Hydrocarbon Vertical Continuity Evaluation in the Cretaceous Reservoirs of Azadegan Oilfield, Southwest of Iran: Implications for Reservoir Geochemistry

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Abstract: A collection of data obtained from analytical methods in geochemistry along with the reservoir engineering and geologic data were used to investigate the reservoir continuity in the Cretaceous Fahliyan, Gadavan, Kazhdumi and Sarvak reservoirs of the super-giant Azadegan oilfield, SW Iran. The geochemical data indicate that the oil samples, with medium to high level of thermal maturity, have been generated from the anoxic marine marl/carbonate source rock(s). The Sargelu (Jurassic) and Garau (Cretaceous) formations are introduced as the main source rocks for the studied oils. The dendrogram obtained from the cluster analysis of high-resolution gas chromatography data introduces two main oil groups including Fahliyan reservoir, and Kazhdumi along with Sarvak/Gadvan reservoirs. This is confirmed by C7 Halpern star diagram, indicating that, the light oil fraction from Fahliyan reservoir is distinct from the others. Also, different pressure gradient of the Fahliyan Formation (over-pressured) relative to other reservoirs (normally-pressured) show the presence of compartments. The relation between toluene/n-heptane and n-heptane/methylcyclohexane represents the compartmentalization due to maturation/evaporative fractionation for Fahliyan and water washing for other studied reservoirs. Also, the impermeable upper part of the Fahliyan Formation and thin interbedded shaly layers in the Kazhdumi, Sarvak and Gadvan formations have controlled reservoir compartmentalization.

Key words: reservoir continuity, geochemistry, pressure gradient, oil-oil correlation, Azadegan oilfield, Abadan Plain

1 Introduction

In order to best evaluate the oil and gas continuity and detection of the compartments in the reservoirs, geochemistry of petroleum and reservoirs have been integrated successfully (Kaufman et al., 1990; Paez et al., 2010; Smalley and England, 1994). Reservoir compartmentalization discusses the fluid flow barriers between two reservoirs/layers, such as low-permeability rocks or tar mats (Smalley and England, 1992). Recognizing the structure of the reservoir and its pressure regime as well as the prediction of fluids behavior with different compositions in separated compartments are of great importance. To reduce the risk of exploration and development activities of the field, increasing the knowledge about geological setting of the area and reservoir characteristics is vital (Smalley and Hale, 1996).

A wide range of analytical methods including reservoir continuity analysis (RCA), geochemical oil-oil correlation (Hwang and Baskin, 1994; Kaufman et al., 1990; Lindberg et al., 1990; Slentz, 1981), C7 light hydrocarbon compounds analysis (Ahanjan et al., 2016; Kaufman et al., 1990; Márquez et al., 2016), high-resolution gas chromatography (HRGC) (Kaufman et al., 1990) and pressure-volume-temperature (PVT) analysis of reservoir (Paez et al., 2010) combined with geological and geophysical connectivity data interpretation (Hovadic and Larue, 2010) are frequently used to identify the uncertainty of the reservoir continuity.

The Azadegan field, located in SW Iran, has been introduced as the largest undeveloped oilfield of the world (Fig. 1) (Motiei, 2011; Liu et al., 2013; Du et al., 2015). The Cretaceous Sarvak, Kazhdumi, Gadavan and Fahliyan formations (Fig. 2) are considered to be the main reservoirs in the field (Bordenave and Hegre, 2010; Alizadeh et al., 2012, 2016; Du et al., 2016). Geological and geophysical properties of these reservoirs have been studied by many researchers (Abdollahie Fard et al., 2006; Bordenave and Hegre, 2010; Abed et al., 2011; Alizadeh et al., 2012, 2016; Du et al., 2016; Kobraei et al., 2017), but their continuity as an influencing factor for the field development has not been investigated yet. Therefore, it is important to elucidate the oil variation and distribution across the reservoirs and also their compartmentalization.
caused by either faults or facies changes. Therefore, the main objective of this research is to assess the reservoirs' continuity utilizing combination of petroleum/reservoir geochemistry with geologic and engineering data. The oil genetic families and the impact of physical processes (e.g. alteration and biodegradation) on the reservoirs have been investigated geochemically. Also, the geologic and engineering data were used to delineate the reservoirs filling scenario, continuity and compartmentalization. The present study illustrates the integrated application of geochemistry, geology and engineering in reservoir compartmentalization, which in turn controls the oil accumulation and helps to prepare a road map for the field development.

2 Regional Geology

The Zagros fold-and-thrust belt (ZFTB) is situated along the NE margin of the Arabian Plate and is currently active compressional belt. The Abadan Plain, as a part of Mesopotamian Foredeep Basin, is located in the southwest of ZFTB and north of Persian Gulf (Fig. 1) (Murris, 1980; Beydoun, 1991; Sharland, 2001; Alavi, 2004). The Mesopotamian Basin, comprising the pre-Neogene N-S trending folds which are introduced as Arabian/Pan African trend structures, was not affected by the main phase of the Zagros tectonic movement. Therefore, structural horsts and tilted fault blocks which are described as reactivated basement structures have formed the giant structures and controlled the compaction of sediments in the Arabian plate (Stocklin, 1968; Berberian and King, 1981). The Azadegan basement paleo-high, as one of the main horst blocks in Mesopotamian basin, includes the Azadegan and some of the other giant oilfields (Abdollahie Fard et al., 2006; Alizadeh et al., 2012, 2016; Du et al., 2016). The collision of Arabian plate with Eurasia continent block in the late Cretaceous reactivated fault systems, salt domes and N-S structures in Iran, Iraq and Kuwait. The result of this event has influenced sedimentary sequences of Mesopotamian basin (Abdollahie Fard et al., 2006; Abeed et al., 2011; Alizadeh et al., 2012, 2016; Beydoun, 1991; Du et al., 2016; Murris, 1980; Sharland, 2001). From the late Cretaceous to middle Miocene, marine carbonates and shales along with some evaporates were affected by the onset of Zagros tectonic movement and Infra-Cambrian basement tectonics (Abdollahie Fard et al., 2006; Bordenave and Hegre, 2010; Zeinalzadeh et al., 2015; Sherkati et al., 2004).
Mesopotamian basin and deposition of the coarse-grained clastic sediments which are sourced from the Zagros Mountains (Murris, 1980; Abdollahie Fard et al., 2006; Du et al., 2016). The significant tectonic movements in Cretaceous conduced to precipitate the platform-type facies of the main carbonate reservoirs (e.g. Fahliyan and Sarvak) in the Azadegan oilfield. Also, the discontinuous input of clastic sediments prograded from the Zubair and Burgan deltas (located in the west and southwest of the area) led to the deposition of the Gadvan and Kazhdumi sandstone reservoirs.

The carbonate Fahliyan (Neocomian) and Sarvak (Cenomanian-Turonian) formations considered to be the main reservoirs in the field, containing the light (33 API degree) and heavy (20 API degree) oils, respectively. On the other hand, the sandstone layer of Gadvan (Barremian-Hauterivian) and Kazhdumi (Albian) formations are the secondary producible reservoirs in the field with the light oil (32 and 30 API degree). The Sarvak Formation consists of shallow ramp/low-gradient shelf facies. The sandy members in the Kazhdumi and Gadvan formations illustrate bird-foot delta to prodelta system in a marginal ramp setting (Du et al., 2016). These successions are represented by Azadegan and Kushk in the Abadan Plain, respectively. The Fahliyan Formation is mainly composed of shoal facies in the south, and shallow to open marine argillaceous limestones in the north of the field (Shakeri and Parham, 2013). This formation has been divided into lower and upper parts. The upper part is composed of an alternation of shales and limestones, while the lower part mostly consists of shallow marine carbonates interbedded with shales and acts as a reservoir (Soleimani et al., 2017). It also laterally changes to basinal mudstones of the Garau Formation (James and Wynd, 1965).

Geochemical studies have introduced the Sargelu (Middle-Upper Jurassic) and Garau (Lower Cretaceous) formations as the main source rocks in Abadan Plain (Abdollahie Fard et al., 2006; Alizadeh et al., 2012, 2016; Bordenave and Hegre, 2010; Du et al., 2016; Kobraei et al., 2017; Zeinalzadeh et al., 2015). Correspondingly, Middle-Upper Jurassic bituminous limestones and shales are reported as the main source rocks in the Mesopotamian basin of Iraq (Pitman et al., 2004; Abeed et al., 2011). Despite the presence of shale layers in the Gadvan Formation, a fair hydrocarbon generation potential is revealed by the low total organic carbon (TOC) contents (Kobraei et al., 2017). The efficient seal rocks for the Cretaceous reservoirs are generally the interbedded/overlaid shaly and argillaceous sediments.

3 Sampling and Methodology

The drill stem test (DST) oil samples from each reservoirs of the exploration well B in the Azadegan oilfield, including lower part of Fahliyan, lower sandstone part of Gadvan, sandstone layer in Kazhdumi and thick limestone of Sarvak (Fig. 2) were collected. Asphaltene fractions from these samples were precipitated by adding an excess amount of n-hexane. The maltenes (deasphalted oils) were separated into three fractions including aliphatic/aromatic hydrocarbons and polar compounds using liquid chromatography on a micro column, filled with alumina:silica gel (2:1, v:v). Prior to chromatography, the column was stored in an oven at 200°C
C for 12 hr. The aliphatic fractions were eluted with 5 mL of n-pentane. The column then poured by a mixture of n-pentane and dichloromethane (40:60, v:v 5 mL) for separation of the aromatic hydrocarbons. Finally, the polar compounds were eluted with 5 mL of methanol.

In order to evaluate the oil composition and identify different compartments within the reservoirs, a collection of data obtained from the standard analytical methods such as bulk composition analysis, gas chromatography (GC), HRGC, gas chromatography-mass spectrometry (GC-MS) and bulk isotope analysis along with pressure data of the reservoirs were used and integrated with the bulk properties of the oils such as API gravity, sulfur content and Ni/V ratio (Table 1).

**Table 1 Nickel/Vanadium, sulfur content, API gravity and pressure data of the studied oil samples in the Well B of Azadegan oilfield**

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Ni (ppm)</th>
<th>V (ppm)</th>
<th>Ni/V</th>
<th>Sulfur (%)</th>
<th>API</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Sv</td>
<td>14.00</td>
<td>74.00</td>
<td>0.19</td>
<td>5.60</td>
<td>20</td>
<td>4500</td>
</tr>
<tr>
<td>B-Kz</td>
<td>39.00</td>
<td>85.00</td>
<td>0.46</td>
<td>2.50</td>
<td>30</td>
<td>5800</td>
</tr>
<tr>
<td>B-Gd</td>
<td>21.00</td>
<td>30.00</td>
<td>0.70</td>
<td>2.10</td>
<td>32</td>
<td>6150</td>
</tr>
<tr>
<td>B-Fh</td>
<td>14.00</td>
<td>10.00</td>
<td>1.40</td>
<td>1.60</td>
<td>33</td>
<td>9150</td>
</tr>
</tbody>
</table>

Sv = Sarvak; Gd = Gadvan; Kz = Kazhdumi; Fh = Fahliyan; Ni = Nickel; V = Vanadium.

Analyses of low molecular weight hydrocarbons in the range of C3 to C6 (Fig. 3) were performed with a Fissions Instruments GC 8000 series, too. The light hydrocarbons derived from gas-chromatography of the whole-oils were used to evaluate the content, distribution and behavior of the oil samples, which are helpful for appraisal of vertical continuity in the reservoirs (Beeunas et al., 1999; Kaufman et al., 1990; Smalley and England, 1994; Smalley and Hale, 1996).

Sulfur contents were measured by Leco S200 sulfur analyzer instrument. ICP-MS system was used for computing the Ni and V elements. On the other hand, API gravity of the oil samples was determined by applying ASTM D-4052 standard method.

Analysis of the bulk stable carbon isotope was performed on the whole oils using a Flash HT 2000 Elemental Analyzer (Thermo Scientific) equipped with combustion and pyrolysis furnaces and coupled with a Delta V Advantage IRMS (Thermo Scientific) ion source, which was capable of performing GC analysis.

The chromatograms were normalized by calculating the peak height ratios of GC. The small peaks located between the normal alkanes in the range of C9 to C13 (Fig. 4), were selected and used for classification of the oils into the distinct groups based on cluster analysis (Kaufman et al., 1990).

### 4 Results and Discussion

#### 4.1 Bulk composition of oils

The n-alkane profiles of oil samples from each reservoir are dominated by low molecular weight (< nC22) components (Fig. 5), suggesting a significant contribution
Fig. 4. Illustrative high-resolution gas chromatographic signatures (Kaufman et al., 1990) for the selected oil samples from the studied reservoirs, showing the 21 peak ratios selected for compartmentalization studies and used for classification of the oils into the distinct groups based on cluster analysis (Sv = Sarvak; Kz = Kazhdumi; Gd = Gadvan; Fh = Fahliyan).

Fig. 5. The GC pattern of n-alkanes for the studied oil samples.
of organic matter from planktonic materials to higher plants (Hunt, 1996). The samples predominate C\textsubscript{12} to C\textsubscript{36} n-alkanes, with a maximum frequency at nC\textsubscript{13} or nC\textsubscript{14}. The values of pristane/phytane (< 1), Pr/nC\textsubscript{17} (0.18–0.42), Ph/nC\textsubscript{18} (0.37–0.42) and carbon preference index (CPI, around 1) (Table 2) indicate that the oils have been generated from anoxic marine marls/carbonates, containing a mixture of type II and II-S kerogen with terrestrial organic matter input during their deposition (Connan et al., 1986; Connan and Cassou, 1980; Peters et al., 2005; Tissot and Welte, 1984; Volkman and Maxwell, 1986). The distribution and relative abundance of the gasoline range hydrocarbons are easily changed by physical processes including biodegradation and water washing (Hunt, 1996; Tissot and Welte, 1984). All the samples, with the exception of Fahliyan oil, have slightly altered in various degrees which are demonstrated by GC patterns of n-alkanes. Furthermore, low values of Pr/nC\textsubscript{17} and Ph/nC\textsubscript{18} (< 1) (Table 2) is an indication of high thermal maturity. The Fahliyan, Gadvan and Kazhdumi oil samples are recognized by moderate to high level of thermal maturity, while the Sarvak oil has less thermal maturity. There is a reverse relationship between sulfur content and thermal maturity. The sulfur contents ranges from 1.6% in Faliyan oil to 5.6% in Sarvak oil, supported by their level of thermal maturity (Fig. 6b). Also, based on the result of Tissot and Welte’s (1984) ternary diagram, the all samples are classified as paraffinic oils (Fig. 6c).

### Table 2 Bulk composition and gas chromatography data of the studied oil samples

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Pr/Ph</th>
<th>Pr/nC\textsubscript{17}</th>
<th>Ph/nC\textsubscript{18}</th>
<th>CPI</th>
<th>%Saturate</th>
<th>%Aromatic</th>
<th>%Polar</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Sv</td>
<td>0.63</td>
<td>0.18</td>
<td>0.37</td>
<td>1.00</td>
<td>74.00</td>
<td>30.00</td>
<td>23.00</td>
</tr>
<tr>
<td>B-Kz</td>
<td>0.54</td>
<td>0.19</td>
<td>0.39</td>
<td>0.95</td>
<td>40.00</td>
<td>21.00</td>
<td>39.00</td>
</tr>
<tr>
<td>B-Gd</td>
<td>0.60</td>
<td>0.22</td>
<td>0.41</td>
<td>0.99</td>
<td>49.00</td>
<td>31.00</td>
<td>20.00</td>
</tr>
<tr>
<td>B-Fh</td>
<td>0.67</td>
<td>0.42</td>
<td>0.42</td>
<td>1.00</td>
<td>52.00</td>
<td>32.00</td>
<td>16.00</td>
</tr>
</tbody>
</table>

Pr = pristane; Ph = phytane; Pr/nC\textsubscript{17} = pristane/n-heptadecane; Ph/nC\textsubscript{18} = phytane/n-octadecane; CPI = carbon preference index (2 [C\textsubscript{23} + C\textsubscript{25} + C\textsubscript{27} + C\textsubscript{29}]/[C\textsubscript{22} + 2 (nC\textsubscript{24} + C\textsubscript{26} + C\textsubscript{28}) + C\textsubscript{30}]); Polar = resin + asphaltene.

Fig. 6. (a) The cross-plot of pristane/nC\textsubscript{17} versus phytane/nC\textsubscript{18} indicate that the oils have generated from anoxic marine marls/carbonates with type II and II-S kerogen and moderate to high level of thermal maturity, (b) plot of the sulfur content versus Ts/Tm showing the enhancement of the sulfur content from Fahliyan to Sarvak reservoir oils supported by their level of thermal maturity and (c) the Tissot and Welte’s (1984) ternary diagram, classifying the all samples as paraffinic oils.
Different biomarker indicators were used to identify depositional environment of the source rock(s) (Fig. 8), including C_{22}/C_{35} tricyclic terpane, C_{24}/C_{33} tricyclic terpane, C_{35}/C_{34} hopane, gammacerane/C_{31} homohopane, C_{27} diasterene/(diasterane + regular sterane) (Peters et al., 2005). The ratios indicate marine marl-carbonate source rock(s) deposited under anoxic environments with some input of the higher plants (Clark and Philp, 1989; Connan and Cassou, 1980; Peters and Moldowan, 1993; Peters et al., 2005; ten Haven et al., 1988; Zumberge, 1984). The low salinity condition as well as restricted stratification in depositional environment of the source rock(s) are represented by the low gammacene parameter for the studied oils (Tulipani et al., 2015).

The concentrations of C_{27}, C_{28} and C_{29} regular steranes were used to characterize depositional setting of the corresponding source rock(s) (Fig. 8c). All the oil samples show identical sterane profiles with higher relative abundance of C_{27} and C_{28} steranes, dominated in the marine organisms and the terrestrial plants, respectively (Volkman and Maxwell, 1986).

Plotting dibenzoanthiophene/phenanthrene versus pristane/phytane indicates less carbonate content in depositional settings of the source rock(s) related to Fahluyan and Gadvan oil samples (Fig. 8d). The crude oils originated from the carbonate source rocks are generally richer in sulfur compounds. Furthermore, dibenzoanthiophene parameter is an indicator of the sulfur content. However, the thermal maturity must be considered while evaluating this parameter (Peters et al., 2005). Based on the plot of dibenzoanthiophene/phenanthrene versus pristane/phytane, the Sarvak oil sample shows stronger marine carbonate signature and consequently the higher relative abundance of the sulfur.

Thermal maturity of the oil samples was evaluated using biomarker isomerization ratios (Fig. 9). The values of Ts/(Ts+Tm) (< 0.3) and C_{31}-hopane 22S/(22S+22R) (0.54–0.68) (Table 3) show medium to high level of thermal maturity. However, the Fahluyan and Gadvan oil samples have higher thermal maturity relative to Kazdumi and Sarvak oils (Seifert and Moldowan, 1986; Peters et al., 2005). This is also demonstrated by the ratios of C_{29} sterane 20S/(20S+20R) (0.39–0.50), C_{29} Sterane ββ/ββ+αα (0.55–0.57) and C_{27} Dia/(Dia+Reg) steranes (0.08–0.21) steranes as well as Ts/Ts+Tm (0.15–0.28). Furthermore, the high values of methylphenanthrene index (0.67–0.75, equivalent to 0.75–0.80% vitrinite reflectance) along with the other triaromatic steroid ratios including C_{26}/C_{27} TAS (0.14–0.27) and C_{27}/C_{28} TAS (0.9–1.1) confirm moderate to high level of thermal maturity (Table 3).

Two factors were used to verify that the Sargelu (Jurassic)/Garau (Cretaceous) formations are the main source rocks for the oil samples. The C_{28}/C_{29} regular sterane ratio as a geologic age indicator, decreases by time (Grantham and Wakefield, 1988). This ratio for the studied oil samples ranges from 0.55 to 0.64, specifying the Jurassic-Lower Cretaceous marine carbonate source rock(s) (Grantham and Wakefield, 1988). This is in accordance with the stable carbon isotope ratio, varying

| Table 3 Calculated biomarker ratios related to maturity of the oil samples |
|---------------------|------------------|-----------------|-----------------|-----------------|------------------|-----------------|-----------------|----------------|
| Reservoir       | Ts/(Ts+Tm) | C_{31} hopane 22S/(22S+22R) | C_{29} Sterane ββ/ββ+αα | C_{27} Sterane 20S/(20S+20R) | C_{28}/C_{27} TAS | C_{27}/C_{28} TAS | Re | MPI-1 |
| B-Sv            | 0.15       | 0.59               | 0.55              | 0.39              | 0.27             | 1.08            | 0.77            | 0.67           |
| B-Kz            | 0.18       | 0.55               | 0.55              | 0.45              | 0.21             | 1.1             | 0.82            | 0.75           |
| B-Gd            | 0.20       | 0.54               | 0.55              | 0.46              | 0.15             | 1.0             | 0.73            | 0.75           |
| B-Fb            | 0.28       | 0.68               | 0.57              | 0.50              | 0.14             | 0.9             | 0.76            | 0.69           |

Ts/(Ts+Tm) = 180°H-triso-hopane/(180°H-triso-hopane + 170°H-triso-hopane), C_{28}/C_{29} TAS = C_{29}/C_{30} triaromatic steroids; C_{27}/C_{28} TAS = C_{27}/C_{28} triaromatic steroids; Re = 0.6 MPI-1 + 0.4 (for 0.65 to 1.35% Ro); MPI-1 = methylphenanthrene index-1 ([1.5 * (2-methylphenanthrene + 3-methylphenanthrene) + phenanthrene + 1-methylphenanthrene + 9-methylphenanthrene]) / phenanthrene + 1-methylphenanthrene + 9-methylphenanthrene]).
from $-28.1\%$ to $-28.8\%$ (Table 4) (Chung et al., 1992; Bordenave and Hegre, 2010; Baniasad et al., 2017).

Plot of aromatic against saturate carbon isotope data (Fig. 8f) (Sofer, 1984) demonstrates the marine carbonate source rock(s) for the samples. Although the oil samples show a slight depletion ($<2\%$) in both saturate and aromatic carbon isotopes due to thermal maturity variations, they have a common genetic family (Clayton, 1991; Peters et al., 2005; Galimov, 2006).

### 4.3 Low-molecular weight hydrocarbons

The star diagram (Fig. 10a) and multivariate statistical cluster analysis (Fig. 10b) were used to evaluate the high-resolution gas chromatography (HRGC) data of the whole oils (Kaufman et al., 1990). Despite the similarities between geochemical and isotopic properties of the oil samples, the dendrogram obtained from the cluster analysis of HRGC offers two main different oil groups. The first group includes only the Fahliyan reservoir, but the second group is divided into two subgroups including Kazhdumi and Gadvan/Sarvak reservoirs.

In order to confirm different compartments within the reservoirs, the C7 light hydrocarbon parameters were investigated. The plot of toluene/nC$_7$ versus nC$_7$/MCH...
suggests common source rock(s) with type II kerogen for the oil samples (Thompson, 1979, 1983, 1987, 1988, 2006). Based on the relationship between the values of heptane and isohexane (Fig. 11a), the source rock has deposited in a marine carbonate environment (Peters et al., 2005; Thompson, 1983, 1987, 1988). This is proved by the very low values of toluene/nC7 and higher values of nC7/MCH (Table 5) (Peters et al., 2005). The cross-plot of toluene/n-heptane versus n-heptane/methylcyclohexane indicates that the evaporative fractionation/maturation and water washing have influenced the compartmentalization in the Fahlīyan and the shallower reservoirs (i.e. Kazhdum, Gadvan and Sarvak), respectively (Fig. 11b) (Thompson, 1979, 1983, 1987, 1988, 2006). Plotting the ratios of toluene/ethylbenzene versus dimethylbenzene confirms the maturity trend of the oils (Fig. 11c). On the other hand, the relation between heptane and isohexane values indicate that all four oil samples are thermally matured (Fig. 11a). These oils are supposed to be originated from the deeper parts of the basin, where the source rock(s) passed the oil window (Lis et al., 2008). The gas chromatograph pattern as well as biodegradation, sulfur content and maturity level of the Fahlīyan reservoir oil are different from the other oil signatures. These evidences confirm the existence of two main compartments in the reservoirs.

The main peak ratios obtained from light hydrocarbons were used to compute the C1 to C5 parameters in Halpern C7 star diagram (Halpern, 1995). This diagram displays the dissimilarities between the plotted light fractions of the oils (Fig. 12a). This represents that the light oil fraction from Fahlīyan reservoir is different from the other studied

Table 4 Different facies and age related biomarker ratios along with the bulk stable carbon isotope data for the studied oil samples in the Azadegan oilfield

<table>
<thead>
<tr>
<th>Facies related biomarkers</th>
<th>Age related biomarker</th>
<th>Whole-oil stable C13 isotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homopane Index</td>
<td>%C27 Sterane</td>
<td>%C28 Sterane</td>
</tr>
<tr>
<td>B-Sv</td>
<td>0.20</td>
<td>0.72</td>
</tr>
<tr>
<td>B-Kz</td>
<td>0.28</td>
<td>0.81</td>
</tr>
<tr>
<td>B-Gd</td>
<td>0.16</td>
<td>0.79</td>
</tr>
<tr>
<td>B-Fh</td>
<td>0.15</td>
<td>0.71</td>
</tr>
</tbody>
</table>

G/C13 Hop = gammacerane/C13 homohopane; C22 Tri/C21 Tri = C22 tricyclic terpane/C21 tricyclic terpane; C23 Tri/C22 Tri = C23 tricyclic terpane/C22 tricyclic terpane; C24/C23 Hopane = C24 hopane/C23 hopane; C29/C28 Hopane = C29 17a-norhopane/C28 17a-hopane; Homo Hopane Index = C20(C19-C13) homohopanes; C27 Dia(Dia+Reg) Steranes = C27 diasterene/(diasterene + regular sterane); C27/C29 Steranes = C27/C29 nnn-20R steranes; C28/C29 Steranes = C28/C29 nnn-20R steranes.

Fig. 9. Maturity related saturated and aromatic biomarker plots including (a) Ts/(Ts+Tm) versus C27 Sterane 20S/(20S+20R), (b) C29 Sterane 20S/(20S+20R) versus C29 Sterane ββ/(ββ+αα) and (c) C30/C34 Triaromatic Steroids versus C32/C31 Triaromatic Steroids, showing medium to high level of thermal maturity increasing by depth from Sarvak to Fahlīyan reservoirs.
Fig. 10. The star diagram (a) and the cluster diagram (dendrogram) (b) of 21 selected HRGC peak ratios for the studied reservoir oils, showing two main oil groups including Fahliyan reservoir and Kazhdumi along with Sarvak/Gadvan reservoirs.

Fig. 11. The C7 light hydrocarbon plots for the studied oil samples include, (a) Heptane versus Isoheptane ratios, indicating a common source rock for the oils (After Thompson, 1983, 1987, 1988; Peters et al., 2005); (b) Toluene/n-Heptane versus n-Heptane/methylcyclohexane, showing the effect of evaporative fractionation, biodegradation, maturation and water washing on the different reservoir oils (After Lafargue, and Thiez, 1996; Thompson, 1983, 1987, 1988; Peters et al., 2005); and (c) Toluene/Ethylbenzene against Dimethylbenzene, representing transpicuous trend of thermal maturity for the oil samples (After Lis et al., 2008).
reservoirs. Halpern (1995) explained that the low TR1 value is in relation with the low value in toluene compound and indicates the long migration path. TR1 and TR2 ratios can be affected by water washing or low level of biodegradation. Therefore, the oil samples with the high values of these ratios (Fig. 12b) have originated from the source rock(s) in adjacent reservoirs.

### 4.4 Engineering framework

Pressure data measured by wireline testers (e.g. MDT and RFT) are required to investigate the reservoir compartmentalization. The cross plot of pressure data versus depth provide valuable information for detecting different reservoir compartments in vertical scale. The reservoirs in this study have different pressure gradients (Fig. 13). These step-like pressure variations confirm different compartments in the reservoirs. In the overpressured oil reservoirs, the subsurface pore-fluid pressure is greater than hydrostatic pressure. The pressure-depth plot for the studied reservoirs demonstrates the overpressure regime in Fahliyan reservoir, represented by a pressure step between this reservoir and the others. Although the Fahliyan reservoir is significantly overpressured, the shallower Gadvan, Kazhdumi and Sarvak reservoirs follow a normal pressure trend. This suggests the presence of two main vertically-separated compartments, confirming the results obtained from the cluster diagram and C7 light hydrocarbon analyses. The overpressure regime in Fahliyan reservoir is due to compaction of the shaly layers in the Upper part of the reservoir, acted as a barrier for fluid flow.

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### Table 5 The main ratios obtained from light hydrocarbon analysis, used for calculating the C7 Halpern correlation start diagrams

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>TR1</th>
<th>TR2</th>
<th>TR3</th>
<th>TR4</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Sv</td>
<td>0.03</td>
<td>0.61</td>
<td>0.11</td>
<td>0.02</td>
<td>0.22</td>
<td>22.24</td>
<td>69.17</td>
<td>28.28</td>
<td>18.37</td>
</tr>
<tr>
<td>B-Kz</td>
<td>0.03</td>
<td>0.58</td>
<td>0.15</td>
<td>0.04</td>
<td>0.21</td>
<td>21.07</td>
<td>71.25</td>
<td>24.03</td>
<td>18.28</td>
</tr>
<tr>
<td>B-Gd</td>
<td>0.02</td>
<td>0.61</td>
<td>0.13</td>
<td>0.02</td>
<td>0.22</td>
<td>19.81</td>
<td>71.05</td>
<td>29.10</td>
<td>19.63</td>
</tr>
<tr>
<td>B-Fh</td>
<td>0.06</td>
<td>0.52</td>
<td>0.20</td>
<td>0.05</td>
<td>0.16</td>
<td>20.78</td>
<td>46.87</td>
<td>16.93</td>
<td>13.43</td>
</tr>
</tbody>
</table>

C1 = 2,2-dimethylpentane/P3; C2 = 2,3-dimethylpentane/P3; C3 = 2,4-dimethylpentane/P3; C4 = 3,3-dimethylpentane/P3; C5 = 3-ethylpentane; TR1 = toluene/X; TR2 = nC7/X; TR3 = 3-methylhexane/X; TR4 = 2-methylhexane/X; TR5 = P2/X; TR7 = 1-trans-2-dimethylcyclopentane/X; TR8 = P2/P3; X = 1,1-dimethylcyclohexane; P2 = 2-methylhexane + 3-methylhexane; P3 = 2,2-dimethylpentane + 2,3-dimethylpentane + 2,4-dimethylpentane + 3,3-dimethylpentane + 3-ethylpentane; MCH = methylcyclohexane.
The reservoir continuity of Fahliyan, Gdavan, Khazdumi and Sarvak Cretaceous reservoirs in the Azadegan oilfield was investigated. For this purpose, a set of reservoir engineering, geologic, and geochemical data obtained from GC, high-resolution GC, GC-MS, C7 light hydrocarbon and bulk isotope analyses were used.

Based on the results of geochemical analyses, the oil samples have medium to high level of thermal maturity, increasing by depth from Sarvak to Fahliyan reservoir oils. This is in accordance with the sulfur contents, ranging from 1.6 to 5.6% in Fahliyan and Sarvak oils, respectively. Various biomarker indicators along with the GC parameters indicate that the oil samples have generated from the anoxic marine marl/carbonate source rock(s), containing a mixture of type II/II-S kerogen. Plot of saturate versus aromatic carbon isotope data, the high contents of nickel and vanadium as well as the relationship between heptane and isoheptane values confirm the marine carbonate source rock(s) for all the oil samples.

The C39/C29 Sterane ratios and the stable carbon isotope values specify the Sargelu (Jurassic) and Garau (Cretaceous) formations as the main source rocks for the oils. The high values of TR1 and TR2 ratios, calculated from the C7 light hydrocarbon analysis, indicate that the oil samples have originated from the source rock(s) in the adjacent reservoirs.

The good correlation between the GC-star diagrams for the oil samples indicate that they have a common genetic family, derived from the same source rock(s). This is supported by the Tissot and Welte’s (1984) ternary diagram, classifying all the samples as paraffinic oils. However, the dendrogram obtained from the cluster analysis of high-resolution GC data represents two main oil groups. The first group includes only Fahliyan reservoir, while the second group is divided into two subgroups Kazhdumi and Gdavan/Sarvak reservoirs. Based on C7 Halpern star diagram, the light oil fraction from Fahliyan reservoir is different from the others. Also, the changes in the pressure by depth for the studied reservoirs show that the Fahliyan Formation follow an overpressure trend, while the shallower Gdavan, Kazhdumi and Sarvak reservoirs are normally pressured. These evidences also suggest different compartments in the studied reservoirs, consistent with the results of the cluster and the C7 light hydrocarbon analyses.

Due to similar composition of the studied oils, it can be concluded that the oil composition has not played an important role in reservoir compartmentalization. On the other hand, the cross-plot of toluene/n-heptane versus n-heptane/methylcyclohexane indicate that the maturation/evaporative fractionation and water washing have influenced the compartmentalization in the Fahliyan and the shallower reservoirs (i.e. Kazhdumi, Gdavan and Sarvak formations), respectively. Furthermore, the impermeable Upper part of the Fahliyan Formation and the thin interbedded shaly layers in the other studied formations can be introduced as the controlling factors for the compartmentalization in studied reservoirs.

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