Organic geochemistry of oil seeps from the Abu-Jir Fault Zone in the Al-Anbar Governorate, western Iraq: Implications for early-mature sulfur-rich source rock

Amer Jassim Al-Khafaji a, Mohammed Hail Hakimi b,c,⁎, El-Khedr Ibrahim d, Ahmed Askar Najaf e, Hussain Al Fai fi d, Aref Lashin f

a Chemistry Department, College of Science for Women, University of Babylon, Al Hilla, Iraq
b Department of Geology, University of Malaya, 50603 Kuala Lumpur, Malaysia
c Geology Department, Faculty of Applied Science, Taiz University, 6803 Taiz, Yemen
d King Saud University, College of Science, Department of Geology and Geophysics, PO Box 2455, Riyadh 11451, Saudi Arabia
e College of Geophysics and Remote Sensing, Al-Karkh University of Science, Iraq
f King Saud University, College of Engineering-Petroleum and Natural Gas Engineering Department, Riyadh 11421, Saudi Arabia

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ABSTRACT

Organic geochemical methods were performed on four oil seep samples collected from the Abu-Jir Fault Zone (AJFZ) in the Al-Anbar Governorate, western Iraq. These oil seeps have undergone biodegradation, showing large unresolved complex mixture (UCM) shapes, with degradation of normal alkanes and isoprenoids. The inorganic elements of the Abu-Jir oil seeps, i.e., S, Ni and V, suggest a marine carbonate-rich source rock deposited under reducing environment conditions. The biomarker ratios and parameters of hopane and sterane further suggest that the oil seeps were derived from source rock rich in lipids from phytoplankton and bacteria with less contribution of terrigenous organic debris. The chemical maturity indicators show that the Abu-Jir oil seeps were generated from early mature sulfur-rich source rock, thus in association with a high S content of more than 1.93%. The geochemical characteristics of the analyzed oil seep samples are similar, which is consistent with most of the crude oils in the northern and southern basins in Iraq, and were generated from the Middle Jurassic Sargelu Formation. The overall geochemical correlations and geological information confirm that the Abu-Jir Fault oil seeps in the western Iraq were sourced from the Middle Jurassic Sargelu Formation that reached an early maturity level of oil-generation window and that they migrated into the ground surface through the Abu-Jir major fault during the middle Miocene.

1. Introduction

The main petroleum sedimentary basins in Iraq, the Mesopotamian and Zagros Fold Belt basins (Fig. 1A), contain proven commercial quantities of oil and have produced several of the world’s largest oil-fields (Al-Sakini, 1992; Sadooni, 1993; Sadooni and Aqrawi, 2000). These basins are highly promising for conventional petroleum exploration and have been developed by petroleum industries and studied by academic researchers. The main basins in the northern and southern Iraq contain thick Mesozoic and Cenozoic sedimentary rocks (Fig. 2), ranging from marine carbonates to lagoonal sediments (Buday, 1980). The oil-bearing Mesozoic and Cenozoic carbonate and clastic reservoir rocks in the Iraqi petroleum basins were sourced mainly from marine carbonate-rich source rocks of the Middle Jurassic Sargelu, Late Jurassic Najmah/Naokelekan, and Late Jurassic-Early Cretaceous Sulaiy/Chia Gara formations (e.g., Al-Ahmed, 2006; Al-Ameri et al., 1999; Pitman et al., 2004; Al-Ameri and Al-Musawi, 2009; Al-Ameri et al., 2009, 2011; Abeed et al., 2011; Abeed et al., 2012; Al-Ameri and Zumberge, 2012; Mohialdeen et al., 2013, 2015; Al-Ameri and Al-Khafaji, 2014; Iden et al., 2015; Sachsenhofer et al., 2015; Hakimi and Najaf, 2016). These source rocks are composed of bituminous limestone and have high total organic matter (TOC) and S contents, with H index (HI) values > 400 mg HC/g; these characteristics are consistent with mainly Type II-S kerogen (Abeed et al., 2011; Mohialdeen et al., 2013; Al-Ameri et al., 2014; Sachsenhofer et al., 2015; El Diasty et al., 2016). The area of interest of the current study is located in the Abu-Jir Fault Zone (AJFZ), belonging...
Fig. 1. (A) Location map for the northeast Arabian Peninsula in Iraq, which shows Iraqi basins with oil and gas field locations. (B) Location map of the Abu-Jir Fault Zone (AJFZ) in the Al-Anbar Governorate, western Iraq, including the oil seeps study area.
Fig. 2. Stratigraphic correlation chart for the Iraq and Kurdistan region (modified after Harland et al., 1990; and El Diasty et al., 2016).
Fig. 3. Gas chromatograms of saturated hydrocarbon fraction of the analyzed oil seeps in the Abu-Jir Fault Zone (AJFZ), western Iraq.
to Al-Anbar Governorate in the western Iraq (Fig. 1B). Western Iraq is a hydrocarbon exploration frontier area, where few oilfields are explored, i.e., Merjen, West Kifi and Kifi (Fig. 1B). The sedimentary cover in this region includes Mesozoic and Cenozoic carbonate and clastic sediments (Fig. 2). Recent works have reported that the sedimentary rocks in western Iraq include organic-rich intervals within the Jurassic and Cretaceous formations (e.g., Al-Ameri and Al-Khafaji, 2014). These intervals are found mainly in the Middle-Late Jurassic Sargelu and Najmah formations and in the Cretaceous Sulaiy, Yamama, Ratawi, Nahr Umr, and Zubair formations (e.g., Al-Ameri and Al-Khafaji, 2014). The oil generation potential is higher in the Jurassic-Early Cretaceous Sargelu, Najmah, Sulaiy, Yamama, and Ratawi carbonate rocks than in the middle Cretaceous Nahr Umr and Zubair clastic rocks (e.g., Al-Ameri and Al-Khafaji, 2014). Although many oil seeps have been recognized at several locations in western Iraq, the petroleum characteristics of these seeps have not been investigated by applying modern geochemical methods. Hence, this study presents the characteristics of four oil seeps in the AJFZ, Al-Anbar Governorate, western Iraq (Fig. 1B), by using multiple geochemical approaches, including analyses of inorganic elements, stable C isotope compositions and saturated biomarker signatures. The AJFZ faults that formed during the middle Miocene controlled the occurrence of oil seepage in the study area (Jassim and Goff, 2006), and created vertical paths for crude oil migration from the deep source rock units into the shallow stratigraphic levels of the western Iraq and that continue to the ground surface. In this respect, the significance of the geochemical characteristics of the oil seeps in this study could encourage further petroleum exploration for commercial oil in shallow reservoir rocks in western Iraq. The main objectives of this study are to (1) characterize the composition of the analyzed oil seeps and their degrees of biodegradation and thermal maturation, (2) assess the organic matter input and environmental conditions of their probable source rock, and (3) infer the genetic relationships among oil seeps in this study, crude oils, and probable source rocks in northern and southern Iraq by using available published works (e.g., Abdula, 2015; Hakimi and Najaf, 2016).

2. Geological setting

The most basins in northern, southern and western Iraq are filled with a thick sedimentary section of marine carbonate and lagoonal
by reservoir intervals of gas and oil accumulations (Agrawi et al., 2010; Al-Ameri and Zumberge, 2012). Oil-bearing reservoir zones are also recognized in the subordinate clastic rocks of the Zubair and Nahr Umr formations in some fields in the southern Mesopotamian Basin. The Cretaceous formations are overlain by a thick Tertiary succession that includes the Aliji, Jaddala, Serikagni, Dhiba, Jeribe, and Fars formations (Fig. 2). The lower Tertiary rocks in the basin are also considered to be gas and oil reservoir rocks (Al-Ameri and Zumberge, 2012). The middle Miocene Lower Fars member, which serves as an excellent seal for the underlying Cretaceous and lower Tertiary reservoirs, is composed primarily of bedded anhydrite with shale intercalations.

3. Sampling and analytical methods

The current study examines four oil seeps based on data from two representative structures located in Heet City and Abu-Jir in the Al-Anbar Governorate, western Iraq (Fig. 1). The oils have seeped through normal faults and have accumulated in the AJFZ (Fig. 1B). The elemental analyses for sulfur (S), nickel (Ni), and vanadium (V) of whole oil seeps were analyzed by utilizing a LECO S200 analyzer. Gas chromatography (GC) was also performed on the whole oil seep samples, the results of which showed losses in most of their normal alkanes and acyclic isoprenoids (Fig. 2).

The asphaltenes in the whole oil seeps were precipitated by using n-pentane solvent, and the remaining maltenes of the oil were fractionated into saturated, aromatic, and polar fractions with n-pentane, dichloromethane, and methanol, respectively, in the alumina silica gel column chromatography. Gas chromatography–mass spectrometry (GC–MS) was subsequently conducted on the saturated hydrocarbons by using an Agilent 7890A or 7890B GC interfaced to a 5975C or 5977A MS with an HP-5MS column of 50 m × 0.2 mm inner diameter (ID) × 0.11 μm film thickness. The oven temperature of the GC increased from 150 C to 325 C at a rate of 2 C/min, and then held at 320 C for 30 min. The biomarker ratios and parameters were calculated from the peak heights of m/z 191 for hopanes and terpanes and m/z 217 for steranes and diasteranes (Appendix 1).

The C isotope compositions of the saturated (δ13Csat) and aromatic (δ13Caro) compositions were further measured following the method of Sofer (1984). The stable C isotope analysis was conducted by using a VistION iso9mass spectrometer (IRMS), with 0.02% analytical precision based on the Pee Dee Belemnite standard.

4. Results and discussion

4.1. Bulk oil fractionation and relation to biodegradation

The bulk oil compositions of the four analyzed oil seep samples, including the saturated, aromatic, and polar fractions, is listed in Table 1. The analyzed samples exhibited a high composition of polar (resins, asphaltenes) and aromatic hydrocarbon fractions, with weight percentages of 35.0–57.1% and 39.0–57.7%, respectively (Table 1), whereas the saturated hydrocarbon ranged from 3.9% to 7.3% (Table 1). These values of oil composition generally suggest that the analyzed oil seep samples contain heavy oil and were subjected to microbial degradation, following Tissot and Welte (1984; Fig. 4). The basic signs of biodegradation are well documented in the analyzed oil seep samples. This is primarily concluded from the shapes of GC results, in which the analyzed oil seeps are characterized by large UCMs, indicating losses of most light n-alkanes or normal alkanes followed by losses of acyclic isoprenoids (i.e., pristane and phytane; Fig. 2). These results are also consistent with high concentrations of asphaltene content (Table 1) because the high asphaltenes are likely the result of a biodegradation process among the oil samples (Peters et al., 2005). The relatively high aromatic hydrocarbons of more than 39% could suggest moderate biodegradation in the analyzed oil seep samples because the aromatic compounds are more resistant to biodegradation (Larter et al., 2005).
The proportion of asphaltene was plotted with other hydrocarbon fractions to illustrate the relationships and to clarify the origin and formation of the rich asphaltene within the analyzed oil seeps. Inverse relations were noted between the proportion of asphaltene and hydrocarbon fractions (Fig. 5), where the quantity of asphaltene increased with decrease in saturated and aromatic hydrocarbons. Therefore, the significance of the high proportion of asphaltenes is likely attributed to the removal of other hydrocarbon fractions (e.g., biodegradation).

4.2. Inorganic geochemical elements

Oil commonly contains inorganic elements such as S and metals, particularly Ni and V, which can provide information of the depositional environment conditions of their probable source rocks (Lewan, 1984; Barwise, 1990; Wenger et al., 2002). In this study, the analyzed oil seep samples exhibited high S content at 5.40–7.24 wt%, exception for one sample Heet-OSP1 which showed a medium S content of 1.98 wt% (Table 1). These S content values generally suggest that the analyzed oil samples were derived from Type II-S high S (Orr, 2001), with atomic S\textsubscript{org}/C ratios greater than 0.04 for the kerogen (Orr, 1986). The S-rich oils were typically derived from Type II-S kerogen at a low thermal maturity level (Baskin and Peters, 1992a,b, Orr, 1986). In accordance with the S content, the analyzed oil seep samples also showed wide-ranging V and Ni trace elements at 37–216 ppm and 11–64 ppm, respectively, which resulted in high ratios of V/Ni and V/(V + Ni) (Table 1). These high ratios, in association collaboration with the S content, further suggest environmental conditions often associated with carbonate-facies source rocks (Fig. 6).

4.3. Carbon isotopic composition

The composition of the C isotope (δ\textsuperscript{13}C) of the saturated and aromatic fractions is widely used to distinguish marine and non-marine (terrigenous) organic matter, and to determine the geochemical correlations of the oils and the potential source rocks (Sofer, 1984; Collister and Wavrek, 1996). The stable C isotope results for the Abu-Jir oil seep samples showed a narrow range of values between 28.44 and 27.93‰ for the saturated hydrocarbons and 28.22 to 27.97‰ for the aromatic hydrocarbon fractions (Table 2). The C isotope of saturated (δ\textsuperscript{13}Csat) and aromatic (δ\textsuperscript{13}Caro) fractions suggest that the Abu-Jir oil seeps were derived mainly from marine organic matter (Fig. 7), according to the method adopted by Sofer (1984). The high canonical variable (CV) values between –3.10 and 2.35 (Table 2) further indicate a marine origin (Sofer, 1984; El Diasty et al., 2016). Furthermore, the δ\textsuperscript{13}Csat fractions of the oils used to determine the deposition ages of their potential source rocks (Sofer, 1984; Andrusievich et al., 1998). Accordingly, the age of the potential source rock of the Abu-Jir oil seeps was generally assigned to Early-Middle Jurassic (Fig. 8), with an average value of 28% for the saturated fraction (Table 2).

4.4. Biomarker characteristics and organic matter input

Most of the normal alkanes and isoprenoids were removed from the saturated hydrocarbon through biodegradation in the analyzed oil seeps (Fig. 3); hence, they could not be used to assess the source of organic matter and environmental conditions for their potential source rocks. Therefore, the saturated biomarkers of terpane and sterane (Fig. 9) were used for this purpose (Trendel et al., 1982; Tissot and Welte, 1984; Peters et al., 2005).

Table 2 summarizes some of the representative terpane and sterane parameters and ratios used to provide specific information on the organic matter precursors, paleoenvironmental conditions, and maturation of the putative source rocks for the Abu-Jir oil seeps in the current work.

The mass fragmentograms of the m/z 191 ion showed that all analyzed samples had low concentrations of tricyclic and tetracyclic terpanes relative to those of pentacyclic terpanes (Fig. 9A). Abundant C\textsubscript{29} norhopane is present in the m/z 191 mass fragmentograms (Fig. 9A), resulting in relatively high C29/C30 ratios of 0.96–1.08 (Table 2); this is commonly observed in the oil generated from marine
carbonate-rich rocks (e.g., Clark and Philp, 1989). In particular, the homohopanes were dominated mainly by C31, which decreased in content gradually as C content increased in all samples (Fig. 9A).

Several ratios of the tricyclic, tetracyclic, and pentacyclic terpanes in this work further suggest a marine carbonate source rock deposited in anoxic environmental conditions. These biomarker ratios are C22/C21, C24/C22 and C26/C24 tricyclic terpanes, C27 18a (H)-trisnorhopane (Ts)/C27 17a (H)-trisnorhopane (Tm), C25/C19 homohopanes, and C312R hopane/C30 hopane (Table 2). For example, the C22/C21 tricyclic terpanes, C35/C34 homohopane, C29 norhopane/C30 hopane and C312R homohopane/C30 hopane ratios showed increases, whereas the ratios of C24/C22 and C26/C24 tricyclic terpanes and Ts/Tm ratios decreased. This indicates that the marine carbonate source rock contains algal/bacterial organic matter with little higher-plant input deposited under reducing environment conditions (Aquino Neto et al., 1982; de Grande et al., 1993; Peters et al., 2005; Hakimi and Abdullah, 2013; Mohialdeen and Hakimi, 2016; Hakimi et al., 2016). Furthermore, the ratio of C22/C21 tricyclic terpane plotted against the C24/C23 tricyclic ratio also supports that the Abu-Jir oil seeps were sourced from a marine carbonate-rich rock (Li et al., 2019, Fig. 10).

One of the prominent features is the presence of gammacerane in low quantities in the m/z 191 mass fragmentograms (Fig. 9A), with gammacerane/C30 hopane (G/C30) ratios ranging from 0.43 to 0.59 (Table 2). The overall relatively high ratios of C25/C24 homohopane indices correlated well with the gammacerane index (Table 2), which offers evidence for a high-salinity environment accompanied by anoxic conditions during sedimentation of the source rock for the Abu-Jir oil seeps (Didyk et al., 1978; Mello et al., 1988; Peters and Moldowan, 1993; Sinninghe Damste et al., 1995). The S content of more than 1.93% for these seeps (Table 1) further indicates significant salinity stratification conditions during the deposition of the source rock.

The source of organisms that accumulate during the deposition of the source rock is commonly identified on the basis of the relative distributions of C27-C29 regular sterane (Huang and Meinschein, 1979; Moldowan et al., 1985; Volkman, 1986; Waples and Machihara, 1991). In the m/z 217 mass fragmentograms, the quantities of sterane were higher than those of diasterane in the analyzed oil seeps (Fig. 9B). The percentages of C27, C28, and C29 regular steranes in all of the oil seep samples were 46.95–49.15%, 12.93–13.88% and 37.43–39.61%, respectively; thus, high C27/C29 sterane ratios of more than 1 were obtained (Table 2). The regular sterane distributions suggest that the analyzed oil seeps were generated from source rock containing predominantly marine plankton/bacterial-derived organic matter with minor terrigenous input (Fig. 11). The analyzed oil seeps have a similar distributions of the C27-C28-C29 regular steranes (Fig. 11), indicating that they were generated from similar source rock. In addition, the carbonate-rich facies of the potential source rock are also indicated by the low values of the diasterane/sterane ratio (Peters and Fowler, 2002), as shown in Table 2.

4.5. Maturity of Abu-Jir oil seeps

Stereoisomerization ratios widely used in biomarkers to indicate the thermal maturity of source rocks and crude oils (Seifert and Moldowan, 1978, 1981, 1986; Mackenzie et al., 1980; Peters et al., 2005). The most reliable maturity ratios in this study were calculated from terpane and sterane saturated biomarkers which are more resistant to biodegradation (Fig. 9). The maturity stereoisomer ratios of C32 hopane 22S/22S 22R and C29 sterane 20S/20S 20R and P/α anti (P), followed by slower reactions such Ts/Tm and moretane/hopane ratios were used to establish the thermal maturity order of the analyzed oil seeps and their source rock (Table 2). Nearly all analyzed oil seep samples, 0.55–0.57%, reached relatively low values of the C32 hopane ratio, which represents thermal maturity equivalent to a vitrinite reflectance of ~0.6–0.7% (Peters et al., 2005) and suggests at least an early oil window for the potential source rock (Seifert and Moldowan,
Fig. 7. Cross-plot of the carbon isotopic ($^{13}$C) for saturated and aromatic fractions. This indicates that the Abu Jir oil seeps in western Iraq are consistent with the crude oils from oilfields in the northern and southern Iraq that were generated from the Middle Jurassic Sargelu source rock and containing mainly marine organic matter.

Fig. 8. Carbon isotope source age assignment, suggesting Early-Middle Jurassic age affinity for the analyzed oil seep samples in western Iraq (modified after Andrusch et al., 1998).

The analyzed oil seeps also have relatively low values of C29 sterane 20S/(20S+20R) and $\beta\beta/(\beta\alpha\alpha)$ ratios in the range of 0.37–0.45 and 0.44–0.47, respectively (Table 2). This indicates that most of the Abu-Jir oil seeps were generated from source rock of low maturity levels (Fig. 12A), which is consistent with onset of oil-generation from early-mature source rock (Fig. 12B). Moreover, the 18a (H)-trisnorneohopane (Ts) index, which is a reliable maturity indicator that increases with maturity relative to 17a(H)-trisnorhopane (Tm), showed relatively low Ts/Tm ratios of 0.10–0.11; this also indicates a low maturity level in the analyzed samples (Peters et al., 2005; Roushdy et al., 2010; El Nady et al., 2014). This result is supported by their association with the morenane/hopane ratio of the analyzed oil seeps (Fig. 13). In addition, the high S content suggests that the Abu-Jir oil seep samples were scoured from carbonate source rock, containing Type II-S kerogen that was able to generate oil at low maturation levels at least for the early oil generation (Baskin and Peters, 1992a,b). This is likely attributed to the presence of C–S weak bounds (Orr, 1986; Baskin and Peters, 1992a,b).

4.6. Geochemical correlations

The geochemical correlations of the recovered oils and their probable source rocks serve as a critical link for establishing petroleum systems in sedimentary basins (Katz, 1995; Hakimi et al., 2012). In this study, the genetic relationship in terms of oil–oil correlation was established on the basis of the bulk geochemical, molecular, and isotopic characteristics of the analyzed Abu-Jir oil seeps and crude oils from north and south basins in Iraq, which have been discussed in previous research (Abdula, 2015; Hakimi and Najaf, 2016). Clustering analysis of these characteristics demonstrated, a positive oil–oil correlation suggesting that the analyzed oil seep samples are similar and are consistent with most of the crude oils in the northern and southern in Iraq and that they are generated from the same source rock (Figs. 6, 7, 10, and 11) at similar levels of maturity (Figs. 12 and 13).

The genetic link of the Abu-Jir oil seeps and their probable source
Fig. 9. Left: terpanes distribution in the m/z191 mass fragmentograms for three analyzed oil seeps. Right: steranes and diasteranes distribution in the m/z217 mass fragmentograms for the three analyzed oil seeps.
Fig. 10. Cross plot of tricyclic terpanes i.e. $C_{22}/C_{21}$ and $C_{24}/C_{23}$ further suggest genetic link between the analyzed oil seeps in the western Iraq and crude oils from oilfields in the north and south Iraq that generated from Sargelu carbonate-rich source rock (modified after Li et al., 2019).
rocks can provide valuable information for the further successful petroleum exploration in the western Iraq. Recently, a source rock geochemical study was performed on potential source rocks in the west Kfi and Kfi oilfields in the western Iraq, which are in close proximity to the study area (e.g., Al-Ameri and Al-Khafaji, 2014). The results indicated the presence of several promising clastic and carbonate sedimentary facies. The carbonate source rocks of the Middle-Late Jurassic Sargelu and Najmah and Lower Cretaceous Sulaiy, Yamama and Ratawi formations have higher potential for oil generation than the clastic source rocks of the middle Cretaceous Nahr Umr and Zubair formations (e.g., Al-Ameri and Al-Khafaji, 2014). In this regard, a genetic relationship can be conducted with the carbonate source rocks because the analyzed Abu-Jir oil seeps were generated from a carbonate-rich facies, as indicated from the geochemical results discussed in the previous subsections (Figs. 6 and 10). Moreover, the δ13Corg data suggest that the Abu-Jir oil seeps were sourced from Early-Middle Jurassic source rock (Fig. 8). Therefore, the Middle Jurassic Sargelu Formation is likely a probable source rock for the analyzed Abu-Jir oil seeps. However, because the characteristics of the Sargelu source rock in the western Iraq have not been studied in detail by applying molecular and isotopic methods, the geochemical correlation was performed on the basis of published data of the molecular and isotopic characteristics of this source rock in the northern Iraq (e.g., Abdula, 2015).

According to the oil-source rock correlation, the organic-rich interval in the Middle Sargelu Formation appears to be the most likely source rock of the analyzed oil seeps, as evidenced from the source rock characteristics such as marine-carbonate enrichment, anoxic environment conditions during the deposition (Figs. 7 and 10) and the mixed organic matter input (Fig. 11). This correlation is also supported by the fact that the source rocks overlie the Sargelu Formation; therefore the oils were very likely generated at a sufficient thermal burial depth of more than 2900 m (Fig. 14) before migrating along vertical migration pathways through Abu Jir major fault up to the shallow stratigraphic reservoir rocks of the Ratawi, Shuaiba and Mauddud formations. However, the tectonic event of the Abu Jir major faults during the middle Miocene (Jassim and Goff, 2006) clearly controlled the occurrence of the oils at the ground surface (Fig. 14). Therefore, the current work provides information helpful for predicting the occurrence of commercial S-rich oils sourced from the Sargelu Formation that accumulated in the overlying reservoir rocks and could significantly benefit further petroleum exploration in western Iraq.

5. Conclusions

Four oil seeps from the AJFZ in the Al-Anbar Governorate, western Iraq were analyzed using bulk geochemical, biomarker, and stable carbon isotopic methods to establish the characterization of the oil seeps and to identify the genetic relationships between the oil seeps and their probable petroleum source rock. The main conclusions of this study are outlined below.

1. The Abu-Jir oil seeps exhibit a wide range of chemical compositions and are classified as heavy and degraded oils, where the most normal alkane and acyclic isoprenoid biomarkers were removed.

2. The relatively high sulfur content in addition to Ni and V trace elements suggest that the Abu-Jir oil seeps were sourced from marine carbonate-rich source rock deposited under a reducing environment.

3. According to the stable carbon isotope compositions and terpane and sterane biomarkers, the Abu-Jir oil seeps were derived from source rock rich in phytoplankton/bentic algae and bacterial organic matter with fair amounts of land plants, which deposited under anoxic and water column stratification conditions.

4. The Abu-Jir oil seeps were generated from early mature sulfur-rich source rock as demonstrated by high sulfur content (>1.93%), and low values of stereoisomer ratio (e.g., $C_{22}$ hopane $22S/(22S + 22R)$ and $C_{29}$ sterane $20S/(20S + 20R)$ and $\beta\beta/\beta\alpha$).

5. The geochemical correlations revealed a genetic link between the analyzed oil seeps in the western Iraq and the most of the crude oils in Iraq. Thus, the seeps are linked with the organic-rich intervals in the Middle Jurassic Sargelu Formation, which is the main oil-source rock in northern and southern Iraq.

6. The overall geochemical correlations and geological information indicate that the Abu-Jir oil seeps were generated from Middle Jurassic Sargelu source rock underground before and migrating up to the ground surface through Abu Jir major faults. Hence, further petroleum exploration for commercial sulfur-rich oils should be focused on the shallow stratigraphic levels of the Al-Anbar Governorate in western Iraq.

Fig. 11. Ternary diagram of regular steranes ($C_{25}-C_{29}$), indicating the relationship between the depositional environments and the organic matter input (modified after Huang and Meinschein, 1979).
Fig. 12. Cross plots of the stereoisomer ratios of C_{32} hopane 22S/(22S + 22R) and C_{29} sterane 20S/(20S + 20R) and ββ/(αα + ββ). This suggests that the analyzed oil seep samples in western Iraq and crude oils from oilfields in the northern and southern Iraq were generated from Sargelu source rock at a low maturity level. These findings are consistent with the onset of oil-generation from early-mature source rock. This interpretation is based on Waples and Machihara (1991) and Peters and Moldowan (1993).
Fig. 13. Range of thermal maturity based on biomarker maturity ratios, i.e., Ts/Tm versus moretane/hopane ratios, indicating the same interpretation as that shown in Fig. 12. The analyzed oil seep samples in western Iraq and crude oils from oilfields in the northern and southern Iraq were generated from Sargelu source rock at an early-mature level of oil-generation window. This interpretation is based on Mackenzie et al. (1980) and Seifert and Moldowan (1986).

Fig. 14. SW–NE cross-section of mega-seismic rock from Kifl field of western Iraq through the East Baghdad field, showing the primary structural setting and migration pathways from Sargelu source rock up to the overlying shallower Lower Cretaceous reservoir rocks that continue to the ground surface (i.e., the Abu-Jir Fault Zone).
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Appendix A

Peak assignments for alkane hydrocarbons in the gas chromatograms of saturated fractions in the m/z 191 (I) and 217 (II) mass fragmentograms.

<table>
<thead>
<tr>
<th>(I) Peak no.</th>
<th>Compound abbreviation</th>
</tr>
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<tbody>
<tr>
<td>Ts</td>
<td>18α(H),22,29,30-trimorneohopane</td>
</tr>
<tr>
<td>Tm</td>
<td>17α(H),22,29,30-trimorneohopane</td>
</tr>
<tr>
<td>29</td>
<td>17α,21(H)-nor-hopane</td>
</tr>
<tr>
<td>30</td>
<td>17α,21(H)-hopane</td>
</tr>
<tr>
<td>29M</td>
<td>17β21α(H)-hopane (moretane)</td>
</tr>
<tr>
<td>30M</td>
<td>17β21α(H)-Moretane</td>
</tr>
<tr>
<td>31S</td>
<td>17α,21(H)-homohopane (22S)</td>
</tr>
<tr>
<td>31R</td>
<td>17α,21(H)-homohopane (22R)</td>
</tr>
<tr>
<td>32S</td>
<td>17α,21(H)-homohopane (22S)</td>
</tr>
<tr>
<td>32R</td>
<td>17α,21(H)-homohopane (22R)</td>
</tr>
<tr>
<td>33S</td>
<td>17α,21(H)-homohopane (22S)</td>
</tr>
<tr>
<td>33R</td>
<td>17α,21(H)-homohopane (22R)</td>
</tr>
<tr>
<td>34S</td>
<td>17α,21(H)-homohopane (22S)</td>
</tr>
<tr>
<td>34R</td>
<td>17α,21(H)-homohopane (22R)</td>
</tr>
<tr>
<td>35S</td>
<td>17α,21(H)-homohopane (22S)</td>
</tr>
<tr>
<td>35R</td>
<td>17α,21(H)-homohopane (22R)</td>
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<table>
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<th>(II) Peak no.</th>
<th>Abbreviation</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>13β,17α(H)-diasteranes 20S</td>
</tr>
<tr>
<td>b</td>
<td>13β,17α(H)-diasteranes 20R</td>
</tr>
<tr>
<td>c</td>
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References


