Petroleum system analysis of the Mishrif reservoir in the Ratawi, Zubair, North and South Rumaila oil fields, southern Iraq

Thamer K. Al-Ameri, Amer Jassim Al-Khafaji and John Zumberge

ABSTRACT

Five oil samples reservoired in the Cretaceous Mishrif Formation from the Ratawi, Zubair, Rumaila North and Rumaila South fields have been analysed using Gas Chromatography – Mass Spectroscopy (GC-MS). In addition, fifteen core samples from the Mishrif Formation and 81 core samples from the Lower Cretaceous and Upper Jurassic have been subjected to source rock analysis and palynological and petrographic description. These observations have been integrated with electric wireline log response. The reservoirs of the Mishrif Formation show measured porosities up to 28% and the oils are interpreted as being sourced from: (1) Type II carbonate rocks interbedded with shales and deposited in a reducing marine environment with low salinity based on biomarkers and isotopic analysis; (2) Upper Jurassic to Lower Cretaceous age based on sterane ratios, analysis of isoprenoids and isotopes, and biomarkers, and (3) Thermally mature source rocks, based on the biomarker analysis.

The geochemical analysis suggests that the Mishrif oils may have been sourced from the Upper Jurassic Najma or Sargelu formations or the Lower Cretaceous Sulaiy Formation. Visual kerogen assessment and source rock analysis show the Sulaiy Formation to be a good quality source rock with high total organic carbon (up to 8 wt% TOC) and rich in amorphogen. The Lower Cretaceous source rocks were deposited in a suboxic-anoxic basin and show good hydrogen indices. They are buried at depths in excess of 5,000 m and are likely to have charged Mishrif reservoirs during the Miocene. The migration from the source rock is likely to be largely vertical and possibly along faults before reaching the vuggy, highly permeable reservoirs of the Mishrif Formation. Structural traps in the Mishrif Formation reservoir are likely to have formed in the Late Cretaceous.

INTRODUCTION

The Mishrif Formation is of Late Cenomanian age (Figure 1; van Bellen et al., 1959) and is the most important oil reservoir in the Mesopotamian Basin (Figure 2), southern Iraq (Al-Khaersan, 1975; Reulet, 1982; Alsharhan and Nairn, 1997; Aqrawi et al., 1998), containing some 30% of Iraq’s total oil reserves (Al-Sakini, 1992). It extends throughout the Mesopotamian Basin reaching thicknesses of 100–200 m in the Basrah District at subsurface depths around 2,100–2,400 m. The Mishrif Formation is dominated by a shallow-water, shelf carbonate sequence composed of bioclastic-detrital limestones, including (in places) algal, coral and rudist bioherms with reservoir porosities exceeding 20% and permeabilities of 100 mD to one Darcy. This formation is widespread throughout the Arabian Peninsula.

The underlying Rumaila Formation consists predominantly of chalky and marly limestones. A conformable and gradational junction with the Mishrif Formation has been documented in the Basrah District. Overlying the Mishrif Formation are dark grey and greenish shales, alternating with grey, fine-grained marly limestones of the Khasib Formation (van Bellen et al., 1959). This unit lies unconformably above limonitic, partly argillaceous limestones forming the upper part of Mishrif Formation (Aqrawi et al., 1998).

Due to a lack of published studies describing the petroleum system in this area, this work was undertaken to correlate oils of the Mishrif Formation with Jurassic and Cretaceous source rocks.
Figure 1: Stratigraphic section and the major tectonic phases relevant to Jurassic through Tertiary Total Petroleum System.

| Age       | Formation I | Depth (m) | Lithology | TOC % | Maturation | Tectonics               |
|-----------|-------------|-----------|-----------|-------|------------|-------------------------|
| TERTIARY  |             |           |           |       |            |                         |
| Pliocene  | Dibdibba    |           | Regional  |       |            | Zagros Orogeny           |
| Miocene   | Fatha       |           | Seals     |       |            |                         |
|           | Ghar        | 500       |           |       |            |                         |
| Eocene    | Dammam      |           |           |       |            | Neo-Tethys              |
|           | Rus         | 1,000     |           |       |            | Ocean Closing           |
| Paleocene | Umm Er Radhuma | 2,000 |           |       |            | Tethys Obduction         |
|           |             |           |           |       |            |                         |
| CRETACEOUS|             |           |           |       |            |                         |
| Maastrichtian | Tayarat      | 1,500     |           |       |            | Neo-Tethys Ocean        |
| Campanian | Shiranish   |           |           |       |            | Opening                 |
| Santonian | Sa'adi      |           |           |       |            |                         |
| Turonian-Coniacian | Tanuma |           |           |       |            |                         |
|           | Khaisib     |           |           |       |            |                         |
|           | Mishrif     |           |           |       |            |                         |
| Cenomanian | Rumaila     | 2,000     |           |       |            |                         |
|           | Ahmadi      |           |           |       |            |                         |
|           | Mauddud     |           |           |       |            |                         |
| Albian    | Nahr Umr    | 2,500     |           |       |            |                         |
| Aptian    | Shu'aila    |           |           |       |            |                         |
| Barremian | Zubair      | 3,000     |           |       |            |                         |
| Hauerivian | Ratawi      |           |           |       |            |                         |
| Valanginian | Yamama     | 3,500     |           |       |            | Mature                  |
| Berriasian |             |           |           |       |            |                         |
| Jurassic  |             |           |           |       |            |                         |
| Tithonian | Sulaiy      | 4,000     | Regional  |       |            |                         |
| Kimmeridgian | Gotnia  |           |           |       |            |                         |
| Oxfordian | Najma       |           |           |       |            |                         |
| Callovian | Sargelu     |           |           |       |            |                         |
| Bathonian | Naokelekan  |           |           |       |            |                         |
| Bajocian  |             |           |           |       |            |                         |

Legend:
- Pink: Anhydrite
- Light blue: Limestone
- Brown: Conglomerate
- Red: Gas reservoir
- Orange: Oil reservoir
- Pink: Regional Seals
- Unconformity
- Source rock

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Figure 2: Location map of the studied wells along with oil fields.
MATERIALS AND ANALYTICAL SCHEME

The Mishrif-reservoired oil samples are from wells Zubair 4, Zubair 8, Rumaila North 81, Rumaila North 170 and Rumaila South 131. Source rock analysis was conducted on 40 samples taken from cores in wells in the Ratawi, Rumaila South, and Rumaila North fields. Techniques employed in this study include biomarker fingerprints, palynomorphs, palynofacies, and pyrolysis. The analysis of samples by gas chromatography-mass spectrometry (Zumberge et al., 2005) and pyrolysis were performed by Geomark Research Ltd. in Houston (Texas, USA) in 2005 and other TOC and pyrolysis were performed in the laboratories of Iraqi Exploration Oil Company during the year 1987 and 1989, while palynomorphs and organic matter extracts were analyzed in the Department of Geology, University of Baghdad. Sample and data are shown in Tables 1 and 2 and Figure 3.

Table 1
Rock-Eval Pyrolysis Data for Lower Cretaceous Formations in Basrah, Southern Iraq

| Fm    | Well | Depth (m) | Sample Type | TOC wt% | S1 mg/g | S2 mg/g | S3 mg/g | Tmax (°C) | HI S2/TOC | OI S3/TOC | PI S1/(S1+S2) |
|-------|------|-----------|-------------|----------|---------|---------|---------|-----------|-----------|-----------|-------------|
| Mishrif | R/1-2 | 2,685 | Core | 0.47 | 0.25 | 3.31 | 0.19 | 427 | 704 | 40 | 0.27 |
| Mauddud | Ru-1 | 2,658 | Core | 0.02 | 0.02 | 0.10 | 0.00 | 485 | 86 | 97 | 0.09 |
| Mauddud | Ru-1 | 2,670 | Core | 0.36 | 0.03 | 0.31 | 0.35 | 425 | 126 | 14 | 0.18 |
| Nahr Umr | Ru-1 | 2,791 | Core | 0.86 | 0.23 | 1.08 | 0.12 | 425 | 126 | 14 | 0.18 |
| Nahr Umr | Ru-1 | 2,774 | Core | 3.77 | 0.50 | 11.48 | 2.38 | 433 | 305 | 63 | 0.04 |
| Zubair | Ru-1 | 3,010 | Core | 0.58 | 0.77 | 2.41 | 0.00 | 436 | 416 | 0 | 0.24 |
| Zubair | R/1-2 | 3,230 | Core | 0.19 | 0.07 | 0.27 | 0.02 | 432 | 102 | 0 | 0.21 |
| Zubair | R/1-2 | 3,388 | Cuttings | 0.56 | 0.15 | 0.57 | 0.00 | 435 | 90 | 0 | 0.08 |
| Zubair | R/1-2 | 3,425 | Cuttings | 0.89 | 0.07 | 0.80 | 0.00 | 435 | 199 | 0 | 0.08 |
| Zubair | R/1-2 | 3,407 | Cuttings | 0.78 | 0.14 | 1.55 | 0.00 | 435 | 67 | 0 | 0.06 |
| Zubair | R/1-2 | 3,507 | Cuttings | 1.09 | 0.05 | 0.73 | 0.00 | 435 | 67 | 0 | 0.06 |
| Zubair | R/1-2 | 3,555 | Cuttings | 0.47 | 0.04 | 0.31 | 0.00 | 434 | 66 | 0 | 0.11 |
| Zubair | R/1-2 | 3,655 | Cuttings | 1.30 | 0.11 | 1.50 | 0.00 | 436 | 115 | 0 | 0.07 |
| Zubair | R/1-2 | 3,730 | Cuttings | 1.49 | 0.07 | 0.86 | 0.00 | 437 | 38 | 0 | 0.08 |
| Zubair | R/1-2 | 3,100 | Cuttings | 0.32 | 0.10 | 0.49 | 1.10 | 446 | 364 | 62 | 0.60 |
| Zubair | R/1-2 | 3,220 | Cuttings | 0.33 | 0.17 | 0.33 | 1.80 | 446 | 364 | 62 | 0.60 |
| Zubair | R/1-2 | 3,301 | Cuttings | 2.58 | 0.58 | 9.40 | 1.61 | 446 | 364 | 62 | 0.60 |
| Ratawi | R/1-2 | 3,728 | Core | 0.06 | 0.05 | 0.07 | 0.00 | 438 | 55 | 0 | 0.12 |
| Ratawi | R/1-2 | 3,688 | Core | 0.10 | 0.09 | 0.35 | 0.00 | 438 | 304 | 0 | 0.31 |
| Ratawi | R/1-2 | 3,730 | Cuttings | 1.19 | 0.09 | 0.66 | 0.00 | 437 | 306 | 0 | 0.11 |
| Ratawi | R/1-2 | 3,400 | Cuttings | 1.85 | 6.00 | 9.60 | 2.95 | 445 | 519 | 159 | 0.38 |
| Ratawi | R/1-2 | 3,450 | Cuttings | 0.25 | 0.11 | 0.28 | 1.32 | 444 | 44 | 0 | 0.30 |
| Yamama | R/1-3 | 3,678 | Core | 0.09 | 0.25 | 0.25 | 0.00 | 436 | 89 | 0 | 0.13 |
| Yamama | R/1-3 | 3,896 | Core | 0.46 | 0.06 | 0.41 | 0.00 | 436 | 89 | 0 | 0.13 |
| Yamama | R/1-3 | 4,091 | Cuttings | 0.56 | 0.78 | 1.70 | 0.00 | 437 | 304 | 0 | 0.31 |
| Yamama | R/1-3 | 4,129 | Cuttings | 0.34 | 0.13 | 1.04 | 0.00 | 437 | 306 | 0 | 0.11 |
| Yamama | R/1-3 | 4,141 | Cuttings | 0.18 | 0.02 | 0.58 | 0.00 | 444 | 44 | 0 | 0.30 |
| Yamama | R/1-3 | 4,210 | Cuttings | 0.47 | 0.75 | 1.78 | 0.00 | 444 | 44 | 0 | 0.30 |
| Yamama | R/1-3 | 3,700 | Cuttings | 1.00 | 1.63 | 4.00 | 1.77 | 437 | 400 | 177 | 0.29 |
| Sulay | R/1-3 | 4,456 | Core | 2.05 | 0.84 | 1.00 | 0.42 | 464 | 49 | 20 | 0.46 |
| Sulay | R/1-3 | 4,375 | Core | 5.90 | 1.82 | 4.15 | 0.00 | 470 | 70 | 0 | 0.30 |
| Sulay | R/1-3 | 4,220 | Cuttings | 0.21 | 0.26 | 0.49 | 0.00 | 468 | 41 | 0 | 0.33 |
| Sulay | R/1-3 | 4,322 | Cuttings | 0.10 | 0.11 | 0.27 | 0.00 | 475 | 130 | 0 | 0.13 |
| Sulay | R/1-3 | 4,379 | Cuttings | 0.16 | 0.17 | 0.26 | 0.00 | 475 | 130 | 0 | 0.13 |
| Sulay | R/1-3 | 4,421 | Cuttings | 0.25 | 0.40 | 0.27 | 0.00 | 470 | 70 | 0 | 0.30 |

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MISHRIF OIL GEOCHEMISTRY

Crude oils produced from the Cenomanian Mishrif Formation in the Basrah District of southern Iraq were geochemically assessed in order to determine source rock type, geologic age, level of thermal maturity, and degree of biodegradation. All of the oil samples are remarkably similar, both in bulk and molecular properties. For example, API gravities average 24.8° ± 1.5° with weight percent sulfur 4.2% ± 0.3. A comparison with oils from 150 different petroleum systems (based on GeoMark Research’s global crude oil geochemical database; www.RFDbase.com) is shown in Figures 4 and 5. Low to medium gravity, high sulfur crude oils are usually derived from carbonate source rocks (containing type IIS kerogen) since, during diagenesis, sulfur can become preferentially incorporated in organic matter (kerogen) that eventually generates high sulfur oils due to insufficient iron (Fe) to scavenge H₂S as pyrite or marcasite.

The stable carbon isotopic compositions of the saturate and aromatic hydrocarbons are all within analytical error, averaging -27.3 % and -27.6 %, respectively (relative to PDB; ± 0.1 %). In contrast to oils from marine shales, the aromatic isotopic composition is often isotopically lighter than the saturate hydrocarbons in low maturity, high sulfur oils. This pattern occurs because high sulfur oils from carbonate source rocks typically have the most negative CV values (-1.65 average for carbonates and -0.25 average for shales; Sofer, 1984) with C15+ aromatic 13C compositions almost as, or even more negative than the C15+ saturate 13C compositions.

Both tricyclic and pentacyclic (hopanes) terpane biomarker ratios confirm the carbonate origin of the Mishrif-reservoired oils, again by a comparison with global analogs (Figures 5 and 6). The standard errors of the terpane ratios are about 5% of the mean values for the Mishrif oils. Low pristane/phytane ratios (0.76 ± 0.04; from gas chromatography) are also suggestive of carbonate source rocks. The pentacyclic terpane gammacerane, a biomarker for hypersaline/restricted source environments, is uniformly low (GA/C₃₀ hopane < 0.1) in all samples. The relatively high C₉₅ tetracyclic to C₂₃ tricyclic terpane ratio of 1.3 suggests shallow, warm water, intra-shelf depositional source rock depositional environments (Zumberge and Summons, 2004).

In petroleum systems with carbonate/marl source units, the C₂₅/C₃₀ regular sterane ratio (αββ 20R isomers based on peak heights from the m/z = 218 mass chromatogram), along with the corresponding triaromatic steranes (C₉₅R/C₅₃R; peak areas from the m/z = 231 mass chromatograms), is useful for predicting source rock ages (Zumberge and Summons, 2004). As illustrated in Figure 7, the calculated C₂₅/C₂₉ ratio of 0.92, employing both regular and triaromatic steranes, and weighted using a saturate to aromatic hydrocarbon ratio of about 0.5, suggests that the Cretaceous Mishrif-reservoired oils were generated from Upper Jurassic to Lower Cretaceous carbonate source rocks.

| OilMod Ratio | Ru/81 | Ru/131 | R/170 | Zb/4 | Zb/8 |
|--------------|------|-------|------|------|------|
| C₂₅/C₂₉      | 0.08 | 0.08  | 0.07 | 0.07 | 0.09 |
| C₂₇/C₂₅      | 1.21 | 1.15  | 1.18 | 1.15 | 1.14 |
| C₂₉/C₂₇      | 0.27 | 0.27  | 0.28 | 0.28 | 0.29 |
| C₃₁/C₂₉      | 0.79 | 0.79  | 0.79 | 0.76 | 0.76 |
| Tel/C₂₃      | 1.31 | 1.33  | 1.30 | 1.33 | 1.30 |
| C₂₉/18C₂₇    | 0.01 | 0.00  | 0.00 | 0.00 | 0.00 |
| C₁₄H               | 0.01 | 0.01  | 0.01 | 0.01 | 0.04 |
| C₁₄H               | 0.1499 | 1.52  | 1.44 | 1.48 | 1.49 |
| C₁₄XH              | 0.00 | 0.00  | 0.00 | 0.00 | 0.00 |
| OILH             | 0.01 | 0.00  | 0.00 | 0.01 | 0.01 |
| C₁₄/RH             | 0.38 | 0.39  | 0.40 | 0.40 | 0.40 |
| GA/C₃₀ R         | 0.23 | 0.24  | 0.22 | 0.22 | 0.21 |
| C₃₀S/C₃₀ S       | 1.12 | 1.13  | 1.16 | 1.16 | 1.09 |
| Ster/Terp         | 0.18 | 0.16  | 0.16 | 0.16 | 0.15 |
| Renn/Reg         | 0.11 | 0.10  | 0.10 | 0.10 | 0.13 |
| C₂₇ %            | 33.4 | 33.3  | 33.7 | 33.7 | 33.1 |
| C₂₅ %            | 25.4 | 25.5  | 26.3 | 25.4 | 26.2 |
| C₂₃ %            | 41.1 | 41.2  | 40.1 | 40.8 | 40.7 |
| C₂₅ 20S/R        | 0.67 | 0.68  | 0.66 | 0.67 | 0.65 |
| C₂₅ Ts/Tm        | 0.18 | 0.17  | 0.18 | 0.18 | 0.18 |
| C₂₅ Ts/Tm        | 0.08 | 0.07  | 0.08 | 0.08 | 0.07 |
| DMH              | 0.01 | 0.01  | 0.01 | 0.01 | 0.01 |
| TAP/(CR)         | 0.22 | 0.20  | 0.22 | 0.22 | 0.21 |
| Ph/Ph            | 0.73 | 0.73  | 0.74 | 0.70 | 0.72 |
| Prn/C₁₇          | 0.20 | 0.20  | 0.20 | 0.21 | 0.21 |
| Prn/C₁₈          | 0.32 | 0.33  | 0.33 | 0.34 | 0.34 |
| nC₁₈/nC₁₇        | 0.19 | 0.19  | 0.20 | 0.22 | 0.21 |
| CPI              | 1.076 | 1.042 | 1.051 | 1.036 | 1.053 |

Ru = South Rumaila; R = North Rumaila; Zb = Zubair

Table 2
Analysis Chart of GC and GC-MS
Oil Biomarkers Data for Lower Cretaceous Formations in Basrah, southern Iraq
Figure 3: Pristane-n C17 versus Phytane-n C18 plot diagram (following Peters et al., 2005) showing marine algal organic matters of mainly kerogen type 2, reducing paleoenvironments and mature source of the Mishrif oil for the studied wells in southern Iraq.

Figure 4: Average API Gravity and weight % sulfur of Mishrif-reservoired oils from southern Iraq. Other data points represent average oil values from 150 global petroleum systems from marine carbonate, distal marine shale, marine marl, and lacustrine shale source rocks from GeoMark Research OILS™ database.
Figure 5. Average tricyclic terpane ratios of Mishrif-reservoired oils from southern Iraq suggesting a carbonate source rock. Other data points represent average oil values from 150 global petroleum systems from marine carbonate, distal marine shale, marine marl, and lacustrine shale source rocks from GeoMark Research OILS™ database.

Figure 6: Average hopane ratios of Mishrif-reservoired oils from southern Iraq suggesting a carbonate source rock (SR). Other data points represent average oil values from 150 global petroleum systems from marine carbonate, distal marine shale, marine marl, and lacustrine shale source rocks from GeoMark Research OILS™ database.
Figure 7: Calculated average C28/C29 sterane ratio (0.92; based on both regular steranes and triaromatic steranes) of Mishrif-reservoired oils from southern Iraq suggesting a source rock of Upper Jurassic to Lower Cretaceous age. Other data points represent average oil values from global petroleum systems from marine carbonate and marine marl source rocks from GeoMark Research OILS™ database.

Figure 8 shows an example geochemical summary sheet for a Mishrif oil from the Zubair Field. The whole crude gas chromatogram indicates a lack of biodegradation due to the presence of abundant n-paraffins. The low API gravity and high sulfur and aromatic content of these oils, as well as very low Ts/Tm terpane ratios, suggest that these oils were generated from a source rock of low to moderate thermal maturity within the oil window.

SOURCE ROCK EVALUATION

Forty samples were selected from the Mishrif, Mauddud, Zubair, Ratawi, Yamama, and Sulaiy formations (Figure 1) for source rock analysis and palynofacies studies.

Source Rock Potential and Palynofacies Assessment

The rock samples were analysed for their total organic carbon by Leco. The samples were also subjected to standard palynological analysis involving dissolving the carbonates with HCl and silicates with HF. Slides were then prepared by strewing and sticking the organic matter for examination by light refracted microscopy. The microscopic study ascertained the proportional occurrences of the different organic matter types (Bujack et al., 1977; Batten, 1996a), palynomorph colour (Staplin, 1969; Batten, 1996b), reworked organic matter (Al-Ameri, 1983 and Tyson, 1995), and foraminiferal test linings (FTL, according to Al-Ameri et al., 1996; Tyson, 1995). The analyses are drafted in a model of Organolog palynofacies for each well to evaluate the paleoenvironment of the organic matter and its capability to generate hydrocarbons from each palynofacies type. Figure 9 shows one example for Rumaila South 172 (Ru-172) well to illustrate the hydrocarbon generation potential. The names for each palynofacies type in Figure 9 are based on the above criteria and are equivalent in correlation to palynofacies types of the Ternary Kerogen Plot suggested by Tyson (1993).

The position of Palynofacies Type IX (Figure 9) in the Ternary Kerogen Plot (Figure 10) corresponds to phytoclast-AOM-palynomorphs. This palynofacies shows peak oil generation and the main phase of oil expulsion for the Upper Jurassic – Lower Cretaceous Sulaiy and Yamama formations (Al-Ameri
Figure 8: Example Geochemical Summary Sheet of a Mishrif-reservoired oil from southern Iraq Zubair field showing bulk properties, whole oil gas chromatogram as well as terpane and sterane biomarker mass chromatograms.
Figure 9: Organlog of palynofacies and assessment of hydrocarbon generation potential for the Upper Jurassic – Lower Cretaceous rocks in well Ru-172, Rumaila South oil field. (See Figure 1 for legend)
et al., 1999). The organic matter accumulated in distal suboxic-anoxic basins and extended across the Southern Mesopotamian Basin (Al-Ameri et al., 1999). Source rock richness can reach up to 7 wt% total organic carbon (TOC) of mainly marine algal components and may contain up to 100% Amorphous Organic Matter (AOM). They form kerogen type A (Thompson and Dembicki, 1986) or equivalently kerogen Type II for the pyrolysis result plotted in a van Krevelen diagram. They are highly oil prone. The high percentage occurrence of foraminiferal test linings of about 10% and very low reworked palynomorphs of about 1%, may confirm high oil generation potential (Al-Ameri, 1983; Al-Ameri et al., 1996; Tyson, 1993, 1995).

The post-depositional alteration of the organic matter is a result of increasing temperature as the formations were buried to depths of around 3,500 m in this area. This process resulted in the thermal maturation of the organic matter to a late oil or early gas maturation stage with a brown colour of the macerals and an equivalent Thermal Alteration Index (TAI) of 3+ (3.75) equivalent to a VRo of 1.0 to 1.4% (Staplin, 1969; Batten, 1996a and b).

Source Rock Potential by Rock-Eval Pyrolysis

Rock samples from core and cuttings in the Sulaiy and Yamama formations, as well as other Upper Jurassic – Lower Cretaceous formations, were analysed using Rock-Eval pyrolysis (Hunt, 1996; Tissot and Welte, 1984). In Figure 11, Rock-Eval parameters are plotted to determine the organic matter type, maturation level, and source quality. They illustrate the following results for each source rock unit:

- The Upper Jurassic – Lower Cretaceous Sulaiy and the Lower Cretaceous Yamama formations have the best oil source potential with TOC values up to 7 wt%. They represent mature (Ro 1.0% to 1.4%) kerogen types II and III with Tmax of 437–471°C. Consequently they currently have good to very good petroleum potential and are probably the Upper Jurassic – Lower Cretaceous source rock responsible for hydrocarbon generation and expulsion.

- The Ratawi Formation has TOC values ranging from 0.06 to 1.9 wt%; kerogen type II and III, mature (Ro = 0.5–1.0%) with Tmax of 430–450°C. These rocks have poor to fair current petroleum potential and have generated relatively low amounts of hydrocarbons.

- The Zubair Formation has TOC values of 0.2–2.6 wt% and varies from immature to mature (Ro = 0.3–0.8%) with Tmax of 420–440°C. Hence it is a poor to fair potential source rock and some oil could have been generated from these clastic rocks.

Accordingly, the most likely source rock for the Mishrif reservoired oils are the Sulaiy and Yamama formations. The Jurassic Najmah and Sargelu formations were not subjected to pyrolysis because of their position bellow the good regional seal of Gotnia Anhydrites. For future work these should be analyzed to find the possible relation with the Cretaceous oil in southern Iraq.
PETROLEUM SYSTEM OF THE MISHRIF OIL

Petroleum system modeling in one dimension (1-D) was performed using the PetroMod™ Basin Modeling software (PetroMod developed by Integrated Exploration Systems - IES) to demonstrate hydrocarbon generation and expulsion for the Sulaiy and Yamama formations. The model was applied to well Zubair 47 (Zb-47) following Pitman et al. (2004) using well information for depths, thickness and temperatures.

The results for this well (Figure 12) demonstrate that the timing of petroleum generation is consistent with the source rocks of the Sulaiy and Yamama formations expelling their oil during the Early Cenozoic (Paleogene). No oil should have passed from below the Gotnia Anhydrite regional seal. This probability is due to the perfect effect of the Gotnia Seal due to its thick and impermeable rocks and the lack of tectonic activity (Alsharhan and Nairn, 1997).

Figure 11: Pyrolysis output plots for source rocks of the Upper Jurassic – Lower Cretaceous Formations in southern Iraq; (a) Kerogen types and maturity, (b) Kerogen conversion and maturity, (c) Van Krevlen diagram, and (d) Petroleum potential diagram.
Figure 12: Timing and extent of Petroleum Generation from Sulaiy-Yamama Source Rocks, Well Zubair 47, southern Iraq.
Traps in the Mishrif Formation Reservoir formed mainly during the Late Cretaceous. These traps are mainly structural anticlines although stratigraphic traps below the Mishrif Formation might also be developed, for example, in the Yamama and Ratawi formations, as structural fault traps.

After expulsion, the oil migrated from the mainly impermeable strata of the Upper Jurassic – Lower Cretaceous Sulaiy and Lower Cretaceous Yamama source rock formations to the high porosity and permeability reservoirs of the early Upper Cretaceous (Cenomanian) Mishrif Formation. These units are algal and detrital limestones that contain vuggy, intra-particle growth frameworks (Figure 13) and form the main sites for hydrocarbon accumulation. The migration path was primarily vertical with relatively short horizontal movement to faults that are shown in the seismic section of the area (Figure 14), as well as dissipation along joints.

Figure 13: Porosities of the Mishrif Formation Reservoir as site for hydrocarbon accumulation.
CONCLUSIONS

The biomarkers of Mishrif Formation oil indicate source rocks of mainly Upper Jurassic and Lower Cretaceous age, thermally mature, and of algal marine carbonate origin. The palynofacies and pyrolysis results indicate hydrocarbon generation and expulsion occurred from the Upper Jurassic – Lower Cretaceous Sulaiy and Lower Cretaceous Yamama formations. Oil migration is mainly from impermeable strata of the Sulaiy Formation into the Mishrif Formation Reservoir. The entire Petroleum System was controlled in this region by migration paths, which were vertical as well as lateral to form the regional Petroleum System. Its main upper seal is the Middle Miocene anhydrites of the Lower Fars Formation and its lower regional seal is Upper Jurassic Gotnia anhydrites.

Figure 14: Seismic section along Rachi-Rumaila-Ratawi oil fields showing migration path to assess hydrocarbon accumulation sites.

and permeabilities in a lateral migration through some of the Cretaceous strata. This hydrocarbon system (Figure 1) has as a lower regional seal the Upper Jurassic Gotnia anhydrites, while the Mishrif Formation reservoir is sealed locally by a clay layer along its upper unconformable boundary with the Khasib Formation. But the main regional upper seal for the Mesopotamian Basin in general is the highest regional seal of the Middle Miocene Lower Fars anhydrites on top of Tertiary strata. The sequence of events in this total petroleum system is tabulated in Figure 15.
ACKNOWLEDGMENTS

Sincere acknowledgments are due to Geomark Research Limited of Houston-Texas for analyzing the oil and source rock samples as well as the laboratories of Iraqi Oil Exploration Company for using their data on TOC and pyrolysis, and to the U.S. Geological Survey, in particular to Dr. Janet Pitman for PetroMod basin modeling to make the Petroleum System clearer. The GeoArabia anonymous reviewers and, in particular, Henry Halpern of Saudi Aramco in Saudi Arabia are greatly acknowledged for their editing of this paper. The final design by GeoArabia’s Arnold Egdane is much appreciated.
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ABOUT THE AUTHORS

Thamer K. Al-Ameri is Professor of Petroleum Geology at the University of Baghdad, Iraq, and a Consultant for the Iraqi Oil Exploration Company. He holds a BSc in Geology from the same university (1969) and a Higher Diploma in Engineering Geology and Sulfur Exploitation from the Polish Academy of Mines in Kragow (1971). Between 1971 and 1975, he was involved in mining sulfur in the Mishraq Sulfur Mine in Iraq. In 1975, Thamer continued his higher education at the University of London, UK, where he received MSc and PhD (1975-1980) in Palynology and Petroleum Geology. He also obtained a certificate in organic geochemistry from the Russian Geochemical Institute in Moscow (1985). Before taking up his present position in 1992, Thamer was Assistant Professor in the University of Salahuddin, Iraq (1980-1991). During his academic career, Thamer has supervised 18 MSc and 20 PhD theses, published five books in Arabic and written more than 100 scientific and general interest articles in international and Iraqi journals.

thamer_alameri@yahoo.com

Amer Jasim Al-Khafaji teaches geology to the chemistry and biology undergraduate students at Babylon University, Iraq. He holds an MSc in Petroleum Geology from the Baghdad University, Iraq. Amer is currently enrolled in the PhD program at Baghdad University and preparing his thesis entitled “Petroleum system and organic geochemistry of the Euphrates River Sub zone, Mesopotamian Basin, Iraq”. He is also involved in the planning of the Petroleum Research Center at Babylon University.

amersalman42@yahoo.com

John Zumberge has been President and cofounder of Geomark Research in Houston, USA, since 1991. He was Manager of geochemical and geological research for cities service-Occidental, General Manager for Ruska, and Director of geochemical services for Core Laboratories. He has global experience in petroleum geochemistry, focusing on crude oil biomarkers. He obtained a BSc in Chemistry from the University of Michigan, USA, and a PhD in Organic Geochemistry from the University of Arizona, USA.

jzumberge@geomarkresearch.com

Manuscript received May 18, 2008
Revised April 27, 2009
Accepted May 15, 2009
Press version proofread by authors June 10, 2009