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FULL LENGTH ARTICLE

Petrophysical properties of Cretaceous clastic rocks (Qishn Formation) in the Sharyoof oilfield, onshore Masila Basin, Yemen

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Abstract The subsurface of Qishn clastic rocks, which are exposed in the Sharyoof oilfield, has been studied. The petrophysical properties, i.e., porosity and permeability of Qishn clastic reservoir rocks were investigated using well logging coupled with core data. The results were used to evaluate the reservoir quality and hydrocarbon occurrence potential. The lithology of the Qishn clastic was computed from well logs, which indicate that the lithofacies of the Qishn clastic at Sharyoof oilfield is mainly composed of sandstone and carbonates with a low amount of shale intercalations.

Generally, the Qishn clastic reservoir rocks have good reservoir quality with porosity values, averaging ~19.0%. These porosity values are mainly intergranular primary and secondary porosity. Permeability is likewise variable with values in the range of 0.001–7270 mD and an average of 413 mD. This is conformed from core porosity and permeability results. However, the relatively high values of effective porosity and permeability are due to lower shale contents in the Qishn clastic rocks. The Qishn clastic reservoir rocks have been differentiated into net-pay and non-pay zones according to the cutoff (i.e., effective porosity ⩾10%, shale volume ⩽30% and water saturation ⩽50%). The Qishn clastic reservoir rocks have high hydrocarbon saturation exceeding 70%, with relatively high movable oil, indicating that the production is mainly oils. Therefore, the Early Cretaceous Qishn Formation acts as a hydrocarbon reservoir in the Sharyoof oilfield, Masila Basin, eastern Yemen.

Reservoir property distributions of the Qishn clastic rocks such as net-pay thickness, porosity, permeability and hydrocarbon potential indicate that the best prospective region for oil accumulation is located in the central part of the study area. Therefore, the Qishn clastic rocks in the central part of the study area have promising reservoir characteristics and hydrocarbon occurrence potential, which should be taken into consideration during future development of the Sharyoof oilfield.

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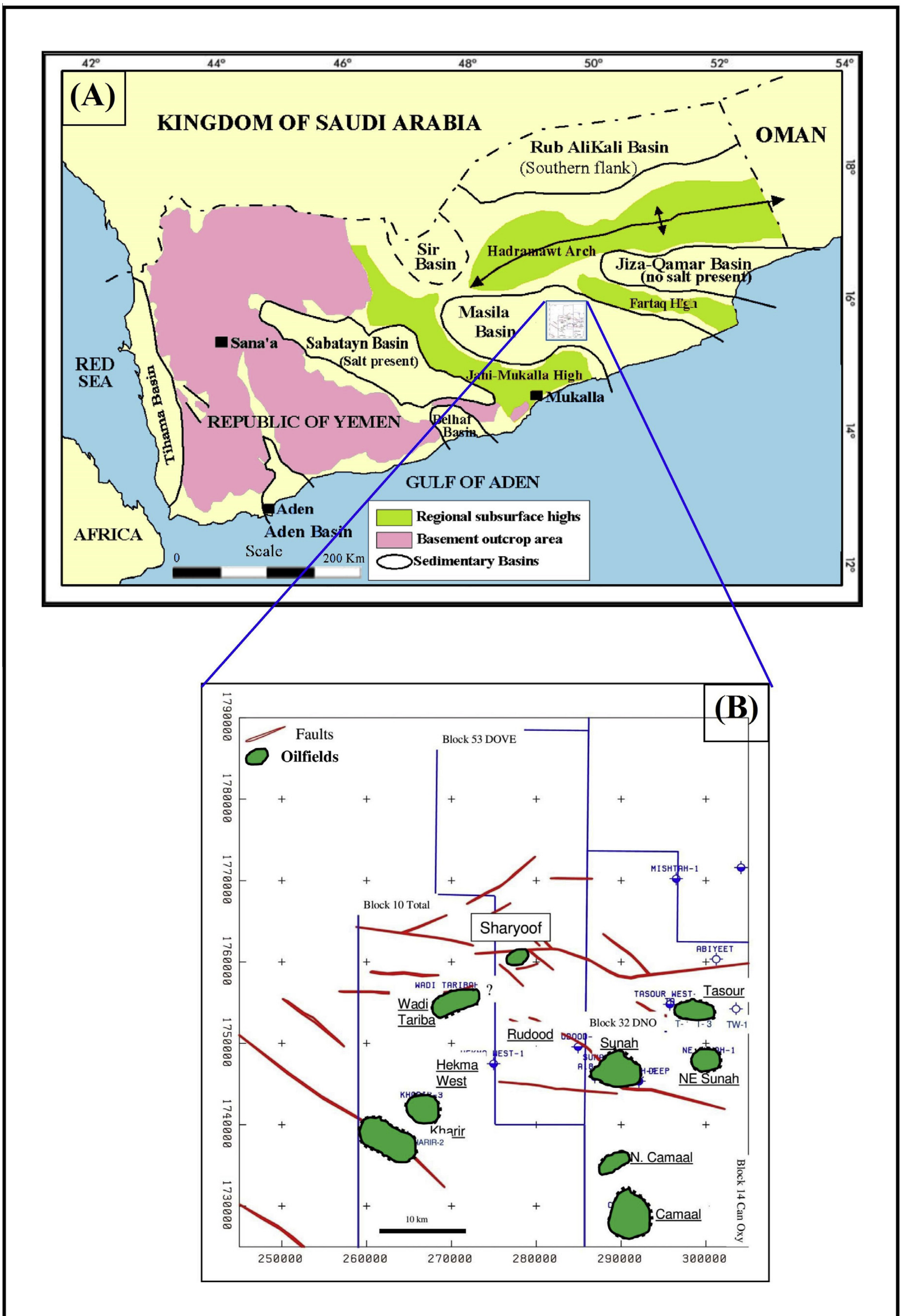

Figure 1 (A) Main sedimentary basins in Republic of Yemen (modified after Beydoun et al. [12]) and (B) location map of some Masila Basin's Blocks including Sharyoof oilfield (Block 53), Hadramawt region of the Republic of Yemen.

1. Introduction

Masila Basin is one of the onshore basins in Yemen, which is located in the east part of Yemen (Fig. 1). The Masila Basin is classified as large hydrocarbon basins in the Yemen and contains several, well known hydrocarbon oilfields (Fig. 1A). However, the area of interest of this study is the Sharyoof oilfield. The Sharyoof oilfield is one of the most productive oil fields in the Masila Basin, located in the N/W sector from the Masila Basin (Fig. 1A). The Sharyoof oilfield is also boarded with several successful producing oilfields such as Sunah, Wadi Taribah, Kharir and Tasour oilfields (Fig. 1B). The production first wells are Rudood-l, Sharyoof-1, and Sharyoof-2, which were drilled in 1999 by the DNO Petroleum Company to depths 2179 m, 1765 m, and 1630 m, respectively. The main structures in the Sharyoof oilfield are characterized by horst, tilted fault blocks (Fig. 2), formed during Late Jurassic-Early Cretaceous and developed during the Oligocene–Middle Miocene time as a result of the opening of the Red Sea and the Gulf of Aden during the Tertiary rifting tectonic event [1–5]. The Sharyoof oilfield contains sedimentary rocks ranging from Jurassic to Tertiary in age, including Qishn Formation (Fig. 3). The Cretaceous Qishn clastic is an important hydrocarbon (oil) reservoir in the Sharyoof oilfield (DNO Oil Company, 1999; unpublished report). Based on operating oil companies (DNO Oil Company, 1999; unpublished report), the productivity varies significantly within the Precambrian/Archean granitic basement, Lower Cretaceous Saar Formation carbonates, and Qishn Formation clastic reservoir rocks. The produced oil at Sharyoof oilfield is intermediate oil and has a specific gravity between 28 and 32 API (DNO Oil Company, 1999; unpublished report). These oils have been generated from marine-source rock of the Late Jurassic Madbi Formation [6,7]. The source rock began to generate oils during Late Cretaceous (99–66 Ma), and reached a maximum during the Paleocene (< 66 Ma) [8]. However the Qishn Formation clastic rocks are represented as main producing reservoir rocks in the Sharyoof oilfield (DNO Oil Company, 1999; unpublished report). This current study focuses on the petrophysical analysis of the Qishn clastics to improve our understanding of the reservoir parameters such as shale content, porosity; permeability and fluid saturations. This study also involves lithology analysis based on computed lithological cross-plots using well log data and compared to previous works [9–11]. This also aims to re-appraise and validate the potential of the Qishn clastic as reservoir rocks, and hence ultimately provides further insights into the geology of the basin, for future petroleum exploration in the field.

2. Geological setting

The Masila Basin is one of the Mesozoic sedimentary basins of Yemen (Fig. 1A), and was formed as a rift-basin linked to the Mesozoic breakup of Gondwanaland and the evolution of the Indian Ocean during the Jurassic and Cretaceous [5,12,13]. Mesozoic and Cenozoic units are widely exposed in the sedimentary basins of Yemen. The definition of the lithostratigraphic units in the Masila Basin including Sharyoof oilfield have been studied by many authors such as Hatitham and Nani [1], Al Areeq [9], Beydoun et al. [12], Bosence et al. [14], Putnam et al. [15], Holden and Kerr [16], Watchorn et al. [17], Cheng et al. [18], Brannan et al. [19] and Leckie

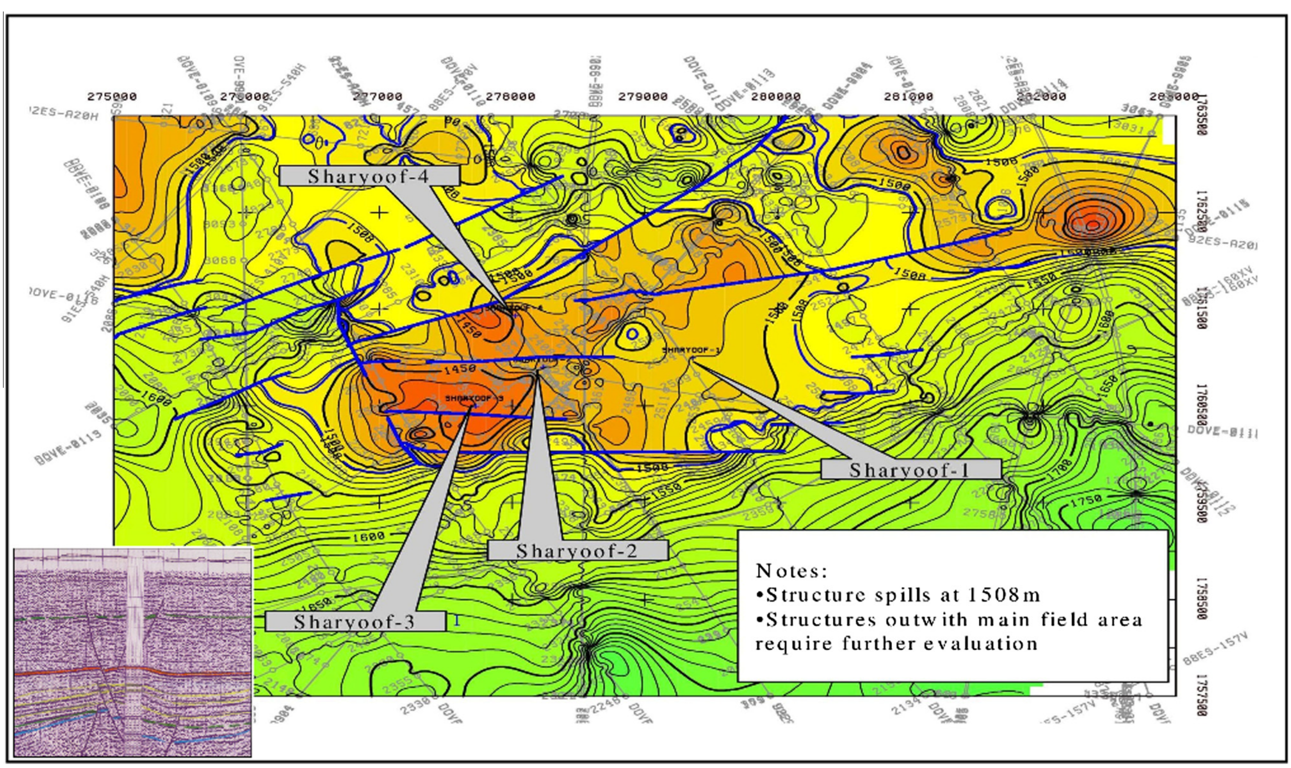

Figure 2 Structure contours at the top of the Qishn Formation in the Sharyoof oilfield showing the structural setting including anticline folds and fault.

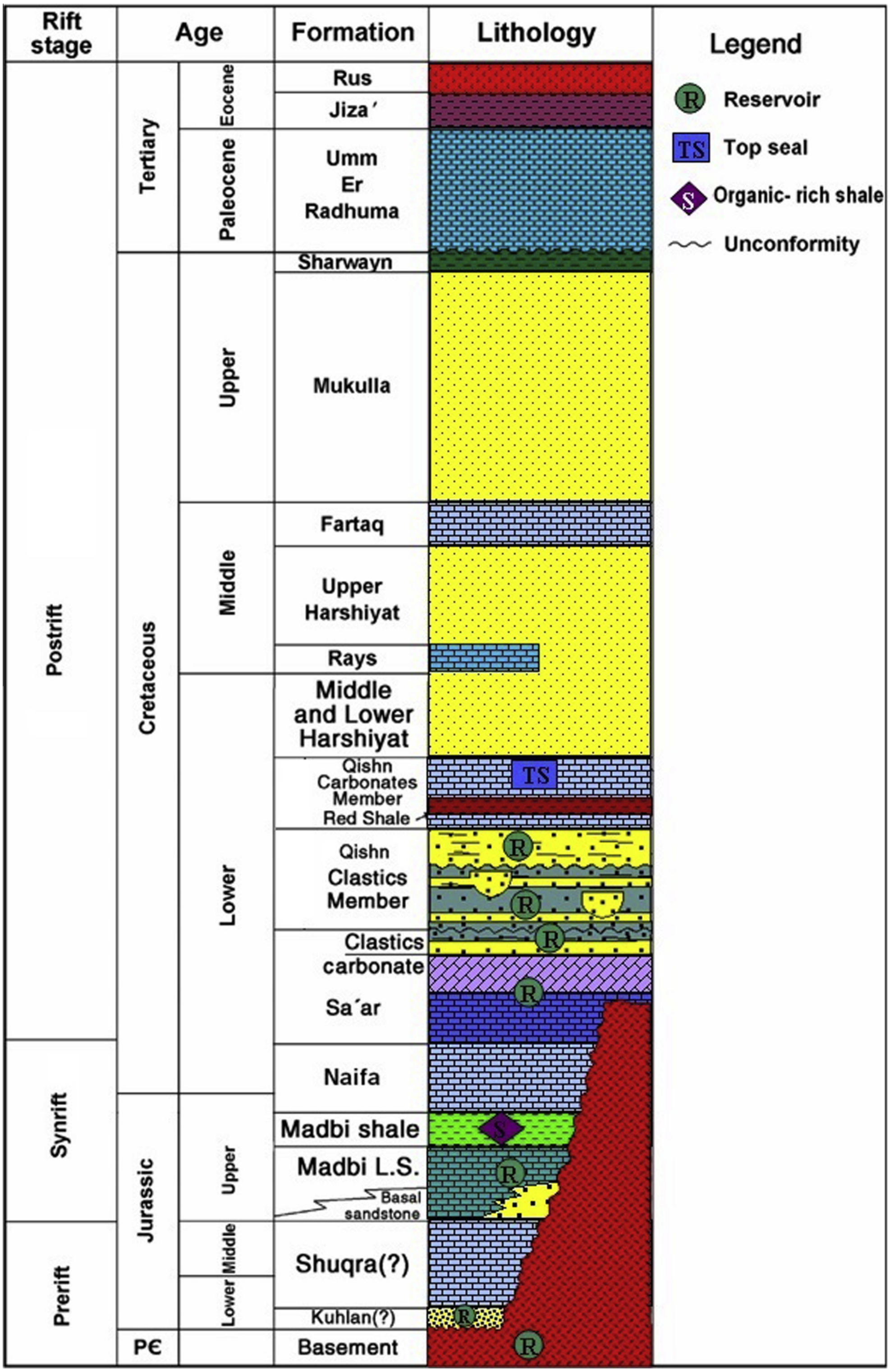

Figure 3 Stratigraphic column in the Masila Basin, including Sharyoof oilfield of the eastern Yemen.

and Rumpel [20]. The stratigraphic section of the Masila Basin including studies Sharyoof oilfield in age from Precambrian to Tertiary (Fig. 3). Basement complex rocks of Precambrian age underlie the Jurassic rocks at a sharp unconformity surface. They consist of granite, diorite and metamorphic rocks. The Jurassic units comprise clastic, carbonate and argillaceous sediments. The lower part of the Jurassic is composed of sandstone and limestone (Kohlan and Shuqra Formations). Here, the Kuhlan and Shuqra are regarded as a discrete pre-rift package [21]. The Kuhlan Formation is predominantly clastic with local basement topography commonly providing the provenance of sediment. This formation includes fluviatile and arkosic red beds that grade upward into a shallow-marine facies and represents the early transgressive phases of the

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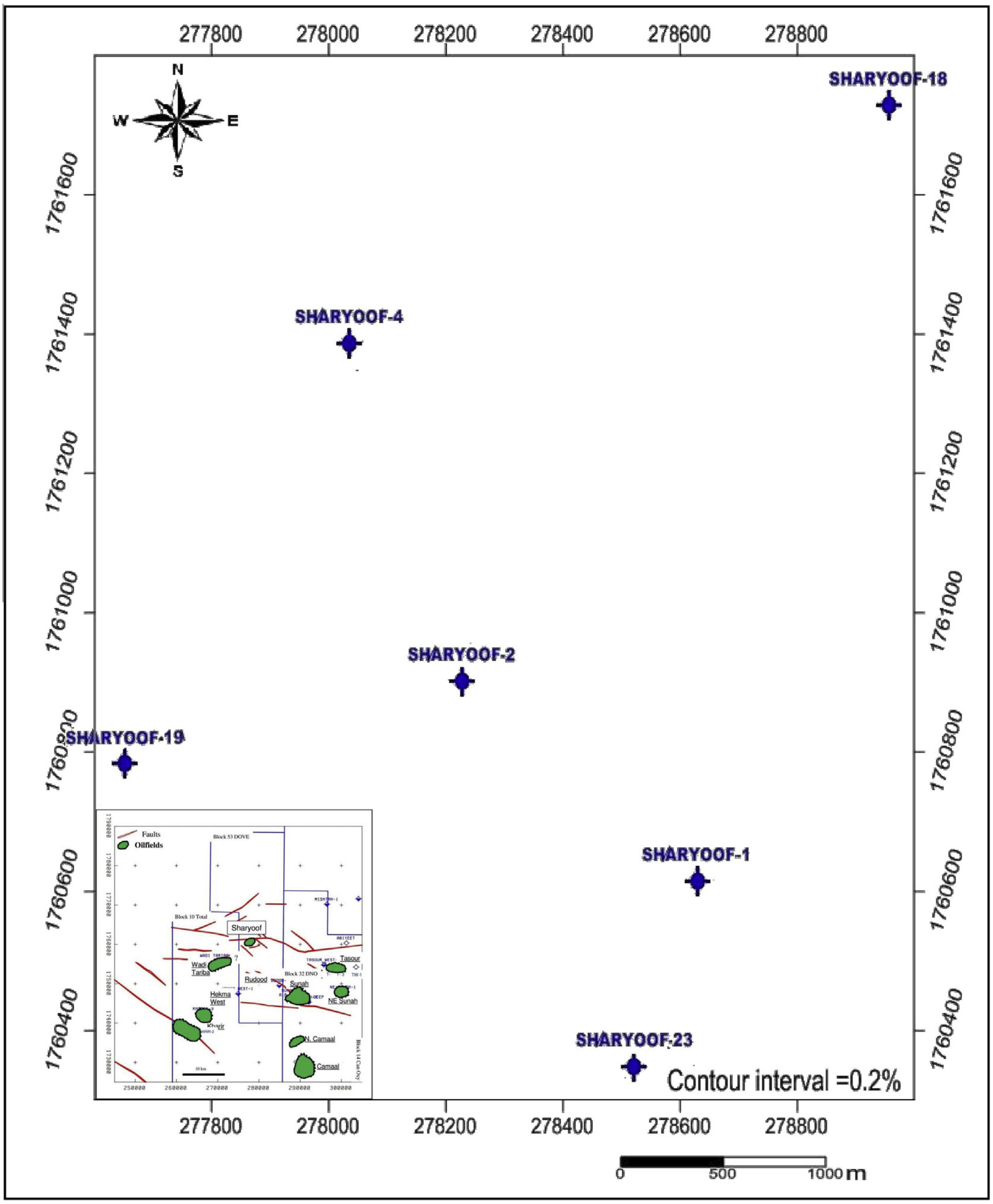

Figure 4 Location map of the studied wells in the Sharyoof oilfield.

Table 1 List of available well log data of the Qishn clastics reservoir rocks in the studied wells from Sharyoof oilfield, Masila Basin.

Well name	Top depth (m)	Bottom depth (m)	Total thickness (m)	Available well logs
Sharyoof-1	1472.4	1621.95	149.6	GR-CALI-LLS-LLD-MSFL-DT-RHOB-NPHI-DRHO-PEF
Sharyoof-2	1455.7	1592.6	136.4	GR-CALI-LLS-LLD-MSFL-DT-RHOB-NPHI-DRHO-PEF
Sharyoof-4	1499.5	1632.3	132.8	GR-CALI-LLS-LLD-MSFL-DT-RHOB-NPHI-DRHO-PEF
Sharyoof-18	1482.8	1548.5	65.7	GR-CALI-LLS-LLD-MSFL-DT-RHOB-NPHI-DRHO-PEF
Sharyoof-19	1467	1528	61	GR-CALI-LLS-LLD-MSFL-DT-RHOB-NPHI-DRHO-PEF
Sharyoof-23	1504	1560	55.4	GR-CALI-LLS-LLD-MSFL-DT-RHOB-NPHI-DRHO-PEF

middle Jurassic seas [12]. These continental rocks are overlain by shallow-marine fossiliferous carbonates such as the Shuqra Formation (Fig. 3). The Shuqra Formation conformably overlies the Kuhlan Formation with a gradational contact. This conformable relationship reflects the gradual transgression and a slight deepening of marine conditions,

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Table 2 Summary of the petrophysical parameters for the Qishn clastic reservoir rocks in the studied wells from Sharyoof oilfield, Masila Basin.

Well name	Top depth (m)	Bottom depth (m)	Total thickness (m)	Number of net pay	Net-pay thickness	Log-derived reservoir petrophysical properties: Shale content (%) Min	Max	Avrg.	Porosity (%) Total Min	Max	Avrg.	Effective Min	Max	Avrg.	Permeability (mD) Min	Max	Avrg.	Water saturation (%) Min	Max	Avrg.	Hydrocarbon saturation (%) Min	Max	Avrg.	Reservoir petrophysical measurements: Helium porosity)%) Min	Max	Avrg.	Horizontal permeability (mD) Min	Max	Avrg.
Sharyoof-1	1472.4	1621.95	149.6	26	78.1	0.0	39	5.5	6.0	32	20.6	6.0	32	20.6	0.01	3433	384	21	66	28.3	34.0	79.0	71.7	—	—	—	—	—	—
Sharyoof-2	1455.7	1592.6	136.4	31	77.4	0.0	33	3.5	2.3	32	20.7	2.3	32	20.7	0.001	6670	822	1.1	100	28.0	0.0	98.9	72.0	22	27	24	85	6318	1651
Sharyoof-4	1499.5	1632.3	132.8	25	56.5	0.0	53	3.5	5.4	45	20.0	5.3	45	19.9	0.005	1825	455	4.4	53	29.7	47.0	95.6	70.3	—	—	—	—	—	—
Sharyoof-19	1482.8	1548.5	65.7	5	11.9	0.0	63	9.1	3.6	30	18.1	3.6	39	17.9	0.004	7270	400	14	79	28.9	21.0	86.0	71.1	—	—	—	—	—	—
Sharyoof-18	1467	1528	61.0	4	16.4	0.0	33	3.1	5.2	29	17.7	5.0	28	17.3	0.001	558	48	10	52	40.6	48.0	90.0	59.4	—	—	—	—	—	—
Sharyoof-23	1504	1560	55.4	11	31.2	0.0	30	2.7	2.4	38	19.4	2.0	35	18.7	0.01	7171	365	5.9	100	33.1	0.0	94.1	66.9	—	—	—	—	—	—
Average			100.2	17	45.3	0.0	42	4.1	4.2	34.3	19.4	4.0	35.2	19.2	0.01	4488	413	9.4	75	31.4	25	90.6	68.6	22	27	24	85	6318	1651

Cutoffs used for net pay: Phi > 10%, Vsh < 30%, Sw < 50%.

corroborating the evidence for a tectonically quiescent platform. The Shuqra Formation is a neurotic limestone with richly fossiliferous marls and does not contain potential source beds [12]. It conformably underlies the Madbi Formation (Fig. 3). During the late Jurassic commencing in the Kimmeridgian, syn-rift sediments of the Madbi Formation were deposited [12]. The lithofacies of this unit reflects open-marine environment [12,22] and can be divided into two members. The lower member, Madbi limestone, is composed mainly of porous limestone, shale layers, with basal sand that forms a good reservoir in some oilfields of the Masila Basin. The upper member is called Madbi shale that is composed of laminated organic-rich shale and mudstone and considered to be the most prolific oil-prone source rock in the basin [6,7,23]. During the latest Jurassic to early Cretaceous time, the rifting system of the Masila Basin continued, but the subsidence became slower. It was accompanied by the accumulation of carbonates in shallow-marine shelf deposits (Naifa Formation). The Naifa Formation consists mainly of silt and dolomitic limestone and lime mudstone with wackestone. The Cretaceous units comprise the Saar, Qishn, Harshiyat, Fartaq, Mukalla and Sharwayn formations (Mahara Group) (Fig. 3). The Saar Formation is mainly composed of limestone and dolomite, with mudstone and sandstone intercalations [12]. The Saar Formation was deposited during transgression in Early Cretaceous time. The Saar Formation conformably overlies the Naifa Formation and unconformably underlies the Qishn Formation [12,21,24]. The Qishn Formation consists mainly of sandstones, with shale and minor carbonate interbeds, deposited in braided river channels, shoreface and shallow-marine settings as predominantly post-rift sediments. The Cretaceous Qishn Formation in the Masila Basin has a variety of usage of the various operating oil companies and authors [5,12,15,20,25]. Redfern and Jones [5] interpreted the Qishn clastics as being age-equivalent of the Biyadh Sandstone of Saudi Arabia. They also identified a clear overall transgressive signature through the Qishn clastics and noted that the upper part of the formation typically consists of carbonates. A down-systems-tract facies change from coarse grained clastic deltas in the west to shale and limestone dominated successions farther east was recognized by Redfern and Jones [5], Holden and Kerr [16] and Brannan et al. [19]. The Qishn clastic underling the Qishn Carbonates, which comprises carbonate rocks with red shale beds at the base and represented the proven seal rock in the Masila Basin (Fig. 3). The Qishn Carbonate sediments were deposited in deep water under alternating open and closed marine conditions [12]. The Tertiary units comprise homogeneous argillaceous, detritus carbonates and hard, compacted, massive and bedded dolomitized fossiliferous limestone with local chert nodules (Umm Er-Radhuma Formation) that changes to shales with minor limestone bands in the upper levels (Jeza Formation).

3. Data and methodology

Six (6) wells were selected from Sharyoof oilfield in the Masila Basin (Fig. 4) and were subjected to reservoir quality and hydrocarbon potential of the clastic reservoir rocks from Qishn Formation. Well log data for six wells and core data for one exploration well were used to evaluate the Qishn reservoir rock in this study. These data (i.e., well log core data) were

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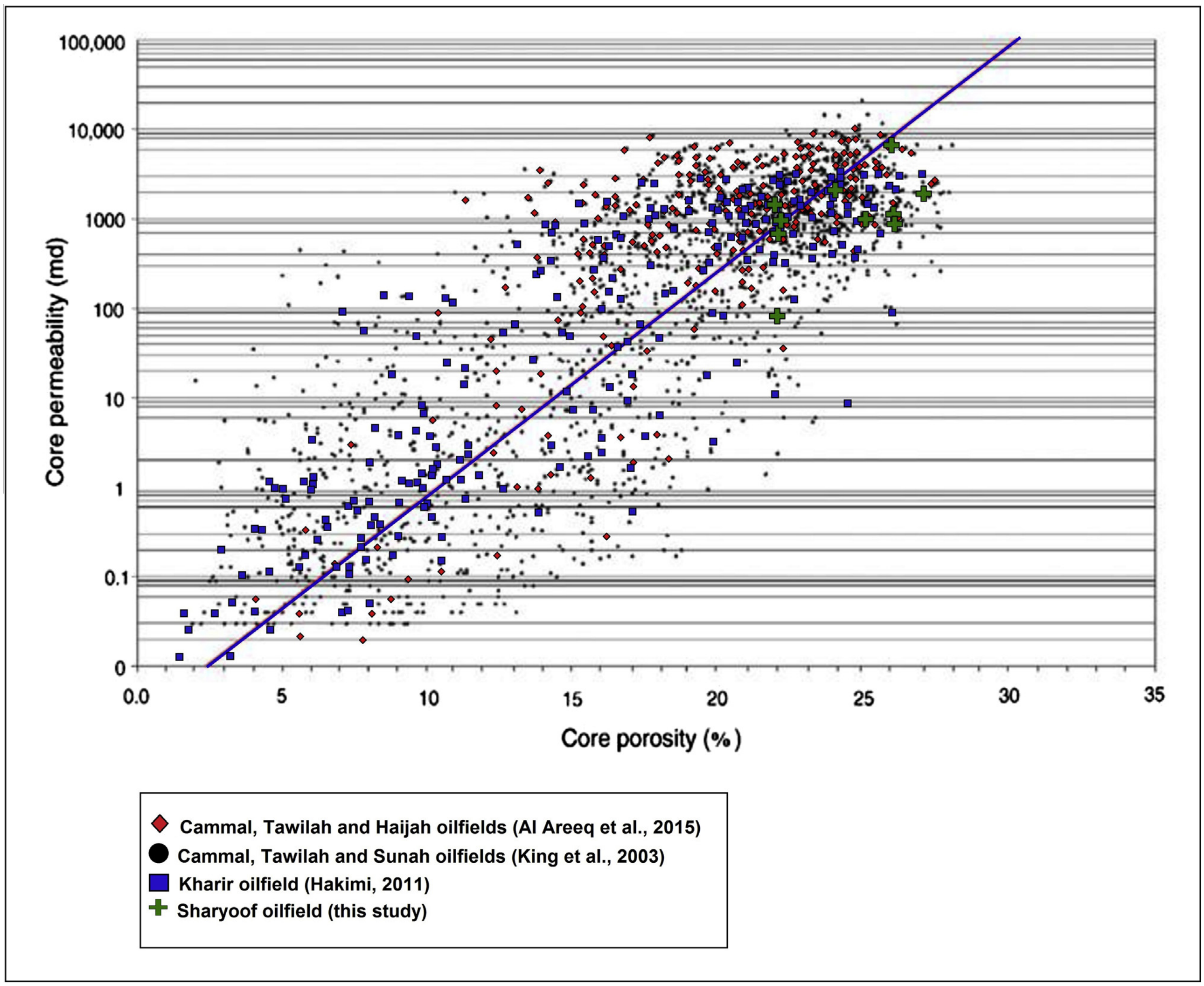

Figure 5 Core porosity and permeability values of the Qishn sandstones in the Sharyoof oilfield compared with the same reservoir rock in the close oilfields (Hakimi [10]; Al Areeq et al. [11]; King et al. [25]).

made available through the Petroleum Exploration and Production Authority (PEPA), Republic of Yemen (personal communication).

The well logs are a complete set of conventional open-hole well log data, which include deep and shallow latero logs (LLD, LLS, and MSFL), neutron porosity (NPHI), bulk density (RHOB), acoustic log (DT) and gamma ray (GR) (Table 1). However, the well logs were digitized and corrected before analyzing. The raw well logs were then converted into estimated quantities of water, gas and oil in a particular formation [26].

In this study, well logs were subjected to detailed qualitative and quantitative analyses by means of the Interactive Petrophysics (IP) software. The software consists of separate programs for reliable interpretation of all petrophysical characteristics including environmental corrections, statistical, petrophysical, and lithological analyses using a number of equations, empirical relations, and charts [27–31]. The hydrocarbon potential evaluation is based on the petrophysical analysis, including determination of the reservoir properties such as porosity, permeability, oil and water saturations, and the movable oil within the Qishn clastic rocks and interpretation of lithological and mineralogical components. The lithology and mineralogy components of the Qishn clastic rocks were investigated using Schlumberger charts such as neutron–density, neutron–gamma ray and M–N cross-plots.

The shale content (Sh_V) was calculated from gamma ray, SP, neutron, neutron–density and resistivity logs. The minimum shale content given by these shale indicators is likely to be close to the actual value of Sh_V. However, the shale-free interval where the porosity is filled with water or oil, the neutron log measures the liquid-filled porosity [32] and the density logs determine the overall density of a rock including the solid matrix and the fluid enclosed in the pore spaces [33]. The corrected porosity was estimated using a combination of these density and the neutron logs (Neutron Density Porosity Model), after applying various corrections. The effective water saturation (Sw) was computed using the Simandoux and Indonesian Models. The deriving permeability values were also calculated from well logs. The calculated permeability was derived from well logs based on several equations set in the IP software. In this study, the permeability equation of Morris

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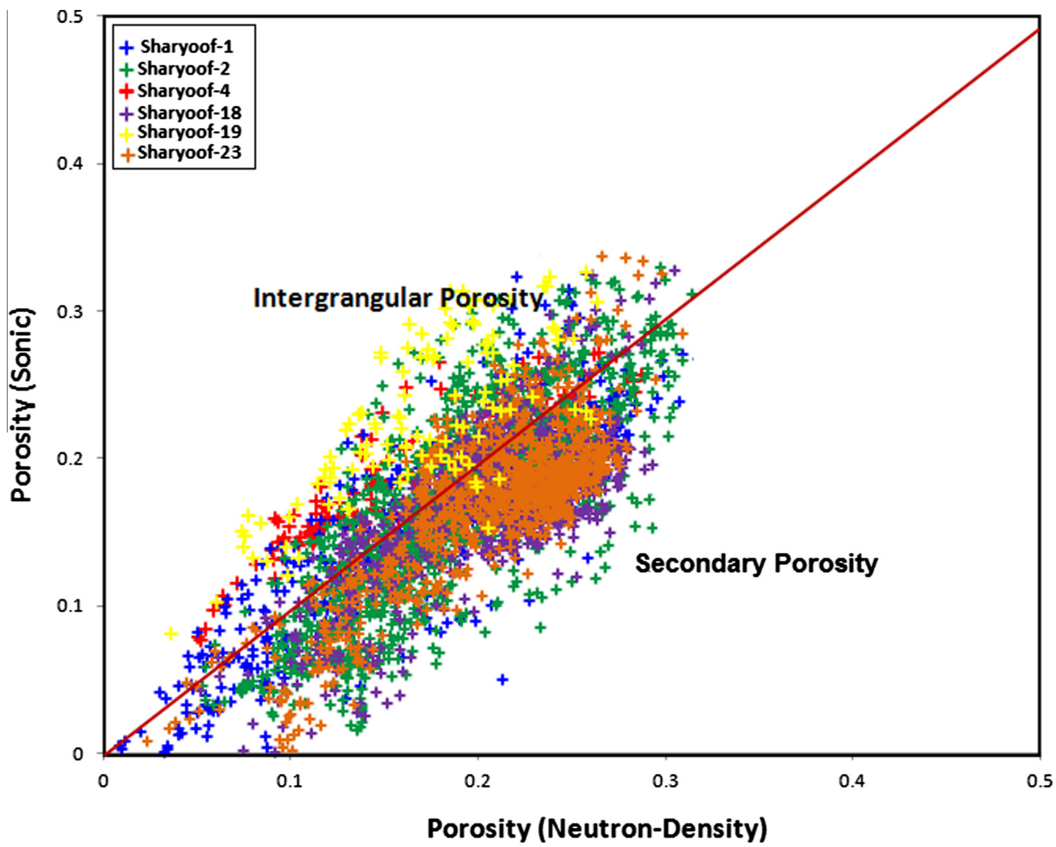

Figure 6 Cross-plot of porosity (neutron–density) versus sonic showing types of porosity in the Qishn clastic reservoir rocks for the studied wells at Sharyoof oilfield.

and Biggs [34] was used to calculate the permeability from well log data. This equation is following:

$K = a^{*}\mathrm{Phi}^{b}/\mathrm{Swi}^{c}$

where: K = permeability (md); Phi = effective porosity; Swi = irreducible water saturation; a = 62,500; b = 6; and d = 2.

However, the validated permeability equation used in this study is confirmed by consistent the calculated permeability values with measured permeability from core samples of the Qishn reservoir rock as shown in the results and discussion subsections.

4. Results and discussion

4.1. Porosity and permeability measurements

Ten (10) core samples from Qishn sandstone reservoir rock were collected from one exploration well (Sharyoof-2) for conventional core analysis to carry out the petrophysical analysis (i.e., porosity and permeability). These core petrophysical results were also compared to those of the Qishn sandstone reservoir in the Sunah, Cammal, Haijah, Tawilah and Kharir oilfields [9–11,25], which are close in location to the studied oilfield (Sharyoof oilfield) (Fig. 1B). In the Sharyoof-2 well, helium porosity of the Qishn sandstones is quiet good and ranges from 22% to 27% (Table 2). Generally, horizontal permeability also obtained all over the Qishn sandstone reservoir is good with a wide range between 84.4 and 6318 mD (Table 2). However, the helium porosity and horizontal permeability values of the Early Cretaceous Qishn sandstone reservoir in this study are consistent with the results of the same reservoir rock in the boarded Sunah, Cammal, Tawilah, Haijah and Kharir oilfields (Fig. 5) as indicated from recent works by Hakimi [10] Al Areeq et al. [11] and King et al. [25].

4.2. Log-derived petrophysical characteristics

4.2.1. Log-derived porosity and permeability

In this study, porosity and permeability were calculated from conventional well log data. The Qishn clastic rocks have low shale contents, indicating that the porosity is filled with water or oil [32]. The porosity values have been calculated using a combination of the density and neutron logs after applying various corrections. The neutron log measures the liquid-filled porosity [32], whereas the density logs determine the overall density of a rock including the solid matrix and the fluid enclosed in the pore spaces [33]. Based on log-derived porosity data for the Qishn clastic reservoir rock, the total and effective porosity values were calculated and shown similar values between them (Table 2). This similarity of the total and effective porosities is generally attributed to the low shale volume content (Table 2) since the effective porosity depends largely on the degree of connection between pores and depending on the total porosity and shale volume. The Qishn clastic reservoir rocks have relatively high total and effective porosity

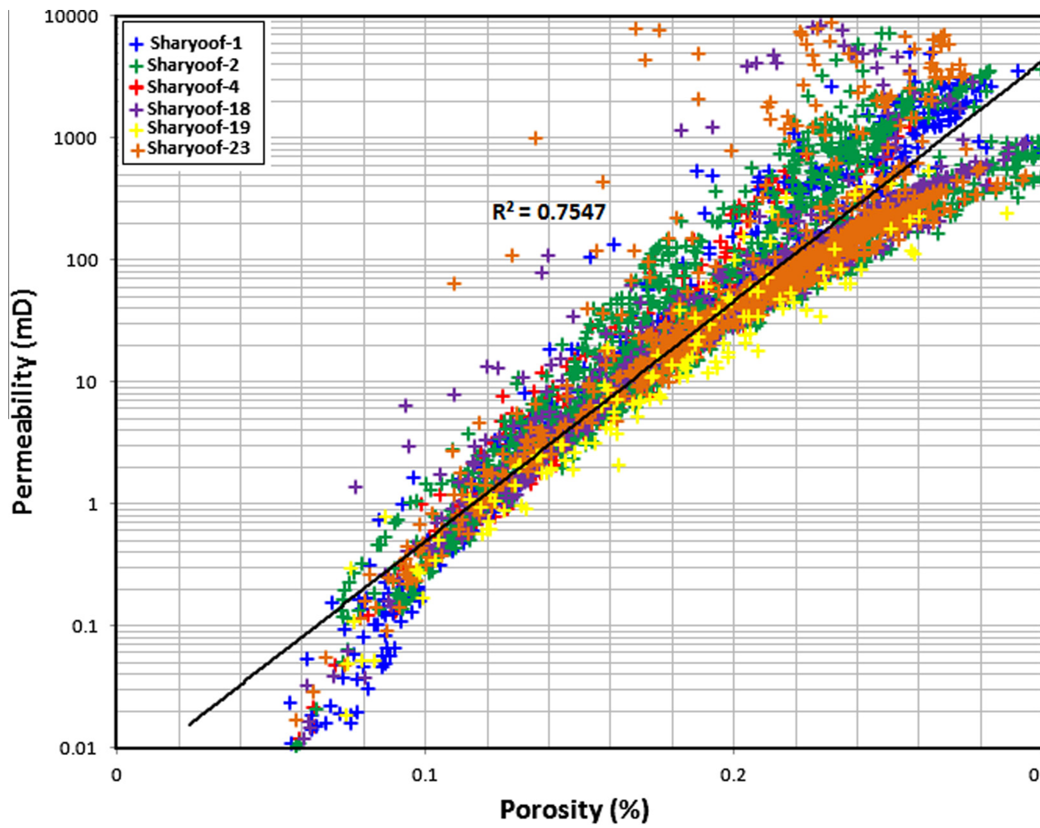

Figure 7 Relationship between log-derived porosity and permeability for the Qishn clastics in the Sharyoof oilfield, showing good positive correlation (R^2 = 0.75).

in the range from 17.3 to 20.7 (Table 2). The porosity type in the Qishn clastic reservoir rocks is represented by the dominance of primary porosity and secondary porosity types (Fig. 6). This secondary pore type may be attributed to the partially or completely dissolution of the presence significant amount of carbonate cements. The dissolution of the carbonate cements within the Early Cretaceous Qishn sandstone reservoir has been reported by Hakimi [10] and Al Areeq et al. [11].

On the other hand, the log-derived permeability is also calculated using a conventional method, i.e., Morris and Biggs [34]. The calculated permeability values range between 0.001 and 7270 mD (Fig. 7). The log-derived permeability and porosity are positively correlated, with significant correlation (R^2 = 0.75) between both of them (Fig. 7). This good correlation between both permeability and porosity values indicates that the permeability decreases or increases as in the case of porosity. Therefore, the permeability is a strong association between porosity and the lithology components of the reservoir rocks. However, the log-derived permeability and porosity values are generally in agreement with measured permeability and porosity from core analysis (Fig. 5).

4.2.2. Fluids in reservoir rocks

The fluid type and saturation in reservoir rocks can be estimated according to water saturation, effective porosity and shale content [35]. This water saturation is the amount of pore volume in a rock that is occupied by formation water and is displayed as a decimal fraction or as a percentage. The water saturation (Sw) has been computed with a shale correction using the Simandoux [36] and Indonesian equations according to the sediment of the Qishn clastic rocks. On the other hand, the hydrocarbon saturation is the amount of pore volume in a reservoir rock that is occupied by hydrocarbons, and is usually determined by the difference between unity and water saturation (i.e. Sh = 1 − Sw). The hydrocarbon saturation can also be divided into fractions; movable hydrocarbon and residual hydrocarbon saturations. The residual hydrocarbon saturation is the difference between unity and the water saturation in the flushed zone [33], (i.e. Shr = 1 − Sxo). The product of formation water saturation (Sw) and porosity represents the bulk volume of water; similarly, the bulk volume of oil is the hydrocarbon saturation multiplied by the porosity [37]. The "movable" oil is the volume of oil which can be produced from a reservoir and can be evaluated using a ratio method: (Sxo − Sw) × PHe = movable hydrocarbons, where Sxo is water saturation in the flushed zone, Sw is the saturation in the uninvaded zone, and PHe is effective porosity. The fluid saturations were computed for all the studied wells (Table 2) and showed that the hydrocarbon saturation is exceeding 70%; with sufficient amounts of movable oil (Fig. 8), indicating the production is mainly oils.

4.2.3. Lithological interpretation with cross-plots

Lithology and mineralogy components of Qishn clastic rocks in the Sharyoof oilfield were interpreted through different cross-plots (Figs. 9 and 10) where different types of matrix appear by combining different well logs (Table 1).

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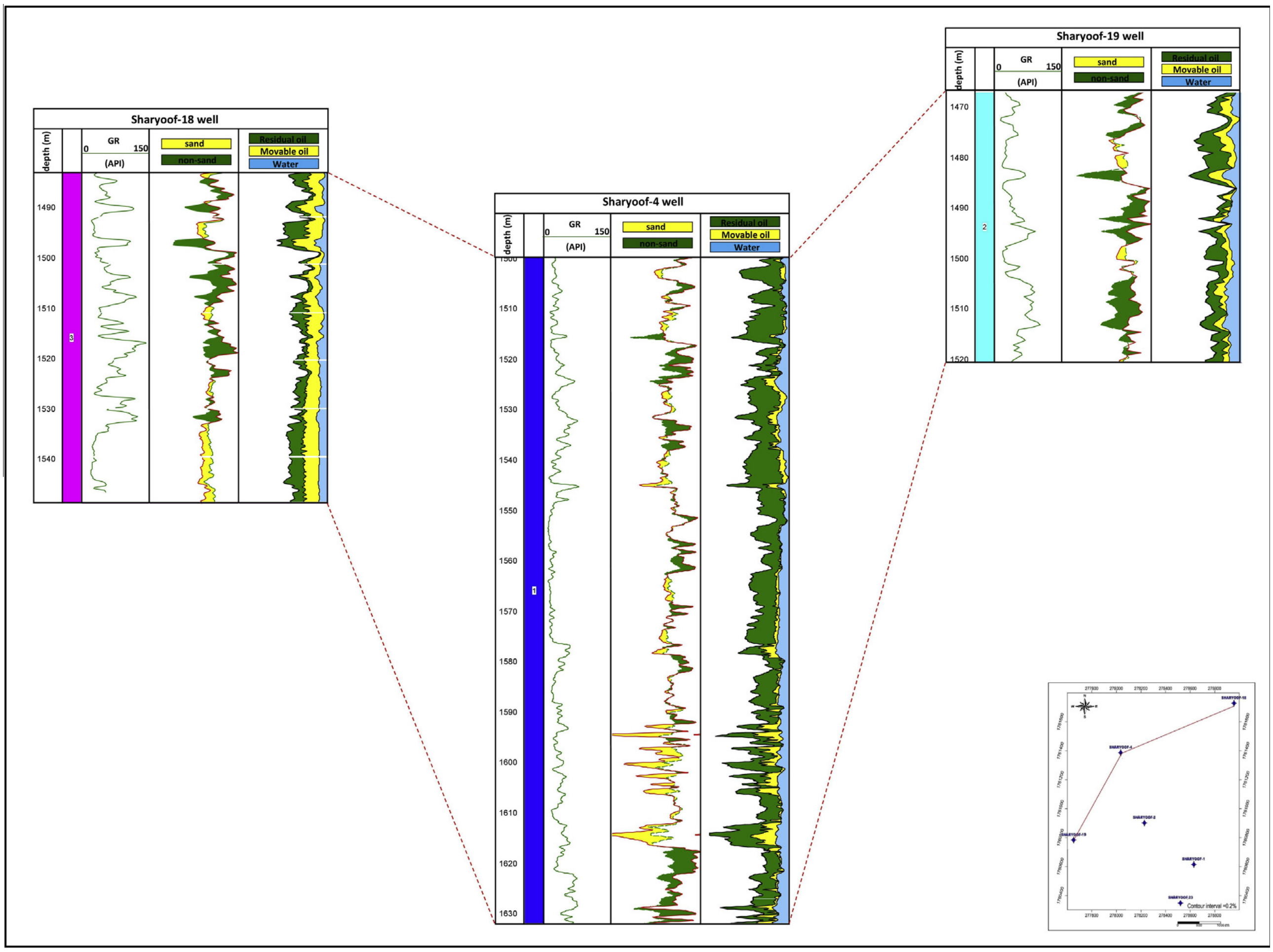

Figure 8 Bulk volume of oil and water showing movable and residual hydrocarbon in the three wells (Sharyoof-4, 18 and 19).

4.2.3.1. Neutron (NPHI) vs. density (RHOB) cross-plot. The cross-plot of neutron (NPHI) versus density (RHOB) shows that the Qishn appears to be composed mainly of sandstone with carbonates (limestone and dolomite) as shown in Fig. 9A. The dolomite content is generally low as illustrated by low values plotted along the limestone line (Fig. 9A). The neutron versus density-log derived cross-plot can also be used to estimate the relationship between porosity and different lithologic types [38]. Most readings fall close to the sandstone line indicating an association with primary porosity with values reaching 30% or more (Fig. 9A). In contrast, the carbonates have porosity in the range 5–20% (Fig. 9A), indicating secondary porosity that formed by partial or complete dissolution of carbonate cements and enhanced the porosity [39–41].

4.2.3.2. Neutron (NPHI) vs. gamma-ray (GR) cross-plots. In the neutron/gamma-ray cross-plots, the scattering points indicate that the Qishn clastics have varied lithology. Low gamma ray (10–30 API) and medium neutron indicate sandstone, while medium gamma-ray (30–60 API) and high neutron (greater than 25) suggest carbonate rocks (Fig. 9B). The shale contents are relatively low with high gamma ray values (> 60 API) and high neutron (> 25). By comparison, the neutron/gamma-ray cross plot (Fig. 9B) are consistent with the neutron/density cross plots (Fig. 9A), suggesting the main lithology of the Qishn clastic rocks is sandstone with occasional carbonates and low amount of shale intercalations.

4.2.3.3. M–N cross-plots. The M–N cross-plots reveal the same interpretation and reflect that the majority of the points are mainly sandstone, while other points suggest the existence of the carbonates shafting of some points downwards is observed indicating the shale effect (Fig. 10). The carbonates are generally high and the highest points plotted along the dolomite area in the cross-plots (Fig. 10). The M–N cross plot can also be used to investigate the secondary porosity associated with the lithology. The N–D cross-plot of the Qishn clastics reflects an association of secondary porosity with carbonate facies (Fig. 10). This finding is confirmed by neutron versus density-log derived porosity cross plot (Fig. 9A).

The log-derived lithology in this study is also compared to the thin sections that were reported by Hakimi [10] and Al Areeq et al. [11]. Thin sections indicated the lithofacies of the Qishn clastic of the Masila Basin oilfields are mainly composed of sandstone with carbonates and an amount of shale cements (Fig. 11). This is in agreement with the lithofacies of the Qishn clastic at Sharyoof oilfield that are derived from well log data (Figs. 9 and 10).

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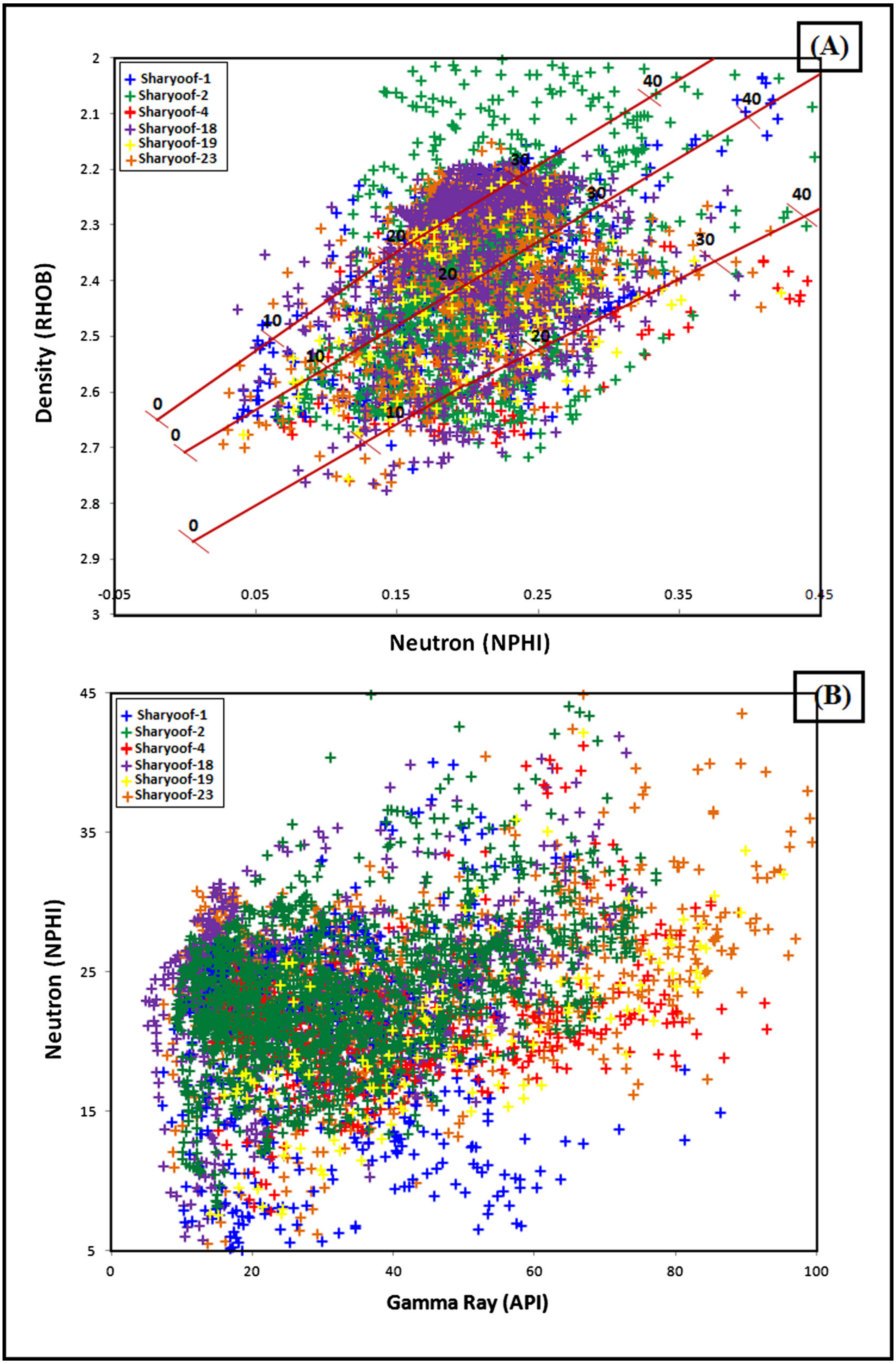

Figure 9 Lithological identification of the Qishn clastic reservoir rocks in the studied wells at Sharyoof oilfield. with (A) neutron/density and (B) gamma-ray/neutron porosity cross-plots.

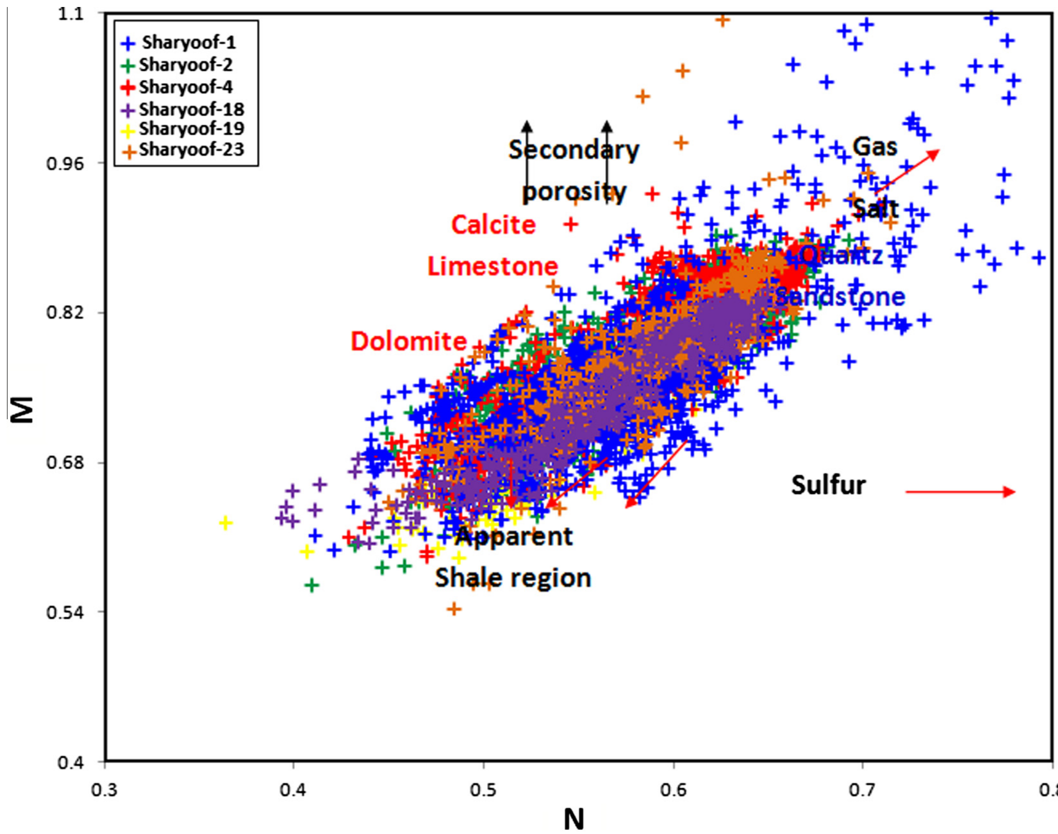

Figure 10 M–N cross-plot showing lithological components of the Qishn clastic reservoir rocks in the studied wells at Sharyoof oilfield.

4.3. Reservoir rocks evaluation

The reservoir rock quality and hydrocarbon potential were primarily evaluated based on petrophysical results from well log analysis as presented in the previous subsections. The results include vertical distributions of the petrophysical properties adjacent to the depths and the lateral distributions of reservoir properties as illustrated by iso-parametric maps [32,42,43].

4.3.1. Vertical distribution of reservoir properties and hydrocarbon potential

The vertical distributions of reservoir properties and hydrocarbon potential were plotted for each well to investigate the vertical petrophysical parameter differentiation, in term of litho-saturation cross-plots (Fig. 12). The litho-saturation cross-plots were adopted to evaluate various of lithology, porosity, permeability and fluid saturation (i.e., water and hydrocarbon) for the reservoir intervals (Fig. 12).

In this study, the petrophysical properties and lithological identification of the Qishn clastic reservoir rocks are formed as a main reservoir in the Sharyoof oilfield, having the majority of sandstones followed by dolomite and limestone and shale in lower amounts (Fig. 12). The formation analysis also includes porosity, permeability and fluid saturation (Fig. 12). The Qishn clastic reservoir rocks have different porosity types, including total, effective and secondary porosities (Fig. 12). The porosity in most of the studied wells is represented by the dominance of effective porosity of the sandstone. The sandstone facies also have good permeability values as in the case of porosity (Fig. 12). However, the higher values of effective porosity and permeability are attributed to low shale contents in the Qishn clastic reservoir rocks (Fig. 12). Fluid saturations and hydrocarbon movability are also important petrophysical parameters used to evaluate reservoir potential. The Qishn clastic reservoir rocks have considerable proportions of hydrocarbon saturation reaching 59.4–72%, and the movable oil is relatively high (Fig. 12). Consequently, the high productive oil from Qishn reservoir rocks can be expected. On the basis of the reservoir evaluation analysis, the Qishn clastic reservoir rocks have been differentiated into net-pay and non-pay zones (Fig. 12). The net pay was computed according to the cutoff (effective porosity $\geqslant$10%, shale volume $\leqslant$30% and water saturation $\leqslant$50%). Intervals that have relatively high effective porosity and permeability with water saturation of less than 50% are pay zones, while intervals with low effective porosity and permeability and relative high water saturation greater than 50% are assumed to be non-productive intervals (Fig. 12). In conclusion, the Qishn clastic rocks reveal good reservoir characteristics and most of the productive hydrocarbon pay zones are marked by a decrease in water saturation and an increase in effective porosity and permeability, as well as low shale contents.

4.3.2. Lateral distributions of reservoir properties

The reservoir properties of the Qishn clastic rocks include gross and net-pay thickness, effective porosity, permeability and fluid saturations extracted from well log data were averaged and mapped to reflect the general distribution throughout the study area (Figs. 13–15).

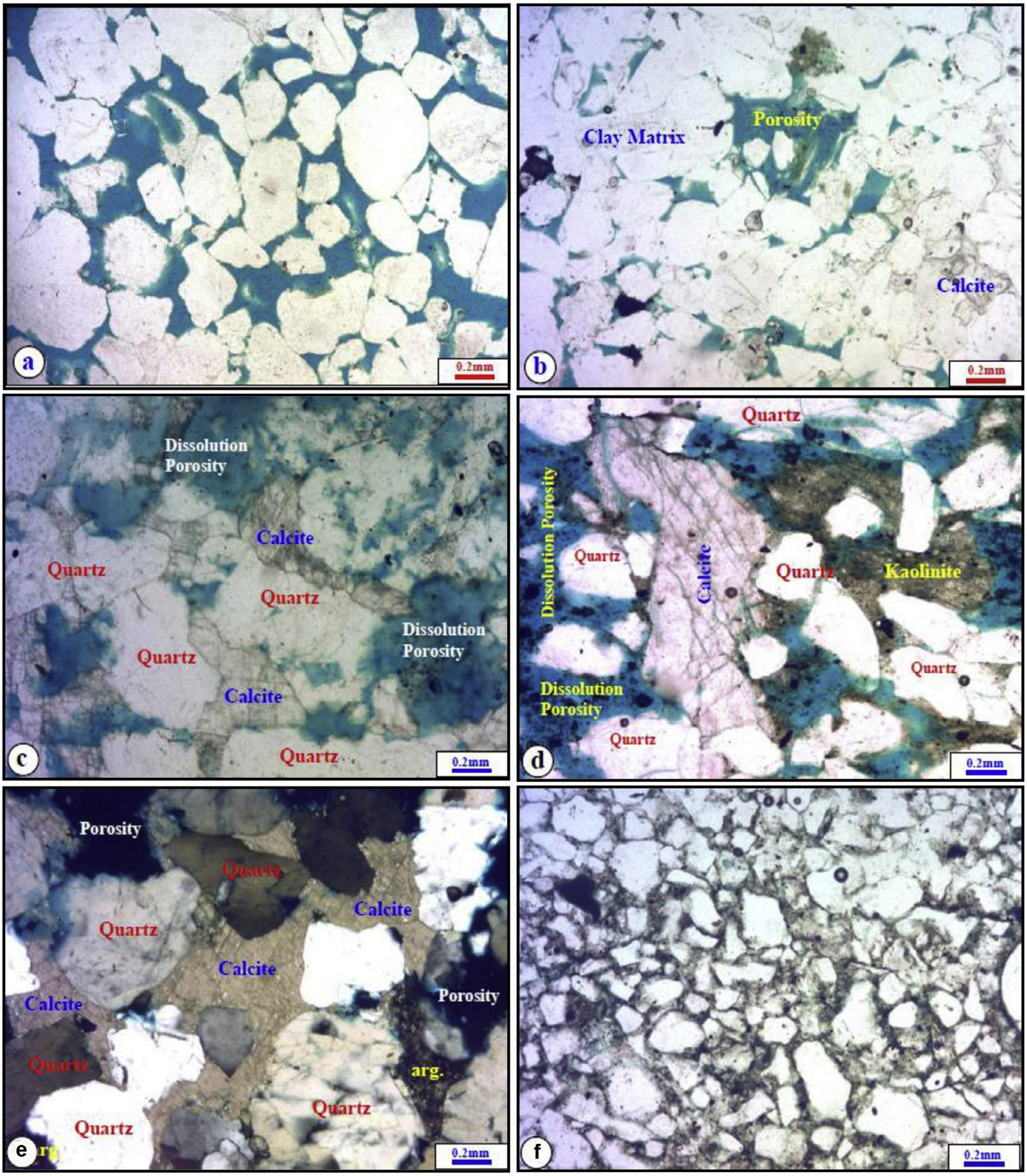

Figure 11 Photomicrographs of Early Cretaceous Qishn sandstones in the Kharir oilfield of the Masila Basin showing mineral and cements assemblages (compiled after Hakimi [10]).

The Qishn clastic reservoir rocks in the Sharyoof Oilfield have a gross thickness in the range of 55.4–149.6 m. The gross thickness increases from the southeast and northwest to the central part of the study area, from ~70 m at wells Sharyoof 19, 18 and 23, to about 140 m at wells Sharyoof-1, 2 and 4 (Fig. 13A). The net pay thickness of the Qishn clastic reservoir rocks ranges from 15 to 30 m at wells Sharyoof 19, 18 and 23 in the southeast, northwest and east parts of the study area (Fig. 13B). In contrast, the high thickness of net pay is recognized in the central part of the study with a range between 50 m and 70 m (Fig. 13B).

The effective porosity of the Qishn clastic reservoir rocks also increases from the southwest and northeast to the central part of the study area (Fig. 14A), reaching the highest value of

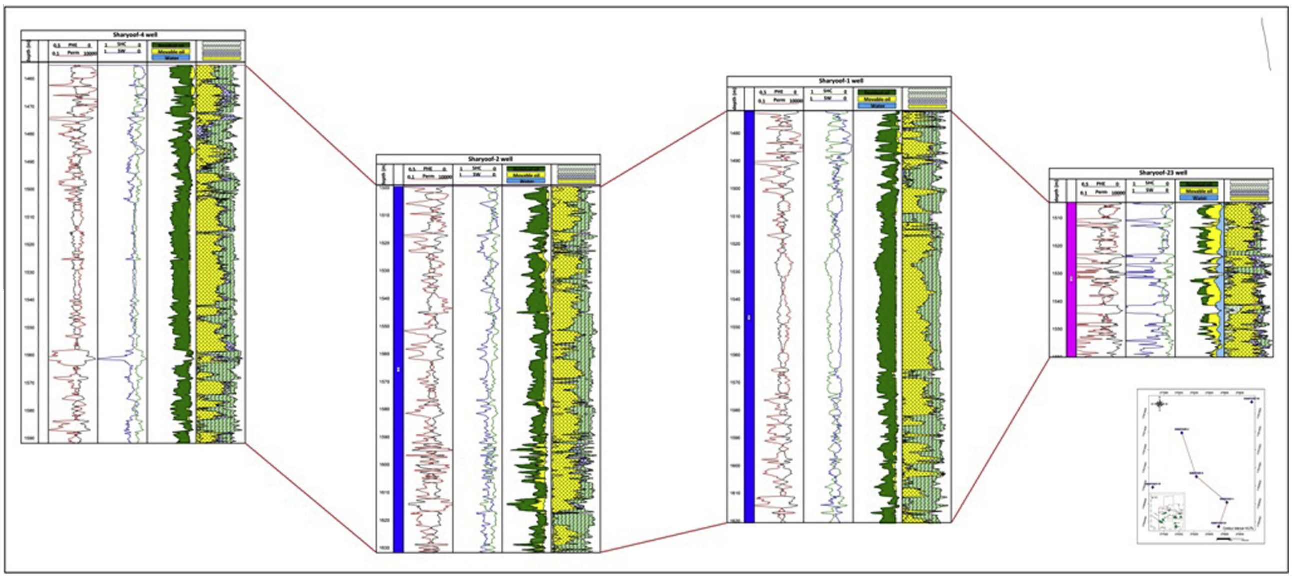

Figure 12 Vertical distributions of the reservoir properties in the Qishn clastic rocks from three well (Sharyoof-1, 2, 4 and 23).

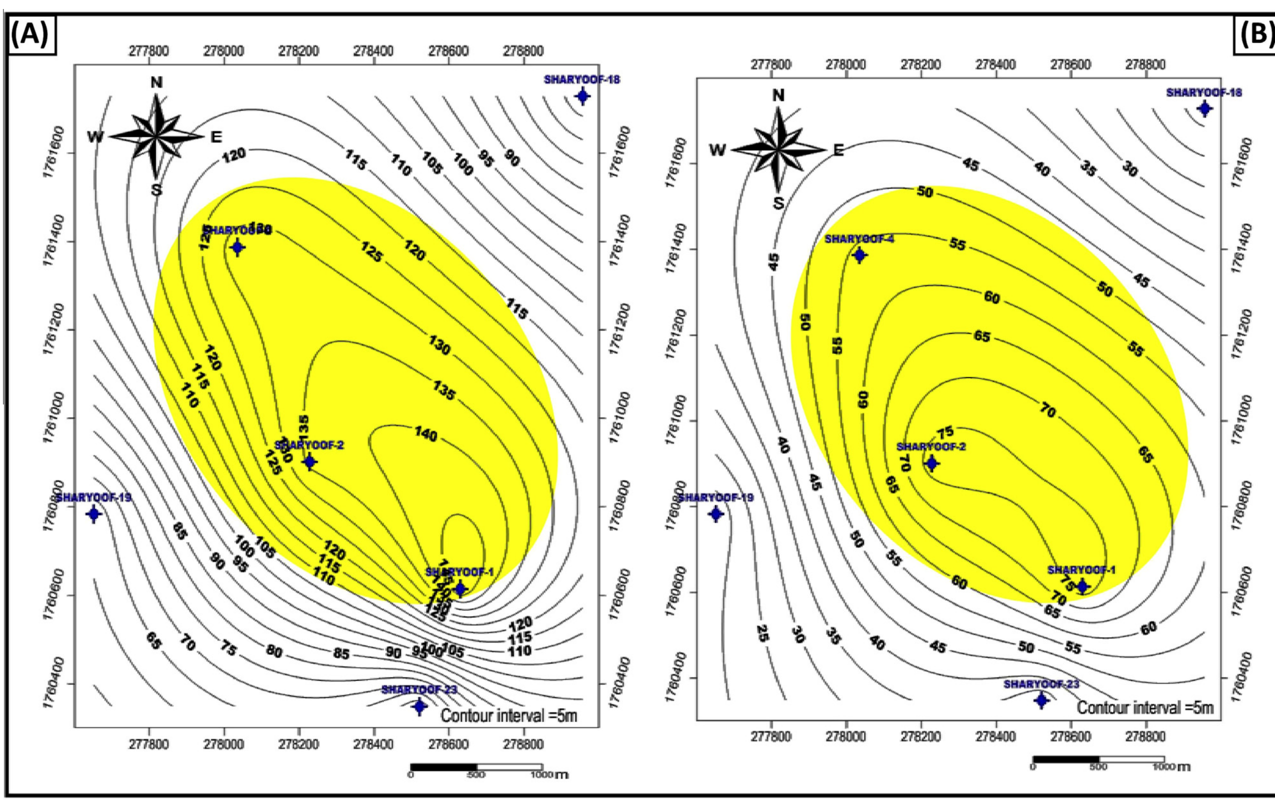

Figure 13 Distribution contour maps of (A) gross thickness and (B) net-pay thickness of the Qishn clastic reservoir rocks in the study area. Note: Yellow color is the most prospective area with high gross and net-pay thickness.

~20% (Fig. 14A). However, the permeability of the Qishn reservoir has the similar distributions and reaches the highest value of ~600 mD in the central part of the study area (Fig. 14B). This may indicate that the permeability decreases or increases as in the case of porosity due to depositions texture or diagenesis processes.

The lateral distributions of fluid saturations (water and hydrocarbon) also are important for evaluation the reservoir potential in the study area. The water saturation distributions of the Qishn clastics reservoir rocks indicate that the maximum values of over 40% are presented at well Sharuof-19 in the east of the study area (Fig. 15A). The minimum water saturation

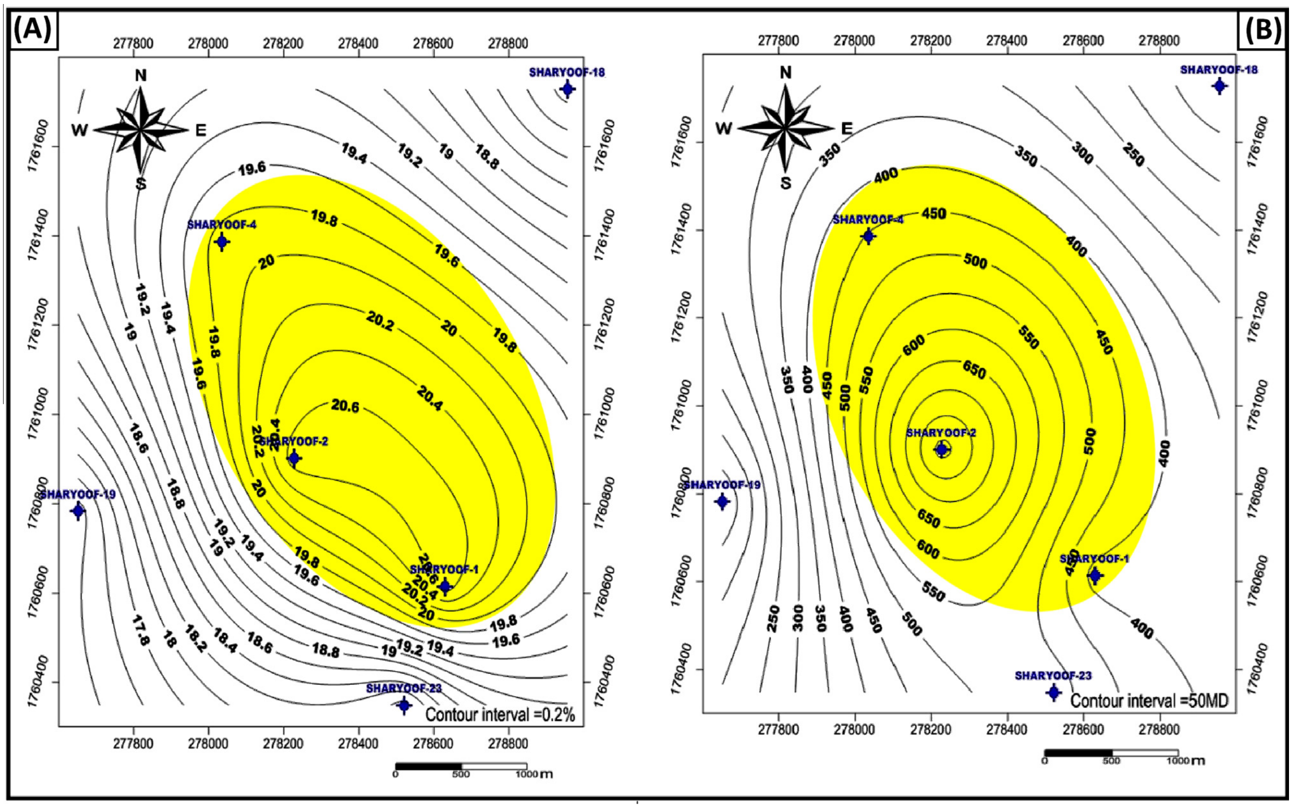

Figure 14 Distribution contour maps of the Qishn clastic reservoir properties (A) effective porosity and (B) permeability. Note: Yellow color is the most prospective area with high effective porosity and permeability.

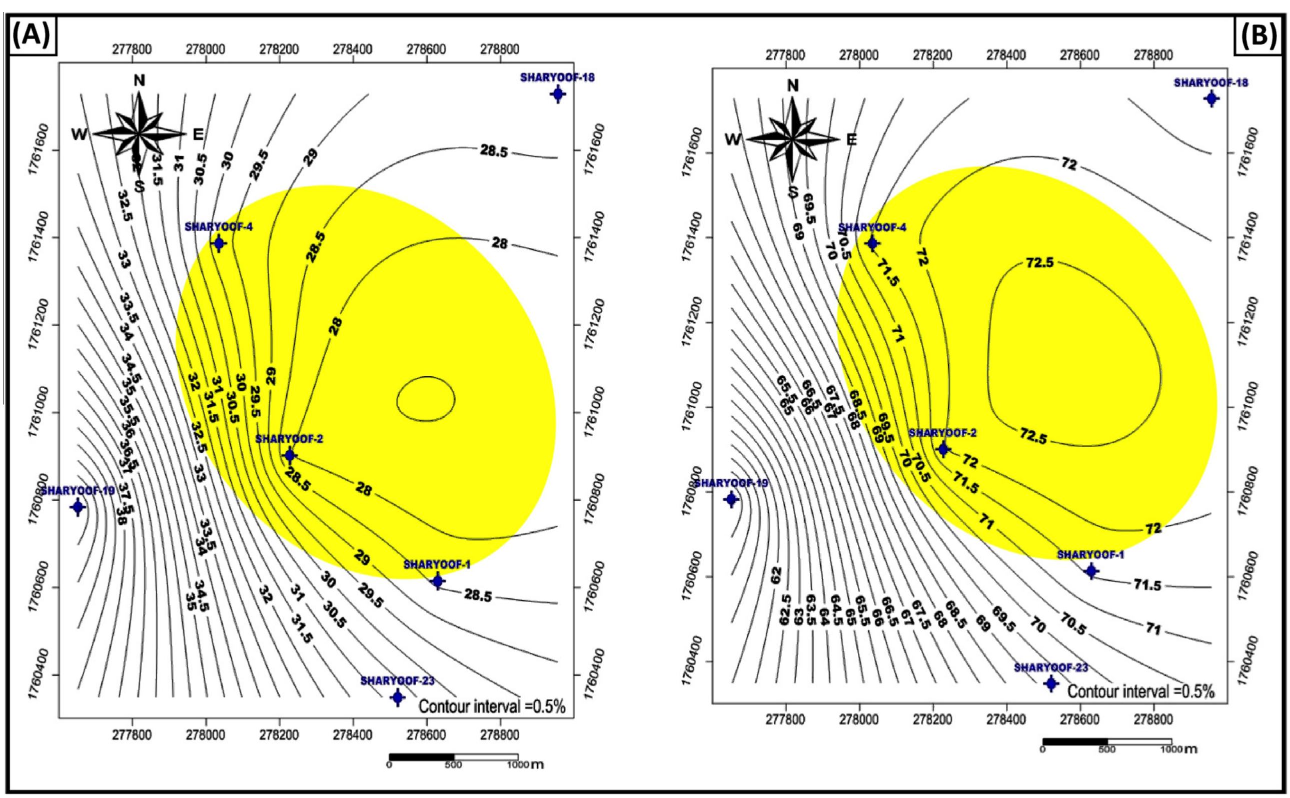

Figure 15 Distribution contour maps of the Qishn clastic reservoir fluid saturations (A) water saturation and (B) hydrocarbon saturation. Note: Yellow color is the most prospective area with high hydrocarbon occurrence potential.

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(~28%) is recognized at well Sharuof-2 in the central part of the study area (Fig. 15A). In contrast, the bulk hydrocarbon saturation in the Qishn clastic reservoir is maximum at well Sharuof-2 in the central part of the study area, and minimum at well Sharuof-19 in the east (Fig. 15B). Consequently, the good reservoir properties are recognized in the central part of the study area and the high prospect for hydrocarbon can be expected.

5. Conclusions

An assessment of petrophysical properties of Early Cretaceous Qishn clastic rocks in the Sharyoof Oilfield, onshore Masila Basin, Yemen was investigated using primary well logging, coupled with core data. The results of this study were used to evaluate the petrophysical characteristics and hydrocarbon prospect of the Qishn clastic reservoir rocks, and have consequently revealed the following:

1. The lithology cross-plots conclude that the lithofacies of the Qishn clastic at Sharyoof oilfield are mainly composed of sandstone and carbonates with a low amount of shale intercalations. This is consistent with those of the Qishn reservoir rocks in the Kharir, Tawilah, Cammal and Haijah oilfield as described by Hakimi [10] and Al Areeq et al. [11].
2. The Qishn clastic reservoir rocks have generally good reservoir properties for oil accumulation with relatively high effective porosity and permeability and low shale contents. The oil mobility is relatively high and the oil producing can be expected.
3. The cutoffs that include shale content 50%, porosity 10%, and water saturation 70% have been used to differentiate the Qishn clastic reservoir into hydrocarbon net-pay and non-pay zones.
4. The lateral distributions of reservoir properties such as net-pay thickness, effective porosity, permeability and hydrocarbon potential indicate that the most prospective region for promising reservoir of the Qishn clastic rocks and oil accumulation is located in the central part of the study area.

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