvedy R (2000) Late quaternary environments in the White Nile region, Sudan. Global Planet Change 26(1–3):305–316