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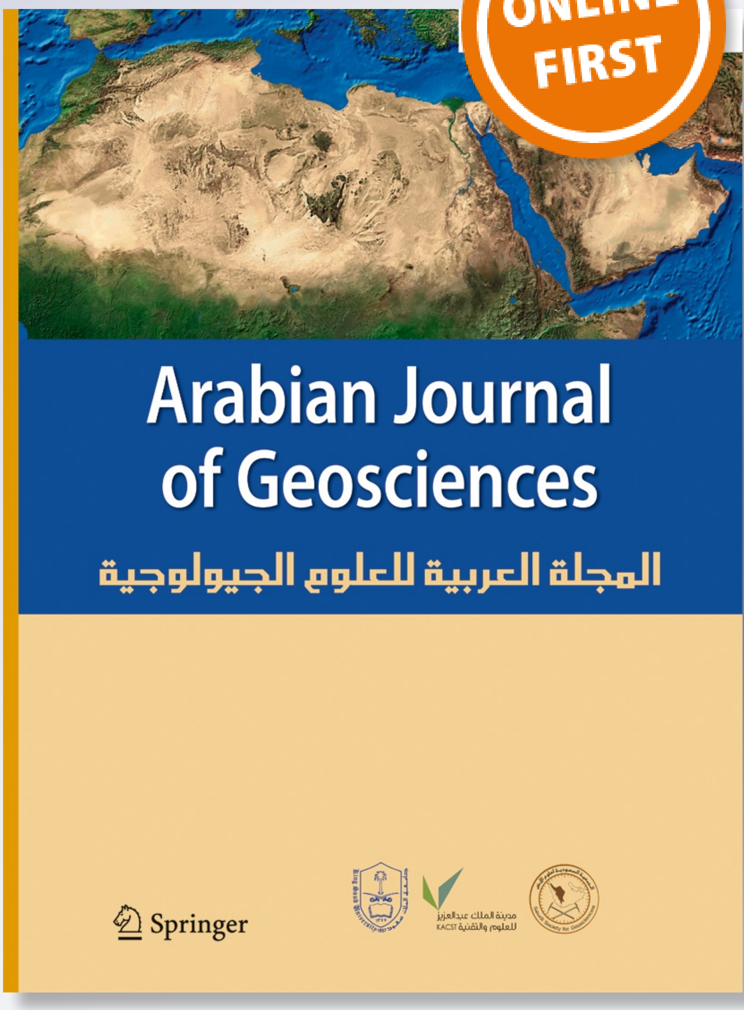

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ORIGINAL PAPER

Hydrocarbon potential of the Sargelu Formation, North Iraq

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Abstract Microscopic and chemical analysis of 85 rock samples from exploratory wells and outcrops in northern Iraq indicate that limestone, black shale and marl within the Middle Jurassic Sargelu Formation contain abundant oil-prone organic matter. For example, one 7-m (23-ft.)-thick section averages 442 mgHC/g S2 and 439 °C Tmax (Rock-Eval pyrolysis analyses) and 16 wt.% TOC. The organic matter, comprised principally of brazinophyte algae, dinoflagellate cysts, spores, pollen, foraminiferal test linings and phytoclasts, was deposited in a distal, suboxic to anoxic basin and can be correlated with kerogens classified as type A and type B or, alternatively, as type II. The level of thermal maturity is within the oil window with TAI=3^{-} to 3^{+}, based on microspore colour of light yellowish brown to brown. Accordingly, good hydrocarbon generation potential is predicted for this formation. Terpane and sterane biomarker distributions, as well as stable isotope values, were determined for oils and potential source rock extracts to determine valid oil-to-source rock correlations. Two subfamily carbonate oil types—one of Middle Jurassic age (Sargelu) carbonate rock and the other of Upper Jurassic/Cretaceous age—as well as a different oil family related to Triassic marls, were identified based on multivariate statistical analysis (HCA and PCA). Middle Jurassic subfamily A oils from Demir Dagh oil field correlate well with rich, marginally mature, Sargelu source rocks in well MK-2 near the city of Baiji. In contrast, subfamily B oils have a greater proportion of R_{28} steranes, indicating they were generated from Upper Jurassic/Lower Cretaceous carbonates such as those at Gillabat oil field north of Mansuriyah Lake. Oils from Gillabat field thus indicate a lower degree of correlation with the Sargelu source rocks than do oils from Demir Dagh field. One-dimension petroleum system models of key wells were developed using IES PetroMod Software to evaluate burial-thermal history, source-rock maturity and the timing and extent of petroleum generation; interpreted well logs served as input to the models. The oil-generation potential of sulphur-rich Sargelu source rocks was simulated using closed system type II-S kerogen kinetics. Model results indicate that throughout northern Iraq, generation and expulsion of oil from the Sargelu began and ended in the late Miocene. At present, Jurassic source rocks might have generated and expelled between 70 % and 100 % of their total oil.

Keywords North Iraq · Oil biomarkers · Middle Jurassic Sargelu Formation · Source rocks · Cretaceous–Tertiary reservoired oil

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Introduction

Oil fields of North Iraq are part of the Zagross Fold Belt in a regional extent and mainly within folded zone of elongated area between the thrust zone in the triple junction boundary with Iran, Turkey and the Mesopotamian Foredeep basin with Khleisya Uplift toward the southwestern part of North

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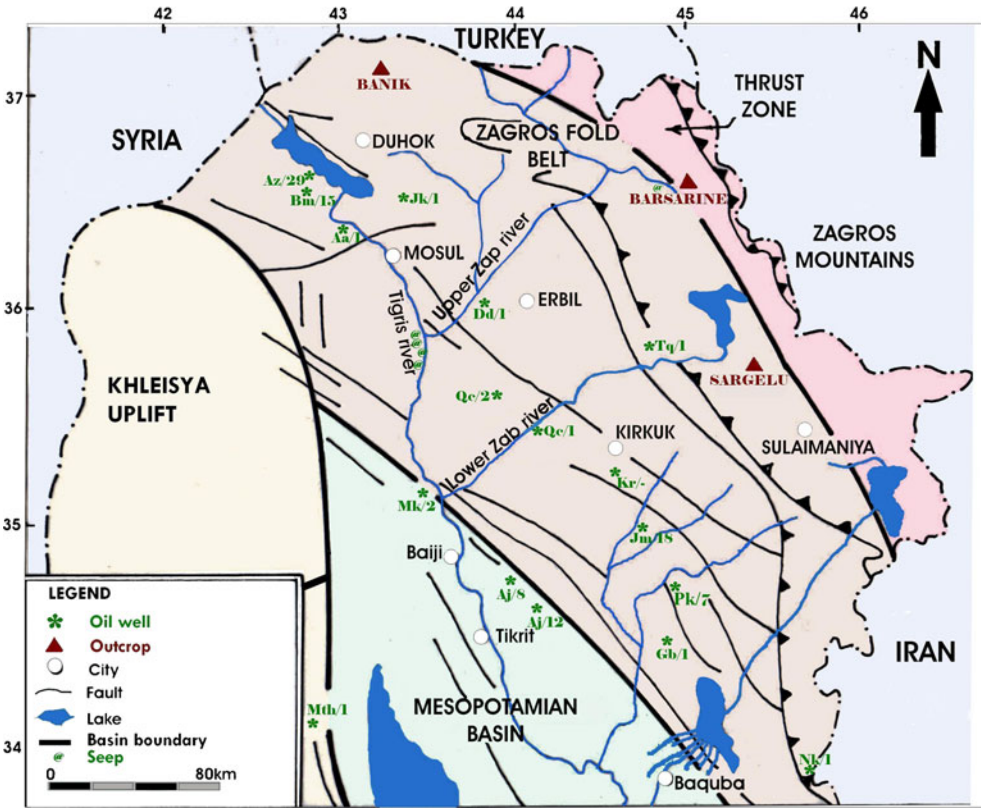

Fig. 1 Location map of Iraq showing studied area of North Iraq with locations of oil exploration wells, seep sites and outcrop sections

Iraq; well locations are plotted on location map of Fig. 1. Locating this studied area is according to Buday (1980), Al-Sharhan and Nairn (1997), Sharland et al. (2001), Aqrawi et al. (2010) and the Arabian Peninsula Basins map prepared by the US Geological Survey (Pollastro et al. 1999). North Iraq is the northeastern part of the Arabian Peninsula, which is a region of tectonic compression of particularly unstable area marked by convergent movements of the Arabian and Eurasian Plates that closed the Tethys palaeo-ocean and formed the Zagross Fold Belt in the northeastern part of the Arabian Plate. This belt contains folded strata and normal faults trending NW–SE in the northeastern part of the Arabian Peninsula toward Iran and turning E–W in its northern part toward Turkey.

Stratigraphically, the sections contain deposits of the Tethys Ocean during the Jurassic and Cretaceous Periods with more offshore eastward. That palaeo-ocean were of mainly dysoxic-anoxic palaeoenvironments along the equator and of tectonically unrest (Sharland et al. 2001) that permitted preservation of high organic matters and development of the highest world oil and gas reserve. The lithostratigraphic section (van Bellen et al. 1959) is constituting marine and subordinate lagoon beds deposited in the southern Tethys Ocean (Buday 1980) as sediment of carbonates, shale and anhydrites in a geologic time extending through the Jurassic, Cretaceous and Palaeogene up to the Middle Miocene Fatha (Lower Fars Anhydrite) Formation, with double plunging anticline closures extending NW–SE (Al-Sharhan and Nairn 1997) turning in the northwestern parts of Iraq, especially in the Sinjar Mountain to W–E trend (Dunington 1958).

A regional stratigraphic column (Fig. 2) shows the presence of a thick Jurassic and Cretaceous succession composed of carbonates, shales and anhydrites. The Jurassic Sargelu Formation is extending through the whole of North Iraq as well as South Iraq. At its type locality at Sargelu Bargelu village (Fig. 3) of the northern part of Sordash and eastern part of Dokan Dam localities within Iraqi Kurdstan, the formation is composed (van Bellen et al. 1959) of thin-bedded, black bituminous limestone, dolomitic limestones and black papery shale, with streaks of thin black chert in the upper part with fossils of mainly *Posidonia* spp., *Parkensonia* sp., *Stephanoceras* sp., *Rhynchonella* spp., plant fragments and poor impression of ammonites. They are overlain by the bituminous limestone and shale of the Upper Jurassic Naokelekan Formation with a contact of apparently gradational and conformable taken below thin-bedded, highly bituminous contoured beds without chert, and above thin-bedded black limestones with abundant chert and *Posidonia ornate*. The underlying formation is Lower Jurassic Allan Anhydrite Formation that marked the lowest regional seal.

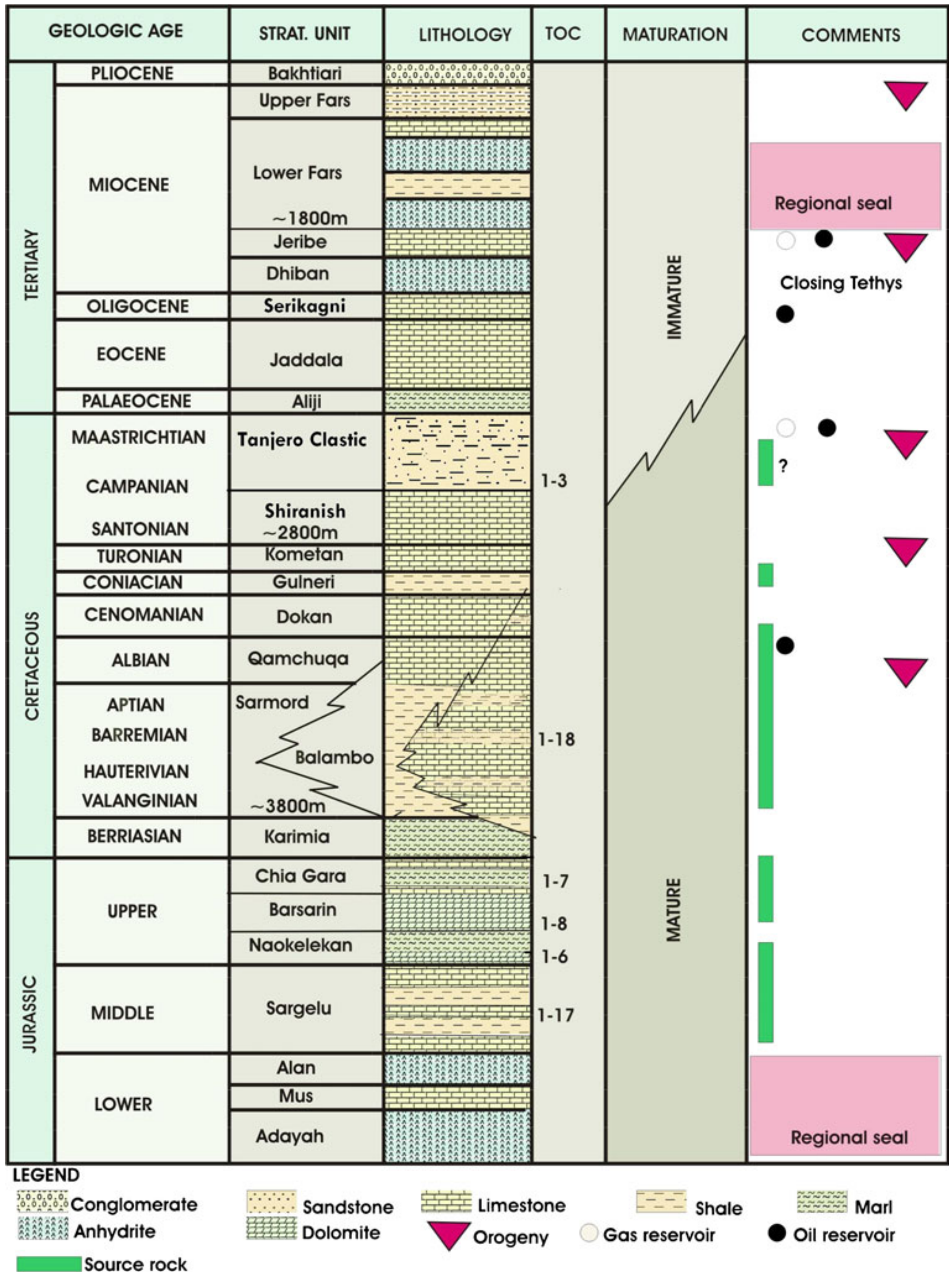

Fig. 2 Stratigraphic column of Northeast Iraq, Kurdistan Region with key source rock, seals and structural events

The aim of this study is to find the hydrocarbon potential of the Middle Jurassic Sargelu Formation in the northern part of Iraq and their charging efficiency to the oil and gas reservoirs of this studied area, as well as assessments of oil families and their source affinities.

Materials and methods

This study is based on analyses of core and cutting samples of shales and limestones, collected by Al-Ameri and Al-Ahmed, from selected wells (Fig. 1) and cover subsurface extensions (Fig. 4) in North Iraq. Samples comprised of the following:

– Seventy-five core samples of the Middle Jurassic Sargelu Formation from wells *Butmah 15* (depths 2,030–2,036 m), *Makhul-2* (2,256–2,453 m), *Taq Taq-1* (depths 3,244–3,338 m), *Qara Chuq-2* and *-1* (depths 1,554–1,651 and 2,664–2,671 m, respectively) and *Jabal Kand-1* (1,651–2,082 m) with ten samples from the type locality at Sargelu Bargelu village in Sulaimaniyah Governorate

Fig. 3 Photographs of the Sargelu Formation outcrop in its type locality section in the village of Sargelu Bargelu 40 km northwest of Sulaymaniyah City toward Dokan Lake. **a** Wide angle view of the whole Sargelu outcrop. **b** Sampling collection from the Sargelu outcrop

– Oil samples were collected from wells *Jambour-15*, from the Lower Cretaceous Qamchuqa Formation (depth 2,381.9 ft.), *Jambour-18*, from the Jeribe Formation (depth 1,840 ft.), *Baba 252* (*Kirkuk field*) from Baba Formation (depths 2,310 and 5,280 ft.) and *Shurau-1* (*Kirkuk field*) from depth 7,485.

Analytical techniques included biomarker analyses, palynofacies analyses and pyrolysis. Gas chromatography–Mass spectrometry and pyrolysis were performed by Geomark Research Ltd. in Houston, TX, USA, in 2005, while TOC screening and pyrolysis were performed in the Laboratories of the Iraq Exploration Oil Company in 1987–1989. Palynological slides are prepared by the second author in the geochemistry laboratory of the Department of Geology, College of Science, University of Baghdad, during his Ph.D. (Al-Ahmed 2006).

Oils biomarkers

Terpane and sterane biomarker distributions, as well as stable isotope values, were determined for oils of five oil fields from Cretaceous and Tertiary pays (Table 1) and potential source rock extracts of Jurassic–Lower Cretaceous strata to determine valid oil-to-source rock correlations in North Iraq. The crude oil samples are collected in this study from wells *Jambour-15*, from the Lower Cretaceous Qamchuqa Formation (depth 2,381.9 ft.), *Jambour-18*, from the Jeribe Formation (depth 1,840 ft.), *Baba 252* (*Kirkuk field*) from Baba Formation (depths 2,310 and 5,280 ft.), *Shurau-1* (*Kirkuk field*) from depth (7,485) and a sample from Geomark data base of well Demir Dagh-1.

To confirm the above-mentioned oil sources, comparison diagram of gas chromatography/mass spectrometry, biomarker sterane and terpane are evaluated in this study for source rock extracts with whole reservoir oil (Fig. 5). Accordingly, Middle Jurassic subfamily A oils from Demir Dagh oil field correlate well with rich, marginally mature, Sargelu source rocks in well MK-2 near the city of Baiji. In contrast, subfamily B oils have a greater proportion of R_{28} steranes, indicating they were generated from younger strata than Sargelu Formation, which belongs to the Upper Jurassic/Lower Cretaceous carbonates such as those at Gillabat oil field north of Mansuriyah Lake. The Upper Jurassic/Lower Cretaceous aged strata in Gillabat field is the Chia Gara Formation according to the matching with lexicon of Iraq by van Bellen et al. (1959). Oils from Gillabat field thus indicate a lower degree of correlation with the Sargelu source rocks than do oils from Demir Dagh field (Fig. 5), and hence, the most appropriate correlation of oil subfamily B might be with Upper Jurassic/Lower Cretaceous Chia Gara source rocks as in the case discussed by Al-Ameri et al. (2011).

Crude oil samples of the above-mentioned families are plotted on diagrams of tricyclic terpane C_{24}/C_{23} versus C_{22}/C_{21} (Fig. 6a), tetracyclic C24/tricyclic C23 versus ETR (TT C29/C27 Ts (Fig. 6b), tricyclic terpane C26/C25 versus hopane C31R/C30 (Fig. 6c) and hopane C29/C30 versus hopane C35S/C34S (Fig. 6d) for evaluating source rock type affinities. Presented in the diagrams of Fig. 6 are identified data points of average values for 150 oil samples from marine carbonate, distal marine shale, marine marl and lacustrine source rocks derived from the Geomark database (Zumberge et al. 2005; Al-Ameri et al. 2009) of global scattering for correlation with the plotted samples from this study. The plot indicates the affinity of the NE Iraq oil samples for a carbonate-rich source rock for oil family type A, carbonate and distal shale for oil family type B and carbonate and marl for oil family type C.

Plots of analyzed pristane/n-C17 versus phytane/n-C18 (Fig. 7) are affixed on pristine–phytane diagram of Hunt (1996) for evaluating kerogen types affinities and palaeoenvironments. The plots of this study indicate a low biodegradation and high maturation sources; the kerogen source is of mixed type II and III that accumulated in marine dysoxic (low oxidation and low reduction) palaeoenvironments of deposition.

The oil isotopic composition of δ 13C aromatic and saturate diagram (Fig. 8) could also document marine

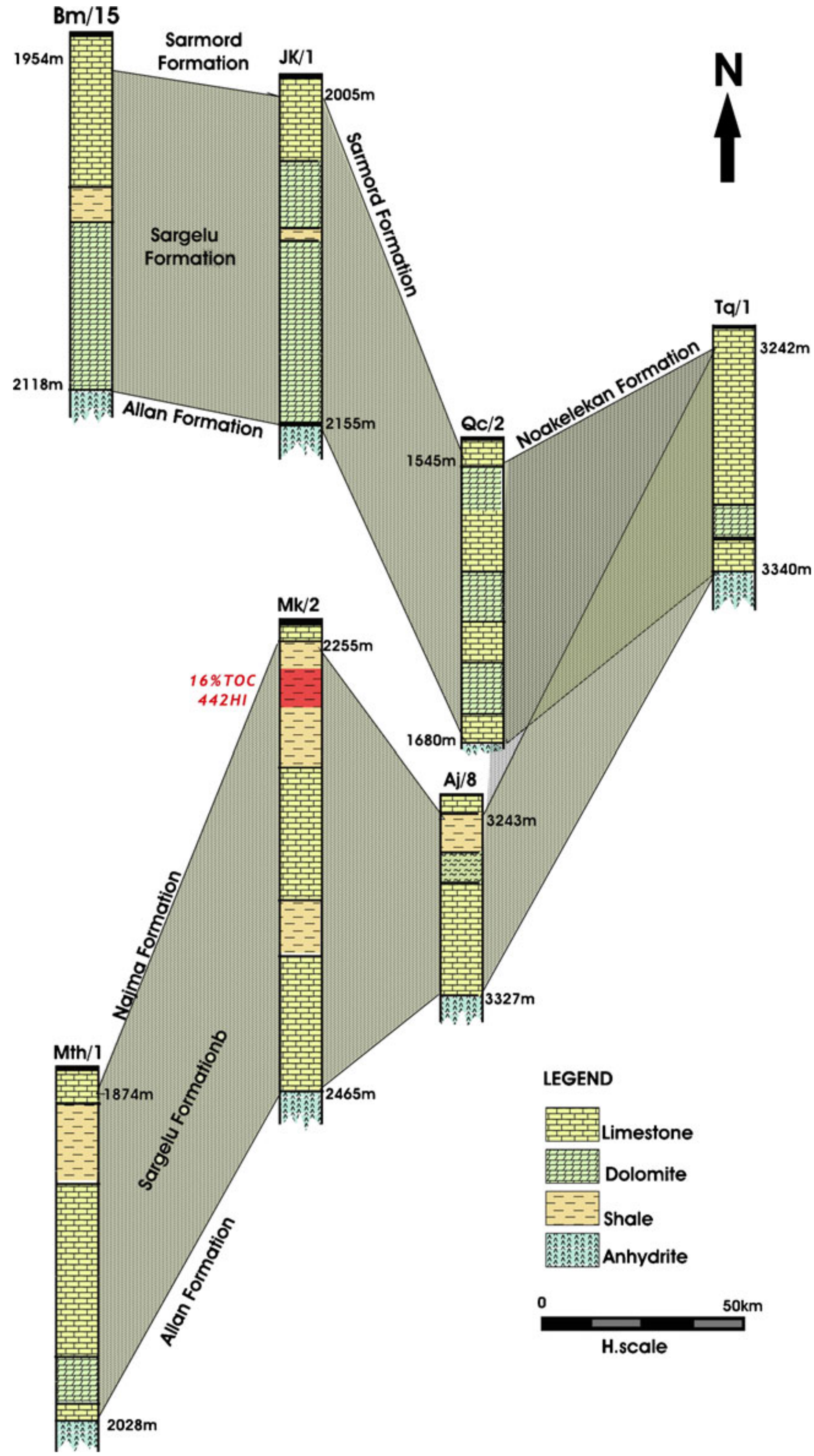

Fig. 4 Panel diagram of the suggested source rock formations in North Iraq

sources due to their position to the right of the Sofer (1984) line and of close position of the oil family type A and the seeps to the Sargelu source rock extract from wells Mk-2 and Qc-2, while oil family type B might have its closeness with the Sargelu as well as the Upper Jurassic–Lower Cretaceous source rocks of the Chia Gara Formation source rocks. The Triassic oil of NW Iraq is of completely different position that could correlate with other sources such as the Middle Triassic Kurrachine Formation of self-total petroleum system as mentioned by Al-Ameri et al. (2009).

Table 1 Analysis chart of GC and GC-MS oil biomarkers data for Cretaceous and Tertiary Formations in the studied oil-producing wells in North Iraq

No.	Field	Well	Depth (m)	Formation	C_{22}/C_{21}	C_{24}/C_{23}	Pr/nC_{17}	$Ph/n\ C_{18}$	$C_{31}R/H$	C_{26}/C_{25}	Age
1	KirKuk	Ba-252	700	Baba	0.71	0.37	0.29	0.33	0.34	0.78	Tertiary
2	KirKuk	Ba-252	1,760	Qamchyqa	0.93	0.31	0.20	0.27	0.34	0.77	Lower Cretaceous
3	Kirkuk	Shurau-1	2,443	Serikagni	0.67	0.41	0.29	0.33	0.34	0.74	Lower Cretaceous
4	Jambour	Ja-18	1,840	Jeribe	0.59	0.48	2.28	0.31	0.37	0.77	Middle Miocene
5	Jambour	Ja-15	2,381	Qamchuqa	0.58	0.43	0.31	0.33	0.36	0.83	Lower Cretaceous

Source rock assessment

Microscopic and chemical analysis were performed on 85 core and cutting samples (Table 2) from exploratory wells for Sargelu (Middle Jurassic) Formations, from wells Mk-2 of Makhul field, Qc-1 and Qc-2 of Qara Chuq field, Tq-1 of Taq Taq field, K-109 of Kirkuk field, Jk-1 of Jabal Kand field and Bm-15 of Butmah oil field, as well as outcrops in the villages of Sargelu Bargelu, Barsarin and Banik (locations in Fig. 1). Source rock assessments were based on Durand (1983), Tissot and Welte (1984), Hunt (1996) and Tyson (1995).

Pyrolysis analysis Source rock data obtained comprised total organic carbon (TOC) content in weight percentage and Rock-Eval results [S1, S2 and S3 in milligram hydrocarbon (HC) to gram of rock; Tmax, degrees Celsius; hydrogen index (HI, milligrams hydrocarbons per gram TOC) and production index, PI=S1/(S1+S2)]. Results are presented on diagrams of hydrogen index versus Tmax (Fig. 9) and production index (PI) versus Tmax (Fig. 10).

Their pyrolysate data and the plots indicated the presence of mixed kerogen types II and III with hydrogen index range of 90–385 mgHC/g TOC that suggest oil and gas prone, oil-window maturities of Tmax equals 432–450 °C with view

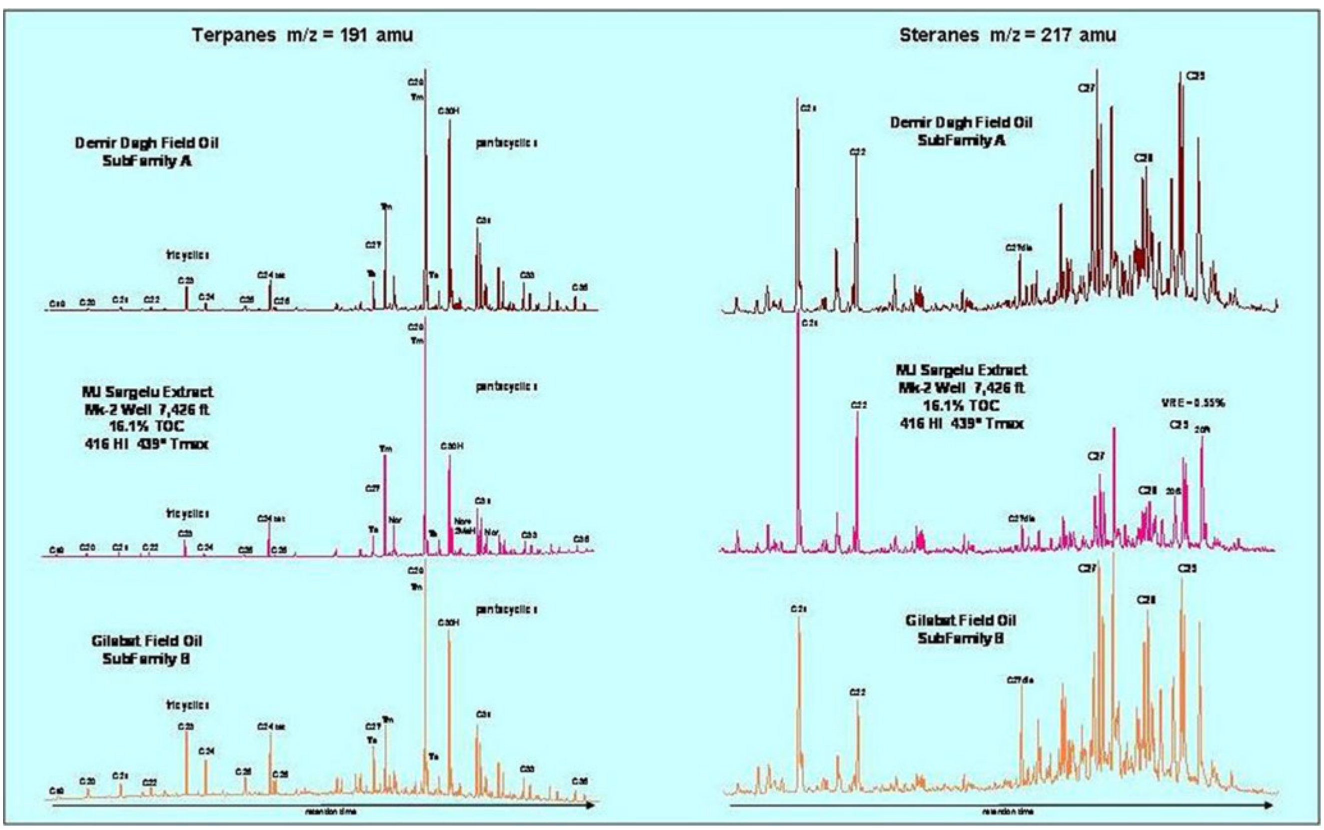

Fig. 5 Sterane and terpane biomarkers correlation diagram between Middle Jurassic Sargelu Formation extract and reservoir oils of the Gillabat and Demir Dagh oils showing close correlation of the Sargelu extract with Demir Dagh oil and slight correlation of the Sargelu extract with Gillabat oil, indicating Middle Jurassic Sargelu source affinity of the Demir Dagh oil and Middle Jurassic Sargelu Formation as well as the Upper Jurassic–Lower Cretaceous source rocks affinities

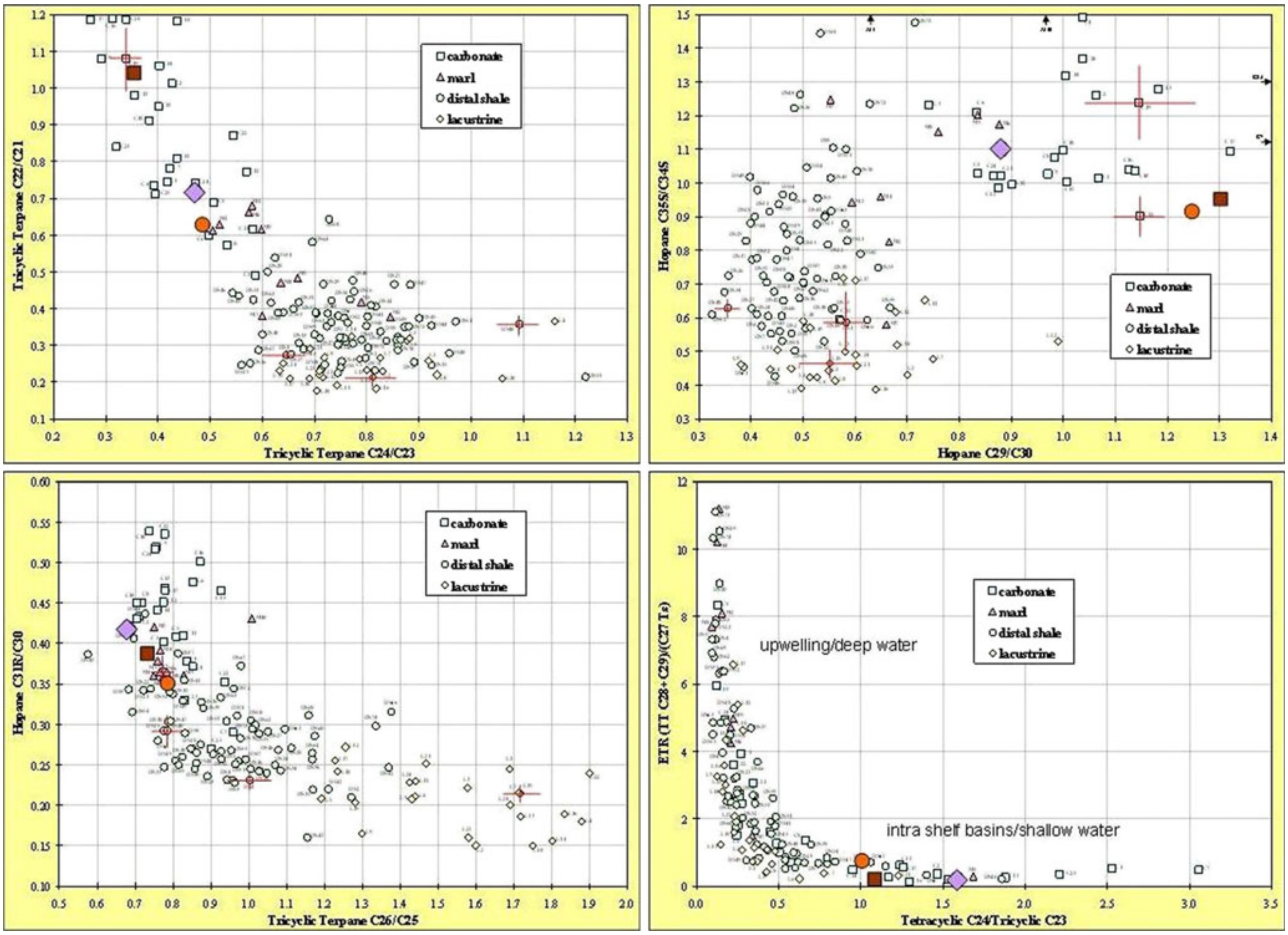

Fig. 6 Biomarker diagrams of this study analyzed oils for source rock type affinity for each oil family assessed in Fig. 5. Other data points represent average oil values from 150 global petroleum systems from marine carbonate, distal marine shale, marine marl and lacustrine shale source rocks from GeoMark Research OILS™ database. **a** Average tricyclic terpane ratios. **b** Tricyclic and ETR ratios. **c** Tricyclic and hopane ratios. **d** Average hopane ratios

plots of up to 580 °C that achieve production index of 0.05–0.70 [0.05–0.40 for the oil generation plus 0.41–0.55 for migrated oil according to Hunt (1996)] and very good petroleum potential (PP) of 0.58–50.90 KgHC/ton rock with very good generated hydrocarbons of up to more than 30 KgHC/ton rock from some strata that already have up to 17.81 wt.% TOC. For example, in a case study, one 7-m (23-ft.)-thick section of the Sargelu Formation averages 44.2 mgHC/g S2 and 439 °C Tmax (Rock-Eval pyrolysis analyses) and 16 wt.% TOC.

Hydrocarbon generation from the Sargelu Formation could be assessed as good to very good according to plots on the hydrocarbon generation diagram (Fig. 11). These generations are from rocks of 1–20 wt.% TOC that could generate 10,000 parts per million hydrocarbons of the total organic carbon of the rocks (10,000 ppm HC).

These generated hydrocarbons were expelled from the Sargelu formation to the nearest carrier bed according to the migration index (MI) of 0.35–1.46 mgHC/g TOC (Table 2), but oil accumulation might be below the seal of Upper Jurassic Gotnia Anhydrites in the south of the studied area where it presented with thick strata. On the other hand, the absence of the Gotnia seal in the north makes the possibility of migration of oil generated from the Middle Jurassic Sargelu Formation to the Cretaceous and Tertiary reservoirs. Comparison with Hunt (1996) studies could rate strata of the Sargelu Formation as of excellent expulsion efficiency.

Palaeoenvironments and age assessments Sargelu Formation is recognized in shaly limestone, marl, shale and limestone becoming more bituminous in wells Mk-2 and Tq-1 with total organic carbon of up to 17.81 wt.% of the rock in some strata. They have mainly marine algal components of up to 8 % of the palynomorphs and of 30–100 % amorphous organic matter (AOM) among the sedimentary organic matters and 02–50 % dinoflagellate cysts and acritarchs among the palynomorphs with up to 15 % foraminiferal test linings, fungi and bacteria (Figs. 12 and 13) and low reworked palynomorphs of

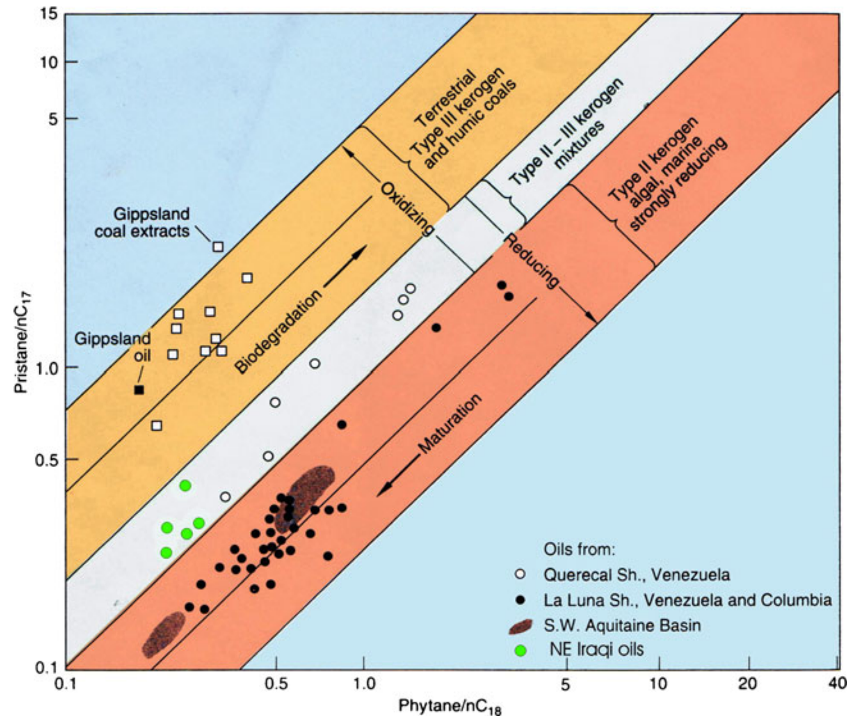

Fig. 7 Plot of pristane-n C_{17} versus phytane-n C_{18} (after Peters et al. 2005) for Cretaceous and Tertiary oils from the studied wells in North Iraq. The plot indicates that the oils from the reservoirs are mature, non-biodegraded and are derived from marine algal organic matter (kerogen types II and III) deposited in a reducing environment while the seeps of the same oil have moderate to high biodegradation

about 1 %. These high percentages of algae, dinoflagellate cysts and foraminifera lining could indicate transgression with upwelling current on outer neritic deeper marine deposition of the organic matters. All these environmental parameters mentioned above could assess highly oil-prone organic matters by comparison with North Sea studies of Tyson (1995) and Batten (1996a, b) and accumulated in mainly distal suboxic-anoxic basins that extended through Mesopotamian Basin and Zagross Fold Belt in Iraq, which can be classified as kerogen type A according to Thompson and Dembicki (1986) equivalent to kerogen type II according to their plot positions in van Krevelen diagram of Espetalie et al. (1977), Tissot and Welte (1984) and Hunt (1996).

Palynomorphs of the Sargelu Formation are illustrated in Fig. 13. They are recorded from rock samples of the oil fields Ajeel (well Aj-8) of depths 3,241–3,328 m, Qara Chuq (well Qc-1 and Qc-2) of depths 2,660–22,680 and 1,660–1,550 m, respectively, Makhole (Mk-2) of 2,480–2,240 m, Jabal Kand (well Jk-1) of depths 2,005–2,155 m and Taq Taq (well Tq-1) of depths 3,240–3,340 m, as well as the outcrops of 148 m thick in its type locality in the Sargelu Bargelu village, 48 m in the Banik village and 14 m in the Barsarin village. Van Bellen et al. (1959) had suggested Bajocian and Bathonian with probable early Callovian on fossil evidences of foraminifera, ammonite and radiolaria.

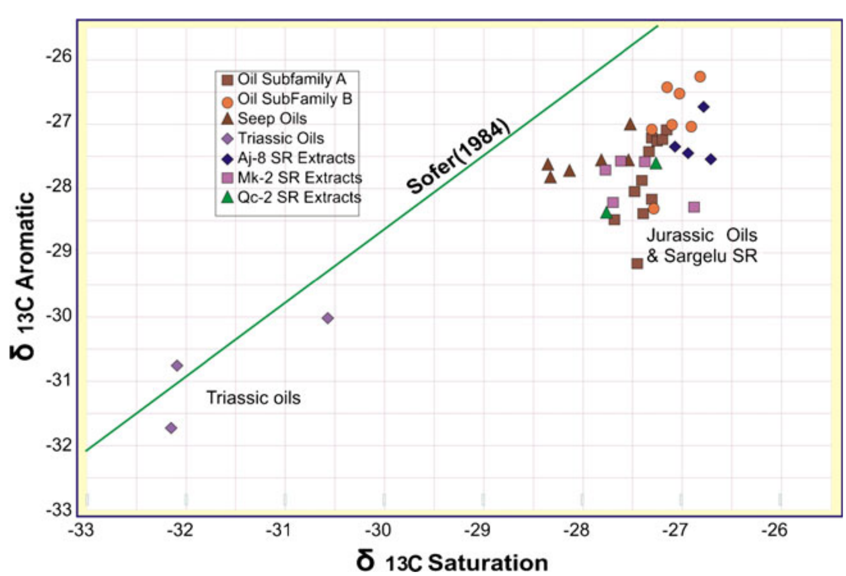

Fig. 8 Carbon isotope diagram of the Cretaceous and Tertiary reservoir oils and the extracts of the Sargelu source rocks illustrating oil families and their source affinity

Table 2 Rock-Eval pyrolysis data are tabulated for the Jurassic Formations in the studied wells, North Iraq

No of sample	Well name	Depth (m)	TOC	S1	S2	S3	Tmax (°C)	Calculated %Ro	HI	OI	S2/S3	S1/TOC	PI
1	Aj-8	3,241	11.81	5.57	45.33	0.95	449	0.92	386	8	48	47	0.11
2	Aj-8	3,248	10.20	3.61	27.06	0.84	447	0.89	265	8	32	35	0.12
3	Aj-8	3,252	1.07	0.95	1.77	0.65	445	0.85	165	52	3	89	0.35
4	Aj-8	3,253	3	1.85	0.33	0.49	439	0.74	211	16	13	62	0.23
5	Aj-8	3,262	2.27	1.59	3.22	0.63	443	0.81	142	28	5	70	0.33
6	Aj-8	3,267	1.05	0.47	1.87	1.61	446	0.87	178	110	2	45	0.20
7	Aj-8	3,271	1.09	0.72	1.45	0.55	445	0.85	133	50	3	66	0.33
8	Aj-8	3,273	1.03	1.50	2.82	0.44	437	0.71	274	43	6	146	0.35
9	Aj-8	3,282	1.42	1.19	2.33	1.09	439	0.74	164	77	2	84	0.34
10	Aj-8	3,287	0.73	0.60	0.67	0.43	445	0.85	92	59	2	82	0.47
11	Aj-8	3,292	1.09	1.12	2.42	0.70	441	0.78	222	64	3	103	0.32
12	Aj-8	3,296	1.21	1.10	1.63	0.68	439	0.74	135	56	2	91	0.40
13	Aj-8	3,300	1.26	1.02	1.79	0.62	447	0.89	142	49	3	81	0.36
14	Aj-8	3,306	0.55	0.32	0.26	0.26	450	0.94	47	47	1	58	0.55
15	Aj-8	3,311	1.62	0.75	1.82	0.51	444	0.83	112	31	4	46	0.29
16	Aj-8	3,312	0.66	0.57	1.32	0.49	441	0.78	200	74	3	86	0.30
17	Aj-8	3,320	1.09	1.00	1.15	0.54	446	0.87	106	50	2	92	0.47
18	Aj-8	3,328	1.05	0.66	1.02	0.47	446	0.87	97	45	2	63	0.39
19	Bm-15	2,030	2.07	0.42	3.91	0.27	446	0.87	189	13	14	20	0.10
20	Bm-15	2,031	0.54	0.22	0.55	0.22	444	0.83	102	41	3	41	0.29
21	Bm-15	2,032	3.18	0.83	6.42	0.29	446	0.87	202	9	22	26	0.11
22	Bm-15	2,033	0.35	0.24	0.25	0.81	442	0.80	71	51	1	69	0.49
23	Bm-15	2,034	0.48	0.19	0.27	0.11	444	0.83	56	23	2	40	0.41
24	Bm-15	2,035	0.22	0.06	0.01	0.07	399	−1.00	5	32	0	27	0.86
25	Bm-15	2,036	1.70	0.41	3.15	0.19	445	0.85	185	11	17	24	0.12
26	Mk-2	2,256	16.20	2.16	80.89	0.84	441	0.78	499	5	96	13	0.03
27	Mk-2	2,258	19.77	2.65	94.69	0.58	444	0.83	479	3	163	13	0.03
28	Mk-2	2,260	20.69	2.53	80.51	0.76	440	0.76	389	4	106	12	0.03
29	Mk-2	2,263	16.09	2.48	66.95	1.39	439	0.74	416	9	48	15	0.04
30	Mk-2	2,264	13.68	2.02	78.77	0.80	440	076	576	6	98	15	0.03
31	Mk-2	2,266	4.47	0.81	23.39	0.68	439	0.74	523	15	34	18	0.03
32	Mk-2	2,267	13.04	0.99	50.81	0.86	439	0.74	390	7	59	8	0.02
33	Mk-2	2,453	0.38	0.12	0.45	0.20	439	0.74	118	53	2	32	0.21
34	Tq-1	3,244	7.53	1.39	1.59	0.38	584	3.38	21	5	4	18	0.47
35	Tq-1	3,250	1.39	0.55	0.49	0.13	567	3.05	35	9	4	40	0.53
36	Tq-1	3,261	0.79	0.42	0.29	0.13	546	2.67	37	16	2	53	0.59
37	Tq-1	3,271	1.38	0.54	0.38	0.11	471	1.32	28	8	3	39	0.59
38	Tq-1	3,280	1.05	0.45	0.21	0.14	424	1.01	20	13	1	43	0.68
39	Tq-1	3,293	2.11	0.80	0.37	0.14	459	1.01	18	7	3	38	0.68
40	Tq-1	3,300	1.24	0.54	0.20	0.15	350	−1.00	16	12	1	44	0.73
41	Tq-1	3,304	2.02	0.10	0.03	0.29	486	1.59	1	14	0	5	0.77
42	Tq-1	3,305	0.00	0.00	0.01	0.11	396	−1.00	−1	−1	0	−1	0.00
43	Tq-1	3,306	0.78	0.01	0.01	0.01	438	0.72	1	17	0	1	0.50
44	Tq-1	3,307	0.16	0.00	0.02	0.03	479	1.46	13	19	1	0	0.00
45	Tq-1	3,308	0.88	0.02	0.02	0.02	473	1.35	2	25	0	2	0.50
46	Tq-1	3,309	1.73	0.11	0.01	0.26	472	1.34	1	15	0	6	0.92
47	Tq-1	3,317	1.83	0.21	0.00	0.28	−1	−1.00	0	15	0	11	1.00
48	Tq-1	3,320	1.76	0.09	0.00	0.24	−1	−1.00	0	14	0	5	1.00
49	Tq-1	3,330	1.65	0.08	0.00	0.24	−1	−1.00	0	15	0	5	1.00
50	Tq-1	3,338	1.37	0.06	0.00	0.21	−1	−1.00	0	15	0	4	1.00
51	Qc-2	1,554	0.97	0.41	3.65	0.36	436	069	376	37	10	42	0.10
52	Qc-2	1,562	0.85	0.35	5.77	0.11	438	0.72	679	13	52	41	0.06
53	Qc-2	1,567	1.12	0.38	3.99	0.40	435	0.67	356	36	10	34	0.09
54	Qc-2	1,571	1.28	0.33	4.84	0.36	437	0.71	378	28	13	26	0.06
55	Qc-2	1,576	0.69	0.24	4.82	0.27	435	0.67	699	39	18	35	0.05
56	Qc-2	1,583	0.86	0.18	2.41	0.31	435	0.67	280	36	8	21	0.07

Table 2 (continued)

No of sample	Well name	Depth (m)	TOC	S1	S2	S3	Tmax (°C)	Calculated %Ro	HI	OI	S2/S3	S1/TOC	PI
57	Qc-2	1,588	0.42	0.32	4.53	0.23	435	0.67	1,079	55	20	76	0.07
58	Qc-2	1,601	0.88	0.27	4.96	0.22	440	0.76	564	25	23	31	0.05
59	Qc-2	1,612	1.00	0.23	3.23	0.28	438	0.72	323	28	12	23	0.07
60	Qc-2	1,622	0.39	0.18	2.14	0.03	437	0.71	549	8	71	46	0.08
61	Qc-2	1,630	0.99	0.12	2.58	0.23	440	0.76	261	23	11	12	0.04
62	Qc-2	1,637	0.77	0.22	4.78	0.04	438	0.72	621	5	120	29	0.04
63	Qc-2	1,647	1.31	0.20	6.97	0.29	440	0.76	532	22	24	15	0.03
64	Qc-2	1,651	0.50	0.20	2.86	0.09	436	0.69	572	18	32	40	0.07
65	Jk-1	2,028	1.57	0.48	2.74	0.49	439	0.74	175	31	6	31	0.15
66	Jk-1	2,039	2.66	1.07	9.99	0.67	432	0.62	376	25	15	40	0.10
67	Jk-1	2,042	1.72	0.61	6.00	0.50	434	0.65	349	29	12	35	0.09
68	Jk-1	2,057	1.84	0.92	9.07	0.52	434	0.65	493	28	17	50	0.09
69	Jk-1	2,069	1.55	0.82	4.12	0.45	435	0.67	266	29	9	53	0.17
70	Jk-1	2,078	1.62	1.91	3.61	0.51	436	0.69	223	31	7	73	0.25
71	Jk-1	2,082	2.24	0.68	8.24	0.54	433	0.63	368	24	15	30	0.08
72	Qc-1	2,664	7.59	–	–	–	440	0.82	160	6	–	–	–
73	Qc-1	2,667	2.47	0.94	2.82	0.20	445	0.85	114	8	14	38	0.25
74	Qc-1	2,670	6.97	2.78	11.58	0.49	448	0.90	166	7	24	40	0.19
75	Qc-1	2,671	7.29	–	–	–	449	0.91	164	8	–	–	–
76	Outcrop	0	0.57	0.01	0.17	0.47	502	1.88	30	82	0	2	0.06
77	Outcrop	0	0.32	0.05	0.21	0.17	504	1.91	66	44	1	16	0.19
78	Outcrop	0	0.30	0.10	0.23	0.04	458	1.08	77	13	6	33	0.30

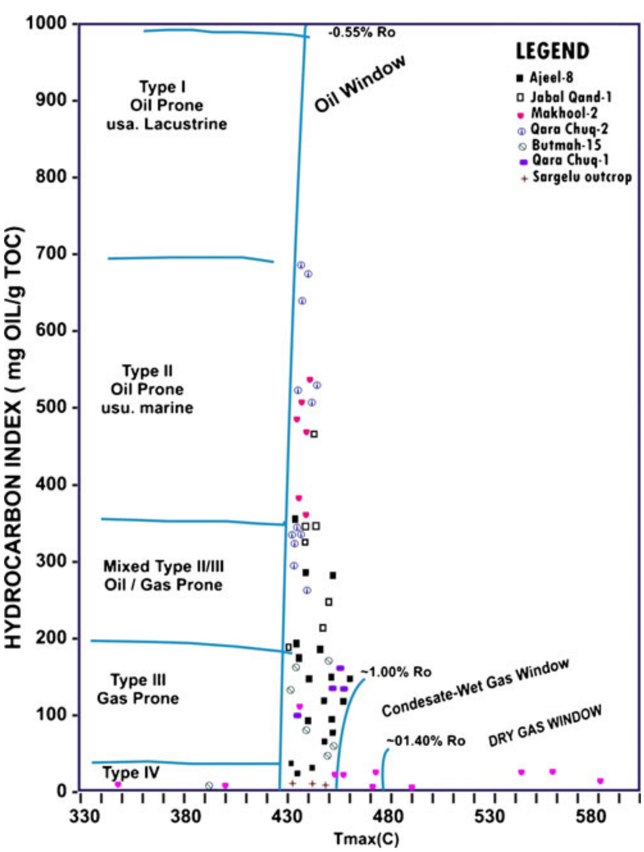

Fig. 9 Plots of the Rock-Eval analysis results (Hydrogen Index= HI, and Tmax) for potential source rocks from Table 2 in North Iraq for Sargelu Formation rocks in the wells of the studied oil fields and the Sargelu outcrop

The published ranges of all the dinoflagellate taxa encountered from the Sargelu Formation are in concurrent ranges through Bajocian, Bathonian and early Callovian ages, and hence, age assignments could be confirmed by the records of this study.

Maturation assessments for palynofacies in the Chia Gara Formation were based on the spore species *Gliechenidites* sp. (Fig. 13). Maturation based on thermal alteration index (following Staplin 1969) indicates the presence of mature organic matter of dark orange and light brown with TAI=2.9–3.1 for the Sargelu Formation.

Microscopic studies of the organic matters of Sargelu palynological slides showed the presence of kerogen type A (Thompson and Dembicki 1986) and mesoleptinite (sensu Rahman and Kinghorn 1995). Amorphous kerogen was distinguished by a mottled, interconnected network or a weakly polygonal texture. It usually occurs in large, compact masses (300–400 microns across) that show a red brown colour under transmitted light, brown to grey colour under reflected light, and fluorescence of patches or flecks of yellow to yellow grey under fluorescing light (Fig. 12). They are both interpreted as highly oil prone.

Modelling hydrocarbon generation

1D PetroMod (Schlumberger/Aachen Technology Centre) was used to model the burial history of wells of the Ajeel,

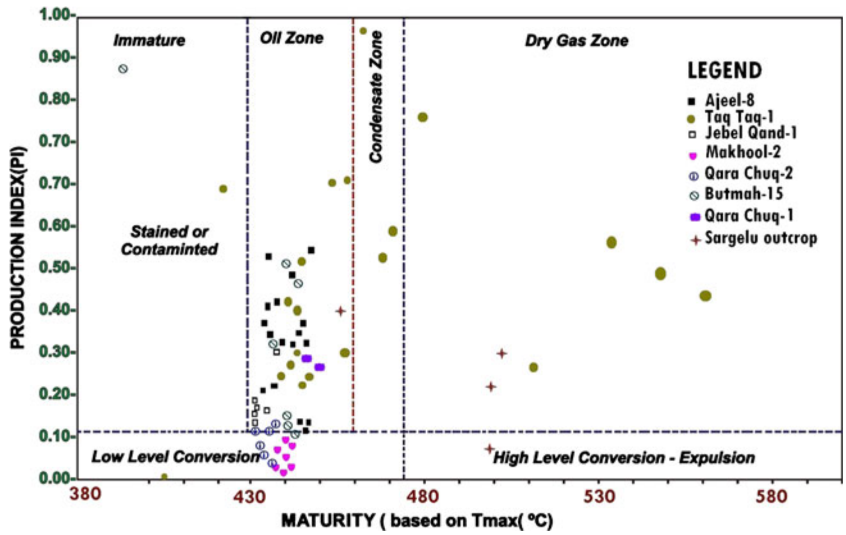

Fig. 10 Plots of Rock-Eval analysis for potential source rocks in North Iraq for Sargelu Formation rocks in the wells of the studied oil fields and the Sargelu outcrop in Tmax versus production index (PI)

Qara Chuq, Taq Taq, Jabal Kand and Butmah fields. Input data comprise formation depths in meters and associated lithologies, numerical ages in million years, well temperatures in degrees Celsius, erosional time (million years) and depths in meters, petroleum system element (as source, reservoir or seal), total organic carbon in percentage, source rock kinetics, and initial hydrogen index (milligrams per gram TOC) of wells Aj-8 (Ajeel Field), Qc-1 (Qara Chuq Field), Tq-1 (Taq Taq Field), Jk-1 (Jabal Kand Field) and Bm-15 (Butmah Field). The ages of depositional and erosional events were designated based on the geologic time scale of Sharland et al. (2001). Lithologies are modelled 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).

1D PetroMod requires calibration of the thermal regime (Fig. 14a) 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 II-S 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 sulphur (NSO=3–18 %).

The modelled vitrinite reflectance (Sweeney and Burnham 1990), as a measure of thermal maturity, indicates that sediments younger than the Mauddud (in well Aj-8), Qamchuqa (in well Tq-1) and Shiranish (in well Bm-15) Formations remain immature (sensu Tissot and Welte 1984), whereas the deeper formations, including the suggested source rocks by chemical analysis, reached thermal maturity. Modelled organic matter (type II-S) transformation ratios (following Lewan and Ruble 2002 and Peters et al. 2005), defined as the ratios between measured hydrocarbon potential of a rock sample divided by the original hydrocarbon potential, are interpreted (Fig. 14b). Transformation started in the Late Cretaceous, while its peak generation and the end generation reached their maximum in the Neogene. Organic transformation is complete

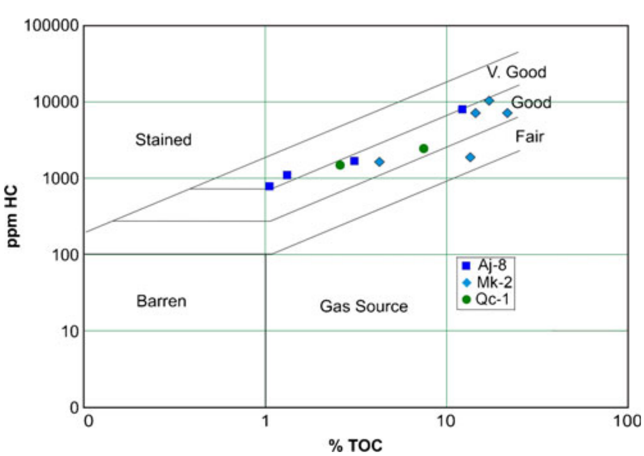

Fig. 11 Plots of TOC versus part per million hydrocarbons (ppm HC) generated for hydrocarbon generation assessment of the Sargelu Formation in Ajeel, Makhole and Qara Chuq oil fields

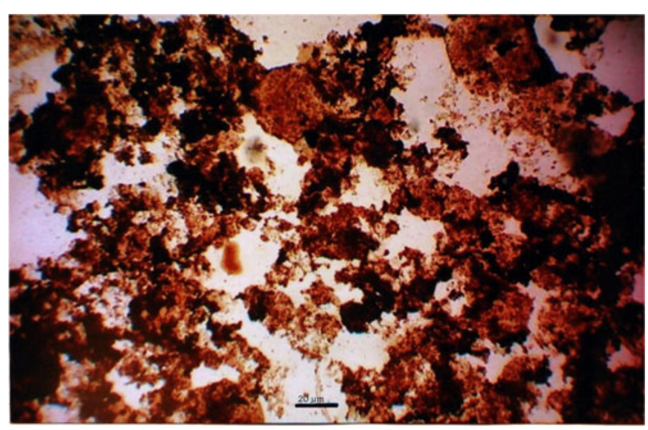

Fig. 12 Microscopic view of kerogen under refracted light from well *Ajeel 12* for Sargelu Formation. *Scale bar= 20 µm*

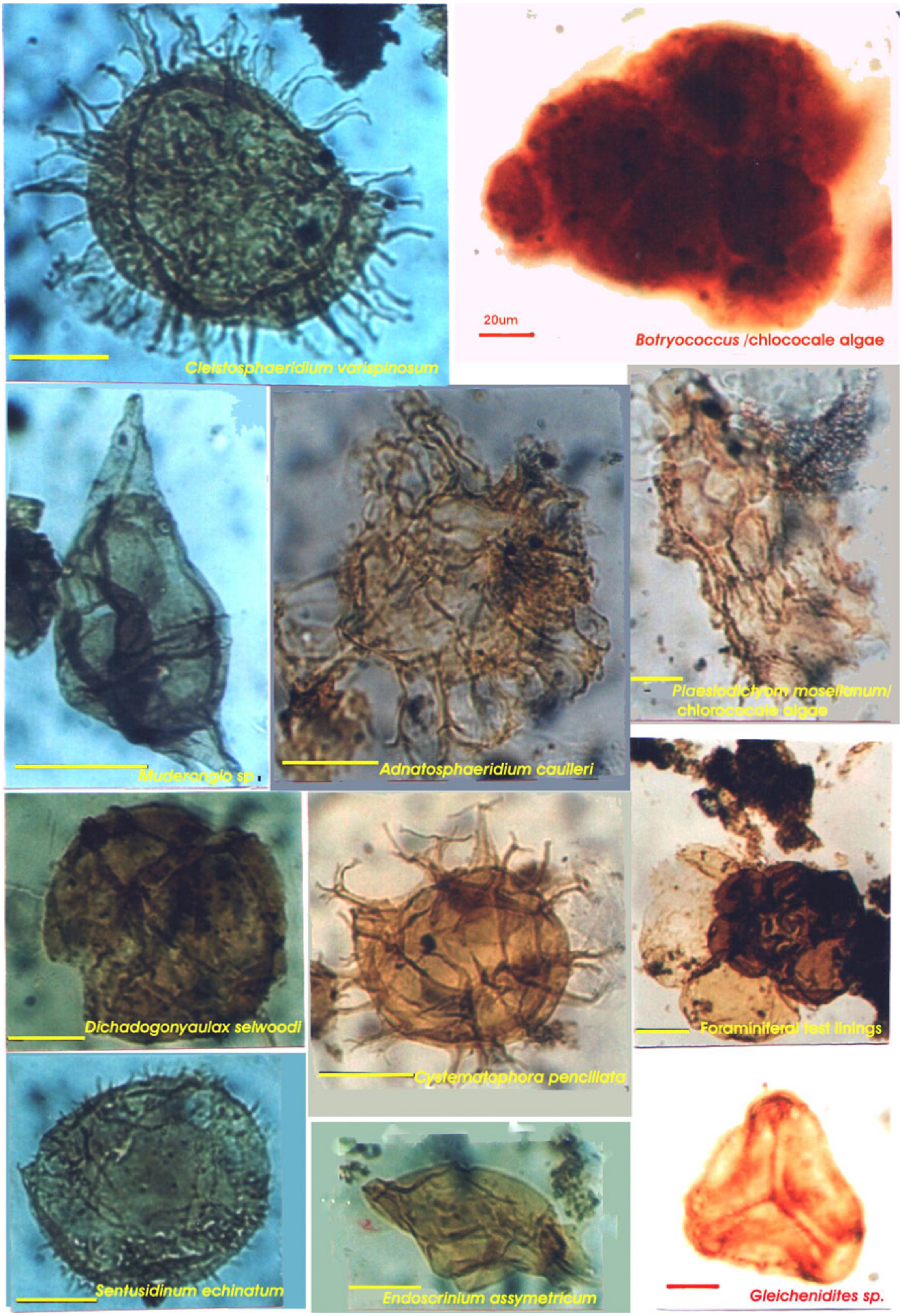

Fig. 13 Dinoflagellate cysts, algae, foraminifera and spore of the Sargelu Formation (Bajocian–Bathonian and early Callovian age) of North Iraq

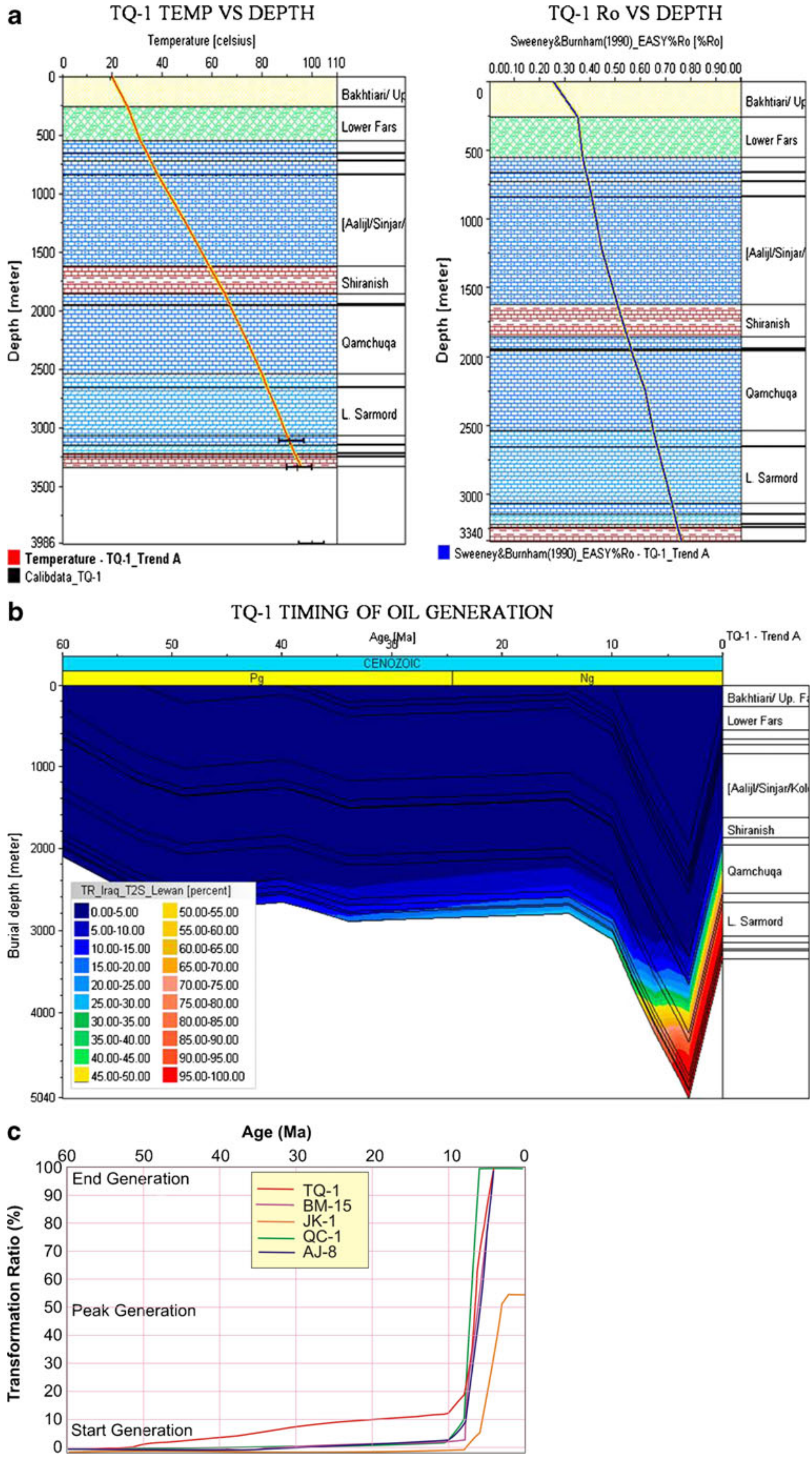

Fig. 14 1D PetroMod software modelling of (**a**) temperature versus depths with vitrinite reflectance (R_0) equivalence for well Tq-1 of the Taq Taq oil field as an example, (**b**) timing of oil generation with depths and time for each formation in well Tq-1 of the Taq Taq oil field as an example and (**c**) transformation ratios extent of the Sargelu formation in all of the studied wells

(TR>0.95, T=120–140 °C) for the Sargelu Formation in the studied wells.

The modelled timing and extent of oil and gas generation events in the area of study are only approximate due to the complex fold geometry in the region; nevertheless, they can be assessed from transformation ratios on each locality. For example, by taking the case of extent of oil generation of the Sargelu Formation (Fig. 14), the Sargelu Strata in all the studied wells (Aj-8, Qc-1, Tq-1 and Bm-15) have generated 100 % of their organic matter potentiality to generate mainly during six to four million years ago in the Miocene time, while well Jk-1 has generated only 70 % of its potentiality because of its shallower depth than the other studied wells.

Accordingly, at present, Sargelu source rocks might have generated and expelled between 70 % and 100 % of their total oil in time of less than ten million years ago, which is equivalent (by comparison with Sharland et al. (2001) and Aqrawi et al. (2010)) to the Zagross Orogeny that caused the close up of the New Tethys Ocean in a convergent plate collision between the Arabian and Eurasian plates and formed structural folding and faulting closures for oil accumulation, as well as faults or the passage of oil in its vertical migration till it seeps to the surface in some outcrop cuts.

Conclusions

Oil accumulated in the Cretaceous and Tertiary reservoirs are of two subfamily carbonate oil types—one of Middle Jurassic age Sargelu carbonate rock (family A) and the other of mixed Sargelu with Upper Jurassic/Lower Cretaceous age (family B)—and another oil family related to Triassic marls. Their identification in North Iraq is based on multivariate statistical analysis (HCA and PCA) and terpane and sterane diagram fitting of the oil with their appropriate source rock extracts.

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