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Quantitative assessment of the tight gas reservoirs in the Obaiyed field, Shushan Basin, NW Egypt

Ahmed I. Diab [a] and Hany M. Khalil [a,b]

[a]Department of Geology, Faculty of Science, Alexandria University, Moharam Bey, Alexandria, Egypt.; [b]School of Earth, Atmosphere and Environment Department, Monash University, Clayton, Victoria, Australia

ABSTRACT

Obaiyed field lies in northern west Shushan Basin, which considers one of the largest Mesozoic coastal basins in northeast Africa, with high thickness sediment from the Jurassic to Palaeogene. The petrophysical parameters show difficulty in the development of the high gas reserve in the field, which led us to assess the geological systems that could constrain the formation and evolution of the basin concerning the study field. We simulated the tectonic evolution of the basin using a 1D-Airy isostasy backstripping technique with python coding and PetoMode® software. Also, we evaluated the current reservoir petrophysical parameters using TechLog® software. Based on integrating our results, we propose that the Shushan Basin represents a natural case of a Continuous Basin-Centred Gas accumulations model (CBCG) because of four main reasons: a) the vast extension of the Khatatba Formation, b) the coexistence of the source and the reservoir rocks in the Khatatba Formation, c) the low-permeability and gas saturation accumulations of the Lower Safa Member and d) the abnormal pressure of the Lower Safa reservoir because of its compartmentalization, where each compartment has its pressure peak. At a regional scale, this study highlights the effect of tectonics in the evolution of the basins.

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1. Introduction

Tight gas reservoirs are classified as unconventional energy sources, typically composed of sandy facies, with extremely low permeability of less than 0.1 millidarcy, and commonly require hydraulic fracturing to harvest at economic rates (Rajput and Thakur 2016). Much of the understanding of how tight gas/condensates accumulate relates to the structural and the tectonic regime of the confined formation. Knowing the stratigraphy, the structure, and the subsidence history of the host basin is vital for the tight gas reservoirs assessment and affects the exploration and production activities.

This study focuses on the assessment of the Obaiyed field as a part of the Shushan Basin, which is considered one of the largest tight gas sand reserve in northwestern Africa (Abdel-Fattah et al. 2019), where the hydrocarbon productions were not feasible because of the geological constraints that control the basin formation, e.g. the compartmentalisation of the field and low permeability of the reservoir sand. Even though, the sedimentary section ranges from the Lower Palaeozoic to Recent and covers a wide range of sedimentary environments, many of which provide favourable conditions for hydrocarbon generation and entrapment. In that context, we focused on understanding the mechanism by which the tight gas formed in the basin, and the geological factors that led to such accumulations. We studied mud-log data from eight wells distributed in the Obaiyed field, the largest field in the basin, using commercial software packages (Techlog®, Petromode®), to track the petrophysical parameters, in each well, and to correlate them between the different wells. We computed the subsidence history along with the changes in the physical properties of different formations, in each well, using the 1D-backstripping technique (Müller et al. 2018). We integrated the output results with previous 3D seismic and fault analysis studies in the basin.

Our results were discussed in the context of the geological controls on the formation and the accumulation of tight gas sand reservoirs in the northeast Africa coastal basins comprehensively and systematically. Also, we proposed a model for the formation of the tight gas sand in the Shushan Basin, based on the basin tectonic evolution, the depositional setting, the reservoir properties along with the charging-accumulation history, and mechanism.

CONTACT Ahmed I. Diab ahmed.diab@alexu.edu.eg Geology Department, Faculty of Science, Alexandria University, Moharam Bey – 21511, Alexandria, Egypt.

1.1. Location

Shushan Basin is one of the Mesozoic coastal basins (i.e. Matruh, Dahab, Shushan, and Natrun) located in the northern region of the Western Desert, and trends northeast-southwest (Figure 1A). It covers an area of about ~3800 km2 that forms the major part of the Egyptian unstable shelf (Said 1990). The basin is considered as a high potential for hydrocarbons accumulations (Berglund et al. 1994).

The Obaiyed field is the largest Jurassic gas/condensate field in the Shushan Basin and the northern region of the Western Desert in general. It lies near the southern coast of the Mediterranean Sea, between

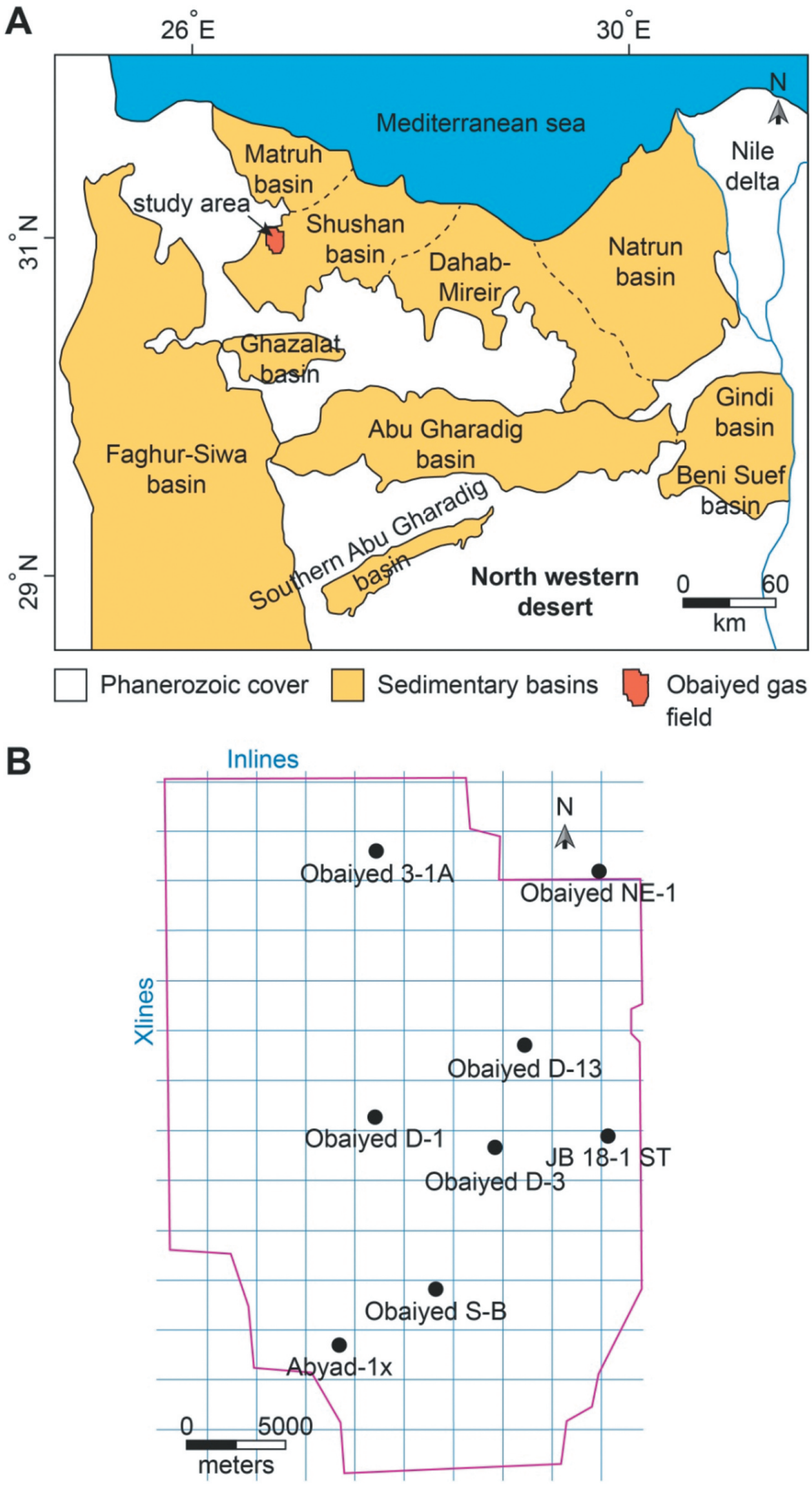

Figure 1. A) location map shows the northern sedimentary basins including the Shushan Basin and the location of the study area, i.e. Obaiyed field. B) the location of the studied wells in the Obaiyed field.

latitudes 31° 02` and 31° 12` N, and longitudes 26° 34` and 26° 45` E. It is mainly an asymmetric fold system due to the inversion of pre-existing Jurassic normal faults at the Late Cretaceous compression event. The reservoirs represent a Bathonian sandstone that unconformably overlying the pre-rift Palaeozoic sequences (Hanter 1990).

2. Geological setting of the studied area

The Mesozoic basins of the Western Desert in Egypt (e.g. Shushan Basin) provide rewarding but difficult hydrocarbon exploration opportunities (Dolson et al. 2001). The exploration of oil and gas from Jurassic sandstones of Khatatba Formation, for the first time in the Western Desert, was in well"Salam-3" well belong to Phonex Oil Company, then successive explorations were designed for Khatatba Formation (Dolson et al. 2001).

2.1. Stratigraphy

The sedimentary column in Shushan Basin combines the sedimentary succession from Middle Jurassic to Recent (Figure 2), it is about 14,000 ft. in thickness (El – Shazly 1977). The basin is located on the northern margin of the Afro-Arabian shield which makes the sedimentary succession part of foreland deposits. These deposits overlay the Pre-Paleozoicbasement that has a regional slope towards the north direction, with the corresponding thickening of all the sedimentary columns to the north (El – Shazly 1977).

The Palaeozoic is characterised by sandstone and siltstone clastic sequences, with minor mudstones, dolomites, and locally developed conglomerates. The uppermost Safa Formation (Callovian Age) is mainly composed of sandstones & siltstones (El Gezeery et al. 1972; El – Shazly 1977). Mudstones and Oolites are also developed indicating continuing marine conditions (Schlumberger 1995). The first Mesozoic deposit of the Western Desert was the Early Jurassic "Bahrein Formation", which is a continental sequence, and followed by shallow marine sediments of the Middle Jurassic. A marine transgressive depositional cycle started at the Lower Cretaceous with a falling system tract. Also, the beginning of this depositional cycle is characterised by fluvial-continental sediments of the Neocomian, at the base. The maximum peak of the transgression cycle was during the age of Middle and Upper Aptian with the deposition of the "Alamein Carbonates" in a restricted marine/lagoonal environment. A return to continental deposits at the end of the Lower Cretaceous, during the Upper Albian to Lower Cenomanian, completed this cycle. A new depositional cycle, of the Upper Cenomanian to the Middle Eocene carbonates dominated, followed by the last depositional cycle, beginning from the Upper Eocene to the Miocene with clastic sediments (Schlumberger 1995).

The main prospective section in the northern region of the Western Desert basins belongs to the Mesozoic age and is confined to the Jurassic and Cretaceous. The Mesozoic succession overlies the eroded Palaeozoic strata with angular unconformity. Rifting began in the Early Jurassic and possibly in the Late Triassic in response to the formation of the northern continental margin of North-East Africa. Syn-rift deposition continued through the rest of the Jurassic, resulting in a thick succession of marine to non-marine strata (Mahmoud and El Barkooky 1998; Moustafa 2008).

2.2. Structural setting

Meshref (1990) built a basement structure map (Figure 3) using the data provided from the seismic, gravity, and magnetic surveys. He used 1206 exploration wells in his model, only 189 wells had been drilled in the entire sedimentary column. This structure map shows that the major faults in northern Egypt extent ENE-WSW direction, forming up-thrown blocks and down-dropped blocks. The up-thrown blocks formed non-prospective ridges, while the down-dropped blocks formed the petroleum basins in the Western Desert. The hydrocarbon accumulation in the Western Desert is located in structure traps along these faults. One of those basins is the Shushan Basin which is a half-graben system with a high sediment thickness from Jurassic to Palaeogene.

The basin is a part of a tectonic system that resulted from the movement of North Africa towards Europe, accordingly, the basin was affected by three main tectonic events (Moustafa 2008), classified from older to younger, as following: a) rifting event (Jurassic to Early Cretaceous), b) compressional event (Late Cretaceous to early Tertiary), c) extensional event (Miocene and Post Miocene)

2.3. Petroleum system in Shushan Basin

Many geochemical studies have been carried out on Shushan Basin, which concluded that the dark coaly shales and organic-rich shales in Khatatba Formation are the source rock for the hydrocarbon which filled the Middle Jurassic reservoirs such as Upper Safa and Lower Safa Member. (Younes 2006; Moustafa 2008; Shalaby et al. 2014; El Diasty 2015; Abd-El Gawad et al. 2015) summarised that the TOC in the basin is up to 10 wt% and reaches 32.5 wt% in particular parts in the basin.

The Khatatba source rock type analysis in Shushan Basin shows that the type of Kerogen consists predominantly of type III vitrinitic and a mixture of types II–III liptinitic with moderately

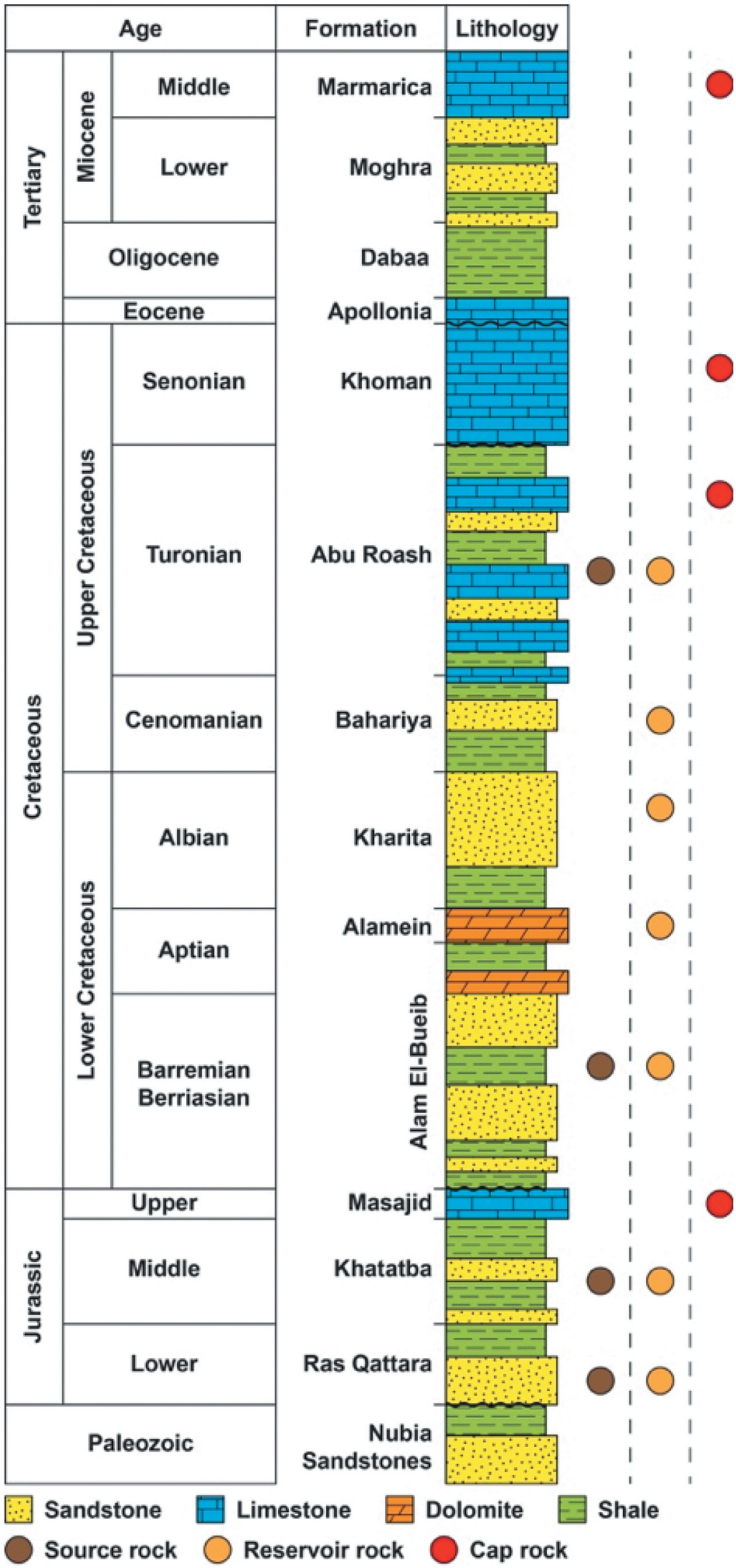

Figure 2. Generalised stratigraphic column of the North Western Desert, Egypt. The petroleum system elements of the different formations are indicated by coloured circles (Abdou 1998).

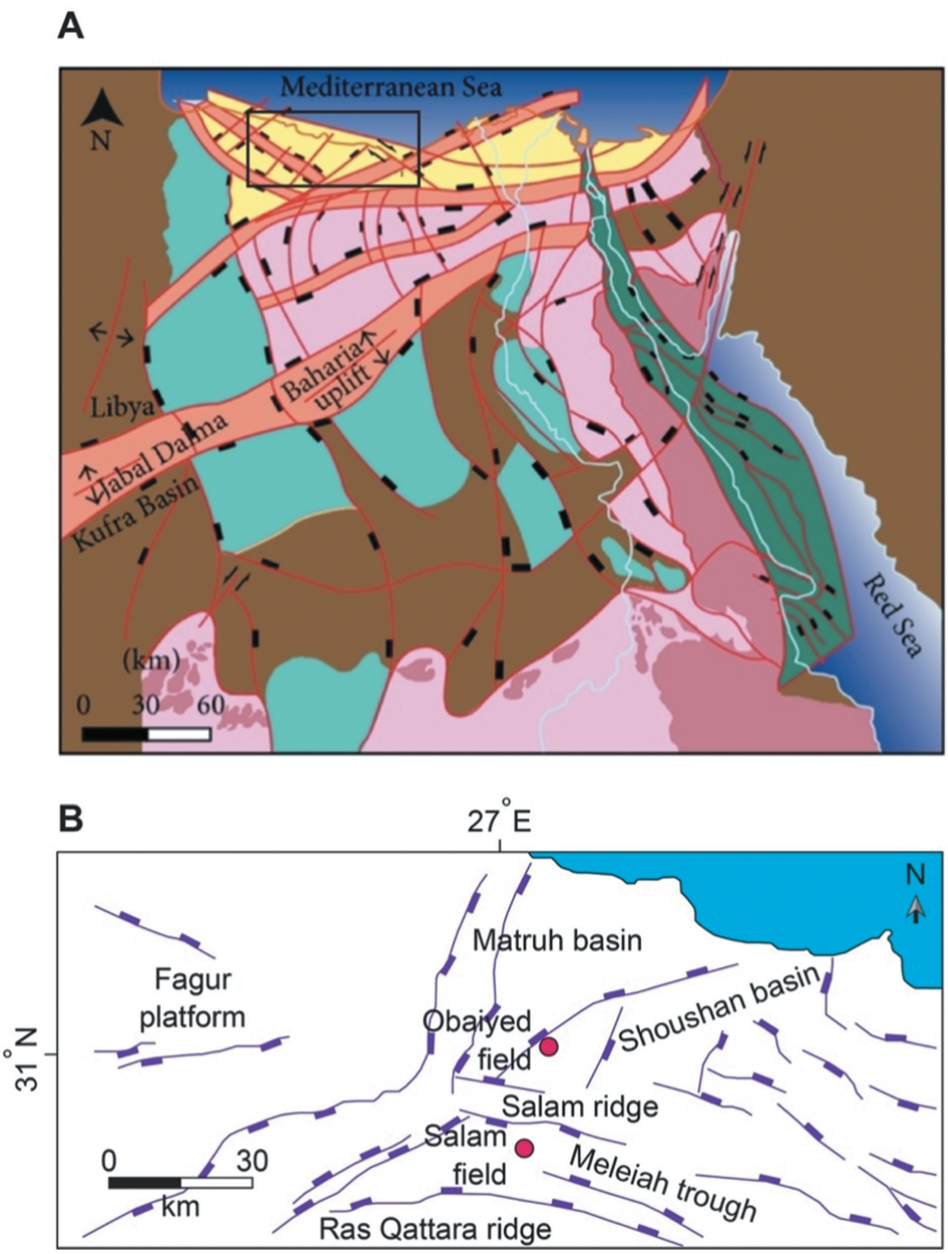

Figure 3. A) basement structure map of the Western desert(After Meshref 1990). B) structure map of the Shushan Basin and the location of the Obaiyed Field(El-Shazly, 1977; Hantar, 1990).

to heavily stained with bitumen (Figure 4A) (El Diasty 2015; Younes 2006). This analysis has been made in Shams and Tut fields where the source rock is represented excellently. In the Obaiyed field, the HI vs. T_{max} plot shows that the hydrocarbon samples lie in the oil and wet gas maturation zones (Figure 4).

The khatatba source rock extent over a large area, and sinking deep towards the north direction beneath Matruh Basin. According to that, the hydrocarbon migrates from the deeper extension of the Khataba source in the northeast to the shallower parts in the south where Obaiyed Field lies. The oil generation peak was found to be during the Aptian age, and hydrocarbon expulsion during the Oligocene time (Berglund et al. 1994).

The shale and the limestone of Kabrit Member that cover all the field, and organic-rich shales of Khataba Formation at some location in the field, represent good cap rocks for the Lower Safa reservoir. Thus, Khatatba Formation considers the source in the deepest parts in the north, while it represents a cap rock for the Lower Safa reservoir in the south where the Obaiyed Field lies.

3. Method and materials

3.1. Well logging

The continuous well-log measurements recorded by the owner company in the drilled boreholes in the study area have been used to study the various physical properties of rocks. The data available for this study

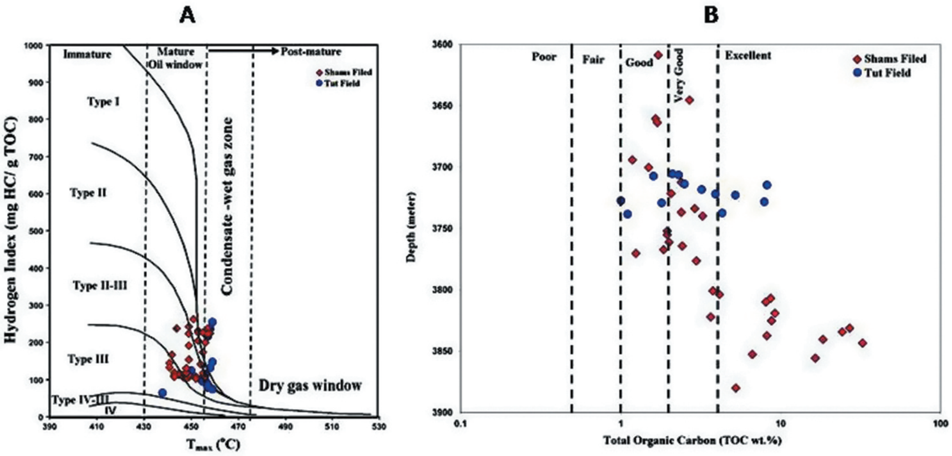

Figure 4. A) The relation between (TOC wt.%) and the depth shows the percentage of TOC in the Khatatba Formation in Shams and Tut oil fields belong to Shushan Basin.; B) Hydrogen index (HI) versus maximum temperature Tmax for the Khatatba source rock, indicate the thermal maturity and Kerogene type (Shalaby et al. 2014).

are collected from 8 wells distributed all over the Obaiyed field. Each well has a composite log comprise Bit Size (BS), Caliper (CALI), Gamma Ray (GR), Shallow Resistivity (RES_SLW), Medium Resistivity (RES_MED), Deep Resistivity (RES_DEP), Density (DEN), Density Correction (DENC), Neutron Porosity (NEU), Sonic (DT), Photo Electric log (PEF) and Lithology (LITH-Petrel). These logs have been used to calculate the volume of shale, porosity, water saturation, and the permeability of the Lower Safa reservoir using Techlog® software.

A basin construction simulation has carried on a combination of well data and geological knowledge to model the evolution of a sedimentary basin using Petromode® petroleum systems modelling software. The petroleum system, hydrocarbon type, charging of the reservoir, and timing were been simulated. Also, the properties like compressibility, subsidence rate, and sedimentation rate which are associated with the time of deposition have been calculated to get the best understanding of the basin life events and characteristics.

3.2. 1-D backstripping method

Backstripping technique (Watts and Ryan 1976; Steckler and Watts 1978) is a straightforward application to quantify the isostatic response of a stratigraphic section in a sedimentary basin(Müller et al. 2018). The backstripping aims to retrieve the geo-history, e.g. subsidence and uplift, of the sedimentary basin as a function of time (Van Hinte 1978). We used the mud log records, of the studied wells in the Obaiyed field, to obtain the present-day thickness of the different stratigraphic units, their lithologies, their petrophysical properties, and the age of the different horizons.

Following the approach of e.g. (Steckler and Watts 1978; Watts 1981; Müller et al. 2018)), we started by de-compacting each sedimentary stratum to the time where it deposited using the following relationships:

$$\emptyset_z = \emptyset_0^{\left(-\frac{z}{c}\right)} \tag{1}$$

$$\int_{d_0}^{d_0+t_0} (1-\emptyset_z)dz = \int_{d_n}^{d_n+t_n} (1-\emptyset_z)dz \tag{2}$$

Where $\emptyset_0$ is the surface porosity of the sedimentary unit, Øz is the porosity at depth z, and c is the porosity coefficient. The values of $\emptyset_0$and c depend on the lithology of each sedimentary unit and summarise in Table 1.d_0 and d_n are the surface position of the sedimentary unit, during its depositional time, and the burial depth of the unit, after time period n, respectively. While t_0 and t_n represent the original unit thickness, during its depositional time, and the compacted thickness, when the unit is at depth d_n, respectively. The term (1-Øz) represents the incompressible component of the sedimentary unit, i.e. the volume of the grains, assuming no cementation or late-stage diagnosis. To do so, we removed the overburden sedimentary load above each unit and restored its de-compacted thickness by solving numerically fort$_0$:

$$t_0 = t_n - vw_n + vw_0. \tag{3}$$

Wherevw$_0$ is a function of t_0 and represents the original pore volume when the sedimentary unit was at the surface, while vw_n represents the pore volume when the sedimentary unit was at depth d_n. Consequently, we corrected the thicknesses of the underlying units and calculated the total subsidence as a sum of the units thicknesses at each time n. Then we separated the tectonic subsidence component from the total subsidence using the following equation:

$$z_n = s_n * \left\{ \frac{\rho_m - \rho_b}{\rho_m - \rho_w} \right\} \quad (4)$$

Where $\rho_m$is the density of the mantle = 3300 kg/m3, ρ_b is the retrieved bulk density of the unit after the de-compaction correction, ρ_w is the water density = 1000 kg/m3, s_n is the total subsidence of the basin at time n. We tracked the total and tectonic subsidence with time. We also provide heatmaps of the recorded changes in the porosity and bulk density of each unit with time.

4. Results and discussion

Although Shushan Basin is categorised as a high potential natural gas reservoir, evident from the gas shows during the exploration phase that most of the developing wells in the Obaiyed field are either abandoned or suspended(Egyptian General Petroleum Company (EGPC) 1992). This is interpreted, yet equivocal, due to the development of gas condensate in the Lower Safa Member, Middle Jurassic, sandstone reservoir of the Khatatba Formation, which is the main target for the natural gas in the basin(Berglund et al. 1994). The integration of our quantitative assessment of the available mud logging data and subsidence analysis allowed us to test the hypothesis of the gas condensate formation in the area.

Comparison of our results with the previous work after Abdel-Fattah et al. (2019) and Diab et al. (2018), it appeared that the present total porosity Φ_{total} in the Lower Safa reservoir is ranging between7.6% along the middle part of the Obaiyed field to 17.4%mostly at its western flank, which comprises the most elevated part of the field (near Obaiyed D-1 well) (Figure 5A). TheeffectiveporosityΦ_{eff} affected by the volume of shale Vsh distribution (Figure 5B). The effective porosity reaches a maximum value of 7.1% along the middle part of the Obaiyed field, while it reaches a minimum value of2.4% in the depocentre of the field, where JB 18–1 ST well is located (Figure 5C). This difference between the magnitude of the total and effective porosities illustrates the drop in the reservoir quality. Also, the permeability (K) values ranges between 1 millidarcy, across most of the Obaiyed field, to a sharp increase of81.2millidarcys in the uppermost part of the field (Figure 5D). These values suggest that the Lower Safa sandstone lies within the upper limit, or maybe higher, to be considered as an ideal tight gas reservoir, which has a typical porosity of 5–10% and a permeability of 0.01–5 mD (Ma et al. 2011), hence, suggests that the accumulation of the tight gas might not be the case during the early developing stages of the reservoir.

4.1. Early subsidence of the basin and the formation of the Lower Safa

The backstripping analysis (Figure 6) shows abrupt subsidence between 185–179 Ma,with a subsidence rate = 3.2x10^{-2}mm/yr[185–181 Ma] and 14.8 × 10^{-2} mm/yr [181–179 Ma], that triggers the initiation of the Shushan Basin. These early subsidence-kicks were mostly tectonic and induced by the sedimentary load of the extensive, Early Mesozoic (Triassic/Jurassic), marine transgression, that probably did not reach the southern portions of Egypt (Said 1990). Later, between ~179 Ma and 170 Ma, the Lower Safa sand was deposited with a very slow subsidence rate of 0.53 × 10^{-2} mm/yr(Figure 7). Accordingly, the initial porosity of

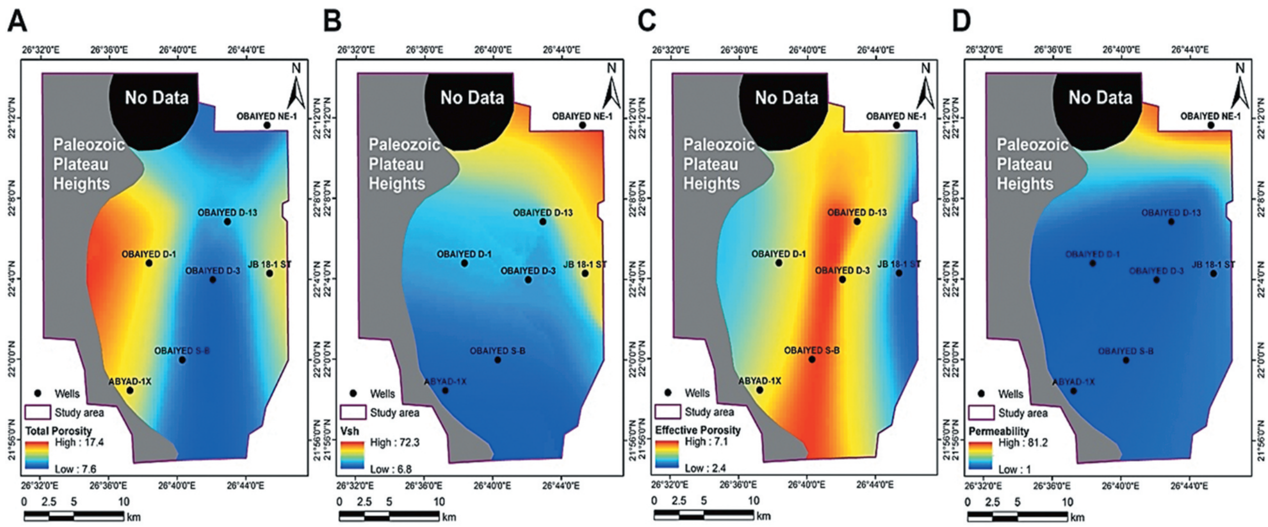

Figure 5. Interpretation maps from TechLog® software showing the changes in the petrophysical parameters throughout the Obaiyed Field. A, total porosity. B, the volume of shale that helps in sealing the fractures. C, effective porosity. D, permeability. The black dots represent the location of the studied wells (Diab et al. 2018).

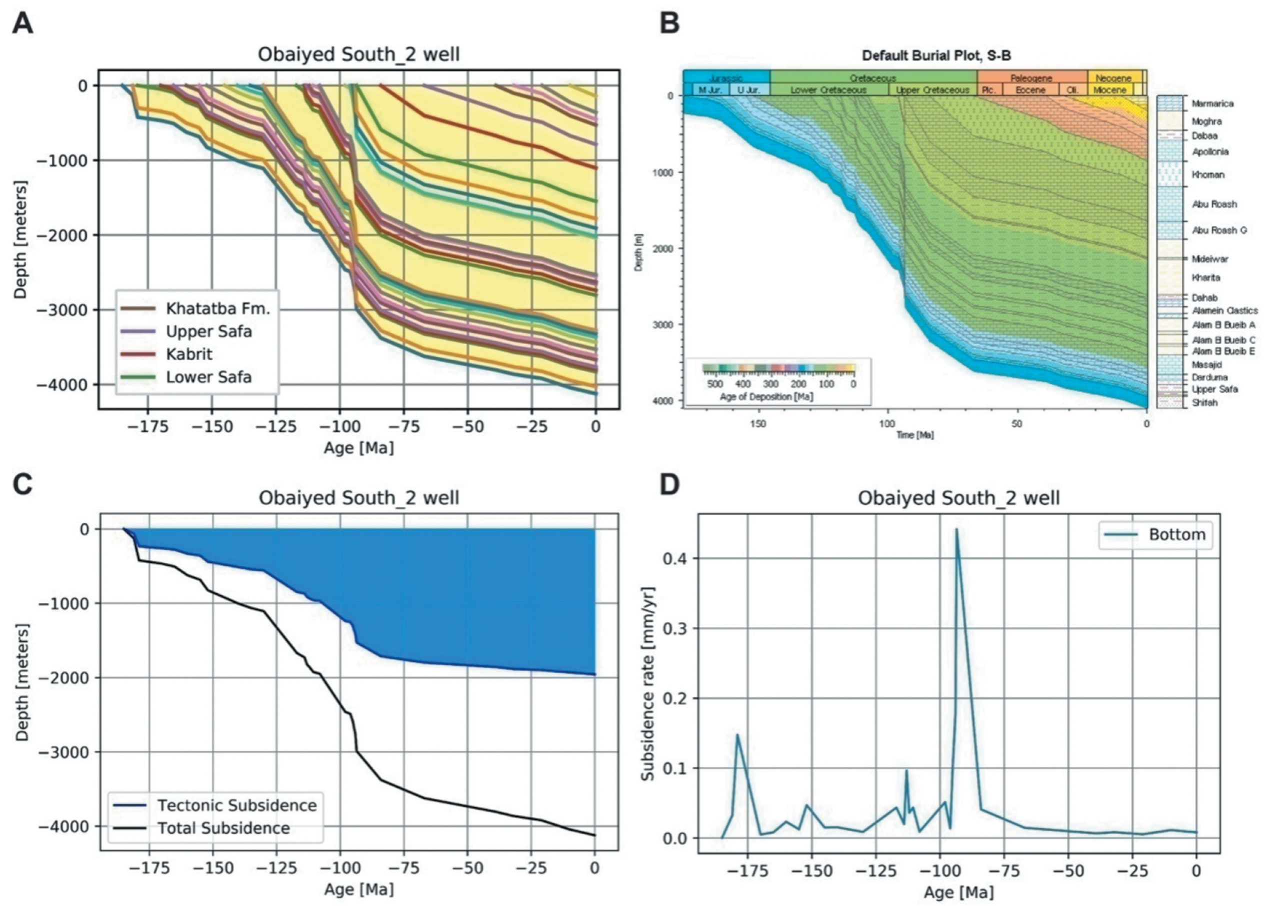

Figure 6. A) 1D modelled geohistory of the Obaiyed South-2 well by backstripping technique using python showing the different formations. B) comparable 1D geohistory model of the Obaiyed South-2 well from Petromode® software. C) the obtained water-loaded subsidence curve from the python coding. D) the calculated subsidence rate based on the total sedimentation rate of the different layers. Notice the two large peaks around 180 Ma and 90 Ma.

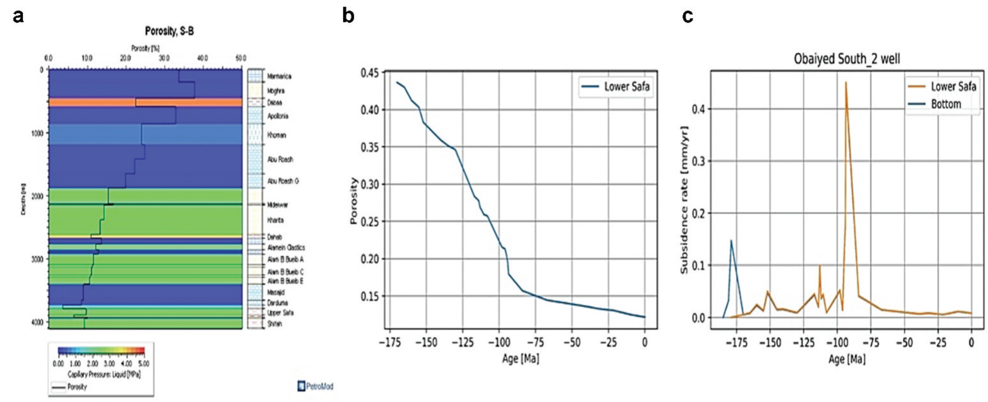

Figure 7. A) retrieved present-day porosity of the different formations from the Obaiyed South-2 well. Notice, the very low porosity of the Lower Safa Member. B) the evolution of the total porosity of the Lower Safa Member through time. C) the calculated subsidence rate of the Lower Safa Member and comparison with the total subsidence in the Obaiyed South-2 well.

the Lower Safahas a value of 44%, with a relatively high initial compressibility of 83.18 GPa-1.

Significant tectonic subsidence at 93.5 Ma, with a drastic subsidence rate of$44.2x10^{-2}$ mm/yr, leads to an increase in the burial depth of the basin, reaching a total depth of ~3 km at the basin margin, and grades to a total depth of > 4.5 km at 0 Ma (Figure 6C). This rapid change in the burial depth is linked to the reduction of the total porosity of the Lower Safa, probably by compaction, as evident from the paleo-porosity and compressibility analysis, and is detrimental to the overall reservoir quality.

4.2. Lithofacies analysis

The Lower Safa lithofacies were extracted and evaluated from seven wells in the Obaiyed field. We plotted the cumulative frequencies distribution of the gamma-ray (GR), the porosity, and the resistivity logs. The resulted histograms show the non-normal distribution of lithologies(Figure 8), characteristic for tight gas reservoirs (Ma et al. 2016). We found that the reservoir is mainly composed of (66 %) sand and (34 %) shale of Kaolinite and Illite types, with a heterogeneous lateral distribution in the field. This compositional heterogeneity, due to the intertwining clays, contributes to lowering the porosity and the permeability in the area, as confirmed by the internal geological reports of the owner company. This is also evident from the cross-plots, of the lithology with porosity and resistivity, which show high resistivity signals for all the facies with low porosities(Figure 8), as an indication of the effect of the shale on the reservoir lithofacies. The question here, **what is the source of the intertwining clays?** To answer this question, we should connect between the subsidence events and migration time. The major subsidence event of the basin (93.5 Ma), as retrieved from the basin subsidence analysis, coincides with the movement of fluids to the reservoir, where the migration happened around 100 million years during the Aptian age(Berglund et al. 1994). This stimulates the smearing of the Illite and Kaolinite shales along with the fault plans, which leads to the filling of the pores and perverted the effective porosity (Abdel-Fattah et al. 2019).

4.3. Reservoir compartmentalisation

Applying fault seal analysis on the faults in the Obaiyed Field structure map (Figure 9), and comparing the results with the historical tectonic events shows that the area was compartmentalised due to increasing the percent of Illite and Kaolinite on the fault planes, because of the tectonic inversion which inverts most of the faults, in Late Cretaceous compression event(Abdel-Fattah et al. 2019).

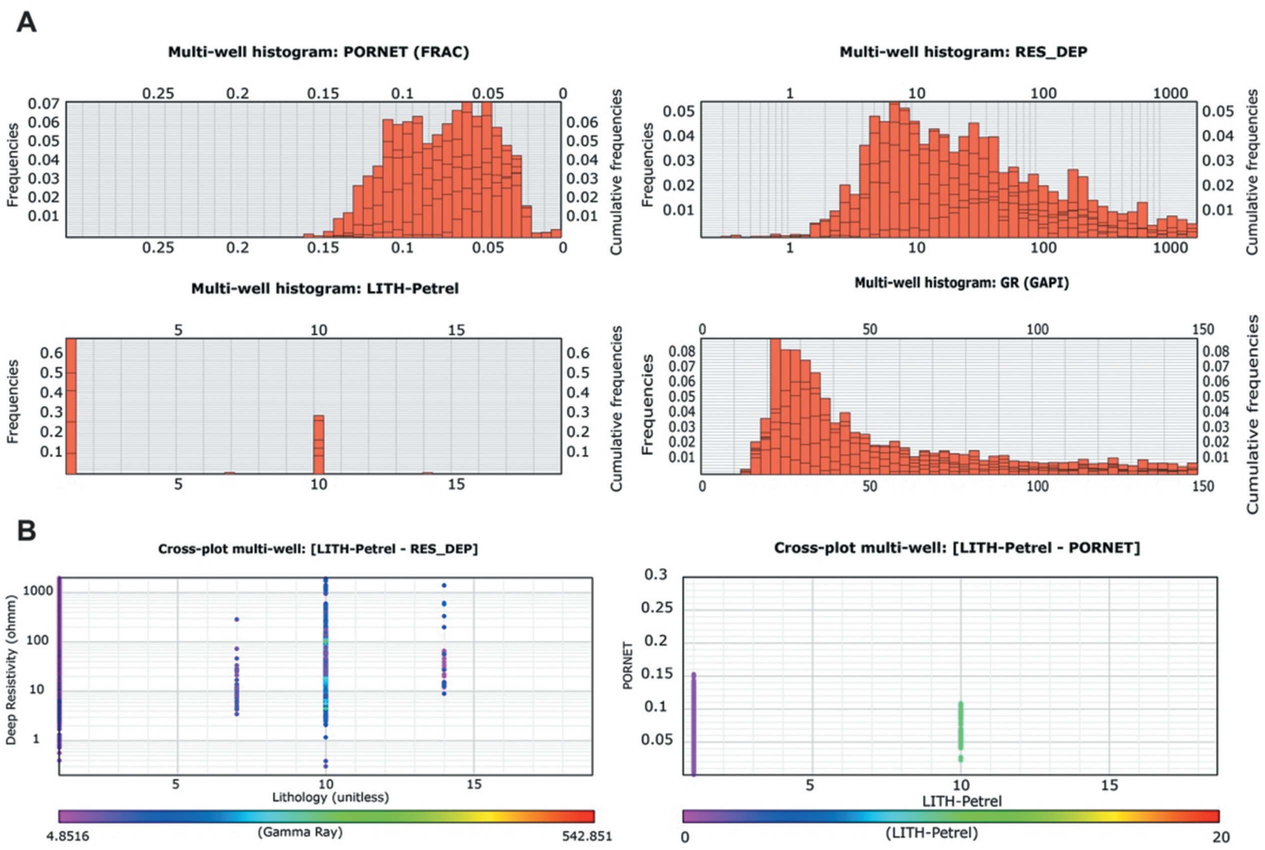

Figure 8. A) the cumulative frequencies distribution of the gamma-ray (GR), the porosity, and the resistivity logs obtained from the Petromode® software. B) the cross-plots, of the lithology with porosity and resistivity from the Petromode® software.

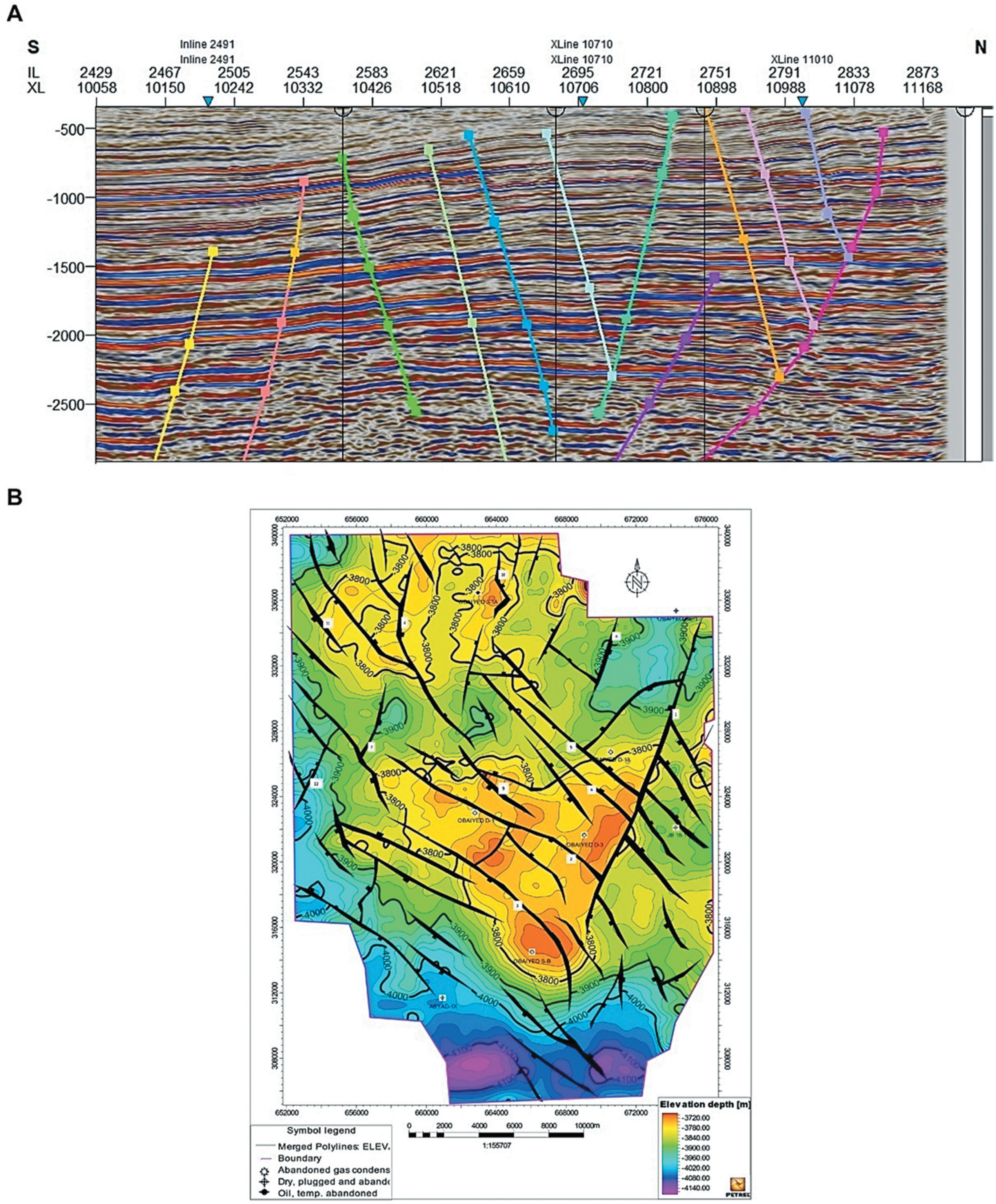

Figure 9. A) seismic cross-section showing the compartmentalisation of the formations. Notice that no displacement is recorded along the fault planes. B) plan view interpretive structure map of the Lower Safa Member showing the distribution of the faults all over the Obaiyed Field (from Abdel-Fattah et al. 2019).

4.4. A model for Continuous Basin-CentredGas (CBCG) accumulations

The field was tested for Continuous Basin-Centred Gas accumulations model (CBCG) criteria according to (Naik 2003). The results show that the basin may belong to this model for the following reasons: The large lateral extent of the Khatatba Formation which covers a vast area in the Northern Western desert and reaches to Baharia Oasis near to the south of Egypt (Said 1990).

(a) The coexistence of the source and the reservoir rocks in the Khatatba Formation. All Khatatba members, except the sandstone of the Lower Safa Member, are composed of limestone and shale, with a high organic matter content, and consider as the main source of the hydrocarbons on the basin (Younes 2006; El Diasty 2015). The generation stage of the Khatatba source was approximately ~100 Ma, during the Aptian, whereas the timing of the maximum expulsion of the hydrocarbons was during the Oligocene. The maturation stage was reached ~25 Ma, during the Miocene, in which the main migration paths to the Obaiyed field were from the North-eastern direction, where the Khatatba Formation sinking and thickened to the north (Figure 10), towards the Matruh Basin (Berglund et al. 1994).

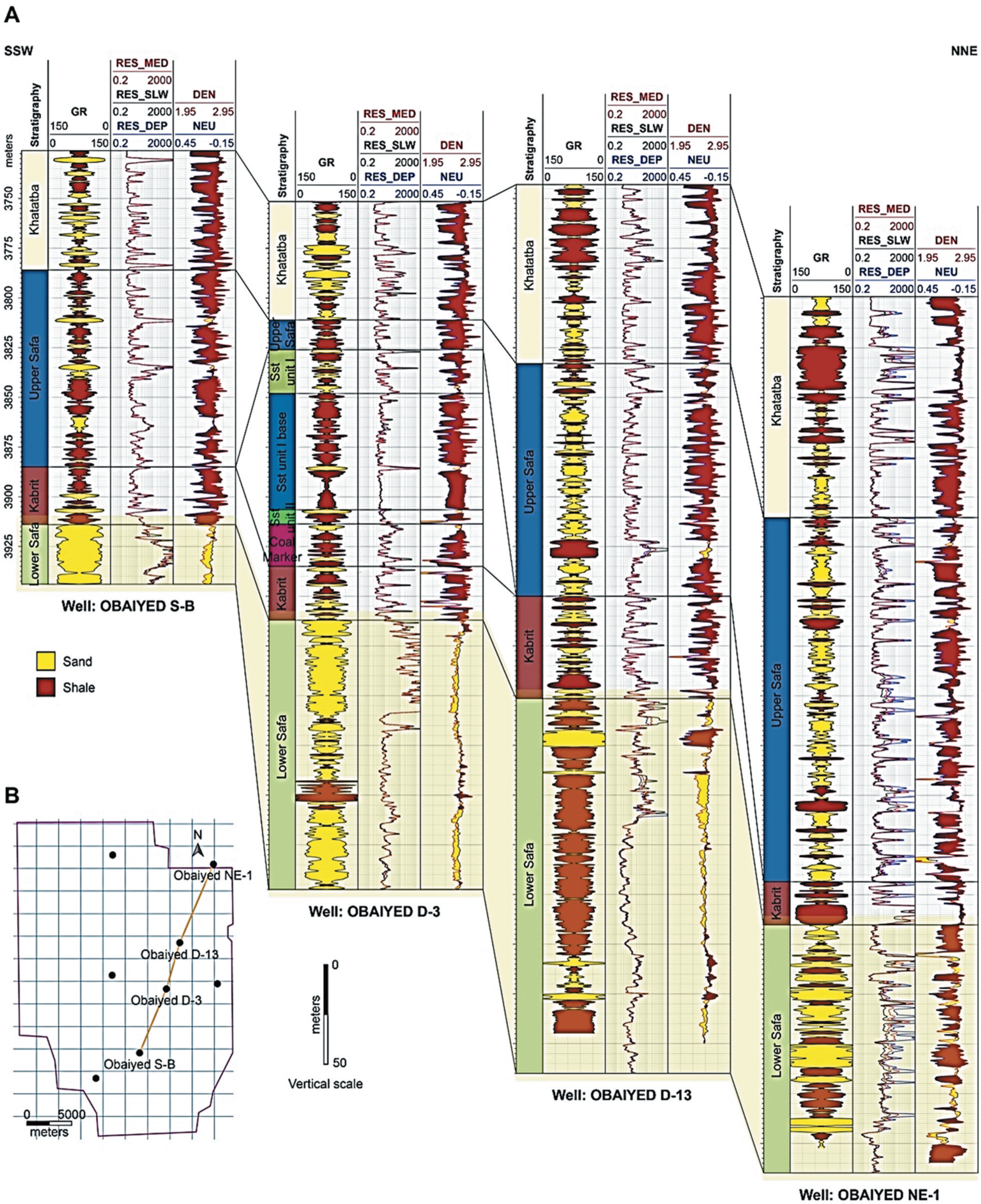

Figure 10. SW-NE Cross-section correlates between Obaiyed S-B, Obaiyed D-3, Obaiyed D-13, and Obaiyed NE-1, and shows increasing the depth and the thickness of Khatatba Formation towards the North.

Therein, the Khatatba source rock is high in shale content and reaches deep burial depths of 4.5 km in the North East of Shushan Basin and more than 5 Km to the North where Matruh Basin is found (Bagge and Keeley 1994).

(b) The low-permeability and accumulations of the Lower Safa Member are gas saturated. Our quantitative assessment of the Shushan Basin suggests that it is of a higher quality tight gas field with permeability mostly with a value of 1.0 mD across the field and effective porosity of 2.4 % at the deepest part of the basin. This agrees with the permeability and the porosity values estimated for the CBCG systems(Ma et al. 2016).

(c) The abnormal pressure of the Lower Safa sand reservoir (Figure 11). Abdel-Fattah et al. (2019) suggest that the whole area is compartmentalised, and each compartment has its pressure peak and lacks the down-dip water contact except in the Obaiyed South-2 well where the contact is down to the gas.

4.5. Implications for the exploration scenarios

Because of the low permeability of tight gas sandstones, more wells are required for the development stage compared to the development of conventional gas reservoirs (Jia et al. 2012). These wells have a long life in which the well initial pressure is very high, yet rapidly drops off. Typically, the Lower Safa stacked sandstone reservoir, which represents a Falling Stage System Tract (FSST) to Low Stand System Tract (LST) that coincides with incised valleys and fluvial channelling events (Moustafa 2008). Hence, the reservoir member is best developed by vertical wells, in contrast to the blanket sandstones, which are developed with horizontal wells, which are not part of the Lower Safa Member or Khatatba Formation.

For this reservoir, designing the hydraulic fracture treatment should be done in the middle of the field where the thickness of the Lower Safa reaches more than 200 metres. However, this approach is not suitable in the southern part of the area where the thickness of the reservoir is less than 20 metres, even though it is fully saturated with hydrocarbons.

5. Conclusion

Shushan Basin, one of the largest coastal basins in North of the Western Desert, has been tested for the geologic control that formed it; either continuous basin-cantered gas accumulations or BCGAs, and gas accumulation in low-permeability tight sandstones of a conventional trap on the basis that the difference between these two theories can have a huge impact on the strategy for gas exploration scenario. The previous studies on this basin and the studies of each geological system were used, and we did some virtual simulations with petrophysical calculations. All this led us to say that this Shushan sedimentary basin depended on BCGA geologic control and has high-quality properties related to this type of geologic system.

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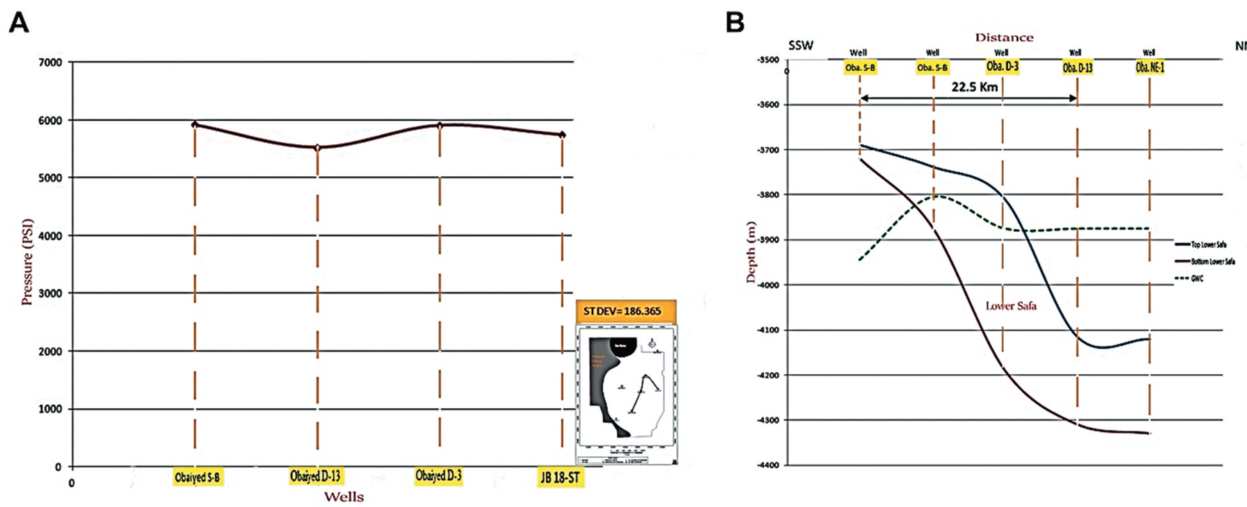

Figure 11. A) the change in the pressure in the Lower Safa Member along with the selected wells in Figure 9. B) the interpreted location of the gas-water contact along with the selected wells in the Obaiyed Field (Abdel-Fattah et al. 2019).

Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the author(s).).

ORCID

Ahmed I. Diab http://orcid.org/0000-0002-8327-7333
Hany M. Khalil http://orcid.org/0000-0003-0063-3994

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