

# Oil biomarkers, isotopes, and palynofacies are used for petroleum system type and migration pathway assessments of Iraqi oil fields

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Received: 24 February 2014 / Accepted: 1 September 2014 / Published online: 13 September 2014  
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**Abstract** Analysis of  $\delta^{13}\text{C}$  aromatic and saturated hydrocarbons plus extracts from source-rock plots in graphical diagram as well as  $\delta^{13}\text{C}\%$  and C28/C29 ratio of source-age sterane biomarkers of 300 scattered crude oil samples have enabled this study to assess groupings of hydrocarbons into families related to sedimentary basins in Iraq. Oil sources include Middle Jurassic strata of Sargelu Formation in the Zagros fold belt of North Iraq and eastern part of Mesan Governorate with Middle Jurassic as well as Upper Jurassic/Lower Cretaceous Chia Gara Formation in the North East based on a C28/C29 ratio of nearly 6 and 8, respectively. Mesopotamian Basin oil sources comprised mainly of Upper Jurassic/Lower Cretaceous Sulaiy Formation above the Upper Jurassic lower regional seal of the Gotnia Anhydrite except were thinned and faulted with a C28/C29 ratio that ranges between 5 and 9, which could cause mixing with Middle Jurassic Sargelu Formation oil. Middle Triassic oil in North West Iraq is recorded within Kurra Chine Formation with a C28/C29 ratio of 4, while Lower Palaeozoic oil sources are recorded in West Iraq. On the other hand, one formation may have multiple pay zones of Jurassic and Lower Cretaceous sources, such as Zubair and Yamama formations. The kerogens of the source rocks are confirmed by chemical analytical studies of pyrolysis and by microscopic studies of palynofacie types of the disseminated organic matters. PetroMod software basin modeling for hydrocarbon generation and palynomorphs for source-rock age assessments are discussed too. Oil accumulations in the reservoirs are assessed in this study using petrophysical properties to obtain hydrocarbon filling of the rocks and trapping dynamically mobile hydrocarbons in structural and stratigraphic traps in structural cross section and seismic sections. Petroleum system framework, interpreted

in this study, could be used for hydrocarbon exploration and for mineral genesis of sulfur deposits through systematic studies and analysis in the proposed oil field especially when they are plotted on seismic section images for assessing the extent of source and reservoir rocks, and hence predicting hydrocarbon migration paths and finding new reservoirs and pay zones.

**Keywords** Petroleum system · Oil and gas fields · Sedimentary basins · Oil biomarkers · Isotopes · Palynofacies · PetroMod software · Migration · Accumulations · Iraq

## Introduction

Iraqi land constitutes a proven oil reserve of 180 billion barrels, while the exploration in Iraq suggested 415 billion barrels of oil reserve that could be proved by detailed exploration.

On basis of well site observations of the hydrocarbons, it could be possible to delineate oil and gas fields in Iraq to be distributed in geographic locations with giant oil fields toward the east and giant gas field toward the West, except for the Diyala Governorate region in the North East (NE), which has separated gas and oil fields. Furthermore, their reservoirs are scattered in subsurface stratigraphic successions of Cretaceous in the Mesopotamian Basin with giant oil fields in Basrah, Emara, and Baghdad Governorates, Tertiary in the Zagros fold belt with giant oil field in Kirkuk, and Lower Paleozoic in Widian Basin with giant gas field in Akkas near the Euphrates River entrance from Syria, while northwestern (NW) Iraq could have Triassic oil as well as Jurassic.

Oil and gas fields extend to the northern part of the Arabian Gulf and are located in the northeastern part of the Arabian plate (Al-Sharhan and Nairn 1997; Sharland et al. 2001;

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Aqrawi et al. 2010). The Gulf and Iraq oil fields represent two thirds of the world's oil reserve, while reserve found only in Iraq could account to 200 billion barrels putting Iraq as the second world's oil producer after Saudi Arabia. They are mainly distributed in the Mesopotamian Foredeep Basin, which constituted the passive margin of the Tethys Ocean during the Cretaceous time. Gradually to the north and north-eastern parts of Iraq is the Zagros fold belt that was affected by the Alpine orogenic belt of the Tertiary time until the close of the Tethys Ocean during the Miocene. Those events were controlled by convergent plate tectonism caused by the collision of the Arabian and Eurasian plates, forming the Zagros Mountains. The formation of Widian interior platform basins in West Iraq has a retarding effect, which formed small basins inside the North Arabian plate by compression (Pollastro et al. 1999; Sharland et al. 2001; Aqrawi et al. 2010). These basins are distributed in the location map of Iraq (Fig. 1) shown as beige for the Zagros fold belt toward northeast and in the east toward the border with Iran, milky gray for the Mesopotamian Foredeep Basin in the Central and Southern Iraq, and pink for the Widian Basin in the west of Iraq. These three basins contain the potential oil and gas reservoirs of Iraq with giant oil fields toward the east and giant gas field toward the west, except for the Diyala region, which has separated gas and oil fields in the northeastern part.

To assess the undiscovered petroleum, a sequence of steps is being undertaken proceeding from defining sedimentary basin with seismic or structural cross sections, allocating oil and gas reservoirs as well as source strata to these sections, defining petroleum systems within the basin, and ultimately assessing the undiscovered petroleum potential of selected locations in the basin through the migration pathways and closures that appeared in the sections.

This work is based on three analytical trends for the fulfillment of the essential elements of the petroleum system. Accordingly, the first trend shows hundreds of source-rock sample collection from selected oil fields, which are then subjected for organic geochemical analysis following Tissot and Welte (1984) and Hunt (1996), using pyrolysis and gas chromatography-mass spectrometry (GC/MS) as well as palynofacies studies (Tyson 1995) and thin sections to assess the hydrocarbon generation sites and the petrophysical properties following Schollem (1978, 1979). The second trend include the collection of hundreds of oil samples from wells and seeps that are subjected for biomarker studies following Peters et al. (2005) and Hunt (1996), using GC/MS device and palynomorph extractions following Traverse (2008) to assess source environment, lithology, maturation, and age. The third trend involve wire line well logging and thin section studies to assess formation evaluation of the reservoir and source rocks following Selley (1998a, b) and Schollem (1978, 1979). The

**Fig. 1** Location map and oil and gas distribution in Iraq. **a** Oil and gas fields and seeps in Iraq with sedimentary basins. **b** Generalized thermal alteration map for isogeothermal contours based on color changes suggested by Staplin (1969) in Paleocene/Lower Eocene equivalent strata with case study of Diyala region to show the oil and gas distribution. The isogeothermal contours are colored red with numerical values of degrees centigrade assessed by thermal alteration indices performed in this study on the verrucate spore species *Hamulatisporites amplus*. Study locations: (1) Zakho, (2) Tel-Hajar, (3) Aqra, (4) Shaqlawa, (5) Dokan, (6) Choarta, (7) Tasluja, (8) Jambour-18, (9) Pulkhana-7, (10) Mansuriyah-1, and (11) Naft Khana. (Baquba in this figure is the main city of Dyala Governorates). **c** Detailed location of the Euphrates River oil and gas fields and surface seeps with section line for megaseismic line 7 of Fig. 17

results of these analyses are elaborated into models, and their stratigraphic positions are fixed on seismic sections, structural cross sections, and maps to interpret the petroleum system processes of migration and accumulations into structural and stratigraphic traps and hence could aid in hydrocarbon production. The studies of van Bellen et al. (1959), Jassim and Goff (2006), Sharland et al. (2001), and Aqrawi et al. (2010) are used as basis for detailed stratigraphy and as structural framework of this study.

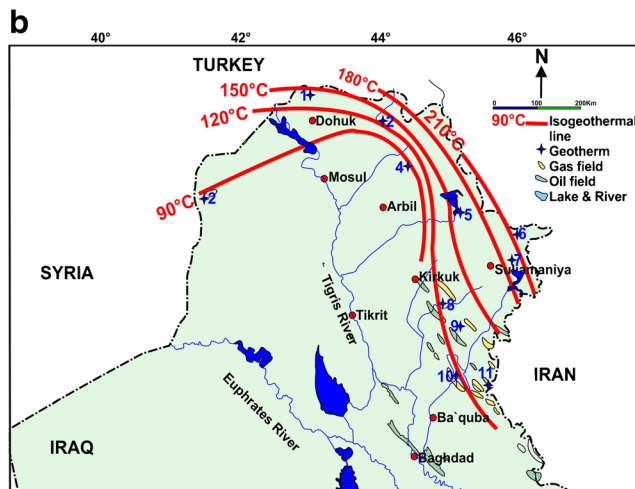
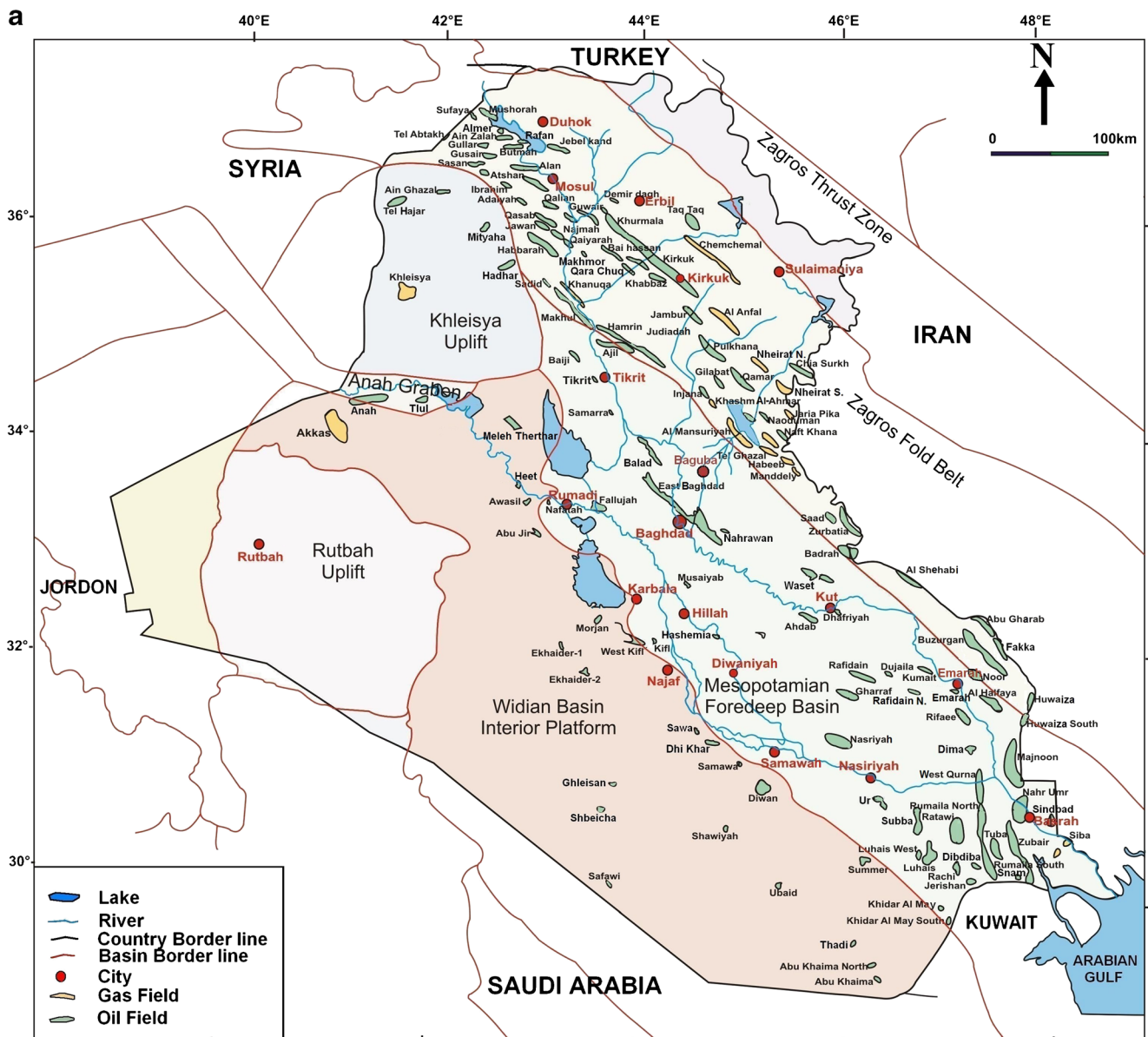
This study aims to group the abovementioned oil and gas fields into petroleum systems that could be used as models for further hydrocarbon exploration strategies in Iraq through oil analysis (biomarkers and isotopes), source-rock palynofacies assessments, and PetroMod software basin modeling. Other experiments on reservoir porosity and seismic and structural cross sections are also performed for inferences and finalization to this study.

## Materials and methods

Two hundred and twenty crude oil and seep as well as bitumen-disseminated samples are used for this study, which were collected from oil fields of drilled wells and exposure cuts in scattered localities in all parts of Iraq. Terpene and sterane biomarkers using GC/MS device as well as  $\delta^{13}\text{C}$  aromatic and sterane isotope ratios are performed by Geomark Research Ltd (Houston, Texas).

Hundreds of source-rock samples from Jurassic time and Lower Cretaceous rock samples of drilled wells and exposed strata in scattered localities in all parts of Iraq are used in this study for hydrocarbon generation assessments referenced from my previous articles on Iraqi oil fields, which are discussed in many paragraphs in this text. Thin section slides of hundreds of reservoir rocks are also studied for their porosity types and hydrocarbon accumulation sites.

Seismic section images are from the Oil Exploration Company of the Ministry of Oil in Iraq.



## Basics for petroleum system classification

Oil from Iraqi oil reservoirs are grouped into families according to their source age, stratigraphic successions, and basin habitat. Diagrammatic presentation (Fig. 2) of  $\delta^{13}\text{C}$  isotopes of plots of aromatic and saturated oil analysis in circular shape and extracts from the kerogen of the source rocks as rectangular shape are grouped into clusters of families (following Zumberge and Summons 2004 in their studies on US fields). Each family contains oil reservoir plots (circular dots) near its source-rocks plots (rectangular dot) based on Sofer's (1984) diagram. Dating of source-age assessments of the Zagros fold belt and Mesopotamian Basin are evaluated by plotting reservoir oil isotopes of  $\delta^{13}\text{C}\%$  based on the stable carbon isotope age-assignment diagram (Fig. 3) of Andrusevitch et al. (2000). Accordingly, the crude oil of the Zagros fold belt and Mesopotamian Basin are sourced from Jurassic and Lower Cretaceous time equivalent strata, while specific age assignment could be evaluated in the forthcoming paragraphs in C28/C29 biomarker diagrams (Zumberge and Summons 2004) for crude oil of each field or reservoir.

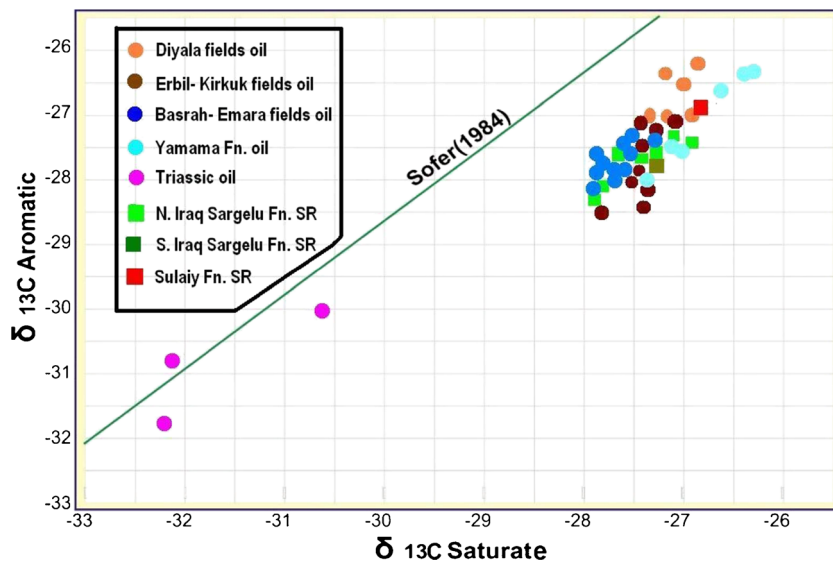
Sofer (1984) isotope diagram shows that plots of oils and source extracts could be grouped into semi-isolated facies of families although they are inter-related. These groups could be assessed by the following observations on oil affinities for scattered geographic locations. Diyala field oil plots of NE Iraq are grouped with Sulaiy-Chia Gara and Sargelu Formations extracts; Erbil-Kirkuk field oil plots are grouped with Sargelu Formation extracts; Basrah-Emara field oil plots are grouped with Sargelu Formation extracts as well as the Sulaiy extracts, and Yamama or Zubair Formation oil plots are coincided with Sargelu Formation in some of their pay zones and with Sulai-Chia Gara Formations in other pay zones (Fig. 2). On the other hand, the Triassic oil of NW Iraq is on a separate grouping, which could assess a different family.

The main source-rock ages in Iraq, based on van Bellen et al. (1959), are Upper Jurassic to Lowermost Cretaceous for the Sulaiy and Chia Gara Formations and Middle Jurassic for the Sargelu Formation.

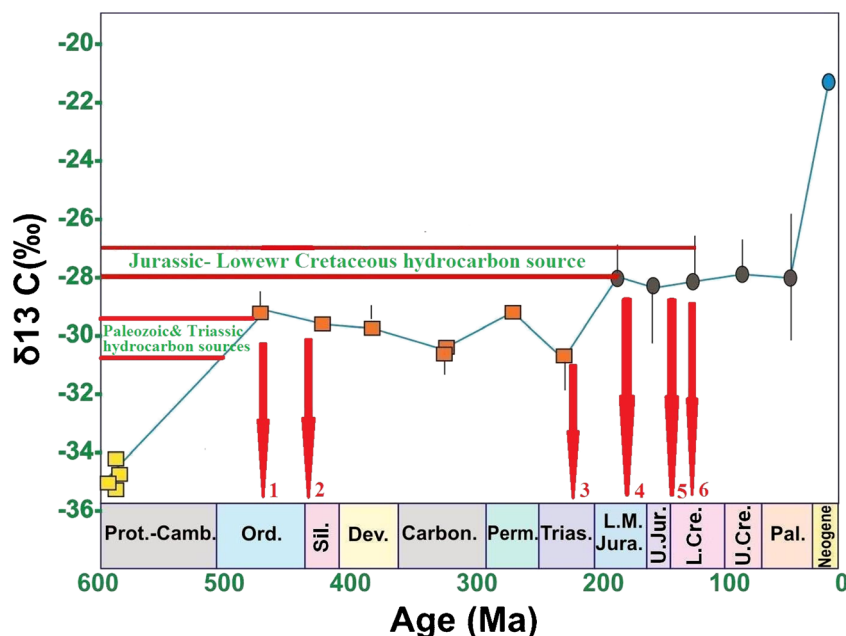
In petroleum systems of carbonate/marl source units as the case of this study source rocks (Al-Ameri and Al-Musawi 2011; Al-Ameri et al. 2009a, b, 2011a, b, 2013b, 2013c; Al-Ameri and Zumberge 2012), the C28/C29 regular sterane ratio ( $\alpha\beta\beta$  20R isomers based on peak heights of GC/MS) is useful for predicting source-rock ages of the crude oil according to Zumberge and Summons (2004). These peaks could come from evolution and extinction of various organisms, such as green algae, acritarchs, dinoflagellates, coccolithophorids, diatoms, and discoasters. It is reflected by increasing C28 on behalf of C29 with increasing age. To help diagrammatic source-age evaluation for this study, the Geomark Research OIL™ database of Houston-Texas founded standard data points that represent average oil values from global petroleum systems from marine carbonate and marl source rocks. Points of this database are used in this study for global correlation and hence approaching the age assessments. The calculation of C28/C29 ratio employs both regular and triaromatic steranes and weighing on a saturated to aromatic hydrocarbon ratio of about 0.5.

Microscopic studies of the palynomorphs (Fig. 4a) and dispersed organic matters from the potential oil source-rock formations in Iraq (Fig. 4b) are the source basis for the biomarkers obtained from a GC device (Peter et al. 2005) and for the hydrocarbon generation assessments by palynofacies analysis (Tyson 1995; Batten 1996b; Al-Ameri and Batten 1997; Al-Ameri et al. 1999). In our studies, it has been observed that all the source-rock organic matters (kerogen) shared palynofacies of dysoxic-anoxic/suboxic-anoxic palaeoenvironments of deposition with degradation of up to 100 % amorphous organic matters (AOM) of the total

**Fig. 2** Isotopes diagram of the aromatic and saturated  $\delta^{13}\text{C}$  of reservoir oil and source rock extract from scattered locations in Iraq



**Fig. 3** Carbon isotopes source age assignment diagram for oil and seeps of the Mesopotamian and Zagros basins



organic carbon (TOC). Kerogen is type A (compared with Thompson and Dembicki 1986), an equivalent to kerogen type II on van Krevlen diagram, mature during catagenesis stage (oil window), and has a TOC of up to 18 %.

Palynomorph assemblages of the source-rock palynofacies of Chia Gara, Naokelekan, and Sargelu formations are dominated by an amorphous organic material, with a low abundance of palynomorphs due to masking. The organic matters comprised principally dinoflagellate cysts with brazinophyte algae, *Tasmanites*, foraminiferal test linings, fungi, phytoclasts, pollen, and spores.

Modeled organic matter (type IIS) transformation ratio (following Lewan and Ruble 2002; Peters et al. 2005), defined as the ratio between measured hydrocarbon potential of a rock sample divided by the original hydrocarbon potential. This type of modeling is done in this study through PetroMod software basin modeling and performed in the US Geological Survey of Denver Colorado on the basis of 1D PetroMod (IES 2007, of Schlumberger/Aachen Technology Centre). Accordingly, confirmation of the hydrocarbon generation age are done in this study using the PetroMod software basin modeling correlated with Pitman et al. (2004), Al-Ameri et al. (2011b), Abeed et al. (2013), and Al-Ameri et al. (2013b).

**Petroleum system types**

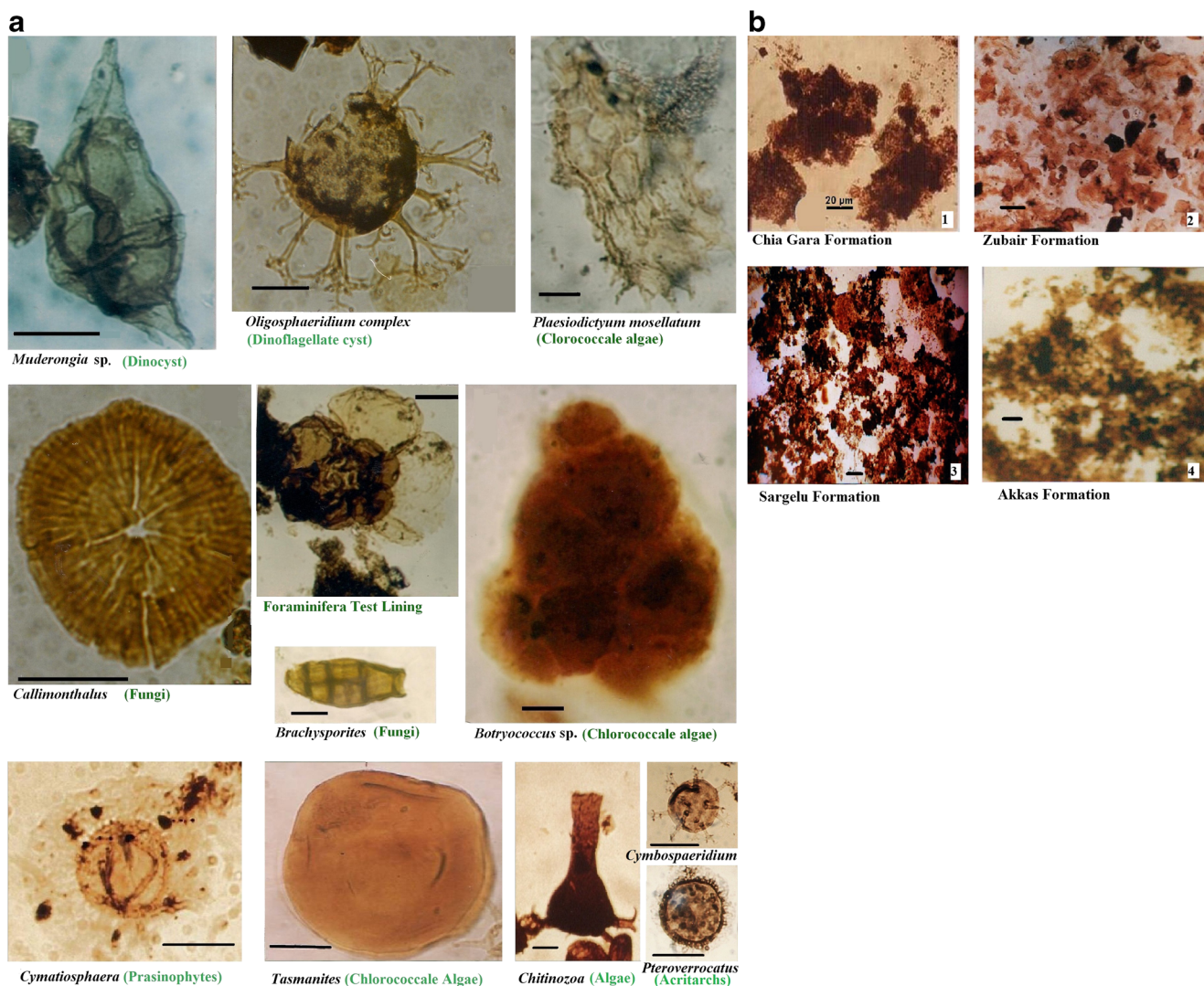
Total Petroleum Systems (TPS)

Total petroleum systems (TPS) could be defined between lowest and highest regional seals that encompass many

stratigraphically successive oil reservoirs and the generally related organic matters (kerogen) of the source rocks. Processes include hydrocarbon dynamicity of generation, expulsion from the source rocks, migration between strata, and accumulations in traps or continuous migration to the surface to form seeps (Tissot and Welte 1984; Hunt 1996; Selley 1998a, b; Peters et al. 2005).

*Oil field of the Mesopotamian Foredeep Basin* This basin covers geographic locations of Central and South Iraq between Zagros fold belt and Widian Basin with southern extension toward Basrah Governorates and further down the Arabian Gulf (Fig. 1a). It extend stratigraphically from the Upper Jurassic regional seal of the Gotnia Anhydrites Formation while its upper regional seal is the Middle Miocene Fatha (Lower Fars) Anhydrite Formation based on sequence stratigraphy of van Bellen et al. (1959), Sharland et al. (2001) and Al-Ameri et al. (2009a, b).

Plots of  $\delta^{13}C$  aromatic and saturated oil isotopes of the oil fields of East Baghdad, Ahdeb, Noor, West Qurna, Nahr Umr, Zubair, Ratawi, Rumaila and Nasiriyah on Sofer (1984) diagram is showing one zone cluster of blue dots nearby a source-rock extract of the Sulaiy and Sargelu formations (Fig. 2). Furthermore, source-age assessment of these oils could confirm Upper Jurassic/Lower Cretaceous age, equivalent to depositional times of the Sulaiy, Chia Gara, and Sargelu formations (arrows 4 and 5, Fig. 3) by plotting reservoir oil isotopes of  $\delta^{13}C\%$  on Andrushevitch et al.’s (2000) stable carbon isotope age-assignment diagram. The organic matter sources of these oils are the sedimentary disseminated particles of the Jurassic and Lower Cretaceous palynomorphs of mainly the Clorococcale algae, fungi, foraminiferal test lining, and



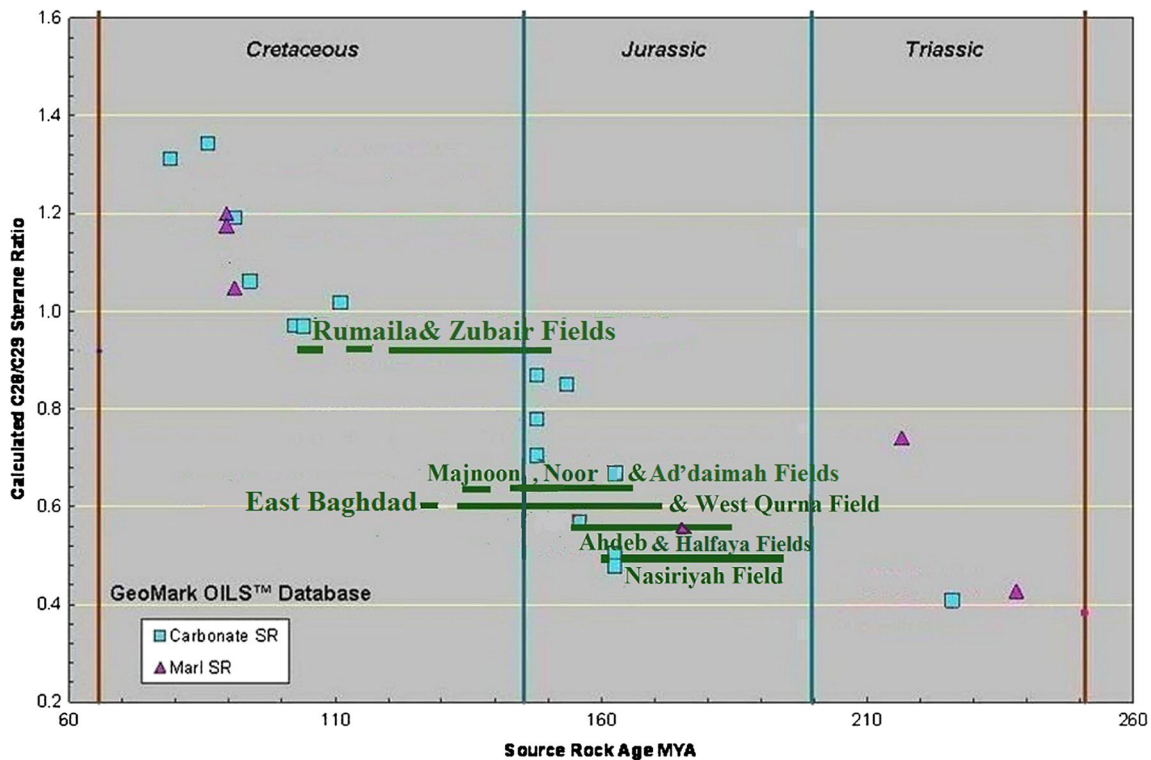
**Fig. 4** Microscopic views of the organic matters in light microscope. **a** Structured organic matter (Palynomorphs) examples of Jurassic and Lower Cretaceous source rocks in Iraq (*the first and second horizontal rows of the photographs*) and of Lower Palaeozoic source rock examples in West Iraq (*the third photographic row*) that could indicate high hydrocarbon generation and form the base for most biomarker peaks in the

Palaeozoic, Cretaceous, and Tertiary reservoir oil. **b** Amorphous organic matter types for the main efficient oil source rocks of the Ordovician Khbour/Lower Silurian Akkas, Middle Jurassic Sargelu, Upper Jurassic/Lower Cretaceous Chia Gara and Sulaiy, and Middle Cretaceous Zubair Formations in Iraq

dinoflagellate cysts, which are fluorescent under fluorescence microscope (Fig. 4a, the upper and middle horizontal row photographs) as well as amorphous organic matters of kerogen type A (Fig. 4b, photographs 1 and 3). This indicates one family for Mesopotamian Basin oil sourced from kerogen of the Upper Jurassic and Lower Cretaceous source rocks with some exceptions of Middle Jurassic Sargelu Formation source for most reservoirs of the fields of this basin.

Oil biomarkers of the accumulated oil were assessed by graphical presentation of the calculated C28/C29 sterane ratios (Fig. 5). Oil grouping in the fields of Mesopotamian Basin could be grouped into two main families; the first family is sourced from Upper Jurassic/Lower Cretaceous source ages of the Sulaiy Formation (Al-Ameri and Batten 1997; Al-Ameri

et al. 2009a) with C28/C29 values about 9.2, especially oil fields of Rumaila and Zubair with other nearby oil fields of the Basrah Governorates. The second family is oil coming from the reservoirs of West Qurna, Majnoon, Halfaya and oil fields in the border with Zagros fold belt in the east, Nasiriyah oil field in the Euphrates subzone, and Abo-Jir fault in the west. Ahdeb and East Baghdad oil fields are two types whose pay zone source comes from the Middle Jurassic Sargelu Formation with C28/C29 values ranging between 5.0 and 6.2 while other pay zones are mixed with oil of Middle and Upper Jurassic of the Sargelu and Naokelekan formations. In general, the fields near well-established faults such as near the Zagros belt and Abo Jir fault as well as Ahdeb field near active Ali Al-Gharbi fault are mainly of Middle Jurassic oil source



**Fig. 5** Calculated average C28/C29 sterane ratio (based on both regular steranes and triaromatic steranes) of reservoir oils from Mesopotamian Basin suggesting a source rock of ages. Other data points represent

average oil values from 150 global petroleum systems from marine carbonate, distal marine shale, marine marl, and lacustrine shale source rocks from GeoMark Research OILS™ database

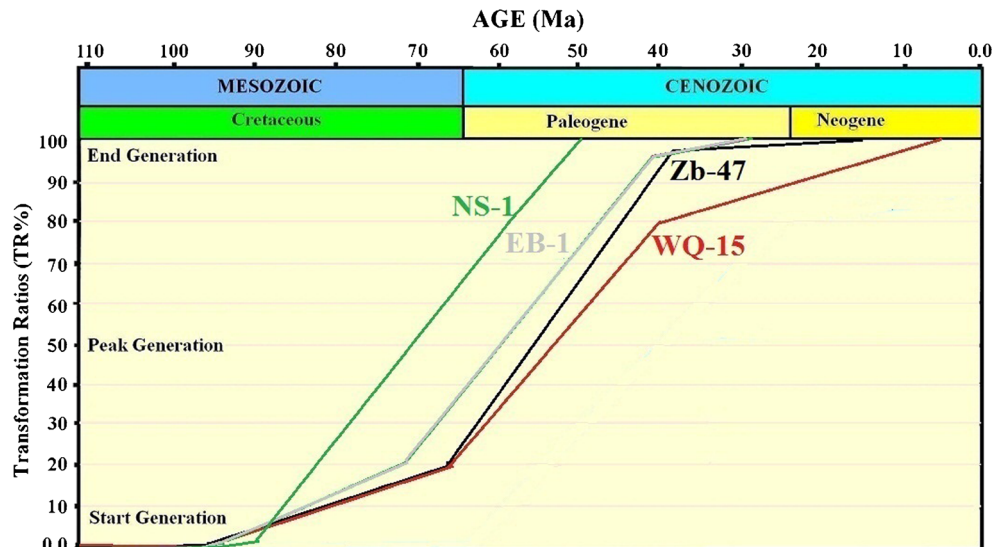
while the fields of Basrah Governorate with thick Upper Jurassic Anhydrite of lower regional seal are mainly sourced from Upper Jurassic/Lower Cretaceous Sulaiy Formation.

Timing hydrocarbon generation and secondary migration, based on PetroMod software modeling (Fig. 6), are performed on Upper Cretaceous/Lower Tertiary (Al-Ameri et al. 2013b) tectonics with 100 % transformation of the potential organic matter to oil and gas and hence accumulated in the already

present traps of mainly Cretaceous structural framework of the Mishrif, Khasib, Tannuma, Saadi, Ahmedi, Maudud, Nahr Umr, Shuiba, Ratawi, Yamama, Tayarat, and Zubair formations. Dismigrated oil from Cretaceous reservoirs was accumulated in the Tertiary reservoirs such as that of the heavy oil in the Miocene Ghar Formation.

Structural framework of mainly low relief folding could form the main traps in these regions with some stratigraphic

**Fig. 6** Hydrocarbon transformation curves of the Mesopotamian Basin through time based on PetroMod software modeling for the Upper Jurassic/Lower Cretaceous of the Sulaiy-Chia Gara Formations in the wells of EB-1 of East Baghdad oil field, WQ-15 of West Qurna oil field, Zb-47 of Zubair oil field, NS-1 of Nasiriyah oil field as case studies

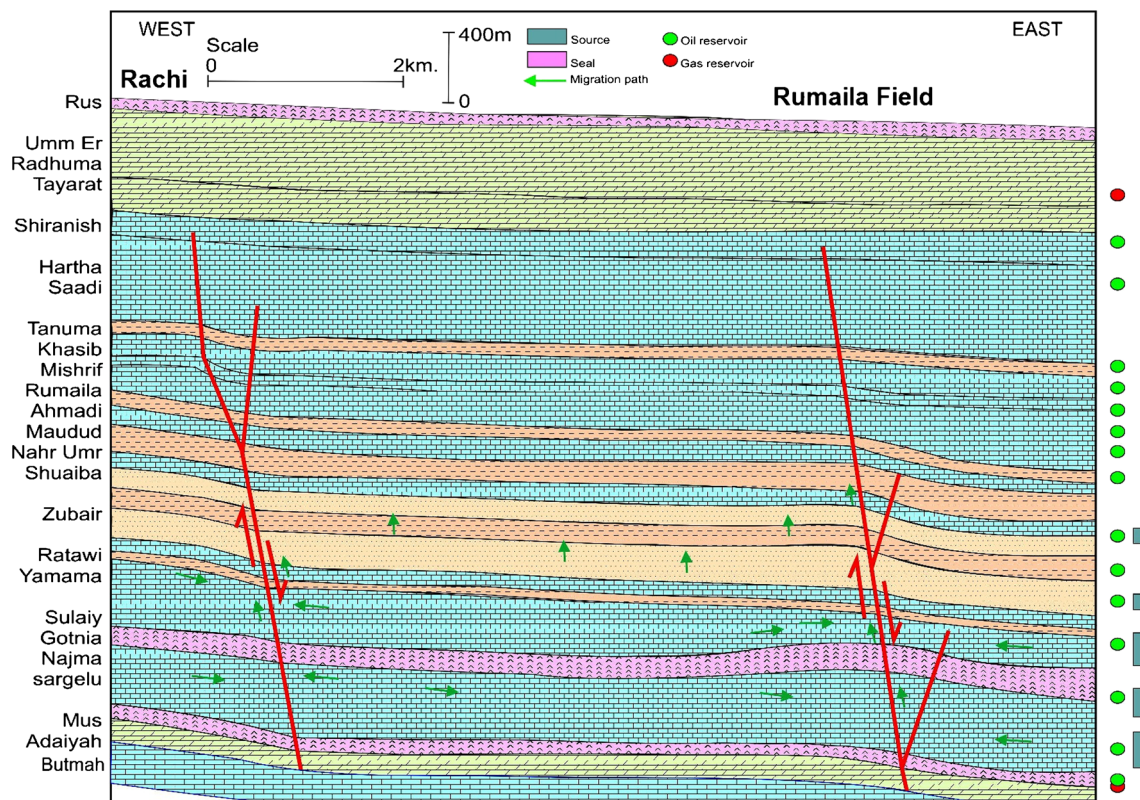


traps and vertical oil movements being the main migration pathways as well as horizontal migration along carrier beds (Fig. 7). The vertical movements are along faults that extend up to the Upper Cretaceous Shiranish Formation of Cretaceous reservoirs from the secondary oil migration. The reservoirs are mainly carbonates such as the Mishrif Formation (Fig. 8) and clastic reservoirs such as Zubair Formation. Accordingly, the generated oil from mainly Upper Jurassic/Lower Cretaceous Sulaiy Formation were generated from horizontal migration along carrier beds of Yamama and Ratawi formations and vertical migration along the faults to charge the Cretaceous reservoirs. The Upper Jurassic Gotnia Anhydrite Formation may act as seal for Jurassic oil passage to the Cretaceous reservoirs with some exceptions along fractures of the fault site to allow mixing of the oil generated from Sargelu and Naokelekan formations to be mixed with the Sulaiy oil in some places.

**Oil fields of the Zagros fold belt** This belt constitutes the mountains of northern (Nineva, Dohuk, and Erbil Governorates), northeastern (Diyala and Sulaymania Governorate), and eastern part of Iraq (eastern part of Wasit and Mesan Governorates) with geographic extension in the east to Zagros Mountains of Iran and Turkey. Its western side border is the Mesopotamian Basin and Khleisya Uplift

(Fig. 1a). The stratigraphic extent of this fold belt is the Lower Jurassic regional seal of Allan Anhydrites Formation while its upper regional seal is the Middle Miocene Fatha (Lower Fars) Anhydrite Formation (Fig. 9) based on sequence stratigraphy of Sharland et al. (2001), while its extent in the northeastern part reaches the low folded Zagros fold Belt of transition to the Mesopotamian zone, which mainly extend from the lower regional seal of the Upper Jurassic Gotnia Anhydrite Formation to the upper regional seal of Fatha Anhydrite Formation (Al-Ameri et al. 2006, 2011a, 2013c; Al-Ameri and Zumberge 2012).

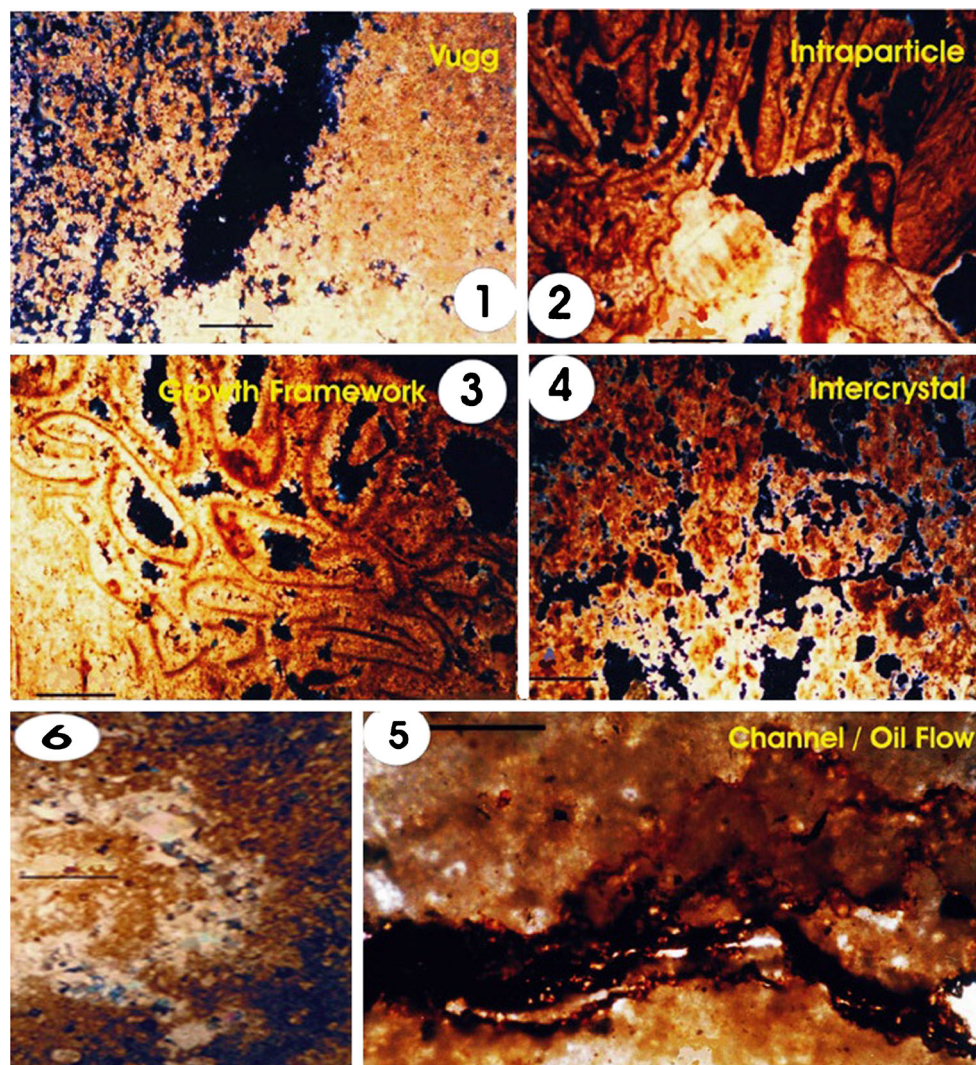
Al-Ameri and Odisho (1992), with modification in Al-Ameri et al (2011a), had constructed isogeothermal map (Fig. 1b) of North Iraq, which helped in the assessment of organic matter maturation and the gas and oil distributions in NE Iraq. The contours are based on thermal alteration indices (TAI) of the color changes of verrucate spores of the species *Hamulatisporites amplus*. These maturation assessments record geothermal effects on the Paleocene–Lower Eocene equivalents of the Kolosh and Aaliji formations in the studied area. The studied localities include outcrop exposures at Zakho, Dokan, Aqra, and Khaneqin and well locations Pulkhana-7, Mansuriyah-1, and Jambour-18. Brown-colored miospores with a thermal alteration index of 2.5–2.8 indicate geothermal temperatures of 120–180 °C and correspond to a



**Fig. 7** Structural cross section based on seismic section along Rumaila-Ratawi-Raje oil fields showing migration path to assess hydrocarbon accumulation sites in Mesopotamian Basin



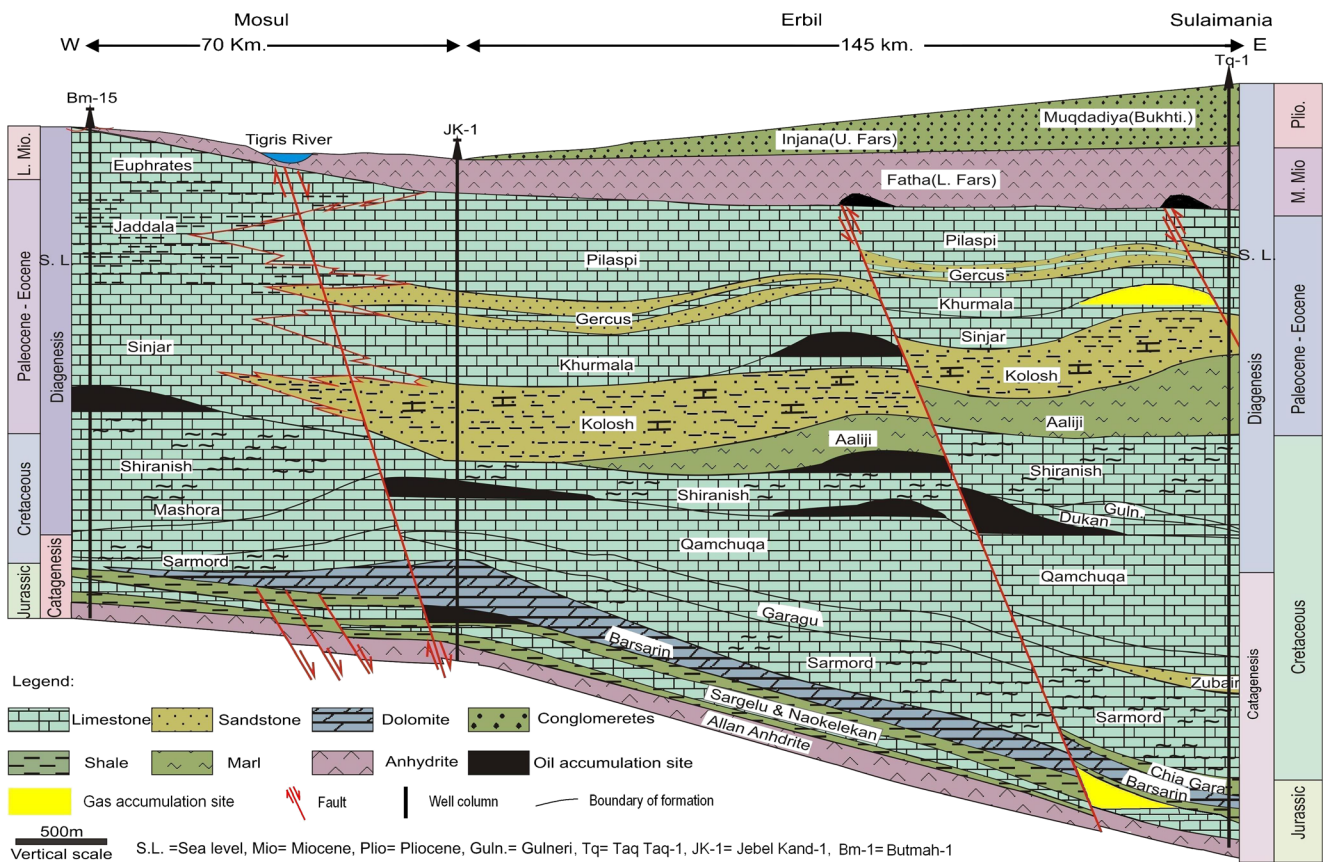
**Fig. 8** Porosities of the Mishrif Formation reservoirs in the Mesopotamian Basin as site for hydrocarbon accumulation



“late mature” level of source-rock maturation with the generation of wet gas and oil. The area bounded by the 120 and 180 °C isogeothermal contours coincides with the area of gas- and oilfields. Geothermal values in the Paleocene/Lower Eocene increase from immature in the Mesopotamian Basin to mature in the Zagros fold belt. At higher maturities, oil is cracked to gas (c.f. Staplin 1977; Tissot and Welte 1984; Batten 1996b; Hunt 1996). The gas-bearing reservoirs at Khashim Ahmar, Mansuriya, Tel Ghazal, Hattaba, Habib, Mandeli, Jaria Pika, and Nheirat fields are located between the 120 and 150 °C iso-contours. Oilfields such as Injana, Gillabat, Qumar, Chia Surkh, Nadoman, and Naft Khana are located between the 90 and 150 °C iso-contours. The promising area for hydrocarbon generation, migration, and accumulation, which were not recorded earlier, could be the area bounded by isogeothermal lines at 60 and 120 °C, including the area of Erbil Governorates as continuity between Kirkuk and Mosul Governorates (Al-Ameri and Odisho 1992) in North Iraq. This zone contains the subsurface oil source rocks

in the case of favorable depositional environments of organic matter quantity and quality of the source rocks which could be Sargelu Formation in this area (Al-Ameri et al. 2006, 2013c).

Plots of  $\delta^{13}\text{C}$  aromatic and saturated oil isotopes of the oil fields of Naftkhana, Gillabat, Jambour, Kirkuk, Che Chamal, Taq Taq, Qara Chuq, Ajeel, Bai Hassan, Demir Dagh, Allan, Butmah, and Ain Zala on Sofer’s (1984) diagram (Fig. 2) are showing three semi-isolated clusters; the first clustered zone comprised the brown dots of the Erbil and Kirkuk Governorates, Duhok and Kirkuk Governorates with green rectangles of the Middle Jurassic source rocks while the second cluster includes the orange dots of the Diyala Governorate oil fields with red rectangle of the Upper Jurassic Sulaiy and Chia Gara Formations source rocks. The third cluster is the purple rectangular dots for the Upper Triassic Qurra Chine Formation oil. Furthermore, source age assessment of these oils could confirm Jurassic, Upper Jurassic/Lower Cretaceous, and Upper Triassic ages, equivalent to the depositional times of the Sargelu, Chia Gara, and



**Fig. 9** Structural cross section of traverse down to the Middle Jurassic Sargelu Formation based on stratigraphic column of the wells Taq Taq oil and gas field (*Tq-1*), Jebel Kand field (*JK-1*), and Butmah oil field (*Bm-*

*15*) and fault locations of Zagros fold belt of North Iraq. Oil accumulation sites in their traps could be assessed on this section

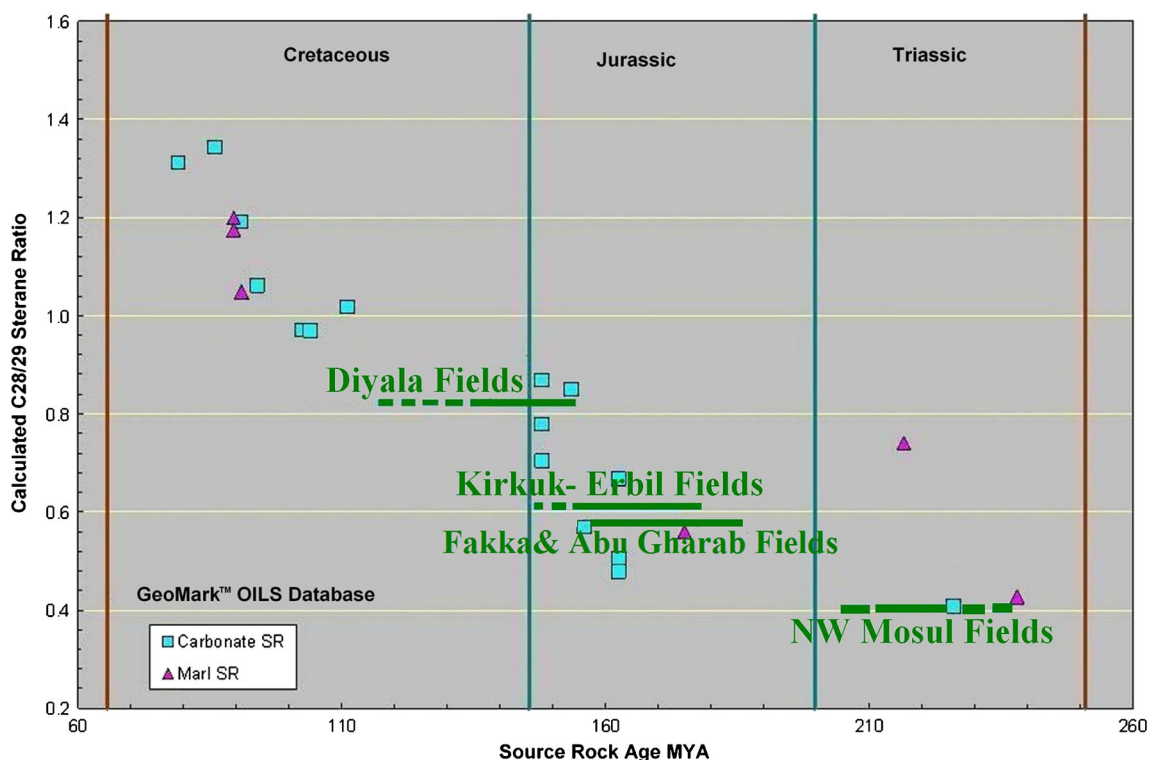
Qurra Chine formations (Fig. 3, arrows 3, 4, and 5) by plotting reservoir oil isotopes of  $\delta^{13}\text{C}\%$  on Andrushevich et al.'s (2000) stable carbon isotope age-assignment diagram. The organic matter sources of these oils are the sedimentary disseminated particles of the Middle Jurassic and Upper Jurassic/Lower Cretaceous palynomorphs of mainly the Chlorococcale algae, fungi, foraminiferal test lining and dinoflagellate cysts that are fluorescent under fluorescence microscope (Fig. 4a, the upper and middle horizontal row photographs) as well as amorphous organic matters of kerogen type A (Fig. 4b, photographs 1 and 3).

Oil biomarkers of the accumulated oil were assessed by graphical presentation of the calculated C28/C29 sterane ratios (Fig. 10) and confirmed these two clusters to show Middle Jurassic oil source age with C28/C29 ratio of 0.6–0.62 for Kirkuk oil fields and Upper Jurassic/Lower Cretaceous oil source age with C28/C29 ratio of 0.8–0.82 for Diyala Governorates oil fields.

This indicates two subfamilies for the mainly Tertiary Zagros reservoir oil; the first is of only Middle Jurassic Sargelu Formation source while the second is of the Upper Jurassic/Lower Cretaceous Chia Gara Formation as well as Middle Jurassic Sargelu Formation source. These Tertiary oil

accumulation and stratigraphic extension of source-reservoir relations in the Zagros are referred to as Tertiary petroleum systems of two oil families. Oil and gas field examples are from pay zones of the Middle Miocene Jeribe Euphrates Formation in the Diyala region (Al-Ameri et al. 2011a) sourced from mixed oil from Sargelu and Chia Gara formations (Fig. 11), Kirkuk group of the Oligocene oil in the Kirkuk region and Demir Dagh in Erbil are sourced from only Sargelu Formation (Al-Ameri et al. 2006, 2013c; Al-Ameri and Zumberge 2012). The extended Zagros fold belt in the Mesan Governorate contains oil of Middle Jurassic source in the Fakka, Buzurkan, and Abo Gharab oil fields that accumulated in the reservoirs of Jeribe, Kirkuk group, Saadi, and Mishrif formations. Nearly similar oil characters in the Zagros of the Mesan Governorates are recorded with C28/C29 ratio of 0.57. The third family is the Triassic oil in the Western part of North Iraq that is sourced from the Triassic with C28/29 ratio of 0.40.

The modeled timing and extent of oil and gas generation events in the area of study are only approximate due to the complex fold geometry in the region; nevertheless, they can be assessed from transformation ratios on each locality. For example, by taking the case of extent of oil generation of the



**Fig. 10** Calculated average C28/C29 sterane ratio (based on both regular steranes and triaromatic steranes) of Cretaceous and Tertiary reservoir oils from Northern Iraq, suggesting three families of a source rock ages for northeastern, northern, and northwestern areas in North Iraq. Other data

points represent average oil values from 150 global petroleum systems from marine carbonate, distal marine shale, marine marl, and lacustrine shale source rocks from GeoMark Research OILS™ database

Sargelu Formation (Fig. 12), the Sargelu strata have generated 100 % of their organic matter potentiality to generate mainly during six to four million years ago in the Miocene time and hence charged mainly Tertiary reservoirs as well as Cretaceous strata in their high porosities (Fig. 13a, b). Accordingly, the controlling factor for the hydrocarbon generation, migration, and accumulations of oil and gas in the Zagros fold belt is the Alpine Orogey.

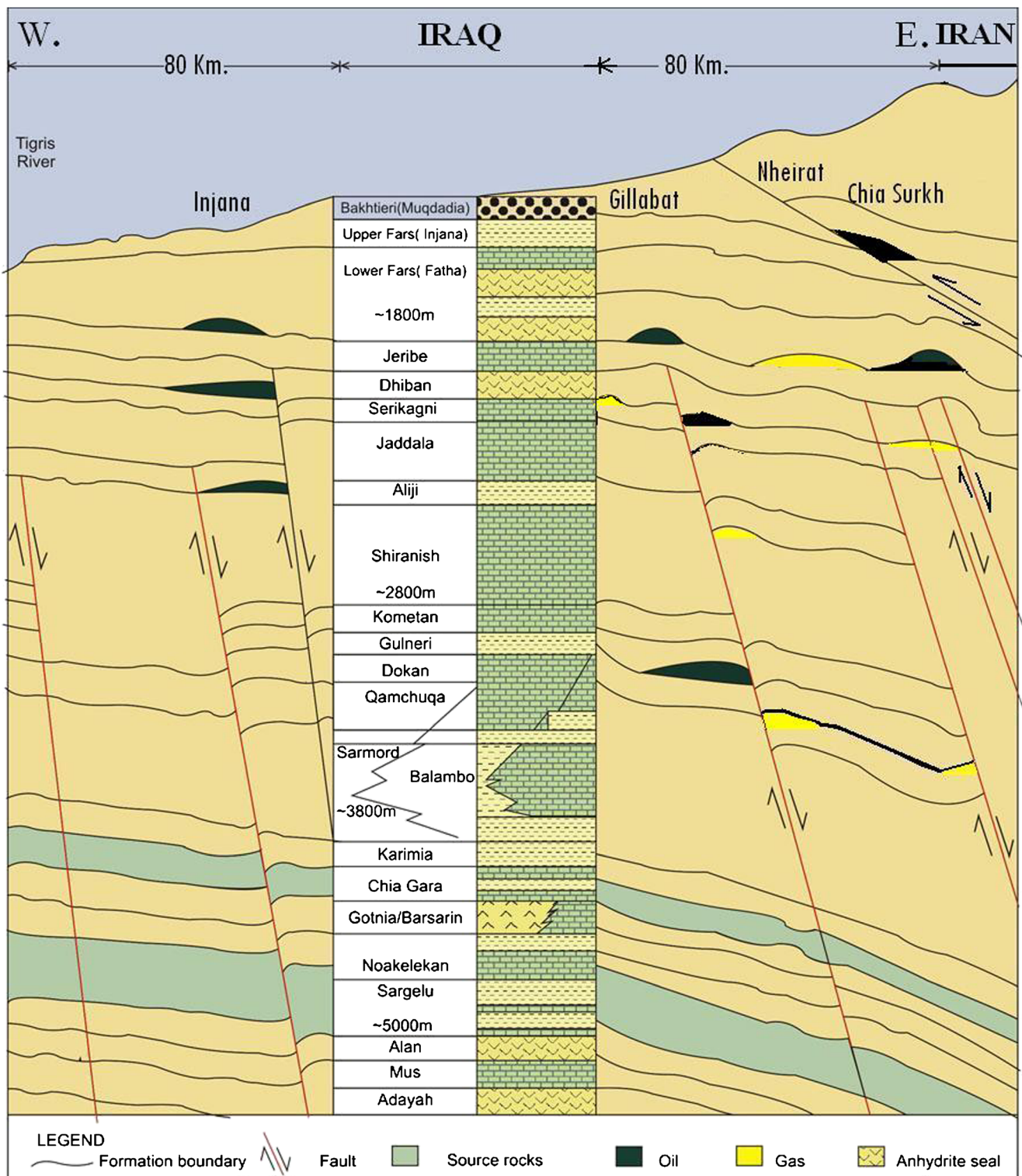
Hydrocarbon seeps could occur in the Zagros as gas in the site of Kirkuk and oil in the sites of Zakho, Rowandoz (Fig. 14), and Naft Khaha. Structural framework of folding and faulting could form the main traps in these regions.

*Trapping of oil in the Euphrates river subzone of West Iraq Area covered for this zone (Fig. 1c) mainly run along the border between the two basins; the Mesopotamian and Widian Basins along Abo Jir fault that extends from Therthar Lake through Euphrates River from the city of Heet down to the city of Nasiriyal (Al-Ameri and Al-Khafaji 2013), extending into Anah Graben to include Haditha localities. Sources of their oil and seeps are obtained by using PetroMod software modeling, which shows migration from the Zagros and Mesopotamian Basin of mainly Jurassic Sargelu (Pitman et al. 2004) and Chia Gara Formation, which accumulated in mainly fault structural traps as well as fold structural of the*

Cretaceous Ratawi, Shuaiba, Khasin, and Hartha formations. Although Pitman et al. (2004) did not include any oil or source-rock analysis, they gave base work for further studies for exploration in this promising area.

Plots of  $\delta^{13}C$  aromatic and saturated oil isotopes of the oil seeps Heet, Abo Jir, Karba, and Najaf as well as oil of Nasiriyah field on Sofer’s (1984) diagram are showing equivalence to Mesopotamian oil (Fig. 2). Furthermore, source age assessment of these oils could confirm Middle Jurassic, Upper Jurassic/Lower Cretaceous age, equivalent to the depositional times of Sulaiy, Chia Gara, and Sargelu formations (Fig. 3, arrows 4 and 5) by plotting reservoir oil isotopes of  $\delta^{13}C\%$  on Andrussevitch et al.’s (2000) stable carbon isotope age-assignment diagram. The organic matter sources of these oils are the sedimentary disseminated particles of the Jurassic and Lower Cretaceous palynomorphs of mainly Chlorococcale algae, fugi, foraminiferal test lining and dinoflagellate cysts that are fluorescent under fluorescence microscope (Fig. 4a, the upper and middle horizontal row photographs) as well as amorphous organic matters of kerogen type A (Fig. 4b, photographs 1 and 3).

Oil biomarkers of the accumulated and seeps in the sites of Abo Jir (Fig. 15a), Heet (Fig. 15b, c), Najaf (Fig. 15d), Karbala, and Haditha were assessed by graphical presentation of the calculated C28/C29 sterane ratios (Fig. 16). They have

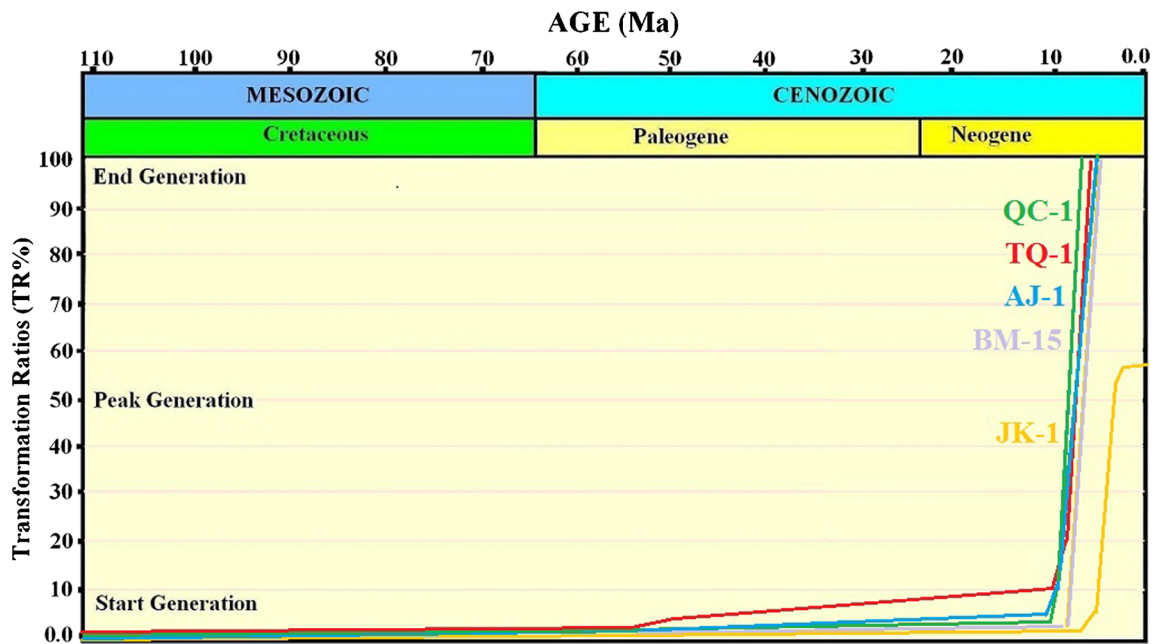


**Fig. 11** Schematic cross section of NE Iraq of Zagros fold belt in Diyala Governorate based on stratigraphic column from Bellen et al. (1959), fault locations of Al-Ameri and Zumberge (2012, Fig. 1), seismic section

of Al-Ameri et al. (2011a, b, Fig. 14), and oil and gas fields of Fig. 1. Mainly structural traps could be assessed on this section with oil and/or gas accumulations

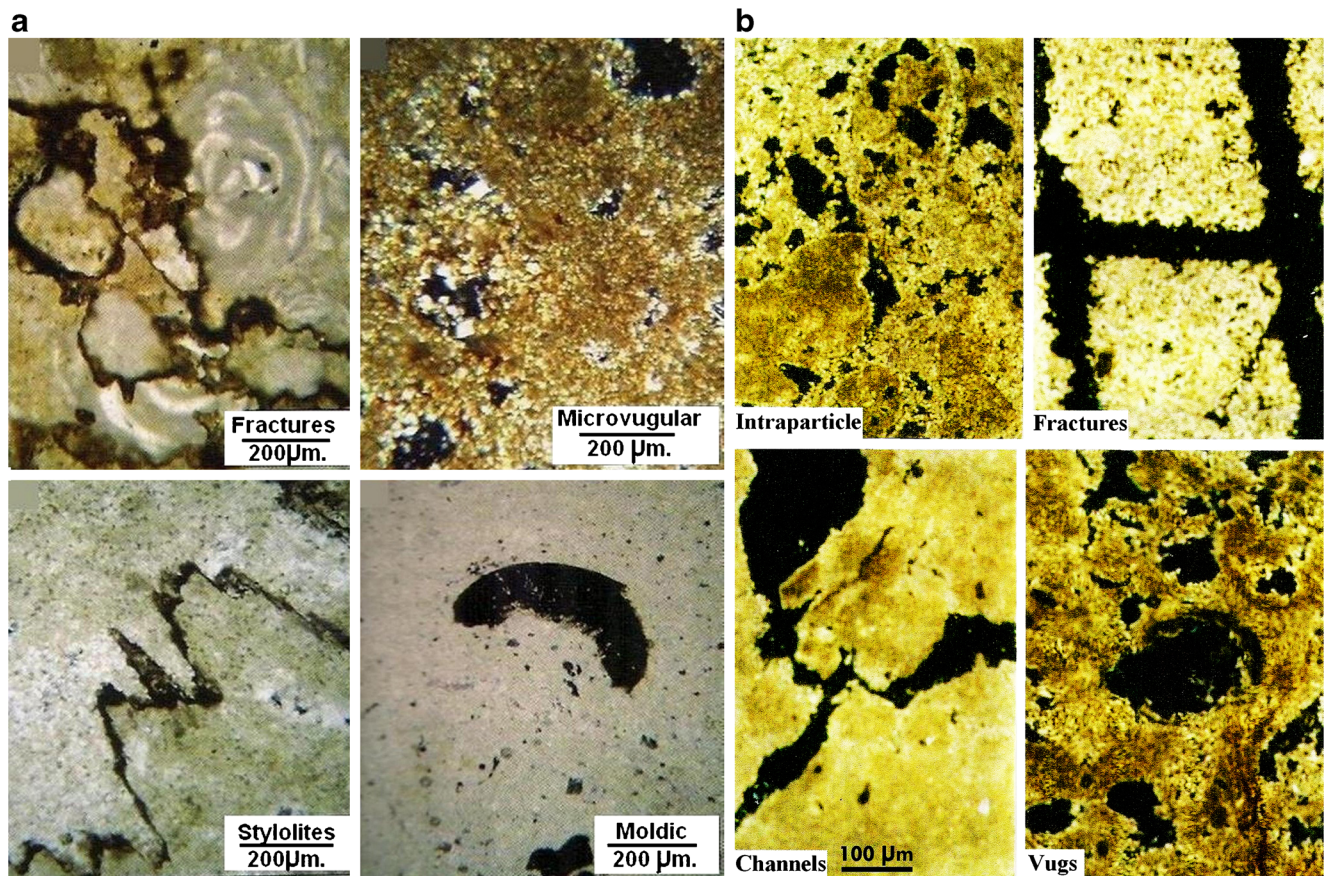
indicated three main clusters to show Jurassic oil source age affinity for Abo Jir and Heet oil seeps, Middle and Upper Jurassic oil source age affinity for Najaf and Haditha oil and

gas seeps, and Upper Jurassic/Lower Cretaceous for Karbala oil and gas seep with C28/C29 ratio of 5.00, 7.00, and 9.00, respectively.



**Fig. 12** Hydrocarbon transformation curves of the Zagros fold belt through time based on PetroMod software modeling for the Jurassic Sargelu formation in the wells QC-1 of Qara Chuq field, TQ-1 of Taq

Taq-1, AJ-1 of Ajeel field, BM-15 of Butmah field, and JK-1 of Jabal Kand field as case studies. After Al-Ameri and Zumberge (2012) and Al-Ameri et al. (2013a, b, c)



**Fig. 13** Carbonate porosity types of the Zagros fold belt reservoirs of **a** Qamchuqa Formation reservoir in Khabbaz oil field (after Aqrawi et al. 2010) and **b** Jeribe Formation in Jambour oil field (after Al-Ameri et al. 2011a, b)



**Fig. 14** Oil seeps near Rowandouz city located in the northern part of Erbil Governorate within Zagros fold belt, Bekhme Formation

Because of low maturation and poor to fair organic matter content of these sites (Al-Ameri and Al-Khafaji 2013; Pitman et al. 2004), the seeped oil and accumulated oil of mainly middle Jurassic Sargelu Formation and the lower part of the Upper Jurassic Naokelekan and Najmah Formations have been primarily migrated to the Euphrates River region; this scenario is confirmed by incomplete transformation of the disseminated organic matters to oil based on PetroMod software basin modeling for the Upper Jurassic/Lower Cretaceous Sulaiy Formation of the case studies of the fields Kifile, West Kifile, Merjan, and Falluja (Fig. 17) while the Middle Jurassic

Sargelu Formation gate complete transformation of the organic matters to oil. The Sargelu Formation in this area is of poor to fair TOC (Al-Ameri and Al-Khafaji 2013, Fig. 9). The main effect of transformation to oil or gas is the back retardation tectonics that cause partial transformation (30–100 %) and continued generation to present time with no effect of Alpine Orogeny.

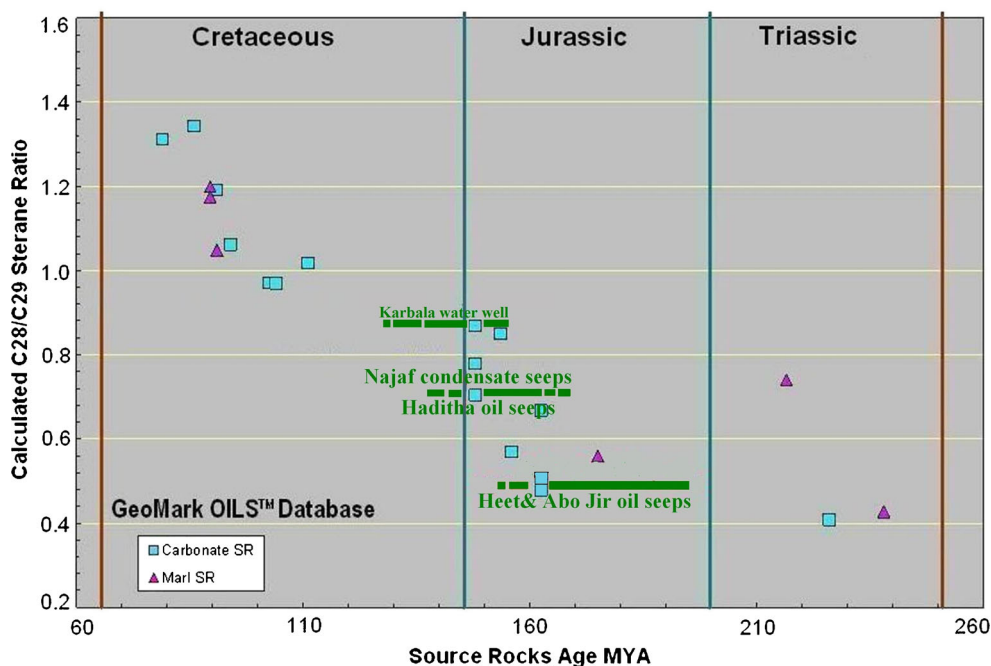
To construct a framework model of the oil migration pathways, a detailed structural cross section could be done for line A–B of Fig. 1c. Abo Jir Fault is shown in the figure to give the site for upward oil migration. For more details, the interpreted seismic section of Mohammed (2006) along Megaseismic line 7 are used in part (Fig. 18), which are showing the faults and anticline folding structure from Central Mesopotamia in East Baghdad oil field through Abo Jir Fault to end with Ekhaider field (Ek-1).

Accordingly, the generated hydrocarbon from Central Mesopotamian Basin expelled to the Upper part of the Najmah Formation. This last formation acted as a carrier bed because of its high porosity, inclination, and the overlying Upper Jurassic Gotnia Anhydrite Formation seal. Oil and gas possessed westward secondary migration within porous and fractured upper unit of the Najmah Formation toward the Kifile area where the Abo Jir major Fault is located. At this last site, the oil and gas started vertical migration, and hence reached the Cretaceous and Tertiary closures of the successive layers with the faults and anticlines and ended with seeps along Abo Jir, Karbala, and Najaf locations.

**Fig. 15** Oil and gas seeps along Euphrates River in **a** Abo Jir village southern of Ramadi city, **b** Heet oil seeps about 180 km northwestern Ramadi, **c** Heet oil seeps from anhydrites of the Fatha Formation, and **d** Najaf gas and condensate seeps that burned vegetation about 10 km west of the Holly city Najaf



**Fig. 16** Calculated average C28/C29 sterane ratio (based on both regular and triaromatic steranes) of oil and gas seeps from the cities of Heet, Abo-Jir, Najaf, and Karbala along Euphrates River and Abo Jir Fault. Other data points represent average oil values from 150 global petroleum systems from marine carbonate, distal marine shale, marine marl, and lacustrine shale source rocks from the GeoMark Research OILS™ database



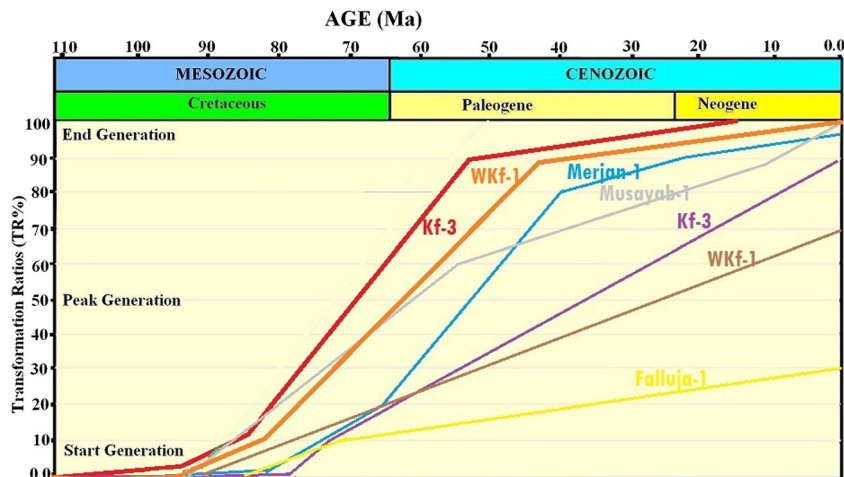
Lateral dissipation of the migrated oil have impregnated all the layers through and charged the main reservoirs of Nahr Umr and Hartha formations with dissipations to higher strata just below the Upper regional seal of Lower Fars (Fatha) Anhydrite. From Fatha Anhydrites, all the seeps are observed, which passed through fractures to the ground surface.

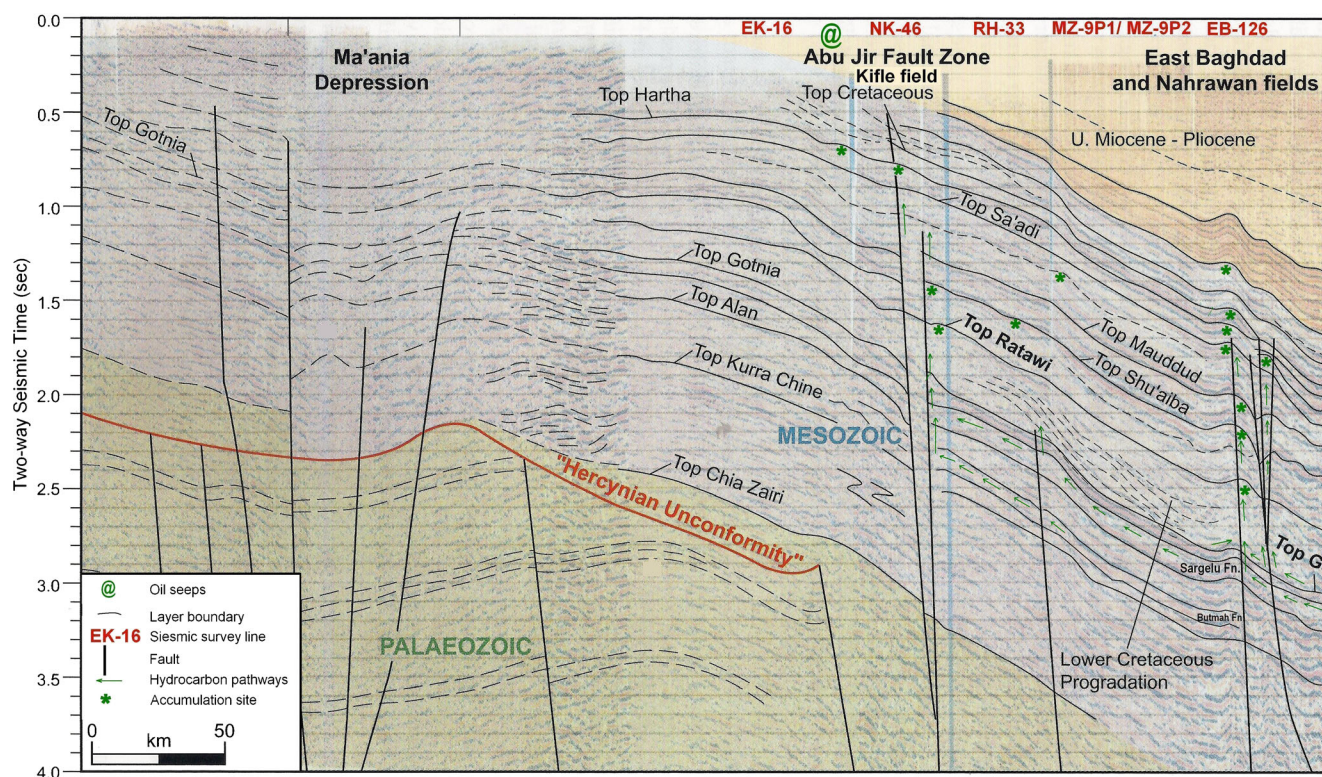
*Gas fields of the Widian basin-interior platform* Giant gas field of Akkas was discovered in the west of Iraq with little oil. It is located in the Widian Basin with Anah Graben to the North and Rutba Uplift to the South (Fig. 1a) with stratigraphic extent in the Lower Palaeozoic Akkas and Khabour Formations and the Upper regional seal is the Upper Devonian impermeable shale of the Kaista Formation (Figs. 20 and 21). Hydrocarbon source assessments are

elaborated by Al-Ameri (2010) mainly on palynofacies basis (Fig. 19). The organic matter sources of these gas and oils are the sedimentary disseminated particles of the Ordovician and Lower Silurian palynomorphs of mainly Clorococcale algae such as *Tasmanites*, Prasinophyte acritarchs, *Pediastrum*, as well as chitinozoa, which are fluorescent under florescence microscope (Fig. 4a, lower horizontal row photographs) as well as amorphous organic matters of kerogen type A (Fig. 4b, photograph 4).

Maturation assessment for the Silurian and Ordovician successions are based on TAI and fluorescence microscopy of the acritarchs *Diexallophasis denticulata* for the Silurian and Upper Ordovician succession along with *Orthosphaeridium ternatus* and *Baltisphaeridium constrictum* for the Ordovician succession. The color measurements of

**Fig. 17** Hydrocarbon transformation curves of the Middle Euphrates River region through time based on PetroMod software modeling for the Upper Jurassic/Lower Cretaceous of the Sulaiy Formation in the wells Kf-3 of Kifle field, WKf-1 of West Kifle field, Me-1 of Merjan field, and Fa-1 of Fallujah field. The Sargelu Formation curves (red and orange) are for the wells Kf-3 and WKf-1





**Fig. 18** Cross sections of Fig. 1b for SW-NE cross section of megaseismic line 7 from Ekheither to Kifle fields through East Baghdad field crossing the Euphrates River in Karbala Governorates, based on the section presented by Mohammed (2006). Vertical black lines are faults.

The constituent seismic line sections are EK-16 for Ekheither, NK-46 for Najaf-Karbala, RH-33 for Razzaza-Habbaniya Lakes, MZ9P for Madaean-Aziziya, and EB-126 for East Baghdad survey areas. Green asterisk are for probable site of hydrocarbon accumulations

these species are compared with the color standards of Philips Petroleum Company (Pearson 1990) and correlated with vitrinite reflectance technique to evaluate the deposit temperature and the maturation level of the studied organic matters. Measurements are taken specifically on borehole Akkas-1 as basic values for organic matters in other boreholes, and hence affixed on the stratigraphic cross section of the investigated wells (Fig. 20) and to be used as guidelines for maturation assessments.

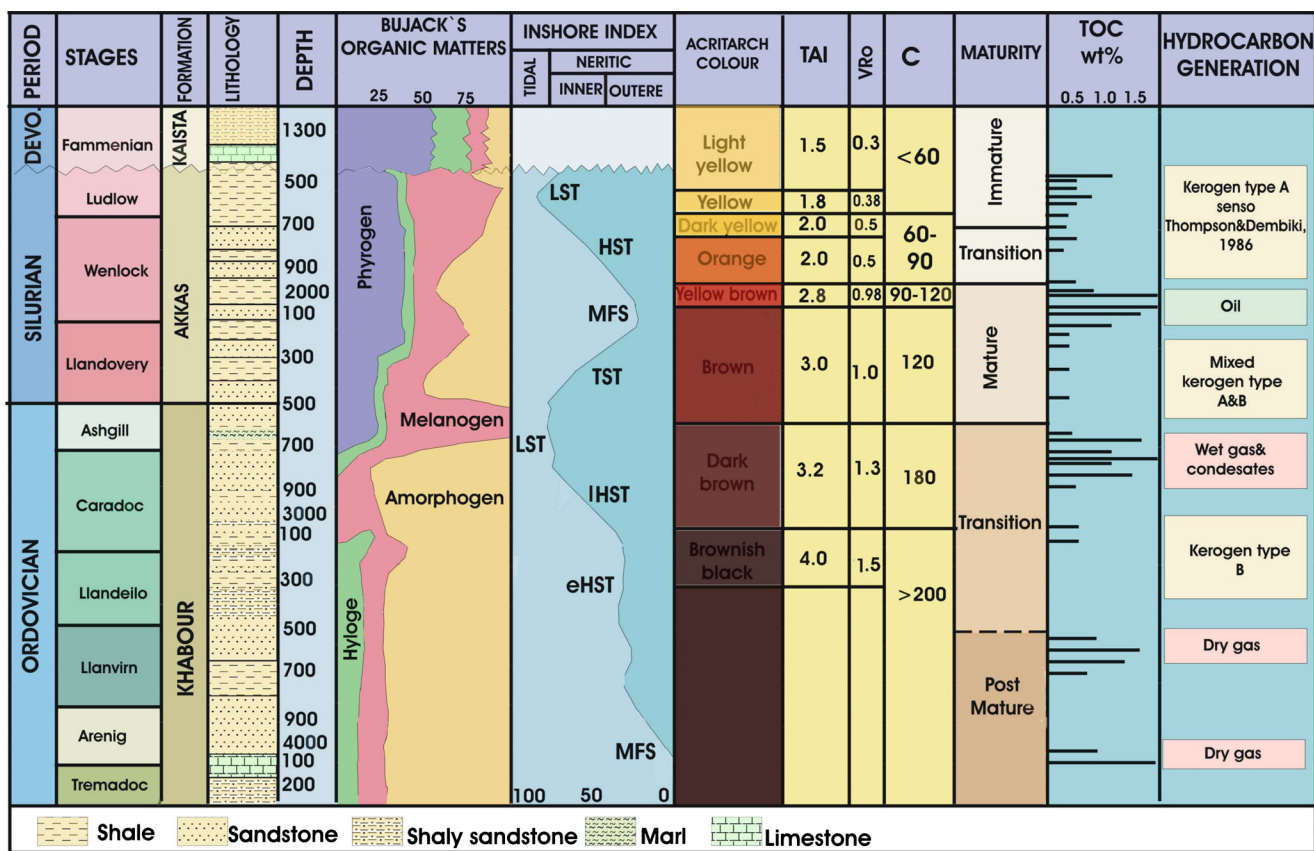
The types of AOM are compared with the ideal and global microscopic kerogen types of Thompson and Dembicki (1986). Other techniques used involved plotting TAI measurements as well as sedimentary organic matter types using Bujak's model (*sensu* Bujak et al. 1977). These organic matters contain up to 16 % TOC, especially for the hot shale of the Lower Silurian Akkaz Formation, very low asphaltene and sulfur, saturated and aromatic hydrocarbons of more than 96 %, and high peaks of C<sub>2</sub>/C<sub>20</sub> GC, which could indicate predominant gas generation with some light oils. The associated gases are mainly methane and ethane of CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, and C<sub>3</sub>H<sub>8</sub>. Accordingly, and on the basis of the assembled parameters chart of organic matters maturity, quantity, and types (Fig. 19), the generated hydrocarbon has been assessed as sweet with no H<sub>2</sub>S. These are wet gas and condensate from

depths of 2,750–3,000 m of Upper Ordovician age with TAI= 3.8 and TOC=0.71–1.42, dry gas from depths of 3,570–3,650 m of Lower Ordovician age with TAI=4.0 and TOC= 0.5– 1.2, and oil from depths 2280–2330 m of Lower Silurian age with TAI=2.0 and TOC=0.4–16 wt.%.

These hydrocarbons are of mainly Lower Paleozoic Petroleum Systems (Al-Ameri 2010) that constitute Upper regional seal of unconformity of the Hercynian Orogeny, followed by deposition of nonpermeable Upper Devonian shale of the Kaista Formation on top of Silurian Akkas Clastic Formation of sandstones and shale. Gas pay zones are found in the Silurian Akkas and Ordovician Khabour formations while their main source could be the Ordovician Khabour Formation as well as the oil shale of the Lower Silurian Akkas Formation (Fig. 20). Maturation variations with depths were the main agents to generate more gas from deeper strata of Ordovician age, while the little oil could have been generated from the hot shale of the Lower Silurian. Al-Ameri (2010) claimed that the Lower Palaeozoic hydrocarbon accumulations in the neighboring Jordan and Syria are also of this petroleum system.

Structural framework of folding and faulting as well as stratigraphic facies changes could form the main traps in these regions.





**Fig. 19** Hydrocarbon generation potential chart predicted from collide stratigraphical variations in kerogen types (senso Bujak et al. 1977) palaeoenvironments, maturation assessments and total organic carbon

(TOC) in Akkas and Khabour Formations of borehole Akkas-1. OM organic matter, TAI thermal alteration index, TR Tremadocian, VRo vitrinite reflectance value, °C degree centigrade

**Formation petroleum system**

This could include naming of petroleum system of pod of reservoir oil in individual formation that could be formed by local seal and divided into these two groups:

*Intra-formational* This type includes hydrocarbon generation, migration, and accumulation in the same formation that contains source, carrier, reservoir, and seal beds to form local petroleum system related to one formation of mainly stratigraphic traps, such as:

- *Clastic*: Barremian-Aptian Zubair Formation in the Basrah region constitutes layers of sand reservoirs and shale source rocks while seal could be the shale itself forming mainly facies stratigraphic traps (Al-Ameri et al. 2011b). Calculated C28/C29 sterane ratio of oil from reservoirs of the Zubair Formation in Rumaila, Ratawi, and Zubair oil fields (Fig. 22) showed 1.18 that could indicate Lower Cretaceous source age of Barremian to Albian for some pay zones. Comparison by plots from Global Geomark Oils™ database could confirm source

for the oil accumulated in other pay zones of the Zubair Formation with either source affinity to Upper Jurassic/ Lower Cretaceous Sulaiy Formation with C28/C29 equals to 9.2 or Middle and Upper Jurassic Sargelu and Naokelekan Formation oil source for the rest of the pay zones with C28/C29 ratio of 6.00. Furthermore, source-age assessment of these oils could confirm Lower Cretaceous age, equivalent to Zubair Formation depositional times of the first group (Fig. 3, arrow 6) by plotting Zubair reservoir oil isotopes of  $\delta^{13}C\%$  on Andrusevitch et al.'s (2000) stable carbon isotope age-assignment diagram. The organic matter sources of these oils are the sedimentary disseminated particles of the Lower Cretaceous palynomorphs of mainly fungi, foraminiferal test lining, resin, and dinoflagellate cysts that are fluorescent under fluorescence microscope (Al-Ameri and Batten 1997; Al-Ameri et al. 2011b), as well as amorphous organic matters of kerogen types A and B (Fig. 4b, photographs 1 and 2).

- *Carbonate*: Middle Triassic Kurrachine Formation of Mosul Region (Al-Ameri et al. 2009b), which constitutes layers of fractured limestone of channel porosity and

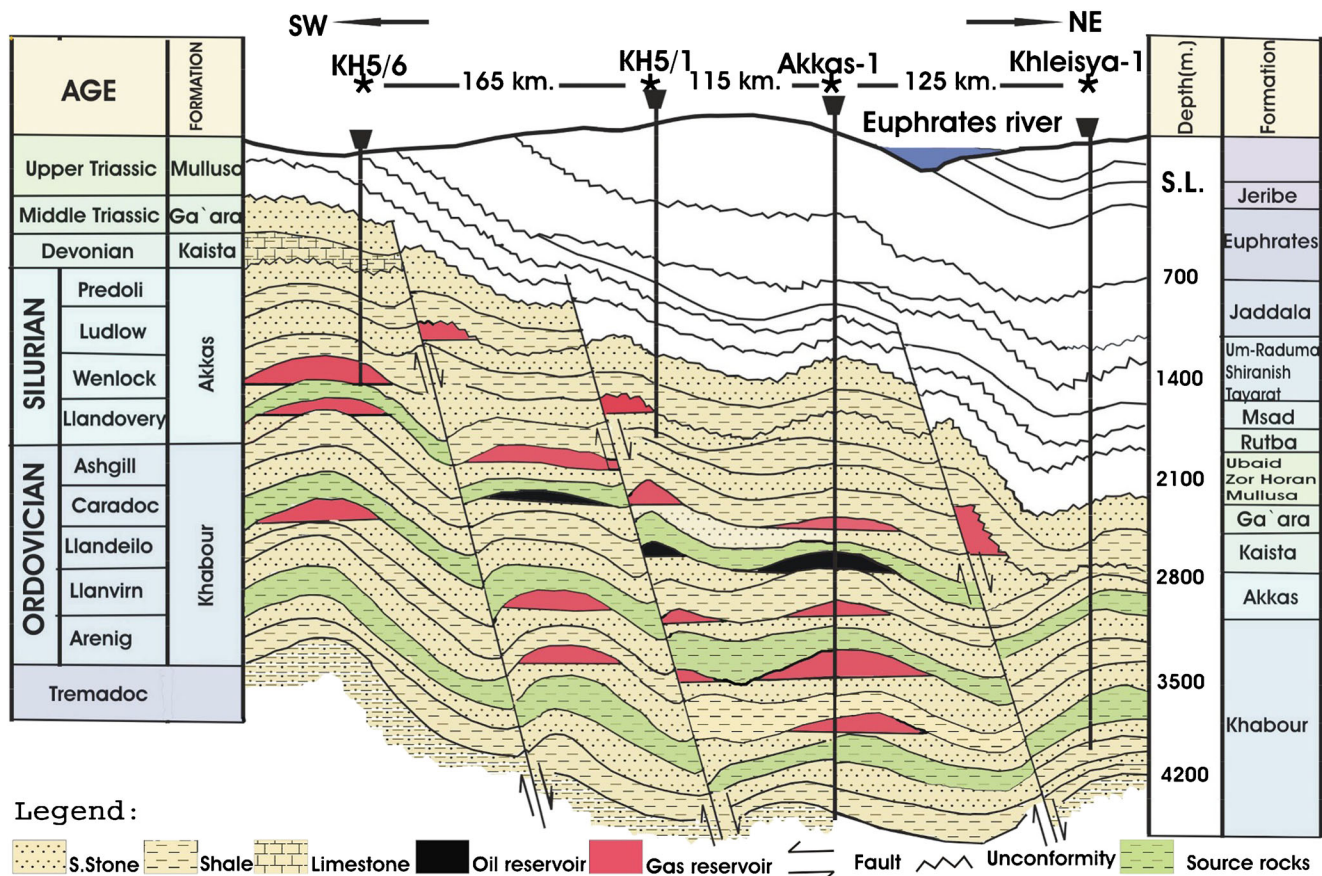


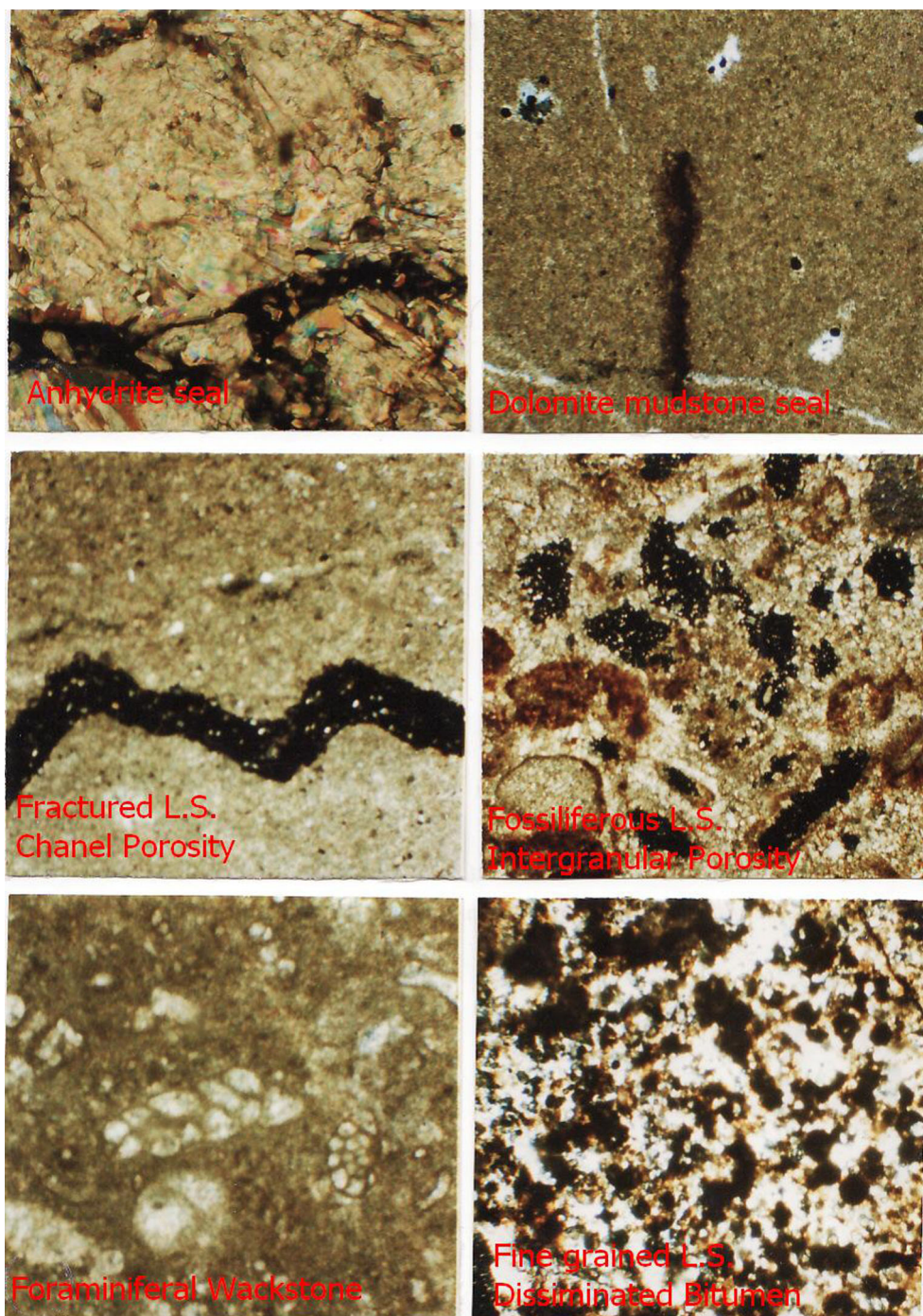
Fig. 20 Structural cross section through the investigated wells with locations of the predicted oil and gas sources and reservoirs in West Iraq

fossiliferous limestone of intergranular porosity as reservoirs and foraminifera wackstone and bituminous fine-grained limestone as source rocks while the impermeable anhydrite and dolomite mudstone as seal (Fig. 21) to form mainly facies traps. Palynofacies and pyrolysate organic matter evidences from the source rock parameters are most appropriate to indicate that Kurrachine Formation have generated hydrocarbon from the fossiliferous and bituminous facies. These generated hydrocarbons based on PY-GC (Al-Ameri et al. 2009a, b) could be heavy gas oil of C19/C25, which exhibited short migration and trapped within Kurrachine Formation due to low ratio of Pr/n C<sub>17</sub> in the kerogen, and hence accumulated near the generated site. A calculated C28/C29 sterane ratio of the generated oil from Kurrachine Formation is 4.0 (Fig. 22), which indicates Triassic source of the oil, which might be comparable to the Kurrachine Formation age. Furthermore, source age assessment of these oils could confirm Upper Triassic age, equivalent to the depositional time of the Qurrachine Formations (Fig. 3, arrow 3) by plotting Qurrachine reservoir oil isotopes of  $\delta^{13}C_0$  on Andrusevitch et al.'s (2000) stable carbon isotope age-assignment diagram.

– *Carbonate*: limestone and marl strata of Yamama Formation in Nasiriyah oil field could have successive permeable and nonpermeable layers. The oil constituents of some pay zones of the Yamama Formation give same age assignment of Lower Cretaceous time as the Yamama Formation with C28/C29 ratio of 6.2 (Fig. 22) in the Nasiriyah Field; the generated oil from the Yamama Formation is trapped in the same formation by the marl seal. Furthermore, source-age assessment of these oils could confirm Upper Jurassic/Lower Cretaceous age, equivalent to the depositional times of Sulaiy Formations (Fig. 3, arrow 5) by plotting Yamama reservoir oil isotopes of  $\delta^{13}C_0$  on Andrusevitch et al.'s (2000) stable carbon isotope age-assignment diagram.

*Affinity formation* Other cases of formation petroleum system is the naming after the reservoir oil of a formation with affinity to a source rock of one or many formations other than the named formation for such petroleum system. An example is the Mishrif oil petroleum system described in the Nasiriyah

**Fig. 21** Thin section photographs of the rocks of Triassic Kurrachine Formation in NW Iraq of, seal (anhydrite and dolomites), reservoir (fractured and Fossiliferous limestones), and source (Foraminiferal wackstone)

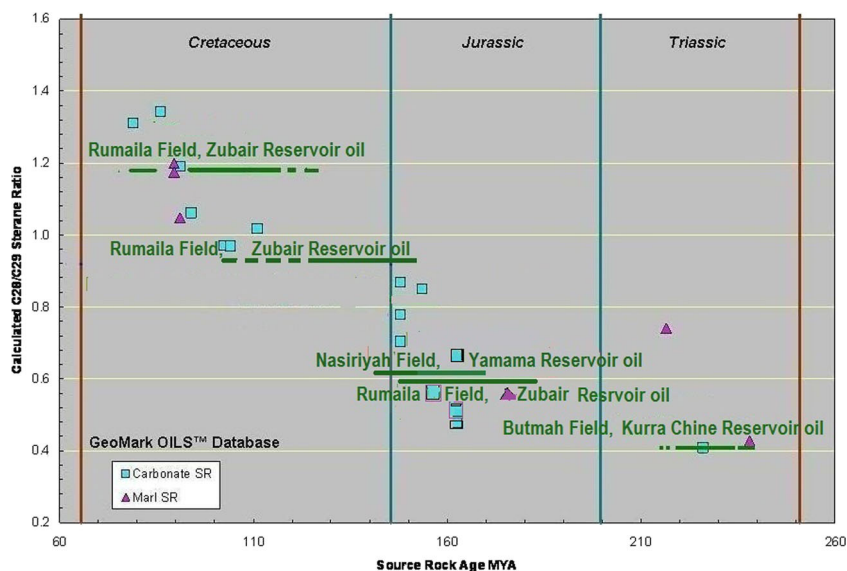


oil field. The oil in this case was accumulated in the porous and permeable carbonate bed of the Upper Cretaceous Mishrif Formation and sealed by the marl and shale interlayers of the same formation while their source affinity is mainly the Jurassic Formation of the Sargelu with a C28/C29 ratio of 6.0 (Fig. 22). Another example is the Mishrif Formation oil (Al-Ameri et al. 2009a, b) in the Rumaila and Zubair fields that is sourced from Upper Jurassic Sulaiy Formation of a C28/C29 ratio of 9.2.

Petroleum system for mineral genesis

It is used to describe petroleum generation and maturation that could help in the genetic identification of minerals. A case study in Iraq for such phenomena is sulfur development from anhydrites and gypsum in the Mishraq Sulfur Mine (Al-Ameri and Al-Jubouri 1992) in Mosul Region. The study was based on observations of sulfurous beds within the Lower Fats (Fatha) Formation in Makhlat borehole and absent in the same

**Fig. 22** Calculated average C28/C29 sterane ratio (based on both regular steranes and triaromatic steranes) of reservoir oil from the Zubair, Yamama, and Kurra Chine Formations. Other data points represent average oil values from 150 global petroleum systems from marine carbonate, distal marine shale, marine marl, and lacustrine shale source rocks from the GeoMark Research OILS™ database



formation in the Shoura borehole, while the associated rocks are anhydrites, limestone, shale, and sandstones with bitumens especially near the sulfur occurrences (Fig. 23)

Data in the genesis include the evolution of nonaerobic bacterial species *Desulfovibrio africano* and *D. vulgaris* as well as *Saccharomyces* and *Escherichia* on the kerogen during diagenetic stage of the hydrocarbon generation ten million years ago; they metabolize on the gypsum to form sulfur crystals and crystalline limestone with increasing thermal energy. This case could confirm the genesis and the increase of sulfur formation in Mishraq Sulfur mine (Fig. 24) based on the following pieces of evidence:

1. Association of bitumen with sulfur, limestone, and gypsum in the same piece of rock could bond their interrelation in the sulfurization genesis.
2. Increased cumulative accumulation of sulfur in the rock with decrease of gypsum and appearance of crystallized limestone could explain their successive stages.
3. Gradual changing of structured organic matter to amorphous organic matter with increased sulfur formation could explain the diagenetic stage of oil generation to evolve the anaerobic bacteria that changed the gypsum to sulfur and limestone with occurrence of the bitumen to get the carbon for this transformation.
4. Darkening of the organic matters with the formation sulfur could explain the thermal maturation due to emission of heat by sulfur crystallization and evolution of calcite crystals.

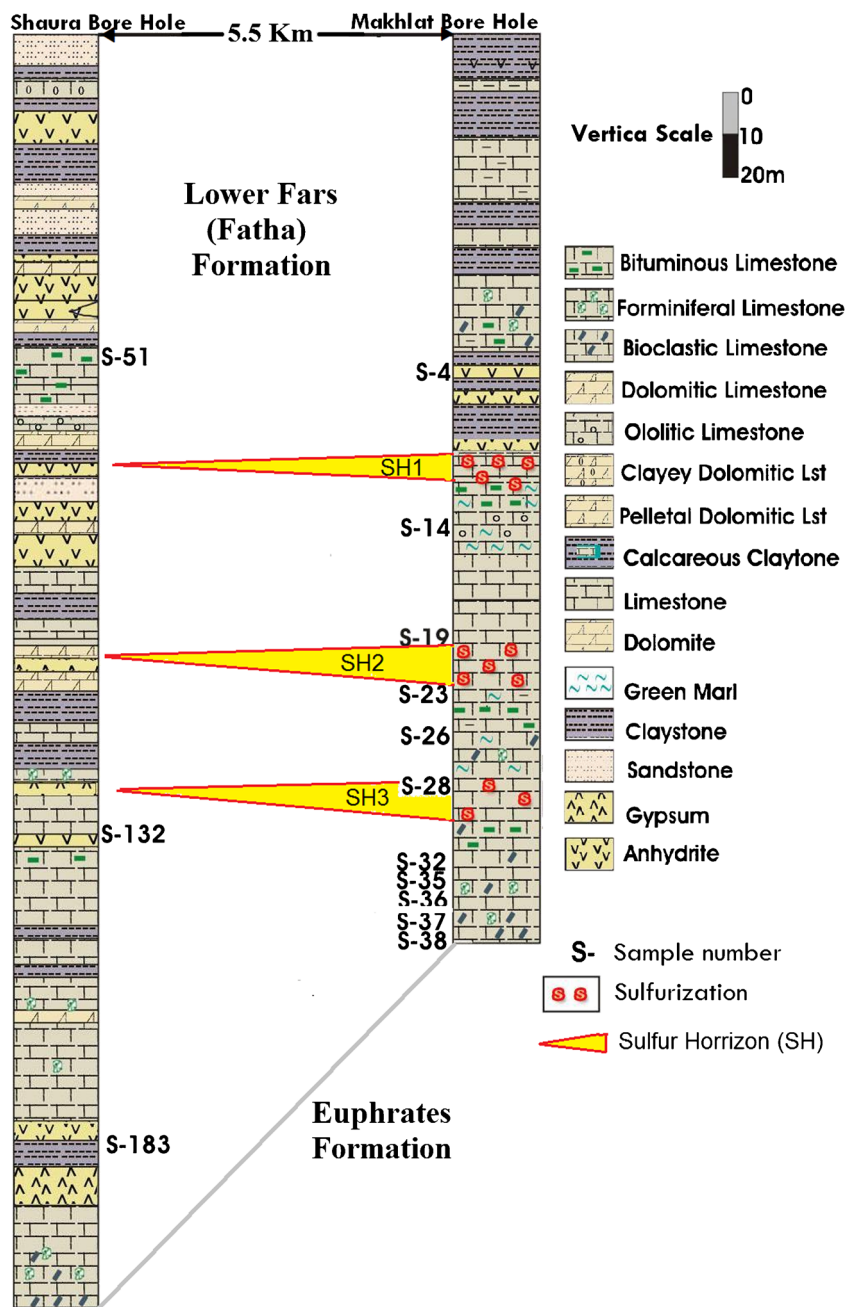
### Conclusions and recommendations

1. Main oil sources in Iraq, which form the base for assessing family types and bonds to petroleum system

types are five that are proved by C28/C29 and grouped together within the  $\delta^{13}\text{C}$  (%) diagram of aromatic versus saturates (Fig. 2), which contains both lots of oil analysis and source rock extracts; these are the following; (i) Middle Jurassic of the Saegelu Formation in North Iraq (Fig. 3, arrow 4), (ii) Sargelu and Chia Gara Formations in Diyala and Baghdad (Fig. 3, arrows 4 and 5), (iii) Upper Jurassic/Lower Cretaceous Sulaiy Formation in Basrah oil fields (Fig. 3, arrow 5), (iv) Triassic Kurracine Formation of Northwest Iraq (Fig. 3, arrow 3), and (vi) Lower Paleozoic Khabour and Akkas Formation of West Iraq (Fig. 3, arrows 1 and 2).

2. Main oil traps are in all parts of Iraq within the structure of the Cretaceous formed by Upper Cretaceous Orogenies and Tertiary formed by the Upper Miocene Alpine Orogeny, which closed the Tethyan Ocean, stratigraphy of the Middle Triassic Kurracine Formation and Lower Cretaceous Rarawi, Zubair, and Nahr Umr formations, as well as reef framework of the Upper Cretaceous Mishrif Formation and Oligocene Kirkuk group. Undiscovered traps within each petroleum system mentioned in this study could be recommended for further studies in the petroleum geology of Iraq.
3. Main gas accumulations are mainly in the Silurian Akkas Formation of West Iraq and Cretaceous-Tertiary of NE Iraq in the high Zagros fold belt as well as associated gas in most oil fields in Iraq.
4. Hydrocarbon migrations are mainly vertical through faults and fractures in most parts of Iraq with special cases in North Iraq as well as horizontal through carrier beds everywhere in Iraq.
5. Accumulation sites are porosities and fractures, especially in the formation of carbonate reservoirs of the Mishrif in the South, Khasib and Tannuma in Central, Hartha in the

**Fig. 23** Stratigraphic successions of the sulfur deposits in the Lower Fars (Fatha) in Mishraq Sulfur Mine based on Makhlat Borehole for the sulfur bed and Shoura Borehole for non sulfurous bed outside the sulfur deposits with extensions of the sulfur horizons in Mishraq



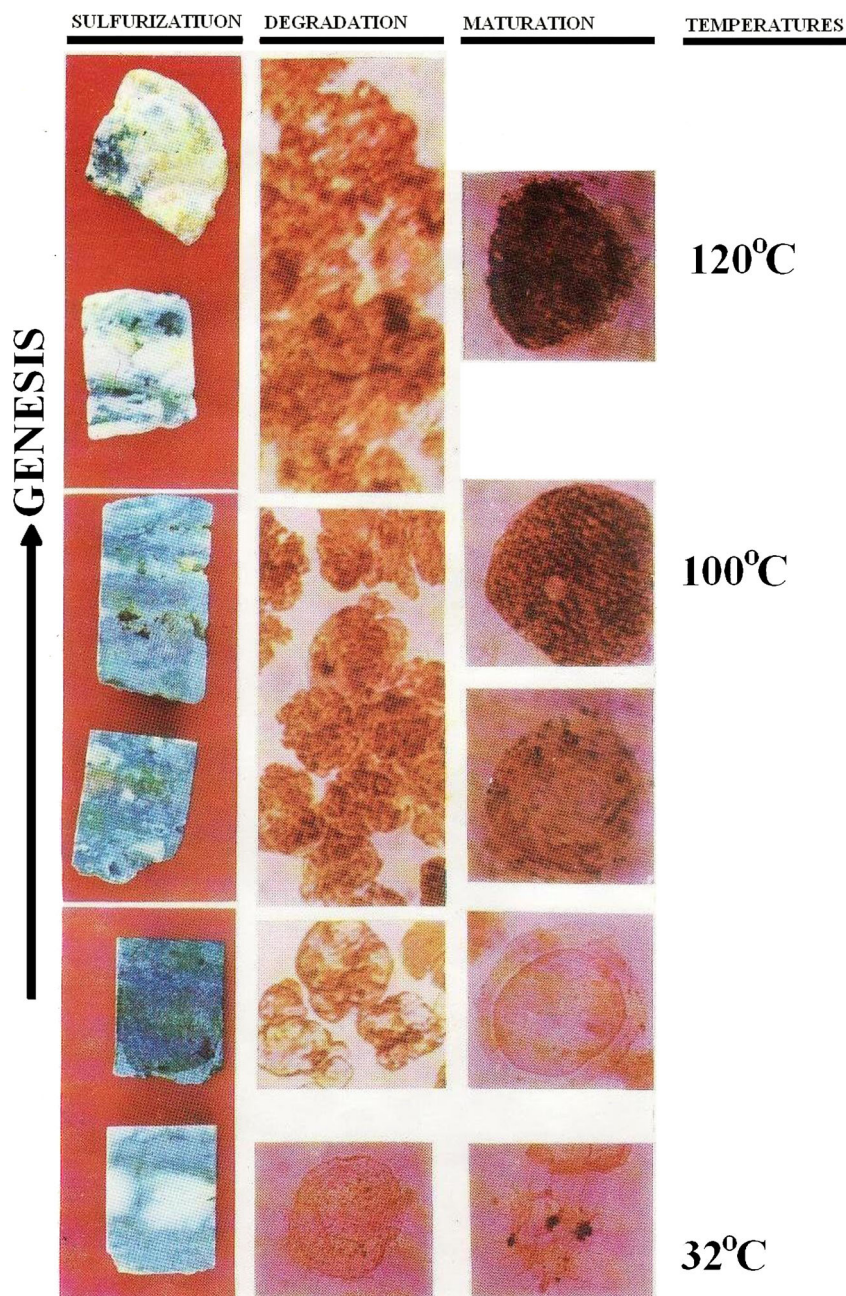
West, and Kirkuk group and Jeribe in the North as well as clastic reservoirs of the Zubair and Nahr Umr.

6. TPS are elements and processes within two (lower and upper) regional seals or could be confined to one formation and exhibit short migration such as Middle Triassic Kurrachine in NE Iraq or wide stratigraphic range as Upper Cretaceous Mishrif Formation sourced from Upper Jurassic/Lower Cretaceous Sulaiy Formation in South Iraq (Fig. 5) and Upper Cretaceous-Tertiary reservoirs sourced from Middle Jurassic Sargelu Formation or from mixed Sargelu Formation and the Upper Jurassic/

Lower Cretaceous Chia Gara Formation of North Iraq (Fig. 10). Special cases include one formation petroleum system of Zubair and Yamama Formations that each fed from the same formation while others fed from older formation such as the Sargelu Formation source rocks (Fig. 22)

7. The main regional seal for the total petroleum system of the Jurassic, Cretaceous, and Tertiary in Iraq are Upper Jurassic Gotnia Anhydrites Formation as lower regional seal while the Middle Miocene Lower Fars (Fatha) Formation is of upper regional seal in the Mesopotamian

**Fig. 24** Collide photographs showing sulfur genesis in the rocks anhydrites containing bitumen in parallel with organic matter changing preservation to amorphous organic matters changing palynomorphs to more mature



Basin and Dyala Governorates. Gotnia Anhydrites disappear in North Iraq in the Zagros fold belt, and hence the lower regional seal would be the Lower Jurassic Allan Anhydrites.

8. Crude oil characterization. It is partly discussed in our previous studies while a detailed description could be recommended for further studies on petroleum geology and geochemistry of Iraq.

**Acknowledgments** Oil biomarkers and isotopes are analyzed by Geomark Research Ltd (Houston, Texas) during the last 10 years through Dr. John Zumberge to whom I give sincere acknowledgments and thanks. Oil and source rock samples as well as the seismic sections are obtained

from the National Oil Companies in Iraq to whom sincere acknowledgments could be given. Many thanks go to my PhD and MSc students who cooperated with me in performing some projects on Iraqi oil fields.

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