Geochemical characterisation, volumetric assessment and shale-oil/gas potential of the Middle Jurassic–Lower Cretaceous source rocks of NE Arabian Plate

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ABSTRACT

The Middle Jurassic–Lower Cretaceous strata of the NE Arabian Plate contain several prolific source rocks providing the charge to some of the largest world-class petroleum systems. They are located within the Zagros Fold Belt and Mesopotamian Foreland Basins covering the northern, central and southeastern parts of Iraq, Kuwait and western and southwestern Iran, particularly the Lurestan and Khuzestan provinces. These source rocks include the Bajocian–Bathonian Sargelu, the Callovian–Lower Kimmeridgian Naokelekan and the Upper Tithonian–Lower Berriasian Chia Gara formations of Iraq and their chronostratigraphic equivalents in Kuwait and Iran. They have charged the main Cretaceous and Cenozoic (Tertiary) reservoirs throughout Iraq, Kuwait and Iran with more than 250 billion barrels of proven recoverable hydrocarbons.

These formations represent the transgressive system tracts of sequences deposited within deep basinal settings and anoxic environments. They are dominated by black shales and bituminous marly limestones, with high total organic carbon (TOC) contents (ranging from 1–18 wt%), and by marine Type IIS kerogen. Their Rock-Eval S2 yields may reach up to 60 mg HC/g Rock, particularly along the depocentre of the Mesopotamian Foreland Basin. The immature hydrogen index (HI) values might have been up to 700 mg HC/g TOC, whereas the present-day observed values vary depending on the location within the basin and the present-day maturity. The Source-Potential Index (SPI; i.e. mass of hydrocarbons in tons, which could be generated from an area of 1 sq m in case of 100% transformation ratio) averages around 2–3, but can even reach up to 14–16 along the basins’ centres.

The Sargelu and the overlying Naokelekan-basinal Najmah formations (and their equivalents) could represent the best potential shale-gas/shale-oil plays in Iraq, Kuwait and Iran, due to their organic richness, favourable maturity and the presence of regional upper and lower seals. The estimated oil-in-place for the potential Sargelu shale-oil play in Iraq only is around 1,300–2,500 billion barrel oil-equivalent (BBOE) and in Kuwait is about 7–150 BBOE.

INTRODUCTION

The Middle Jurassic–Lower Cretaceous formations of north, central and eastern Iraq, as well as western and southwestern Iran contain some of the richest source rocks for one of the world’s largest petroleum systems (Ahlbrandt et al., 2000; Verma et al., 2004; Pitman et al., 2004; Jassim and Goff, 2006; Aqrawi et al., 2010). They are located within the Zagros Fold Belt and the Mesopotamian Foreland Basins of Iraq, Kuwait and the Lurestan and Khuzestan provinces of Iran (Figure 1). These principal source rocks include the Bajocian–Bathonian Sargelu, the Callovian–Lower Kimmeridgian Naokelekan/basinal Najmah and the Upper Tithonian–Lower Berriasian Chia Gara/Sulaiy/basal Garau formations (Beydoun et al., 1992; Al-Shididi et al., 1995; Sadooni, 1997; Pitman et al., 2004; Jassim and Goff, 2006; Al-Ameri et al., 2009; Aqrawi et al., 2010; Abeed et al., 2013; Figure 2). These source rocks have charged most Cretaceous reservoirs of Iraq and Iran and even some younger Cenozoic reservoirs (such as the Kirkuk Group of northern Iraq) through secondary migration (Verma et al., 2004; Goff, 2005; Jassim and Goff, 2006; Aqrawi et al., 2010; Abeed et al., 2011, 2013).

Other younger proven/potential Cretaceous source rocks, such as the Ratawi, Nahr Umr/
Kazhdumi and Ahmadi formations, and the older Palaeozoic source rocks and petroleum systems are not included in this study; they are summarised in Aqrawi (1998), Fox and Ahlbrandt (2002), Jassim and Goff (2006) and Aqrawi et al. (2010).

The main objectives of this study are to:

(1) assess and map the main Middle Jurassic–Lower Cretaceous source rocks of NE Arabian Plate, particularly in eastern Iraq, Kuwait and western Iran;
(2) quantify their thickness, lateral extent, organic richness and hydrocarbon generation potential throughout the entire Mesopotamian Foredeep and Zagros Fold Belt Basins;
(3) investigate their burial, thermal and maturity evolution and the timing of petroleum generation with 3-D basin modeling, in order to estimate the volumes of hydrocarbons generated;

(4) compare the estimated volumes to the proven in-place hydrocarbon resources volumes within certain discovered fields;

(5) After calculating the generated volume of hydrocarbons, the potential shale-gas and shale-oil plays are also identified and characterised based on these source rocks’ properties, lithology, burial depth and maturity. The main criteria for shale-gas or shale-oil plays were considered to be: (i) organic richness; (ii) kerogen type; (iii) maturity; (iv) thickness; (v) mineralogy (fracability and natural fracturing); (vi) the presence of upper/lower barriers; and (vii) the concept of the amount of residual (unexpelled) oil and gas (Jarvie et al., 2007).
This work is based on the presentation by Aqrawi and Badics (2013) and a more detailed unpublished study by the present authors. The present paper only employs published maps and organic geochemical information, and some of the utilised material was only available in Arabic.

GEOLOGICAL SETTING

Tectonically, the study area (Figure 1) comprises the Mesopotamian Foredeep Basin (i.e. USGS Province Code 2024), the Zagros Fold Belt (USGS Province Code 2030), the Zagros Thrust Zone and the easternmost parts of the Khleisia Uplift and Interior Platform (USGS Province Code 2023) as defined by the USGS (Pollastro et al., 1997; Ahlbrandt et al., 2000; Verma et al., 2004). Geographically the area includes central, northern and eastern Iraq, Kuwait and western Iran. The Mesopotamian Foredeep Basin forms a narrow zone that extends from northern Iraq to the northern Arabian Gulf. The basin is bounded to the east by the Zagros Fold Belt and to the west by the Interior Platform province. To the northwest, the basin converges with the Zagros Fold Belt, which extends along the Zagros Thrust Zone in both Iraq and Iran.

The Mesopotamian Foredeep Basin formed during the continental collision of the Arabian Plate with the continental blocks of Eurasia during Late Cretaceous (Murris, 1980; Ameen, 1992; Beydoun et al., 1992; Jassim and Goff, 2006). In Early Palaeogene the plate-margin deformation decreased, but in the late Palaeogene and Neogene continental convergence was renewed resulting in the Zagros orogenic event. The Zagros Orogeny was most active in the Late Miocene until Pliocene and resulted in the closure of the Neo-Tethys Ocean and development of the Mesopotamian Foredeep (Hooper et al., 1995). Reactivation of older fault systems was common, with compressional folding and faulting represented by the present-day Zagros Fold Belt (Beydoun, 1988, 1993; Ameen, 1992; Hessami et al., 2001; Homke et al., 2010; Csontos et al., 2012). The final uplift was accompanied by erosion that was locally extensive in the high folded belt.

The structural evolution of the Mesopotamian Foredeep Basin and Zagros Fold Belt is reflected in the NW-SE orientation of the present structures. The Mesopotamian Foredeep Basin was relatively less affected by tectonic compression; therefore it is mildly folded with increasing deformation eastward approaching the Zagros Mountains (Figure 1). Broad, pre-Neogene folds are oriented N-S in the southern part of the basin, which was referred to the activity of deep-seated Cambrian Hormuz salt tectonics following the trend of other giant structures of the Arabian Plate towards the south, such as Burgan and Ghawar anticlines (Al-Husseini, 2000; Sharland et al., 2001; Jassim and Goff, 2006). They were reactivated during the Carboniferous–Permian, Mesozoic and Cenozoic (Jassim and Goff, 2006). The structurally complex Zagros Fold Belt has a linear, NW-SE fold pattern that was created during Late Palaeogene and Neogene tectonics (Beydoun, 1993). Narrow compression structures, locally continuous for more than 100 km, developed during this event such as most of the high folded zone anticlines of Iraqi Kurdistan.

Figure 2 illustrates the Precambrian to Cenozoic stratigraphic section showing the lithostratigraphic units, and the tectonic phases in addition to the main source, reservoir and seal rocks, with an emphasis on Iraq, Kuwait and SW Iran. The investigated Middle Jurassic to Lower Cretaceous stratigraphy is shown in greater detail in Figure 3. The stratigraphic section varies from a maximum thickness of about 6.5 km along the axis of the Mesopotamian Foredeep Basin to 3–5 km towards the western margins. In the Zagros Fold Belt, the equivalent section ranges in thickness from 3 km in topographic lows to less than 1.5 km at deeply eroded topographic highs. During the Mesozoic and early Cenozoic, sedimentation was controlled by local tectonics, eustatic sea-level changes and climate variations (Sharland et al., 2001). From Jurassic through Late Cretaceous, sea-level fluctuations in conjunction with slow subsidence led to the formation of large shallow intrashelf basins on the passive margin of the Neo-Tethys Ocean and the Arabian Plate (Murris, 1980; Stoneley, 1987; Alsharhan and Nairn, 1997). Organic-rich sediments such as the Middle–Upper Jurassic Sargelu and Naokelekan source rocks accumulated in such basins under anoxic conditions, while high-energy bioclastic and oolitic carbonates were deposited along the basin margins on the carbonate-evaporite shelves. The Upper Jurassic Najmah limestone is the primary Jurassic carbonate-platform reservoir. This shallow-carbonate unit consists of oolitic limestones, dolomites and anhydrites that were deposited in a shallow-marine and transitional marine setting composed of lagoons and shoals (Sadooni, 1993, 1997; Sharland et al., 2001; Fox and Ahlbrandt, 2002).
In the Late Jurassic, depositional conditions culminated in the formation of thick evaporites forming an impermeable regional seal (i.e. the Gotnia Formation) above the older Jurassic rocks. The distribution of hydrocarbons in the Cretaceous reservoirs in the southern Mesopotamian Foredeep Basin was influenced by the nature of these evaporites (Murris, 1980; Beydoun et al., 1992; Abeed et al., 2013). The Gotnia Formation is a regional seal in central and southern Iraq (Jassim and Goff, 2006). It was also deposited within the Lurestan region of Iran as lowstand basinal salt interbedded with laminated anhydrite and shales (Murris, 1980). It is about 200 m thick and forms a tight seal for local oil and gas migration to the overlying Cretaceous limestones (Fox and Ahlbrandt, 2002).

Marine carbonate sedimentation took place during most of the Cretaceous and Cenozoic with numerous well-documented unconformities and periods of non-deposition (Sharland et al., 2001; Alsharhan and Habib, 2005; Jassim and Goff, 2006; Al-Husseini, 2008; Aqrawi et al., 2010). Large influx of clastic sediments from the west and southwest prograded across the inner carbonate-shelf area, first in the Hauterivian to Early Aptian, forming the Zubair deltaic system deposits, then in the Early Albanian, forming the Nahr Umr–Burgan deposits (Alsharhan and Nairn, 1997). The Zubair sandstones and the Mauddud and Mishrif carbonates are the main reservoirs in the supergiant fields of southern Iraq and Kuwait, together with the Sarvak shelf carbonates in the Abadan Plains and Dezful Embayment of SW Iran.

The Upper Cretaceous section shows a decrease in clastic material and an increase in pelagic limestone by the Late Cenomanian (Sadooni and Aqrawi, 2000). From the Late Cretaceous to the Middle Miocene, various intra-shelf basins coalesced to form a single NW-trending basin that was filled with marine carbonates and shales such as the Upper Cretaceous Najaf Intra-shelf Basin in Iraq (Aqrawi et al., 2010). Deposition during the Late Eocene to Early Miocene resulted in the shallow-marine limestones and dolomites. Reefal limestones deposited along the shelf margins form the reservoirs of the Oligocene Kirkuk Group, which are volumetrically the most important reservoirs in northern Iraq (Al-Sakini, 1992). In the Middle Miocene, evaporites accumulated in numerous restricted sub-basins that formed as the tectonic compression increased. In the Late Miocene and Pliocene, during the main Zagros tectonic event, a thick wedge of fine-to-coarse-grained sandstone and conglomerate, shed from the rising Zagros Mountains, was deposited in the rapidly subsiding Zagros foredeep (Beydoun et al., 1992; Sadooni and Aqrawi, 2000; Jassim and Goff, 2006; Aqrawi et al., 2010). Deposition of these mollases and other clastics represents the transition from marine to continental conditions and the final filling of the foredeep basin.

**PREVIOUS STUDIES**

The Sargelu Formation outcrops in the Sardash Anticline in the Sulaimania Province of the Zagros High Folded Zone in northeastern Iraqi Kurdistan were first recognised and described by Wetzel (1948) in van Bellen et al. (1959-2005). The stratigraphic succession at the Emam Hasan and Masjid-e Suleiman of western Iran was correlated by James and Wynd (1965) with the Adaiyah, Mus, Sargelu, Najmah and Gotnia formations of Iraq, which were described and defined in the Lexique Stratigraphique International for Iraq by van Bellen et al. (1959-2005). Aliti (1966) and Dubertret (1966) compared the Sargelu Formation to the Cudi Group of southern Turkey and to the black shale of the uppermost part of the Dolaa Group in Syria, respectively. Qaddouri (1972) studied the Sargelu Formation in the Benavi area of Duhok Province in northern Iraqi Kurdistan. Al-Omari and Sadiq (1977) included the Sargelu Formation within the Middle Jurassic.

In a general review of the formation, Buday (1980) agreed with the original description given by Wetzel (1948) and interpreted the depositional environment as euxinic marine environment. Al-Barzanji (1989) studied the Muhaiwir Formation in the Iraqi Western Desert, pointing out that this formation was deposited within the same sedimentary cycle of the Sargelu Formation. The more detailed study regarding the age and depositional environment of the Muhaiwir Formation was performed by Al-Hadithi (1989), who focused on the ostracods to estimate its age. Al-Dujaily (1994) studied the Middle–Upper Jurassic stratigraphic section in northern Iraq and determined the age of the Sargelu Formation to be Aalenian–Bajocian. Ahmed (1997) described the sedimentary facies and depositional environments of Jurassic rocks in northwestern Iraq. The lower contact of the
| Geologic Age | Ma | Mega Sequences | Stratigraphic Unit Iraq | Stratigraphic Unit Iran | Lithology | Comments |
|--------------|----|----------------|-------------------------|------------------------|-----------|----------|
| Pliocene (+) | 23.03 | AP 11 | Bakhtliari | Bakhtliari | Lower Fars | Agha Jari | source rock |
| Oligocene (+) | 66.0 | AP 10 | Palan/Kirkuk Gp | Gachsaran | | | |
| | | | Jaddala | Asmani | | | |
| | | | Adilji | Kuhur | | | |
| | | | | | | | |
| Late | 100.5 | AP 9 | Shiranish | Purp | | | |
| | | | Hartha | | | | |
| | | | Sadi/Kometan | | | | |
| | | | Tamuna-Khasibi | | | | |
| Early | 145.0 | AP 8 | Mehr | Hb/Ha | | | |
| | | | Rumal | U. Sarvak | | | |
| | | | Ahmadi | Ahmadi | | | |
| | | | Ma'dad | L. Sarvak | | | |
| | | | Nahr Umr | Kuhur | | | |
| | | | Shu'ala | Darly/Garau | | | |
| | | | Zuber | Gaday Garau | | | |
| | | | Ratawi | | | | |
| | | | Yamama | Fazliyan/Garau | | | |
| Late | 163.5 | AP 7 | Najmah | | | | |
| | | | Nakoilkelekan | | | | |
| | | | Najmah | | | | |
| Middle | 174.1 | AP 6 | Gotma | Hb/Gotma | | | |
| Early | 201.3 | | Mus | Surmah | | | |
| | | | Adayah | Neyriz | | | |
| | | | Butmah | | | | |
| Late | 252.2 | AP 5 | Chia Zari | Kangan | | | |
| | | | Satina Evaporite | Dalan | | | |
| | | | Chia Zari | | | | |
| Middle | 298.9 | | Galara | Faraghan | | | |
| Early | 358.9 | AP 4 | Harun/Dra | | | | |
| | | | Kaista/Pirispoki | | | | |
| Early | 418.2 | AP 3 | Jaf Group | Jaf-equivalent | | | |
| | | | | | | | |
| Carboniferous | 443.4 | AP 2 | Akkas | Gakhum | | | |
| Early | 541.0 | AP 1 | Khoubour | Zard Kuh | | | |
| Early | | Pre AP 1 | Basement | | | | |

Figure 2: Tectono-stratigraphic megasequences, lithology and petroleum systems of Iraq and Iran (modified from Alsharhan and Nairn, 1997; Sharland et al., 2001; Verma et al., 2004; Jassim and Goff, 2006; Aqrawi et al., 2010). The column for Iraq was also used for Kuwait in this study. See legend in Figure 3.
Sargelu Formation with Lower Jurassic formations was described by Surdashy (1999) in a sequence-stratigraphic study of the Early Jurassic formations in central and northern Iraq. Salae (2001), in a stratigraphic and sedimentologic study of the Upper Jurassic succession in northern Iraq, described the upper contact of the Sargelu Formation with the Naokelekan Formation to be concordant.

Dunnington (1955), Al-Haba and Abdulla (1989), Othman (1990) and Odisho and Othman (1992) were the first to study the generation, migration and maturation of hydrocarbons of the Upper Jurassic–Lower Cretaceous formations in northern Iraq, and identified the types of kerogen that occur in both the Sargelu and Naokelekan formations. Al-Ahmed (2013) used palynofacies to determine the depositional environment and source potential for hydrocarbons of the Sargelu Formation in northern Iraq. Alsharhan and Habib (2005) studied organic matter and maturation of the Sargelu Formation in southern Iraq.

Al-Ameri et al., (2006) classified oils in the northern and central parts of Iraq into two subfamilies. In the same way, Al-Ahmed (2006) recognised two types of facies in source rock samples and two
subfamilies of carbonate Jurassic oils in the central and northern parts of Iraq. Al-Ameri et al.
(2008) studied the stratigraphic section between the Alan Anhydrite and Lower Fars formations
in northeastern Iraq, and showed that the Sargelu Formation has no molecular contribution to
the oil found in the Jeribe Formation. Al-Ameri et al. (2009) studied the hydrocarbon potential
of the Middle Jurassic Sargelu Formation in the Zagros Folded Belt from exploratory wells and
outcrops in northern Iraq. Balaky (2004) studied the stratigraphy and sedimentology of the Sargelu
Formation in the outcrops in Kurdistan, while Abdullah (2010) carried out several new Rock-Eval
measurements and organic geochemical analyses to describe the source rock potential and organic
geochemistry of the Sargelu.

The Sargelu and Naokelekan formations have been interpreted as the main contributors to the
hydrocarbons charge in the Mesopotamian Foredeep and Zagros Fold Belt Basins by Beydoun et al.
(1992), Sadooni (1997) and Al-Shididi et al. (1995).

The source rock potential of the Lower Cretaceous Sulaiy/Makhul/Chia Gara and basal Garau
has been reported by Al Habba and Abdullah (1989), Stoneley (1990), Beydoun et al. (1992), Al-
Shididi et al. (1995), Alsharhan and Nairn (1997) and Abdullah et al. (1997). Al-Ameri et al. (2006,
2008, 2011, 2012a) and Al-Gailani and Marouf (2010) investigated the burial and thermal evolution
and hydrocarbon generation of the Middle Jurassic to Lower Cretaceous source rocks in Iraqi
Kurdistan, while Pitman et al., (2004), Al-Ameri and Al Khafaji (2008), Pietraszek-Mattner et al.
(2008), Al-Ameri et al. (2009, 2012b) and Abeed et al. (2011, 2012, 2013) carried out similar work in
the southern areas of Iraq. Recently English et al. (2015) have published a detailed study on the
geological evolution of the Iraqi Zagros and its influence on the distribution of the hydrocarbons in
Iraqi Kurdistan region.

Abdullah and Kinghorn (1996), Abdullah et al. (1997), Yousif and Nouman (1997) and Rabie et al.
(2014) evaluated the source rocks and thermal history of Kuwait; while Ala et al. (1980), Bordenave
and Burwood (1990, 1995), Rabbani and Kamali (2005), Badics and Rashidi (2007) and Alimi (2014)
performed the same approach in southwestern Iran.

DATABASE

A part of this study was based on the compilation of all available depth maps in the public domain,
together with well tops and data about these source rocks. The organic geochemical data were
obtained through the analyses of hundreds of samples collected from 39 exploratory wells that
are regionally distributed among the study area (Figure 1). These analyses included measurement
of the total organic carbon (TOC wt%) contents, pyrolysis (S1, S2, S3, HI, PI, OI) and vitrinite
reflectance (%Ro) (Table 1). Most of the data are from English-language public sources; other
findings come from sources available only in Arabic such as Al-Sakini (1992) and Al-Habba and
Abdullah (1989). Additional data come from many analysed rock samples collected from 9 outcrops
along the Zagros and Taurus mountain ranges in both north and northeast Iraqi Kurdistan and also
in the Lurestan Province of western Iran (Figure 1, Table 1).

Similar organic geochemical data were extracted from many previous published and unpublished
studies (including MSc and PhD theses; Al-Habba and Abdullah, 1989; Othman, 1990; Odisho and
Othman, 1992; Abdallah and Kinghorn, 1996; Ashkan, 1998; Al-Ameri et al., 1999, 2006, 2008, 2009,
2011, 2012a, b; Marouf, 1999; Surdashy, 1999; Salae, 2001; Balaky, 2004; Rabbani and Kamali, 2005;
Mohyaldin and Al-Beyaty, 2007; Mohyaldin, 2008; Abdullah, 2010; Abeed et al., 2011, 2012, 2013).
All the available data were reviewed and used to prepare accurate regional mapping of the source
rocks and their parameters. The well tops were adapted from Jassim and Goff (2006) and Aqrawi et
al. (2010).

METHODOLOGY

The generated volume of petroleum was calculated in two different methods. The simple one
utilised the newly created source rock maps and a simple mass-balance approach developed by
Demaison and Huizinga (1991) and Schmoker (1994).
### Table 1
Organic Geochemical Data Used in the Current Study and Their Sources

| Well or Outcrop Name   | Type    | Country | Litho-stratigraphic Name | TOC   | S1   | S2   | Tmax | HI   | OI   | PI   | Vitrinite | Data Source                      |
|-----------------------|---------|---------|--------------------------|-------|------|------|------|------|------|------|----------|---------------------------------|
| Bekhma Valley         | outcrop | Iraq    | Chia Gara                | 0.73  | 1.01 | 3.84 | 449  | 526  | nd   | nd   | nd       | Odisho and Othman, 1992          |
| Ghelli Mezerka Valley | outcrop | Iraq    | Chia Gara                | 11.99 | 0.74 | 59.51| 436  | 496  | nd   | nd   | nd       | Odisho and Othman, 1992          |
| Shiranish Valley      | outcrop | Iraq    | Chia Gara                | 11.85 | 1.75 | 53.94| 437  | 455  | nd   | nd   | nd       | Odisho and Othman, 1992          |
| Kirkuk-109            | well    | Iraq    | Chia Gara                | 46    | 3.46 | nd   | 5.19 | 438  | 163  | nd   | nd       | Al-Habba and Abdullah, 1989      |
| Pulikhana-5           | well    | Iraq    | Chia Gara                | 2     | 4.67 | nd   | 6.29 | 439  | 138  | nd   | nd       | Al-Habba and Abdullah, 1989      |
| Taq Taq-1             | well    | Iraq    | Chia Gara                | 1     | 2.15 | 0.52 | 2.14 | 423  | 100  | nd   | nd       | Odisho and Othman, 1992          |
| North-Rumaila-158     | well    | Kuwait  | Sulay        | 0.93  | 0.76 | 0.83 | 445  | 88   | nd   | 0.91 | nd       | Abeed et al., 2011               |
| Rumaila-167           | well    | Kuwait  | Sulay        | 3.74  | 1.05 | 2.12 | 459  | 52   | nd   | 1.19 | nd       | Abeed et al., 2011               |
| Rumaila-172           | well    | Kuwait  | Sulay        | 6.03  | 57.79| 9.35 | 441  | 188  | nd   | 0.70 | nd       | Abeed et al., 2011               |
| Minagish-001          | well    | Kuwait  | Sulay        | 0.40  | nd   | 4.35 | nd   | nd   | nd   | nd       | Abdullah et al., 1997           |
| Raudhatain-206        | well    | Kuwait  | Sulay        | 4.61  | nd   | 4.54 | 0    | nd   | nd   | nd       | Abdullah et al., 1997           |
| Riqiath-1             | well    | Kuwait  | Sulay        | 2.68  | nd   | nd   | nd   | nd   | nd   | nd       | Abdullah et al., 1997           |
| Gurpi-1               | well    | Iran    | Garau       | 10    | 0.86 | 0.96 | 0.57 | 471  | 76   | 0.61 | nd       | Ashkan, 1998 PhD                |
| Samand-1              | well    | Iran    | Garau       | 18    | 1.04 | 0.68 | 0.50 | 449  | 61   | 29   | 0.58    | Ashkan, 1998 PhD                |
| Sarkan-1              | well    | Iran    | Garau       | 4     | 0.84 | 0.90 | 0.79 | 426  | 95   | 24   | 0.54    | Ashkan, 1998 PhD                |
| Barsarin              | outcrop | Iraq    | Naokelekan   | 6.24  | 1.18 | 6.41 | 469  | 88   | 10   | 0.21   | 1.28    | Abdulla, 2010 MSc              |
| Sargelu               | outcrop | Iraq    | Naokelekan   | 3.20  | 0.08 | 0.41 | 464  | 28   | 38   | 0.29    | nd       | Abdulla, 2010 MSc              |
| Kirku-109             | well    | Iraq    | Naokelekan   | 4.01  | nd   | 4.03 | 462  | 103  | nd   | nd   | nd       | Al-Habba and Abdullah, 1989      |
| Qara Chauq-1          | well    | Iraq    | Naokelekan   | 13    | 4.31 | nd   | 19.09| 439  | 507  | nd   | nd       | Al-Habba and Abdullah, 1989      |
| Taq Taq-1             | well    | Iraq    | Naokelekan   | 1     | 4.66 | 0.47 | 1.04 | 568  | 22   | nd   | nd       | Odisho and Othman, 1992          |
| Gara                  | outcrop | Iraq    | Sargelu      | 2     | 3.38 | 0.46 | 23.52| 436  | 690  | 11   | 0.02   | 0.68    | Abdulla, 2010 MSc              |
| Ghali Kuh             | outcrop | Iran    | Sargelu      | 11    | 7.95 | 0.91 | 26.47| 437  | 305  | nd   | 0.03   | nd       | Ashkan, 1998 PhD                |
| Hanjeera              | outcrop | Iraq    | Sargelu      | 5     | 0.42 | 0.05 | 0.05 | 378  | 27   | 84   | 0.55   | nd       | Abdulla, 2010 MSc              |
| Sargelu               | outcrop | Iraq    | Sargelu      | 4     | 1.44 | 0.23 | 0.64 | 477  | 50   | 42   | 0.26   | 1.42    | Abdulla, 2010 MSc              |
| Gurpi-1               | well    | Iran    | Sargelu      | 8     | 0.79 | 0.85 | 0.45 | 400  | 71   | nd   | 0.65   | nd       | Ashkan, 1998 PhD                |
| Guwair-2              | well    | Iraq    | Sargelu      | 8     | 1.30 | 0.40 | 6.83 | 439  | 382  | 40   | 0.12   | 0.77    | Abdulla, 2010 MSc              |
| Hawler-1              | well    | Iraq    | Sargelu      | 5     | 1.74 | 0.77 | 6.12 | 430  | 343  | 51   | 0.12   | 0.59    | Abdulla, 2010 MSc              |
| Jabil Kand-1          | well    | Iraq    | Sargelu      | 1     | 3.10 | 0.94 | 13.20| 441  | 426  | nd   | 0.07   | nd       | Odisho and Othman, 1992          |
| Qara Chauq-1          | well    | Iraq    | Sargelu      | 10    | 4.94 | nd   | 18.84| 439  | 381  | nd   | nd   | nd       | Al-Habba and Abdullah, 1989      |
| Qara Chauq-2          | well    | Iraq    | Sargelu      | 5     | 0.94 | 0.22 | 4.37 | 433  | 463  | 20   | 0.05   | 0.63    | Abdulla, 2010 MSc              |
| Samand-1              | well    | Iran    | Sargelu      | 11    | 1.03 | 0.65 | 0.30 | 450  | 50   | 50   | 0.52   | nd       | Ashkan, 1998 PhD                |
| Taq Taq-1             | well    | Iraq    | Sargelu      | 1     | 0.49 | 0.06 | 0.50 | 515  | 102  | nd   | nd   | nd       | Odisho and Othman, 1992          |
| Tawke-15              | well    | Iraq    | Sargelu      | 6     | 16.31| 8.52 | 34.78| 434  | 346  | 29   | 0.19   | 0.65    | Abdulla, 2010 MSc              |

Includes immature and thermally mature samples.  
*nd* = no data available
The more accurate method is to create a regional three-dimensional petroleum system model of the study area. Quantifying the entire petroleum system within a basin requires a more detailed understanding of the geological history of source, reservoir and seal rocks, and the detailed analysis of the various geological processes affected the basin through geological time, such as erosion, uplift, or the evolution of salt diapirs. Moreover, generation of petroleum using different kinetics, together with expulsion of petroleum and secondary migration need to be interpreted correctly to assess the available petroleum volume for trapping. The more sophisticated model used Schlumberger’s PetroMod, which is a finite-element basin modelling software that simulates the burial and thermal history of sediments, calculating source rock maturities and petroleum generation and migration through time. The modelling required input data that describe the present-day geology, especially the depth, thickness and facies maps, and the geological history of the area. The geological history was forward modelled throughout the oldest event towards the most recent one.

SIMPLE VOLUMETRIC CALCULATIONS

To calculate the volume of generated petroleum (oil and gas) a simple mass-balance approach was employed using the method of Schmoker (1994). This technique requires that the volume of thermally mature source rock to be estimated, and the richness (TOC) and quality (HI) of the immature and thermally mature source rocks to be known. The generated volume of petroleum was calculated by first creating the source rock facies and thickness maps using the well database and the original maps in Yousif and Nouman (1997), Sharland et al. (2001), Jassim and Goff (2006) and Agrawi et al. (2010). Then the source rock parameters were analysed to create the immature TOC, S1+S2 and HI maps using the measured and back-calculated immature TOC and HI values. The back-calculation of original, immature TOC and HI values was carried out using the Peters and Moldowan’s (1993) method. Following that, the SPI maps of Demaison and Huizinga (1991) were calculated by multiplying the thickness, and the calculated immature S1+S2 maps with a constant sediment density (2,500 kg/m3) and divided by 1,000. Measurements were then carried out for the immature, early-oil, peak-oil, late-oil, and wet-gas and dry-gas mature areas of each source rock unit as sq km per USGS basin in ArcGIS. Transformation ratios (TR) were assigned to each maturity area indicating that early mature oil is 0.25 TR, peak-oil = 0.6 TR, wet-gas = 0.75 TR and dry-gas = 0.95 TR. Finally, the SPI maps were multiplied with the TR maps to calculate the generated volumes of petroleum. For the oil and gas generation kinetics, and for the ratio between generated mass of oil and gas, the Pepper and Corvi (1995) Type IIS kinetics was used.

3-D REGIONAL BASIN MODELLING

Basin and petroleum system modelling refers to numerical computer models that incorporate geoscience data and can be used to investigate the formation and evolution of sedimentary basins. In the commercial software packages usually a finite-element, forward-modelling approach is used to simulate the burial history of sediments, compaction, pressure and temperature evolution, as well as the maturation of organic matter, petroleum generation, migration and accumulation through time. Principles of basin modelling have been published in detail by Welte and Yalcin (1988) and Hantschel and Kauerauf (2009).

Model Input

The thermal and maturity history together with the timing of hydrocarbon generation were investigated by PetroMod software. Firstly, a 3-D basin model covering the study area was created using regional depth and thickness maps of AP1 to AP11 mega-sequences (Sharland et al., 2001) for Kuwait (Yousif and Nouman, 1997) and Iraq (Jassim et al., 2006; Jassim and Buday, 2006a, b; Jassim and Goff, 2006; Agrawi et al., 2010; Csontos et al., 2012; Abeed et al., 2013; Table 2). The thickness maps for Iran were based on Koop and Orbell (1977). The surface geology maps were adapted from Jassim and Goff (2006) and Agrawi et al. (2010). The contour data on the maps were digitised using ArcGIS and interpolated into grids with a cell dimension of 2 x 2 km. The maps had UTM 38...
### Table 2
Main Input Data for 3-D Geologic Basin Model

| Mega-sequence | Layer | Stratigraphic Unit (Iraq) | Stratigraphic Unit (Iran) | PSE | Lithology | Deposition (Ma) | Erosion (Ma) | Figure number (Table 2) |
|---------------|-------|--------------------------|--------------------------|-----|-----------|----------------|-------------|------------------------|
| Quaternary    | Upper Miocene to Pliocene | Upper Fars, Bakhtijari, Dibbiba Formations | Agha Jari, Bakhtijari Formations | Overburden | Clastics | 0.1–0 | 15.2 | 109 |
|               | Middle Miocene | Lower Fars Formation | Gascharan Formation | Seal | Evaporite | 11.6–6.2 | 5.2–0 | 14.13 |
|               | Lower Miocene | Jereh, Esphatnatis, Dhiban, Ghar, Serinkang Formation | Asmari, Mishan, Gurpi Formations | Reservoir | Limestone (grainstone) | 21–16 | 5.2–0 | 14.7 |
|               | Oligocene | Bajewan, Baba, Anah, Azkand, Khurmala, Dammam, Gercus, Pila Spi, Awanah, Jaddala Formations | Kahrur, Asmari Formations | Reservoir | Limestone (shaly) | 33.9–21 | 5.2–0 | 14.4 |
|               | Danian to Upper Eocene | Rus, Umm-ar-Radhuha, Sinjar, Kosheh, Aalij, Khurmala, Dammam, Gercus, Pila Spi, Awanah, Jaddala Formations | Pablikh, Juhum, Amiran, Takh Zang, Kashkan Formations | Overburden | Marl | 59.8–33.9 | 13.0 | 13.2 |
|               | Turonian to Maastrichtian | Khasib, Tanuma, Sadi, Koma, Serinkang, Shu'ayb, Aspalashone, Tanjero Formations | Surgah, Ram, Gurpi, Amiran Formations | Reservoir | Limestone (grainstone) | 90–59.8 | 13.0 | 12.2 |
|               | Albian to Lower Turonian | Maudid, Rubah, Anadad, Rumaha, Kii, Balambo Formations | Sarvak Formation | Reservoir | Limestone (grainstone) | 100–90 | 13.0 | 11.10 |
|               | Albian | Nahm Umr Formation | Kazhdimi, Gurari Formations | Reservoir | Sandstone (shaly) | 113–100 | 13.0 |  |
|               | Upper Berriasian to Aptian | Yamama, Garagu, Zangara, Ratai, Za'bak, Quanchu, L. Samond, L. Balambo, Shu'ayb Formations | Fahljan, Gardan, Darfyen, Garari Formations | Reservoir | Limestone (grainstone) | 142–113 | 13.0 | 11.7 |
|               | Tithonian to Lower Berriasian | Chia Gara, Sulak, Karimia, Formations | Garau (basal) | Source | Limestone (micritic) | 146–142 | 13.0 | created |
|               | Tithonian | Gottra, Barsan Fms | Gottra, Hth Fms | Seal | Evaporite | 153–146 | 13.0 | 10.7 |
|               | Upper Callovian to Upper Kimmeridgian | Najmah, Nakelekan Formations | Nackalekan Formations | Source | Limestone (micritic) | 164–153 | 13.0 | created |
|               | Bajocian to Lower Callovian | Sargelu, Muhale Formations | Sargelu Formation | Source | Limestone (micritic) | 170–164 | 13.0 | created |
|               | Hettangian to Toarcian | Bakuti, Butmah, Adayalah, Mus, Alan Formations | Neytiz, Surmeh, Khanehs Khah, Dashtak Formations | Underburden | Limestone (50%), Evaporite (50%) | 254–182 | 13.0 |  |
|               | Upper Triassic | Kunra Chine Formation | Dashtak Formation | Seal | Evaporite | 237–200 | 13.0 | 9.7 |
|               | Lower-Middle Triassic | Mirja Mir, Beduh, Aghar, Giel Khana Formations | Dashtak, Kangan Formations | Underburden | Limestone (grainstone) | 251–237 | 13.0 | 9.6 |
|               | Middle, Upper Permian to Induan | Ga'ara, Chia Zari Formations | Kangan, Dalan Formations | Reservoir | Sandstone (shaly) | 272–251 | 13.0 | 9.5 |
|               | Sakmarian to Kungurian | Ga'ara, Raha Formations | Faragan Formation | Reservoir | Sandstone (shaly) | 307–272 | 315–283 |  |
|               | Famennian to Moscovian | Hanur, Ora, Kaista, Prisipki Formations | Hanur, Ora, Kaista, Prisipki Formations | Underburden | Sandstone (50%), Shale (50%) | 359–315 | 315–307 | 8.9 |
|               | Lower Silurian to Upper Devonian | Akkas Formation | Taweel Jubab equivalents | Source | Shale (typical) | 445–360 | 8.6 |  |
|               | Lower Cambrian to Upper Ordovician | Burj, Khabour Formations | Mla, Ishebey, Zard Kh Formations | Reservoir | Sandstone (typical) | 521–445 | 8.4 |  |
|               | Verdenian to Lower Cambrian | Nukhash Salt Basin (undrilled) | Zaqug, Lakum Formations | Underburden | Sandstone (typical) | 600–521 | 8.3 |  |

Chronostratigraphy (Sharland et al., 2001; Jassim and Goff, 2006; Al-Husseini, 2008; Aqrawi et al., 2010). PSE: Petroleum System Element in 3-D basin model. Lithology: main lithology used in PetroMod.
Northern Hemisphere projection and use the WGS84 global datum. The 3-D model was constructed by stacking the grids below the surface topography and on the top crystalline basement surface determined by Aqrawi et al. (2010). The thickness maps for the AP1 to AP11 mega-sequences are based mainly on the maps by Jassim and Goff (2006) (Table 2). However, the maps of Mega-Sequences; AP6, AP7, AP8 and AP11 have been subdivided in order to further enhance the burial history differences.

**Ages and Deposition**

Chronostratigraphic units in the model were assigned absolute ages of deposition, while amounts and ages of the erosion and/or periods of non-deposition were defined as accurately as possible. The ages of depositional and erosional events are calibrated in the most recent IUGS 2013 geologic time scale, based on earlier works (van Bellen et al., 1959-2005; Jassim and Goff, 2006; Al-Husseini, 2008; Aqrawi et al., 2010). Lithologies as end-member rock types or as compositional mixtures were assigned to the facies in each unit. The physical and thermal properties of the rock units and mixtures, including their thermal conductivities and heat capacities were either user-defined or assigned as software default values.

The regional 3-D basin model (Figure 4) was then refined using published depth maps and well-top databases. Also, several sub-layers were created to assess the source rock thickness values, focusing on the Sargelu, Naokelekan, Gotnia and Chia Gara/basal Garau units in order to understand their Jurassic to Cenozoic burial history. The model grid-point distance was 2 km x 2 km, with 600 grid points on the west-east direction and 616 grid-points in the north-south one. The final refined model had 24 layers (Table 2), spanning from the Precambrian Hormuz Salt to the Holocene fluvial sediments. Three west-east 2-D cross-sections extracted from the 3-D basin model across three selected main fields of Kirkuk, East Baghdad and Majnoon are shown in Figure 5. In addition, the top Sargelu depth map is shown in Figure 4.

Lithological information was derived from well reports and from the published literature (e.g. van Bellen et al., 1959-2005; Alsharhan and Nairn, 1997; Jassim and Goff, 2006; Aqrawi et al., 2010). The palaeogeographical maps of Sharland et al. (2001), Jassim and Goff (2006) and Aqrawi et al., (2010) were used to create the facies changes within each layer. For each facies, a lithology was defined in the PetroMod software. The main palaeogeographic maps for the Sargelu (Bathonian, 167 Ma), Naokelekan (Oxfordian, 160 Ma) and Chia Gara/basal Garau (Tithonian, 146 Ma) were especially important in defining the source rock facies belts (Figure 6).

The basin model was used to assess the present-day maturity and maturity evolution of the main source rocks, and to calculate the generated, expelled and un-expelled volumes of petroleum and to simulate the primary and secondary migrations. In the regional 3-D model, thermal maturity and petroleum generation and expulsion histories were simulated on a cell-by-cell basis with fully integrated pressure-volume-temperature (PVT) calculations between neighboring cells. Secondary migration and accumulation of petroleum were modelled using the Hybrid modelling technology (Hantschel and Kauerauf, 2009).

**Confidence Zones**

The complete structural complexity of the Zagros Fold Belt in Kurdistan and in Iran could not be accurately reconstructed with the available maps due to the numerous erosional and folding/thrusting events. Therefore, a detailed zonation was devised to show the confidence levels of the input depth maps for the different areas (Figure 1b). The Zagros Thrust Zone in Iran is a highly folded and thrust area, with limited well and outcrop control, thus it is of low confidence. The Kurdistan High Fold Belt is the continuation of this unit into Iraq, with similarly low confidence. The Foothills Tectonic Zone in northern Iraq and the Zagros Low Fold Belt Mountains of Kurdistan have more well and outcrop control points, and can be of medium confidence in the source rock and overburden thickness; however, the exact uplift and erosion, and the amount of eroded section.
Jurassic–Cretaceous source rocks of Northeast Arabia

Figure 4: Map showing depth below sea level to the top of the Sargelu Formation in Iraq, Kuwait and SW Iran. Contour intervals are 0.5 km and negative values represent depth above sea level. The map was used in the regional 3-D basin model and is based on data from several sources (Koop and Orbell, 1977; Yousif and Nouman, 1997; Pitman et al., 2004; Jassim and Goff, 2006; Aqrawi et al., 2010; Csontos et al., 2012; Abeed et al., 2013). Structural traverses AA', BB' and CC' are shown in Figure 5.

per anticline is difficult to estimate over an area of 100s of anticlines. The confidence becomes better in the Kurdistan Foothills Zone in northern Iraq and in the Zagros Fold Belt Foothills in Iran, where more wells are available, and the uplift and erosion are not as significant and variable as in the previous elevated areas. The highest confidence areas are the Mesopotamian Basin areas in Iraq, Kuwait and Iran. The area southeast of Kuwait, in Saudi Arabia, is partly included in the 3-D basin model. It also has very low confidence because no detailed depth maps were available. Despite these limitations, the 3-D model can be confidently used to evaluate the total petroleum system on a regional scale across the study area.
Aqrawi and Badics

Figure 5: Extracted 2-D depth cross-sections from the regional 3-D basin model showing layers and structural styles. (a) Section from northern Iraq, across the Kirkuk-109 Well and the Kirkuk Field.

Figure 5: (b) Section from central Iraq across the East Baghdad Field.

Figure 5: (c) Section from southern Iraq across the Majnoon Field. See Figure 4 for location.
Calibration of Heat Flow

Reservoir and bottom-hole temperature data for 26 wells (Ibrahim, 1984; Pitman et al., 2004; Jassim and Al-Gailani, 2006; Abeed et al., 2013) were used to estimate the present heat flow. A good fit between calculated and measured temperature values was achieved using estimated heat-flow values that varied from 40–43 mW/m² in the southern Mesopotamian Foredeep Basin to 48–50 mW/m² in the Zagros Fold Belt, assuming a mean surface temperature of 25°C. The computed geothermal gradients for the wells in the Mesopotamian Foredeep Basin ranged about 15–20°C/km. However, some higher values occur around the Kirkuk, East Baghdad and Hamrin anticlines and in the Tawke Field area. In the Zagros Fold Belt, calculated thermal gradients are similar to those in the south, varying at a range of 18–26°C/km, and reaching higher values in the elevated, deeply eroded areas. The highest present-day heat flow is actually in the west, towards the Jordanian and Syrian border, reaching 62–65 mW/m².

Vitrinite reflectance (%Ro) in 12 wells and Rock-Eval Tmax values in 19 wells and 9 outcrops were used to evaluate the thermal history. Calibration required matching measured Ro values for each well with values of Ro calculated using the EasyRo method of Sweeney and Burnham (1990). The best-fit between measured and modelled values was achieved by adjusting the estimated amount of stratigraphic section eroded at each well location and by varying the regional heat-flow. Modelled Ro-depth trends constructed for the thermal analysis and erosion maps from Jassim and Goff (2006) and the surface geological maps in Aqrawi et al. (2010) were used to estimate the amount of Cenozoic strata eroded in the modelled area, especially in the mountainous areas of the low confidence zones (Figure 1b). In the wells, the Ro trend that best fits the data was extrapolated to a Ro value of 0.20%, the vitrinite reflectance at surface conditions.

Computed Ro trends for the wells in the Mesopotamian Foredeep Basin and others located in the southern part of the Zagros Fold Belt and Foothills area intersected the present-day surface at approximately 0.25–0.30%Ro, indicating that erosion during the Cenozoic was minimal. In contrast, calculated Ro trends for three wells in the central Zagros Fold Belt, when extrapolated to a value of 0.20%, indicate that approximately 1,000–1,500 m of Cretaceous to Upper Cenozoic section was removed by erosion. Near the Thrust Belt to the northeast, maximum erosional loss may have been as high as 2,000–2,500 m, as indicated by surface geology maps (Jassim and Goff, 2006; Aqrawi et al., 2010; Csontos et al., 2012). Prior to the extensive loss of stratigraphic section during the Late Cenozoic, episodic erosion could have occurred locally at the base Cenozoic, Cenomanian–Turonian, and Berriasian–Aptian events, which resulted in exhumation and reworking of Middle Jurassic to Upper Cretaceous sediments in uplifted areas close to the Zagros Mountains (Dunnington, 1955).

Petroleum Generation Kinetics

Pitman et al. (2004) indicated that the oils in Iraq were probably generated from Type IIS kerogen. The same conclusion was drawn by Abeed et al. (2013), who measured kerogen kinetics on 3 source rock samples from the Basra area. In order to compare the generated and expelled petroleum volumes and especially the timing and rate of hydrocarbon generation, different published Type IIS kerogen kinetics have been used in the current study. These kinetics included: Type IIS for the Phosphoria Formation (Lewan and Ruble, 2002); Type IIS for the Monterey Formation (Lewan and Ruble, 2002); Pepper and Corvi Type IIS (Pepper and Corvi, 1995); Behar Type IIS (developed also for the Monterey Formation) (Behar et al., 1997); Abeed et al. (2013) Type IIS (developed for the Ynama Formation) and the Type IIS kinetics developed by Santamaria-Orozco (Santamaria-Orozco and Horsfield, 2003) for the Mexican carbonate-rich source rocks in the Campeche area.

RESULTS

Sharland et al. (2001) have used maximum flooding surfaces (MFS) for the regional correlation purposes across the Arabian Plate. Jassim and Goff, (2006) and Aqrawi et al. (2010) adapted most of these MFSs for defining the petroleum system elements of northern Arabian Plate, particularly...
Figure 7: Organic geochemical plots for the Sargelu, Naokelekan and Sulaiy/Chia Gara/basal Garau samples. The immature and thermally mature samples are also shown: (a) HI versus Tmax; and (b) S2 versus TOC.

Figure 6: Maps of key Late Jurassic to Early Cretaceous time-slices showing shallow-water platform carbonate or ramp grainy facies and basinal organic-rich micritic carbonate facies belts (modified from Goff, 2005; Jassim and Goff, 2006; Aqrawi et al., 2010). (a) Facies belts of Sargelu and Muhaiwir formations during Bathonian (ca. 167 Ma); (b) Facies belts of Naokelekan and Najmah formations during Oxfordian (ca. 160 Ma); (c) Facies belts of Sulaiy and Chia Gara formations, and Garau basinal facies in Late Tithonian (ca. 146 Ma).

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Figure 7: Organic geochemical plots for the Sargelu, Naokelekan and Sulaiy/Chia Gara/basal Garau samples. The immature and thermally mature samples are also shown: (a) HI versus Tmax; and (b) S2 versus TOC.
in Iraq (Figures 2 and 3). Based on these timelines the formations consisting of some of the most prolific source rocks have been selected from the Middle Jurassic to Lower Cretaceous sequences. These principal source rock formations are the Bajocian–Bathonian Sargelu, the Callovian–Lower Kimmeridgian Naokelekan/basal Najmah and the Upper Tithonian–Lower Berriasian Chia Gara/basal Garau, which are quite similar to their time equivalents in Kuwait and Iran (Figures 1b, 7 and 8, Table 1).
Sargelu Formation

Stratigraphy and Depositional Setting

The thickness, facies and source rock properties of the Sargelu Formation were analysed in 28 wells in Iraq, 7 wells in Kuwait and 15 wells in Iran, in addition to four outcrops in Iraq and one in Iran. Organic geochemical data were available from 6 wells in Iraq and 3 wells in Iran. The Bajocian–Bathonian Sargelu Formation was deposited across central, north and eastern Iraq and western Iran within a deep marine or basinal setting (Dunnington et al., 1959; Buday, 1980; Jassim and Buday, 2006b; Aqrawi et al., 2010). Towards the west of Iraq it is replaced laterally by the shallower carbonate platform facies of the Muhaiwir Formation (Figure 6a; Al-Barzanji, 1989; Al-Hadithi, 1989). Towards the southeast of the study area (in Iran), the Sargelu Formation passes into the Surmeh platform carbonates. The far eastern extension of the formation could have probably been eroded during the Zagros Orogeny (Figure 9a). The Sargelu Formation rests sharply upon transitional facies of the Adaiyah Formation (Figure 3; Surdashy, 1999). Generally, it is disconformably overlain by the Najmah Formation above a slightly erosional surface, which was described between the Middle and Upper Jurassic of the Qalian-Najmah area of northern Iraq. Along the depositional basin centre, the Sargelu Formation is conformably overlain by the Naokelakan Formation (which is called basal Najmah Formation in Kuwait and Iran) (Figure 3).

In Iraq’s Kurdistan region, the Sargelu Formation crops out throughout the high-folded, imbricated and thrust tectonic zones (Figures 1a and 8). The thickness of the formation varies progressively from 125 m in the southeast (Sirwan area) to about 20 m in the northwest (Ora and Chalki areas; Al-Dujaily, 1994; Ahmed, 1997; Balaky, 2004; Abdulla, 2010). In the subsurface sections of the Foothill and Mesopotamian tectonic zones of Iraq, the thickness ranges between 77 to 446 m (Figures 6a and 9a). In the far west Iraqi deserts, the Late Jurassic erosion has probably removed most of the Sargelu succession. The Sargelu Formation extends towards southwestern Iran within the Lurestan and Khuzestan provinces, where its thickness ranges between 28 to 316 m (Figure 9a).

Lithologically the formation consists of dark grey limestones and dark shales (Figures 8a to 8c). The lower part of the Sargelu Formation is usually represented by bituminous marly limestone (often dolomitised) and shale, while the middle part is composed of limestone and the upper is an intercalation of shale and bituminous limestone (Ahmed, 1997; Balaky, 2004). In the uppermost part of the formation the lithology becomes black laminated shale with a continuous transition to the Naokelakan Formation conformably (Figure 8; Salae, 2001).

The Sargelu facies could have been deposited in water depths that gradually increased from 250 to 350 m (Aqrawi et al., 2010). Towards the west of the basin, the palaeo-water depths became shallower along a gentle slope until reaching the inner ramp depositional belt of the Muhaiwir platform carbonates. The Sargelu deposition was initiated during a major transgression, which started in the Bathonian. Large depositional accommodation space was created along the depositional basin centre, where the water depth was at maximum of 300–350 m.

Geochemical Characterisation

The Sargelu source rock geochemical properties indicate TOC averages within the range of 1.5–5.0 wt% (Figures 7 and 9b, c, Table 1), Rock-Eval S2 yield of 1.5–13.23 mg HC/g TOC, and HI ranges of 100–600 mg HC/g TOC. The values measured at Hawler-1, Qara Chauq-2 and Tawke wells and in the Gara, Ghali Kuh and Hanjeera outcrops can be considered immature (Table 1). The Sargelu Formation becomes progressively more mature towards the east of Iraq (see Figure 12a); so the measured samples in the Sargelu outcrop and in the Jebel Kand-1, Samand-1 and Taq Taq-1 wells represent reduced, oil- to dry-gas mature values (Table 1). The measured TOC values in this region can be as high as 10–16 wt%, especially at Tawke Field (Abdulla, 2010) and in the Ghali Kuh outcrop in Iran (Ashkan, 1998), as well as within the gas-mature sections of some wells drilled in the Lurestan Province of western Iran. This means that the immature source properties could have been excellent with 5–18 wt% TOC and HI up to 600–700 mg HC/g TOC. In the west closer to the shallow platform depositional setting, both the immature TOC (1.5 wt%) and the HI (200 mg HC/g TOC) values are lower (Figures 7 and 9b, c, Table 1). The extracted kerogen is amorphous of oil- and gas-prone Type II, and in the eastern Iraq it could have been excellent of oil-prone Type I/II.
The Source-Potential Index (SPI; i.e. mass of hydrocarbons in tons which could be generated from an area of 1 m² in case of 100% transformation ratio, Demaison and Huizinga, 1991) ranges from 1–4 in the palaeo-shallow-water areas, increasing to 8–10 in the basinal parts (e.g. Kirkuk Field), and even reaching 16–18 in the palaeo-depocentre areas, around the Majnoon and Azadegan fields (Figure 9d). Based on these values, the Sargelu Formation represents a very good to excellent quality, oil-prone source rock in the area (Figures 7 and 9).

Figure 9: Sargelu Formation maps: (a) Thickness (m); (b) Estimated immature TOC (%); (c) Estimated immature HI (mg HC/g TOC); and (d) Calculated Source-Potential Index of Demaison and Huizinga (1991) (ton HC/m²).
At present, there is a systematic increase in thermal maturity of the Sargelu Formation from west to east across the study area (see Figure 12a) indicating that source rock maturation was predominantly controlled by burial depth and overburden thickness. In the Mesopotamian Basin, the Sargelu source rock maturities become the highest (1.2–1.9%Ro) along the eastern margin (i.e. along Iranian borders), where the rocks are very deeply buried (Figure 4). Then they systematically decrease in maturity up dip towards the western Iraq reaching the lowest values within an immature zone (of 0.6%Ro) along the Euphrates River or the Abu Jir Fault Zone (see Figure 12a).

In the Zagros Fold Belt, the source rock maturity exceeds 0.8%Ro and reaches a maximum of 1.9%Ro in the southern part of Iraqi Kurdistan region. So by calculations the study area for the Sargelu Formation could be subdivided into: the early oil mature area that is around 55,000 sq km; the peak oil mature area, which is about 167,000 sq km; and the gas-mature area that reaches 101,000 sq km (see Figure 12a). However, as the vitrinite reflectance (%Ro) shows only the max temperature or max overburden per area, it is important to mention that the maturity maps are inaccurate for Iraqi Kurdistan folded zones (Figure 1b), because the depth maps are very uncertain due to less data control. This may also apply to high folded parts of the Lurestan Province of western Iran.

Naokelekan Formation

Stratigraphy and Depositional Setting

The thickness, facies and source rock properties of the Naokelekan and basinal Najmah formations were analysed in 13 wells in Iraq and 5 wells in Iran, in addition to four outcrops in Iraq and one in Iran. Organic geochemical data were available from 5 wells in Iraq and 3 wells in Iran (Table 1). The Callovian–Early Kimmeridgian Naokelekan Formation was deposited across northern and eastern Iraq (Dunnington et al., 1959) in addition to some parts of western Iran along the border with Iraq. In central and southeastern Iraq, Kuwait and western Iran the Naokelekan Formation is called basinal Najmah Formation of the same lithology and age (Yousif and Nouman, 1997; Aqrawi et al., 2010). Towards the west of the study area the Naokelekan Formation passes laterally into the shallow platform carbonate facies of the Najmah Formation of Iraq (Figure 6b). Towards the southeast within the Dezful Embayment of Iran it passes into the shallower-water Surmeh platform carbonates. In the deep basin centre, the Naokelekan conformably overlies the Sargelu Formation, and it is overlain by the Gotnia evaporites or the Barsarin Formation (Figure 3).

In Iraqi Kurdistan the Naokelekan Formation crops out on the high-folded, imbricated and thrust zones (Figure 8), where basinal facies are dominant throughout (Figure 6b). Stratigraphically the Naokelekan is extremely condensed, representing a sedimentation rate of only 0.7–2.0 m/Myr. The Naokelekan Formation is only 14 m thick at its type section in Iraqi Kurdistan (van Bellen et al., 1959-2005). It ranges between 10 to 30 m in thickness across all outcrop sections of the Kurdistan region, wherever the Jurassic section is exposed (Figures 1a, 10a). In most exploration wells the thickness of the Naokelekan Formation ranges between 5 and 32 m. In western Iraq, the Naokelekan facies are replaced by the shallower carbonate platform facies of the Najmah Formation (Figure 6b). The geographic distribution of the Naokelekan Formation extends towards southwestern Iran within Lurestan and partly Khuzestan Provinces (Ala et al., 1980; Ashkan, 1998). There the thickness of the formation ranges between 17 to 30 m (Figure 10a).

The very condensed thin-bedded lithology of the Naokelekan Formation comprises also bituminous limestones and dolomites, with intercalated black, bituminous shales. Where the shale is very rich in organic matter it is locally called “coal” in some parts of the Iraqi Kurdistan (Dunnington et al., 1959), and historically was used for heating by the inhabitants. The Naokelekan was probably deposited in water depths of 250 to 350 m, and mostly during Callovian (Aqrawi et al., 2010), because from Middle Kimmeridgian the deposition of Götia evaporites started taking place (Figure 3).

Geochemical Characterisation

The source rock properties of the Naokelekan Formation indicate TOC averages within the range of 4–5 wt%, which may even reach up to 10 wt% in some wells, like Qara Chauq-1 (Al-Habba and
Jurassic–Cretaceous source rocks of Northeast Arabia

Abdullah, 1989) and at the Barsarin and Sargelu outcrops in Iraqi Kurdistan (Abdulla, 2010; Figures 7, 8 and 10b, c, Table 1). Their immature Rock-Eval S2 yields is of 2–40 mg HC/g; the HI ranges are between 400–700 mg HC/g TOC (Figure 7). The Naokelekan Formation becomes progressively mature towards the east of study area, so the observed values in the Barsarin and Sargelu outcrops, and Kirkuk-109 and Taq Taq-1 wells are well below the original, immature ones (Table 1). The

Figure 10: Naokelekan Formation maps: (a) Thickness (m); (b) Estimated immature TOC (%); (c) Estimated immature HI (mg HC/g TOC); and (d) Calculated Source-Potential Index of Demaison and Huizinga (1991) (ton HC/m²).
TOC values at the Barsarin and Sargelu outcrops reach up to 10–11 wt% and have Tmax values of 460–490, meaning wet-gas to dry-gas mature samples. The latter reflects that the immature source properties could have been excellent with 5–18 wt% TOC, and HI of up to 600–700 mg HC/g TOC. Based on vitrinite reflectance and Tmax values, the Qara Chauq-1 Well could be the only location where the immature source rock potential is present; all other measured values representing thermally mature values (Table 1).

Towards the western part of the study area, closer to the Najmah carbonate platform, the HI values are lower and down to around 350 mg HC/g TOC, but the TOC content may still be high. The extracted kerogen is amorphous of oil- and gas-prone, and in the eastern region the original immature kerogen could have been excellent of Type I/II. As the vitrinite reflectance (%Ro) shows only the max temperature or max overburden thickness, it is important to mention that the maturity maps (see Figure 12c) are inaccurate for Iraqi Kurdistan folded zones (Figure 1a). This is because the constructed depth maps are very uncertain due to less well control, particularly around the synclines. This may also apply to some parts of the Lurestan Province of western Iran, because it is an elevated region too.

The Source-Potential Index (SPI) for the Naokelekan source rocks ranges from 1–2 in the basinal part of the depositional environment, reaching 3–4 within the palaeo-depo-centre areas. The SPI of Naokelekan Formation is lower when compared to the previous Sargelu Formation mostly due to the much lower thickness (Figure 10d). Based on these values, the Naokelekan and Basinal Najmah formations are condensed, but still very good to excellent quality, oil-prone source rocks in the area of study (Figures 7 and 10).

Sulaiy/Chia Gara/ Basal Garau Formations

Stratigraphy and Depositional Setting

The thickness, facies and source rock properties of the Sulaiy/Makhul/Chia Gara formations in Iraq and Kuwait, and their time-equivalent basal Garau in Iran were analysed in 50 wells in Iraq and 36 wells in Iran, in addition to three outcrops in Iraq and two in Iran. Organic geochemical data were available from 3 wells and 3 outcrops in Iraq, and 4 wells and 2 outcrops in Iran (Table 1). In the Middle Tithonian, evaporitic sedimentation in the Gotnia Basin ceased and the deposition of very condensed basinal organic-rich shales and marls took place again (Figure 3) (Goff, 2005; Jassim and Buday, 2006b; Aqrawi et al., 2010). This Late Tithonian–Berriasian stratigraphic unit is called Chia Gara or Lower Balambo Formation in Iraqi Kurdistan (van Bellen et al., 1959-2005), Sulaiy or Makhul Formation in central and southern Iraq (Jassim and Goff, 2006) and Kuwait (Yousif and Nouman, 1997), and basal Garau in western Iran (James and Wynd, 1965; Ala et al., 1980; Bordenave and Burwood, 1990). Towards the west of Iraq these basinal formations pass laterally into the shallow platform carbonate facies of the Yamama Formation. In southwestern Iran they pass into the equivalent Fahlalian platform carbonates. Within the basin centre, the Chia Gara/ Garau Formation conformably overlies the Gotnia/Barsarin/Hith evaporites, and it is overlain by the Yamama/Fahlalian platform carbonates or the Ratawi shales (Figure 3).

The Chia Gara Formation ranges in thickness from 30–290 m at the Iraqi Kurdistan outcrops (Figures 1a, 8 and 11a). In the subsurface it ranges between 60–340 m in Iraq. In Iran the equivalent Garau Formation is around 100–900 m thick, but only the basal 150–250 m is of Tithonian–Berriasian age, which is the time-equivalent of the Chia Gara Formation (Figure 11a).

The lithology of the Chia Gara Formation consists of thin-bedded, bituminous limestones and dolomites, with intercalated black, bituminous shales (Dunnington et al., 1959). These facies are basinal in eastern Iraq at the border with Iran and were deposited in an estimated water depth of 200 m that gradually decreased to 150 m.

Geochemical Characterisation

The Chia Gara source rock properties indicate TOC averages within the range of 3–5 wt%, which may reach up to 12 wt% in the Geli Mezerka and Shiranish Valley outcrops (Odisho and Othman, 1992) (Figure 7, Table 1). They have immature Rock-Eval S2 yields of 2–60 mg HC/g, and the HI
ranges between 350–650 mg HC/g TOC. The Chia Gara/Garau becomes progressively mature towards the eastern Iraq (Figure 12e); so the observed values are well below the original immature ones. The TOC values in this eastern region may reach up to 3 wt% within the wet gas-mature sections of the exploration wells and outcrops. This means that the immature source properties could have been excellent with a range of 4–5 wt% TOC (Figure 11b) and had HI reaching up to 450–550 HC/g TOC (Figure 11c).

Figure 11: Sulaiy /Chia Gara/basal Garau maps: (a) Thickness (m); (b) Estimated immature TOC (%); (c) Estimated immature HI (mg HC/g TOC); and (d) Calculated Source-Potential Index of Demaison and Huizinga (1991) (ton HC/m²).
In western Iraq, only some 5–10 m of the basal part of the formation represents a good source rock. It is worth mentioning that the maturity maps are inaccurate for Iraqi Kurdistan and Iranian Lurestan folded zones (Figure 1b). This is because the depth maps are very uncertain due to the sparse well control, particularly within the synclines.

Figure 12: Maps of modelled thermal maturity (% Ro) and calculated mass of generated hydrocarbons (ton HC per square meter): (a and b) Sargelu Formation; (c and d) Neokelekan Formation; and (e and f) Sulaiy, Chia Gara and basal Garau formations."
See facing page for continuation.
The Source-Potential Index (SPI) ranges from 2–6 in the basinal areas, and may be reaching 10–14 within the depocentres around the Kirkuk Field in northern Iraq and Majnoon Field in the south together with the Azadegan Field of SW Iran at the border with SE Iraq (Figure 11d). Therefore the Sulaify/Makhul/Chia Gara and basal Garau formations are also very good to excellent quality, oil-prone source rocks in most parts of the study area (Figures 7 and 11).

GENERATION AND ACCUMULATION OF PETROLEUM IN SELECTED MAJOR FIELDS OF IRAQ

Based on the detailed source rock thickness, TOC and HI maps (Figures 9–11) together with the reconstructed and calibrated 3-D basin model (Figures 4 and 12, Table 2), the generated volume of petroleum could be calculated for the Kirkuk, East Baghdad and Majnoon fields of Iraq (Figures 13 and 14, Table 3). The field outlines were from Ahlbrandt et al. (2000), Verma et al. (2004) and Aqrawi et al. (2010). First the drainage areas of the fields were calculated in the PetroCharge module of PetroMod software using the detailed Top Sargelu depth map (Figure 4). The size of the drainage areas is shown in Table 3. The Majnoon Field in the Basra Province has probably the smallest drainage area, around 1,375 sq km. The Kirkuk Field has 2,600 sq km, NW-SE elongated drainage areas, whereas the East Baghdad Field has the largest one, around 3,700 sq km. The latter field has also the highest uncertainty, as it could be much larger towards SE direction.

| Field   | Recoverable Reserves Oil (BBO) | Recoverable Reserves Gas (TCF) | Recoverable Reserves OE (BBOE) | In-place Resources (BBOE) | Recovery Factor (%) | Drainage Area (km²) | Generated HC (BBOE) | Generation-Accumulation Efficiency (%) |
|---------|--------------------------------|--------------------------------|-------------------------------|---------------------------|---------------------|---------------------|----------------------|----------------------------------------|
| Kirkuk  | 25                             | 8.2                            | 26.4                          | 53                        | 50                  | 2,600               | 208                  | 26                                     |
| East Baghdad | 16                        | 2.5                            | 16.4                          | 40                        | 20                  | 3,700               | 309                  | 13                                     |
| Majnoon | 11                             | 5.6                            | 12                            | 38                        | 31                  | 1,375               | 303                  | 12                                     |
Figure 13: Burial-thermal histories of the Middle Jurassic–Early Cretaceous source rocks in the deepest parts of the drainage area for: (a) Kirkuk Field, (b) East Baghdad Field, and (c) Majnoon Field. See Figure 1a for locations.
One-dimensional burial history plots (Figure 13) at the deepest points of the mapped drainage areas have been extracted from the 3-D model to illustrate the burial history and temperature evolution. The thermal history in the Kirkuk drainage area in the northern part of the fold belt (Figure 13a) was complex during the late Neogene. In the deepest part of the Kirkuk drainage area the source rock temperatures reached their peak (ca. 155°C) at a depth of about 4,800 m in the Late Miocene (during the Upper Fars Formation deposition) and then decreased to their present-day value (ca. 125°C at 4,300 m) in the late Holocene, implying about 500 m uplift of the drainage area (Aqrawi et al., 2010). However, the uplift and erosion on the Kirkuk Anticline itself could have been even greater. Also, the present burial temperatures in the nearby synclines are approximately 25°C cooler than they were in the past.

The present burial temperatures of source rocks in East Baghdad drainage area in central Iraq (Figure 13b) have reached about 160°C, which corresponds to a depth of approximately 5,400 m. At the Majnoon Field in the south (Figure 13c), maximum source rock temperature has reached approximately 150°C at a depth of about 4,800 m, at the base of the Sargelu layer. These results are very similar to the findings by Pitman et al. (2004), Al-Ameri et al. (2006, 2008, 2011, 2012b), Al-Gailani and Marouf (2010), English and Davies (2013) and Najaf (2014).

Oil transformation (TR) ratios and the temperatures of petroleum generation were simulated for the Kirkuk (Figure 14a), East Baghdad (Figure 14b) and Majnoon (Figure 14c) drainage areas to determine the temperature and timing of generation at the same locations as the burial history plots. Vitrinite reflectance (EASY%Ro) and calculated temperature (Celsius) curves illustrating thermal stress are shown for comparison. The timing and rate of hydrocarbon generation was compared using different published Type IIS kerogen kinetics (Figure 14) using the typical Type IIS kerogen kinetics from Pepper and Corvi (1995), Behar et al. (1997), Lewan and Ruble (2002), Santamaria-Orozco and Horsfield (2003) and Abeed et al. (2013). TR curves represent the fraction of petroleum (both oil and gas) that was generated at a given moment in geologic time. The beginning, peak and end of oil generation correspond to TRs of 0.01, 0.50 and 0.95, respectively (Pitman et al., 2004).

In the Kirkuk drainage area oil generation commenced (TR 0.01) during Palaeogene–Neogene folding and faulting, and trap formation, and ceased (TR 0.95) at the onset of Pliocene uplift and erosion (Figure 14a). The source rock temperatures here increased rapidly from about 80°C at the beginning of generation to a maximum of 155°C at peak generation and then declined to approximately 120°C at present day. In the Kirkuk drainage area oil generation is still ongoing at 120–130°C.

In the East Baghdad drainage area (Figure 14b) in the central Mesopotamian Foredeep Basin, TR and thermal curves indicate that oil generation started (TR > 0.01) in the Late Cretaceous at temperatures of about 80°C using all published Type IIS kinetics. The rate intensified in the Late Miocene, with the deposition of the thick Lower and Upper Fars formations.

In the Majnoon drainage area (Figure 14c) in southern Mesopotamian Foredeep Basin, TR and thermal curves indicate that oil generation started (TR > 0.01) in the Late Cretaceous at temperatures of about 80°C using all published Type IIS kinetics. However, the rate of oil generation is quite different. According to the Lewan and Ruble (2002) Phosphoria kinetics, the oil generation is completed by Middle Miocene times (TR > 0.95) when burial temperatures were approximately 140°C. The other Type IIS kerogen kinetics generated oil much later, and in a shorter time period, when the temperatures exceeded 110°C in the Miocene. The total TR is also lower with this kinetics, reaching only 60–70% (Pepper and Corvi, 1995; Abeed et al., 2013); and up to 90% (Behar et al., 1997). The timing of oil generation and expulsion post-dated the formation of the Majnoon Anticline and was highly favourable for trap charging.

Then the generated petroleum was calculated using PetroMod within these drainage areas from the Sargelu, Naokelekan and Chia Gara source rocks respectively (Figure 15a, Table 3). The calculated generated volumes were compared with the publicly available recoverable reserves and in-place resources per field. According to Ahlbrandt et al. (2000) and Verma et al. (2004) the Kirkuk Field had originally 25 billion barrels oil (BBO) and 8.2 trillion cubic feet (TCF) gas (= 1.4 billion barrels oil equivalent, BBOE); East Baghdad had 16 BBO and 2.5 TCF (0.43 BBOE) gas; while Majnoon
Aqrawi and Badics

Figure 14: Temperature (Celsius) in red, calculated vitrinite reflectance (EASY%Ro) in purple curves together with kerogen-oil transformation ratio (TR) curves of different published Type IIS kinetics showing the time of petroleum generation at the: (a) Kirkuk Field; (b) East Baghdad Field; and (c) Majnoon Field. The kinetics are from Sweeney and Burnham (1990), Pepper and Corvi (1995), Behar et al., (1997), Lewan and Ruble (2002), Santamaria-Orozco and Horsfield (2003) and Abeed et al. (2013). See Figure 1a for locations.
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had 11 BBO and 5.6 TCF (0.96 BBOE) gas recoverable reserves (Table 3). The generated petroleum volume, using the Pepper and Corvi Type II S kerogen kinetics; is approximately 208 BBOE in the Kirkuk drainage area and 300 BBOE in the East Baghdad and Majnoon drainage areas, meaning a generation-accumulation efficiency (GAE) of 26% for the Kirkuk Field, and 12–13% for the East Baghdad and Majnoon fields. These results are very similar of the published GAE values per fields and their respective drainages by Bird (1994), Schmoker (1994) and Biteau et al. (2010). The higher GAE for the Kirkuk Field can be explained by the shape of the drainage, which is very elongated and the hydrocarbon migration pathway is short, and quite focused towards the anticline. Also, the formation and migration of hydrocarbons at the Kirkuk Field have happened at the same time as the trap formation. The Majnoon Anticline and the East Baghdad Horst were formed before the oil generation started, and in these cases, the hydrocarbon migration was not as focused towards the traps and not as effective as in the Kirkuk case.

GENERATED HYDROCARBON VOLUMES PER BASIN USING SCHMOKER METHOD

The generated hydrocarbons from each of the three studied formations were calculated first using a simple mass-balance approach, as described previously under methodology. The results obtained showed huge volumes of oil and gas that been generated from these prolific source rocks.

After the final thickness, immature TOC and immature HI maps were created in ArcGIS, the P90, P50, mean and P10 values of these maps were calculated (Table 4). The effective source rock thresholds for carbonate source rocks were considered to be at least 0.3 wt% TOC and 50 mg HC/g TOC by Welte and Yalcin (1988) and Biteau et al. (2010). Therefore the same screening criteria were used, to eliminate areas below such threshold values. So assuming a mean net source rock (> 0.3 wt% TOC) thickness of 168 m, a mature area of 327,000 sq km, 2.73 wt% mean immature TOC and an HI of 380 mg HC/g TOC (Table 4), the Sargelu Formation could have generated up to 6,600 BBO and 2,800 BBOE gas in the Mesopotamian Foreland and Zagros Fold Belt Basins, using the simple method of Schmoker (1994) (Table 5).

The Naokelekan Formation is much thinner, so a net source rock thickness of 9 m was considered together with a mature area of 303,000 sq km, 3.50 wt% mean immature TOC and an HI of 450 mg HC/g TOC, so the formation could have generated up to 585 BBO and 146 BBOE gas (Table 5) within the study area.

The Chia Gara/Basal Garau Formation was considered with a mean net source rock thickness of 181 m, a mature area of 270,000 sq km, 2.85 wt% mean immature TOC and an HI of 420 mg HC/g TOC, then this formation could have generated up to 8,800 BBO and 975 BBOE gas in the study area, using the simple method of Schmoker (1994) (Table 5).

Table 4

| Screening Criteria for Studied Formation | Sargelu | Naokelekan | Chia Gara |
|-----------------------------------------|---------|------------|-----------|
| Thickness (m) [where TOC > 0.3 wt%]    | P90     | 40         | 152       | 348       |
|                                         | P50     | 152        | 8.5       | 348       |
|                                         | Mean    | 168        | 9.2       | 22        |
|                                         | P10     | 348        | 22        | 292       |
| TOC immature (wt%) [where TOC > 0.3 wt%] | P90   | 0.65       | 1.08      | 0.76      |
|                                         | P50     | 2.82       | 3.01      | 2.82      |
|                                         | Mean    | 2.73       | 3.5       | 2.85      |
|                                         | P10     | 4          | 8.57      | 3.8       |
| HI immature (mgHC/g TOC) [where HI > 50 mgHC/g TOC] | P90 | 300        | 190       | 300       |
|                                         | P50     | 400        | 380       | 415       |
|                                         | Mean    | 380        | 450       | 420       |
|                                         | P10     | 490        | 560       | 475       |
| SPI immature (ton HC/m²) [where all 3 above apply] | P90 | 2.6        | 0.5       | 2.4       |
|                                         | P50     | 6          | 0.8       | 5.4       |
|                                         | Mean    | 5.73       | 0.63      | 3.25      |
|                                         | P10     | 9.7        | 2.5       | 9.35      |

Table 5

| Screening Criteria for Source Rock | Sargelu | Naokelekan | Chia Gara |
|-----------------------------------|---------|------------|-----------|
| Mean Thickness (m)                | 168     | 9.2        | 181       |
| Mature Area (km²)                 | 327,000 | 303,000    | 270,000   |
| Mean Immature TOC (wt%)           | 2.73    | 3.5        | 2.85      |
| Mean immature HI (mg HC/g TOC)    | 380     | 450        | 420       |
| Mean Transformation Ratio (TR)    | 0.85    | 0.85       | 0.85      |
| Mean Generated Oil (BBOE)         | 6,600   | 585        | 8,800     |
| Mean Generated Gas (BBOE)         | 2,800   | 146        | 975       |
The generated hydrocarbons from each studied formation were also calculated using the detailed 3-D basin model through employing the same source rock maps as input in order to get some more precise results. In the PetroMod model, the generated mass of petroleum (oil, gas-condensate and gas) is calculated using the finite-element grid, with the individual values of source rock thickness, immature TOC and HI per grid-cell. However, the net source rock is not calculated in this method, but the total thickness is taken into account in the volume calculations.

In immature areas or areas with 0 wt% TOC or very low HI values, no generation is calculated. The thermal maturity and petroleum generation and expulsion histories were simulated on a cell-by-cell basis, using the same geometrical input (i.e. depth and thickness maps), heat-flow

Figure 15: (a) Comparison of in-place petroleum (oil, gas-condensate and gas) resources in BBOE (billion barrel oil-equivalent) and generated volume of petroleum within the drainage areas of the Kirkuk, East Baghdad and Majnoon fields, using Pepper and Corvi (1995) Type IIS kinetics. (b) Comparison of generated volume of petroleum using the different published kinetics (Pepper and Corvi, 1995; Behar et al., 1997; Lewan and Ruble, 2002; Santamaria-Orozco and Horsfield, 2003; Abeed et al., 2013) for the entire study area per source rock unit; and (c) generated volume of petroleum per confidence/ basin area from each source rock unit.
and surface temperature maps, but with different kerogen kinetics to compare their effects on the total generated petroleum volume. The generated (not the expelled) petroleum volume per source rock for the study area is shown in Figure 15b, using the Type IIS kerogen kinetics from several studies (Pepper and Corvi, 1995; Behar et al., 1997; Lewan and Ruble, 2002; Santamaria-Orozco and Horsfield, 2003; Abeed et al., 2013). It is clear both in the transformation ratio through time (Figure 14), and the total generated volume per source rock (Figure 15b), that the most labile kinetics (Lewan and Ruble, 2002: created for the Phosphoria and Monterey formations using hydrous pyrolysis) result in the earliest generation and the largest generated petroleum volume. The Pepper and Corvi (1995) Type IIS kinetics is less labile, meaning HC generation at higher temperatures. This was used in most of the further calculations. The Behar et al. (1997) and Santamaria-Orozco and Horsfield (2003) Type IIS kinetics is even more stable, generating at higher temperatures. The Abeed et al. (2013) kinetics, developed for the Yamama Formation, is the most stable, resulting in HC generation at highest temperatures and the lowest generated volumes.

Figure 15c and Table 6 summarise the generated volume of petroleum as BBOE using the Pepper and Corvi (1995) Type IIS kerogen kinetics, showing the different USGS provinces and the confidence zones.

The Western Interior Platform of Iraq was mainly covered with ramp or platform carbonate facies during the Middle to Late Jurassic and therefore has only small areas of source rock facies (Figure 6). The area is also largely immature (Figure 12), so the generated volumes are small here (Figure 15c, Table 6). Also, the Sargelu Formation is the only contributor to the area bordered by wells (Diwan-1, Samawa-1 and Kifl-1) because the generated volumes from the Naqeelekan and Chia Gara formations are not significant.

The Mesopotamian Foredeep Basin has been subdivided into different confidence zones according to data coverage and country borders (Figure 1b). The “Gulf” part is mainly in Saudi Arabia, where the original map coverage and confidence are very low, as it was not the main focus of the present study. In this area, the main contributor is probably the organic-rich Sulaiy source rocks overlying the Hith evaporites, sourcing the giant offshore fields, like Al Khafji, Manifa and Safaniya (Figure 15c, Table 6). The Sulaiy is not mapped completely in this area in this study, so only qualitative estimates can be made.

| USGS Basin          | Confidence Area      | Sargelu (BBOE) | Naqeelekan (BBOE) | Chia Gara/Basal Garau (BBOE) | From all 3 Source Rocks (BBOE) |
|---------------------|----------------------|----------------|-------------------|-------------------------------|--------------------------------|
| Interior Platform   | Iraq Interior Platform | 432            | 8                 | 33                            | 473                            |
| Mesopotamian Foredeep | Gulf Mesopotamian Basin | 0              | 0                 | 75                            | 75                             |
|                     | Kuwait Mesopotamian Basin | 193            | 28                | 272                           | 492                            |
|                     | Iraq Mesopotamian Basin | 5,112          | 851               | 5,027                         | 10,990                         |
|                     | Iran Mesopotamian Basin | 1,857          | 229               | 1,229                         | 3,318                          |
|                     | Total Mesopotamian Basin | 7,162          | 1,108             | 6,602                         | 14,873                         |
| Zagros Fold Belt    | Iraq Zagros FB. Foothills | 1,015          | 253               | 787                           | 2,054                          |
|                     | Iraq Kurdistan FB.     | 373            | 114               | 697                           | 1,184                          |
|                     | Iraq Kurdistan Foothills | 682            | 210               | 477                           | 1,369                          |
|                     | Iran Zagros FB. Foothills | 1,742          | 489               | 1,477                         | 3,708                          |
|                     | Iran Zagros FB. Mountains | 1,806         | 720               | 1,057                         | 3,584                          |
|                     | Total Zagros Fold Belt | 5,619          | 1,786             | 4,496                         | 11,900                         |
| Zagros Thrust       | Iran Zagros Thrust     | 309            | 131               | 1                             | 441                            |
| Total 3-D Basin Model |                     | 13,522        | 3,033             | 11,132                        | 27,687                         |

Pepper and Corvi (1995) Type IIS kerogen kinetics was used in the calculation of generated petroleum mass. FB = Foreland Basin; BBOE = Billion Barrel Oil Equivalent
In the Kuwaiti part of the Mesopotamian Foredeep Basin, the thickness and depth maps are from several papers (Abdullah and Kinghorn, 1996; Abdullah et al., 1997; Yousef and Nouman, 1997; Rabie et al., 2014), and therefore the confidence is higher. The main contributors are the Sargelu (193 BBOE) and the Chia Gara/Sulaiy (272 BBOE), which charged some giant fields such as the Burgan, Minagish, Raudhatain and Sabriyah (Figure 15c, Table 6).

The Iraqi part of the Mesopotamian Foredeep Basin has the largest generated petroleum volume reaching up to 11,000 BBOE, where the main charge is from the Sargelu (5,112 BBOE) and the Chia Gara/Sulaiy (5,027 BBOE), with limited addition from the Naokelekan/basinal Najmah (851 BBOE) (Figure 15c, Table 6). The confidence level is very high due to the large number of wells covering this region, so these estimates are quite reliable. Interestingly, the largest giant fields, like Rumaila, Zubair, Nahr Umr and Majnoon, are located where the SPI and the generated petroleum volume are the highest (Figures 9, 10, 11 and 12).

As previously discussed, the Majnoon drainage area alone has generated around 300 BBOE from a drainage area of 1,375 sq km, giving a GAE of 12% (Table 3). Similar ranges can be expected for the Rumaila, Zubair and other giant fields in southern Iraq. These results correspond to the findings by Pitman et al. (2004) and Abeed et al. (2013). However, it is not possible, to use these organic geochemical methods to determine which of the three studied carbonate formations (Sargelu, Naokelekan and Chia Gara) sourced which reservoir and in which field. This limitation is because the biomarkers, light hydrocarbons and isotope signatures of the three formations are quite similar. The crude oils are possibly derived from anoxic, carbonate, Type IIS kerogen, at the early to middle stage of maturity. They are usually characterised by low Pr/Ph, low diasteranes, dominance of norhopane over hopane, high relative abundance of homohopanes and high C29 over C27 steranes (Al-Ameri and Al Khafaji, 2008; Al-Ameri et al., 2009; Al-Ameri et al., 2012b). Some recent studies by Al-Ameri and Al Khafaji (2008) and Abeed et al. (2011, 2012), indicate that based on age-diagnostic biomarkers, the Lower Cretaceous Chia Gara/Sulaiy seems to be the main candidate source rock for the oils due to the absence or scarcity of oleanane and the low norcholestane ratios. It seems possible that methods such as diamentoids could indicate the contribution from the pre-Gotnia (of higher maturity) Sargelu and Naokelekan versus the lower maturity, post-Gotnia Sulaiy/Chia Gara source rocks per field/reservoir.

The Iranian part of the Mesopotamian Foredeep has the second largest generated petroleum volume totaling up to 3,316 BBOE, where the main charge is from the Sargelu (1,857 BBOE) and the Chia Gara/Sulaiy (1,229 BBOE), with some limited addition from the Naokelekan/basinal Najmah (229 BBOE) (Figure 15c, Table 6). The confidence map and the number of wells in this area are high, so these estimates are quite reliable. The largest field in the area is Azadegan (about 20 BBOE reserves), which is clearly partly sourced from the Chia Gara/basal Garau source rocks. The contribution from the deeply buried Sargelu and Naokelekan to the commercial fields is currently unknown. The other younger but very effective source rock in this area is the Albian Kazhdumi Formation, which is clearly the largest contributor to the giant fields of SW Iran (Bordenave and Burwood, 1990, 1995; Rabbani and Kamali, 2005). The current study did not focus on the Kazhdumi Formation, so the volume of petroleum generated from it was not calculated, but it might exceed the volume generated from the basal Garau in the area based on the previous mentioned studies.

The Zagros Fold Belt has also been subdivided into several confidence zones, to reflect country borders and data availability. The Iraqi Foothills part was defined as the area of the Zagros Fold Belt, which is entirely in Iraq but not in Kurdistan, extending from the Iranian border in the southeast to the Mansuriyah and Pulkhana fields towards Kirkuk and Qualian in the northwest (Figure 1b). This area has also large generated petroleum volume totaling up to 2,054 BBOE, where the main charge is from the Sargelu (1,015 BBOE) and the Chia Gara (787 BBOE), with addition from the Naokelekan/basinal Najmah (253 BBOE) (Figure 15c, Table 6). The map confidence and the number of wells in this area are medium, so these estimates are not as reliable as in the southern part of the Mesopotamian Foredeep. As previously discussed, the Kirkuk drainage area alone has generated around 208 BBOE from a drainage area of 2,600 sq km, giving a GAE of 26% (Table 3). Similar ranges can be expected for the Bai Hassan, Qara Chauq and other fields of this region. In this area, the traps are mainly elongated anticlines, with steep limbs, where top seal is fractured...
and hydrocarbon leakage could have occurred, but the yet-to-find (YTF) potential is large, which is indicated by the recent giant discoveries at Shakal-1 and Sarquala-1.

Towards the northeast, in the Kurdistan Foothills area, the confidence in the depth and thickness maps decreases due to the many narrow anticlines and synclines (Figure 1a). By using the source rock maps (Figures 9, 10, 11 and 12), the total generated petroleum of this area could be around 1,369 BBOE, with the main contribution from the Sargelu (682 BBOE) and the Chia Gara (477 BBOE) formations (Figure 15c, Table 6). The amount of generated gas increases towards the northeast, due to greater burial. The main older fields are Khor Mor, Chemchemal and Taq Taq in this area, with recent large discoveries farther north such as Atrush, Shaikan and Miran.

The Kurdistan Fold Belt is an area with very high uncertainty and low confidence in the depth and thickness maps, due to the numerous anticlines and the high erosion. The total petroleum volume generated is around 1,184 BBOE, with main contribution from the Chia Gara (697 BBOE) Formation (Figure 15c, Table 6). The source rocks could be studied in numerous outcrops of this region (Figure 8, Table 1), but the creation of high-confidence depth maps and an accurate 3-D basin model accounting for the erosion over each anticline was not possible. Most of the generated petroleum volume was probably lost during the Neogene tectonic phases via thrusting and folding events, but still some large fields such as the Tawke may occur in the area, where a good seal occurs. Recent discoveries, like Behr Bahr, Summail, Swara Tika and Bina Bawi indicate that there is a significant YTF potential; it decreases towards the northeast of Kurdistan, where the traps have been greatly elevated and probably breached or completely destroyed during Neogene tectonism.

In Iran, the Zagros Foothills area (or low folded zone) contains the largest fields of Iran. Most have been charged by the Albian Kazhdumi Formation (Ahwaz, Shadegan, Marun, Agha Jari and Pazanan fields), or by the Eocene Pabdeh Formation (Lab-E-Safid and Qualeh Nar fields), according to Bordenave and Burwood (1990, 1995). As mentioned previously the present study did not focus on the Kazhdumi, so the exact volume of petroleum generated from the Kazhdumi was not calculated, but might exceed the volume generated from the Basal Garau in the area. There could be, however, large contribution from the Sargelu (1,742 BBOE) and Basal Garau (1,477 BBOE; Figure 15c, Table 6) in the area, particularly into the deeper pools in the Fahliyan and Surmeh reservoirs where the Kazhdumi and Pabdeh are not present or not mature (e.g. Lurestan fields such as the Azar, Changuleh and Deluran fields, Badics and Rashidi, 2007).

The confidence in the map and data in the Zagros Fold Belt of Iran (Figure 1b) is low because of the numerous exposed anticlines and the great erosion. The total generated petroleum volume could have been very large, up to 3,584 BBOE, with contribution mostly from the Sargelu (1,806 BBOE) and the basal Garau (1,057 BBOE; Figure 15c, Table 6). Most of the generated petroleum has been lost in the area due to the unfavourable timing of early generation and very late trap formation. However, the discovery of the Sarkhan and Maleh Kuh fields indicate that in some local areas seal integrity exists. Finally, the Zagros Thrust Zone is an area where analyses have extremely low confidence due to the numerous thrusts and repeated sections. It is probable that all the generated petroleum was lost during the Neogene due to the intense tectonic activities.

DISCUSSION

Yet-To-Find Estimates versus Generated Hydrocarbon Volumes

Ahlbrandt et al. (2000) and Verma et al. (2004) estimated the yet-to-find (YTF) potential of the Jurassic Gotnia/Barsarin/Sargelu/Najmah System (TPS 202302) in the Iraqi part of the Mesopotamian Foreland Basin and in the Zagros Fold Belt to be 5.3 BBO and 17.6 TCF (3 BBOE) gas (Table 7), totaling together about 8.3 BBOE. The petroleum in the undiscovered accumulations in Jurassic reservoirs below the regional Gotnia seal could only have been sourced from the pre-Gotnia Sargelu and Naokelekan source rocks. The overlying composite Zagros-Mesopotamian Cretaceous-Cenozoic Petroleum System (TPS 203001) was estimated to contain undiscovered
Generation-Accumulation Efficiency (%) = 100 x \( \frac{\text{Proven mean in-place resources} + \text{Yet-to-Find (YTF) in-place resources}}{\text{Generated petroleum volume from all three source rocks (Sargelu, Naokelekan and Chia Gara formations)}} \)

Table 7

| Resources | Data Source | USGS Basin/Province |
|-----------|-------------|---------------------|
|           |             | Mesoopotamian Foredeep | Zagros Fold Belt |
| Proven Mean Recoverable (BBOE) | Ahlbrandt et al., 2000; Verma et al., 2004 | 134 | 197 |
| Proven Mean In-place Estimated (BBOE) | Ahlbrandt et al., 2000; Verma et al., 2004 | 340 | 500 |
| YTF Mean Recoverable (BBOE) | Ahlbrandt et al., 2000; Verma et al., 2004 | 57.5 | 80 |
| YTF Mean In-place Estimated (BBOE) | Ahlbrandt et al., 2000; Verma et al., 2004 | 172.5 | 240 |
| YTF Mean Recoverable (BBOE) | Pitman et al., 2012 | 33 | 55 |
| YTF Mean Recoverable (BBOE) | Pitman et al., 2012 | 99 | 165 |
| Generated from 3 SRs (BBOE) | This article | 14,873 | 11,900 |
| Generation-Accumulation Efficiency (%) | This article | 2.9–3.4 | 5.5–6.2 |

Generation-Accumulation Efficiency (%) = 100 x (Proven mean in-place resources + Yet-to-Find (YTF) in-place resources) divided by Generated petroleum volume from all three source rocks (Sargelu, Naokelekan and Chia Gara formations).

In the most recent USGS estimates Pitman et al. (2012) combined the previous Jurassic (TPS 202302) and Cretaceous–Cenozoic (TPS 203001) total petroleum systems into a combined Mesozoic–Cenozoic Composite TPS, where they have assessed 23 assessment units (AUs). The so-called “Zagros Fold Belt Structures” is the same area as the previously defined Zagros Fold Belt Basin; and the “Mesopotamian Basin Anticlines” equals the Mesopotamian Foredeep Basin of the current study. Most of the undiscovered petroleum is estimated to be in the Zagros Fold Belt Structures having a total YTF of 55 BBOE oil, condensate and gas (Table 7). Within in the Mesopotamian Basin Anticlines, a total YTF of 33 BBOE was estimated by Pitman et al. (2012).

Combining the discovered in-place and the estimated YTF in-place resources, the Mesopotamian Foredeep has an ultimate petroleum endowment of 440–512 BBOE; whereas the Zagros Fold Belt has around 665–740 BBOE. For the Mesopotamian Basin all the discovered petroleum has been generated exclusively from the Middle–Upper Jurassic and Lowermost Cretaceous source rocks; so in this USGS province, a direct comparison can be made between the total generated and the proven plus YTF resources (Table 7). For the whole Mesopotamian Foredeep Basin then, the GAE is between 2.9–3.4%, which is typical of foreland basins (Bird, 1994; Schmoker; 1994; Biteau et al., 2010).

As discussed previously, individual fields and their respective drainage areas can have a much higher GAE, up to 12–26%. In the Zagros Fold Belt, all of the dry gas in Permian Kangan-Dalan reservoirs was probably sourced from the deeply buried Palaeozoic Qusaiba/Gakhum shale. In the Dezful Embayment, which is the Iranian Mesopotamian Basin and some areas of the Zagros Fold Belt Foothills Zones, in the present study, significant petroleum volume was also generated from the Kazhdumi, and some volume in the deepest northeastern parts, from the Pabdeh source rocks. Therefore no direct comparison could be made between the total proven in-place and YTF resources. If one only considers the proven and YTF in-place oil; then the Zagros Fold Belt has around 120 BBOE proven recoverable reserves, 380 BBOE in-place resources (Ahlbrandt et al., 2000, Verma et al., 2004) and an estimated oil YTF recoverable reserves of 38.4 BBOE (Pitman et al. 2012) or 55.6 BBOE (Verma et al., 2004). The total oil endowment (discovered and YTF oil in-place) would then be around 545 BBOE, giving a GAE of 4.5% (Table 7).
In their global evaluation, Biteau et al. (2010) estimated for the whole Central Arabian Foreland (which includes the USGS-defined Mesopotamian Foredeep Basin and the Saudi Arabian and Qatar parts of the basin), a GAE of around 7–8%. For the foreland basin types they estimated a GAE of between 2 and 10%. For the Mesopotamian Foredeep we estimated a GAE of 2.9–3.4%. If this GAE was just 1% greater, it would represent 150 BBOE in added new reserves, which implies that huge YTF potential may exist in this area.

Interestingly, since 2000, the discovered total petroleum in Iraq, especially in Iraqi Kurdistan is about 8.4 BBOE (English and Davies, 2013). Within the Zagros Fold Belt in Iran, since 2000 approximately 29 BBOE of petroleum has been discovered in Jurassic to Cenozoic reservoirs, with the Azadegan, Azar and West Changuleh fields being the largest discoveries. These exclude the recent Permian Kangan-Dalan gas discoveries, like Mokhtar, which are sourced by the Palaeozoic (Lower Silurian) “hot” shales, within the study area.

**SHALE-OIL/GAS POTENTIAL**

The proven and economic shale-oil and shale-gas plays in the USA and Canada (e.g. Barnett, Eagle Ford, Haynesville, Marcellus and Montney) all have high original TOC values. The average immature TOC is usually over 2 wt%, but sometimes may be 4–6 wt%. The immature kerogen is oil-prone, Type II, with HI higher than 250 mg HC/g TOC (Jarvie et al., 2007). The gas occurring in the gas shales probably formed from cracking of the oil, which could not be expelled from the shales. The minimum thickness of the shale-oil and shale-gas plays exceeds 20 m, their quartz and carbonate contents are often high and their clay content is low; these factors are all required for economic artificial fracturing or fracking. They should also have upper and lower fracture barriers, which act as seals during the fracking (Jarvie et al., 2007).

The Sargelu and the overlying Naokelekan-basinal Najmah formations could represent the best potential shale-gas/shale-oil plays in Iraq, Kuwait and Iran, due to their organic richness, favourable maturity and the presence of lower (Mus and Adaiyah) and upper (Gotnia and Hith) evaporites, which can act as fracture barriers or regional seals. In Iraq, for example, the area of wet-gas mature Sargelu (Figure 12c) is close to the Iranian border, in a 30–90 km-wide zone running from the Rifai and Halfaya fields in the southeast towards the Ahdab and East Baghdad fields, with a total area of around 20,000 sq km. The depth of burial is between 5,300–6,500 m. The area of oil-mature section is even larger, around 60,000–75,000 sq km, representing a 120–170 km-wide zone in the western part of the Mesopotamian Foredeep Basin, from the western border of the basin to the start of the wet-gas generation zone in the east. The peak oil (0.7–1.0 %Ro) to late oil (1.0–1.3 %Ro) mature area includes the southern Basra area, the areas between Nasiriyah and Ahdab fields, and towards the north to the Ajeel and Hamrin fields (Figure 12c). The oil-mature section is at 3,300–5,300 m depth in the Mesopotamian Foredeep Basin, representing a potential shale oil play.

The unexpelled oil-in-place is difficult to estimate. Jarvie et al. (2007) estimated it to be 40% for North American shale-plays, whereas Jassim and Goff (2006) reported it to be 75% for the carbonate source rocks of Iraq. This means that the Mesopotamian Foredeep Basin, in only the oil-mature areas of the Sargelu in Iraq, may contain un-expelled oil-in-place of 1,300–2,500 BBOE. For Kuwait, the Sargelu Formation may contain about 77–150 BBOE oil-in-place. It is worth mentioning that oil has been produced from the Sargelu Formation at the Rumaila Field in southern Iraq, wherever it is fractured.

The Sulaiy/Chia Gara/basal Garau formations overlying the regional Gotnia and Hith evaporites are also very rich in organic matter and have the light oil- and wet-gas maturity. However they generally lack the upper barrier, as they are overlain by porous limestone reservoirs of the Yamama Formation in the south and Quamchuqa Formation in the north. In areas, where the Chia Gara/ Garau is covered by tight limestones, they might also represent a shale-oil play.
CONCLUSIONS

The main Middle Jurassic–lowermost Cretaceous source rocks of the NE Arabian Plate are the Bajocian–Bathonian Sargelu, the Callovian–Lower Kimmeridgian Naokelekan (or basinal Najmah) and the Upper Tithonian–Lower Berriasian Chia Gara/Sulaiy/basal Garau formations in Iraq, and their chronostratigraphic equivalents in Kuwait and Iran. These source rocks are bituminous, often dolomitised marly limestones and shales, which were deposited within 150–350 m water depth in vast areas of the intra-shelf basins of NE Arabia.

The Sargelu Formation ranges in thickness from 20–125 m at the Iraqi Kurdistan outcrops and increases to 77–446 m in the subsurface in the rest of Iraq; in Iran it is around 28–316 m thick. The TOC averages of the Sargelu Formation per wells and outcrops are within the range of 1.5–5 wt%; a Rock-Eval S2 yields is of 1.5–13.23 mg HC/g TOC; and HI ranges are between 100–600 mg HC/g TOC. The immature TOC map has a P90–P10 range of 0.65–4.0 wt% and a mean of 2.73 wt%; the immature HI has a range of 300–490, with a mean of 380 mg HC/g TOC. The SPI mean is 5.7 ton HC/m², with a P90–P10 range of 2.6 and 9.7, reaching 16–18 ton HC/m² in some areas. The Sargelu Formation alone could have generated up to 7,100 billion barrel oil-equivalent (BBOE) petroleum in the Mesopotamian Foredeep Basin, and 5,600 BBOE in the Zagros Fold Belt.

The Naokelekan (or basinal Najmah Formation) thickness ranges between 5–32 m thick as a condensed section in the Iraqi Kurdistan outcrops, while it is 17–30 m in the subsurface of both Iraq and Iran. The TOC averages of the Naokelekan Formation are within the range of 4–5 wt%; a Rock-Eval S2 yields is of 2–40 mg HC/g TOC; and HI ranges are between 400–700 mg HC/g TOC. The immature TOC map has a P90–P10 range of 1.08–8.6 wt% and a mean of 3.5 wt%; the immature HI has a range of 190–560, with a mean of 450 mg HC/g TOC. Due to the low thickness, the SPI mean is only 0.63 ton HC/m², with a P90–P10 range of 0.5 and 2.5. The Naokelekan/basinal Najmah could have generated up to 1,100 BBOE petroleum in the Mesopotamian Foredeep Basin, and 1,800 BBOE in the Zagros Fold Belt.

The Sulaiy/Chia Gara/basal Garau Formation thickness is 30–290 m in the Iraqi Kurdistan outcrops and ranges between 60–340 m thick in the studied wells within Iraq, and 150–250 m within Iran. The TOC averages of this formation per wells are within the range of 3–5 wt%; a Rock-Eval S2 yields is of 2–60 mg HC/g TOC; and HI ranges are of 350–650 mg HC/g TOC. The immature TOC map has a P90–P10 range of 0.76–3.8 wt% and a mean of 2.85 wt%; the immature HI has a range of 300–475, with a mean of 420 mg HC/g TOC. The SPI mean is 3.2 ton HC/m², with a P90–P10 range of 2.4 and 9.3, but reaching 10–14 ton HC/m² in some areas. The Sulaiy/Chia Gara/basal Garau alone could have generated up to 6,600 BBOE petroleum in the Mesopotamian Foredeep Basin, and 4,500 BBOE in the Zagros Fold Belt.

The generated petroleum volume per drainage area calculated by Pepper and Corvi (1995) Type II S kinetics was compared to the discovered recoverable reserves and estimated in-place resources for three selected fields namely: Majnoon, East Baghdad and Kirkuk. The GAE is 26% for the Kirkuk Field, and 12–13% for the East Baghdad and Majnoon fields.

The generated volume of petroleum as BBOE was also calculated for the whole Mesopotamian Foredeep Basin and the Zagros Fold Belt, using the simplistic method from Schmoker (1994) and the detailed finite-element 3-D basin modelling. These results indicate that the total generated petroleum volume could have been very large, up to 14,800 BBOE in the Mesopotamian Foredeep Basin and around 12,000 BBOE in the Zagros Fold Belt.

The conventional and unconventional shale-oil and shale-gas yet-to-find potential of these areas are still enormous, with modest estimates for the conventional YTF to be 33–58 BBOE for the Mesopotamian Foredeep Basin and 55–80 BBOE for the Zagros Fold Belt. The Sargelu, and the overlying Naokelekan-Basinal Najmah formations (and their equivalents) could represent the best potential shale-gas/shale-oil plays in Iraq, Kuwait and Iran. The estimated oil in place for the potential Sargelu shale-oil play in Iraq only is around 1,300–2,500 BBOE, and in Kuwait about 77–150 BBOE.
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REFERENCES

Abdulla, R. 2010. Petroleum source rock analysis of the Jurassic Sargelu Formation, northern Iraq. MSc Thesis, Colorado School of Mines, 106 p.
Abdullah, F.H.A. and R.R.F. Kinghorn 1996. A preliminary evaluation of Lower and Middle Cretaceous source rocks in Kuwait. Journal of Petroleum Geology, v. 19, p. 461-480.
Abdullah, F.H.A., P.J.R. Nederlof, M.P. Ormerod and R.R.F. Kinghorn 1997. Thermal History of the Lower and Middle Cretaceous Source Rocks in Kuwait. GeoArabia, v. 2, no. 2, p. 151-164.
Abeed, Q., A. Alkhafaji and R. Littke 2011. Source rock potential of the Upper Jurassic-Lower Cretaceous succession in the southern Mesopotamian Basin, southern Iraq. Journal of Petroleum Geology, v. 34, p. 117-134.
Abeed, Q., D. Leythaeuser and R. Littke 2012. Geochemistry, origin and correlation of crude oils in Lower Cretaceous sedimentary sequences of the southern Mesopotamian Basin, southern Iraq. Organic Geochemistry, v. 46, no. 1, p. 113-126.
Abeed, Q., R. Littke, F. Strozyk and A.K. Uffmann 2013. The Upper Jurassic-Cretaceous petroleum system of southern Iraq: A 3-D basin modeling study. GeoArabia, v. 18, no. 1, p. 179-200.
Ahlbrandt, T.S., R.M. Pollastro, T.R. Klett, C.J. Schenk, S.J. Lindquist and J.E. Fox 2000. Region 2 Assessment Summary—Middle East and North Africa. In United States Geological Survey World Petroleum Assessment 2000—Description and Results, chapter R2, DDS-60, 46 p.
Ahmed, M.A. 1997. Sedimentary facies and depositional environments of Jurassic rocks, NW Iraq. PhD Thesis (unpublished). Science College, University of Mosul, Mosul, Iraq 170 p. (in Arabic).
Aha, M.A., R.R.F. Kinghorn and M. Rahman 1980. Organic geochemistry and source rock characteristics of the Zagros petroleum province, southwest Iran. Journal of Petroleum Geology, v. 3, no. 1, p. 61-89.
Al-Ahmed, A.A.N. 2006. Organic geochemistry, palynofacies and hydrocarbon potential of Sargelu Formation (Middle Jurassic), northern Iraq. PhD Thesis, University of Baghdad, Baghdad, Iraq, 120 p.
Al-Ahmed, A.A.N. 2013. Determination and applications of chemical analysis to evaluate Jurassic hydrocarbon potentiality in northern Iraq. Arabian Journal of Geoscience, v. 6, no. 8, p. 2941-2949.
Al-Ameri, T.K., F.S. Al-Musawi and D.J. Batten 1999. Palynofacies indications of depositional environments and source potential for hydrocarbons: Uppermost Jurassic – basal Cretaceous Sulaiy Formation, southern Iraq. Cretaceous Research, v. 20, p. 359-363.
Al-Ameri, T.K., A.A. Najaf, J.E. Zumberge and S.W. Brown 2006. Petroleum potential and oil correlation of the Middle Jurassic Sargelu Formation, Iraq. American Association of Petroleum Geologists Annual Convention and Exhibition, Houston, Texas, April 9–12, 2006. American Association of Petroleum Geologists Search and Discovery Article #90052.
Al-Ameri, T.K., A.A. Al-Ahmed, J. Zumberge and J. Pitman 2008. Hydrocarbon potential of the Middle Jurassic Sargelu Formation, Zagros Fold Belt, northern Iraq. 8th Middle East Geosciences Conference, GEO 2008. GeoArabia, Abstract, v. 13, no. 1, p. 111.
Al-Ameri, T.K. and A.J. Al-Khafaji 2008. Mishrif Formation oil biomarkers used to assess hydrocarbon generation, migration path and accumulation sites in the Ratawi, Zubair, Rumaila North and South oil fields, southern Iraq. 8th Middle East Geosciences Conference, GEO 2008. GeoArabia, Abstract, v. 13, no. 1, p. 110.
Al-Ameri, T.K., A.J. Al-Khafaji and J. Zumberge 2009. Petroleum system analysis of Mishrif reservoir in the Ratawi, Zubair, North and South Rumaila oil fields, southern Iraq. GeoArabia, v. 14, no. 4, p. 91-108.
Al-Ameri, T.K., J. Zumberge and Z.M. Markarian 2011, Hydrocarbons in the Middle Miocene Jeribe Formation, Dyala, NE Iraq. American Association of Petroleum Geologists Annual Convention and Exhibition, April 10-13, 2011, Houston, Texas. American Association of Petroleum Geologists Search and Discovery Article #90124.

Al-Ameri, T.K., S. Al-Nagshbandi, A.A. Al-Ahmed, J. Zumberge and J. Pitman 2012a, Middle and Upper Jurassic Palynostratigraphy and Hydrocarbon Potential in the Zagros Fold Belt, Northern Iraq. GEO-2012, 10th Middle East Geosciences Conference and Exhibition, 4-7 March 2012, Manama, Bahrain. American Association of Petroleum Geologists Search and Discovery Article #90141.

Al-Ameri, T.K., J. Mohammad and K. Pitman 2012b, Hydrocarbon Generation Modeling of the Basrah Oil Fields, Southern Iraq. GEO-2012, 10th Middle East Geosciences Conference and Exhibition, 4-7 March 2012, Manama, Bahrain. American Association of Petroleum Geologists Search and Discovery Article #90141.

Al-Barzanji, S.T.M. 1989. Facies analysis for Muhaivir Formation – West Iraq. MSc Thesis (unpublished), Science College, University of Baghdad, Baghdad, Iraq, 86 p. (in Arabic).

Al-Dujaily, L.S. 1994. Stratigraphic section of Middle–Upper Jurassic system and Lower Cretaceous, northwestern Iraq. MSc Thesis (unpublished), University of Baghdad, Baghdad, Iraq, 98 p. (in Arabic).

Al-Gailani, M. and N. Marouf 2010. Modeling of source rock maturation and hydrocarbon formation in northern Iraq. Poster presentation at American Association of Petroleum Geologists Convention, New Orleans, Louisiana, April 11-14, 2010. American Association of Petroleum Geologists Search and Discovery Article #10264.

Al-Habba, Y.K. and M.B. Abdullah 1989. A geochemical study of hydrocarbon source rock in northwestern Iraq. Oil and Arab Cooperation Journal, v. 15, p. 11-51. (in Arabic with English abstract).

Al-Hadithi, J.N.A., 1989. Ostracods of Muhaivir Formation (Middle Jurassic) in Iraqi Western Desert. MSc Thesis (unpublished), Science College, University of Baghdad, Baghdad, Iraq, 103 p. (in Arabic).

Al-Husseini, M.I. 2000. Origin of the Arabian Plate structures; Amar collision and Najd Rift. GeoArabia, v. 5, no. 4, p. 527-542.

Al-Husseini, M.I. 2008. Launch of the Middle East Geologic Time Scale. GeoArabia, v. 13, no. 4, p. 11 and p. 185-188.

Alimi, H., 2014. Geochemical characteristics of source rocks and crude oils from the Khuzestan Province in southwest Iran. GEO-2014, 11th Middle East Geosciences Conference and Exhibition, 10-12 March 2014, Manama, Bahrain. American Association of Petroleum Geologists Search and Discovery Article #90188.

Al-Omari, F.S. and A. Sadiq 1977. Geology of Northern Iraq. Dar Al-Kutib Press, Mosul University, Iraq, 198 p.

Al-Sakini, J.A., 1992. Summary of the petroleum geology of Iraq and the Middle East. In: Northern Oil Company Press (Naft-Al Shamal Co.) Kirkuk, Iraq (in Arabic), 179 p.

Alsharhan, A.S. and K.H. Habib 2005. Geological setting and hydrocarbon potential in the Mesopotamian Basin, Iraq. Annual Meeting (June 19-22), Calgary, Alberta, Canada. American Association of Petroleum Geologists Search and Discovery Article, no. 90039.

Alsharhan, A.S. and A.E.M. Nairn 1997. Sedimentary Basins and Petroleum Geology of the Middle East: Elsevier, Amsterdam, 942 p.

Al-Shididi, S., G. Thomas and J. Delfaud 1995. Sedimentology, diagenesis and oil habitat of Lower Cretaceous Qamchuqa Group, northern Iraq. American Association of Petroleum Geologists Bulletin, v. 79, p. 763-779.

Altinli, I.E. 1966. Geology of eastern and southeastern Anatolia, Turkey. Bulletin of Mineral Research Exploration Institute of Turkey, Foreign Edition, Ankara, no. 60, p. 35-76.

Ameen, M.S. 1992. Effect of basement tectonics on hydrocarbon generation, migration, and accumulation in northern Iraq. American Association of Petroleum Geologists Bulletin, v. 76, no. 3, p. 356-370.

Aqrawi, A.A.M. 1998. Paleozoic stratigraphy and petroleum systems of the western and southwestern deserts of Iraq. GeoArabia, v. 3, no. 2, p. 229-247.

Aqrawi, A.A.M., J.C. Goff, A.D. Horbury and F.N. Sadooni 2010. The petroleum geology of Iraq. Scientific Press Ltd, Beaconfield, UK, 424 p.
Jurassic–Cretaceous source rocks of Northeast Arabia

Aqrawi, A.A.M. and B. Badics 2013. Geochemical characterization and volumetric assessment of the prolific Mesozoic source rocks of the northeastern Arabian Plate. In Late Jurassic–Early Cretaceous Evaporite-Siliciclastic Systems of the Arabian Plate, Abstracts of the EAGE’s Fourth Arabian Plate Geology Workshop, Abu Dhabi, United Arab Emirates, GeoArabia, v. 18, no. 2, p. 188.

Ashkan, S.A.M. 1998. Géochimie organique des roches mères et des huiles du basin du Zagros (Iran). PhD Thesis, Université Henri Poincaré, Nancy, France.

Badics, B. and M. Rashidi 2007. Basin modeling study of the Anaran block, Iran. 7th Middle East Geosciences Conference, GEO 2006. GeoArabia, Abstract, v. 12, no. 1, p. 149-150.

Balaky, S.M.H. 2004. Stratigraphy and sedimentology of Sargelu Formation (Middle Jurassic) in selected sections in Erbil and Duhok Governorates, Iraqi Kurdistan. MSc Thesis (unpublished), Salahadin University, Erbil, Iraq, 109 p.

Behar, F., M. Vandembroucke, Y. Tang, F. Marquis and J. Espitalié 1997. Thermal cracking of kerogen in open and closed systems: Determination of kinetic parameters and stoichiometric coefficients for oil and gas generation. Organic Geochemistry, v. 26, p. 321-339.

Beydoun, Z.R. 1988. The Middle East: Regional geology and petroleum resources. Scientific Press Limited, Beaconsfield, UK, 292 p.

Beydoun, Z.R. 1993. Evolution of the northeastern Arabian Plate margin and shelf: Hydrocarbon habitat and conceptual future potential. Revue de l’Institut Français du Pétrole, v. 48, no. 4, p. 311-345.

Beydoun, Z.R., M.W.H. Clarke and R. Stoneley 1992. Petroleum in the Zagros Basin—a Late Cenozoic foreland basin overprinted onto the outer edge of a vast hydrocarbon-rich Paleozoic-Mesozoic passive-margin shelf. In R.W. MacQueen and D.A. Leckie (Eds.), Foreland Basins and Fold Belts. American Association of Petroleum Geologists Memoir v. 55, p. 309-339.

Bird, K.J. 1994. Ellesmerian(!) petroleum system, North Slope of Alaska, USA. In L.B. Magoon and W.G. Dow (Eds.), The Petroleum System – From Source to Trap. American Association of Petroleum Geologists Memoir 60, p. 339-358.

Biteau, J-J., J-C. Heidmann, G.Ch. De Janvry and B. Chevallier 2010. The whys and wherefores of the SPI–PSY method for calculating the world hydrocarbon yet-to-find figures. First Break, v. 28, p. 53-64.

Bordenave, M.L. and R. Burwood 1990. Source rock distribution and maturation in the Zagros orogenic belt: Provenance of the Asmari and Bangestan reservoir oil accumulations. Organic Geochemistry, v. 16, p. 369-387.

Bordenave, M.L. and R. Burwood 1995. The Albian Kazhdumi Formation of the Dezful Embayment, Iran: One of the most efficient petroleum generating systems. In B.J. Katz (Ed.), Petroleum Source Rocks. Springer Verlag, Berlin, p. 183-207.

Buday, T. 1980. The Regional Geology of Iraq, v. 1, Stratigraphy and Paleogeography. Dar Al-Kutub Publishing House, Mosul, Iraq, 445 p.

Csontos, L., Á. Sasvári, T. Pocsai, L. Kósa, A.T. Salae and A. Ali 2012. Structural evolution of the northwestern Zagros, Kurdistan Region, Iraq: Implications on oil migration. GeoArabia, v. 17, no. 2, p. 81-116.

Demaison, G. and B.J. Huizinga 1991. Genetic classification of petroleum systems. American Association of Petroleum Geologists Bulletin, v. 75, p. 1626-1643.

Dubertret, L. 1966. Liban, Syria et bordure des Pay Voisines: I, tableau stratigraphique et carte au millionième. Extrait de Notes et Memoire Moyen-Orient VIII, Muséum National d’Histoire Naturelle, Paris.

Dunnington, H.V. 1955. Generation, migration, accumulation and dissipation of oil in northern Iraq. In L.G. Weeks (Ed.), Habitat of oil: American Association of Petroleum Geologists Symposium, p. 1194-1251.

Dunnington, H.V., R. Wetzel and D.M. Morton 1959. Mesozoic and Palaeozoic. In R.C. van Bellen, H.V. Dunnington, R. Wetzel and D.M. Morton (Eds.), Lexique Stratigraphique International III. Asie, International Geological Congress Commission on Stratigraphy, 333 p.

English, J. and L. Davies 2013. Regional trends in Jurassic and Triassic thermal maturity in northern Iraq. Presentation at the Hydrocarbon Exploration in the Zagros Mountains, Geological Society of London Conference, 23rd January, 2013.

English, J.M., G.A. Lunn, L. Ferreira and G. Yaku 2015. Geologic evolution of the Iraqi Zagros, and its influence on the distribution of hydrocarbons in the Kurdistan Region. American Association of Petroleum Geologists Bulletin, v. 99, no. 2, p. 231-272.
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Fox, J.E. and T.S. Ahlbrandt 2002. Petroleum geology and total petroleum systems of the Windyan Basin and Interior Platform of Saudi Arabia and Iraq. United States Geological Survey Bulletin 2202E, 26 p.

Goff, J.C. 2005. Origin and potential of unconventional Jurassic oil reservoirs on the northern Arabian Plate. SPE-93505.

Hantschel, T. and A.I. Kauerauf 2009. Fundamentals of Basin and Petroleum Systems Modeling. Springer-Verlag, Berlin, 476 p.

Hessami, K., H.A. Koyi and C.J. Talbot 2001. The significance of strike-slip faulting in the basement of the Zagros Fold and Thrust belt. Journal of Petroleum Geology, v. 24, no. 1, p. 5-28.

Homke, S., J. Vergès, P. van der Beek, M. Fernández, E. Saura, L. Barbero, B. Badics and E. Labrin 2010. Insights in the exhumation history of the NW Zagros from bedrock and detrital apatite fission-track analysis: Evidence for a long-lived orogeny. Basin Research, v. 22, p. 659-680.

Hooper, R.J., I.R. Baron, S. Agah and R.D. Hatcher 1995. The Cenomanian to Recent development of the southern Tethyan margin in Iran. In M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences, Geo’94. Gulf PetroLink, Bahrain, v. 2, p. 505-516.

Ibrahim, M.W. 1984. Geothermal gradients and geothermal oil generation in southern Iraq: A preliminary investigation. Journal of Petroleum Geology, v. 7, no. 1, p. 77-86.

James, C.A. and J.G. Wynd 1965. Stratigraphic nomenclature of Iranian oil consortium agreement area. American Association of Petroleum Geologists Bulletin, v. 49, no. 12, p. 2182-2245.

Jassim, S.Z. and M. Al-Gailani 2006. Hydrocarbons. In S.Z. Jassim and J.C. Goff, (Eds.), Geology of Iraq, first edition. Brno, Czech Republic, Prague and Moravian Museum, chapter 18, p. 232-250.

Jassim, S.Z. and T. Buday 2006a. Units of the Unstable Shelf and the Zagros Suture, chapter 6. In S.Z. Jassim and J.C. Goff, (Eds.), Geology of Iraq, first edition. Brno, Czech Republic, Prague and Moravian Museum, p. 71-83.

Jassim, S.Z. and T. Buday 2006b. Late Toarcian-Early Tithonian (Mid-Late Jurassic) Megasequence AP7. In S.Z. Jassim and J.C. Goff, (Eds.), Geology of Iraq, first edition. Brno, Czech Republic, Prague and Moravian Museum, chapter 10, p. 117-123.

Jassim, S.Z. and J.C. Goff 2006. Geology of Iraq. Dolin, Prague and Moravian Museum, Brno, Czech Republic, 341 p.

Jassim, S.Z., T. Buday, I. Cicha and M. Opletal 2006. Tectonostratigraphy of the Zagros Suture. In S.Z. Jassim and J.C. Goff (Eds.), Geology of Iraq. p. 199-211.

Jarvie, D.M., R.J. Hill, T.E. Ruble and R.M. Pollastro 2007. Unconventional shale-gas systems: The Mississippian Barnett Shale of northcentral Texas as one model for thermogenic shale-gas assessment. American Association of Petroleum Geologists Bulletin, v. 91, p. 475-499.

Koop, W.J. and G. Orbell 1977. Regional chronostratigraphic thickness and facies distribution maps of SW Iran area (Permain and younger), NIOC, Technical Report 1269.

Lewan, M.D. and T.E. Ruble 2002. Comparison of petroleum generation kinetics by isothermal hydroys and nonisothermal open-system pyrolysis. Organic Geochemistry, v. 33, p. 1457-1475.

Marouf, N.Z. 1999. Dynamic evolution of the sedimentary basins in northern Iraq and hydrocarbon formation, migration and entrapment. PhD Thesis (unpublished), Science College, University of Baghdad, Baghdad, Iraq, 236 p.

Mohyaldin, I.M.J. 2008. Source rock appraisal and oil/source correlation for the Chia Gara Formation, Kurdistan-north Iraq. PhD Thesis (unpublished), Science College, University of Sulaimani, Sulaimani, Iraq, 140 p.

Mohyaldin, I.M.J. and F.M. Al-Beyati 2007. Sedimentology and hydrocarbon generation potential of Middle Tithonian-Berriasian Chia Gara Formation, Well K-109, Kirkuk Oil Field, NE Iraq. Journal of Kirkuk University-Scientific Studies, v. 2, no. 1, p. 27-43.

Murris, R.J. 1980. Middle East: Stratigraphic evolution and oil habitat. American Association of Petroleum Geologists Bulletin, v. 64, p. 597-618.

Najaf, A. 2014. The Interpretation of 1-Dimension models to enhance potentiality of the Sargelu formations in North and South Iraq. GEO-2014, 11th Middle East Geosciences Conference and Exhibition, 10-12 March 2014, Manama, Bahrain. American Association of Petroleum Geologists Search and Discovery Article #90188.

Odisho, K.Y. and R.S. Othman 1992. Preliminary geochemical evaluation of hydrocarbon source rock in northern parts of Iraq. Iraqi Geological Journal, v. 25, no. 2, p. 136-153.

Othman, R.S. 1990. Generation, migration and maturation of the hydrocarbons in northern Iraq.
Jurassic–Cretaceous source rocks of Northeast Arabia

(Upper Jurassic-Lower Cretaceous). MSc Thesis (unpublished), Science College, University of Salahaddin, Erbil, Iraq, 208 p. (in Arabic).

Pepper, A. and P.J. Corvi 1995. Simple kinetic models of petroleum formation. Part I: Oil and gas generation from kerogen. Marine and Petroleum Geology, v. 12, no. 3, p. 291-319.

Peters, K.E. and J.M. Moldowan 1993. The Biomarker Guide: Interpreting Molecular Fossils in Petroleum and Ancient Sediments. Prentice Hall, Englewood Cliffs, 363 p.

Pietraszek-Mattner, S.R., G.J. Grabowski, R. Chaker, W.B. Maze, G.A. Ottinger and M.J. Hardy 2008. Thermal maturity model of the Arabian Plate. SPE 118201, presented at the 2008 Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, UAE, 3-6 November 2008.

Pitman, J.K., D. Steinsbouer and M.D. Lewan 2004. Petroleum generation and migration in the Mesopotamian Basin and Tagros Fold Belt of Iraq: Results from a basin-modeling study. GeoArabia, v. 9, no. 4, p. 41-72.

Pitman, J.K., C.J. Schenk, M.E. Brownfield, R.R. Charpentier, T.A. Cook, T.R. Klett and R.M. Pollastro 2012. Assessment of undiscovered conventional oil and gas resources of the Arabian Peninsula and Zagros Fold Belt, 2012. United States Geological Survey Fact Sheet 2012-3115, 4 p.

Pollastro, R.M., A.S. Karshbaum and R.J. Viger 1997. Maps showing geology, oil and gas fields and geologic provinces of the Arabian Peninsula. United States Geological Survey Open File Report 97-470B, http://pubs.usgs.gov/of/1997/ofr-97-470/OF97-470B/.

Qaddouri, A.K.N. 1972. Jurassic formations in northern Iraq (Benavi area). Unpublished report, State Organization for Minerals, Baghdad, Iraq.

Rabbani, A.R. and M.R. Kamali 2005. Source rock evaluation and petroleum geochemistry, offshore SW Iran. Journal of Petroleum Geology, v. 28, no. 4, p. 413-428.

Rabie, A., R. Husain and A.M. Al-Fares 2014, Unconventional petrophysical workflows for evaluation of shale plays: A case study from Kuwait. GEO-2014, 11th Middle East Geosciences Conference and Exhibition, 10-12 March. Search and Discovery Article #80570.

Sadooni, F.N. 1993. Stratigraphic sequence, microfacies and petroleum prospectus of the Yamama Formation, Lower Cretaceous, southern Iraq. American Association of Petroleum Geologists Bulletin, v. 77, no. 11, p. 1971-1988.

Sadooni, F.N. 1997. Stratigraphic and petroleum prospects of Upper Jurassic carbonates in Iraq. Petroleum Geoscience, v. 3, p. 233-243.

Sadooni, F.N. and A.A.M. Aqrawi 2000. Cretaceous sequence stratigraphy and petroleum potential of the Mesopotamian Basin, Iraq. In A.S. Alsharhan and B. Scott (Eds.), Middle East Models of Jurassic/Cretaceous Carbonate Systems. Society of Economic Paleontologists and Mineralogists Special Publication no. 69, p. 315-334.

Salae, A.T.S. 2001. Stratigraphy and sedimentology of the Upper Jurassic succession northern Iraq. MSc Thesis (unpublished), Science College, University of Baghdad, Baghdad, Iraq, 95 p.

Santamaria-Orozco, D. and B. Horsfield 2003. Gas generation potential of Upper Jurassic (Tithonian) source rocks in the Sonda de Campeche, Mexico. In C. Bartollini, R.T. Buffler and R.F. Brickwede (Eds.), The Circum-Gulf of Mexico and the Caribbean: Hydrocarbons Habitat, Basin Formation and Plate Tectonics. American Association of Petroleum Geologists Memoir 79, chapter 15, p. 349-363.

Schmoker, J.W. 1994. Volumetric calculation of hydrocarbons generated. In L.B. Magoon and W.G. Dow (Eds.), The Petroleum System – From Source to Trap. American Association of Petroleum Geologists Memoir 60, p. 323-326.

Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate sequence stratigraphy. GeoArabia Special Publication 2, Gulf PetroLink, Bahrain, 371 p., with 3 charts.

Stoneley, R. 1987. A Review of petroleum source rocks in parts of the Middle East. In J. Brooks and A.J. Fleet (Eds.), Marine Petroleum Source Rocks. The Geological Society of London Special Publication no. 26, p. 263-269.

Stoneley, R. 1990. The Middle East Basin: A Summary Overview. In J. Brooks (Ed.), Classic Petroleum Provinces. Geological Society of London, Special Publication no. 50, p. 293-298.

Surdashy, A.M. 1999. Sequence stratigraphic analysis of the Early-Jurassic central and northern Iraq. PhD Thesis (unpublished), Science College, University of Baghdad, Baghdad, Iraq, 145 p.

Sweeney, J.J. and A.K. Burnham 1990. Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. American Association of Petroleum Geologists Bulletin, v. 74, no. 10, p. 1559-1570.
van Bellen, R.C., H.V. Dunnington, R. Wetzel and D.M. Morton 1959-2005. Lexique Stratigraphique International. 03 10 Asie, (Iraq), 333 pages. Reprinted by permission of CNRS by Gulf PetroLink, Bahrain.

Verma, M.K., T.S. Ahlbrandt and M. Al Gailani 2004. Petroleum reserves and undiscovered resources in the total petroleum systems of Iraq: Reserve growth and production implications. GeoArabia, v. 9, no. 3, p. 51-74.

Welte, D.H. and M.N. Yalcin 1988. Basin modeling – A new comprehensive method in petroleum geology. Organic Geochemistry, v. 13, p. 141-151.

Wetzel, R. 1948. Sargelu Formation. In R.C. van Bellen, H.V. Dunnington, R. Wetzel and D.M. Morton (Eds.), Lexique stratigraphic international. Paris, v. III, Asie, Fascicule 10a Iraq, p. 250-253.

Yousif, S. and G. Nouman 1997. Jurassic geology of Kuwait. GeoArabia, v. 2, no. 1, p. 91-110.

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