Source rock characteristics of Albian Kazhdumi Formation in Zagros Region

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Source rock characteristics of Albian Kazhdumi Formation in Zagros Region

Ebrahim Sefidari · Abdolhossein Amini · Ali Dashti

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Abstract During Albian time, a large but gentle depression was developed over Dezful Embayment extending to the northern part of Persian Gulf. Strong anoxic condition prevailed development of bituminous marls of Kazhdumi Formation in central part of the depression. Organic richness, quality, distribution, and maturity of Kazhdumi Formation in northeast margin of Arabian plate (Dezful Embayment, Persian Gulf, Abadan Plain and Fars Region) are evaluated in this study. Rock-Eval pyrolysis data, such as $T_{\text{max}}$, $S_1$, $S_2$, oxygen index (OI), and total organic carbon (TOC), petrographic studies, and burial history information of 64 wells in 37 oil and gas fields and five outcrops are applied to achieve focused aims. Based on the interpretations of TOC and $S_2$ data, Kazhdumi organic matter richness increases toward Dezful Embayment and the lowest values are recorded in central Persian Gulf (Qatar Arch). Using constructed burial and temperature histories, $T_{\text{max}}$ and vitrinite reflectance (VR$\text{r}$) values, the variation of maturity level are found similar to that of organic matter richness which highest and lowest maturities are observed in Dezful Embayment and Qatar Arch, respectively. Kerogen type studies were carried out based on Rock-Eval parameters and type II/III kerogen assessed for organic matter of Dezful Embayment and terrigenous or type III for those of Persian Gulf.

Keywords Kazhdumi Formation · Dezful Embayment · Thermal modeling · Persian Gulf

Introduction

This paper is concerned with organic richness, quality, and maturity level of the Albian Kazhdumi Formation in the northeastern part of the Afro-Arabian plate. The formation is composed of alternating dark gray marls and clay-rich limestones. It is time equivalent of nearshore sandstones and shales of the Burgan Formation in Kuwait and the Nahr Umr Formation in Iraq and Qatar (Alavi 2004; Alsharhan 1997; Ibrahim and Al-Hitmi 2000).

Organic geochemical studies are extensively applied to identify the main characteristics of organic matter such as amount, type, and thermal maturity (Alaug et al. 2013; Alizadeh et al. 2012a; Alizadeh et al. 2012b; Espitalié et al. 1984; Hunt 1996; Kamali et al. 2012; Opera et al. 2013; Peters 1986; Peters and Cassa 1994). Rock-Eval pyrolysis and petrographic studies are applicable tools to achieve mentioned goals of organic geochemistry.

Several studies on the regional geology, organic geochemistry, and evolution of the Arabian plate specially its north and eastern margin (Zagros region) have been carried out (Alavi and Mahdavi 1994; Alizadeh et al. 2012a; Alizadeh et al. 2012b; Ameen 1991; Bahroudi and Koyi 2004; Bahroudi and Talbot 2003; Beydoun 1991; Bordenave and Burwood 1995; Bordenave and Hegre 2005; Dunnington 1967; Hessami 2002; Homke et al. 2004; Kamali et al. 2012; Kazmin 1991; Opera et al. 2013; Sherkati et al. 2005; Stöcklin 1974; Takin 1972; van Buchem et al. 2010; Vincent et al. 2010). Nevertheless, few studies have been conducted on geochemistry and petroleum potentials of organic matters in regional scale (Alizadeh et al. 2012b; Bordenave 2002; Bordenave and Hegre 2005; Bordenave and Burwood 1995; Opera et al. 2013).

The main contribution of this paper is to evaluate the Kazhdumi source rock by analytical, geochemical, and petrographical data to provide geochemical maps in the regional
scale. These maps represent richness, type, and thermal maturity of the organic matters in the Kazhdumi source rock.

**Geological setting**

**Tectonic**

The Zagros region, extending from eastern Turkey to the strait of Hormuz, is one of the most prolific hydrocarbon provinces in the world which contains 8.6 and 15% of world’s oil and gas proven hydrocarbon reserves, respectively (Bordenave and Hegre 2005). This region along with Persian Gulf characterize the NW parts of the large Arabian continental plate (Fig. 1) that extends to the Red Sea (SW), the Gulf of Aden (SE) to the Taurus Mountains (NW). This plate is characterized by different nature of boundaries including rifting in the Red Sea and Gulf of Aden, collision and subduction in the Zagros-Bitlis suture and Makran Zone, and transform along the Dead Sea and Owen-Sheba fracture zone. This region embraces several tectonic events from Late Precambrian to Quaternary. Detailed investigations have historically concentrated on the structural features of this region (Agard et al. 2005; Alavi 1994; Al-Husseini 2000; Berberian 1995; Berberian and King 1981; Beydoun 1991; Blanc et al. 2003; Dunnington 1967; Falcon 1958, 1961; Hessami et al. 2001; Heydari 2008; McQuarrie 2004; Sepehr and Cosgrove 2004; Stöcklin 1968; Talbot and Alavi 1996).

After establishment of the Neoproterozoic granitic basement of the region which was part of Gondwana supercontinent during the 900–600 Ma, the Pan-African Orogeny, tectonic behavior, and relations with sedimentary facies of this region have caused three sequential phases in the area (Berberian and King 1981; Beydoun 1991; Davoudzadeh 1997; Ramezani and Tucker 2003; Sengör 1987; Stöcklin 1968). The first phase is recorded from Late Proterozoic to the Late Paleozoic of Arabia, Turkey, and Central and Northwest Iran as part of northern passive margin of Gondwana, bordering the Paleo-Tethys Ocean (Berberian and King 1981; Beydoun 1991; Davoudzadeh and Schmidt

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Fig. 1 Location map of the studied area

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The second phase with stretching and rifting in the Late Permian led to the separation of the Iranian plate from Gondwana supercontinent along fractures parallel to the present “Main Zagros Reverse Fault” and resulted the opening of Neo-Tethys Ocean (Dercourt et al. 1986; Golonka 2000; Kazmin 1991; Ruttner 1993; Stampfli et al. 1991). From this time, the studied area became part of the Arabian Platform until the Late Cretaceous in which the Arabian plate was part of a larger passive margin along the eastern flank of the Afro-Arabian continent (Heydari 2008). The third phase with converging of the Arabian plate to Central Iran started at the beginning of Late Cretaceous and led to formation of the Zagros Foreland basin (Golonka 2000; Sepehr and Cosgrove 2004; Sharland et al. 2001; Sherkati and Letouzey 2004; Sherkati et al. 2006). These movements eventually led to closing of the Neo-Tethys Ocean and establishment of the Zagros fold and thrust belts (Alavi 1980, 1994; Berberian and King 1981; Golonka 2000; Hessami et al. 2001; Horton et al. 2008; Fakhari et al. 2008; Sherkati and Letouzey 2004).

**Stratigraphy**

The Precambrian basement of the Arabian plate is exposed in the west of the plate (Falcon 1961; Konert et al. 2001) and the Central Iran (Alavi 1991). During the Late Precambrian–Early Cambrian, rifting of the Arabian plate along N-S trends in south and southeast of Iran led to formation of evaporate basins of Hormuz complex. This complex consists of salt, anhydrite, dolomite, and shale, with some volcanic and metamorphic blocks. During the Early Paleozoic, Hormuz basin was site of deposition of fluvial to shallow-marine sandstones, siltstones, and shales (Ghazban 2007; Heydari 2008). During Late Silurian, the passive margin of Arabian plate became active as a consequence of Hercynian Orogeny. Epirogenic movement in the Zagros region led to a regional regression and general emergence of the region which resulted in a
sedimentary gap in the Carboniferous time. The regional shallow marine transgression during Permian resulted in basal costal clastic development overlying the Ordovician, Silurian, and Devonian rocks.

The Early Triassic period is characterized by marine carbonates, while Middle-Late Triassic by evaporites (Murris 1980). During Jurassic to Middle Cretaceous, sedimentation occurred in a steadily subsiding basin in which the subsidence was controlled by vertical movement of basement fault (Berberian and King 1981; Setudehnia 1978; Ziegler 2001). A carbonate platform was developed during the Cretaceous over the studied area which was deepening northwest (Lurestan). The Kazhdumi Formation is stratigraphically positioned between the Aptian Darian Formation and Cenomanian Sarvak Formation. Regionally, Kazhdumi thickens to northwest and eastward from less than 30 m in the Qatar Arch to the 350 m in the central Dezful Embayment (see Fig. 2).

Method and materials

The present study is based on the integration of geochemical data from pyrolysis analysis, vitrinite reflectance, well and seismic data, and thermal 1D modeling. Our databases are collected from published and unpublished works. The data contribution came from published papers including the following: Alizadeh et al. (2012a), Alizadeh et al. (2012b), Bordenave (2002), Bordenave and Burwood (1995), Bordenave and Hegre (2005), Ghasemi-Nejad et al. (2009), Kamali and Rezaee (2003), Kamali et al. (2012), Mirzaloo and Ghasemi-Nejad (2012), Opera et al. (2013), Rabbani and BagheriTirtashi (2010), Rahmani et al. (2010), and Vincent et al. (2010).

Present study identifies and characterizes thickness, organic richness, quality, distribution, and thermal maturity of Kazhdumi Formation in the northeastern part of the Arabian plate. To achieve this aims, 2200 total organic carbon (TOC), 1700 hydrogen index (HI), oxygen index (OI), S1 and S2, 1800 T max, and 300 vitrinite reflectance (VRr) from 64 wells in 37 oil and gas fields and five outcrop sections are applied in our database to identify and characterize source rock according to Peters (1986) (TOC>0.5 wt.%, S2>2 mg HC/g rock, T max>430 °C, and PI<0.3). Presented data of 22 wells and two outcrops are over finding of this work. These new used data are composed of 1400 Rock-Eval pyrolysis and 200 vitrinite reflectance measurements. In addition of these unpublished data, a comprehensive geological study and seismic data handling are applied to recognize the formation tops and all geological events. Geochemical signatures of the Kazhdumi source rock were mapped to understand their distribution and their characteristics over the northeastern part of the Arabian plate.

Rock-Eval pyrolysis

Rock-Eval pyrolysis have been extensively applied for oil and gas exploration and recently are the most widely used method to acquire information on the quantity, quality, and thermal maturity of organic matters in a rock and its potential and ability to generation of hydrocarbon (Espitalié et al. 1997, Espitalié et al. 1984). Details of this method can be found in Tissot and Welte (1984) and Peters and Cassa (1994). This method involves a temperature-programmed heating of a small amount of rock (70–50 mg, depending on the darkness of the sample), in an inert atmosphere (helium or nitrogen) in order to measure parameters S1, S2, S3, T max, and additional parameters that are calculated from this measurement that include HI, OI, and PI (Lafargue et al. 1998). The S1 and S2 are expressed as mg HC/g rock in which S1 represents the amount of free hydrocarbons that released from the rock without cracking the kerogen, whereas S2 represents the hydrocarbon yield from decomposition of the kerogen. TOC is expressed as the relative dry weight percentage of organic carbon in the sediments and is accepted as a strict indicator for assessing of rocks as source for hydrocarbon (Batten 1996). The T max value is a standard parameter calculated from the temperature at which the S2 peak reaches its maximum value and is used as a maturity parameter.

Optical analysis

VRr is a measurement of reflected incident light percentage. Measured light is reflected from the surface of a type of woody kerogen named vitrain. VRr values increase with thermal maturity of the source rock. It is considered by many to be one of the most reliable techniques for determining thermal maturity of source rocks and frequently applied to achieve this aim.

Organic matter characteristics

Organic matter in sedimentary rocks is mostly referred as kerogen which is composed of macerals. The relationship between macerals and kerogen is just the same as minerals and rock. Van Krevelen (1961) applied the atomic ratios of hydrogen, oxygen, and carbon to identify the types of kerogens which involved in coals. Applied atomic ratios were presented as O/C and H/C. Later, this diagram was modified to be applicable in sedimentary rocks and not be limited in coals. In the modified diagram, O/C and H/C were replaced by OI and HI, respectively (Tissot et al. 1974). In this diagram, by decrease of HI (type I kerogen toward type IV), source rock hydrocarbon potential decreases and gas-prone kerogen (type III) presents less HI.
This is due to the thermal maturity and sustained hydrocarbon depletion during maturation (Hunt 1996; Peters and Cassa 1994). The sort of generated hydrocarbon is another aspect of kerogen type. Cross plot of TOC versus HI indicates this aspect of kerogen and suggests three categories: oil-prone, gas-prone, and barren.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Erosional and depositional event as input data for modeling of site E</th>
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<tbody>
<tr>
<td>Event</td>
<td>Formation</td>
</tr>
<tr>
<td>11</td>
<td>Aghajari</td>
</tr>
<tr>
<td>10</td>
<td>Mishan</td>
</tr>
<tr>
<td>9</td>
<td>Gachsaran 7</td>
</tr>
<tr>
<td>8</td>
<td>Gachsaran 2-6</td>
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<tr>
<td>7</td>
<td>Asmari</td>
</tr>
<tr>
<td>6</td>
<td>Pabdeh</td>
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<tr>
<td>5</td>
<td>C/PG Uncon</td>
</tr>
<tr>
<td>4</td>
<td>Gurpi</td>
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<tr>
<td>3</td>
<td>Ilam</td>
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<tr>
<td>2</td>
<td>Sarvak</td>
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<tr>
<td>1</td>
<td>Kazhdumi</td>
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<thead>
<tr>
<th>Table 2</th>
<th>Petrophysical properties of various types of lithologies used in modeling</th>
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<tbody>
<tr>
<td>Lithology</td>
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</tr>
<tr>
<td>Marl and lime-marly</td>
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</tr>
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<td>Marl and sandstone</td>
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<tr>
<td>Shale</td>
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<tr>
<td>Shale–silt</td>
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<tr>
<td>Shale and silt</td>
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<tr>
<td>Shale–carb</td>
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<tr>
<td>Shale and lime</td>
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<tr>
<td>Shale and shale–carb</td>
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<td>Salt</td>
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<td>Anhydrite and marl</td>
<td>2770</td>
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<tr>
<td>Anhydrite and shale–silty</td>
<td>2780</td>
</tr>
</tbody>
</table>
Organic matter maturation is another critical parameter in evaluating source rock hydrocarbon generation. Rock-Eval pyrolysis, petrographic features, burial and thermal history are main methods to determine source rocks’ maturity. To determine the maturity, \( T_{\text{max}} \) is a Rock-Eval data and the most important optical features are palynofacies analyses, thermal alteration index (TAI), vitrinite reflectance (VRr), and conodont alteration index (CAI).

A combination of Rock-Eval output (\( T_{\text{max}} \) and HI) cross plot and vitrinite reflectance is applied to evaluate the source rock maturation. Applying two critical values of VRr (0.5 and 1.35 %) on the simple diagram, three major maturity domains are determinable based on the upgraded diagram.

**Geochemical map**

Geochemical maps are constructed based on our geochemical database in incorporation with geostatistical approaches. First, geochemical parameter and VRr averages were prepared in all wells containing this parameter. Consequently, based on geographical coordination for each well and mean of geochemical
parameters, using simple kriging algorithm, geochemical map is constructed.

Thermal modeling

Construction of the maturity and burial histories of three sites in the studied area (sites B, D, and E) were modeled using Schlumberger PetroMod 1D software version 11 in order to assess the thermal maturity of the formation and its variation through time. The stratigraphic succession of the formation including depositional units and erosional events (unconformities) was prepared based on well reports, seismic data, geological notes of the National Iranian Oil Company (Motiei 2007), and results from Walker and Geissman (2009) for geological time scale. These parameters for site E are shown in Table 1. Lithological information and software package tools were applied for calculation of thermal conductivity, porosity, and density (Table 2).

Meanwhile, heat flow information was based on Bordenave and Hegre (2005), Rudkiewicz et al. (2007), and Opera et al. (2013). For all wells, constant heat flow values (40–80 mW/m²) were assumed for Cretaceous to present time in accordance with the global average heat flow for foreland basins suggested by Allen and Allen (2005). To calculate the present-day

![Fig. 4 Frequency of TOC, S1+S2, S2, HI, and Tmax of the seven sites (A, B, C, D, E, F, and G) for the Kazhdumi samples](image-url)
heat flow, thermal history was calibrated using $T_{\text{max}}$ data along with actual measured vitrinite reflectance and bottom-hole temperatures (BHTs). The BHTs were corrected using the Horner Plot method (Dowdle and Cobb 1975).

Among several models which have been proposed to simulate modification of $R_o$ with increasing depth or thermal stress (e.g., Lopatin 1971; Sweeney and Burnham 1990; Waples 1980), the chemical kinetic Easy % VR$_e$ approach (Sweeney and Burnham 1990) was applied here.

Results and discussions

Rock-Eval pyrolysis

Source rock analyses were obtained from 2200 samples of well cuttings from 64 petroleum exploration wells in northeastern part of the Arabian plate. For geochemical interpretation, seven sites are selected over the studying area that cover the geochemical properties of the basin. These site locations are as follows: two sites from central Dezful Embayment (sites A and B), two sites from southern Dezful Embayment (sites C and E), one site from Costal Fars (site F), and two sites (sites D and G) from Persian Gulf (Fig. 3). The selected sites are shown in red squares and the outcrops and other wells in red dots (Fig. 3). The geochemical maps were constructed for regional interpretation of the formation. Organic richness, quality and type of organic matter, and level of maturity are three main parameters for assessing of source rock evaluation (Dow 1977; Barker 1996; Peters and Cassa 1994; Hunt 1996).

Organic richness and TOC

The TOC, $S_1+S_2$, $S_2$, HI, and $T_{\text{max}}$ measurements of rock samples of the formation in the selected sites are summarized in Fig. 4. Based on these results, the Kazhdumi Formation as a whole have an average TOC of about 0.86, 5.02, 3.08, 0.97, 2.46, 0.18, and 0.48 wt.% for sites A, B, C, D, E, F, and G, respectively. The organic carbon content of the formation in the site A, from north of the central Dezful Embayment, ranges from 0.15 to 2.74 wt.%, with an average of 0.86 wt.%. In this site, $S_2$ and genetic potential ($S_1+S_2$) values range from 0.37 to 6.48 mg HC/g rock with an average of 2.66 mg HC/g rock and 0.58 to 22 with an average of 6.57 mg HC/g rock, respectively. These values indicate a very good to excellent source rock for this formation in this site. In site B, the TOC ranges from 1 to 6.9 wt.%, $S_2$ ranges from 1.5 to 39 mg HC/g rock with an average of 13.74 mg HC/g rock, and $S_1+S_2$ values range from 1.58 to 40.95 mg HC/g rock with an average of 14.14 mg HC/g rock. Based on Peters (1986), this formation exhibits good to excellent source rock in site C. The Kazhdumi Formation in site D (northeast of Persian Gulf) has TOC content of 0.2 to 0.95 wt.% that are consistent with source rocks that have poor to fair source rock potential. The $S_2$ values (0.14 to 1.56 mg HC/g rock with average of 0.71 mg HC/g rock) and that of $S_1+S_2$, ranging 40.6 mg HC/g rock. All the TOC, $S_1$, and $S_2$ values indicate a very good to excellent source rock for this formation in this site. In site C, the TOC ranges from 1 to 6.9 wt.%, $S_2$ ranges from 1.5 to 39 mg HC/g rock with an average of 13.74 mg HC/g rock, and $S_1+S_2$ values range from 1.58 to 40.95 mg HC/g rock with an average of 14.14 mg HC/g rock. Based on Peters (1986), this formation exhibits good to excellent source rock in site C. The Kazhdumi Formation in site D (northeast of Persian Gulf) has TOC content of 0.2 to 0.95 wt.% that are consistent with source rocks that have poor to fair source rock potential. The $S_2$ values (0.14 to 1.56 mg HC/g rock with average of 0.71 mg HC/g rock) and that of $S_1+S_2$, ranging
from 0.18 to 2 mg HC/g rock with an average of 0.92 mg HC/g rock, confirm the conclusion (cf. Peters and Cassa 1994). In the site E (from southern Dezful Embayment), the TOC content ranges from 0.6 to 5 wt.% indicating source rocks with fair to very good petroleum potential with $S_2$ values ranging from 0.28 to 25.39 mg HC/g rock with average of 7.21 mg HC/g rock. In Site F (from Costal Fars), the TOC content ranges from 0.16 to 0.19 wt.% but all $S_2$ measurements are less than 0.22 mg HC/g rock. These two results show that the Kazhdumi Formation in this area is consistent with none hydrocarbon potential with respect to organic concentration. Eventually, in the site G (from Persian Gulf), the TOC content ranges from 0.12 to 1.2 wt.% and $S_2$ ranges from 0.13 to 2.85 mg HC/g rock with average of 0.77 mg HC/g rock. These figures show that the formation in this site is poor to good in terms of production potential.

The plot of $S_2$ versus TOC shows that the sites B, C, and E have best source rock quality, i.e., they are positioned in the good to excellent zones. Sites E and G coincide with poor to fair source rock potential, and site F is consistent with poor quality. The site A has wide range of quality from poor to good in terms of source potential (Fig. 5).

Meanwhile, plot of $S_1+S_2$ versus TOC is applied to identify source rock potential. Figure 6 shows this plot for the Kazhdumi Formation in the seven sites. As can be seen in this figure, this formation in the sites B, C, and E coincides with good to very good source rock potential. Other sites are located in the poor to fair zone except two samples of the site A that are located in the very good zone. The site B has the best source rock quality, and the site F has the lowest source rock potential (Fig. 6).

**Iso-TOC and Iso-$S_2$ maps**

As mentioned earlier, the Rock-Eval parameters are mostly applied to get a comprehensive thought about the organic matter richness of source rock. Increase of organic matter in the rocks causes the TOC and $S_2$ increase. So, distribution map of the mentioned parameters (Figs. 7 and 8) helps their understanding in an instant view. In Fig. 7, the TOC
distribution pattern is displayed, which maximum and minimum values are observed in central Dezful Embayment and central Persian Gulf (Qatar Arch), respectively. In central Dezful Embayment, the TOC values are more than 3.5 wt.%, which indicate a very good source rock, based on Peters (1986). The formation efficiency as a source rock decreases toward northeast of the Arabian plate, although remains as a good source rock (TOC ranges 1–2 %). From

![Fig. 8 S2 distribution map which confirms the proposed results of TOC studies in the area](image)

![Fig. 9 Main identified kerogen types of Kazhdumi Formation in six studied sites using modified van Krevelen diagram](image)

![Fig. 10 Plot of TOC versus HI to assess the kerogen type, this plot confirms concluded interpretations of Fig. 9](image)
Fig. 11 Distribution of HI (various kerogen types) in the studied area

Fig. 12 $T_{max}$ versus HI diagram and $VR_r$ critical values which determine both the kerogen type and maturity

Fig. 13 Plot of production index (PI) versus $T_{max}$, which indicates the maturity level for scattered data
central Dezful Embayment toward central Persian Gulf, richness of organic matter in the formation decreases and source rock quality changes from excellent to poor. These changes can be traced in southern Dezful Embayment with TOC values of 1–2 wt.% (good), Coastal Fars with TOC values of 0.5–1 wt.% (fair), and to central Persian Gulf with TOC values of 0–0.5 wt.% (poor). The TOC values’ variation trends can be easily recognized in Fig. 7. Another recognizable increase is observed toward east of Persian Gulf (Hormuz Strait), in which the formation can be classified as a good source rock (TOC ranges 1–2 wt.%).

Another signature of organic matter richness is also mapped to gain a comprehensive and absolute conclusion about the Kazhdumi Formation organic matter richness. Figure 8 shows the $S_2$ distribution map. The richest zones are mainly placed in Dezful Embayment, especially central Dezful Embayment, which its $S_2$ values range from 11 to 16 mg HC/g rock, indicative of a very good source rock (Peters and Cassa 1994) (Fig. 8). The second rich zone of the formation is observed in the northeast of Arabian plate, in which the $S_2$ changes from 5 to 10 mg HC/g rock (good source rock). From the richest zone toward Coastal Fars and Persian Gulf, the richness decrease and the least measurements or the worst source rock quality (poor) are again recorded in central Persian Gulf (Qatar Arch) for the formation ($S_2$ values range 0–2.5 mg HC/g rock).

Type of organic matter

Figure 9 shows modified van Krevelen diagram of seven studied sites. According to the figure, the samples in sites A, B, C, and E overlap each other and type II/III kerogen can be designated to them. In these sites, HI ranges 215–663, 226–474, 116–558, and 152–574 mg HC/g TOC, respectively. The OI ranges of mentioned sites are also similar (17–162, 13–47, 17–175, and 17–125 mg CO2/g TOC, respectively) and apparently certify the resemblance of organic matter type of the formation in these sites. Based on this cross plot, type III
kerogen is considered for site D samples. Site F data are placed in type III/IV kerogen. Site G samples in this diagram are also recognized as the type III kerogen. Sites D and G are similar and these resemblance is observable in their HI values. As shown in Fig. 3, these sites are located in Persian Gulf and prove a terrigenous source for Kazhdumi Formation. These kerogen types of introduced zones are also confirmed by petrographic studies on Kazhdumi Formations in Dezful Embayment and Persian Gulf (Ghasemi-Nejad et al. 2009; Alizadeh et al. 2012a; Opera et al. 2013).

Cross plot of the TOC versus HI presents three kerogen types, too. As seen in Fig. 10, this cross plot proposes an oil-prone kerogen for majority of the studied samples in sites A, B, C, and E. Kerogen type of sites D and G is displayed as gas-prone ones. Site F data are scattered in barren or poor section of the standard diagram. The analogy between sites D and G is also observed in the modified Van Krevelen diagram, and both of them represent type III kerogen for the formation in Persian Gulf. In this diagram, types I and II kerogen are merged in oil-prone category, while gas-prone kerogen represents type III kerogen and type IV kerogen and barren category are also the same.

Iso-HI map

The HI is another indirect of Rock-Eval parameter that is frequently applied for kerogen type determination. The HI variation for the Kazhdumi Formation in the studied area is shown in Fig. 11. The central and southern Dezful Embayment have HI values more than 340 mg HC/g TOC and have been considered as type II or oil-prone kerogen. In the northwest of the Persian Gulf, the formation has HI value between 250 and 330 mg HC/g TOC displaying type II to the type II/III kerogen and oil and gas source. From northwest of the Persian Gulf toward central Persian Gulf, the HI of the Kazhdumi sediments is decreased which reflects more contribution of terrigenous organic matter and gas generation potential (type III kerogen) for this formation.

Fig. 15 Measured T_{max} values distribution map in the studied area, maturity changes in this figure confirm the conclusions of Figs. 12 to 14
As discussed in “Type of organic matter” section, sites D and G present type III kerogen and their locations in Iso-HI map (Figs. 9 and 10) is in agreement with concluded result.

Level of maturity

The Kazhdumi samples’ maturation is shown in Fig. 12. Results of kerogen types are in agreement with earlier discussed methods. Results on this diagram suggest that all Kazhdumi samples are placed in immature and mature stages, and none of them endured postmature condition. The Kazhdumi Formation samples in sites A and B are almost mature and placed in mid oil generation window. In those of sites A and B, the T_max values ranges 435–450 and 434–446 °C, respectively. Samples of site C are distributed around the beginning of the oil generation window, and its position suggests the early stages of maturity and late stages of immaturity for the formation. The T_max in this site (422–449 °C) is slightly decreased, compared to sites A and B. The T_max data of site D almost present immature stage for the formation. A minor association of data entered the mature stage and early oil generation window (416–436 °C), but the majority are immature and the average T_max is 426.16 °C that prove this conclusion. In site E, the T_max data distribution is around the VRr 0.5 % and presents an intermediate stage of immature to mature for the samples. Its T_max values range from 424 to 441 °C. In both sites of F and G, the T_max data are far from oil generation window and propose immature stage for the formation. The T_max for site F data range from 408 to 420 °C, which indicates immaturity. The maturity of formation in site G is the least among all sites (from 400 to 425 °C) that certifies this conclusion.

Maturity level of organic matter can also be determined using the cross plot of T_max versus production index (PI) (Tissot and Welte 1984). A section of diagram is introduced as hydrocarbon generation which its T_max and PI range 430 to

(Supplementary figure 16) Depth to the Kazhdumi Formation. Maximum burial depth occurred in the Hormuz Strait and Dezful Embayment. Qatar Arch has minimum depth to the Kazhdumi sequence
470 and 0.05 to 0.7 °C, respectively. Based on this plot (Fig. 13), sites A, B, C, and E are placed in section with thermal maturity. This plot also indicates the generated hydrocarbon paternity and proves that generated hydrocarbons in

Fig. 17  a Burial depth diagram of Kazhdumi Formation in site B, b burial depth diagram of Kazhdumi Formation in site D, and c burial depth diagram of Kazhdumi Formation in site E
sites D, F, and G are non-indigenous and invalid to confirm samples of these sites’ maturity.

Iso-VRr map

The VRr is mentioned one of the optical parameters which directly represents samples’ maturity (“Optical analysis”). Two critical values of this indicator were applied to determine the maturity stages (Fig. 12). About 300 VRr values are mapped to trace the maturation trend in the studied area (Fig. 14). Based on the results, maturation increase intensively toward sites A and B (central Dezful Embayment). In these sites, maturity stage is around mid oil generation window (1 % VRr). Based on the Iso-VRr map, a decrease from central Dezful Embayment (sites A and B) toward southern Dezful Embayment (sites C and E) is visible. The formation displays the least maturity in sites G and F. This is reflected in the Iso-VRr map too (Fig. 14). The maximum value of VRr is much less than end of oil generation window (1.35 %), which indicates no postmaturity of the formation in the studied area. The map also presents the increasing maturity level from central Persian Gulf (Qatar Arch) and Coastal Fars region toward Dezful Embayment. This finding is in agreement with maturation results from the studied sites. A notable increase in VRr is apparent in west of the Persian Gulf (Hormuz Strait) that indicates early oil generation window (0.5 % VRr) around this area.

Iso-Tmax map

The Tmax is a Rock-Eval pyrolysis parameter which could be related to maturation of samples. The Tmax values of oil generation window top and bottom are about 435 and 470 °C, respectively. According to earlier discussed maturity signature (VRr), the Kazhdumi Formation in the studied area endured low to medium thermal maturity. The Iso-Tmax values of the formation in the studied area are shown in Fig. 15. This map strongly confirms the presented results in “Iso-VRr map.” The Low Tmax values in central Persian Gulf and Costal Fars have led to immaturity in these areas. This map indicates the mid oil generation window for the Dezful Embayment and early oil generation window for west and east of Persian Gulf. The Tmax values are far less than beginning of the oil generation window which the formation immature in this area. The most and the least mature areas have the same Iso-VRr map and show similar maturity changes. The Tmax values are notably in agreement with measured vitrinite reflectance data (Fig. 14). This agreement is predictable because of both parameters dependency on depth factor.

Burial depth

The depth to the Kazhdumi Formation is an important variable for considering the effects of geologically related properties, such as thermal maturity. For this reason, a map of its burial was prepared (Fig. 16). This map reflects the structure of the Albian Basin in the studied area. Depth to the Kazhdumi Formation varies from 920 m in central Persian Gulf to 4421 m in Dezful depression. Depth to the Kazhdumi succession increases gradually to northwest and east. In general, the highest burial depth is recorded in the Dezful depression that decreases toward the central Persian Gulf (Qatar Arch) and Qatar-Ghavbandi Paleo-high. This is in agreement with findings on the thermal indicator maps (Iso-Tmax and Iso-VRr maps).

Burial history and thermal modeling

The constructed burial and temperature histories of the B, D, and E studied sites are shown in Figs. 17a–c. Constant various steady heat flow values (64 mW/m² for site B, 50 mW/m² for site D, and 54 mW/m² for site E) resulted in the best fit between the calculated and the observed vitrinite reflectance and bottom-hole temperatures for our modeling.

Based on the modeling results (Fig. 17), the Kazhdumi Formation in site B was reached to the peak of oil generation window (Tmax (430 to 445 °C) and VRr (0.6 to 0.8 %)). It is in early mid of oil generation in site E, and at the site D, the formation has not reached to the onset oil generation. Because of woody kerogen type and low potential, the formation seems not oil source rock anymore, and it is unable to generate commercial hydrocarbon quantity in the site D.

According to the burial depth diagram (Fig. 17), maturation of studied formation is directly related to its burial depth and the basin heat flow values. As shown in Iso-Tmax and Iso-VRr maps (Figs. 14 and 15), in central Dezful Embayment, a combination of these mentioned parameters have granted the most maturity to Kazhdumi Formation, while burial depth diagram of this formation also proposes decreased maturity level (the lowest maturity) in central Persian Gulf. So, as the Kazhdumi organic matters reach their maturity in deep enough structures, they generate and expel hydrocarbon to charge the Dezful Embayment petroleum system.

Conclusion

Kazhdumi Formation characteristics are evaluated applying an integrated source rock study with the aim of a comprehensive assessing on geochemical and petrographic features.

Based on the Iso-TOC and Iso-S2 maps, the richest zones of Kazhdumi Formation are recognized in Dezful Embayment.
which parameters are presented as more than 5 wt.% and 11–16 mg HC/g rock. This richness decreases toward Coastal Fars and Persian Gulf, and the poorest zone is central Persian Gulf (Qatar Arch). According to HI map, a type II/III kerogen and type III kerogen is recognized for Kazhdumi organic matters of Dezful Embayment and Qatar Arch, respectively. These kerogen types are also determined using modified Van Krevelen diagram for mentioned areas. Iso-T$_{\text{max}}$ and Isos-VR$_{\text{r}}$ maps recommended central Dezful Embayment as the most mature area (441 °C and 1 %, respectively), while the Qatar Arch as the least maturity area (340 °C and 0.3 %, respectively). The depth to Kazhdumi found increasing from central Persian Gulf toward Dezful Embayment and Hormuz Strait, which indicates the interpreted maturity trend in the studied area. Constructed burial and temperature histories indicate that the insufficient burial depth and heat flow values toward Persian Gulf caused immaturity in this areas, whereas these parameters were favorable for organic matter maturity and hydrocarbon generation in Dezful Embayment.

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References


