Paleozoic Petroleum System of Central Saudi Arabia

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ABSTRACT

An integrated geochemical model was developed to reconstruct the history of expulsion, migration and entrapment of Paleozoic oil and gas in the main regional Permian Unayzah Sandstone Reservoir in Central Saudi Arabia. The model indicates that by the Late Jurassic, approximately 140 million years ago (Ma), the principal Paleozoic source rock, the Lower Silurian Qusaiba “hot” shale, was mature in the deepest hydrocarbon “kitchens”. Hydrocarbon expulsion started during the Aptian and Albian (late Early to early Middle Cretaceous, 100 to 120 Ma).

Expulsion of oil and gas is linked to three geochemical events. Primary kerogen cracking led to a first episode of expulsion about 120 Ma. Secondary heavy component and oil cracking resulted in a second episode of expulsion at approximately 100 Ma. Between 20 to 10 Ma, later uplift, and the resulting pressure drop in the source rock, led to a third expulsion phase. The first two expulsion episodes were gradual, whereas the third was more rapid and related to uplift of the Arabian Arch, opening of the Red Sea and the Zagros Orogeny during the Miocene. Expulsion of oil nearly terminated after the Late Cretaceous, while gas continued to be expelled, though at a lower rate, in the Tertiary. Peak gas expulsion occurred post Early Eocene with significant gas generation from secondary cracking of oil retained in the source rock.

Gas was sourced either directly from kerogen, or from secondary cracking of heavy absorbed components or non-migrated oils. The expulsion of gas coincides with oil expulsion for the first two episodes because the gas and oil formed as a single phase. As a result of Tertiary Uplift, gas separated from the oil and re-migrated in the final episode (20 to 10 Ma).

INTRODUCTION

The Paleozoic Petroleum System of Central Saudi Arabia has been penetrated by numerous wells. Many major oil and gas fields have been found since the Hawtah discovery well in 1989 (McGillivray and Al-Husseini, 1992). The Qusaiba hot shale (gamma ray log response exceeds 150° API units), in the basal portion of the Qusaiba Member of the Silurian Qalibah Formation, is the main source rock for this system (Abu-Ali et al., 1991; Mahmoud et al., 1992; Cole et al., 1994). The thickness of the Qusaiba hot shale varies from a few tens of meters (m) to 70 m (Mahmoud et al., 1992; Jones and Stump, 1999). The Permian Unayzah Formation is the major regional drainage system and reservoir (McGillivray and Al-Hussein, 1992; Senalp and Al-Duaiji, 1995; Evans et al., 1997; Wender et al., 1998).

This paper demonstrates how an integrated study of the generation and expulsion of oil and gas from the Qusaiba hot shale provides new insights into the petroleum system of Central Arabia. This work differs from previous studies of this petroleum system in several aspects (Abu-Ali et al., 1991; Cole et al., 1994). In this study, compositional kinetics experiments were performed for the first time on the Qusaiba source rocks. These experimental results were combined with a dynamic set of maps to model the generation and expulsion of oil and gas from the Qusaiba hot shale. The model shows that the generation of hydrocarbons differs from their expulsion. Also source rock maturation maps, expressed as transformation ratios (TR), are compared to oil and gas expulsion maps.
The study area extends from Ghawar field, in the east, to the region west of Riyadh (Figure 1). The study is limited to the pre-Khuff Unayzah reservoir and the Qusaiba source rock (Figure 2). Although the Permian Khuff gas reservoir in Ghawar field is almost certainly sourced by the Qusaiba hot shale, it is not discussed in this paper.

**METHODOLOGY**

**Source Rocks**

Maturation experiments simulating oil and gas generation were conducted to estimate compositional kinetic parameters and stoichiometric coefficients. These parameters are required for the generation and expulsion model. Three source rock samples, representing immature (Tayma well, which is outside the study area), early mature (Hilwah, Figure 1) and post mature (Mazalij, Figure 1) stages, were selected based on geochemical data available in publications and Saudi Aramco internal reports. Insoluble organic matter (kerogen) was isolated from these samples and pyrolysed in both open and closed anhydrous systems (Behar et al., 1997). Table 1 shows the initial geochemical data for these three samples.

![Figure 1: Map of the study area showing the main pre-Khuff Paleozoic oil and gas fields in Central and Eastern Arabia. The wells used for the 3-D data set are also shown. Note hypothetical ‘Model Well’ which is used to model the deepest kitchen.](https://pubs.geoscienceworld.org/geoarabia/article-pdf/4/3/321/4553115/abuali.pdf)
Figure 2: Saudi Arabian Paleozoic stratigraphic column.
The three samples were heated from 300° Centigrade (°C) to 650° C at increments of 5°, 15° and 30° C per minute in a Rock-Eval pyrolysis device to quantify their primary cracking parameters. This device, through a system of traps, separates the pyrolysis products according to their Carbon number. Pyrolysis allowed recovery of the C6+ (carbon chains longer than six carbon atoms) products in order to quantify the C6 to C14 and the C15+ fractions. Rock-Eval also measured the amounts of saturates, aromatics and heavy components (NSOs: nitrogen, sulfur and oxygen compounds) in the C15+ fractions, and the proportion of saturates and aromatics in the C6 to C14 fraction. Gases in the C5 - fraction were split into C1, C2 and C3 to C5 with a vacuum line equipped with a Toepler pump.

Kinetic parameters resulting from the pyrolytic analyses indicate that gases are generated simultaneously with oils and heavy components (Figure 3). The immature Tayma sample has a total gas potential of 101 milligram per gram (mg/gm) Total Organic Carbon (TOC), which accounts for more than 20% of the total generative potential. The amount of generated heavy components (NSOs) reaches up to 190 mg/gm TOC, almost 40% of the total generated amount. Compared to standard Type II samples (Behar et al., 1997) or to other Silurian organic matter, the Central Saudi Arabian samples have higher NSO and lower C14+ saturates components. Together with the low maturity of the Tayma sample, this suggests that the samples were chemically altered shortly after deposition, either through oxidation or bacterial reworking.

The parameters of the early mature Hilwah and post mature Mazalij samples are consistent with the immature Tayma sample, both for the pre-exponential factor and the chemical nature of pyrolysates (Figure 3). In addition, the amount of NSOs versus C14+ saturates are also high in these samples. This suggests that the Silurian organic matter can be considered to be homogeneous with respect to its cracking parameters, at the time scale modeled in this study. Also, the Tayma sample can be regarded as being representative of an immature Qusaiba source rock.

Most of the NSO components do not escape from the source rock, due to low mobility (Rudkiewicz et al., 1993). Hence, secondary cracking of these components also contributes to the later generation of gas. For secondary cracking, comprehensive cracking parameters were derived from experiments on oils and hydrocarbons generated from kerogen (Behar et al., 1992).

### 3-D Data Set

Maps of the study area (264,000 square kilometers) were compiled based on well-data (Figure 1) and seismic data. To avoid sampling bias the maps were resampled with 168 hypothetical wells at a regular grid spacing of 2 x 2 kilometers (km).
Figure 3: Compositional kinetic parameters of Qusaiba source rock samples. Tayma (outside the study area) sample is immature, Hilwah early mature and Mazalij over-mature. Also shown is the Arrhenius Equation where ‘A’ is the frequency in second-1, ‘e’ is the activation energy in Kcal/mole. The activation energies are sliced every 2 Kcal/mole between 40 and 80 Kcal/mole.
The top Unayzah and base Qusaiba structure maps are shown in Figures 4 and 5, respectively. To compute the 3-D burial history of the Qusaiba source rock, structure maps for 13 horizons were used. The 13 layers were then back-stripped in time to reconstruct the evolution of sedimentation, erosion, and temperature. Care was taken to select layers that reconstruct the shape of the regional drainage horizons at the time of primary expulsion.

Lithology plays an important role in estimating compaction during burial and thermal conductivity. Twelve composite facies, representing the different lithologies in the area were defined using five end-member lithologies (Table 2). Lateral changes in lithology were included in the model based on reconstructed paleo-environments (Powers et al., 1966; Stump, 1995, unpublished Saudi Aramco report).

**Maturity History**

Since hydrocarbon generation is mostly temperature-driven, the assumed paleo-temperature gradient is critical. Appropriate boundary conditions can be selected by calibrating present-day observed temperatures with paleo-temperature indicators, such as vitrinite or vitrinite-like reflectance. Only heat conduction was taken into account. Convective heat transfer, due to compaction or hydrodynamic
Composition of Lithologies Used in the Study, as a Percent of End-Member Lithologies

| Composite Facies          | Shale | Limestone | Sandstone | Salt | Dolomite |
|--------------------------|-------|-----------|-----------|------|----------|
| Shale                    | 100   |           |           |      |          |
| Source Rock (poor)       | 100   |           |           |      |          |
| Sandstone                |       |           |           |      |          |
| Limestone                |       |           |           |      |          |
| Evaporitic Limestone     |       |           | 100       | 100  |          |
| Sandy Shale              |       |           | 80        |      |          |
| Clastic Carbonate        |       |           |           | 50   |          |
| Shaly Limestone          | 50    | 70        | 30        |      |          |
| Silt                     | 70    | 30        | 80        |      |          |
| Poor Sandstone           | 20    | 80        | 30        |      |          |
| Dolomitic Limestone      |       |           |           | 30   |          |
| Source Rock (rich)       | 100   | 70        | 80        |      |          |

Figure 5: Structural map of base Qusaiba shale. Oil and gas fields are both Mesozoic and Paleozoic.
The thermal regime was calibrated using 13 wells. Figure 6 shows the computed and observed temperatures for five of these wells: Hawtah, Mazalij, Nuayyim, Udaynan and Tinat. Calibrations were achieved by matching present-day temperatures using a constant heat flow through time of 54 milliWatt/square meter (mW/m²) at the bottom of a 10 km thick crustal buffer. Measured downhole temperatures are usually lower than the subsurface ambient temperature because of thermal disequilibrium in the well. This is compensated for by making the calibrated temperatures higher than the measured ones.

Surface temperatures were assumed to be constant at 25°C (77°F) from present-day to 89 Ma, and 15°C (59°F) from 89 Ma to 255 Ma. Due to colder conditions during the Paleozoic, the surface temperature was reduced to 10°C (50°F) from 255 Ma to 440 Ma.

Vitrinite-like reflectance data were calibrated from four wells (Hawtah, Mazalij, Udaynan and Nuayyim) (Figure 7) using a constant heat flow. The uncertainty of this data for Silurian source rocks is great as vitrinite macerals are rare or absent in Silurian rocks, as shown from the Udaynan well.
MODEL RESULTS

Transformation Ratio Maps

Based on modeling results, a series of maps depicting Transformation Ratios (TR) were constructed through time (Figure 8). TR is the ratio of the difference between the initial and present-day source rock hydrocarbon potential, to the initial potential, at the time of deposition.

\[ \text{Transformation Ratio} = \text{TR} = \frac{(\text{Initial Potential} - \text{Current Potential})}{\text{Initial Potential}} \]

In the Triassic, the basin was not yet in the generating stage (only 1% to 20% TR). In the Late Jurassic only the deepest parts of the basin were in the gas generation window (dark orange color, 80% \leq \text{TR} \leq 100%). Maturation then progressed towards the west and north. Today, only the western parts and the highs are immature (pale color), and the rest of the area is in the generation window (60% \leq \text{TR} \leq 100%).
Figure 8: Qusaiba Transformation Ratio (TR) is the ratio of the difference between the original and present-day source rock potential to the original potential at the time of deposition. The maps show the percentage change in the Qusaiba hot shale for the late Middle Triassic (approximately 230 Ma), Late Jurassic (approximately 142 Ma), Early Cretaceous (approximately 110 Ma) and present-day, when the source rock was deposited. TR maps alone are not sufficient to describe the oil and gas migration.
The TR results cannot accurately address the expulsion history. This is due to the difference in TOC and reduced compaction of the Qusaiba hot shale, which is shallower to the north than south. The expulsion maps demonstrate that TR maps are not sufficient to describe the oil and gas migration. They just show where hydrocarbons were generated. Expulsion takes effect when the rock porosity reaches a given hydrocarbon saturation threshold.

Gas and Oil Expulsion Maps

Gas and oil expulsion were computed using the actual wells and the 2 x 2 km grid of 168 hypothetical wells. The expulsion of hydrocarbons from the Qusaiba hot shale source rock was computed using the kerogen kinetic parameters from the Tayma sample, which is considered representative of an immature Qusaiba source rock. Two facies of the Qusaiba were used, one organic-rich (TOC = 4%) in the south, and one organic-poor (TOC = 2%) in the north.

Expulsion history was modeled assuming that a saturation threshold of 20% was required for effective expulsion from all source rock facies. All generated NSOs were considered immobile, hence they underwent secondary cracking. The generated and expelled products were lumped together as an “oil group” comprising all C_5+ compositional classes, and a “gas group” comprising all C_5- classes.

Figure 9 shows the timing of hydrocarbon expulsion for two wells. Udaynan is an actual well used in the calibration, while Model Well is a hypothetical well located in the deepest part of the kitchen (Figure 1). Peak kerogen cracking occurred around the Late Jurassic; however, due to an inadequate saturation threshold...
threshold and lack of secondary cracking, expulsion was delayed. The expulsion profiles in Figure 9 show three modes:

(1) Onset, around the Late Jurassic (approximately 142 Ma) is linked to early generation.

(2) A second increase, around the late Early Cretaceous (approximately 100 Ma) is due to the cracking of adsorbed NSOs and continued subsidence.

(3) A third increase, around the Eocene to Miocene (approximately 50 to 20 Ma) results from late cracking.

The total expelled oil and gas are shown in Figures 10 and 11, respectively, from the beginning of expulsion (142 Ma for oil and 110 Ma for gas) until present-day. An interesting result is that the expulsion of oil and gas was limited to a small region in the southeastern part of the basin. This is apparent expulsion due to a lack of source rock data or wells penetrating the Qusaiba hot shale in the north. A minor and late contribution of gas from deeper in the basin, to the north, occurs following the uplift of the Arabian Shield (20 Ma to present). A higher TOC assumption in the North would lead to more oil and gas expulsion.

Based on the maps, expulsion extended to a larger area only after the Albian (approximately 100 Ma). Oil and gas were expelled almost simultaneously, but gas expulsion continued for a longer time. Expulsion areas extended to a maximum limit at the end of the Cretaceous. Afterwards, the expelled amounts increased, but the geographic area remained unchanged. This is linked to the sedimentation and subsequent burial, which is less in the Tertiary than the Cretaceous.

Oil expulsion ceased at 20 to 10 Ma due to the uplift (Figure 9) of the western part of the Arabian Shield as a result of the Red Sea Rift. During this time the western side of the study area continued to expel mostly gas due to volume expansion caused by a decrease in pressure and sediment unloading. This is evident in the maps of expelled gas from the Qusaiba, at present and 52 Ma (Figure 11). Greater quantities of gas are being expelled at present than at 52 Ma toward the western part of the study area.

The total amount of expelled gas reaches almost 3 mg gas/gm rock in the deepest parts of the basin. Most of the gas was expelled during the Late Cretaceous as can be seen on the expulsion plot of the Model Well (Figure 9). Expulsion of aromatics and saturates reaches 1.5 and 4.0 mg HC/gm rock, respectively. Expulsion of oil nearly ceases after the Late Cretaceous, while gas continues to be expelled, though at a lower rate, during the Tertiary.

**DISCUSSION AND CONCLUSIONS**

Oil and gas generation and expulsion from the Silurian Qusaiba hot shale was assessed through geologic time for the Eastern, and a portion of Central, Saudi Arabia. Results were based on integration of regional depth maps, compositional kinetic parameters derived from source rock samples, and paleo-temperatures determined from maturity data as assessed by organic petrography.

The Qusaiba source rock was mature by the Late Jurassic in the deepest part of the basin whereas hydrocarbon expulsion started in the Early Cretaceous. Oil and gas expulsion is linked to three geochemical events. Primary kerogen cracking led to a first episode of expulsion (approximately 120 Ma). Secondary cracking of heavy components and oils then led to a second episode (approximately 100 Ma). Later uplift resulted in a third expulsion pulse (20 to 10 Ma). The first two expulsion events are linked to ongoing sedimentation and were gradual, whereas the last expulsion phase was more rapid as a result of relatively rapid uplift. This third episode coincides with the uplift of the Arabian Shield, the opening of the Red Sea and Zagros Orogeny (20 to 10 Ma).

Gas is sourced either directly from kerogen, or from secondary cracking of heavy adsorbed components or of non-migrated oils. Expulsion of gas coincides with the expulsion of oil for the first two episodes with gas and oil forming a single phase. Only with later uplift is gas thought to separate from the oil and re-migrate. This separation may play an important role in explaining migration pathways.
This study demonstrates that present-day transformation ratios of kerogen are insufficient to determine the correct expulsion timing. There is a time lag between generation and expulsion. Hydrocarbon expulsion is delayed compared to peak generation because expulsion of hydrocarbons from the source rock first requires saturation of pore space in the source rock shales.

Figure 10: Total oil expelled from Qusaiba shale (m³/m²). C₅+ components are combined to represent oil.
Figure 10: Total gas expelled from Qusaiba shale (m$^3$/m$^3$). C$_5$- components are combined to represent gas.
In this paper, the Unayzah migration history has not been addressed. The assumption is that trapped gas, and probably oil, in the deepest parts of the basin re-migrated with the uplift, which led to a late stage gas re-migration. Source kitchens south of Ghawar existed since the end of the Late Cretaceous. Northern (north and northwest of Ghawar) source areas may have existed, but have been active only recently in the basin’s history. A better understanding of the Unayzah migration pathways and processes affecting hydrocarbon migration would further benefit identification of areas for future exploration.

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