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Geochemical Evaluation of Oils from the Asmari Reservoir of the Qale-nar Oilfield: Implication for Field-scale Reservoir Compartmentalization

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Highlights

- Bulk and molecular geochemical data on oils are investigated;
- The genetic relationship between oils is defined;
- The lateral continuity of the Asmari reservoir is evaluated.

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Abstract

The Qale-Nar oilfield is an asymmetric two-humped anticline located in the northernmost part of the Dezful embayment, in which the fractured Asmari carbonates are the primary reservoir rock. In this study, for the first time, the organic geochemistry of oils produced from the Asmari reservoir is used to investigate the reservoir continuity and possible compartmentalization. To this end, geological information from the studied oilfield was combined with bulk geochemistry (e.g., °API gravity) and molecular characteristics (e.g., gas chromatography (GC) and gas chromatography–mass spectrometry (GC–MS) data) of the produced oils. Two oil samples obtained from wells 6 and 10 of the studied oilfields indicate significant differences in their bulk and molecular geochemical properties. Accordingly, a scenario was presented to better explain the reservoir charging and compartmentalization in the Qale-Nar oilfield. In this scenario, low-maturity hydrocarbon pulses first charge the eastern culmination of the Qale-Nar oilfield. The activity of a fault plane located between wells 6 and 10 could induce a barrier between the two wells. Consequently, the late hydrocarbon charges with higher maturity could only charge the compartment belonging to well 6. Therefore, well 10 could not receive these high-maturity hydrocarbon pulses due to the lack of lateral connectivity. The information obtained from this study can be of great help in future reservoir studies with important implications for field development projects and enhanced-recovery plans.

Keywords: Asmari reservoir; Gas chromatography–mass spectrometry (GC–MS); Compartmentalization; Qale-Nar oilfield; Gas chromatography (GC); Reservoir continuity

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1. Introduction

Demand for oil production has risen in recent years since both the economic and political growth of nations depend on this valuable energy source. Oil-producing countries regularly put various projects of reservoir management, field development, and enhanced recovery on their agenda. The design and planning of these projects require an extensive knowledge base covering a wide range of disciplines, including a good understanding of the reservoir structure. In-depth knowledge about the reservoir architecture allows the geoscientists to mitigate problems associated with the continuity or compartmentalization of the reservoir rock quickly and cost-effectively. For example, the design and implementation of field development plans and enhanced oil recovery (EOR) projects require the consideration of reservoir compartmentalization (Mehdipour & Sadegh Tabaqi, 2020). In recent decades, only pressure, seismic, geological, and petrophysical log data were used as primary tools for detecting continuity or compartmentalization of reservoir (Cubitt et al., 2004). However, the science of organic geochemistry has been used to examine the degree of reservoir continuity in recent years (Mehdipour and Sadegh Tabaqi, 2020). Organic geochemical techniques can help directly identify the continuity or discontinuity of reservoir zones, especially when adequate geological data are lacking or high-quality seismic information is absent (Páez et al., 2010).

The Dezful embayment is one of the richest oil provinces globally, with more than 45 hydrocarbon fields and estimated reserves of about 360 billion barrels (Bordenave and Hegre, 2005). The Qale-Nar oilfield is one of the vital oilfields located in the northernmost part of the Dezful embayment (see Figure 1). The main producing intervals in this oilfield are the fractured carbonates of the Oligo-Miocene Asmari formation drilled at 11 wells since 1975 (Motiei, 1995). At the Asmari level, the Qale-Nar anticline is an asymmetric 3 × 18 km fold with a WNW-trending hinge line with double culminations (Motiei, 1995; Razvi Pash et al., 2020). Several faults are observed on the underground contour map of the Asmari reservoir in the studied oilfield (Figure 1). The impact of these faults on the continuity of the Asmari reservoir has not been investigated so far.

Previous studies have investigated the structural style changes along the axis of the Qale-Nar oilfield using seismic indices (Razavi Pash et al., 2020). Similarly, analog modeling has been used to investigate the role of the Bala Rud fault (as a pre-existing basement fault) in the deformation of neighboring structures (including the Qale Nar structure) in the study area (Razavi Pash et al., 2021). Limited studies have been conducted on the geochemical evaluation of oils and rock samples from the Qale-Nar oilfield. It is worth mentioning that oil–oil correlation is previously conducted in the Dehluran oilfield (north Dezful embayment) (Tezheh et al., 2021). They analyzed oil samples from the Asmari and Bangestan reservoirs to assess the vertical continuity in the studied oilfield. There are other studies dealing with oil–oil correlation studies in the Dezful embayment (Alizadeh et al., 2007; Asadi Mehmandosti et al., 2015; Kamali et al., 2013) and offshore Persian Gulf basin (Alipour, 2017; Alizadeh et al., 2017; Baniasad et al., 2016). In the Qale-Nar oilfield, two oil samples (from wells 6 and 7) and seven rock samples (from Shahbazan and Pabdeh formations) were previously studied (Basiri et al., 2011). Using geochemical techniques such as the Rock-Eval pyrolysis, gas chromatography (GC), and pyrolysis–gas chromatography (PY–GC), they concluded that the Pabdeh and Shahbazan formations were the primary source rocks in this field. In a recent study, a total of seven oil-based drill cutting samples from the

Shahbazan formation were investigated in the Qale-Nar oilfield (Alizadeh et al., 2019). They used the Rock-Eval pyrolysis and gas chromatography techniques to analyze their samples and concluded that the Shahbazan formation is likely an active source rock in this field. However, none of the previous studies have tried to incorporate geological knowledge of the studied oilfield to interpret geochemical variations. In addition, no biomarker parameters were presented in the mentioned studies, while their interpretations were based on the results obtained from bulk geochemical analyses.

In this study, for the first time, we intend to investigate the lateral continuity of the Asmari reservoir in the Qale-Nar oilfield utilizing advanced geochemical techniques and detailed biomarker parameters. Furthermore, we combine geological information from the Asmari level of the studied oilfield to better interpret the existing geochemical variations. To this end, the bulk (°API gravity) and molecular characteristics (GC and gas chromatography–mass spectrometry (GC–MS) data) of two oil samples from wells 6 and 10 located on the opposite sides of a fault plane were investigated (see Figure 4). The novelty and importance of this study are that for the first time, the detailed molecular parameters of the oil samples are combined with geological information to conduct oil–oil correlation and deduce the continuity of the Asmari reservoir in the Qale-Nar oilfield. The results from this study can be helpful in reservoir management, field reserve estimation, development, and design of enhanced oil recovery methods in the studied oilfield.

2. Geological setting

The Zagros fold-thrust belt (ZFTB) is a part of the Alpine–Himalayan belt resulting from the closure of the Neo-Tethyan ocean at Tertiary time (Late Miocene) (Alavi, 1994; Berberian and King, 1981; Sherkati et al., 2006; Stocklin, 1968). The convergence between the Arabian and Iranian plates started in the Late Cretaceous (Agard et al., 2005), with the main folding phase in the Zagros belt in Dezful embayment (Emami et al., 2010; Homke et al., 2004). The ZFTB is divided into several zones based on their tectonic and sedimentary histories, including the Lurestan zone, the Dezful embayment, the Izeh zone, and the Fars zone (Falcon, 1969; Motiei, 1995; Sherkati and Letouzey, 2004) (see Figure 1).

The Dezful embayment contains most of the significant hydrocarbon fields of Iran and is limited by the mountain front fault from the north, the Qatar–Kazerun fault on the east, and the Bala Rud fault on the west (see Figure 1) (Motiei, 1995; Berberian, 1995; Sepehr and Cosgrove, 2004).

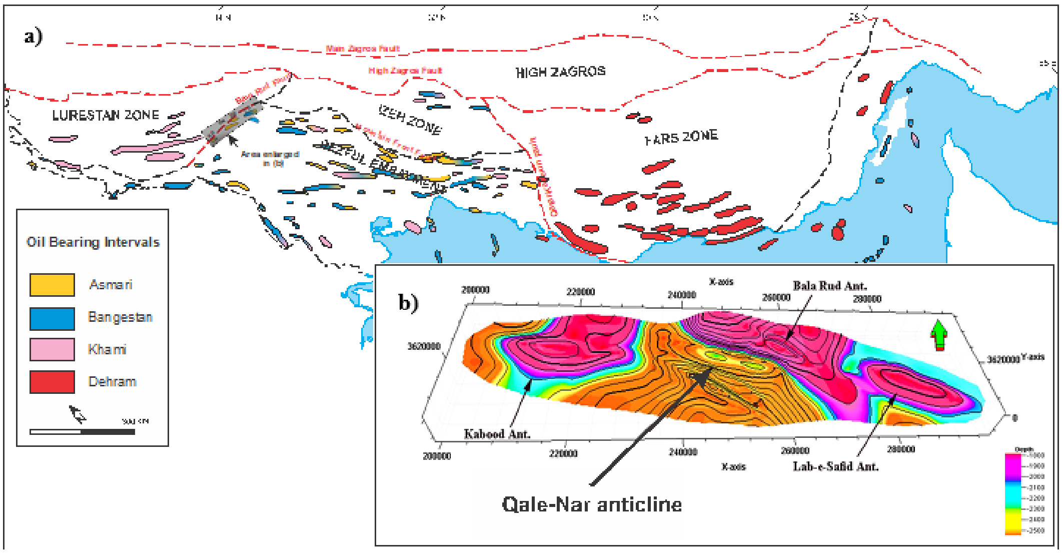

Figure 1

a) The major structural domains of the Zagros fold and Thrust belt with main producing reservoirs and b) the underground contour map of the Asmari reservoir in the studied Qale-Nar oilfield (modified after Bordenave, 2014; Razavi Pash et al., 2020).

Several factors, including a) the pre-existing basement structures (Iaffa et al., 2011), b) the amount of shortening (Sherkati and Letouzey, 2004), and (c) the mechanical stratigraphy of different horizons (Callot et al., 2012; Najafi et al., 2014; Spratt et al., 2005), influence the structural style of the study area. The presence of ductile layers in the stratigraphic column plays a vital role during the deformation by forming intermediate detachment levels (Callot et al., 2012; Najafi et al., 2014; Sherkati et al., 2005; Spratt et al., 2005).

In the Qale-Nar oilfield, the Asmari formation comprises shallow marine limestone, a typical example of a fractured carbonate reservoir (Alizadeh et al., 2019; Memariani and Bani Asad, 2011). The Miocene Gachsaran formation acts as an influential evaporitic cap rock immediately above the Asmari reservoir (Motiei, 1995). These evaporites constitute variable thicknesses in the studied area due to various processes such as folding, faulting, and diapirism (Motiei, 1995). In addition, they act as a significant detachment surface during structural deformation in the area (Sepehr and Cosgrove, 2005; Sherkati and Letouzey, 2004) (Figure 2). Finally, the Pabdeh and Kazhdumi formations are identified as the primary hydrocarbon source rocks in this oilfield (Asemani et al., 2020) (see Figure 2).

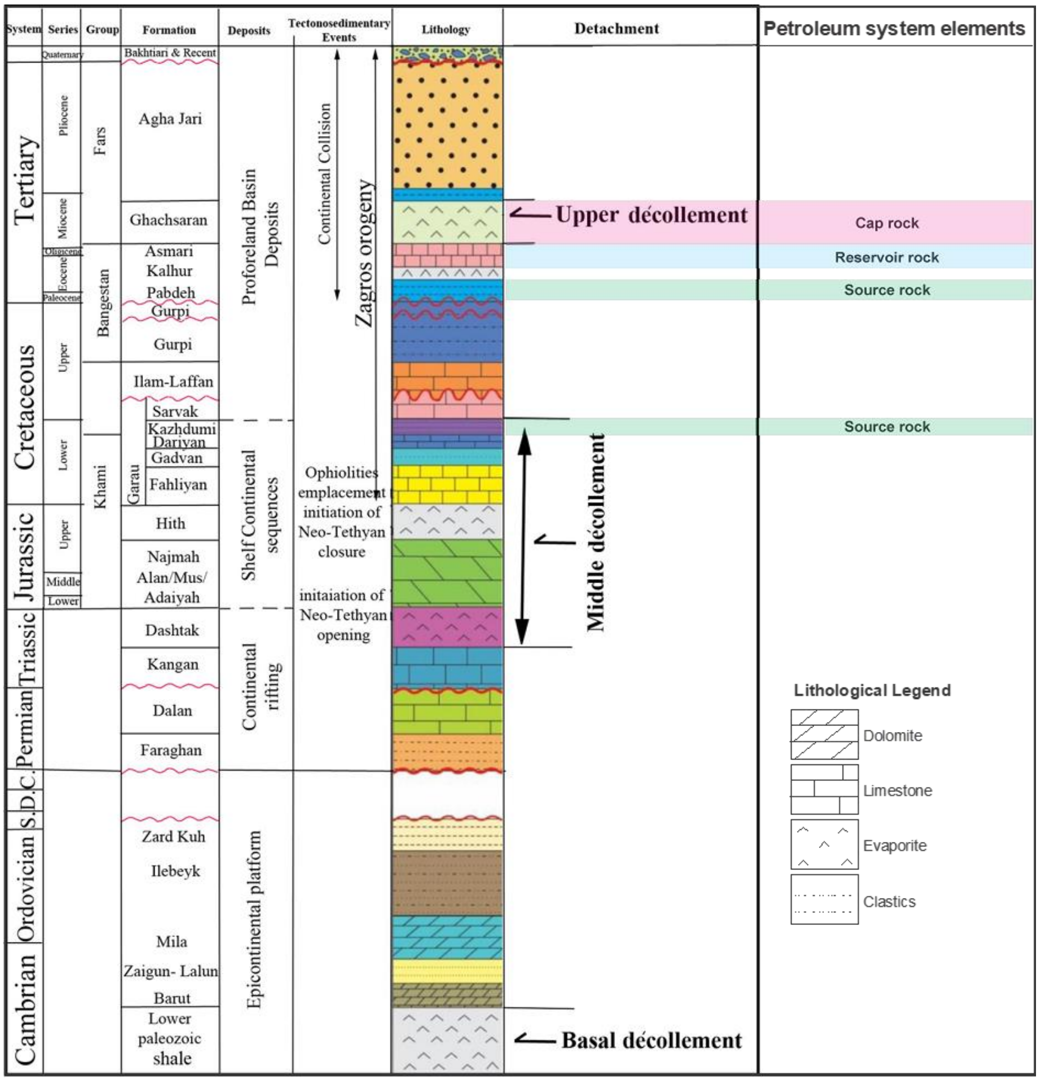

Figure 2

The generalized stratigraphic chart of the northern Dezful embayment based on surface and well data (Fard et al., 2006; Razavi Pash et al., 2020; Sherkati et al., 2006). The primary detachment levels and the elements of the Cretaceous petroleum system are shown.

3. Materials and methods

In order to conduct the present study, we collected two oil samples from the Asmari reservoir at wells 6 and 10 of the Qale-Nar oilfield (Figure 3). Our main objective was to test the continuity of the Asmari reservoir across the fault line present over the eastern culmination of the Qale-Nar oilfield (see Figure 3).

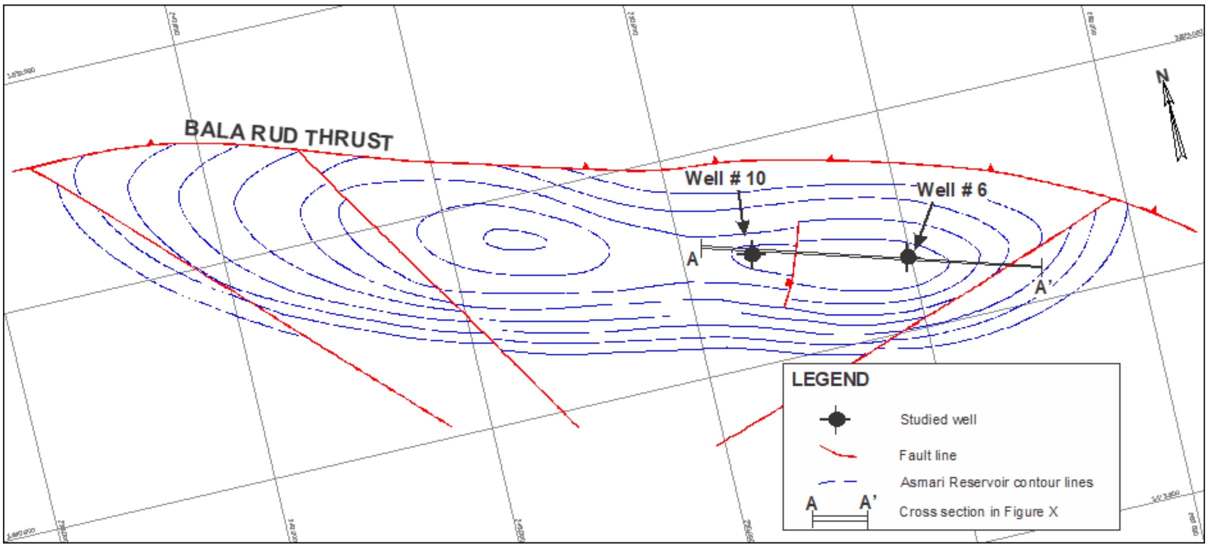

Figure 3

The location of studied wells projected on top of the underground contour map of the Asmari reservoir in the Qale-Nar oilfield.

The Anton Paar DMA 4100 instrument measured the °API gravity of the studied oil samples in atmospheric conditions. For the geochemical analysis of the oil samples, various fractions (saturates, aromatics, resins, and asphaltenes) were separated using the SARA fractionation technique described elsewhere (Alizadeh et al., 2017; Mehmandosti et al., 2015). The saturated and aromatic hydrocarbon fractions were separately analyzed using gas chromatography and gas chromatography–mass spectrometry techniques. The gas chromatography device used in this study contained a flexible capillary glass column with a length of 30 m and an inner diameter of 0.25 mm. A thin layer (about 0.25 µm) of organic polymer (dimethylpolysiloxane) covered the inner surface of the column as the stationary phase. The carrier gas was helium, and a mixture of air and nitrogen was used for the FID detector. The temperature program of the GC oven was set to increase linearly from 50 to 300 °C at a rate of 1.7–4.0 °C/min.

The saturated and aromatic hydrocarbon fractions were run through a GC–MS instrument to obtain biomarker parameters of the studied oils. For this purpose, the analysis was conducted on a similar GC instrument equipped with a mass spectrometer. Various types of biomarkers (i.e., terpanes, hopanes, and steranes) were monitored based on specific mass-to-charge ratios (m/z) (Peters et al., 2004). The hopane and sterane biomarkers were measured using an m/z of 191 and 217 mass chromatograms, respectively. Similarly, different mass-to-charge ratios were monitored to calculate aromatic biomarker ratios (e.g., an m/z of 178 for the phenanthrenes, an m/z of 235 for the monoaromatic steroid, and an m/z of 253 for tri-aromatic steroids) (Peters et al., 2005). Biomarker parameters are used to geochemically evaluate the origin and alteration of the oil samples (Peters et al., 2005). In addition, these parameters can provide valuable information about various characteristics of the source rock responsible for oils (e.g., the type/maturity of the organic matter, depositional environment, geological age, and facies of the possible source rock) (Peters et al., 2005).

4. Results

4.1. Geochemical characterization of oil samples

Petroleum is a complex mixture of semi-stable compounds, moving to thermodynamically stable conditions during thermal maturation. Determining the maturity level of oil samples is critical for identifying reservoir heterogeneity and the presence of different compartments (Cubitt, J.M., England, W.A., Larter, 2004; Smalley and Muggeridge, 2010).

Comparing the bulk geochemical parameters obtained for the studied oils (Table 1) indicates that the oil sample from well 6 of the Qale-Nar oilfield has a remarkably higher maturity than the sample from well 10, which is supported by the relatively higher °API gravity, the higher content of saturated hydrocarbons, and the lower concentration of the polar fraction in well 6 compared to well 10 of the studied oil field (see Table 1 and Figure 4).

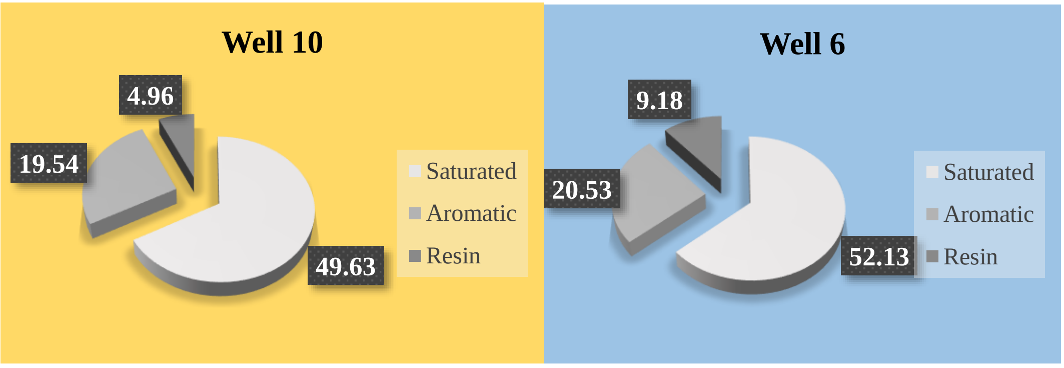

Figure 4
The pie diagrams of various fractions separated from the studied crude oils at wells 6 and 10 of the Qale-Nar oilfield, indicating relatively higher maturity for samples from well 6.

Additional support for the higher maturity of oil samples from well 6 of the Qale-Nar oilfield comes from the ratios of isoprenoids to normal alkanes (see Table 1). It is suggested that the ratios of pristane /n-C_{17} and phytane/n-C_{18} progressively decrease with increasing thermal maturation (Hunt, 1995; Peters et al., 2005; Tissot and Welte, 1984). Comparing these ratios for our studied oils indicates that the oil sample from well 6 has a higher maturity than the sample from well 10, as shown in Figure 5.

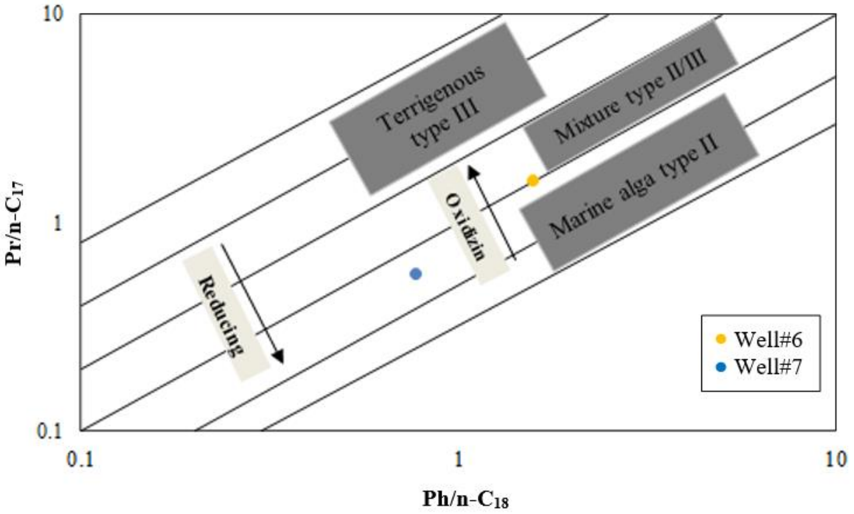

Figure 5

The pristane/nC$_{17}$ versus phytane/nC$_{18}$ for the studied oil samples (Hunt, 1995).

Biomarker parameters based on the ratios and distributions of specific isomers provide essential tools for assessing the maturity of oil samples (Peters et al., 2005). Within the hopane series, the C$_{32}$ 22S/(22S+22R) ratio increases from 0 to 0.6 with increasing the maturity (Seifert and Moldowan, 1980). Another useful maturity parameters from the regular sterane series are the C$_{29}$ 20S/(20S+20R) ratio which ranges from 0 to 0.5 with increasing the maturity (Waples and Machihara, 1991). A cross-plot of these two crucial maturity ratios indicates that the thermal maturity of the oil samples from the Qale-Nar oilfield corresponds to the early-to-peak stages of oil generation (Figure 6a and Table 1), which is further supported by a cross-plot of the C$_{29}$ 20S/(20S+20R) versus C$_{29}$ ββ/(αα+ββ) from regular steranes (Figure 6b).

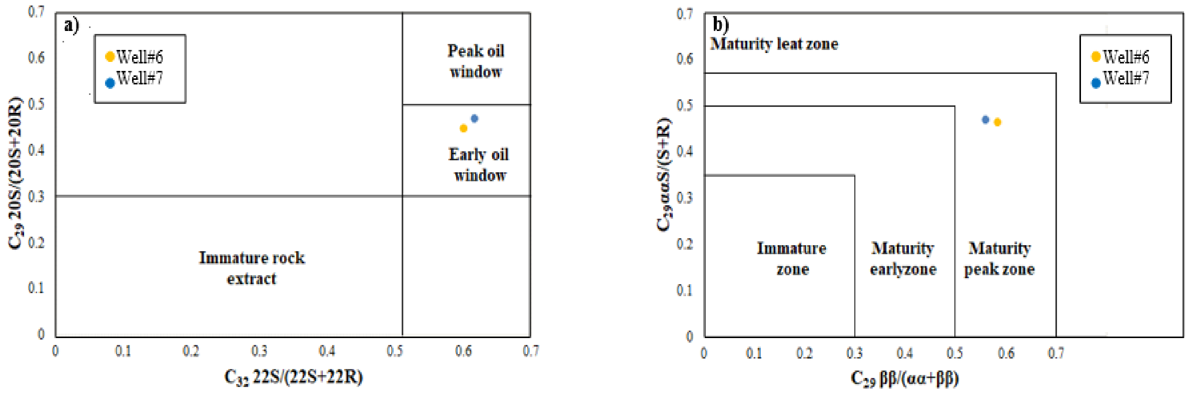

Figure 6

The cross-plots of a) C$_{32}$ 22S/(22S+22R) versus C$_{29}$ 20S/(20S+20R) ratios and b) C$_{29}$ 20S/(20S+20R) versus C$_{29}$ ββ/(αα+ββ) ratio for determining the thermal maturity of the studied oils (modified after Peters et al., 2005).

The ratio of moretane/hopane is suggested to decrease with increasing the maturity, with values around 0.05 in mature oils (Mackenzie et al., 1980; Seifert and Moldowan, 1980). The moretane/hopane values for our studied oils vary from 0.07 to 0.08, implying that these oils belong to a source rock with a relatively high level of maturation (Peters et al., 2005) (see Table 1).

4.2. Geochemical characteristics of parent source rock for studied oils

Biomarker parameters of oils can determine the geochemical characteristics of their source rock (Peters et al., 2005). Therefore, it is possible to identify the most likely source rock for oils even in cases where access to representative source rock samples is impossible (Walters, 2006). In the present study, we have used biomarker parameters of oils to infer the geochemical properties of the possible source rock that generated the oils presently accumulated in the Asmari reservoir of the Qale-Nar oilfield.

a. Organic matter type and depositional environment

Several biomarker parameters can be used to define the origin of organic matter in the source rock and its paleo-depositional conditions (Alizadeh et al., 2012, 2015, 2017). The homologous distribution of regular steranes is the most commonly used biomarker for defining the organic matter type and depositional environments of hydrocarbon source rocks (Moldowan et al., 1985). The C_{29} steranes are suggested to generally originate from terrestrial plants, while the C_{27} and C_{28} homologs originate from marine phytoplankton and lake algae, respectively (Ekweozor et al., 1979; Peters et al., 2005). Our studied oils have a higher concentration of the C_{27} steranes than C_{29} homologous, indicating that the organic matter in the related source rock is of predominantly algal origin (Table 1). Additionally, plots of the pristane-to-phytane ratio (Pr/Ph) versus the C_{29}/C_{27} regular steranes are consistent with algal organic matter deposited under anoxic conditions (Figure 7).

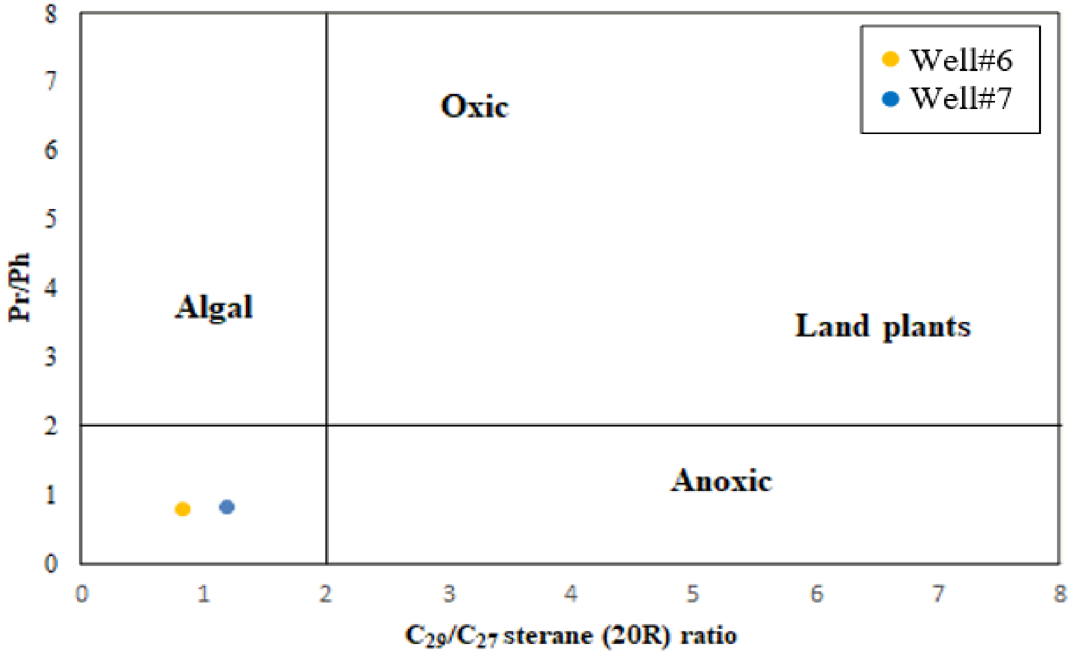

Figure 7
The cross-plot of Pr/Ph versus the C_{29}/C_{27} regular sterane ratio for defining the type of organic matter in the source rocks for our studied oils (after Peters et al., 2005).

The Pr/Ph is commonly used to differentiate oxic from anoxic conditions (Peters et al., 2005; Tissot and Welte, 1984). This ratio is less than unity for the oil samples studied from the Qale-Nar oilfield (Table 1), implying that the source rock of these oils was deposited in a reducing environment (Powell and Mokirdy, 1973), which is further supported by the relatively high $C_{35}S/C_{34}S$ homohopane for our studied oils (see Table 1). High values of this ratio are reported from anoxic depositional conditions (Peters et al., 2005).

Additional support for this conclusion is provided by plotting the canonical variable (CV) versus the Pr/Ph of the studied oils (Sofer, 1984). The studied oil samples from the Qale-Nar oilfield are plotted in the reducing marine area on this graph (Figure 8). The marine depositional setting for the source rock of our studied oils is also evident in the ternary plots of regular sterane homologs, as shown in Figure 9.

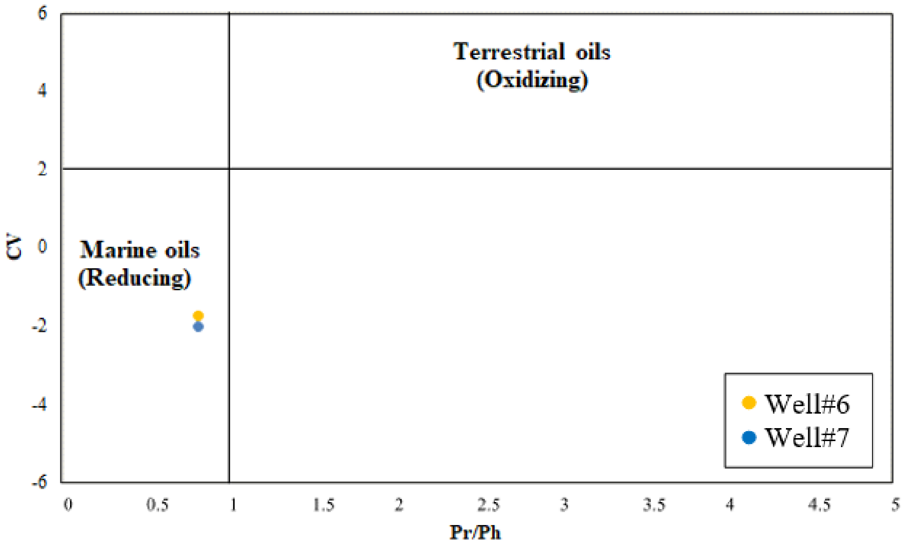

Figure 8

The cross-plot of the CV versus the Pr/Ph for the studied oil samples (after Sofer, 1984).

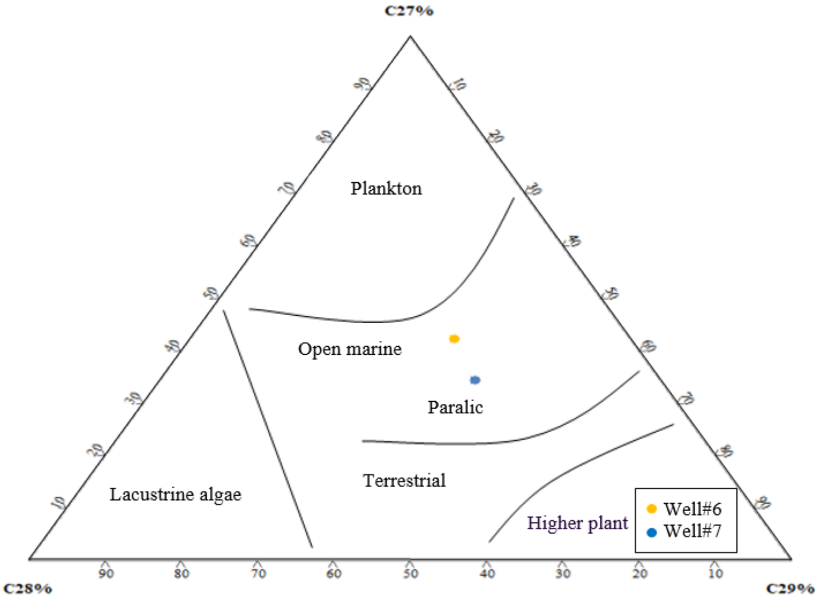

Figure 9

The ternary diagram of the C_{27}–C_{28}–C_{29} regular steranes showing the depositional setting of the source rock for the studied oil (after Moldowan et al., 1985).

b. Lithology of the source rock for studied oils

The C_{29}/C_{30} and C_{35}/C_{34} hopane ratios can be used in tandem to define the lithology of oils (Figure 7a). The C_{35}/C_{34} hopane ratio in this plot uses the 22S epimer rather than 22S and 22R to avoid interference. Many crude oils from coal/resin source rocks show lower C_{35}/C_{34} hopanes (< 0.6) than marine shale, carbonate, or marine source rocks, consistent with more oxic depositional conditions. Most oils from marine carbonate source rocks show high C_{35}/C_{34} hopane (> 0.8) combined with high C_{29}/C_{30} hopane (> 0.6). A cross-plot of C_{29}/C_{30} hopane versus $C_{35}S/C_{34}S$ homohopane ratios for our studied oils indicates that the lithology of their parent source was marl, as depicted in Figure 10a (Peters et al., 2005). Similar conclusions are drawn based on the diagrams of the Pr/(Pr+Ph) versus C_{27} Dia/(Dia +Reg) ratios, as presented in Table 1 and Figure 10b.

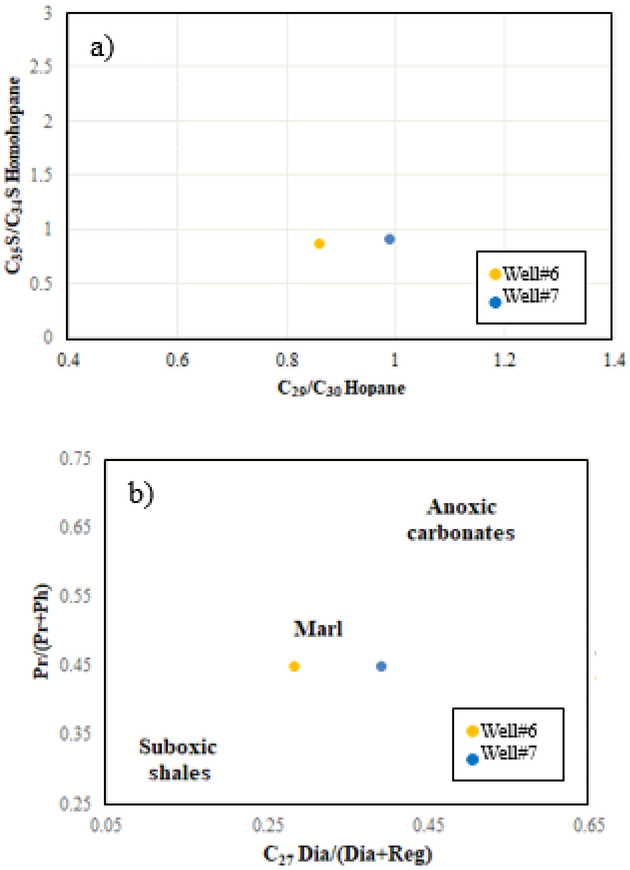

Figure 10

The cross-plot of a) C_{29}/C_{30} hopane versus $C_{35}S/C_{34}S$ homohopane and b) Pr/(Pr+Ph) versus C_{27} Dia/(Dia +Reg), indicating that the lithology of the source rock for our studied oils was composed of marl (after Peters et al., 2005).

Table 1

The summary of the biomarker data from the gas chromatography–mass spectrometry of crude oil samples.

		Well 6	**Well 10**
Bulk parameters	Depth (m)	2827.5–3222.5	2822–3263.5
	°API gravity	29.85	29.13
	Saturates (%)	52.13	49.63
	Aromatics (%)	20.53	19.54
	Resins (%)	9.18	4.96
	Asphaltenes (%)	18.16	25.87

Molecular Parameters	Pr/Ph	0.81	0.81
	Pr/*n*-C_{17}	0.57	1.61
	Ph/*n*-C_{18}	0.77	1.58
	Pr/(Pr+Ph)	0.45	0.45
	CPI§	1.04	0.94
	TAR£	0.51	0.74
	C_{29} sterane (20R) ratio	7051.9	7956.356
	C_{27} sterane (20R) ratio	5898.867	7872.217
	C_{29}/C_{27} sterane (20R)	1.19	0.81
	C_{29}/C_{30} Hopane	0.98	0.86
	$C_{35}S/C_{34}S$ Hopane	0.91	0.87
	DBT/Phen†	4.17	0.708
	C_{27} Dia/(Dia+Reg) Sterane	0.39	0.28
	Ts/(Ts+Tm)	0.42	0.43
	C_{32} Hopane(22S/22S+22R)	0.61	0.59
	Mortane/hopane	0.07	0.08
	C_{29} Sterane 20S/20S+20R	0.46	0.44
	C_{29} Sterane ββ/(ββ+αα)	0.55	0.57

4.3. Reservoir continuity between wells 6 and 10 of the Qale-Nar oilfield

Oil–oil correlation techniques are the best method to investigate reservoir continuity (Mehdipour V, Sadegh Tabaqi Z, 2020). This technique is used to define the geochemical similarity between a set of oil samples and to prove the existence or absence of a genetic link between them (Beaumont and Nelson, 1999; Dembicki, 2016). Based on the available data in this study, the oil–oil correlation was performed utilizing gas chromatography data (Figure 11). The structure of the star diagram indicates that there is no correlation between the two oil samples, which is further supported by the visual examination of the related gas chromatograms of both oil samples shown in Figures 12.

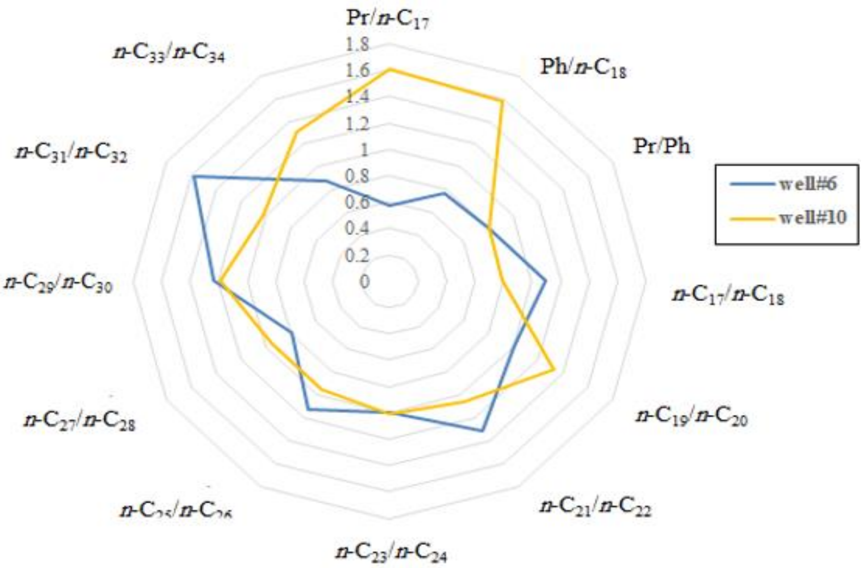

Figure 11

The star diagram of various parameters obtained from the gas chromatography analysis of the studied oils, showing the lack of geochemical similarity between them.

A careful examination of the gas chromatograms indicates that the oil sample from well 6 has a higher concentration of short-chain alkanes than the sample from well 10 (see Figure 12). We believe that this phenomenon results from lateral compartmentalization in the Asmari reservoir. In other words, there is a lack of continuity between wells 6 and 10 of the Qale-Nar oilfield.

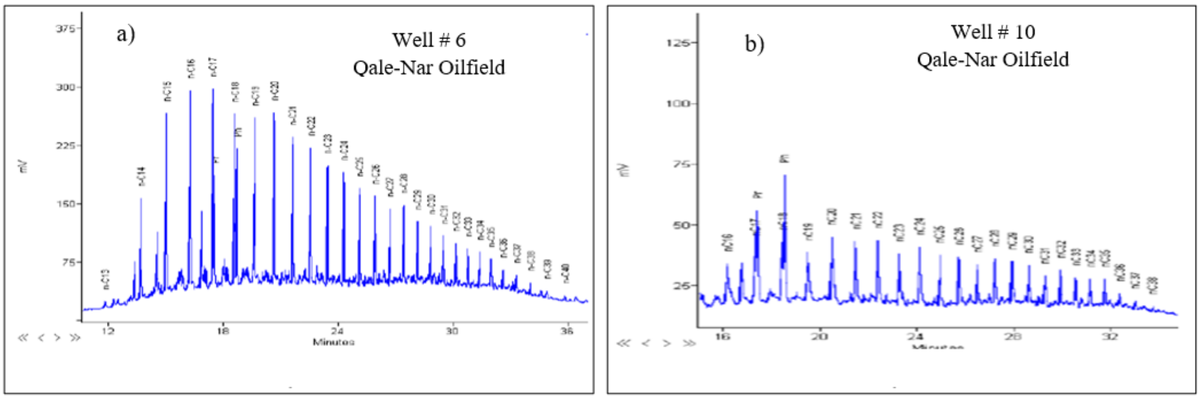

Figure 12

The representative gas chromatogram of the oil samples from a) well 6 and b) well 10 of the Qale-Nar oilfield.

Based on the preceding discussions, we provide a scenario for reservoir charging and compartmentalization of the Qale-Nar oilfield, as shown in Figure 13. In this scenario, the original hydrocarbon charges with lower maturity fill the eastern culmination of the Qale-Nar oilfield (see Figure 13a). However, the activity of a fault plane between wells 6 and 10 created a barrier between the two wells (see Figure 13b). Therefore, the late hydrocarbon charges with higher maturity could only charge the compartment belonging to well 6. This model can explain the present differences in geochemical characteristics and thermal maturity levels of the two wells.

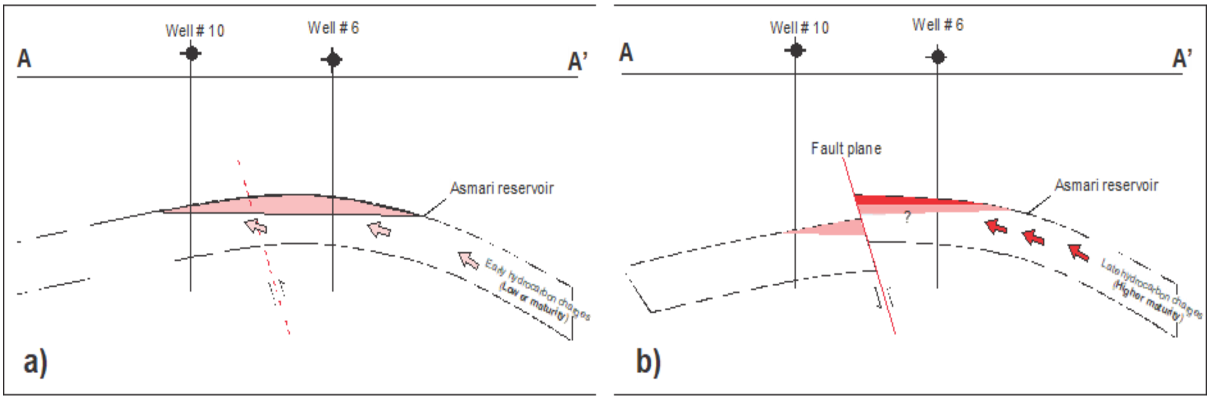

Figure 13

Hypothetical cross section along line A–A' (see Figure 13) illustrating a scenario for filling and compartmentalizing the Asmari reservoir in the Qale-Nar oilfield.

The lack of reservoir continuity between the studied wells in the Qale-Nar oilfield can have important implications for future development and enhanced oil recovery projects. However, we believe that additional biomarker analyses of the different wells of the studied oilfield are required. In addition, other important geological and reservoir engineering information (e.g., the oil–water contacts and downhole pressure readings) support the geochemical conclusions presented in this study.

5. Conclusions

In this study, the continuity of the Asmari reservoir between wells 6 and 10 of the Qale-Nar oilfield was investigated using a combination of geological and geochemical information. °API gravity data were combined with the results of the detailed molecular approaches such as gas chromatography and gas chromatography–mass spectrometry. According to our results, both oils were generated by a marine source rock with marl lithology deposited under reducing conditions. The organic matter in the source rock for the studied oils was a predominantly algal type with a relatively high level of thermal maturity, i.e., corresponding to the early-to-peak stages of oil generation. The gas chromatography results showed a significant difference between the two oil samples (e.g., the star diagrams). In parallel with the geological structure of the studied oilfield, these observations strongly indicate that there are some flow barriers between wells 6 and 10, causing a lateral discontinuity in the Asmari reservoir. According to our findings, a scenario for reservoir charging and compartmentalization of the Qale-Nar oilfield was presented, in which the fault plane (located between wells 6 and 10) causes reservoir compartmentalization. This dynamic model of hydrocarbon charging and fault activation can better explain the present differences in the geochemical characteristics of the studied oils. The lack of reservoir continuity between the studied wells in the Qale-Nar oilfield can have important implications for future field-development projects. Additional biomarker and geological information from other wells in the Qale-Nar oilfield, along with other reservoir engineering data such as reservoir pressure and oil–water contacts, can further support the geochemical conclusions presented in this study.

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Nomenclature

GC	Gas Chromatography
GC-MS	Gas chromatography-mass spectrometry
EOR	Enhanced-Oil-Recovery
ZFTB	Zagros Fold-Thrust Belt
m/z	Mass-to-charge ratio
Ph	Phytane
Pr	Pristane
DBT/Phen	Dibenzothiophene/Phenanthrene
CPI	Carbon Preference Index
TAR	Terrigenous/Aquatic Ratio
Dia	Diasteranes
Reg	Regular
Tm	Trisnorhopane
Ts	Trisnorneohopane
CV	Canonical Variable

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