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# Thermal History of the Lower and Middle Cretaceous Source Rocks in Kuwait

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## ABSTRACT

The thermal history of Kuwait was reconstructed with Shell's "Cauldron" basin modeling software and calibrated with maturity indicators from four wells. Maturity measurements were carried out on source rock samples from wells in the Ash-Shaham, Minagish, Raudhatain and Riqua (offshore) fields. The analytical data indicate that 'top oil window' is located at a depth of around 2,500 meters (8,250 feet). Due to the low structural dips of the sequences in Kuwait, thermal modeling in one-dimension was found to be adequate. The Cretaceous source rocks subsided without major anomalies in burial rate or heatflow. Modeling results indicate that the Cretaceous Sulaiy, Minagish and Zubair formations entered the oil window during the Late Cretaceous and Early Tertiary, whereas oil expulsion occurred throughout Tertiary time. Quantification of expelled oil volumes suggests that the Sulaiy Formation is the most productive source rock in Kuwait, whereas the Upper Cretaceous Burgan and Maudud formations are presently at the top of the oil window.

## INTRODUCTION

The assessment of the maturity of organic matter is one of the main and most difficult tasks in source rock evaluation. There are many different maturity measurements, based on elemental analysis, microscopy, pyrolysis and solvent extraction (Hunt, 1995). Among the most widely used maturity indicators are vitrinite reflectance (VR), thermal alteration index (TAI), spore color index (SCI) and a whole spectrum of molecular parameters based on gas chromatography (GC) and gas chromatography-mass spectrometry (GCMS) (Peters and Moldowan, 1993). All maturity indicators, however, have shortcomings and only through cross checking of several parameters can accurate maturity levels be established.

Maturity indicators are useful in evaluating the present-day depth of the oil window. They do not, however, provide information on the timing of oil generation. Timing of oil generation, and particularly expulsion, is important in relation to the age of reservoirs and traps. Information on timing and duration of oil expulsion is obtained from charge modeling, which is based on the temperature history of a source rock and on the assumption that experimentally determined activation energies can be extrapolated to geological time scales (Connan, 1974; Hood et al., 1975; Waples, 1994; Tissot and Welte, 1984). Charge modeling software is currently undergoing a rapid development. The latest version of Shell's "Cauldron", for instance, allows probabilistic sampling of ill-defined input parameters (i.e. thickness and quality of undrilled source rock). In addition to timing of generation, results of charge prediction now typically include volumes and quality (API gravity) of oil expelled from the source rocks.

This study follows our earlier 1996 paper and its objective is to determine the level of thermal maturation and depth of the oil window of the Cretaceous source rocks of Kuwait. In this study, modeled maturity levels are correlated to various maturity indicators in order to reconstruct the thermal history of the area. The software was run in a Monte Carlo mode resulting in different burial histories to fit the measured maturity data.

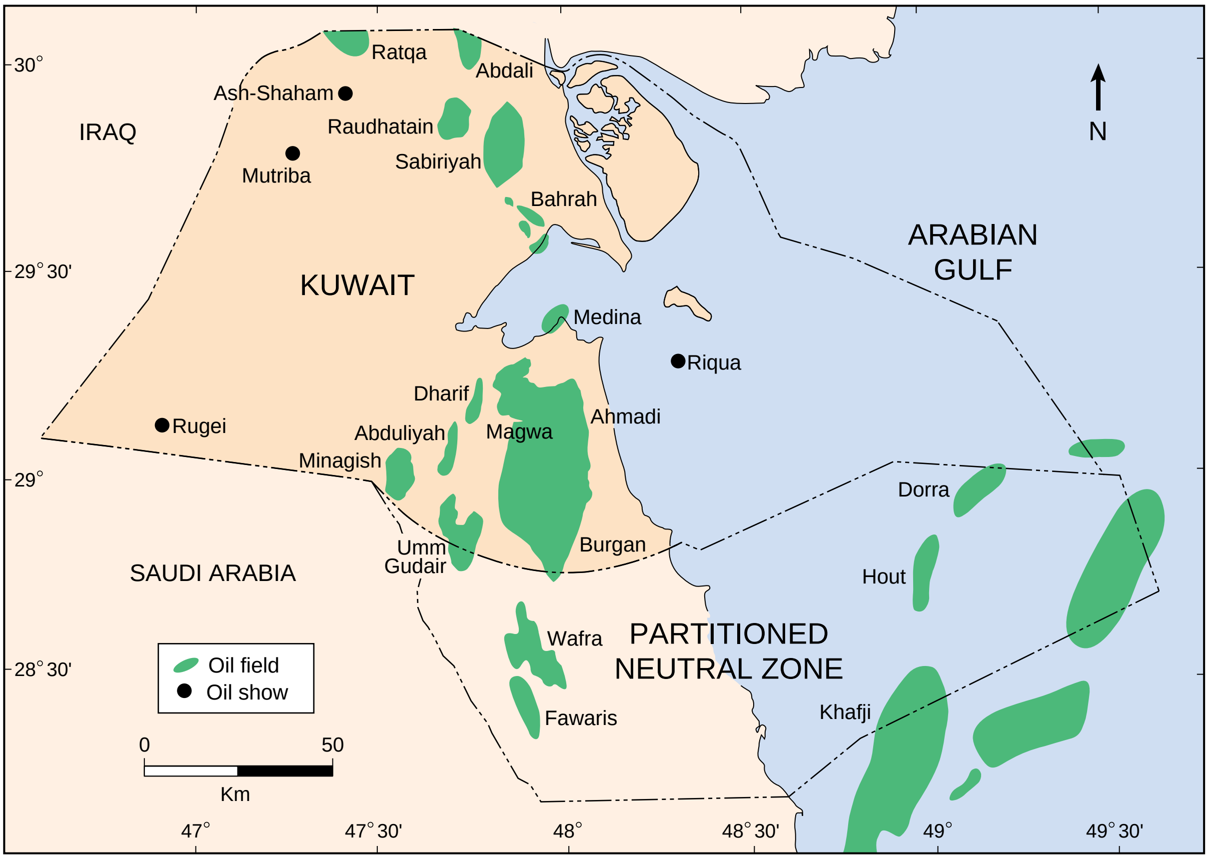



**Figure 1: Kuwait oil fields produce mostly from Cretaceous reservoirs. Rock samples from wells in Ash-Shaham, Minagish and Raudhatain onshore and offshore Riqua locations were used in this study. The four locations share a similar geologic setting.**

**Table 1**
**Main Oil Fields in Kuwait and Partitioned Neutral Zone**

| Location | Marrat | Sargelu | Minagish | Ratawi | Zubair | Burgan | Mauddud | Wara | Ahmadi | Mishrif | Tayarat | Radhuma | Ghar |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abdali | | | | x | x | | | | | | | | |
| Ahmadi | | | | | | x | x | x | | | | | |
| Bahrah | | | | | | x | x | | | | | | x |
| Burgan | | | x | | | x | x | x | | | | | |
| Magwa | x | | | | | x | x | x | | | | | |
| Minagish | x | x | x | | | x | | x | | x | | | |
| Mutriba | | | x | | | | x | | | | | | |
| Ratqa | | | | | x | | | | | | | | x |
| Raudhatain | | | x | x | x | x | x | | | | | | x |
| Riqua | | | | | x | | | | | x | | | x |
| Sabriyah | | | | | | x | x | | | | | x | |
| Umm Gudair | x | x | x | | | | | | | | | | |
| **Partitioned Neutral Zone** | | | | | | | | | | | | | |
| Dorra | | | x | | | | | | | | | | |
| Fawaris | | | x | | | | | | | | | | |
| Hout | | | x | | | | x | | x | | | | |
| Khafji | | | x | | | x | x | x | x | | | | |
| Wafra | | | x | | | | | x | | | x | x | |

## CRETACEOUS PETROLEUM GEOLOGY

Kuwait is located in the northwestern corner of the Arabian Gulf Basin (Figure 1). Generally, the beds in Kuwait dip gently to the northeast and the average sedimentary thickness is 6,780 meters (m) or 22,240 feet (ft). The sequence ranges from Pleistocene to Permian (Figure 2; Kuwait Report, 1989). The Mesozoic rocks in Kuwait are a thick sequence of carbonates and clastics which average 3,800 m (12,600 ft) in thickness (Figure 2, modified after Carman, 1996; Yousif and Nouman, 1997).

High tectonic activity characterized Cretaceous time and this is reflected by the three regional unconformities. These occur at the base of the Barremian Zubair, Albian Burgan and above the Turonian-Cenomanian Mishrif Formation. The regional tectonic interpretation of these unconformities is shown in Figure 2 (Carman, 1996).

The main structural features in Kuwait are a series of north-south trending anticlines associated with some minor faults (Carman, 1996). The anomalously thin formations above these structures indicates growth since Middle Cretaceous, or even earlier, as a result of epeirogenic movement. The Ahmadi anticline is the exception as it resulted from regional horizontal shortening (Fox, 1959; Carman, 1996).

Much of Kuwait's oil is trapped in doubly plunging anticlines (Figure 1). The Kuwait Arch forms the largest structural trap in Kuwait, with culminations in Burgan, Magwa and Ahmadi fields. The Greater Burgan field covers an area of about 770 square kilometers (sq km) and has oil reserves of approximately 60 billion barrels (Adasani, 1965).

The main Cretaceous reservoirs are the Zubair, Burgan and Wara sandstones and the Minagish, Mauddud, Mishrif and Tayarat limestones (Figure 2).

## KUWAIT'S PETROLEUM SYSTEMS

Most of the Kuwait's oil fields produce from Cretaceous reservoirs (Figure 1 and Table 1). Tertiary and Jurassic reservoirs account for some minor production. The Permian Khuff Formation, a major gas producer in most of the Arabian Gulf region, is not developed in Kuwait (Figure 2). Below the Khuff Formation the deepest well in Burgan field penetrated steeply-dipping beds of probable Precambrian age (Khan, 1989).

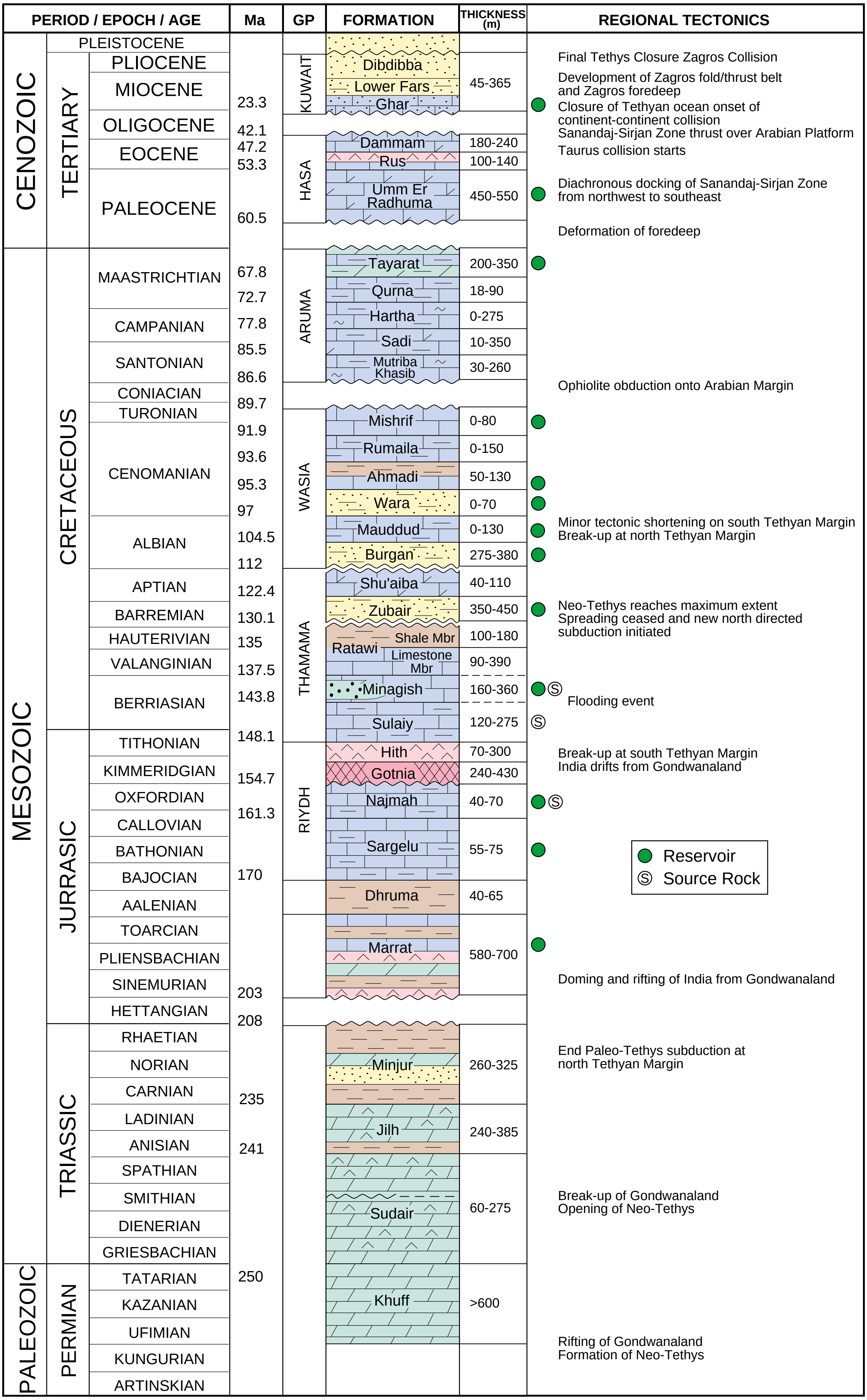
Murris (1980) suggested that the Cretaceous oil in Kuwait's largest field, Burgan (Figure 1), may have migrated laterally from the Luristan Basin in Iran. The potential source rock is the Middle Cretaceous Kazhdumi Formation (Ala, 1979; Beydoun, 1993).

More recently however, Abdullah (1993) and Abdullah and Kinghorn (1996) concluded that Kuwait's Cretaceous oil was generated from the Minagish and Sulaiy formations (Figure 2). The Sulaiy Formation is equivalent to the Makhul Formation in the Kuwait Oil Company Stratigraphic Column (Lababidi and Hamdan, 1985).

In Kuwait the deeper Jurassic petroleum system is probably separated from the Cretaceous one (Figure 2). Using wire logs, Hussain (1987) suggested that the oil accumulations in the Jurassic Najmah, Sargelu and Marrat reservoirs are generated by these same formations (Beydoun, 1993). Yousif and Nouman (1997) also highlight the good source rock signature, consisting of a high gamma ray and low density log response, in the lower section of the Najmah Formation.

## METHOD OF STUDY

Well logs from four locations, Ash-Shaham, Minagish and Raudhatain onshore, and Riqua offshore (Figure 1) were correlated and formation tops and unconformities were identified. The age of the formations and time gaps were obtained from the stratigraphic section of Kuwait (Figure 2) and the geologic time scale of Harland et al. (1989).


PERIOD / EPOCH / AGE
Ma
GP
FORMATION
THICKNESS (m)
REGIONAL TECTONICS
CENOZOIC
TERTIARY
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
MESOZOIC
CRETACEOUS
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
JURRASIC
TITHONIAN
KIMMERIDGIAN
OXFORDIAN
CALLOVIAN
BATHONIAN
BAJOCIAN
AALENIAN
TOARCIAN
PLIENSBACHIAN
SINEMURIAN
HETTANGIAN
TRIASSIC
RHAETIAN
NORIAN
CARNIAN
LADINIAN
ANISIAN
SPATHIAN
SMITHIAN
DIENERIAN
GRIESBACHIAN
PALEOZOIC
PERMIAN
TATARIAN
KAZANIAN
UFIMIAN
KUNGURIAN
ARTINSKIAN
23.3
42.1
47.2
53.3
60.5
67.8
72.7
77.8
85.5
86.6
89.7
91.9
93.6
95.3
97
104.5
112
122.4
130.1
135
137.5
143.8
148.1
154.7
161.3
170
203
208
235
241
250
KUWAIT
HASA
ARUMA
WASIA
THAMAMA
RIYDH
Dibdibba
Lower Fars
Ghar
45-365
Dammam
180-240
Rus
100-140
Umm Er Radhuma
450-550
Tayarat
200-350
Qurna
18-90
Hartha
0-275
Sadi
10-350
Mutriba Khasib
30-260
Mishrif
0-80
Rumaila
0-150
Ahmadi
50-130
Wara
0-70
Mauddud
0-130
Burgan
275-380
Shu'aiba
40-110
Zubair
350-450
Ratawi
Shale Mbr
100-180
Limestone Mbr
90-390
Minagish
160-360
Sulaiy
120-275
Hith
70-300
Gotnia
240-430
Najmah
40-70
Sargelu
55-75
Dhruma
40-65
Marrat
580-700
Minjur
260-325
Jilh
240-385
Sudair
60-275
Khuff
>600
Final Tethys Closure Zagros Collision
Development of Zagros fold/thrust belt and Zagros foredeep
Closure of Tethyan ocean onset of continent-continent collision
Sanandaj-Sirjan Zone thrust over Arabian Platform
Taurus collision starts
Diachronous docking of Sanandaj-Sirjan Zone from northwest to southeast
Deformation of foredeep
Ophiolite obduction onto Arabian Margin
Minor tectonic shortening on south Tethyan Margin
Break-up at north Tethyan Margin
Neo-Tethys reaches maximum extent
Spreading ceased and new north directed subduction initiated
Flooding event
Break-up at south Tethyan Margin
India drifts from Gondwanaland
Reservoir
Source Rock
Doming and rifting of India from Gondwanaland
End Paleo-Tethys subduction at north Tethyan Margin
Break-up of Gondwanaland
Opening of Neo-Tethys
Rifting of Gondwanaland
Formation of Neo-Tethys

The four locations share a similar geologic setting and therefore only the deepest well from the Raudhatain field was used in the model. Table 2 shows the data from the Raudhatain field.

Maturity measurements were carried out on samples (cores and cuttings) taken from the same four locations. A combination of methods was used to limit the systematic errors of the individual maturity indicators and improve the accuracy of the outcome (Nuccio, 1990, 1991).

The maturity indicators used in this study include two parameters based on Rock Eval Pyrolysis: Tmax and Production Index (Peters, 1986; Espitalie and Joubert, 1987), one based on elemental analysis: (H / C vs. O / C) and the three microscopic indicators vitrinite reflectance, spore color index and thermal alteration index (Staplin, 1969; Tissot and Welte, 1984).

Most maturity indicators are dependent on the type of organic matter in the source rock. The kerogen in the Cretaceous source rocks of Kuwait were characterized as Type II and II/III (Abdullah and Kinghorn, 1996) and the values of the maturity measurements were interpreted accordingly.

**Table 2**
**Data used from Raudhatain Field as Input for Charge Modeling**

Number of formations and unconformities: 23; Number of formations: 19
Geothermal Gradient: 0.024°C/m; Surface Temperature: 20°C

| DEPOSITIONAL UNIT and EROSION | THICKNESS (meters) | TIME INTERVAL (million years) |
|---|---|---|
| Kuwait Group | 361 | 23.3 |
| **Erosion** | -650 ±250 | 18.8 |
| Dammam | 155.5 | 5.1 |
| Rus | 192 | 6.1 |
| Umm Er Radhuma | 128 | 7.2 |
| **Erosion** | -200 ±150 | 4.5 |
| Tayarat | 570 | 2.8 |
| Harth/Qurna | 234.7 | 10 |
| Sadi | 134 | 7.7 |
| Khasib/Mutriba | 213.4 | 1.1 |
| **Erosion** | -300 ±250 | 3.1 |
| Mishrif | 51.8 | 2.2 |
| Rumaila | 131 | 1.9 |
| Ahmadi | 88.4 | 1.7 |
| Wara | 0 | 1.7 |
| Mauddud | 97 | 7.5 |
| Burgan | 283.5 | 7.5 |
| Shu'aiba | 76.2 | 10.4 |
| Zubair | 399.2 | 7.7 |
| Ratawi Shale | 167.6 | 4.9 |
| Ratawi Limestone | 146.3 | 2.5 |
| Minagish | 310.9 | 6.25 |
| Sulaiy | 228.6 | 4.35 |

**Figure 2 (facing page): Stratigraphic column and regional tectonics, onshore Kuwait (after Carman, 1996). The Jurassic stratigraphy is after Yousif and Nouman (1997), and the ages are after Harland et al. (1989). In Kuwait, the Minagish and Sulaiy formations (Sulaiy = Makhul Formation of Kuwait Oil Company) are the main Cretaceous source rocks.**

## CHARGE MODELING

Shell's software "Cauldron" was used to reconstruct the thermal history in the area. "Cauldron" is a sophisticated basin modeling package which calculates subsurface temperatures based on the transient heatflow from the mantle and crust, the burial and uplift history, and an extensive thermal conductivity database. The hydrocarbon generation model uses the kinetics of 16 reaction species. Hydrocarbon expulsion is based on a thermally activated diffusion model (Stainforth and Reinders, 1990). The heatflow is vertical only (1D), an acceptable assumption given the predominantly shallow-dipping strata.

The following constraints and assumptions were made when applying the calculations:

(1) The present-day reservoir temperature at 3,000 m (92°C) is taken from a study by Watkin (1979). The geothermal gradient however, is slightly non-linear along the stratigraphic section because thermal conductivity varies due to changes in lithology. The key constraint on the model is that it is consistent with this (present-day) temperature.

(2) The average annual sea bottom temperature in the Arabian Gulf at present-day is 20°C (Emery, 1956; Purser and Seibold, 1973). This temperature, with variations of up to ±5°C, was taken as surface temperature from Early Cretaceous to the present. The "surface temperature" refers to a mean near-surface temperature averaged over many thousands of years. Elevation changes are negligible as the area was predominantly a stable shelf.

(3) The compaction and surface porosities of the various rock formations were calculated by the program, based on rock compositions given in the stratigraphic description by Lababidi and Hamdan (1985). The compaction algorithm used is based on effective stress.

(4) The temperatures measured in the subsurface were used to constrain the modeled present-day heatflow. This produced a present-day surface heatflow of 40 $mW/m^2$, and mantle-derived heatflow of 25 $mW/m^2$, both of which are consistent with the tectonic setting. The mantle-derived heatflow of the area is assumed not to have been affected by tectonic activity, and to have decayed linearly from 30 $mW/m^2$ in the Early Jurassic to the 25 $mW/m^2$ of present time. The high temperatures created around the Zagros collision zone (Perrodon and Masse, 1984; Fowler, 1990) do not affect the temperatures in the modeled wells, as the distance between Kuwait and the suture zone in the Zagros region (400-500 km) is too large.

(5) The activation energy ranges of the source rocks were estimated *a-priori* from the kerogen type (Type II and II/III, Abdullah and Kinghorn, 1996) and the sulfur content (moderate).

(6) The estimates of missing overburden are consistent with the rate of deposition before erosion. The main unconformity during the middle Tertiary was assumed to have eroded between 400 to 900 m.

The program requires geochemical parameters such as source rock TOC, hydrogen index and vitrinite reflectance. Measured TAI values were converted into an estimated vitrinite reflectance (VR/E). The best fit with the experimental data was chosen to represent the actual burial and thermal history of the area (Figure 4). The program was run in a Monte Carlo mode, so that many burial histories were created by probabilistic sampling of key parameters for the prediction of oil generation and expulsion timing. The parameters which were allowed to vary were: amount of missing overburden; heat production from shales; mantle heatflow; surface porosity of sediments; compaction coefficient; surface temperature; source rock TOC%, HI, OI, thickness and activation energies. The largest uncertainty in the timing and depth of oil generation is caused by the possible variation in the source rock kinetics.

## DISCUSSION AND CONCLUSION

The measured maturity data of the samples is shown in Table 3 and Figure 3. A comparison of the different parameters, taking into consideration the kerogen type, indicates that oil generation (VR 0.6%) starts at a depth around 2,500 m ± 300 m (8,250 ft ± 1,000 ft). The base of the oil window (onset of gas generation) cannot be established from this sample set.

**Table 3**

**Results of kerogen elemental analysis, pyrolysis, spore coloration and vitrinite reflectance for samples from Raudhatain (RA), Riqua (RI), Ash-Shaham (SH) and Minagish (MN). Refer to Figure 1 for sampling location.**

| Formation | Sample Number | Depth (meter) | TOC | H/C | O/C | Tmax | $\frac{S_1}{S_1+S_2}$ | Kerogen or Spore Color | TAI | Mean $R_o$% |
|---|---|---|---|---|---|---|---|---|---|---|
| Sulaiy | RA*/1 | -3907.2 | 1.55 | 0.67 | 0.04 | 471 | 0.32 | dark brown to black | | |
| | RA*/2 | -3762.5 | 1.91 | 1 | 0.06 | 449 | 0.32 | brown | | |
| | RA*3 | -3709.1 | 1.38 | 1.01 | 0.07 | 443 | 0.19 | brown | | |
| Minagish | RA*4 | -3654.2 | 0.53 | 0.94 | 0.08 | 418 | 0.16 | light brown | | |
| | RA*7 | -3489.7 | 0.43 | 1.24 | 0.1 | | | | | |
| | RA*9 | -3402.8 | 0.88 | 1.11 | 0.19 | 425 | 0.18 | | | |
| Ratawi | RA*/10 | -3347.9 | 0.55 | 0.97 | 0.13 | 428 | 0.1 | | | |
| Limestone | RA*/11 | -3280.3 | 0.8 | 1.22 | 0.16 | 434 | 0.13 | | | |
| | RA*/12 | -3239.4 | 0.38 | 0.91 | 0.11 | 429 | 0.05 | | | |
| Ratawi Shale | RA/1 | -3091.9 | 1.86 | 0.85 | 0.2 | 429 | 0.03 | orange | 2+ | 0.589 |
| Zubair | RA/2 | -3079.7 | 2.84 | 0.72 | 0.18 | 435 | 0.03 | orange | 3- to 2+ | 0.667 |
| | RA/4 | -2793.2 | 2.83 | 0.91 | 0.16 | 430 | 0.03 | orange | 2+ | 0.469 |
| | RA/5 | -2745.9 | 0.94 | 0.99 | 0.15 | | | dark yellow | 2+ | 0.533 |
| | RA/6 | -2701.7 | 0.88 | | | 430 | 0.06 | | | |
| Shu'aiba | RA/8 | -2585.9 | 1.29 | 1.22 | 0.1 | 429 | 0.04 | brown | | |
| Burgan | RA/9 | -2572.2 | 2.18 | 0.97 | 0.18 | 423 | 0.04 | yellow to orange | 2+ to 2 | 0.363 |
| | RA/10 | -2392.4 | 1.64 | 0.77 | 0.17 | 429 | 0.05 | yellow to orange | 2+ to 2 | 0.525 |
| | RA/12 | -2304 | 0.64 | | | 412 | 0.07 | | | |
| Mauddud | RA/13 | -2259.8 | 2.02 | 1.65 | | 418 | 0.29 | orange | | |
| | RA/14 | -2206.4 | 0.72 | 1.55 | | 405 | 0.07 | orange | | |
| Sulaiy | RI/1 | -3823.7 | 2.68 | 1.14 | 0.09 | | | brown | | |
| Ratawi Shale | RI/4 | -3490 | 1.5 | 0.99 | 0.12 | | | brown | 3- | 0.677 |
| | RI/6 | -3418.3 | 2.69 | 0.92 | 0.09 | | | brown to orange | 3- to 2+ | 0.817 |
| Zubair | RI/7 | -3354.3 | 1.1 | 0.99 | 0.11 | | | brown to orange | 3 to 3- | 0.612 |
| | RI/8 | -3217.2 | 1.6 | 1.07 | 0.07 | | | brown to orange | 3- to 2 | |
| | RI/9 | -3098.3 | 1.79 | 0.96 | 0.13 | | | | 2+ | |
| Burgan | RI/12 | -2668.5 | 2.37 | 1.15 | 0.1 | | | yellow to orange | 2+ | 0.521 |
| Wara | RI/15 | -2458.2 | 1.16 | 1.35 | 0.26 | | | yellow to orange | 2+ | 0.535 |
| Ahmadi | RI/19 | -2330.2 | 0.97 | 1.43 | 0.13 | | | | | |
| Mishrif | RI/23 | -2135.1 | 0.55 | 1.04 | 0.28 | | | light yellow | | |
| Minagish | SH/1 | -4146.8 | 1.3 | 1.73 | 0.13 | | | brown | | |
| | SH/2 | -4085.8 | 2.84 | 1.37 | 0.11 | | | brown | | |
| | SH/3 | -4024.9 | 1.33 | 1.46 | 0.19 | | | | | |
| Ratawi Shale | SH/7 | -3758.2 | 1.28 | 1.01 | 0.08 | | | light brown | | |
| | SH/8 | -3720.1 | 2.27 | 1.12 | 0.1 | | | light brown | | |
| | SH/9 | -3674.4 | 3.25 | 0.9 | 0.1 | | | light brown | | |
| Zubair | SH/13 | -3290.3 | 1.01 | 1.01 | 0.16 | | | light brown | 2+ | 0.711 |
| Burgan | SH/17 | -3131.8 | 2.46 | 1.19 | 0.09 | | | | 2 to 2+ | 0.592 |
| | SH/18 | -2932.2 | 3.36 | 1.29 | 0.11 | | | | 2 to 2+ | 0.508 |
| Ahmadi | SH/20 | -2737.1 | 0.89 | 1.54 | 0.08 | | | orange to yellow | | |
| | SH/21 | -2630.4 | 0.62 | 1.27 | 0.12 | | | | | |
| Sulaiy | MN*/1 | -3267.8 | 0.4 | 1.05 | 0.07 | 435 | 0.13 | light brown | | |
| Minagish | MN*/3 | -3042.2 | 1.29 | | | 429 | 0.11 | | | |
| | MN*/4 | -2995 | 1.96 | 1.09 | 0.12 | 431 | 0.33 | | | |
| | MN*/5 | -2956.6 | 0.54 | 1.24 | 0.12 | 419 | 0.01 | | | |
| | MN*/6 | -2908.1 | 0.51 | 0.99 | 0.13 | | | | | |
| Ratawi Lst | MN*/8 | -2794.4 | 0.8 | 1.21 | 0.17 | 423 | 0.05 | | | |
| | MN*/9 | -2782.5 | 0.39 | | | | | | | |
| Ratawi Shale | MN*/10 | -2764.8 | 0.44 | 1.16 | 0.15 | | | dark yellow | 2 to 2+ | |
| | MN*/11 | -2752 | 0.64 | 0.8 | 0.13 | 417 | 0.02 | yellow | 2 to 2+ | |
| Zubair | MN*/13 | -2310.7 | 3.09 | 0.89 | 0.2 | 426 | 0.02 | yellow | 2 to 1+ | 0.38 |
| Shu'aiba | MN*/23 | -2278.4 | 0.67 | 1.22 | 0.24 | 413 | 0.25 | | | |
| Burgan | MN/1 | -1969 | 3.41 | 1.02 | 0.18 | 421 | 0.13 | yellow | 2 to 2- | |
| | MN/2 | -1930.6 | 3.36 | 0.87 | 0.08 | 428 | 0.11 | yellow | 2 to 2+ | 0.451 |
| | MN/3 | -1890.7 | 1.82 | 0.81 | 0.19 | 431 | 0.04 | light yellow | 1+ to 1 | 0.394 |
| Mauddud | MN/4 | -1884.9 | 4.05 | 1.44 | 0.21 | 416 | 0.08 | orange | | |
| Wara | MN/5 | -1880.6 | 0.56 | 0.87 | 0.23 | 422 | 0.04 | light yellow | 1 | 0.384 |
| Ahmadi | MN/30 | -1848.6 | 2.43 | 1.21 | 0.14 | 416 | 0.72 | light yellow | | |
| | MN/6 | -1830.6 | 0.5 | 0.96 | 0.16 | 423 | 0.07 | light yellow | 1 | 0.334 |
| Rumaila | MN/33 | -1729.7 | 2.1 | 1.29 | 0.13 | 398 | 0.43 | | | |
| Mishrif | MN/34 | -1684 | 1.38 | 1.27 | 0.14 | 412 | 0.29 | | | |

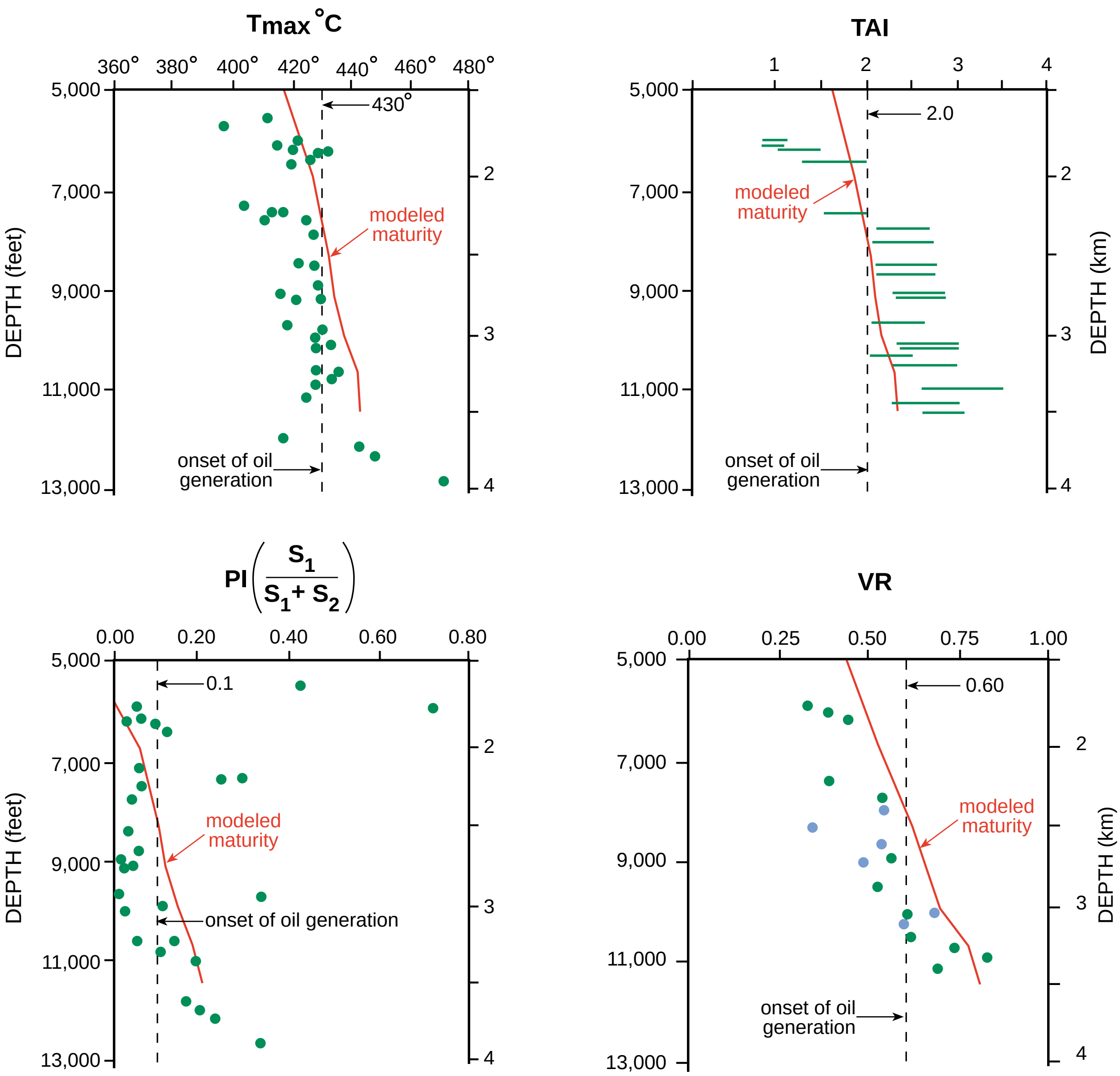



**Figure 3: Maturity indicators as a function of depth. Tmax, PI and Vitrinite Reflectance (VR) are from rock samples from wells in Raudhataian and Minagish fields. The Thermal Alteration Index (TAI) is from rock samples from wells in Ash-Shaham, Minagish and Riqua. Blue dots indicate data from modeled well RA-1.**

The Sulaiy Formation has kerogen type II and although it has reached peak oil generation stage it still has an average TOC weight value of 1.5%. The Minagish Formation has an amorphous Type II and II/III kerogen. The Zubair Formation has the lowest kerogen quality, Type III, but with an average TOC weight value of 2%. Using all the input data and taking into consideration the geologic condition of the area, the model effectively concludes that some of the vitrinite reflectance data has measured maturity too low while some of the TAI data is somewhat overestimating maturity.

Applying the charge model to the corrected maturity data on the above source rocks reveals that most oil generation took place during the Late Cretaceous and Early Tertiary time, while most of the oil expulsion occurred during the entire Tertiary time (Figures 4 and 5). The Sulaiy Formation reached its peak oil generation in Late Cretaceous (75 Ma) when it was at a temperature of 100°C and a depth of 3,000 m (Figures 4 and 5).

The Sulaiy Formation reached its peak expulsion during the Paleocene (62 Ma) when the formation was at a depth of 3,750 m (Figures 4 and 5). The two peaks in Figure 5 are related to the highest temperature levels reached during the latest two subsidences which were followed by two uplifts

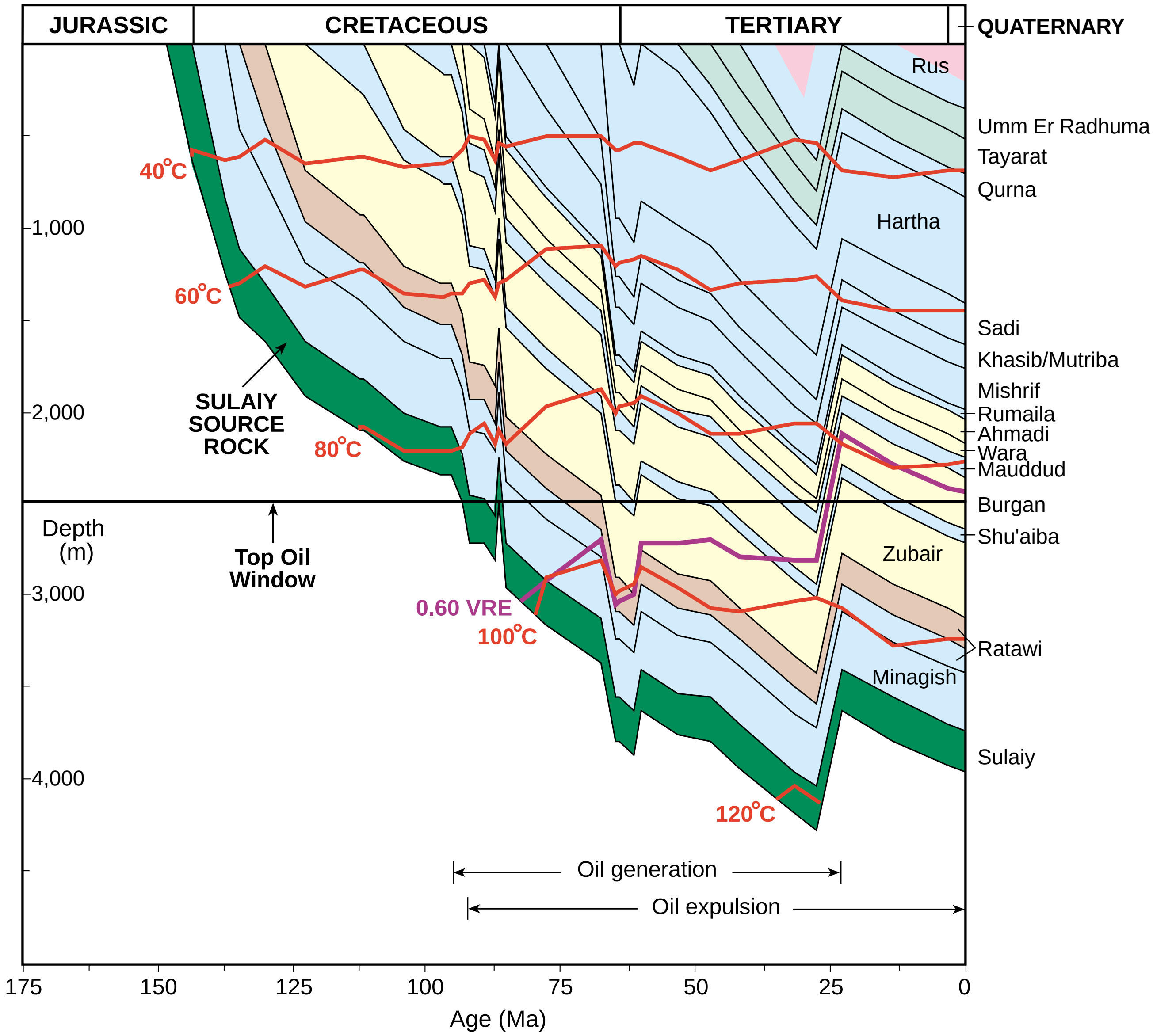



**Figure 4: Decompacted burial history for the Raudhatain well. Modeling results indicate that Kuwait has been subsiding at an average rate of 25 meters/million year. The thermal model reveals that most oil generation from the Sulaiy Formation took place during the Late Cretaceous and Early Tertiary, while most of the oil expulsion occurred during the Tertiary.**

**Table 4**
**Time of Structural Growth in Kuwait and Surrounding Area**

| Time Start Structural Growth | Structural Trap Name | Reference |
|---|---|---|
| Turonian | Ahmadi | Brennan, 1990 |
| Cenomanian | Raudhatain | Milton and Davis, 1965 |
| Aptian | Raudhatain was higher than Sabriyah | Al-Rawi, 1981 |
| Hauterivian-Valangian | Minagish | Youash and Mukhopadhayey, 1982 |
| Early Cretaceous | Burgan | Fox, 1959 |
| Early Jurassic | Dukhan Anticline, Qatar | Kamen-Kaye, 1970 |

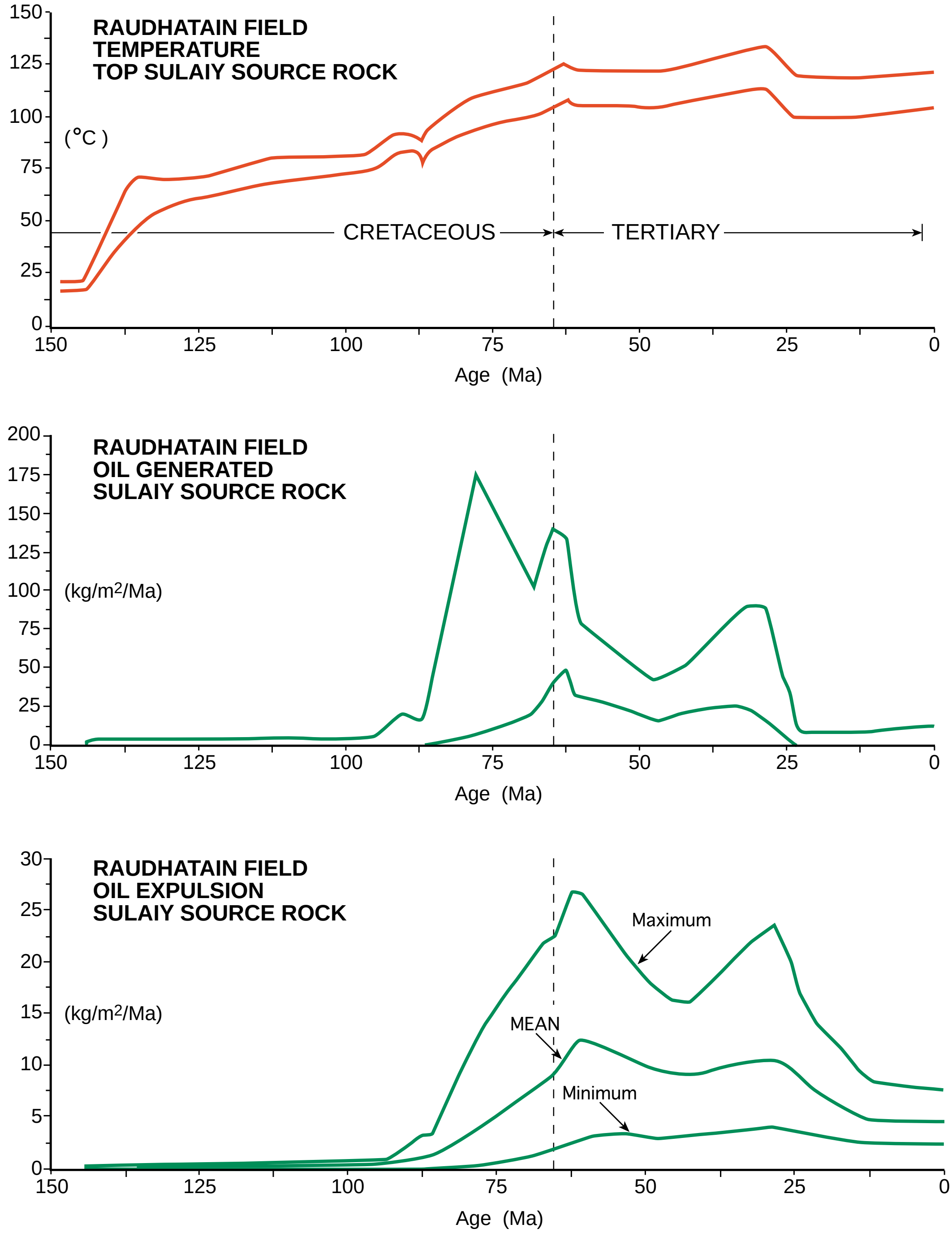



**Figure 5: The Sulaiy Formation reached its peak oil generation in Late Cretaceous (75 Ma) when it was at a temperature of 100°C and a depth of 3,000 m (Figure 4). The Sulaiy Formation reached its peak expulsion during the Paleocene (62 Ma) when the formation was at a depth of 3,750 m.**

**Table 5**
**Oil Generation and Expulsion for the Modeled Source Rocks**

| **Main Source Rock** | **Start Expulsion** Time:Depth (Ma:m) | **Peak Expulsion** Time:Depth (Ma:m) | **Peak Rate** million ($m^3/km^2/Ma$) | **Cumulative Oil Expelled** (M $m^3/km^2$) | **Cumulative Oil Generated** (M $m^3/km^2$) |
|---|---|---|---|---|---|
| Zubair | 75:2,300 | 27:3,200 | 3.24 (0-19.2) | 84 (0-528) | 240 (0-1,260) |
| Minagish | 80:2,700 | 27:3,800 | 3.12 (0.6-6.6) | 156 (36-396) | 780 (240-1,440) |
| Sulaiy | 90:2,600 | 62:3,750<br>27:4,150 | 15 (3.6-33.6) | 780 (240-1,560) | 3,240 (1,800-4,560) |

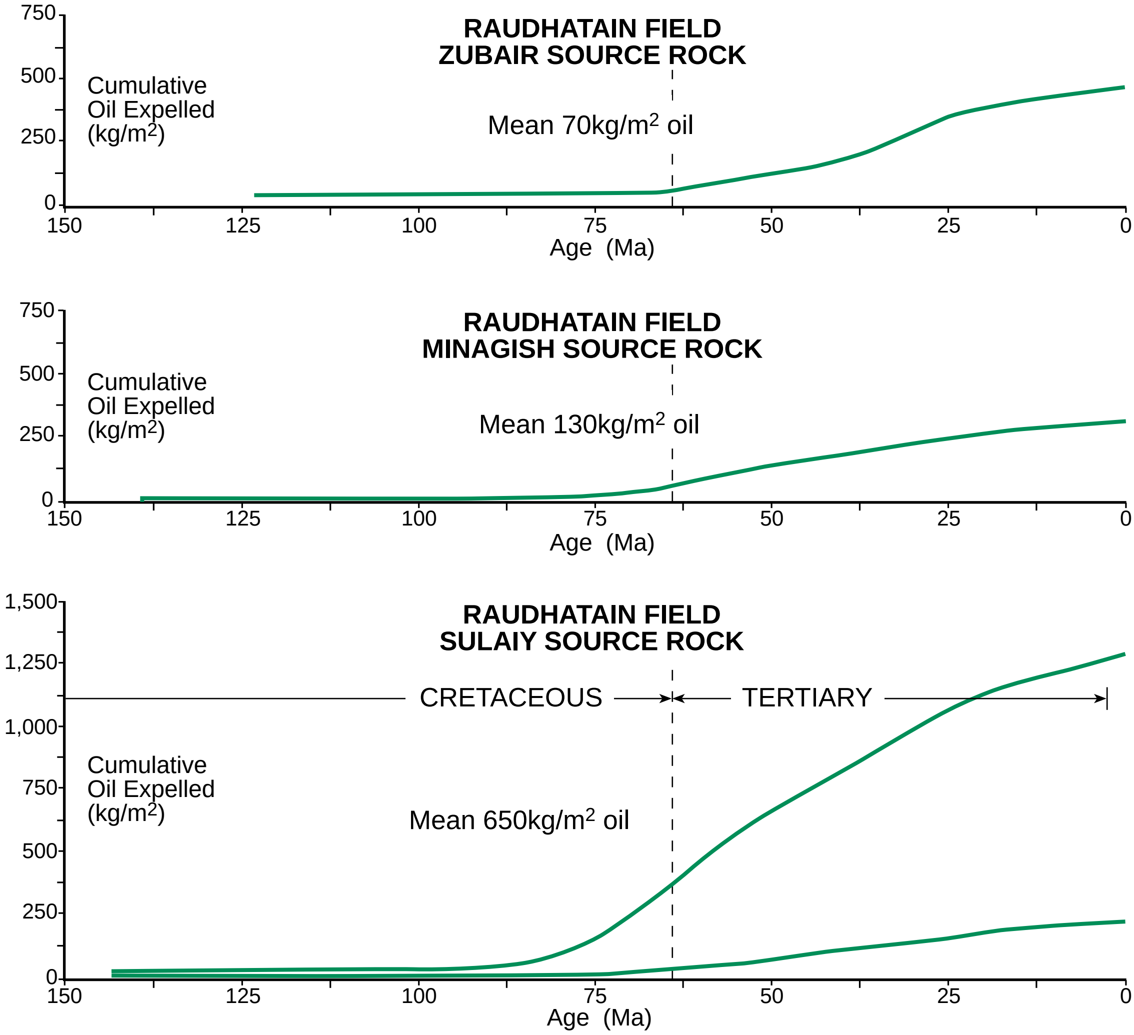



**Figure 6: Numerical measurements for the cumulative oil expelled by the three main Cretaceous source rocks.**

(Figure 4). These occurred during the Paleocene and Oligocene, and are the result of the Zagros mountain building. Note that the Sulaiy has only expelled 25% of its generated oil.

Although the structural traps in the area started growing at different times (Table 4), the Zagros movements rejuvenated most, if not all, of them. This created new traps and possible migration paths from the deep Sulaiy Formation to the shallow Cretaceous reservoirs.

Calculations of the cumulative oil expelled from the three sources rocks are shown in Table 5 and Figure 6. The volumes are based on the assumption of a 150 m average thickness for the Minagish and Sulaiy formations. The 150 m average thickness for the Zubair Formation represents only the shaly facies. The average cumulative oil expelled from the Sulaiy Formation reached 780 million $m^3/km^2$, from the Minagish 156 million $m^3/km^2$ and from the Zubair 84 million $m^3/km^2$. Therefore the Sulaiy Formation is the most productive source rock in the studied geologic section in Kuwait.

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