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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.

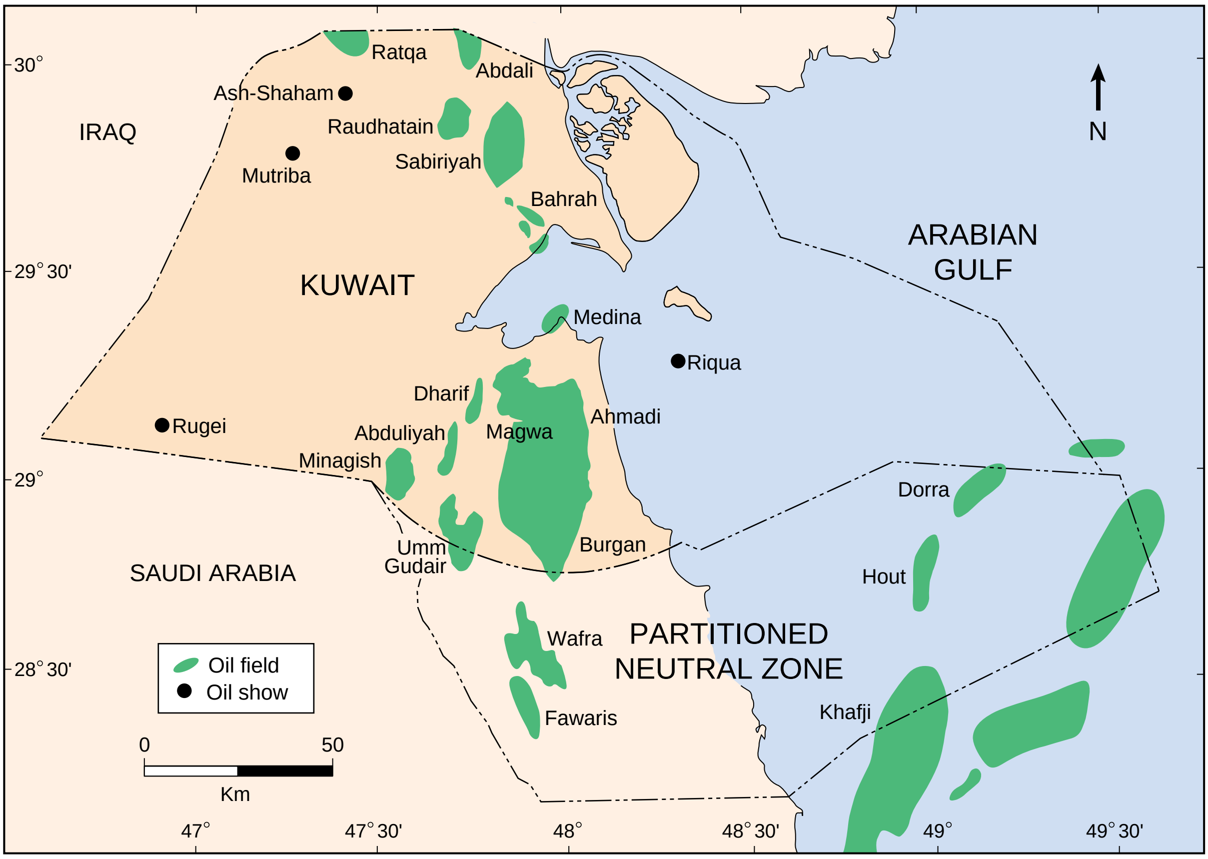


Figure 1: Kuwait oil fields produce mostly from Cretaceous reservoirs. Rock samples from wells in Ash-Shaham, Minagish and Raudhatain onshore and offshore Riqua locations were used in this study. The four locations share a similar geologic setting.

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).

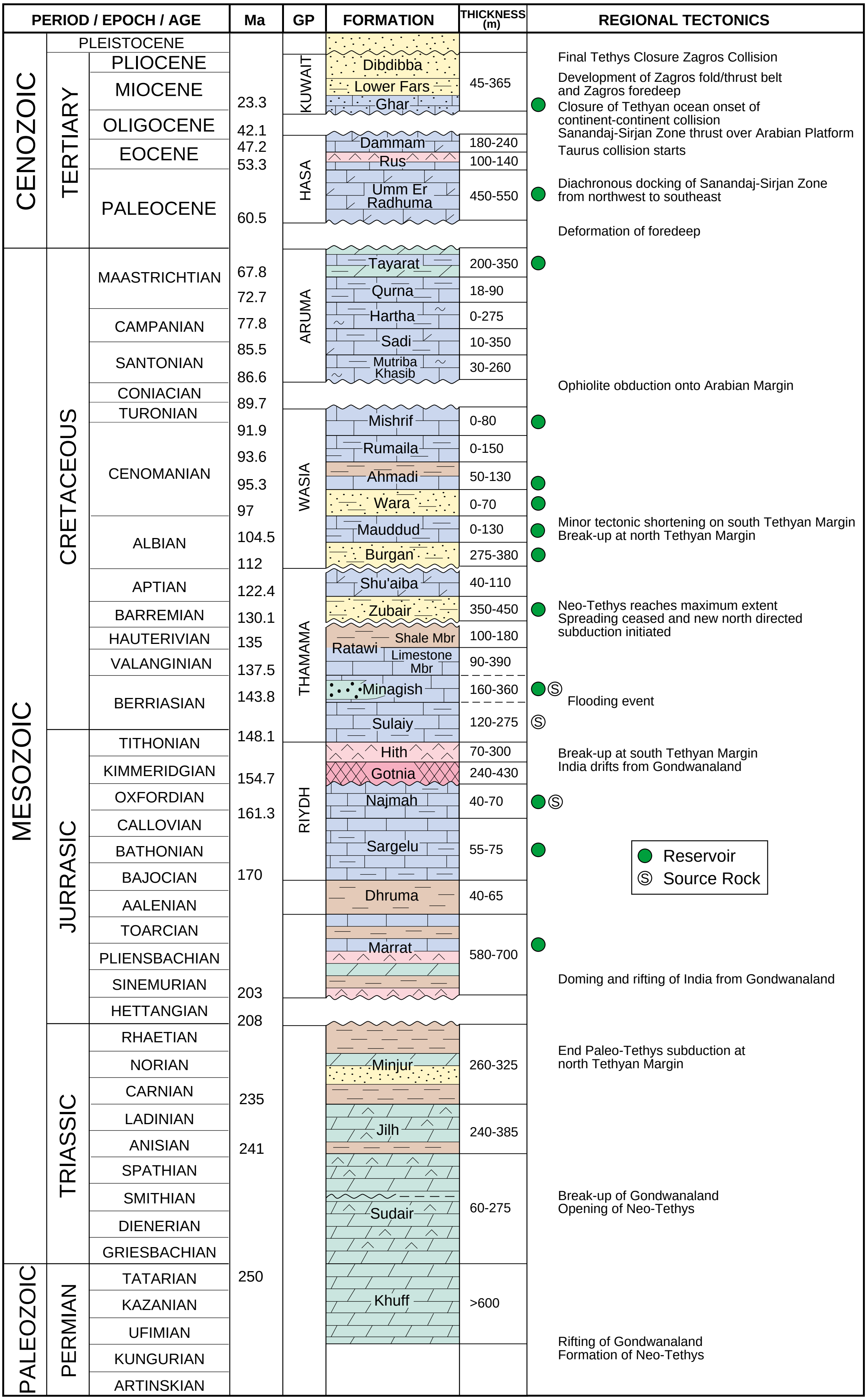
Murris (1980) suggested that the Cretaceous oil in Kuwait's largest field, Burgan (Figure 1), may have migrated laterally from the Luristan Basin in Iran. The potential source rock is the Middle Cretaceous Kazhdumi Formation (Ala, 1979; Beydoun, 1993).

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
23.3
42.1
47.2
53.3
60.5
KUWAIT
Dibdibba
Lower Fars
Ghar
45-365
HASA
Dammam
Rus
Umm Er Radhuma
180-240
100-140
450-550
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
MESOZOIC
CRETACEOUS
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
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
ARUMA
Tayarat
Qurna
Hartha
Sadi
Mutriba
Khasib
200-350
18-90
0-275
10-350
30-260
Ophiolite obduction onto Arabian Margin
WASIA
Mishrif
Rumaila
Ahmadi
Wara
Mauddud
Burgan
0-80
0-150
50-130
0-70
0-130
275-380
Minor tectonic shortening on south Tethyan Margin
Break-up at north Tethyan Margin
THAMAMA
Shu'aiba
Zubair
Ratawi
Shale Mbr
Limestone Mbr
Minagish
Sulaiy
40-110
350-450
100-180
90-390
160-360
120-275
Neo-Tethys reaches maximum extent
Spreading ceased and new north directed subduction initiated
Flooding event
JURRASIC
TITHONIAN
KIMMERIDGIAN
OXFORDIAN
CALLOVIAN
BATHONIAN
BAJOCIAN
AALENIAN
TOARCIAN
PLIENSBACHIAN
SINEMURIAN
HETTANGIAN
154.7
161.3
170
203
208
RIYDH
Hith
Gotnia
Najmah
Sargelu
Dhruma
Marrat
70-300
240-430
40-70
55-75
40-65
580-700
Break-up at south Tethyan Margin
India drifts from Gondwanaland
Reservoir
Source Rock
Doming and rifting of India from Gondwanaland
TRIASSIC
RHAETIAN
NORIAN
CARNIAN
LADINIAN
ANISIAN
SPATHIAN
SMITHIAN
DIENERIAN
GRIESBACHIAN
235
241
250
Minjur
Jilh
Sudair
260-325
240-385
60-275
End Paleo-Tethys subduction at north Tethyan Margin
Break-up of Gondwanaland
Opening of Neo-Tethys
PALEOZOIC
PERMIAN
TATARIAN
KAZANIAN
UFIMIAN
KUNGURIAN
ARTINSKIAN
Khuff
>600
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			

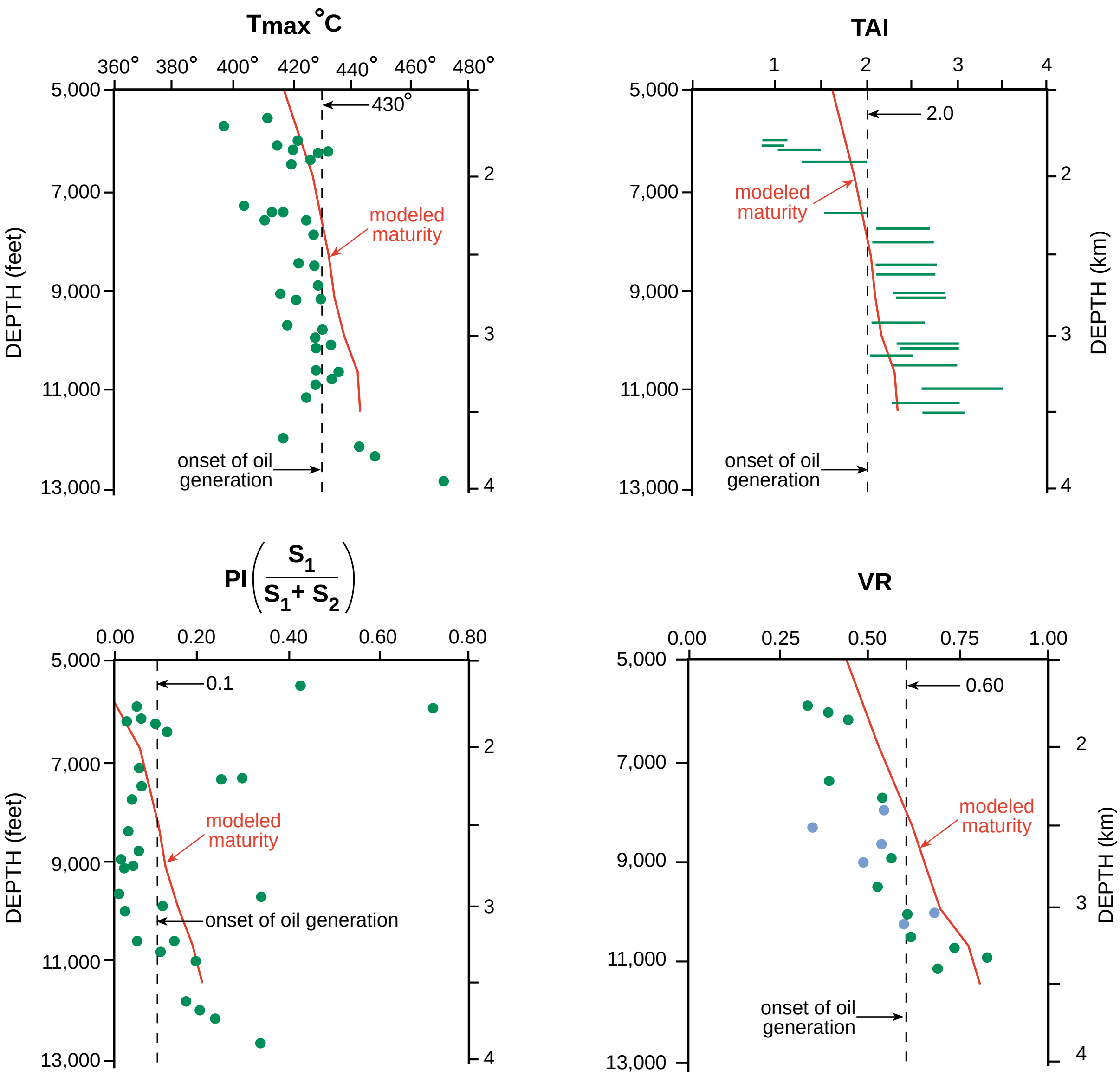


Figure 3: Maturity indicators as a function of depth. Tmax, PI and Vitrinite Reflectance (VR) are from rock samples from wells in Raudhataian and Minagish fields. The Thermal Alteration Index (TAI) is from rock samples from wells in Ash-Shaham, Minagish and Riqua. Blue dots indicate data from modeled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

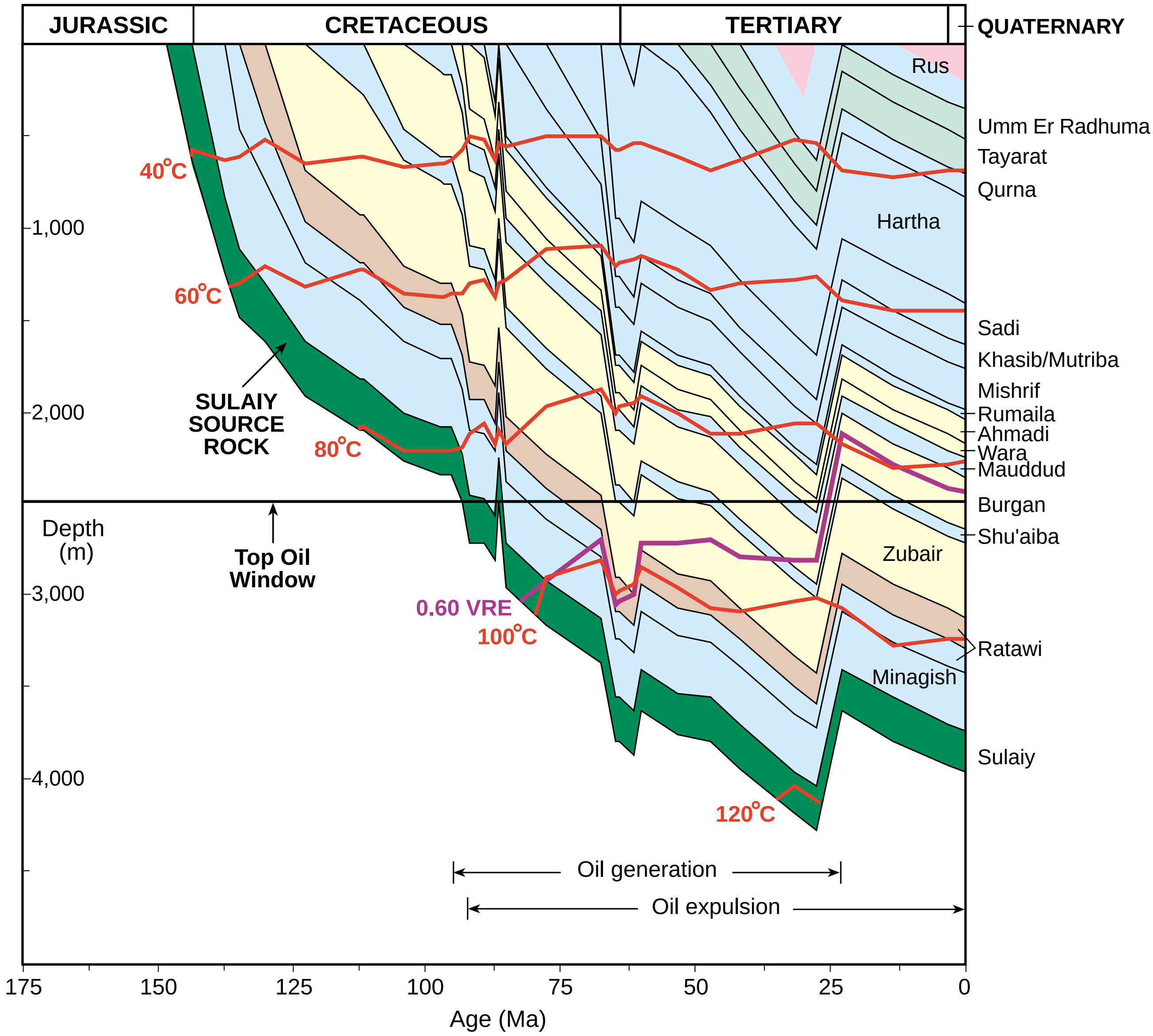


Figure 4: Decompacted burial history for the Raudhatain well. Modeling results indicate that Kuwait has been subsiding at an average rate of 25 meters/million year. The thermal model reveals that most oil generation from the Sulaiy Formation took place during the Late Cretaceous and Early Tertiary, while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

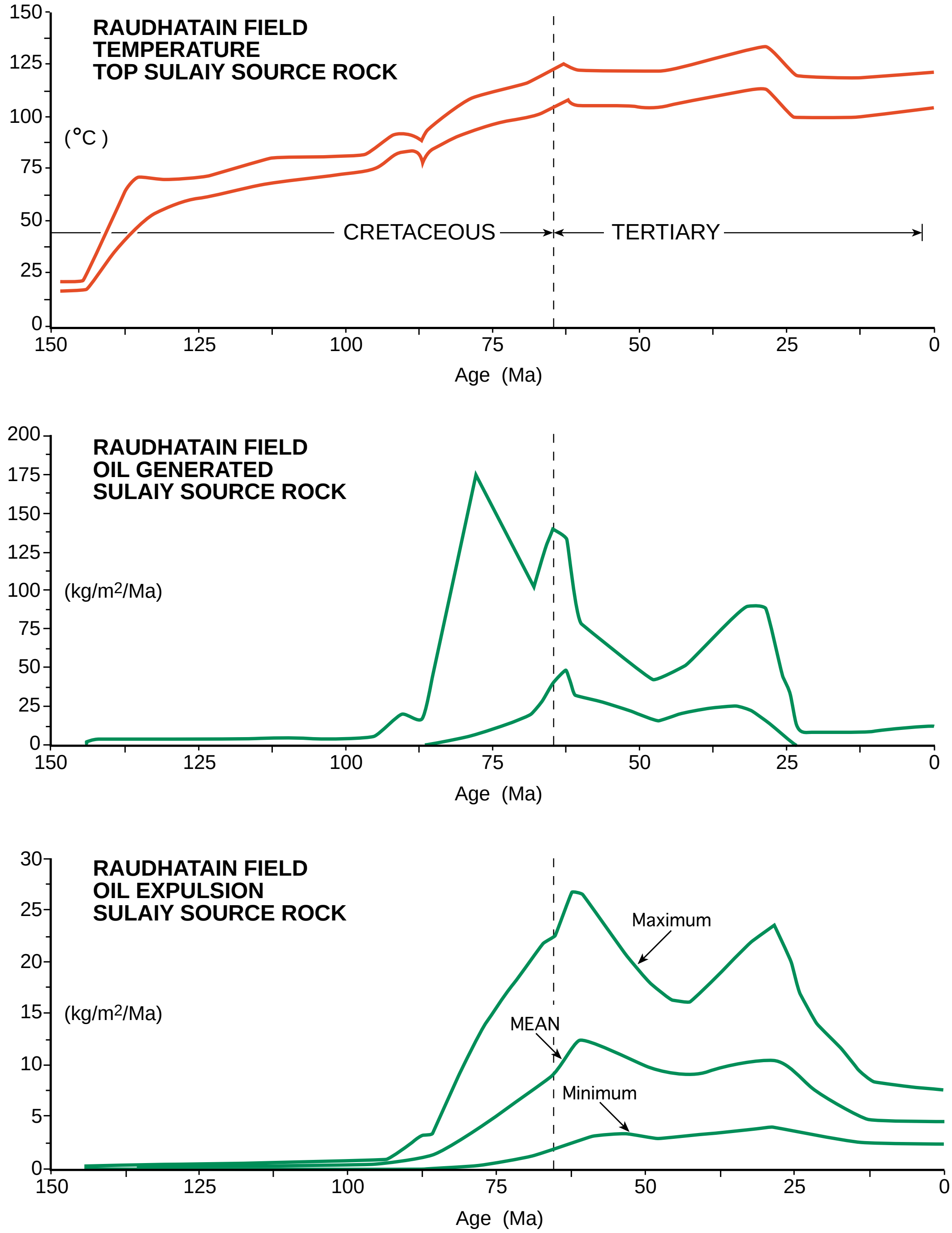


Figure 5: The Sulaiy Formation reached its peak oil generation in Late Cretaceous (75 Ma) when it was at a temperature of 100°C and a depth of 3,000 m (Figure 4). The Sulaiy Formation reached its peak expulsion during the Paleocene (62 Ma) when the formation was at a depth of 3,750 m.

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 27:4,150	15 (3.6-33.6)	780 (240-1,560)	3,240 (1,800-4,560)

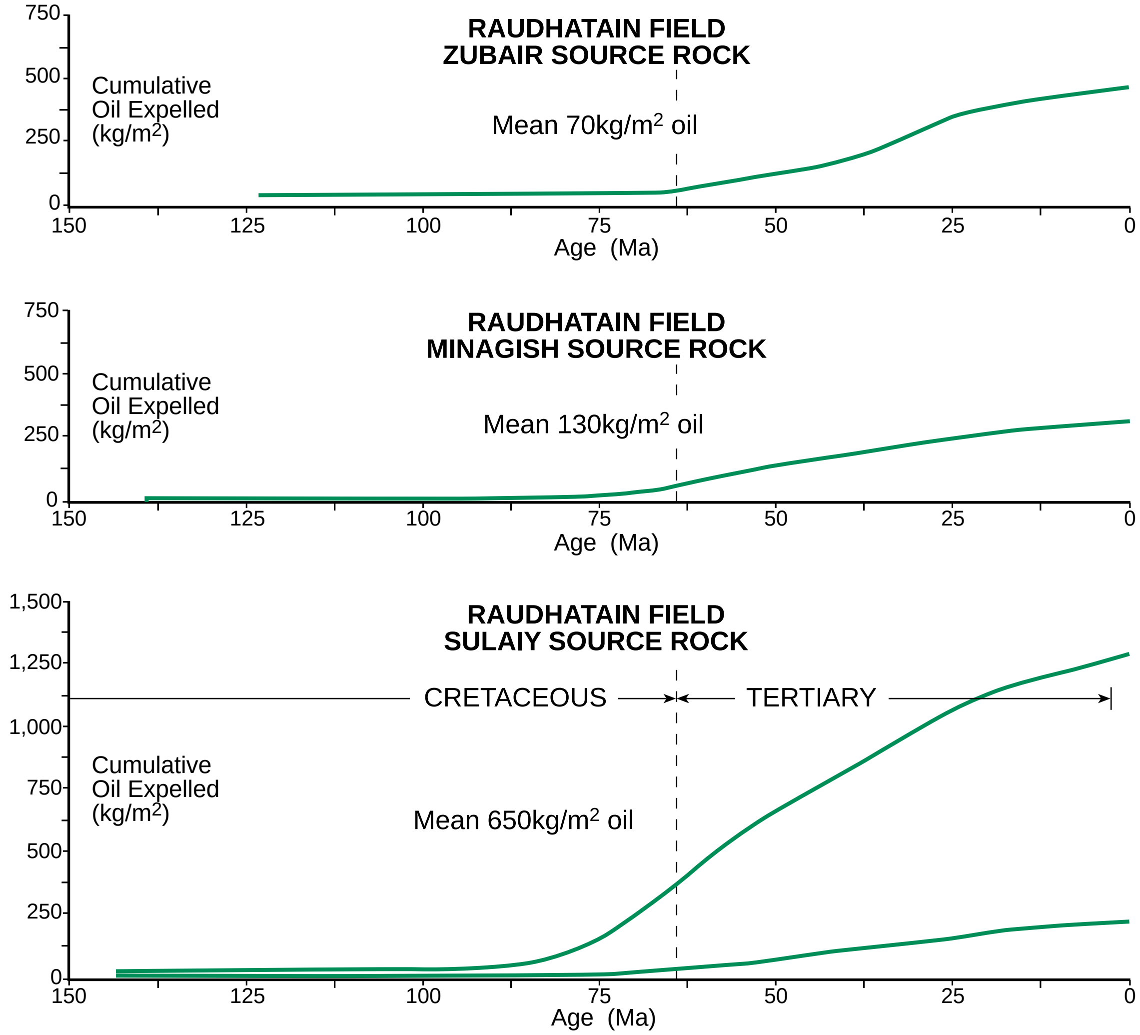


Figure 6: Numerical measurements for the cumulative oil expelled by the three main Cretaceous source rocks.

(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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