Hydrocarbon Generation Modeling of the Basrah Oil Fields, Southern Iraq*

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Summary

This paper discusses 1D (Petromod) hydrocarbon-charge modeling and source-rock characterization of the Lower Cretaceous and Upper Jurassic underlying the prolific Cretaceous and Tertiary reservoirs in the Basrah oilfields in southern Iraq. The study is based on well data of the Majnoon (Mj), West Qurna (WQ), Nahr Umr (NR), Zubair (Zb), and Rumaila (R) oil fields. Burial histories indicate complete maturation of Upper Jurassic source rocks during the Late Cretaceous to Paleogene followed by very recent (Neogene) maturation of the Low/Mid Cretaceous succession from early to mid-oil window conditions, consistent with the regional Iraq study of Pitman et al. (2004). These two main phases of hydrocarbon generation are synchronous with the main tectonic events and trap formation associated with Late Cretaceous closure of the neo-Tethys; the onset of continent-continent collision associated with the Zagros orogeny and Neogene opening of the Gulf of Suez / Red Sea.

Palynofacies of the Lower Cretaceous Sulaiy and Lower Yamama formations and of the Upper Jurassic Najmah/Naokelekan formations confirm their source rock potential, supported by pyrolysis data. To what extent the Upper Jurassic source rocks contributed to charge of the overlying Cretaceous reservoirs remains uncertain because of the stratigraphically intervening Upper Jurassic Gotnia evaporite seal. The younger Cretaceous rocks do not contain source rocks nor were they buried deeply enough for significant hydrocarbon generation.

Introduction

The Basrah region in southeast Iraq is well known for its giant oil fields. It is situated in what is known as the Mesopotamian Basin near the eastern edge of the Arabian plate (Figure 1). The Mesopotamian Basin is the NW-trending foredeep to the Zagros fold and thrust belt that formed in response to the continental collision of the Arabian and Eurasian plates. Collision started during the Late Cretaceous and increased in intensity during the Paleogene/Neogene (Beydoun et al., 1992). The Mesopotamian Basin is relatively unaffected. Deformation increases in intensity from west to east, towards the Zagros Mountains. The fields in the Basrah region occur along N-S trending folds in the southern part of the basin (Figure 2). N-S striking, basement-cored anticlines in this part of the basin began forming in the Paleozoic, with continued but with more limited growth throughout the Mesozoic and Early Cenozoic. At least some of the structures may be related to salt diapirism of the Precambrian to Cambrian Hormuz Formation (Al Sharhan and Nairn, 1997; Sharland et al., 2001, and Jasim and Goff, 2005).

The Jurassic and the Cretaceous of the Arabian plate host the most prolific hydrocarbon systems in the world. Widely developed platform and basinal carbonates separated by a thick evaporite unit (the Upper Jurassic Gotnia Formation) provide multiple source-rock, reservoir, and seal combinations. In combination with the subsequent development of a large foredeep with deep burial, and Zagros tectonics, this creates the right ingredients and timing for late source-rock maturation, large-scale structural development, and hydrocarbon entrapment.

The lithostratigraphy of the Jurassic to Lower Cretaceous in Iraq was first described by van Bellen et al. (1959, 2005). Aqrawi et al. (2010) provide a detailed compilation of the stratigraphy, structural geology, and petroleum systems. The regional basin modeling study by Pitman et al. (2004) provides a good framework for this study while the main oil source rocks for this region were assessed by Al-Ameri et al. (1999, 2009) and Abeed et al. (2011) to be mainly of Upper Jurassic-Lower Cretaceous Sulaiy Formation with some other sources of Middle Jurassic Sargelu Formation (Al-Ameri et al., 2011) and Lower Cretaceous Zubair Formation (Al-Ameri and Batten, 1997). Figure 3 provides a summary of the stratigraphy of the region from the Late Jurassic to the Neogene.

Figure 1. Location map of Iraq showing northeast Arabian Peninsula, with locations of basins and oil fields.

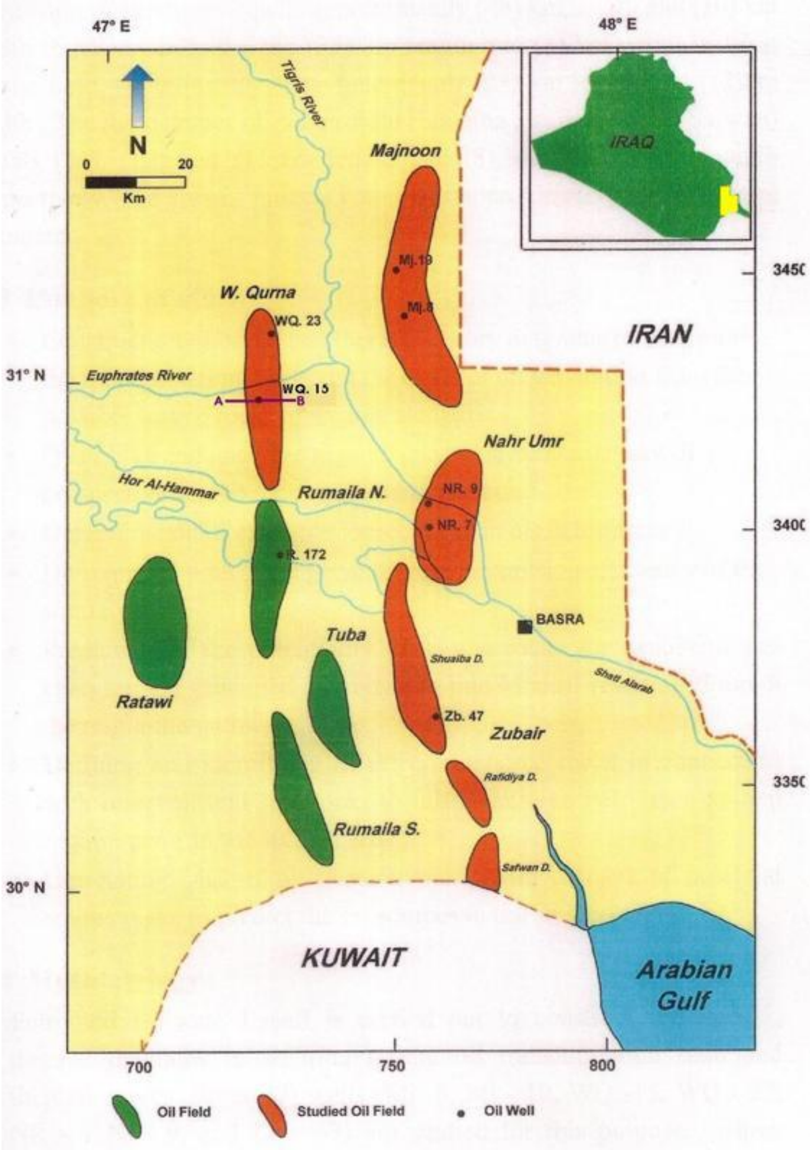


Figure 2. South Iraq with locations of the oil fields and wells used in this study. A-B is line of seismic section.

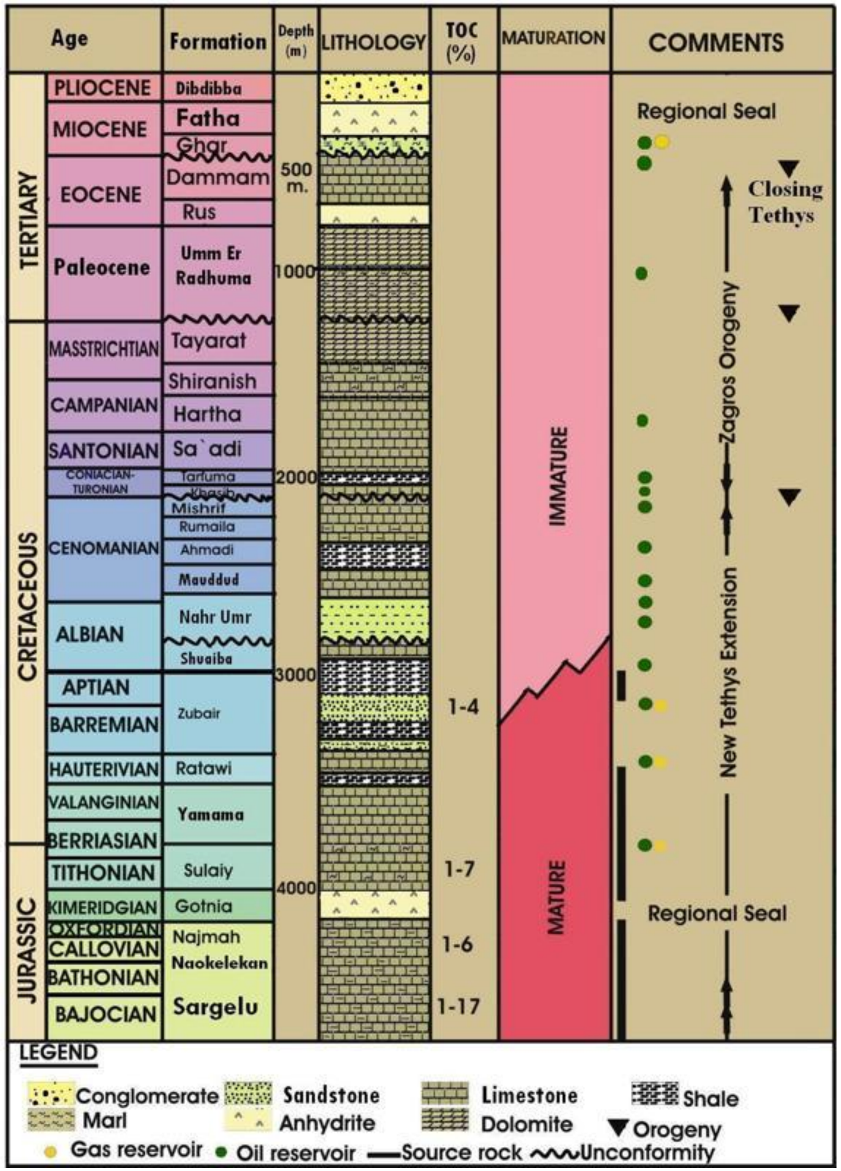


Figure 3. Stratigraphic column of South Iraq, Basrah region (Rumaila and Zubair oil fields), showing key source rocks, seals, and structural events.

Method and Data

1D Petromod (Schlumberger / Aachen Technology Centre) was used to model the burial history of wells of the Majnoon, West Qurna, Nahr Umr, Zubair, and Rumaila fields. Input data (Tables 1, 2, 3, and 4) comprise formation depths and associated numerical ages, ideologies, and formation temperatures of wells Mj-8 and Mj-19 (Majnoon Field), WQ-15 and WQ-23 (West Qurna Field), NR-7 and NR-9 (Nahr Umr Field), Zb-40 and Zb-47 (Zubair Field) and R-172 (Rumaila Field). The ages of depositional and erosional events were designated, based on the geologic time scale of Sharland et al. (2001). Lithologies are modeled as end-member rock types or as compositional mixtures of rock types assigned to each unit, using software default parameters of Pitman et al. (2004).

Core-rock samples for source-rock characterization and palynofacies assessment were taken from wells R-172 (Rumaila North Field) and WQ-1 (West Qurna Field) for the Upper Jurassic Najmah/Naokelekan, Sargelu, Upper Jurassic to Lower Cretaceous Sulaiy, and Lower Cretaceous Ratawi and Zubair Formations. Palynological analysis was done in the department of geology, College of Science, University of Baghdad, where the samples are stored. Source-rock pyrolysis was done by Geomark Research Ltd in Houston-Texas.

1D Petromod requires calibration of the thermal regime at each model location, based on crustal heat-flow parameters, calculated thermal conductivities of the rock succession and burial history tied to present-day surface and subsurface temperatures (Pitman et al., 2004). Type IIS kerogen kinetics were used for source-rock maturation because extracts of the kerogen for the Jurassic and Lower Cretaceous source rocks have considerable amounts of Sulfur (NSO=1-34%).

Table 1. Formation tops and temperature of well Mj-8 and Mj-19 at Majnoon oil field.

Formation	*(Mj – 8) RTKB=14.28m*	*(Mj -19), RTKB=11.8m*	*Temp. (^oC)*	*Comment*						
	Depth (m)	*Thickness (m)*	*Depth (m)*	*Thickness (m)*						
	From	*To*		*From*	*To*					
Hammer	12	54	42							
Dibddiba	54	895	841							
Fatha(L. Fars)	895	1186	291	983	1279	296		●		-
Ghar	1186	1317	131	1279	1415	136	51.6	●		
Damman	1317	1524	207	1415	1584	169				
Umm Er Rad.	1524	1836	312	1584	1920	336				
Aaliji	1836	1964	128	1920	1955	35			■	
Shiranish	1964	2106	142	1955	2113	158				
Hartha	2106	2237	131	2113	2209	96	78.8	●		
Sadi	2237	2349	112	2209	2297	88		●		
Tanuma	2349	2395	46	2297	2338	41			■	
Khasib	2395	2452	57	2338	2390	52	87.2	●		
Mishrif	2452	2704	252	2390	2626	236	80.5	●		
Rumaila	2704	2712	8	2626	2640	14				
Ahmadi	2712	2881.5	169.5	2640	2810	170	97.7	●		
Mauddud	2881.5	3063	181.5	2810	2985	175				
Nahr Umr	3063	3247	184	2985	3166	181	107.7	●	■	
Shuaiba	3247	3391	144	3166	3325	159		●		
Zubair	3391	3691.5	300.5	3325	3615	290	118.8	●	■	
Ratawi	3691.5	3754	62.5	3615	3697	82				-
Yamama	3745	4126	481	3697				●		
Sulaiy	4126								■	

● Reservoir rock unit ■ Source rock unit - Seal rock unit

Table 2. Formation tops and temperature of well WQ-15 and WQ-23 at West Qurna oil field.

Formation	*(WQ - 15) RTKB=11.1 m*	*(WQ -23), RTKB=8.39m*	*Temp. (°C)*	*Comment*						
	Depth (m)	*Thick-ness (m)*	*Depth (m)*	*Thick-ness (m)*						
	From	To		*From*	*To*					
Dibddiba	230	413	183	296	509	213				
Fatha (L. Fars)	413	831	418	509	937	428		●		-
Ghar	831	915	84	937	1055	118		●		
Damman	915	1161	246	1055	1281	226				
Rus	1161	1168	7	1281	1283	2				
Umm Er Rad.	1168	1631	463	1283	1787	504				
Tayarat	1631	1751	120	1787	1935	148				
Shiranish	1751	1862	111	1935	2069	134				
Hartha	1862	2037	175	2069	2254	185		●		
Sadi	2037	2170.5	133.5	2254	2378.5	124.5	78.3	●		
Tanuma	2170.5	2213	42.5	2378.5	2426.5	48			■	
Khasib	2213	22705	575	2426.5	2492	65.5		●		
Mishrif	2270.5	2425	154.5	2492	2736	244	71.6	●		
Rumaila	2425	2513	88	2736	2781	45				
Ahmadi	2513	2648.5	135.5	2781	2950	169		●		
Mauddud	2648.5	2781	132.5	2950	3114	164				
Nahr Umr	2781	2991	210	3114	3342	228		●	■	
Shuaiba	2991	3081	90	3342	3443	101		●		
Zubair	3081	3420.5	339.5	3443	3822	379	104.4	●	■	-
Ratawi	3420.5	3529	108.5	3822	3952	130			■	
Yamama	3529	3852.5	323.5	3952	4304	352	104.4	●		
Sulaiy	3852.5	4120	267.5	4304					■	
Gotnia	4120	4400	208							-
Najmah	4400		171 +					●		

● Reservoir rock unit ■ source rock unit - seal rock unit

Table 3. Formation tops and temperature of well NR-7 and NR-9 at Nahr Umr oil Field.

Formation	*(NR - 7), RTKB=11.4m*	*(NR -9), RTKB=11.4m*	*Temp. (^oC)*	*Comment*						
	Depth (m)	*Thickness (m)*	*Depth (m)*	*Thickness (m)*						
	From	*To*		*From*	*To*					
Dibddiba				65	541	476				
Fatha (L. Fars)	330	749	419	541	854.6	313.5		●		-
Ghar	749	868	119	854.6	957	102.5		●		
Damman	868	1146.5	278.5	957	1333.5	376.5				
Umm Er Rad.	1146.5	1556	409.5	1333.5	1733	399.5				
Tayarat	1556	1700.5	144.5	1733	1847	114				
Shiranish	1700.5	1862	161.5	1847	2005	158				
Hartha	1862	1981	119	2005	4142	137		●		
Sadi	1981	2113.5	132.5	2142	2360	218		●		
Tanuma	2113.5	2123	9.5	2360	2390	30			■	
Khasib	2123	2184.5	61.5	2390	2461	71		●		
Mishrif	2184.5	2375	190.5	2461	2720	259		●		
Rumaila	2375	2384	9	2720	2728	8				
Ahmadi	2384	2484.5	100.5	2728	2872	144		●		
Mauddud	2484.5	2604	119.5	2872	3024	152				
Nahr Umr	2604	2816	212	3024	3218	194	90	●	■	
Shuaiba	2816	2933.5	117.5	3218	3353	135		●		
Zubair	2933.5	3218	284.5	3353	3654	301	121	●	■	-
Ratawi	3218	3308	90	3654	3741	87			■	
Yamama	3308	3668	360	3741	4113	372	115.5	●		
Sulaiy	3668		10+	4113		228+				

● Reservoir rock unit ■ source rock unit - seal rock unit

Table 4. Formation tops and temperature of well Zb-47 at Zubair oil field.

Formation	*(Zb – 47) RTKB=21.2m*	*Temp. (^oC)*	*comment*				
	Depth (m)	*Thickness (m)*					
	From	*To*					
Fatha (L. Fars)	292.5	472	179.5		●		-
Ghar	472	624.9	152.9		●		
Damman	624.9	849	224.1	41.1			
Rus	849	990	141				
Umm Er Rad.	990	1440	450				
Tayarat	1440	1655	215				
Shiranish	1655	1794	139				
Hartha	1794	1959	165		●		
Sadi	1959	2284.4	325.4	63.3	●		
Tanuma	2284.4	2324	39.6			■	
Khasib	2324	2380.8	56.8		●		
Mishrif	2380.8	2549	168.2		●		
Rumaila	2549	2652	103				
Ahmadi	2652	2818	166		●		
Mauddud	2818	2959	141				
Nahr Umr	2959	3291	332		●	■	
Shuaiba	3291	3344.5	53.5		●		
Zubair	3344.5	3725	380.5		●	■	-
Ratawi	3725	3872	147	90.5		■	
Yamama	3872	4258	386		●		
Sulaiy	4258	4510	252			■	
Gotnia	4510		15+	121			

● Reservoir rock unit ■ source rock unit - seal rock unit

Model Results

Figure 4 shows the burial and modeled thermal history of WQ-15 as an example. Model results indicate that Late Cenozoic uplift and erosion was minimal (less than 500m) in this region. Additional sensitivity tests also indicate that the poorly constrained Mesozoic uplift and erosion, although locally intense, had little impact on the Jurassic source rock maturation history.

The modeled vitrinite reflectance (Sweeney and Burnham, 1990), as a measure of thermal maturity, indicate that sediments younger than the Shuaiba Formation remain immature (sensu Tissot and Welte, 1984), whereas the Zubair and deeper formations reached thermal maturity. Modeled organic-matter (type IIS) transformation ratio's (following Lewan and Ruble, 2002 and Peter et al., 2005), defined as the ratio between measured hydrocarbon potential of a rock sample divided by the original hydrocarbon potential, are shown in Figurea 5a, 5b, and 5c. Transformation started in the Late Cretaceous and reached its maximum in the recent Neogene. Organic transformation is complete (TR>0.95, T=120-140°C) for the Jurassic and Lower Cretaceous rocks up to lower part of Zubair Formation in well Mj-8 of the Majnoon field (Figure 5a), to the middle part of Yamama Formation in well WQ-15 of the West Qurna field (Figure 5b), and up to lowest part of Ratawi Formation in well Zb-47 of the Zubair field (Figure 5c). The models show partial organic transformation (0.5<TR<0.95, T = 100-120°C) for sediments of the upper part of Zubair to lower part of Nahr Umr Formation in well Mj-8 (Figure 5a), the upper part of Yamama to lower part of Zubair Formation in well WQ-15 (Figure 5b), and to the Ratawi and Zubair formations in well Zb-57 (Figure 5c). Onset of organic transformation (0.01<TR<0.5, T=90-100°C) applies to the upper part of Nahr Umr to lower part of Mishrif Formation in well Mj-8 (Figure 5a), the upper part of Zubair to Mauddud Formation in well WQ-15 (Figure 5b), and Shuaiba to Mauddud Formation in well Zb-47 (Figure 5c). Figure 6a,b,c and Figure 6d,e,f shows modeled organic transformation through time for the most important stratigraphic levels in well WQ-15 of the West Qurna field.

To better evaluate the charge history in the area, a 2D seismic section was also modeled. The seismic cross section shown in Figure 7 is taken along a dip line in the West Qurna oil field (Figure 2, Line A-B), through well WQ-32, and in a strike direction near well WQ-15. The interpreted horizons of Gotnia, Yamama, Shuaiba, and Mishrif Formation levels are identified by the Iraqi Oil Exploration Company, while the other horizons are interpolated in this study from well calibration. The model is calibrated by well WQ-15 and 4 additional pseudo wells, using PetroMod 1D software.

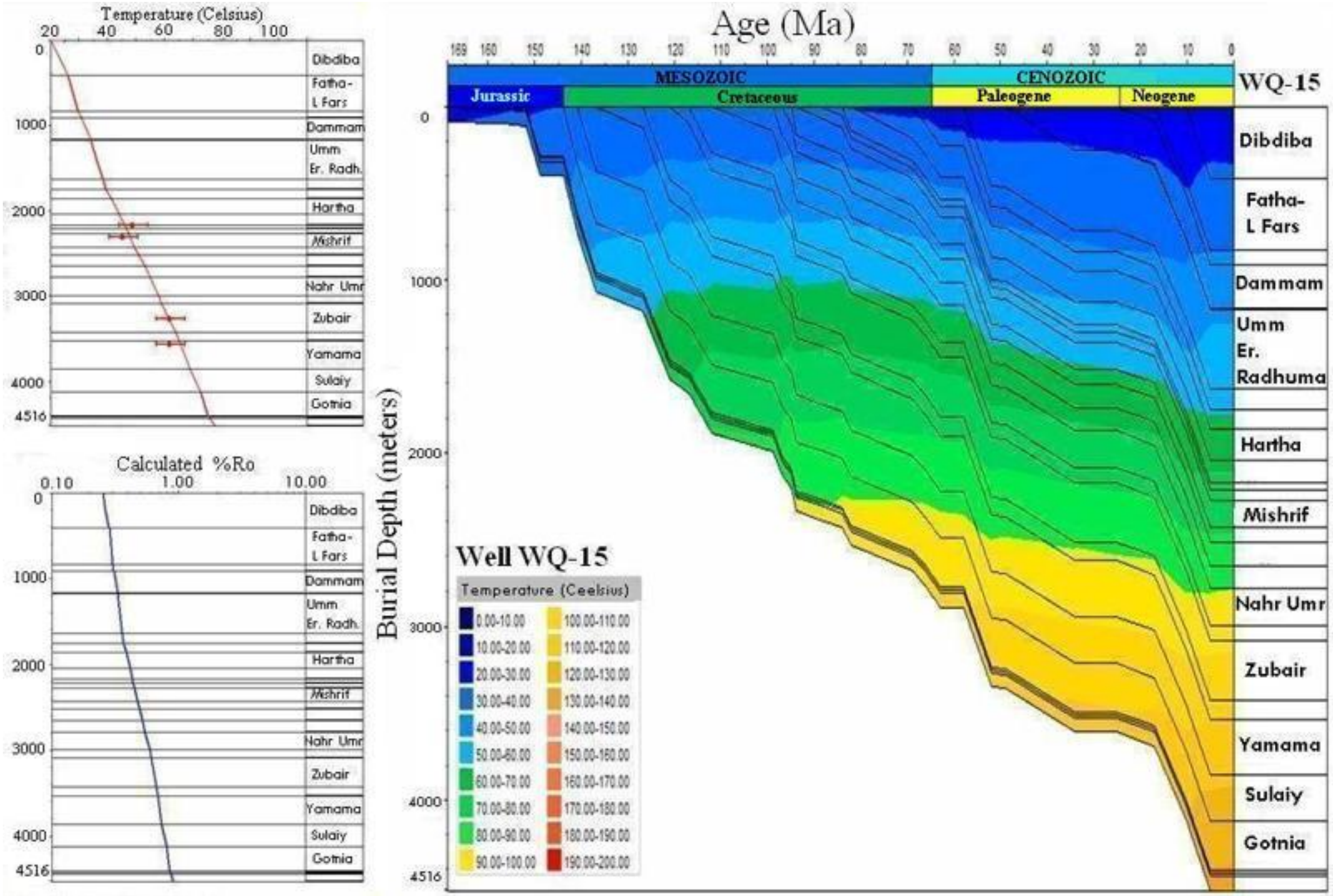


Figure 4. Thermal burial /thermal history diagram of West Qurna oil field, well WQ15.

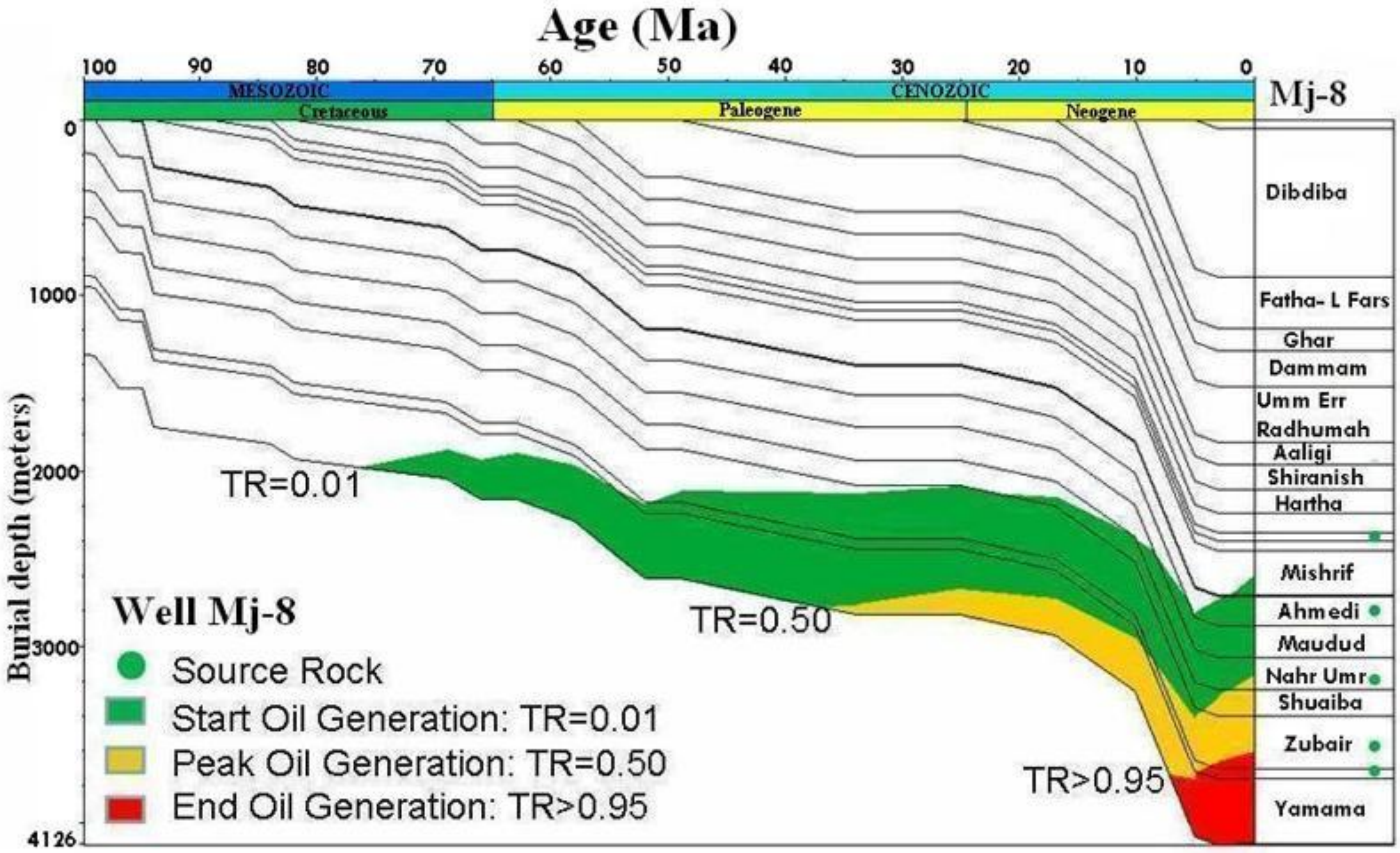


Figure 5a. Hydrocarbon transformation ratios, Majnoon oil field, well Mj-8.

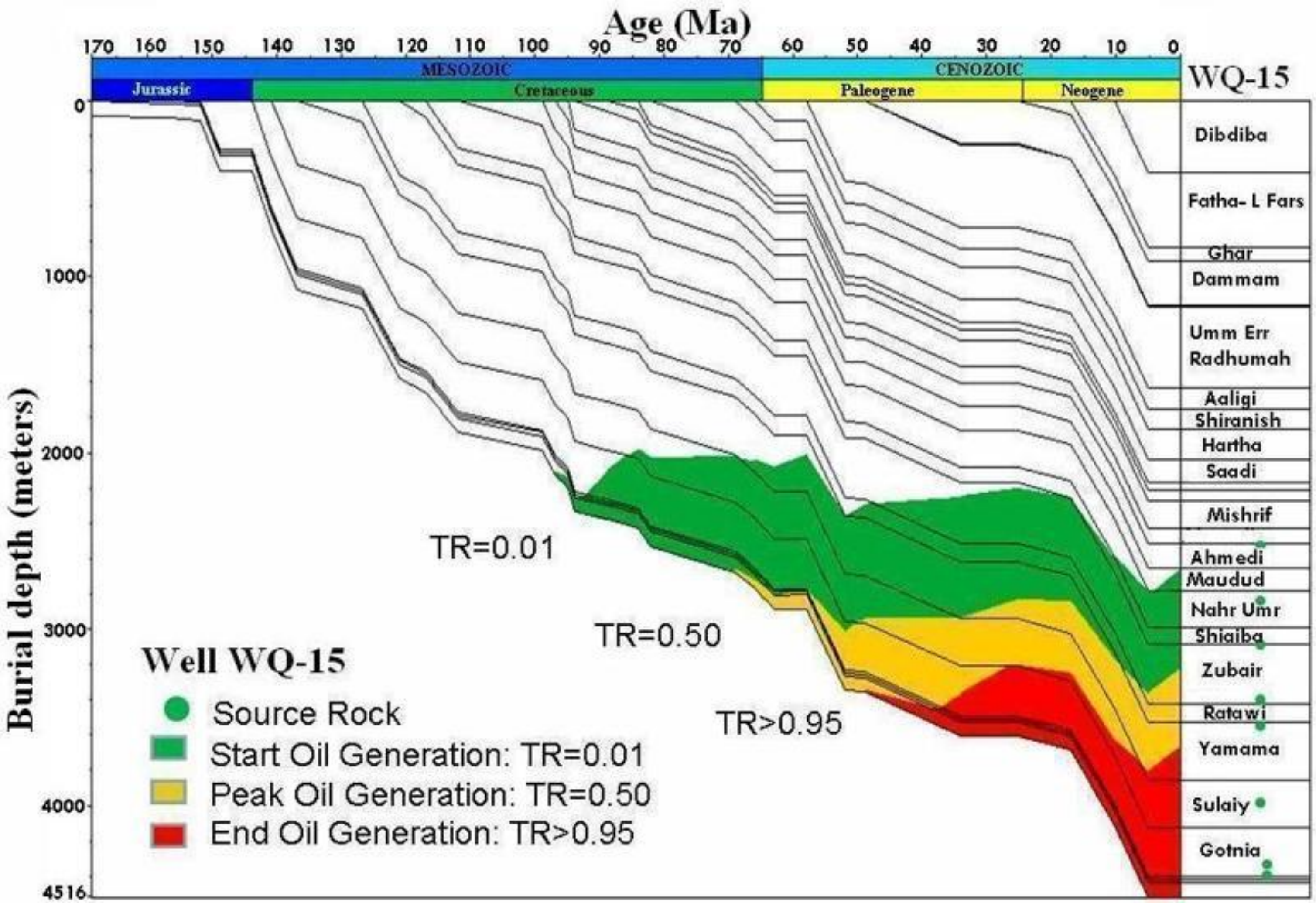


Figure 5b. Hydrocarbon transformation ratios, West Qurna oil field, well WQ-15.

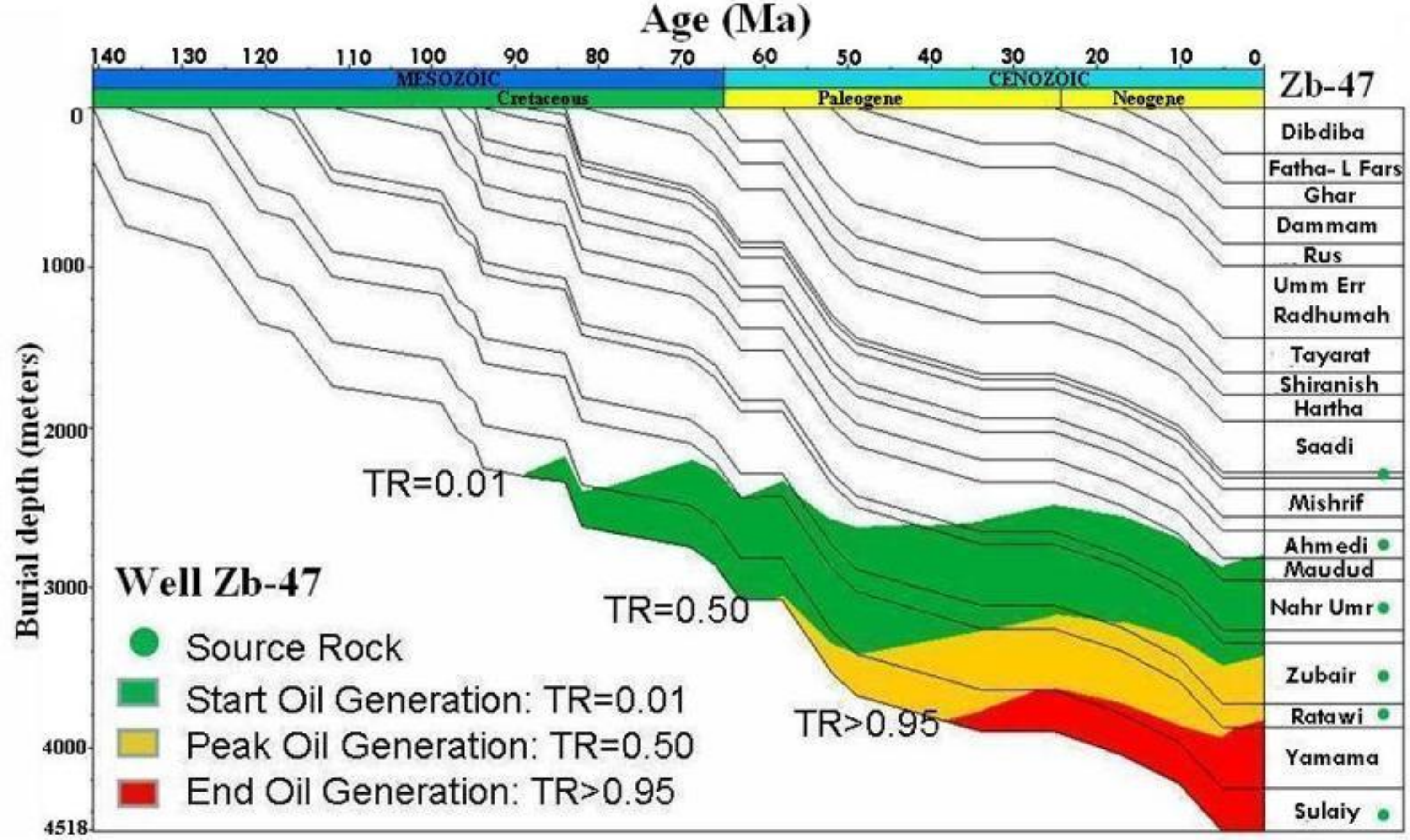
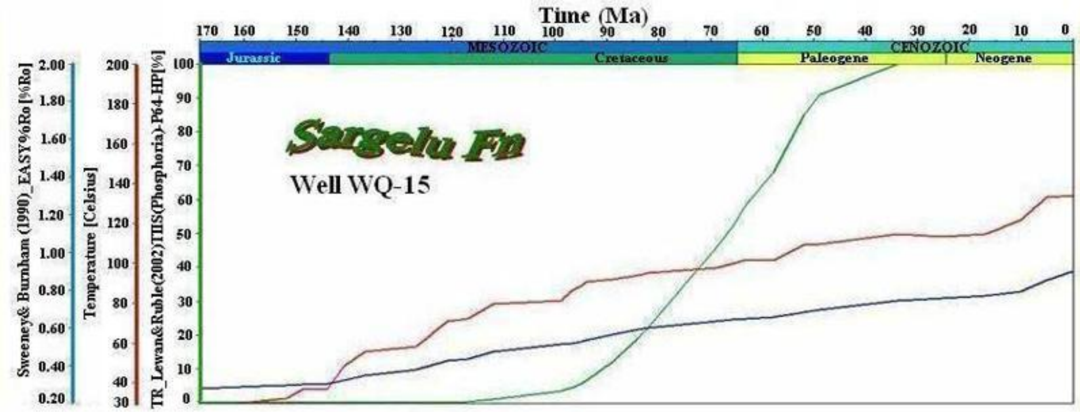
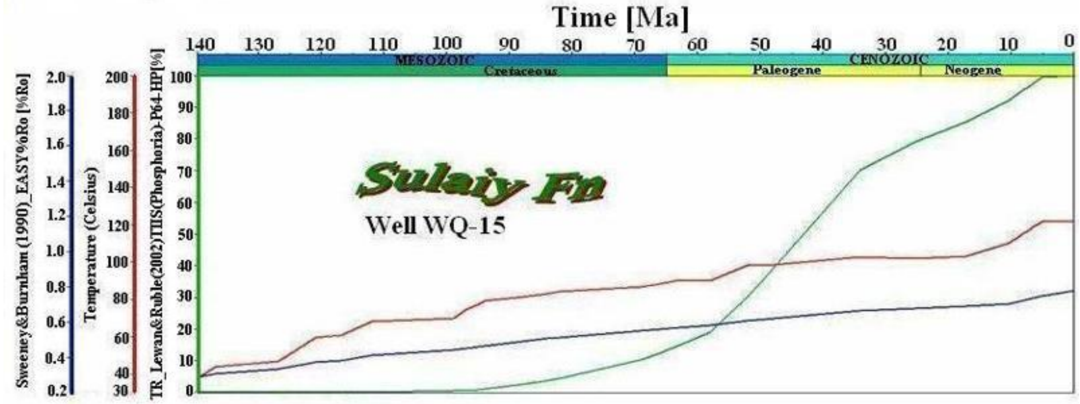


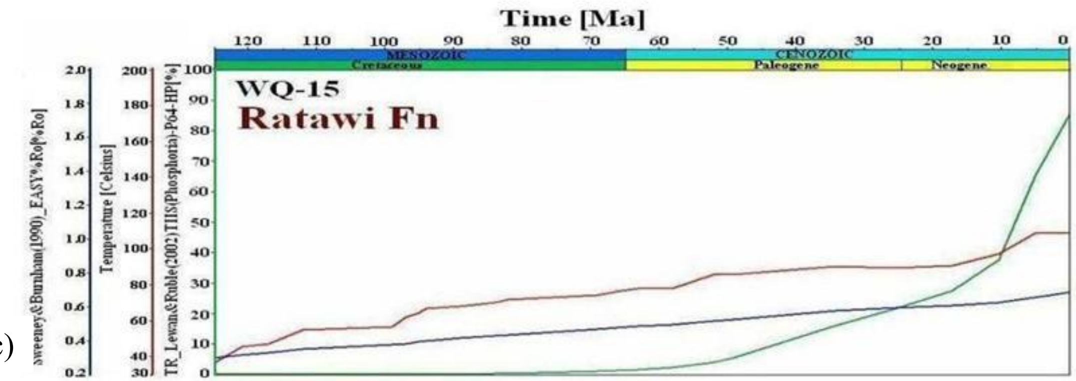
Figure 5c. Hydrocarbon transformation ratios, Zubair oil field, well Zb-47.



(a)



(b)



(c)

Figure 6a, b, c. Maturity, temperature, and transformation ratio: a. the Middle Jurassic Sargelu Formation; b. Sulaiy Formation; c. Ratawi Formation, well WQ15.

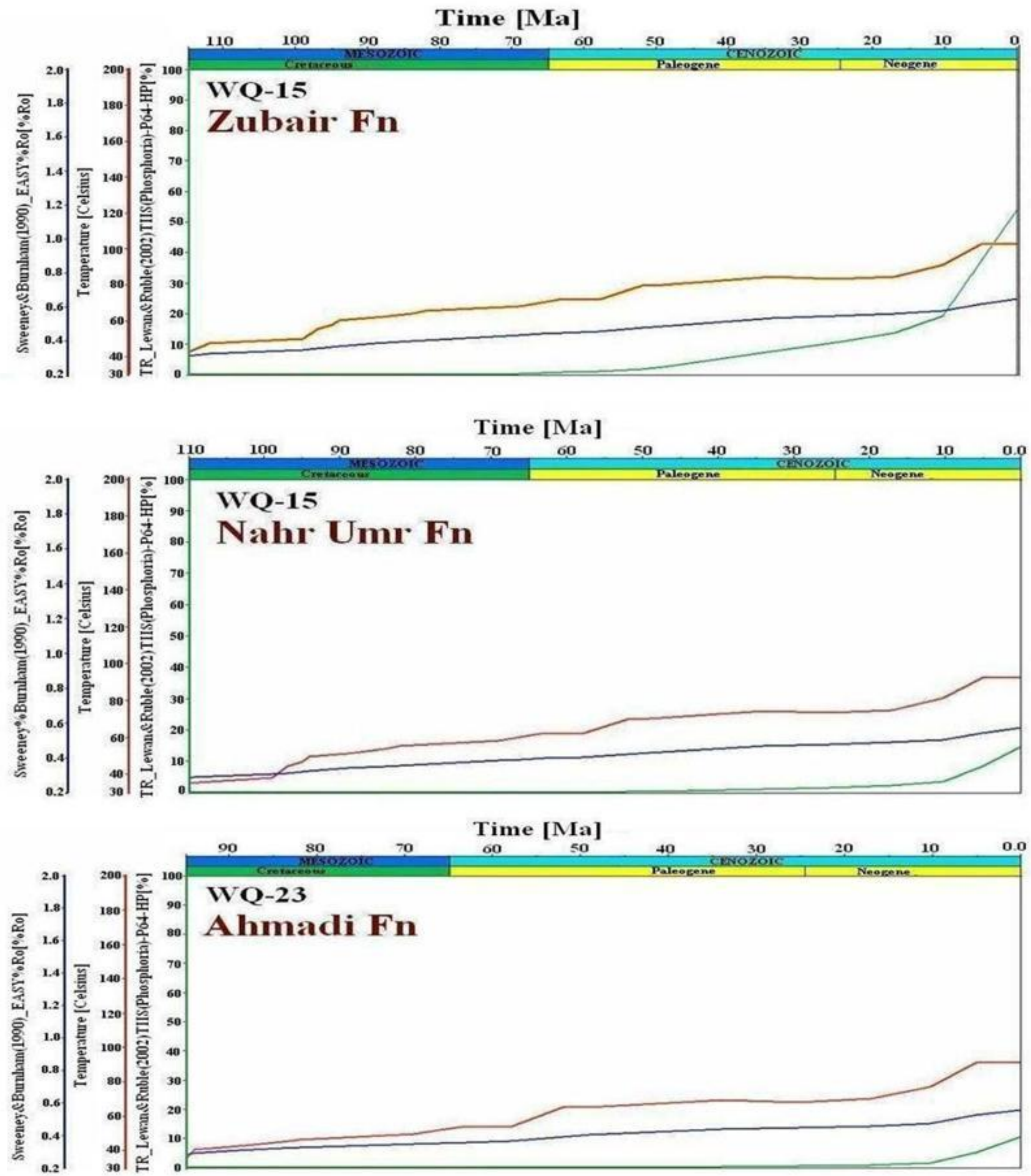
(d)
(e)
(f)


Figure 6d, e, f. Maturity, temperature, and transformation ratio: d. Zubair Formation; e. Nahr Umr Formation; f. Ahmadi Formation, well WQ15.

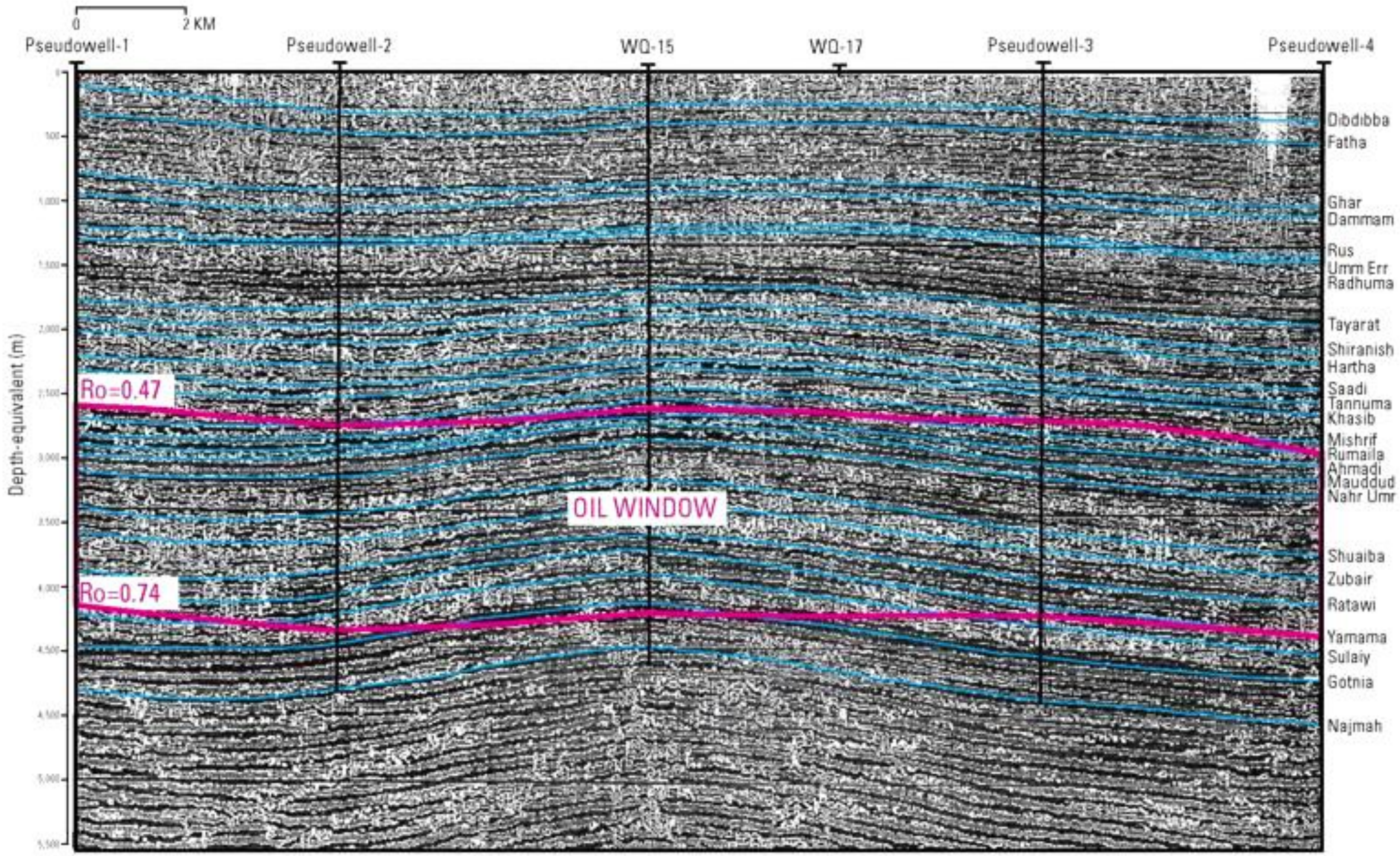


Figure 7. Seismic profile across width of West Qurna oil field passing through wells WQ-15 and WQ-17, with interpreted stratigraphic levels and calculated maturity levels. See Figure 2 of location of profile.

Palynofacies Assessments

The palynofacies assessment of this study is modified after Al-Ameri et al. (2009), identifying source rocks from palynofacies assessment and subsequently combining this information with source-rock pyrolysis data to further constrain the charge model for the area.

The rock samples were analyzed for their total organic carbon (Leco). They were also subjected to standard palynological analysis involving dissolution of the carbonate constituents with HCl and the silicates with HF to extract the disseminated organic matter of the rock samples. Slides were then prepared by strewing and sticking the organic matter for examination by light refracted microscopy. The microscopic study of the organic matter and total organic carbon (TOC) analyses are combined in the palynofacies Organolog following Tyson (1995), Bujak et al. (1977), and Batten (1996a) for paleoenviromental and hydrocarbon potential. Quantification of reworked organic material gives an indication of inert organic material (Al-Ameri, 1983; Tyson, 1995), whereas foraminifera test linings are used to assess hydrocarbon richness (Al-Ameri et al., 1996; Tyson, 1995). Combining these indications with overall organic richness (TOC) provides a good estimate of quantity and quality of organic matter and a measure of source-rock richness. Palynomorph color, following Staplin (1969; Batten, 1996b), is used for maturation assessment. Figure 8 shows one example for the Rumaila North 172 (R-172) well. The palynofacies types that have been recognized in the Jurassic Cretaceous section are described below:

Palynofacies Type IX

This palynofacies is recognized in the Lower Cretaceous Sulaiy and Upper Jurasic Najmah / Naokelekan / Sargelu formations based on samples analysed in this study. The fine-grained mudstones accumulated in distal suboxic-anoxic basins that extended across the Southern Mesopotamian Basin (Al-Ameri et al., 1999; Aqrawi et al., 2010). Their source-rock richness is up to 7 wt% total organic carbon (TOC) with mainly marine algal components and up to 100% Amorphous Organic Matter (AOM). The organic material contains approximately 10% foraminiferal test linings, with fungi, bacteria and dinoflagellate cysts (Figures 9 and 10), and reworked palynomorphs of about 1%. It is therefore highly oil prone (Al-Ameri, 1983; Al-Ameri et al., 1996; Tyson, 1995) and can be classified as kerogen type A, equivalent to kerogen Type II, according to Thompson and Dembiki’s (1986) plots in Van Krevelen diagram of Espetalie (1977), Tissot and Welte (1984), and Hunt (1996).

Palynomorphs (Figure 9) from the Sargelu Formation are equivalent to palynomorph records from well Aj-8 and Aj-12 of the Ajeel field, Mk-2 of the Makhole field and Qc-1 of the Qara Chuq field between Kirkuk and Tikrit cities in North Iraq (Figure 1), with a confirmed Middle Jurassic (Bajocian-Bathonian) age, based on M.Sc. studies of Ahmed (2001) and of Al-Jubouri (1989) performed under supervision of first author. On the other hand, the palynomorphs recovered from the samples of the Sulaiy Formation (Figure 10) confirm an Late Juassic-Tithonian up to the Early Cretaceous Beriassian consistent with the findings of Al-Ameri et al (1999) and Al-Ameri and Al-Musawi (2011). The Najmah/Naokelekan and the Gotnia formations have a Late Jurassic age (Van Bellen et al. 1959-2005).

Palynofacies Type VII

This palynofacies has been recognized in the Ratawi Formation but with low TOC (0.10-1.85 wt %), mature organic matter (Tmax= 438-445^{o}C and Thermal Alteration Index= 3^{-}), and overall poor petroleum potential (0.1-0.7 mg HC/g Rock). The lowest part of this unit on the other hand has exceptional good petroleum potential (15.0 mg HC/g Rock). The organic matter contains 30-60% amorphous material with up to 8% foraminifera linings (from the total palynomorphs) and 5% reworked material. The carbonates were deposited in distal dysoxic-anoxic shelf with fair to good potential for the preservation of organic material.

Dinoflagellate cysts of the Ratawi Formation (Figure 11) confirm a Hauterivian age by correlating their concurrent range zone with previously documented ranges of Al-Egabi (2000), Helby et al. (1987), Milliod et al. (1974), and Uwins and Batten (1998).

Palynofacies Type V

This palynofacies comprises sediments deposited in subsiding deltaic deposits with favorable conditions for the preservation of the accumulated organic matter, albeit mostly in a biodegraded state (Al-Ameri and Batten, 1997). Thermal alteration of the organic matter to generate hydrocarbons led in particular to the abundance of amorphous organic matter, especially in the upper part of the Zubair Formation. The maximum observed TOC is up to 6.5wt%. The organic matter is of mixed kerogen type II and III, comparable to oil-prone kerogen type A of Thompson and Dembiki (1986). The rocks are mature with a thermal alteration index (TAI) of 2.5, indicating moderate oil to gas potential (Staplin, 1969; Batten, 1996b). This palynofacies has been recognized in the Zubair and the lower part of Nahr Umr Formation.

The Zubair Formation is of Barremian and Aptian age based on palynomorph constituents (Figure 12) in line with previous studies of Al-Ameri and Batten (1997). The Nahr Umr Formation is of middle and late Albian to earliest Cenomanian age (Al-Ameri et al., 2001).

Palynofacies Type IV

Recovered organic matter consists mainly of melanogen, hylogen, phyrogen, and amorphogen. The hylogen and melanogen components are dark brown to black, dense masses of particles 50-300 µm in diameter that vary in shape from rounded to angular and would be regarded as black wood by many palynologists (Batten, 1973) and vitrinite by organic petrologists (Batten, 1996a). The palynomorphs are well to very well preserved, but dinoflagellates are much more common (up to 56% of the palynomorph assemblage) of mainly chorates with foraminifera lining. The palynofacies is mainly associated with limestone, but it is recovered also from minor associated sandstone, marl, and shale. The sediments were deposited in mainly platform-limestone environment of shelf-to-basin transition with dysoxic-suboxic (IVa) and suboxic-anoxic (IVb) conditions. The TOC content is between 0.4 and 0.95 wt% with poor hydrocarbon potential (0.12- 1.31 mg.HC/g.Rock) for the bulk of the samples analised. The samples are transitional immature to mature with TAI= 1.8 (Staplin, 1969), equivalent to a range of 2^{-} to 2 of the pollen/spore colour standard (Pearson, 1990) and Tmax of 425- 433°C. This palynofacies has been recognized in the Shuaiba and the upper part of Nahr Umr Formations.

The Shuaiba Formation is of Lower Albian age based on palynomorph constituents (Figure 8) in agreement with previous studies of Al-Ameri and Batten (1997). The Nahr Umr Formation is of Middle and Upper Albian to earliest Cenomanian age (Al-Ameri et al., 2001).

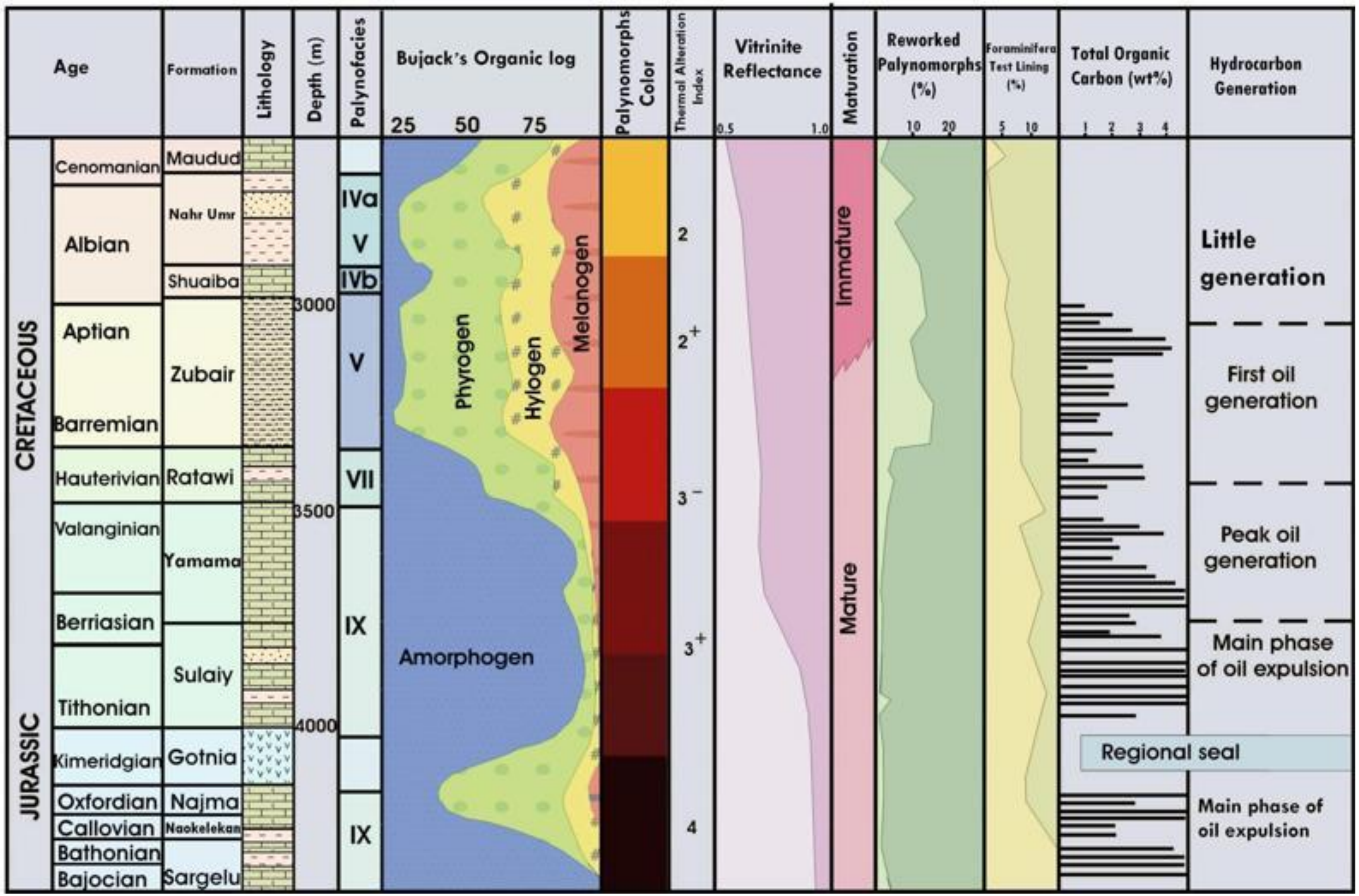


Figure 8. Organolog of palynofacies and assessment of hydrocarbon generation potential for the Upper Jurassic – Lower Cretaceous rocks in well R-172, Rumaila North oil field.

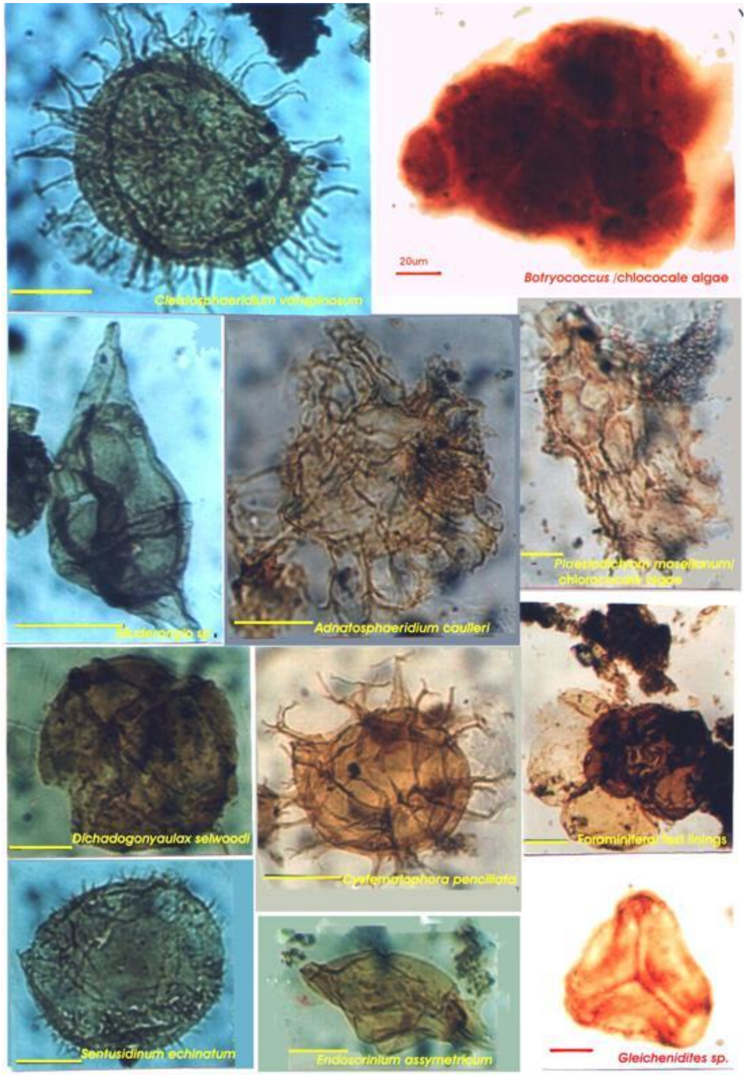


Figure 9. Dinoflagellate cysts, chlorococcale algae and spore recovered from Middle Jurassic (Bajocian- Bathonian) Sargelu Formation in North Iraq. Scale bar= 20 microns.

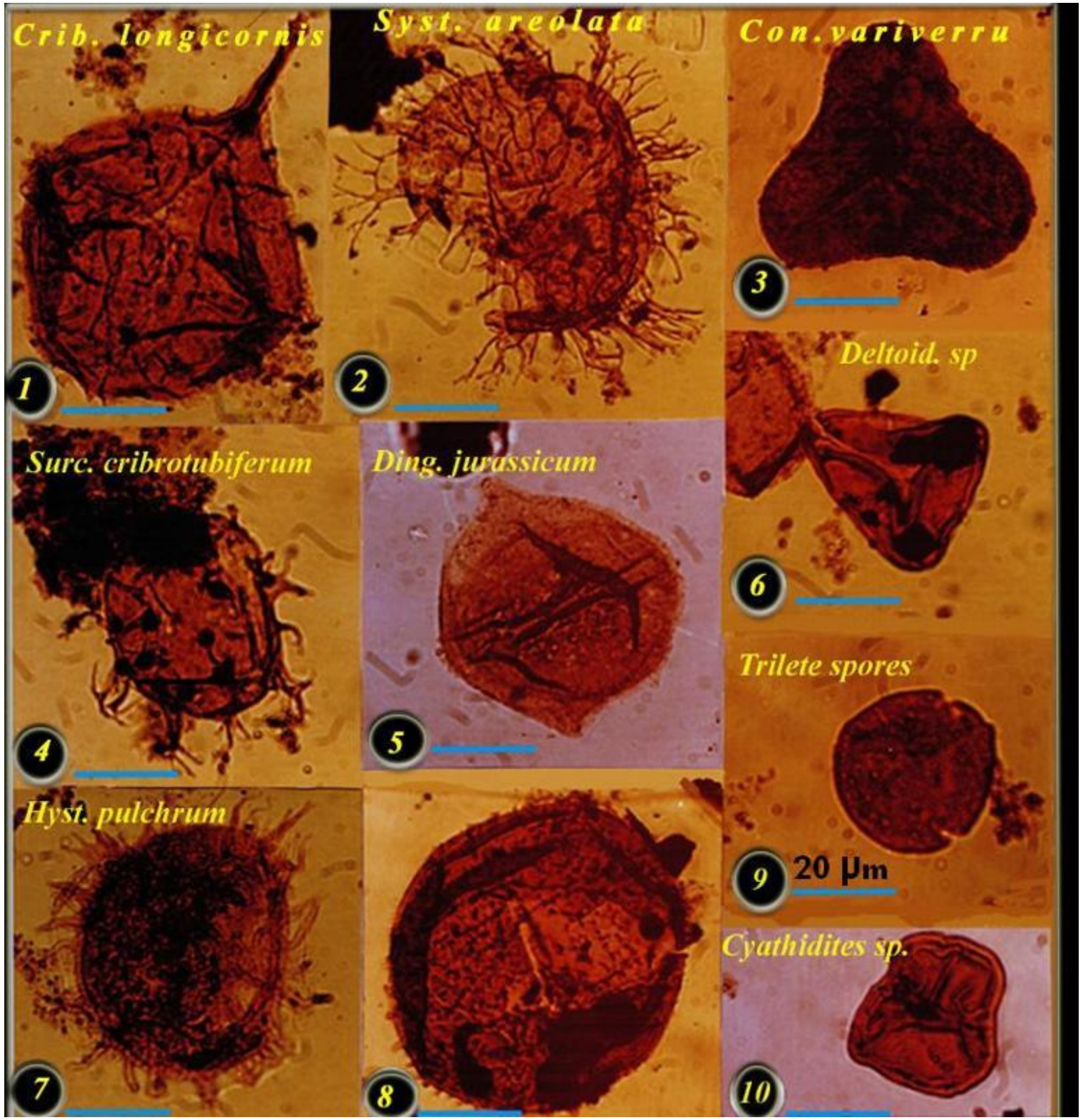


Figure 10. Spores and dinoflagellate cysts recovered the Upper Jurassic - Lower Cretaceous (Tithonian-Berriassian) Sulaiy Formation in South Iraq. Scale bar= 20 microns.

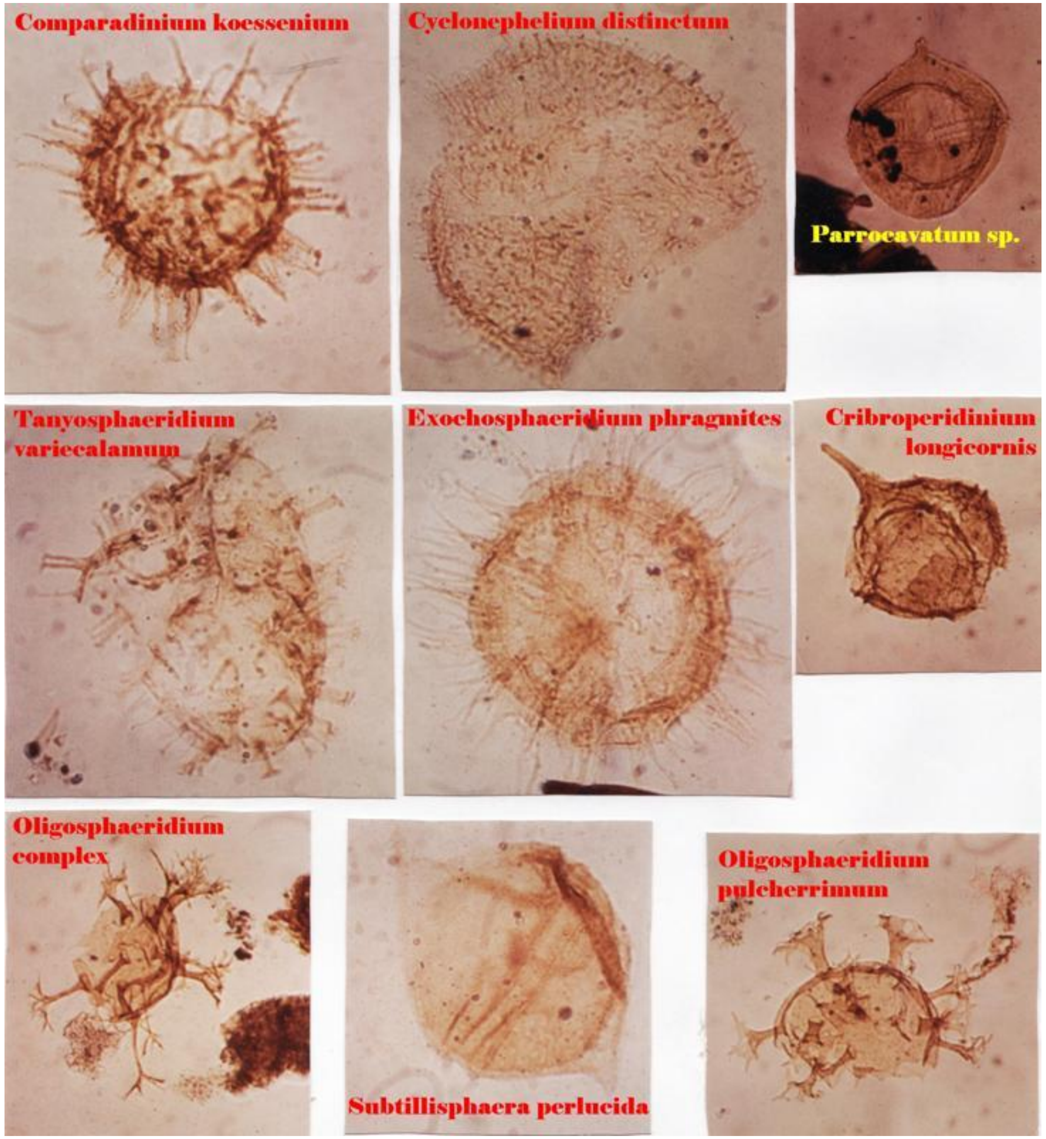


Figure 11. Dinoflagellate cysts recovered from Lower Cretaceous (Hauterivian) Ratawi Formation in South Iraq. Scale bar= 20 microns.

Figure 12. Spores and dinoflagellate cysts recovered Lower Cretaceous (Barremian-Albian) Zubair Formation in South Iraq. Scale bar= 20 microns.

Source-Rock Pyrolysis Data

Rock samples have been analysed through pyrolysis for source-rock-richness assessment from wells R-1, R-2, R-167, R-172, Zb-40, Zb-47, NR-7, NR-9, WQ-1, WQ-2, WQ-13, WQ-15, and WQ-60, as summarized in Table 5a,b,c of this study and in Al-Ameri et al. (2009, Table 1).

Pyrolysis data indicate good source rock potential in the Sulaiy and Najmah/Sargelu/Naokelekan formations, as shown on van Krevelen plot (Figure 13). Samples of the Sulaiy Formation have PI= 0.1-0.4 (S1/S1+S2) indicating indigenous hydrocarbons (Hunt, 1996). Plots of production index versus Tmax graph (Figure 14) indicate a moderate level of conversion. Classification ranges in the diagram are according to the global petroleum systems from marine carbonate and marine marl source rocks (GeoMark Research OILS™ database) and Peter et al. (2005). Samples of the Yamama Formation indicate poor source rock quality of lower maturity and higher levels of contamination/migrated hydrocarbons.

A ratio of S1/TOC between 0.1-0.2 is typical for source rocks entering the oil window. Values exceeding 1.5 indicate a contribution of non-indigenous oil (Smith, 1994). A range of S1/TOC= 0.4-1.6 in the samples analyzed for Sulaiy and Najmah formations therefore suggests mainly indigenous hydrocarbons (Figure 15) with free (reservoir) hydrocarbons.

The Ratawi Formation has TOC values ranging from 0.06 to 1.9 wt%, kerogen type II and III, early mature (TAI= 3- to 3+ [Pearson, 1990]) with Tmax of 430–450 ^{o}C. These rocks have poor to fair current petroleum potential.

The deltaic clastics of the Zubair Formation have TOC values of 0.2–2.6 wt% with Tmax of 420–440 ^{o}C, suggesting low to mid-maturity. Pyrolysis data indicate poor to fair potential source rock, and some oil could have been generated from these rocks.

Pyrolysis data of the deltaic clastics of the Nahr Umr Formation (Al-Ameri et al., 2001) suggest a low maturity (TAI= 2 to 3- [Pearson, 1990]) and low to moderate source-rock quality (kerogen type II and III and TOC= 0.4-1.8).

Table 5a. Rock-Eval pyrolysis data of the studied samples: Analyses by GeoMark Laboratories, Houston-Texas.

Sample No.	*Well No.*	*Depth (M)*	*Formation*	*TOC %*	S_1	S_2	S_3	T_{max}	*PI* $S_1/(S_1+S_2)$	*HI* S_2/TOC	*OI* S_3/TOC	*PP* S_1+S_2	S_2/S_3	S_1/TOC	R_O *(calcu.)*
1	Ru-1	3663	Mauddud	0.19	0.1	0.23	0.33	421	0.3	121	174	0.33	0.696	0.526	0.41
2	Ru-1	2788	Nahr Umr	4.96	1.2	12.87	0.8	431	0.08	259	16	14.07	16.087	0.241	0.59
3	Ru-1	2794	Nahr Umr	1.21	3.86	4.27	0.54	421	0.47	353	45	8.13	7.907	3.19	0.41
4	Ru-1	3088	Shuaiba	0.18	0.09	0.11	0.35	410	0.45	61	194	0.2	0.314	0.5	0.22
5	Ru-1	3163	Shuaiba	4.11	1.38	11.6	0.62	425	0.1	282	15	12.98	18.709	0.335	0.49
6	R-167	4493	Sulaiy	0.57	0.21	0.37	0.1	451	0.36	65	17	0.58	3.7	0.368	0.95
7	Zb-40	3172	Zubair	1.15	0.05	0.63	0.22	429	0.07	55	19	0.68	2.863	0.043	0.56
8	Zb-40	3444	Zubair	2.38	0.78	5.63	0.24	428	12	236	10	6.41	23.458	0.327	0.54
9	Zb-47	3934	Yamama	0.18	0.12	0.42	0.13	437	0.22	233	72	0.54	3.23	0.666	0.7
10	Zb-47	4017.5	Yamama	0.11	0.04	0.07	0.07	390	0.36	64	64	0.11	1	0.363	0.14
11	NR-7	3050.5	Zubair	0.97	1.77	1.58	0.29	432	0.52	163	30	3.35	5.448	1.824	0.61
12	NR-7	3076	Zubair	1.56	1.16	1.93	0.23	427	0.37	124	15	3.09	8.391	0.743	0.52
13	NR-7	3344	Yamama	0.43	1.05	0.49	0.31	420	68	114	72	1.54	1.58	2.441	0.4
14	NR-7	3370	Yamama	0.66	1.43	1.41	0.32	424	0.5	214	48	2.84	4.406	2.166	0.47
15	NR-7	3400	Yamama	0.25	0.08	0.43	0.14	434	0.15	172	56	0.51	3.071	0.32	0.65
16	NR-9	3570	Zubair	1.07	0.11	1.19	0.23	432	0.08	111	21	1.3	5.173	0.102	0.61
17	NR-9	3815	Yamama	0.37	0.42	0.37	0.13	430	0.53	100	35	0.79	2.846	1.135	0.58
18	NR-9	3909	Yamama	0.2	0.28	0.16	0.17	428	0.63	80	85	0.44	0.941	1.4	0.54
19	NR-9	4034	Yamama	0.18	0.05	0.09	0.06	411	0.35	50	33	0.14	1.5	0.777	0.23
20	WQ-2	3220	Zubair	1.38	0.23	1.31	0.11	430	0.15	95	8	1.54	11.909	0.166	0.58
21	WQ-2	3276	Zubair	4.96	1.23	16.87	1.05	431	0.06	340	21	18.1	16.066	0.247	0.59
22	WQ-13	2818	Mauddud	0.23	0.05	0.25	0.25	435	0.16	108	100	0.3	1.086	0.217	0.67
23	WQ-15	3649	Yamama	1.07	5.42	2.91	2.91	418	0.65	272	45	8.33	6.062	5.065	0.36
24	WQ-15	3739	Yamama	2.6	2.55	5.32	5.32	445	0.32	205	13	7.87	15.647	0.98	0.85
25	WQ-60	4010	Yamama	0.42	0.22	0.55	0.55	438	0.28	131	45	0.77	2.894	0.523	0.72
26	R-172	4823	Najmah	4.43	42.2	11.7	1.5	432	0.78	215	34	43.9	7.13	9.53	-
27	R-172	4837	Najmah	5.35	52.35	10.4	2.0	431	0.84	193	37	63.1	5.20	9.85	-
28	R-172	4842	Najmah	6.57	61.8	15.7	3.4	434	0.80	239	51	77.5	3.29	9.49	-
29	R-172	5098	Najmah	2.44	24.40	6.5	1.5	437	0.79	265	63	30.5	4.33	9.80	-

Table 5b. Rock-Eval pyrolysis data of the studied samples from Well WQ-1: Analyses by Oil Exploration Company Laboratories in Iraq.

Sample No.	*Depth (M)*	*Formation*	*TOC %*	S_1	S_2	S_1/TOC	*HI* S_2/TOC	*PI* $S_1/(S_1+S_2)$	*PP* S_1+S_2	T_{max} (ºC)	R_O *(calcu.)*
1a	**2670**	**Mauddud**	**0.69**	**1.8**	**5.52**	**2.61**	**800**	**0.245**	**7.32**	**430**	**0.58**
2a	**2820**	**Nahr Umr**	**0.81**	**0.32**	**0.77**	**0.39**	**95**	**0.293**	**1.09**	**436**	**0.68**
3a	**2850**	**Nahr Umr**	**0.099**	**0.68**	**1.3**	**0.69**	**131.3**	**0.343**	**1.98**	**430**	**0.58**
4a	**2860**	**Nahr Umr**	**0.87**	**0.19**	**0.78**	**0.22**	**89.6**	**0.195**	**0.97**	**436**	**0.68**
5a	**2884**	**Nahr Umr**	**0.94**	**0.39**	**1.18**	**0.41**	**125.5**	**0.248**	**1.57**	**436**	**0.68**
6a	**2892**	**Nahr Umr**	**1.32**	**0.33**	**2.12**	**0.25**	**164.4**	**0.132**	**2.5**	**432**	**0.61**
7a	**2900**	**Nahr Umr**	**1.37**	**0.34**	**2.01**	**0.25**	**146.7**	**0.144**	**2.35**	**430**	**0.58**
8a	**2908**	**Nahr Umr**	**1.25**	**0.23**	**1.51**	**0.18**	**120.8**	**0.132**	**1.74**	**436**	**0.68**
9a	**2920**	**Nahr Umr**	**1.49**	**0.77**	**5.58**	**0.52**	**390.6**	**0.116**	**6.59**	**430**	**0.58**
10a	**2962**	**Nahr Umr**	**1.25**	**0.27**	**1.25**	**0.22**	**100**	**0.117**	**1.52**	**430**	**0.58**
11a	**2980**	**Shuaiba**	**0.69**	**0.19**	**0.54**	**0.27**	**78.3**	**0.26**	**0.73**	**434**	**0.65**
12a	**3198**	**Zubair**	**1.26**	**0.14**	**2.26**	**0.11**	**179.4**	**0.058**	**2.4**	**439**	**0.74**
13a	**3210**	**Zubair**	**1.44**	**0.19**	**2.93**	**0.13**	**203.5**	**0.06**	**3.12**	**439**	**0.74**
14a	**3216**	**Zubair**	**0.96**	**0.74**	**2.86**	**0.77**	**297.9**	**0.205**	**3.6**	**435**	**0.64**
15a	**3225**	**Zubair**	**1.14**	**0.33**	**1.29**	**0.29**	**113.2**	**0.203**	**1.62**	**431**	**0.59**
16a	**3228**	**Zubair**	**5.83**	**5.83**	**22.08**	**1**	**378.7**	**0.208**	**27.91**	**441**	**0.77**
17a	**3235**	**Zubair**	**0.53**	**0.09**	**1.52**	**0.17**	**286.8**	**0.055**	**1.61**	**439**	**0.61**
18a	**3254**	**Zubair**	**0.97**	**2.11**	**4.88**	**2.17**	**503.1**	**0.301**	**6.99**	**432**	**0.54**
19a	**3266**	**Zubair**	**0.96**	**0.27**	**0.88**	**0.28**	**91.7**	**0.234**	**1.15**	**428**	**0.63**
20a	**3268**	**Zubair**	**1.24**	**3.11**	**7.08**	**2.51**	**571**	**0.305**	**10.19**	**433**	**0.52**
21a	**3272**	**Zubair**	**0.69**	**0.47**	**1.14**	**0.68**	**165.2**	**0.291**	**1.61**	**427**	**0.68**
22a	**3277**	**Zubair**	**1.23**	**0.12**	**1.9**	**0.09**	**154.5**	**0.059**	**2.02**	**436**	**0.68**
23a	**3286**	**Zubair**	**2.24**	**0.2**	**3.47**	**0.09**	**154.9**	**0.054**	**3.67**	**442**	**0.79**
24a	**3290**	**Zubair**	**0.54**	**0.09**	**0.49**	**0.17**	**90.7**	**0.155**	**0.58**	**436**	**0.68**
25a	**3294**	**Zubair**	**0.55**	**0.09**	**0.33**	**0.16**	**60**	**0.214**	**0.42**	**436**	**0.68**
26a	**3440**	**Ratawi**	**0.73**	**0.3**	**2.15**	**0.41**	**294.5**	**0.122**	**2.45**	**434**	**0.65**

Table 5c. Rock-Eval pyrolysis data of the studied samples from Well NR-7: Analyses by Oil Exploration Company Laboratories in Iraq.

Sample No.	*Depth (M)*	*Formation*	*TOC %*	S_1	S_2	S_1/TOC	*HI* (S_2/TOC)	*PI* S_1/S_1+S_2	*PP* (S_1+S_2)	T_{max} (ºC)	R_O (calcu.)
1 b	3032	Zubair	0.33	0.07	0.32	0.21	97	0.179	0.39	433	0.63
2 b	3035	Zubair	1.63	0.19	6.03	0.12	372.2	0.03	6.22	431	0.59
3 b	3041	Zubair	1.27	2.04	3.39	0.16	266.9	0.375	5.43	420	0.4
4 b	3050	Zubair	0.52	2.04	1.61	3.92	309.6	0.558	3.65	427	0.52
5 b	3051	Zubair	0.31	0.07	0.23	0.23	138.7	0.14	0.5	432	0.61
6 b	3052	Zubair	0.71	0.22	2.16	0.31	304.2	0.092	2.38	438	0.72
7 b	3054	Zubair	0.46	0.14	1.17	0.3	254.3	0.106	1.31	434	0.74
8 b	3063	Zubair	0.17	0.11	0.12	0.65	123.5	0.343	0.32	417	0.34
9 b	3066	Zubair	0.96	0.38	6.04	0.39	629.2	0.059	6.42	433	0.63
10 b	3071	Zubair	0.4	0.21	1.88	0.53	470	0.1	2.09	429	0.56
11 b	3074	Zubair	0.84	0.3	3.66	0.36	435.7	0.075	3.96	426	0.5
12 b	3080	Zubair	1.16	0.06	1.19	0.05	102.6	0.048	1.25	436	0.68
13 b	3084	Zubair	0.42	0.1	1.44	0.24	342.9	0.064	1.54	437	0.7
14 b	3088	Zubair	0.2	0.08	0.4	0.4	200	0.166	0.48	424	0.47
15 b	3094	Zubair	0.22	0.11	0.49	0.5	222.7	0.183	0.6	433	0.63
16 b	3096	Zubair	0.22	0.19	0.55	0.86	250	0.256	0.74	434	0.65
17 b	3099	Zubair	0.17	0.07	0.16	0.41	94.1	0.304	0.23	428	0.54
18 b	3100	Zubair	0.12	0.07	0.09	58	75	0.437	0.16	435	0.67
19 b	3221	Ratawi	0.5	0.13	0.33	0.26	66	0.282	0.46	432	0.61
20 b	3225	Ratawi	0.42	0.17	0.28	0.4	66.7	0.377	0.45	432	0.61
21 b	3235	Ratawi	0.39	0.14	0.23	0.77	59	0.378	0.37	430	0.58

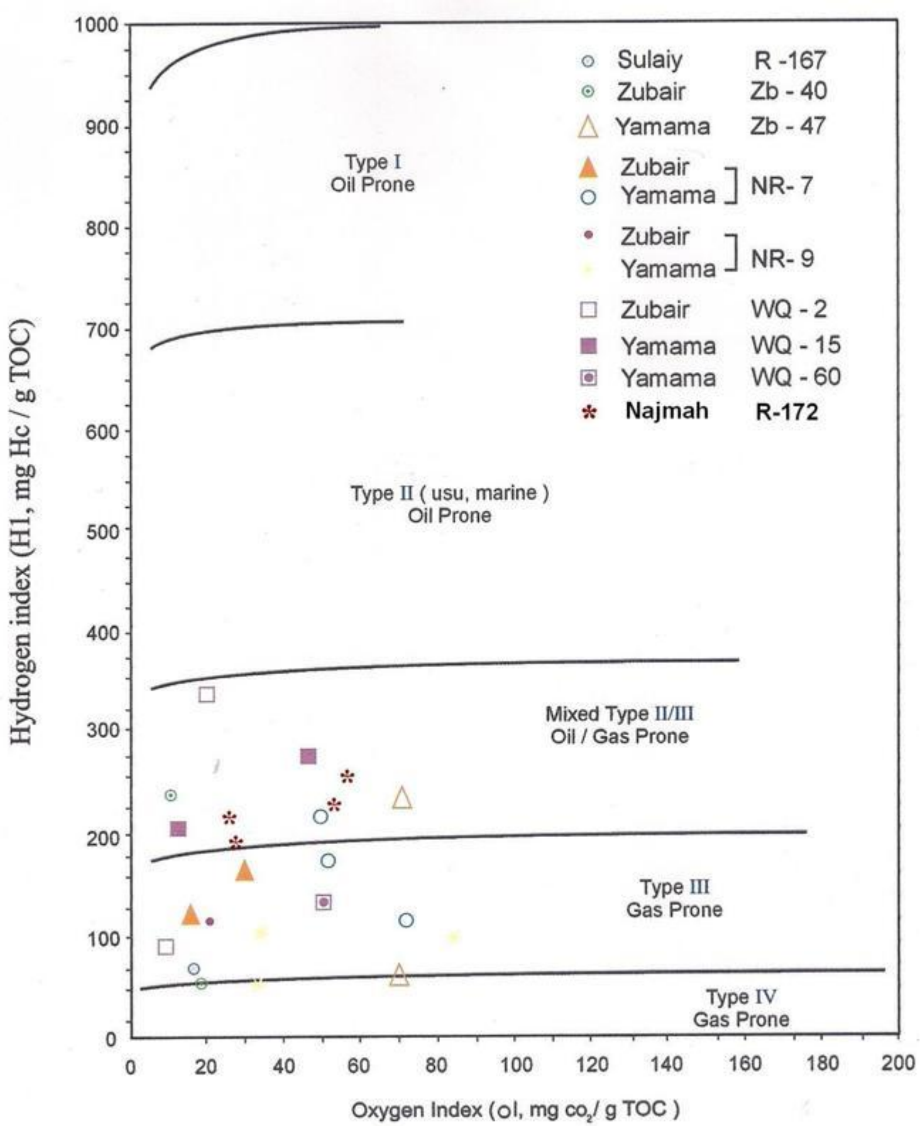


Figure 13. Van Krevelen plots of the pyrolysis results from the studied Upper Jurassic- Lower Cretaceous formations in wells R-167, R-172, Zb-40, Zb-47, NR-7, NR-9, WQ-2, WQ-15, and WQ-60 in Basrah region.

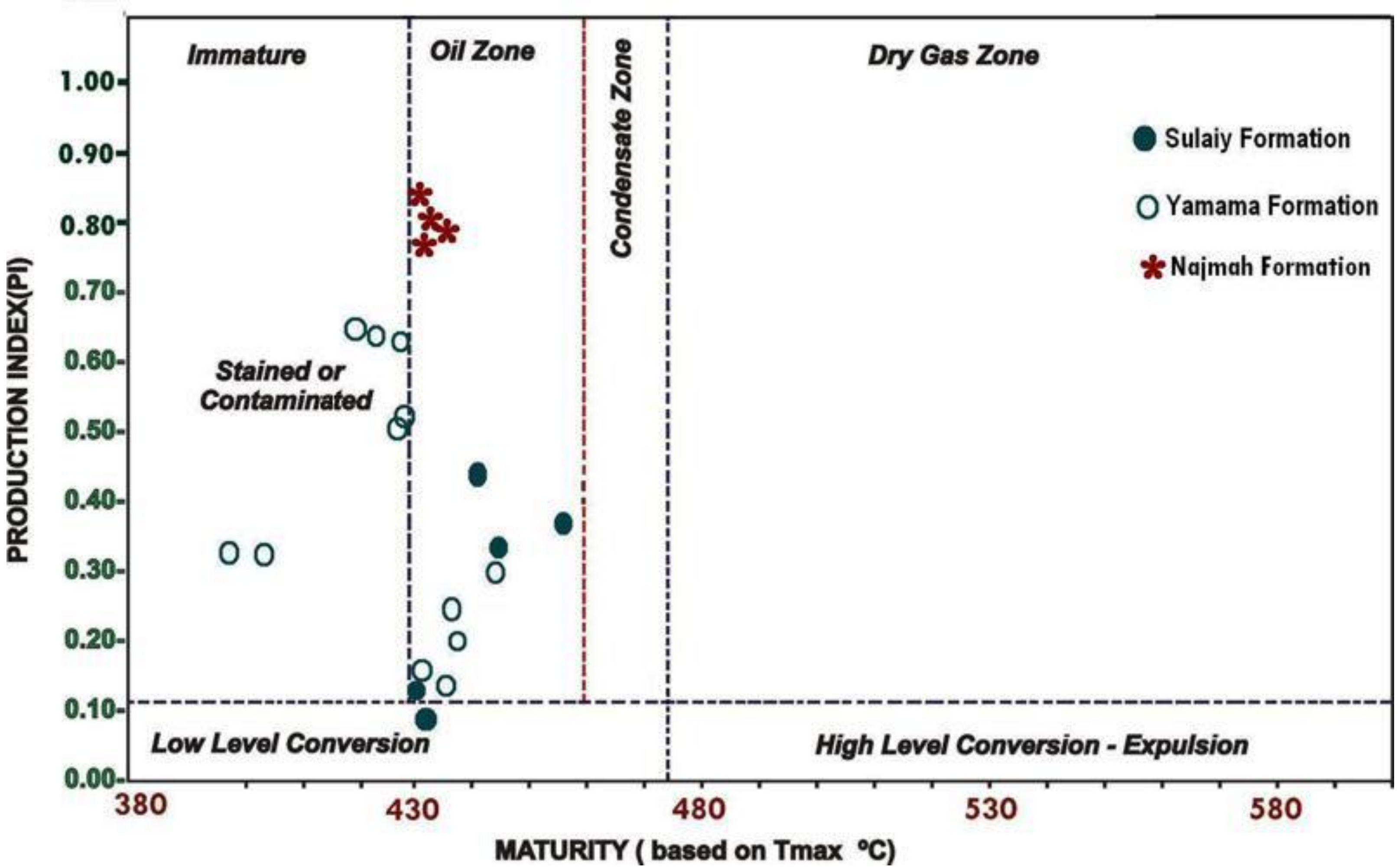


Figure 14. Pyrolysis plots for source rocks of the Sulaiy and Yamama formations in Basrah oil fields from wells R-167, Zb-47, NR-7, NR-9, and WQ-15 of kerogen conversion and maturity for values of production index (mgOil/gRock) and maturity (°C Tmax).

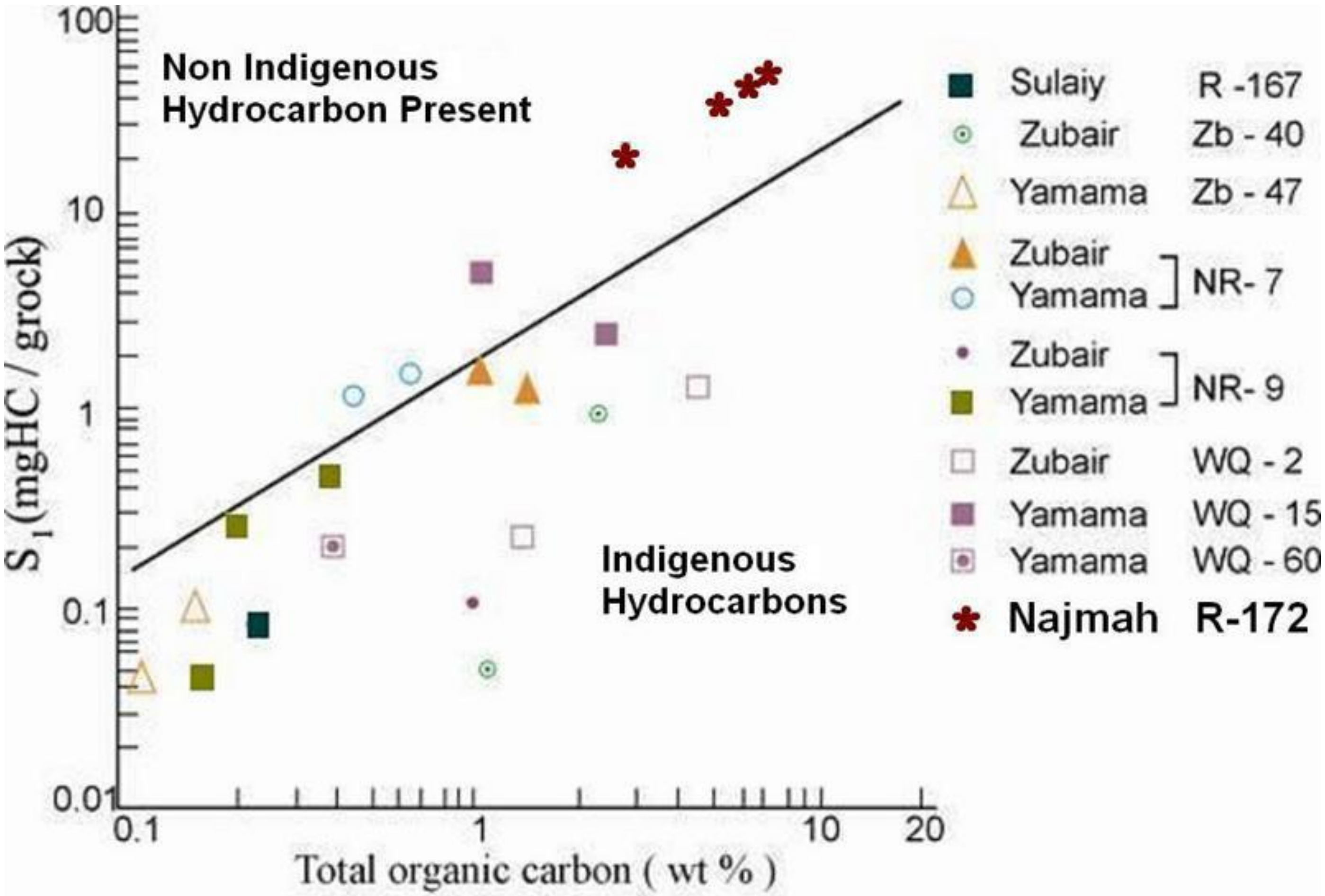


Figure 15. Plot of S_1 versus TOC wt% illustrating the indigenous nature of hydrocarbons in the Sulaiy samples versus samples of likely migrated hydrocarbons in the overlying Yamama Formation.

Oil-Affinity Assessment

Oil-affinity assessment could be based on biomarker crude oil geochemistry studies already mentioned by Al-Ameri et al. (2009) as well as the from the Gas Chromatography - Mass Spectrometry analysis to be mentioned in this section. From that reference, it could be assessed of mainly Late Jurassic-Early Cretaceous age of the oil accumulated in the reservoirs of the Cretaceous strata in South Iraq. To confirm this statement, biomarker studies by Gas Chromatography- Mass Spectrometry (GCMS) of analyzing mainly Mishrif Formation Reservoir crude oil from West Qurna, Majnoon, and Zubair oil fields and bitumen extracts of Sulaiy, Yamama, Zubair, Shuaiba, Nahr Umr, and Mauddud source rock formations are part of this study (Tables 6 and 7). The main reliable graphical presentation to show this comparison is the sterane ternary diagram of C_{27} - C_{28} - C_{29}.

The principal use of C_{27} - C_{28} - C_{29} sterane ternary diagrams is to distinguish groups of crude oils from different sources (plankton, open marine, bay or estuary, terrestrial, and higher plants), or different organic facies of the same source rock, determined in conjunction with other biomarkers parameters (Al-Ameri et al., 2009), such as Pr/ Ph ratio and tricyclic terpane. The diagram can be used to infer genetic relationships among oil and bitumen samples if they plot in close proximity (Peters et al., 2005).

Figure 16 shows that the Mishrif crude oils in West Qurna, Majnoon, and Zubair oil fields are represented as one oil group and suggests a close genetic relationship between these oils and rock extracts, according to their similar distribution plots of C_{27} - C_{28} - C_{29} sterane in the sterane triangle diagram. The plots in this diagram show the oils generated mainly from marine algal with some terrigenous organic matter disseminated in marine carbonate and shale and with similar genetic relation to East Baghdad oil discussed by Al-Ameri (2011).

Table 6. Results of mass chromatograms of steranes (m/ z 217) for the studied crude oil samples.

Sample No.	*Well No.*	*Depth (M)*	*Formation*	*% C_{27}*	*% C_{28}*	*% C_{29}*	*C_{28}/ C_{29}*
1	WQ-268	2213	Mishrif	33.4	24.9	41.7	0.59
2	WQ-245	2234	Mishrif	33.0	24.8	42.3	0.58
3	WQ-238	2298	Mishrif	33.5	25.1	41.4	0.60
4	WQ-269	2328	Mishrif	33.8	24.9	41.2	0.60
5	WQ-284	2359.5	Mishrif	33.9	24.8	41.3	0.60
6	Mj-10	2402	Mishrif	33.7	25.8	40.6	0.63
7	Mj-8	2452	Mishrif	33.9	24.6	41.5	0.59
8	Mj-20	2485	Mishrif	33.3	25.2	41.5	0.60
9	Mj-17	2497	Mishrif	33.7	24.9	41.4	0.60
10	Zb-21	2195.5	Mishrif	33.5	25.2	41.3	0.61
11	Zb-160	2237	Mishrif	33.7	24.5	41.8	0.58
12	Zb-157	2259	Mishrif	33.7	25.3	40.9	0.61
13	Zb-158	2268	Mishrif	34.6	24.4	41.0	0.59

Table 7. Results of mass chromatograms of hopanes (m/ z 217) for the studied rock extract samples.

Sample No.	*Well No.*	*Depth (M)*	*Formation*	*% C_{27}*	*% C_{28}*	*% C_{29}*	*C_{28}/ C_{29}*	*C_{29}20S/ R*
1	WQ-13	2818	Mauddud	32.5	22.0	45.6	0.48	0.68
2	Ru-1	2788	Nahr Umr	27.3	27.7	45.0	0.61	0.31
3	Ru-1	3088	Shu'aiba	39.5	26.1	34.4	0.75	0.55
4	NR-7	3050.5	Zubair	32.9	25.4	41.7	0.60	0.86
5	NR-7	3076	Zubair	34.9	24.2	40.9	0.59	0.85
6	WQ-2	3276	Zubair	18.5	23.3	58.2	0.40	0.48
7	Zb-40	3444	Zubair	35.7	21.5	42.8	0.50	0.78
8	NR-7	3344	Yamama	35.9	22.0	42.0	0.52	0.81
9	NR-7	3400	Yamama	32.8	25.2	42.0	0.60	0.82
10	WQ-15	3649	Yamama	33.9	24.3	41.8	0.58	0.87
11	NR-9	3815	Yamama	32.0	23.5	44.6	0.52	0.83
12	NR-9	3909	Yamama	32.0	24.9	43.1	0.57	0.85
13	ZB-47	3934	Yamama	30.7	20.5	48.8	0.42	2.32
14	WQ-60	4010	Yamama	35.6	22.7	41.8	0.54	0.86
15	Zb-47	4017.5	Yamama	31.9	20.9	47.2	0.44	2.00
16	R-167	4493	Sulaiy	30.1	35.0	34.9	1.02	0.13

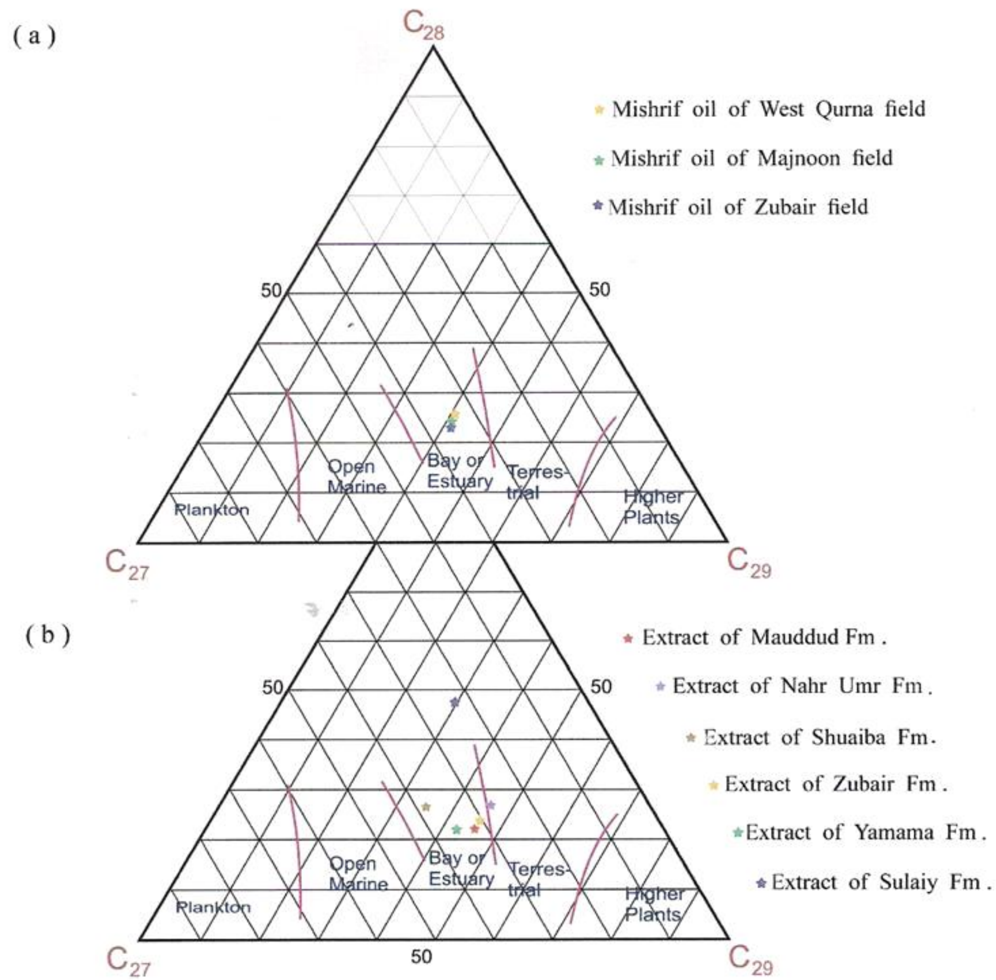


Figure 16. Ternary diagram showing the relative abundances of C_{27}, $C2_8$, and C_{29} regular steranes in the saturate fractions of (a) crude oil samples of the Mishrif reservoir and (b) extract samples of potential source rocks to describe the source-rock depositional environment and to infer genetic relationships among oil and bitumen samples (after MoO and JAPEX, 2006).

Discussion

Combining the charge-modeling results with source-rock quality information from palynofacies and source-rock pyrolysis provides the key ingredients for the understanding of the hydrocarbon systems in the Basrah area. Good source rocks have been identified from palynofacies and pyrolysis work in Upper Jurassic and Lower Cretaceous basinal, restricted mudstones. These would have entered the oil window by fast burial at the end of the Cretaceous and are currently gas mature. Additional source-rock potential, in the Zubair and Nahr Umr formations is of lesser quality and at best reaches marginal maturity during recent, Neogene, burial. The large amounts of hydrocarbons in the Cretaceous and Tertiary reservoirs of the Basrah fields must therefore be derived from either the Jurassic or Lower Cretaceous sources, as also supported by pyrolysis data. Microfractures with oil impregnations observed in samples of the Sulaiy Formation (Figure 17) could represent primary migration pathways from expelled hydrocarbons, analogous to the Monterey carbonate source rocks described by Bordenave (1993) in California.

Pitman el al. (2004) discussed the role of the sealing Gotnia evaporites that are capping the Upper Jurassic source rocks. Formation pressures increase in the Lower Cretaceous to Upper Jurassic succession through the Yamama, Sulaiy, and Gotnia formations from essentially hydrostatic at the top of the Yamama to lithostatic in the base of the Gotnia Formation. The Gotnia seems to be the boundary between two different pressure regimes as calibrated by deep wells in Northern Kuwait, Rumaila-172, and WQ-15 (Goff, 2005). The pressure differential suggests that the Gotnia provides a major seal between these source rocks, which in turn would imply that most of the oils at Cretaceous and younger levels would be derived from possible Lower Cretaceous source rocks. The carbonate source rocks in the Lower Cretaceous and Upper Jurassic would show similar geochemical characteristics in their associated oils, which therefore would be rather difficult to distinguish. It is unlikely that oil geochemistry would provide a clear distinction between the oils, but this could be tried in the future when Jurassic oil samples would become available. The Jurassic source rocks became gas mature following Late Cretaceous burial; this is inconsistent with the overall under-saturated nature of the Cretaceous and younger oils, and it too also suggests an Early Cretaceous origin, consistent with the maturity of the oils.

For the relatively under-explored Jurassic succession in the Basrah fields, the charge models and nature of the Upper Jurassic source rocks predict a gas prone charge, either volatile oils with high GOR (as in northern Kuwait) or gas.

Hydrocarbons generated during Late Cretaceous deep burial from the Sulaiy and Najmah/Neokelekan carbonate source rocks would be trapped by structures already in existence and reactivated during this tectonic phase. Additional traps and reactivation of traps also developed in the Neogene associated with the Alpine phase, impacting the northeastern edge of the Arabian plate (Al Sharan and Nairn, 1997; Sharland et al., 2001).

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Additional hydrocarbons may have been generated during the Neogene burial from more marginal source rocks in the Ratawi and Zubair formations, taking these rocks into the lower part of the oil window, associated with low to moderate, under-saturated oils. Any shallower units did not contribute to charge, and accordingly hydrocarbons found in them have to be charged by migration from deeper levels.

Some of the domal structures in the Basrah region were formed by salt diapirs of the pre-Cambrian to Cambrian Hormuz Salt (Sharland et al., 2001).

Examples of such domes are observed on seismic sections of Zubair oil field (Figure 18a, b). Phase seismic sections of West Qurna oil field (Figure 19a, Figure 19b, and Figure 19c) are showing structural trend of double-plunging anticline in through wells WQ-12, WQ-14, WQ-20, WQ-32, and WQ-34 (Figure 19a). Top Upper Jurassic Gotnia Anhydrite Formation reflector shows the behavior of this strike line. The domical structure is shown by the behavior of Upper Jurassic Gotnia Formation reflector in seismic cross section through wells WQ-15 and WQ-17 (Figure 19b) while more closure is shown by the Gotnia Formation reflector (marked by yellow color), with some variation in quality due to thinning or fracturing (Figure 19c). These fractures in Qutnia Formation may have formed the passage ways for little oil from the Upper Jurassic to be mixed with the Lower Cretaceous oil.

Figure 20 summarizes the charge-model results in a stratigraphic panel across the fields. Total transformation ratio from the deposit of each effective source rock until the present could be evaluated from this study, as illustrated in Figure 20 (and other figures), with use of the following key:

- Start oil generation zone (green color in Figure 5a, Figure 5b, Figure 5c) is of TR= 0.01. It is equivalent to transitional mature with very little oil generation within well temperatures of 90-100°C. Examples are the Nahr Umr, Maudud, and Ahmedia formations and lower part of Mishrif Formation in well Mj-8 (Figure 5a), Upper Zubair, Shuaiba, Nahr Umr, and Maudud formations in wells WQ-15 (Figure 5b) and Zb-47 (Figure 5c).
- Peak oil generation zone (yellow color in Figure 5a, Figure 5b, Figure 5c) is of TR= 0.50. It is equivalent to early mature with considerable oil generation within well temperature of 100-120°C. Examples are Upper Zubair and Shuaiba formations in well Mj-8 (Figure 5a), Upper Yamama, Ratawi and Lower Zubair formations for well WQ-15 (Figure 5b) and Ratawi and Zubair formations for well Zb-47 (Figure 5c).
- End oil generation zone (red color) is of TR= 0.95. It is equivalent to late mature with complete oil generation within well temperatures of 120-140°C. This zone extends to the deepest drilled depth of the investigated wells. Examples are Lower Zubair, Ratawi, Yamama and Sulaiy formations for well Mj-8 (Figure 5a), Lower Yamama, Sulaiy, Najmah, Naokelegan and Sargrlu formations for well WQ-15 (Figure 5b), and Yamama and Sulaiy formations for well Zb-47 (Figure 5c).

On the basis of the data gathered from PetroMod software modeling analysis as well as the palynofacies, source-rock pyrolysis data and crude oil affinity was determined in this study for the Total Jurassic-Cretaceous/ Tertiary Petroleum System in South Iraq; the events of timing developments of source, reservoir, and seal-rock materials, trap formation, and burial (overburden) processes are tabulated parallel with geologic time scale in the chart shown in Figure 21. These materials and processes form spaces for the hydrocarbon generation, migration, and accumulation span as well as their preservation in situ or possessing tertiary migration to another locality. Accordingly, any of these events could have time equivalent for their documentation in the events chart (Figure 21) to become valuable for hydrocarbon exploration in South Iraq, in particular. This events chart could explain the petroleum system as defined by essential elements of Jurassic-Lower Cretaceous active source rocks mainly of Upper Jurassic - Lower Cretaceous Sulaiy Formation with their kerogen transformation to oil and gas that migrated and accumulated in traps of Cretaceous reservoir beds with further migration to the Tertiary traps.

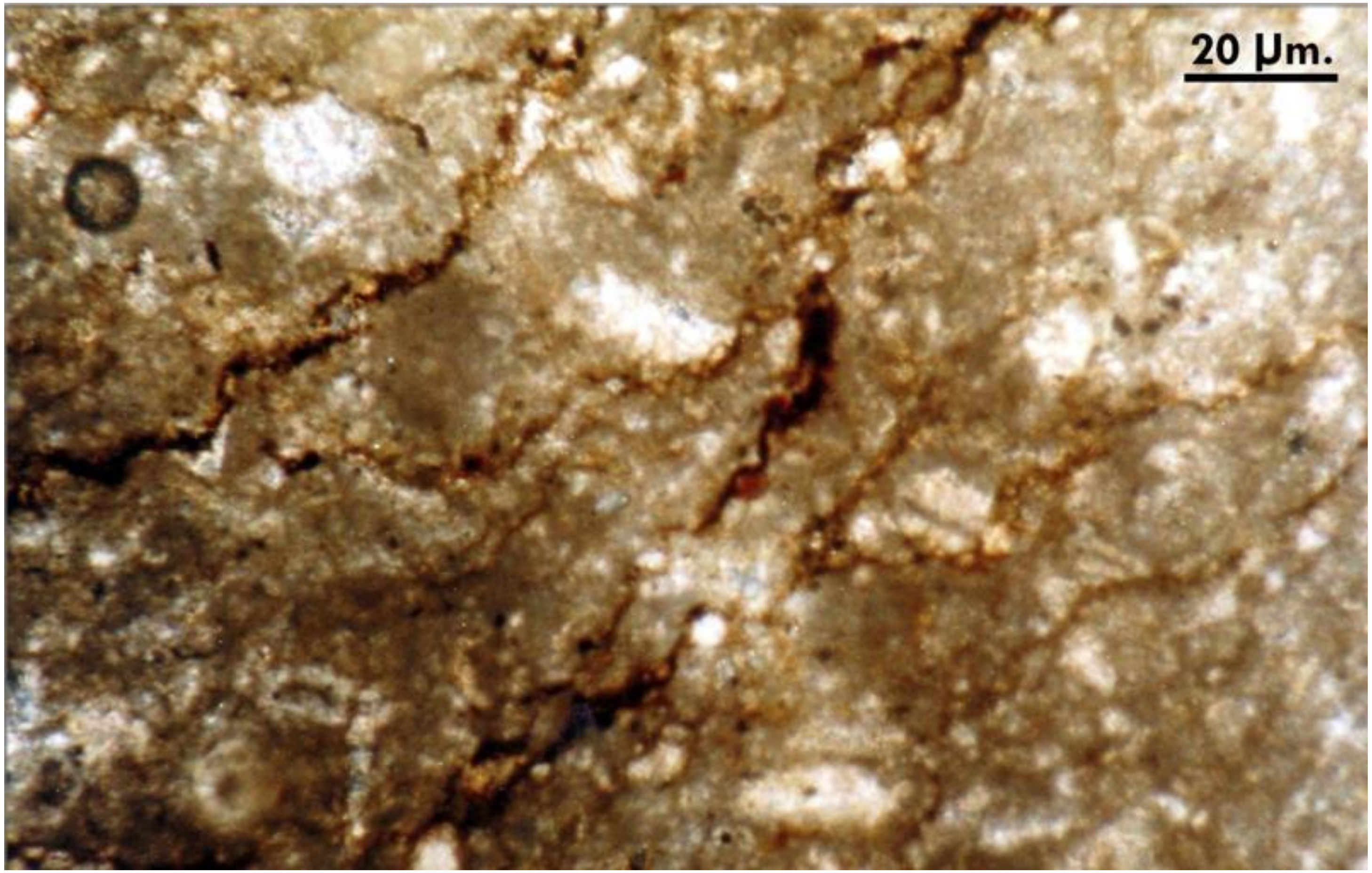


Figure 17. Thin section of the Sulaiy Formation source rocks showing nearly hairy, vertical cracks which were formed by fracturing of the rock during oil generation with oil “fill” that confirms primary migration and expulsion.

(a)

(b)

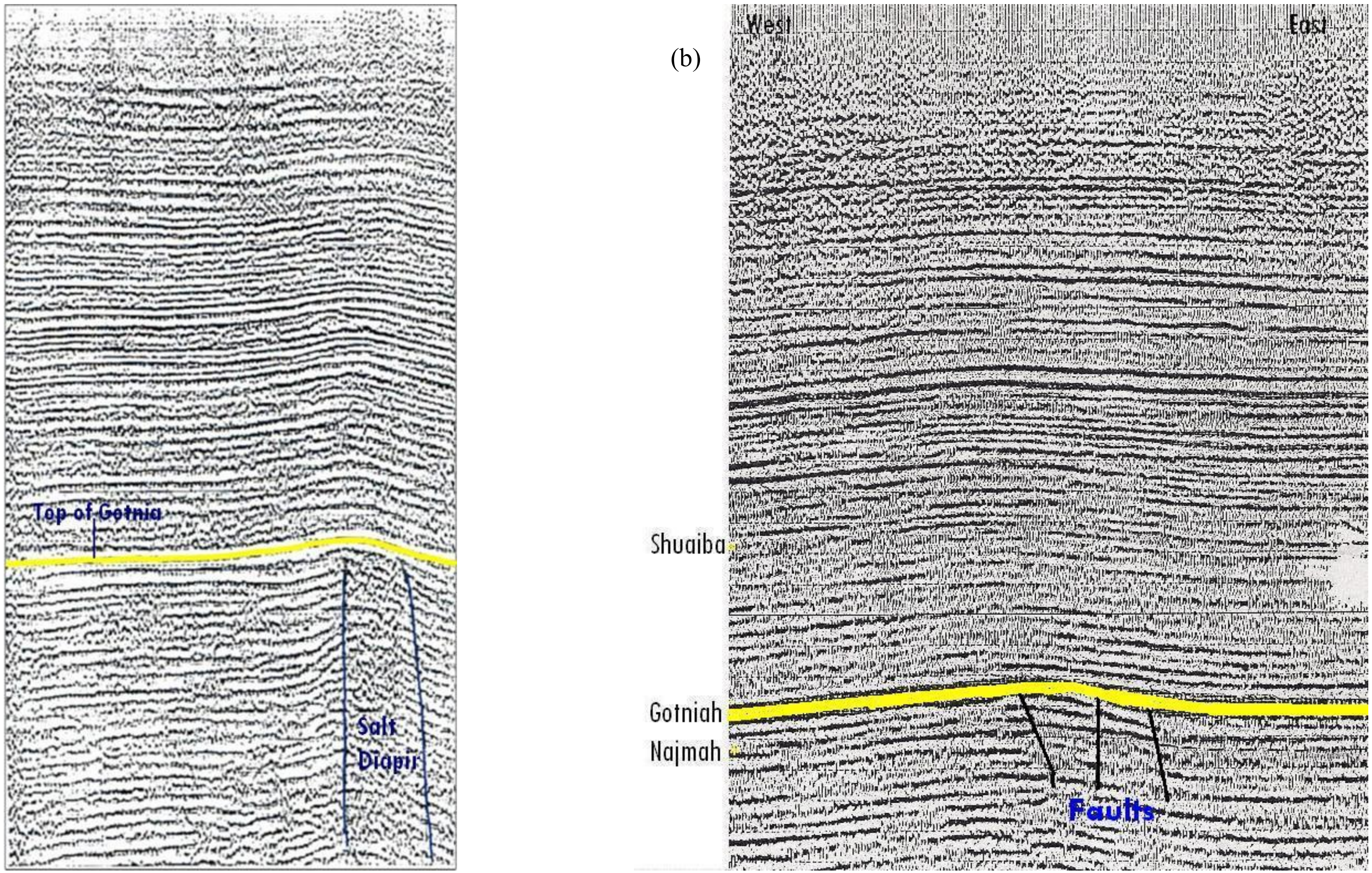


Figure 18. “Final” seismic section with residual static corrections across Zubair Field, showing the diapiric salt effect. a. Uplift of the Gottnia Anhydrite Formation and the overlying formations. b. Faults underneath the Gotnia.

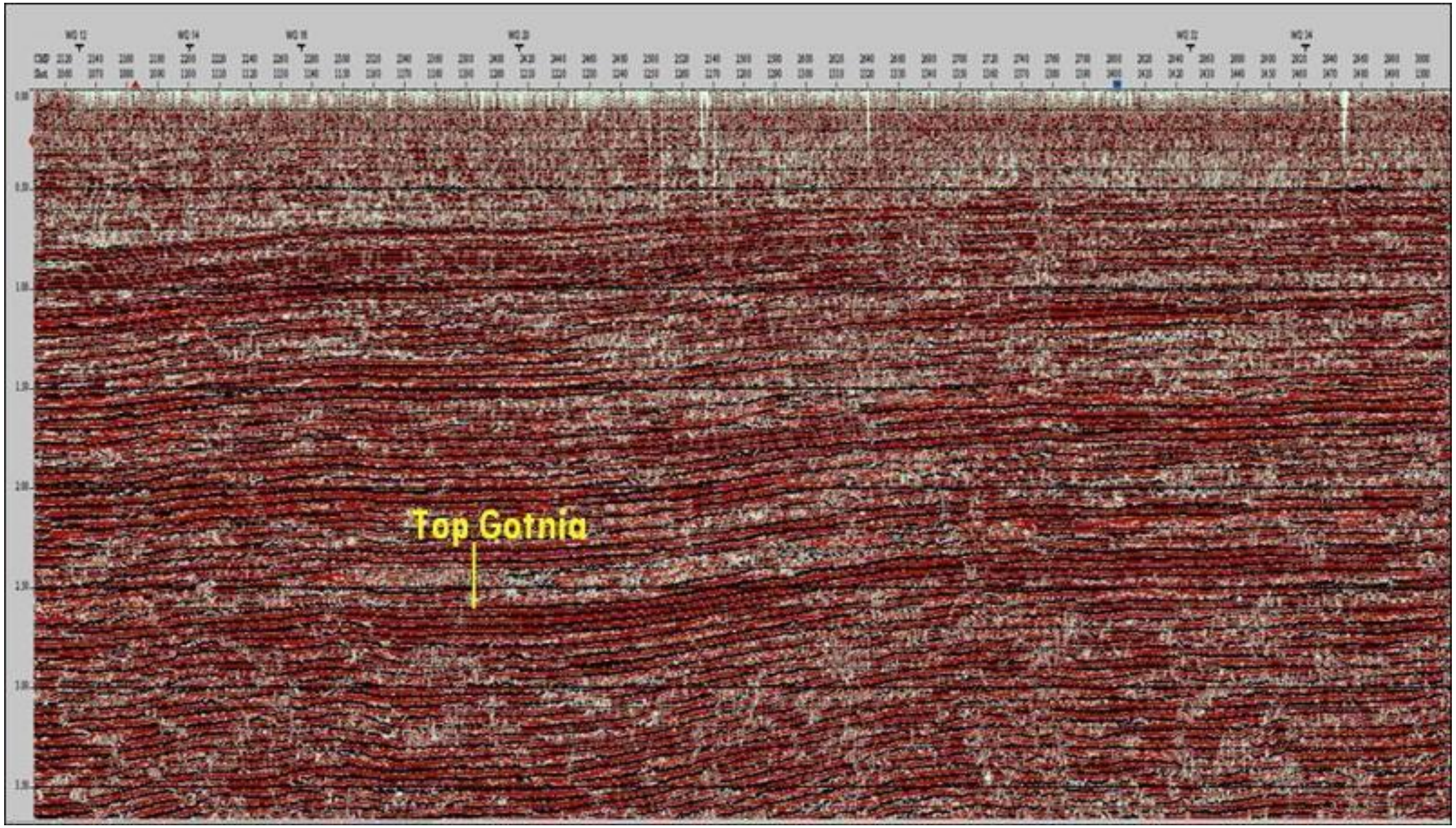
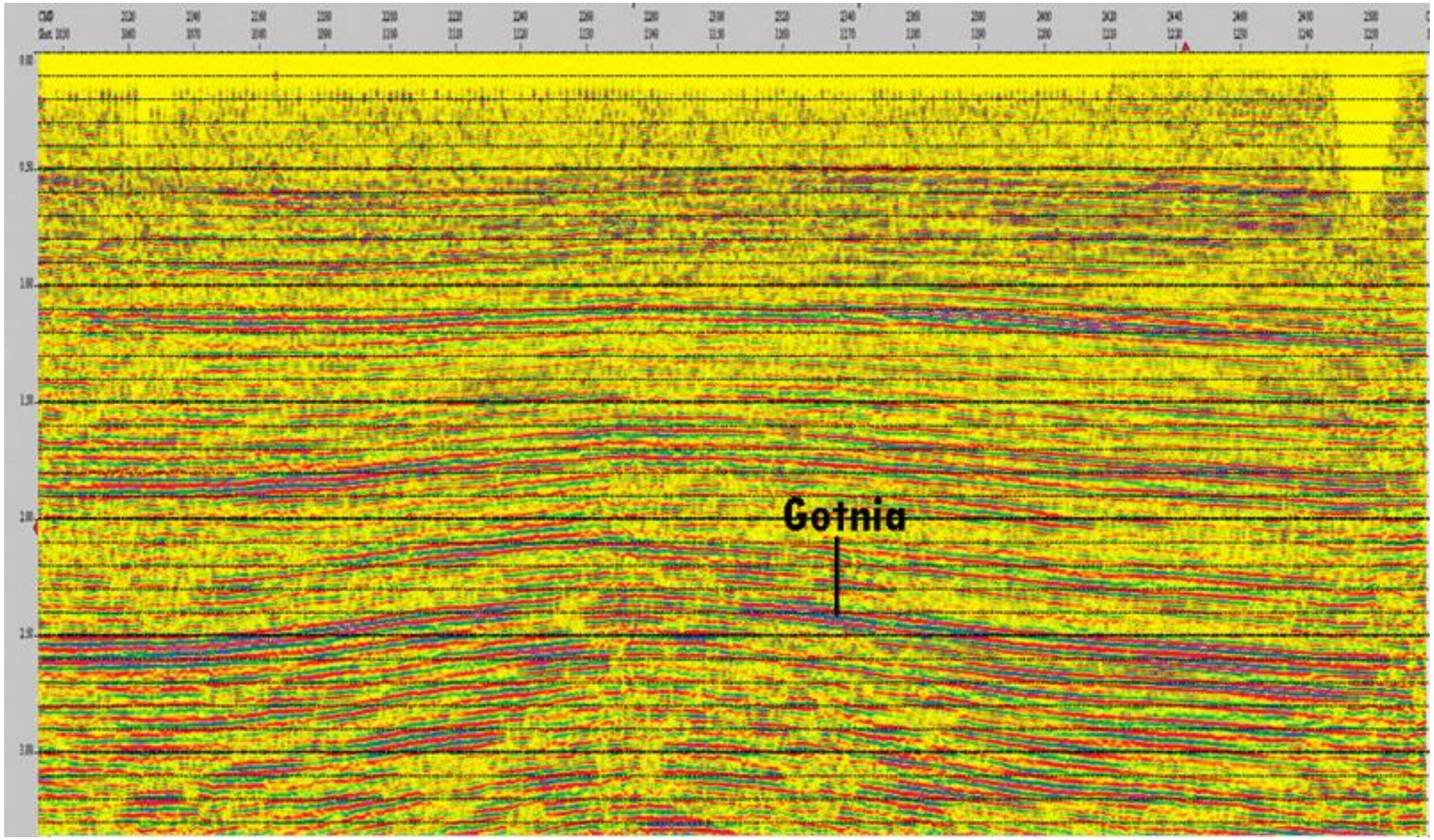


Figure 19a. “Final” seismic section with residual static corrections of West Qurna Field: Section paralleling part of length of field.



Section 19b. “Final” seismic section with residual static corrections of West Qurna Field: Section across width of field, through wells WQ-15 and WQ-17.

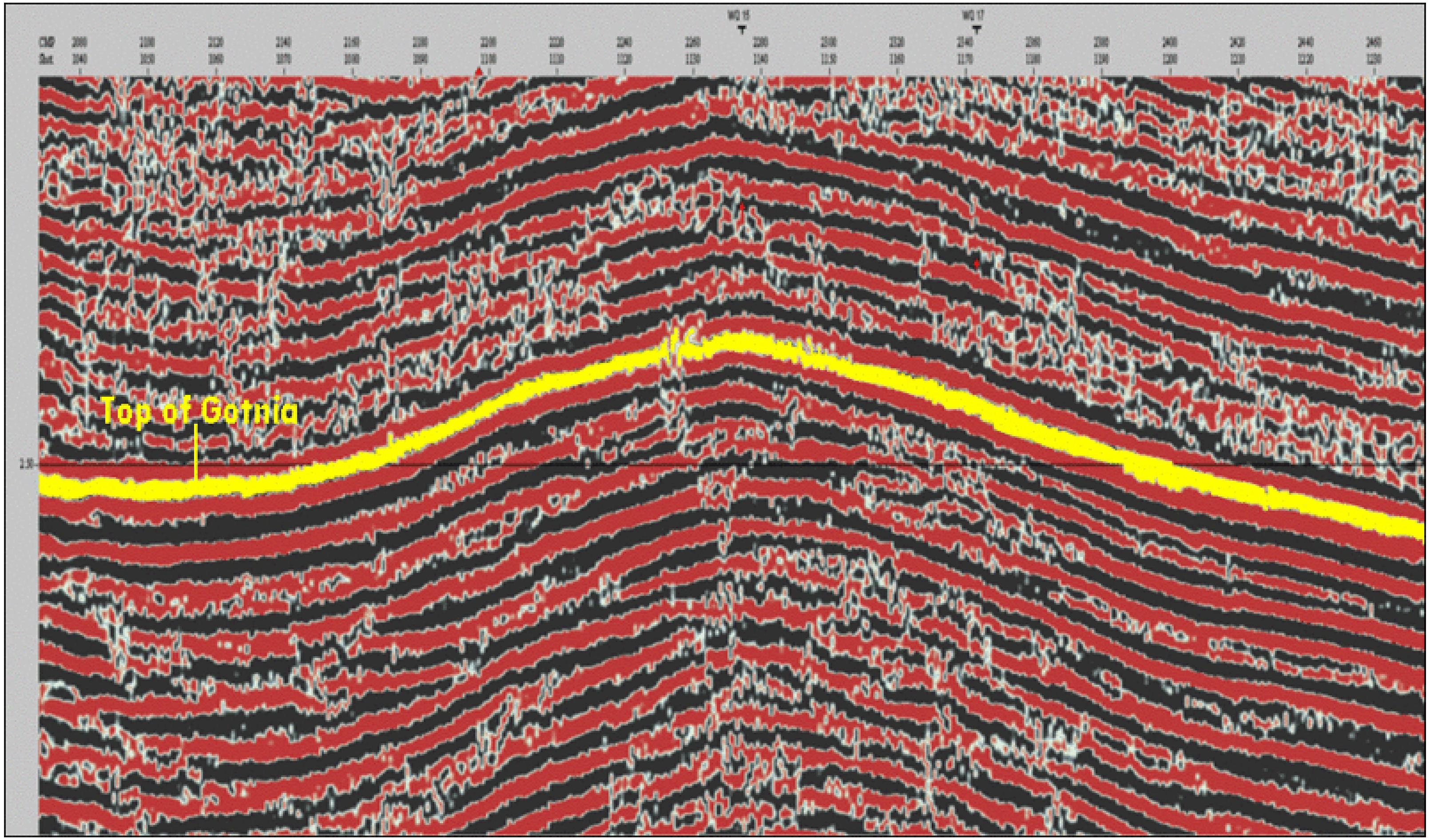


Figure 19c. Close view of the section in Figure 19b.

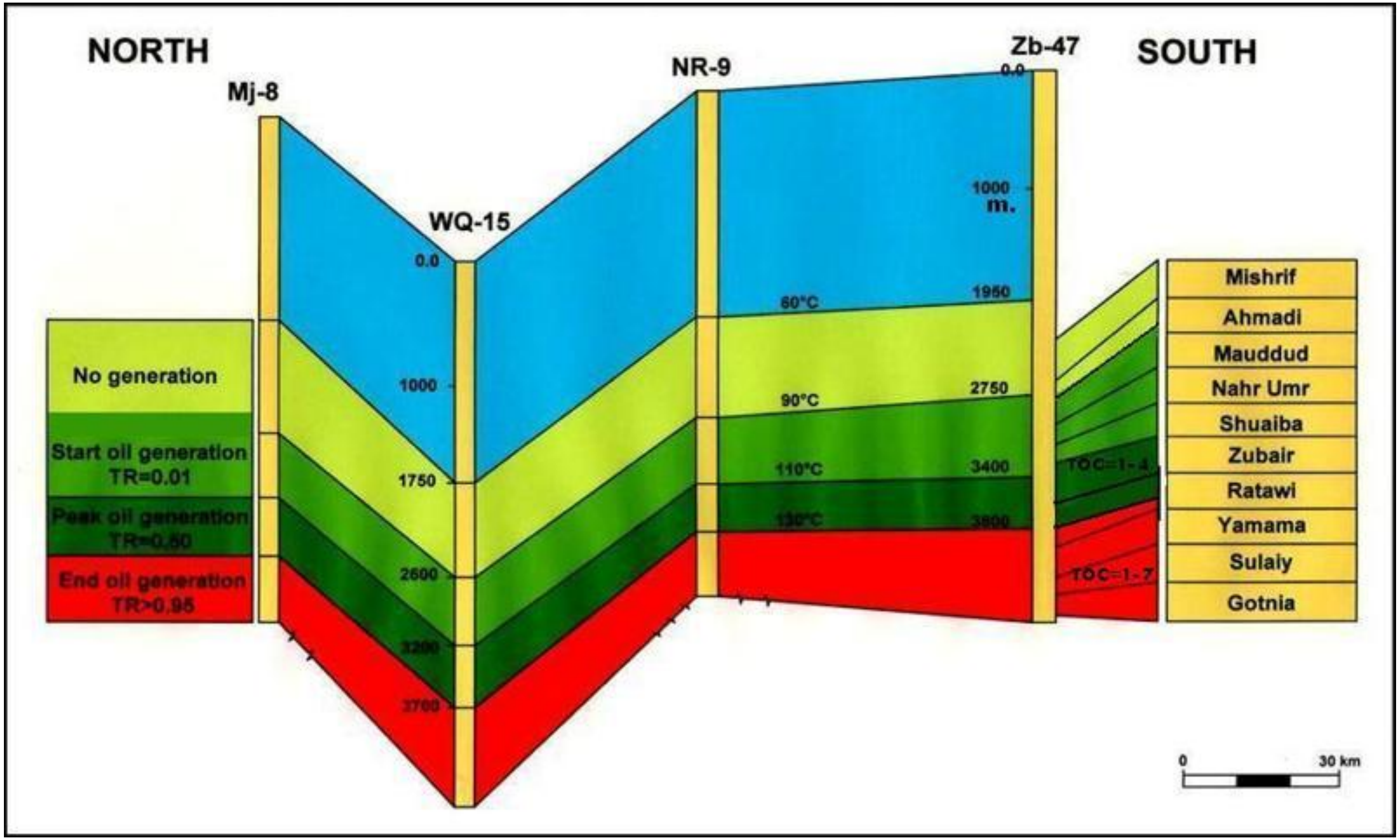


Figure 20. 2D well correlation diagram with superposed charge-model results for selected wells in Majnoon, West Qurna, Nahr Umr, and Zubair oil fields.

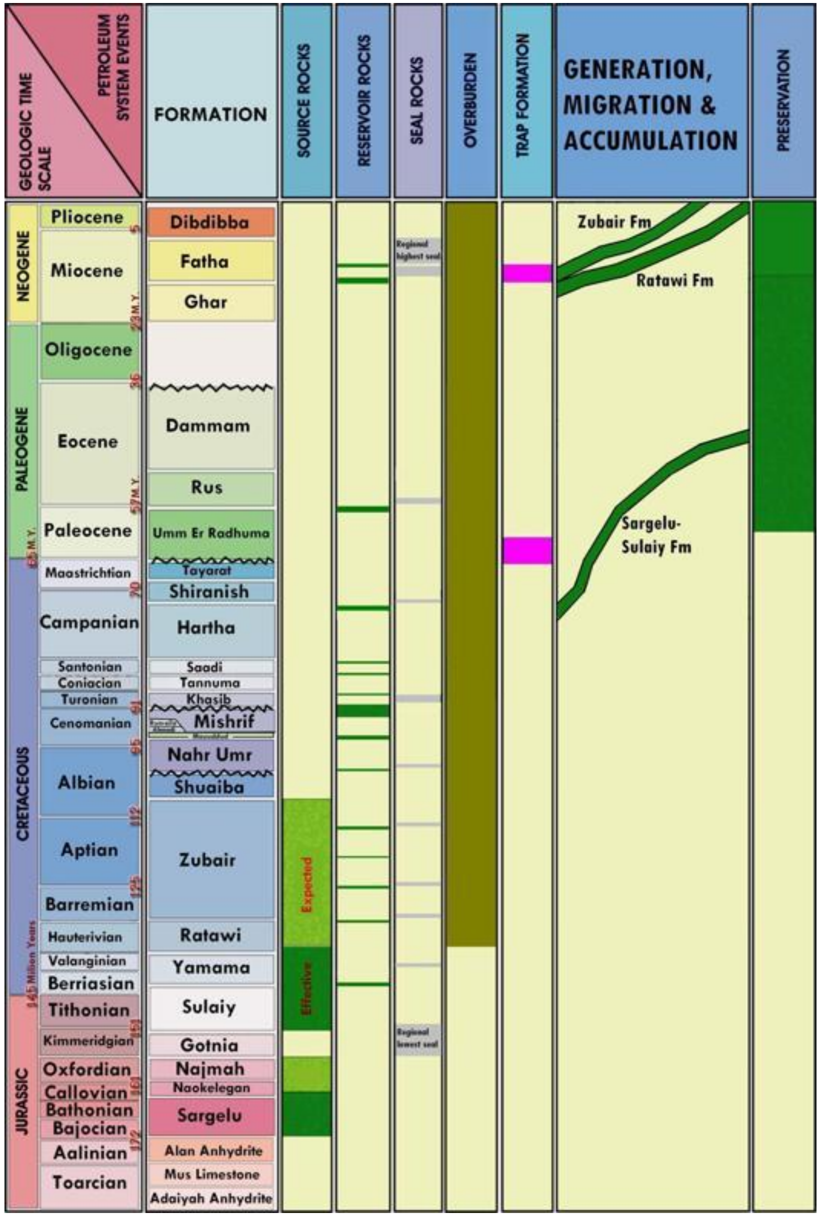


Figure 21. Petroleum systems events chart summarizing key elements of the hydrocarbon system in the Basrah area.

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