



Oil And Gas Generation History Based On Burial History Reconstruction And Thermal Maturity Modeling Of Petroleum Systems In Northern Iraq

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Abstract:

Burial history, thermal maturity, and timing of hydrocarbon generation were modeled for five key source-rock horizons at five locations in Northern Iraq. Constructed burial-history locations from east to west in the region are: Taq Taq-1; Qara Chugh-2; Zab-1; Guwair-2; and Shaikhan-2 wells. Generally, the thermal maturity status of the burial history sites based on increasing thermal maturity is Shaikhan-2 < Zab-1 < Guwair-2 < Qara Chugh-2 < Taq Taq-1. In well Qara Chugh-2, oil generation from Type-IIS kerogen in Geli Khana Formation started in the Late Cretaceous. Gas generation occurred at Qara Chugh-2 from Geli Khana Formation in the Late Miocene. The Kurra Chine Formation entered oil generation window at Guwair-2 and Shaikhan-2 at 64 Ma and 46 Ma, respectively. At Zab-1, the Baluti Formation started to generate gas at 120 Ma. The Butmah /Sarki reached peak oil generation at 45 Ma at Taq Taq-1. The main source rock in the area, Sargelu Formation started to generate oil at 47, 51, 33, 28, and 28 Ma at Taq Taq-1, Guwair-2, Shaikhan-2, Qara Chugh-2, and Zab-1, respectively. The results of the models demonstrated that peak petroleum generation from the Jurassic oil- and gas-prone source rocks in the most profound parts of the studied area occurred from Late Cretaceous to Middle Oligocene. At all localities, the Sargelu Formation is still within the oil window apart from Taq Taq-1 and Qara Chugh-2 where it is in the oil cracking and gas generation phase.

Keywords: Burial history, PetroMod, Taq Taq-1, Zab-1, Qara Chugh-2, Guwair-2, Shaikhhan-2

تاريخ نشوء النفط والغاز القائم على إعادة بناء هيكل تاريخ الدفن وتصميم النضوج الحراري لأنظمة البترول في شمال العراق

المستخلص:

تم تصميم تاريخ الدفن و النضج الحراري و توقيت توليد الهيدروكربونات على غرار آفاق صخور المصدر الرئيسية في خمسة مواقع شمال العراق و هي طق-١، قره جوغ-٢، زاب-١، گویر-٢، و شيخان-٢ مرتبة من الشرق الى الغرب . بشكل عام، و حالة النضج الحراري لمواقع تاريخ الدفن بناءً على زيادة النضج الحراري هي شيخان-٢، زاب-١، گویر-٢، قره جوغ-٢، طق-١. في بئر قره جوغ-٢، وقد بدأ توليد النفط من الكيروجين من نوع الثاني الغني بالكبريت (IIS) المتواجد ضمن التكوين كليخانة في أواخر العصر الطباشيري. و قد حدده توليد الغاز من التكوين كليخانة في بئر قره جوغ-٢ في العصر الميوسيني المتأخر. و دخل تكوين قره جابن إلى نافذة توليد النفط في بئر گویر-٢ و شيخان-٢ قبل ٦٤ مليون و ٤٦ مليون سنة، على التوالي. في زاب-١، وكما بدأ التكوين البلوطي بتوليد الغاز قبل ١٢٠ مليون سنة. ووصل تكوين ساركى/بطمة الى ذروة توليد النفط عند ٤٥ مليون سنة في بئر طق-١. بدأ الصخرة المصدرية الرئيسية، تكوين سرگلو، في المنطقة بتوليد النفط في ٤٧، ٥١، ٣٣، ٢٨ و ٢٨ مليون سنة في طق-١، گویر-٢، شيخان-٢، قره جوغ-٢ و زاب-١، على التوالي. أظهرت نتائج التصاميم أن ذروة توليد البترول من الصخور الجوراسية المولدة للنفط والغاز في الأجزاء الأكثر عمقاً في المنطقة التي تمت دراستها حدثت من أواخر العصر الطباشيري إلى الاوليگوسيني الأوسط. في جميع المناطق، ولا يزال تكوين سارگلو داخل نافذة النفط في المنطقة باستثناء طق-١ و قره جوغ-٢ حيث يقع التكوين في مرحلة تكسير النفط وتوليد الغاز.

Introduction:

A petroleum system as defined by Magoon and Dow [1] is “a pod of active source rock and all genetically related oil and gas accumulations. It includes all of the geologic elements and processes that are essential if an oil and gas accumulation is to exist”. The petroleum system is a combining conception that includes all of the different elements and processes of petroleum geology, including: the necessary elements (source, reservoir, seal, and overburden) and processes (trap formation, generation, migration, and accumulation).

This study abridges the burial history, thermal maturity, and timing of petroleum generation at five locations for five key petroleum system source rock horizons in

Kurdistan region, Iraq to reduce petroleum exploration risk. The studied area covers most of south-southwestern, northwestern, and eastern regions of Erbil City Figure (1). The key horizons are the Middle Triassic Geli Khana, Upper Triassic Kurra Chine, Upper Triassic Baluti, Lower Jurassic Butmah/ Sarki, and Middle Jurassic Sargelu Formations.

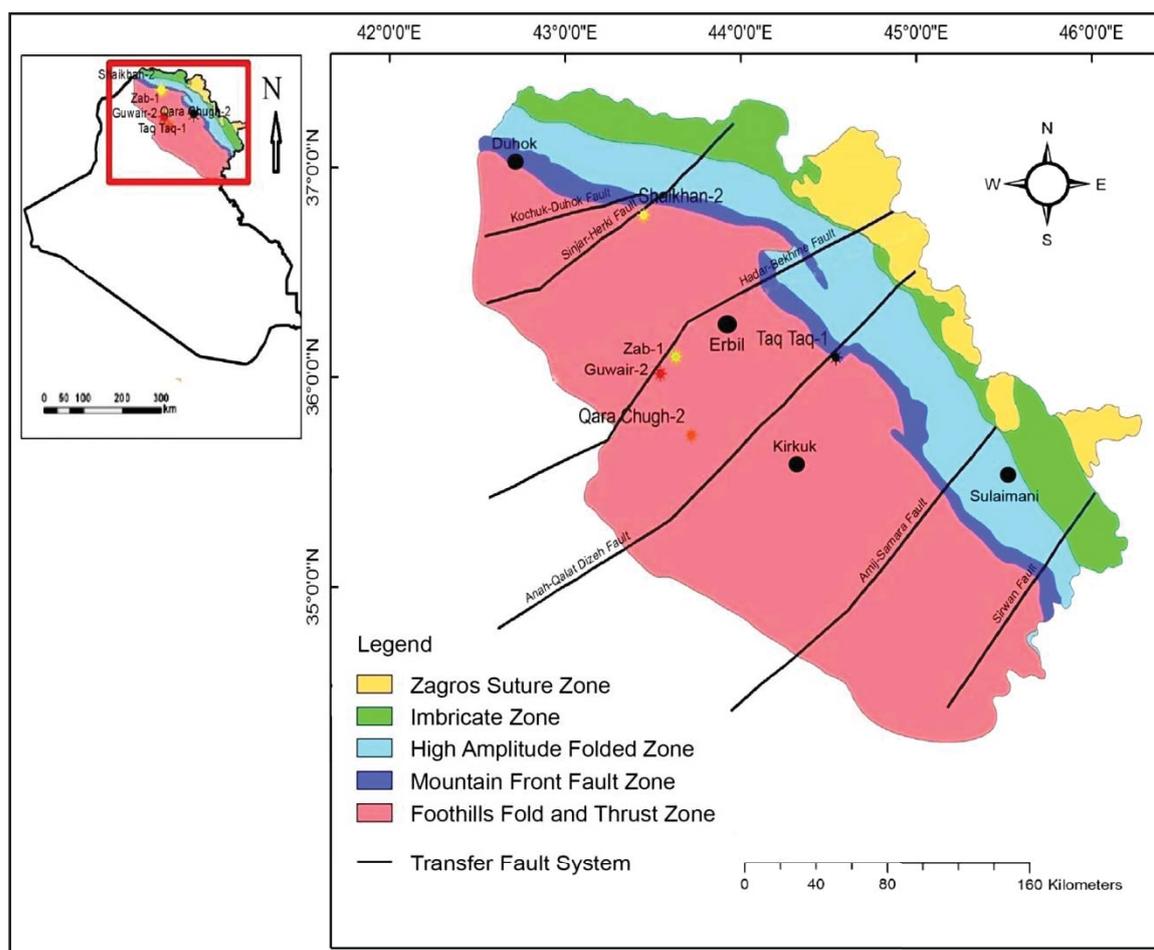


Fig. (1) Index map of Iraqi Kurdistan showing the locations of the studied wells [2].

Stratigraphy:

The area of Iraqi Kurdistan region is wide and has complex stratigraphy; therefore combining some of the stratigraphic units is needed. The 1-D model includes 37 formations from the base of the Middle Triassic Geli Khana Formation to the Miocene Upper Fars (Injana) Formation. The Lower Jurassic Butmah and Sarki are

combined and the Upper Jurassic Naokelekan is present only at the burial-history locations that are on the Shaikhan-2 and Taq Taq-1 wells (Fig. 1). The age equivalent unit to Naokelekan Formation, in the Low Folded Zone, is the Najmah Formation [9, 10, 11]. The Naokelekan Formation is transitional to the south with the neritic and restricted lagoonal Najmah Formation [9]. Thus, the Najmah Formation occurs in the Qara Chugh-2, Zab-1, and Guwair-2. The Cretaceous stratigraphy and nomenclature is complex within the region and these units do not comprise main source rocks. The Lower and Middle Cretaceous Group in the region comprise of numerous formations whose names differ from site to site. The rock units of the Cretaceous Group that are above the Jurassic unconformity at the base of the limestone are alluded to as the lower part of the Garagu/ Yamama Formation. The interval below the unconformity is alluded to as the upper part of the Jurassic formations.

There is no proof for this unconformity at Shaikhan-2 Well [12]; accordingly, the whole interim is alluded to as the Lower-Middle Cretaceous formations combined and named informally inferable from multifaceted interfingering relationships of the beds. Each of Qamchuqa, Maudud, and Jawan rocks is joined. The nomenclature differs for the Upper Cretaceous sequence that includes the Bekhme, Shiranish, Hartha, Sa'adi, and Tanuma within the region. Lower Tertiary units are additionally joined as a result of the complex interfingering relationship among the Aalajji, Kolosh, Sinjar, Khurmala, Gercus, Jadala, Pilaspi, and Avanah across the region. To simplify tables and figures in this review, we allude to this interval as "Aalajji (and reciprocals)".

The unconformity within the Triassic between Kurra Chine and Baluti Formations [3] probably does not represent a significant amount of erosion in the region that would affect the thermal maturity of the non-penetrated underlying formation source rocks.

It is included an erosional event between the Middle Jurassic Sargelu and Upper Jurassic Najmah Formations and between Najmah and Garagu Formations at Qara Chugh-2, Guwair-2, and Zab-1 wells to burial-history [9]. Elsewhere in the Shaikhan-2 and Taq Taq-1, these two unconformities do not exist because the contact between Sargelu and Naokelekan Formations is gradational with no unconformity [9, 13]. In the same way, the gap between Lower Sarmord Formation and underlying Chia Gara Formation does not exist [3] at the Taq Taq-1 Well, but the gap exists between Chia Gara and Garagu Formations at Shaikhan-2 Well.

More than one hiatus exists within the Lower Cretaceous formations [3, 14]. A hiatus for the unconformity at the base of Qamchuqa, Dokan, and Gulneri Formations at Taq Taq-1 Well is applied [3, 9]. At well Zab-1, the Upper Qamchuqa (Maudud) Formation unconformably rests on Upper Sarmord Formation. The unconformity between Upper Sarmord and Jawan/ Qamchuqa, Upper Sarmord and Jawan/ Qamchuqa, Upper Sarmord and Upper Qamchuqa (Maudud), Upper Sarmord and Jawan/ Qamchuqa, and Middle Sarmord and Qamchuqa Formations is included at Shaikhan-2, Guwair-2, Zab-1, Qara Chugh-2, and Taq Taq-1, respectively [3]. In the same way, the depositional break or non-deposition on the top of Qamchuqa or its equivalents is included in all localities, excluding Shaikhan-2 and Zab-1 wells where Kometan Formation rests unconformably on Jawan/ Qamchuqa Formation directly, the Dokan Formation rests unconformably on Qamchuqa and its equivalents in other wells. In well Guwair-2 and Taq Taq-1, the Gulneri Formation overlies Dokan Formation but in Zab-1, Gulneri Formation is not present and Kometan Formation overlies Dokan Formation while in Qara Chugh-2 this depositional hiatus does not occur as Ahmedi and Mishrif Formations are overlying Dokan Formation conformably. The Upper Cretaceous formations are represented by Wajnah and Aqra in Shaikhan-2, Bekhme and Shiranish in Guwair-2, only Shiranish in Zab-1 and Taq Taq-1 with significant depositional breaks. On the contrary, in Qara Chugh-2, the Upper Cretaceous formations that unconformably rest on Mishrif Formation are represented by Khasib, Tanuma, Sa'di, Hartha, and Shiranish Formations occur without any depositional break [3, 9, 15].

The unconformity is also included between Tertiary Aalaji and Maastrichtian Shiranish Formations in all locations except well Shaikhan-2. In Shaikhan-2 Well, the Aalaji Formation overlies the Aqra Formation unconformably. The Kolosh Formation rests on Aalaji Formation conformably in Taq Taq-1, Zab-1, and Guwair-2 wells while Kolosh Formation is absent in Shaikhan-2 and Qara Chugh-2 [12, 16]. In the latter well, the Jadala Formation which underlies Oligocene rocks unconformably rests directly on Aalaji. The Gercus and Pilaspi Formations overlie the Kolosh Formation in well Zab-1 and Shaikhan-2. In Shaikhan-2 Well, the Khurmala, Gercus and Pilaspi Formations rest over Aalaji Formation. In this well, the contact between Khurmala and Gercus is gradational and conformable while basal

conglomerate which designates unconformity separates Gercus and Pilaspi Formations. The Gercus Formation is absent in well Guwair-2 and Avanah Formation instead of Pilaspi Formation overlies the Khurmala Formation. The Paleocene-Eocene formations are well represented in well Taq Taq-1 and they are from older to younger in addition to Aalaji and Kolosh are Sinjar, Khurmala, Gercus, and Pilaspi Formations [17].

In Iraqi Kurdistan, the Oligocene unconformity occurs in all locations excluding Qara Chugh-2 Well. The maximum erosion amount or non-deposition above Pilaspi Formation is documented in Shaikhan-2 Well where Pilaspi Formation outcrops to surface. The erosion and/or non-deposition occur in Taq Taq-1, Guwair-2, and Zab-1 where Lower Fars (Fatha) Formation overlies unconformably the Pilaspi Formation or its equivalent, Avanah Formation. In the latter well, the Upper Fars (Injana) Formation overlies the Lower Fars (Fatha) Formation. At Taq Taq-1 and Guwair-2 wells, among Oligocene, Miocene, Pliocene, and Pleistocene rocks only Middle Miocene Lower Fars (Fatha) Formation is present [17, 18]. The geology of areas adjoining the Shaikhan region is used to estimate the post-Eocene sedimentation and erosion due to the absence of post-Eocene rocks preservation. Accordingly, the amount of post-Eocene deposition is estimated at 2900m [12]. In the same way, the amount of post-Oligocene deposition is estimated at 2500m for Qara Chugh-2 locality [16].

Methodology:

The studied wells are modeled for burial history using one-dimensional modeling software and thermal maturity are performed on five well locations (Fig. 1) utilizing PetroMod1D Express (version 1.1) of Integrated Exploration Systems GmbH (IES), Germany. The one dimensional internment history models are point sites, primarily wells. The well sites are selected because (1) they are drilled to a depth that penetrated a substantial part of the geologic section under study, (2) they represent different geologic settings within the region, and (3) they have measured T_{max} , and down-hole temperature data to help in calibrating maturation models.

Ages of stratigraphic units are assessed using the time scale of the Lexique Stratigraphique International [3] as a guide for the generalized ages of stratigraphic

components and times of regional unconformities throughout the region. Additionally, modifications made since 1959 are taken into consideration regarding the age of the beds and unconformities. The ages at system and sequences boundaries were attuned to the International Commission on Stratigraphy [4].

Thickness of the stratigraphic units is inferred from geophysical logs or is determined from tops of units recorded in the final reports. Thicknesses of eroded sections denoted by unconformities in the subsurface are modified from published MSc thesis, PhD dissertations, published books, reports, and papers. Lithologies of the stratigraphic units are also deduced from strip logs and final well reports and are summed up and connected for displaying purposes. The exact sources from which the erosion values have been taken are mentioned in the following sections.

The thermal conductivities and heat capacities with their thermal properties of different rock types are either user characterized or programming default estimates. The bottom-hole temperatures are acquired from well-log headers of the particular wells used in modeling.

The T_{\max} values and their mathematically calculated % R_o equivalent, determined by Rock-Eval pyrolysis, are used for calibration. The T_{\max} values are reported by Abdula [5] and Abdula [6]. It is plausible to assume that heat flow varied through time, but it is not required to make assumptions about the time of heat flow changes because using a constant heat flow through time resulted in a suitable context of designed % R_o values, as decided by EASY% R_o [7] with the measured % R_o values. The mean surface temperature for the entire burial-history sites is assumed to be 21 °C according to recorded data by Iraqi Meteorological Organization and Seismology-Kirkuk Station for years 2010-2015 and the results from this study. This mean surface temperature is 4 °C less than the data that were used by Pitman et al. [8] for southern Iraq.

Results:

Burial History

The present depth (Table 1) is less than the calculated maximum depth of burial. Consequently, intended temperatures at extreme depth for the source-rock prospects

from the burial-history restorations are different from the present temperature. The following is a brief description of the burial history at each of the locations.

Table (1) The current thickness of burial beds from different geological times at five localities in Iraqi Kurdistan.

Name of Location	Triassic Sediments Thickness (m)	Jurassic Sediments Thickness (m)	Cretaceous Sediments Thickness (m)	Tertiary Sediments Thickness (m)	Total Sediments Thickness (m)	Thickness over Sargelu (m)	Total Eroded Beds (m)	Total Eroded Beds during Tertiary (m)
Taq Taq-1		1554	1493	1570	4617	3242	2705	2135
Qara Chug-2	1927	1122	1095	274	4418	1552	3768	2600
Zab-1	352	1930	610	1586	4126	2575	3542	2875
Guwair-2	569	1588	795	885	3837	2130	2686	1734
Shaikhan-2	728	1077	1000	495	3300	1706	4010	3020

Taq Taq-1

This well is located on the crest of the Taq Taq anticline, which is about 13km southeast of Koi Sanjak Figure (1). The well was completed in 1978 [17]. The Taq Taq structure is a slightly asymmetrical anticline some 29km long and about 11km wide with a general northwest-southeast trend. This structure is situated immediately southwest of the Kurdistan Orogenic Mountain Zone [17]. Only minor faults are recorded at the surface. Dips are generally slightly steeper on the southwest flank. Closure on top of the Pilaspi with the Baba Bawi structure of the main orogenic belt is in the order of 610m [17]. The structural trap occurred by Early Eocene (Fig. 2A) during Alpine Orogeny. The Alpine Orogeny started in the Late Mesozoic after deposition of the main Middle and Upper Jurassic source rocks in the region.

During Jurassic, the sediment accumulation rate appears to be fairly constant and continuous; a total of 1554m of sediments of this age was deposited in this area. This amount of sediment is roughly the same amount that was preserved at Guwair-2 site, but more than what was preserved at Qara Chugh-2 and Shaikhan-2 locations and less than what was preserved at Zab-1 area (Table 1). Dissimilar to Jurassic, during Cretaceous, the sediment buildup rates seem to be fairly constant and comparatively

fast, a maximum thickness (1493m) of sediments of this age was deposited in this area, more than what was deposited at other modeled localities. The high amounts of foreland basin sediments (3705m) were deposited during Tertiary but the majority of these deposits (2135m) were removed. Its burial-history curves are similar to Shaikhan-2, especially the steep decline of the curve at 11.6 Ma representing the rapid increase in subsidence/sedimentation rate during deposition of Upper Fars Formation in Taq Taq-1 and during deposition of Pilaspi Formation in Shaikhan-2 at 33 Ma. The time of maximum burial (5850m) is 11.6 Ma for stratigraphic units in this part of the region (Fig. 3).

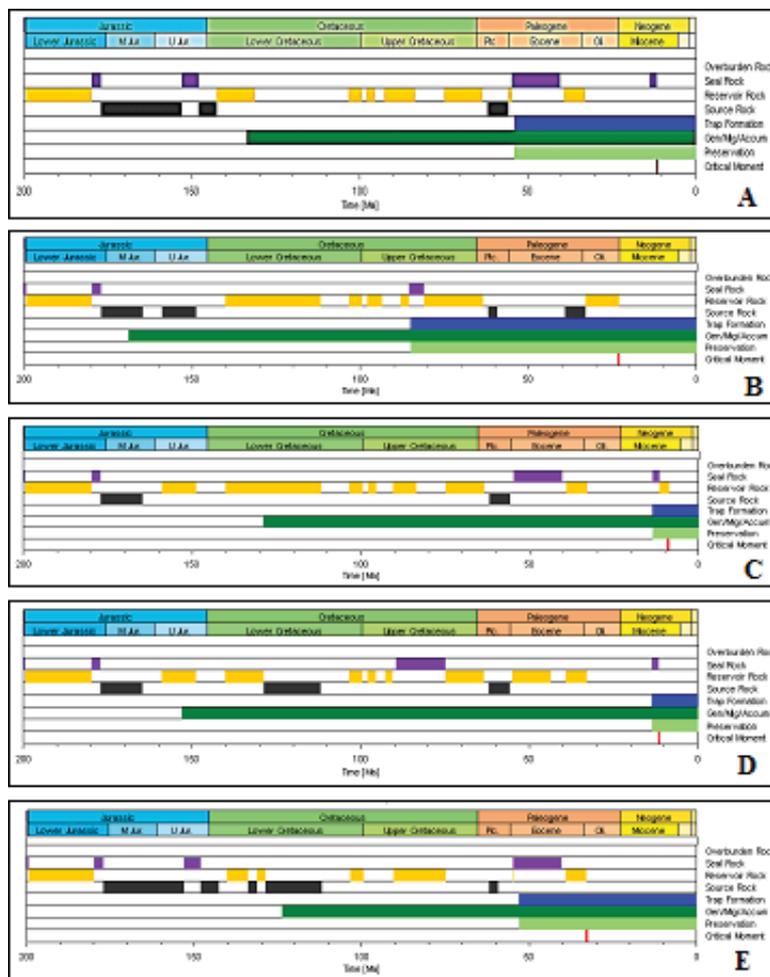


Fig. (2) Events Chart showing the timing of the essential elements and processes in the total petroleum system in: A) Taq Taq-1 Well; B) Qara Chugh-2 Well; C) Zab-1 Well; D) Guwair-2 Well; E) Shaikhan-2 Well.

Qara Chugh-2

The Qara Chugh-2 Well is located 20km to the northwest of Makhmour City (Fig. 1). The ground level elevation is 793m above sea level. The well was completed in 1979. The Qara Chugh structure is 23km long and 2km wide. This structure is a long, twisting structure with a minimum of three peaks on top of Tertiary rocks. The well is located on the southern dome [16]. Neogene uplift of Qara Chugh relative to neighboring structures (Paleogene rocks are exposed in its core) suggests that it is an inverted graben [19]. The anticlinal trap in this site started to exist after deposition of Sargelu Formation by Upper Cretaceous (Fig. 2B).

From 202 Ma to about 149 Ma, subsidence/sedimentation rates appear to be fairly constant and relatively slow and a total of 1122m sediments deposited with one break at the base of Najmah 164.7 Ma to 159 Ma. The rate of deposition from 140.2 Ma to 63.6 decreased by roughly 7m per m.y (total of 1095m deposited) and was not constant for three periods of non-deposition and erosion from 112 Ma to 103.5 Ma, 99.6 Ma to 98 Ma, and 93.5 Ma to 88 Ma. The Tertiary time was characterized by frequent uplifting, thus the sedimentation rate appears to be slow (7m per m.y) but actually, this reflects erosion that was fast. The total of 2600m sediments was eroded during this time frame and the highest amount eroded from 23 Ma to Present. The time of maximum burial, 6200m is 23 Ma for stratigraphic units at this well (Fig. 4).

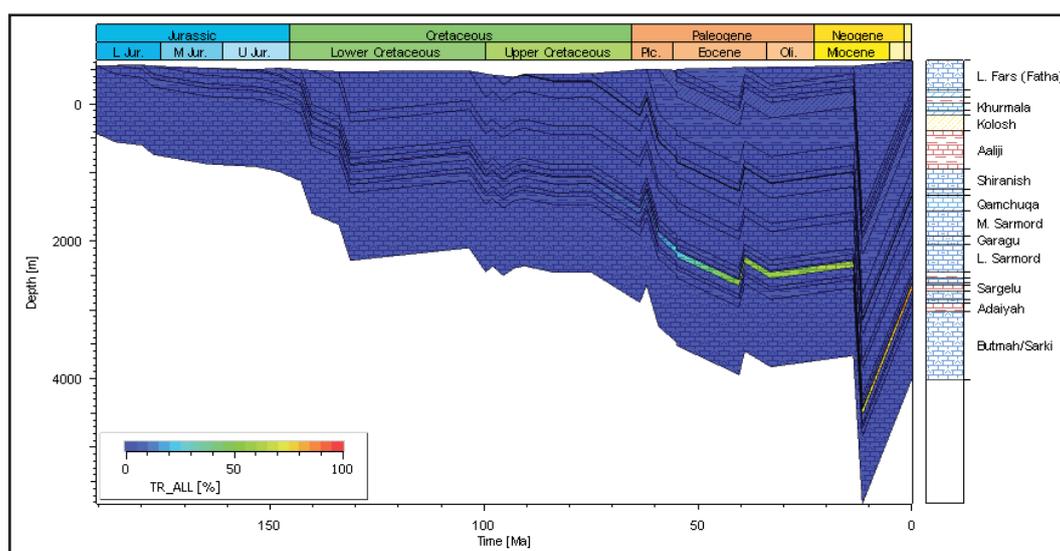


Fig. (3) Burial-history curve at the Taq Taq-1 location. Location is shown in figure 1.

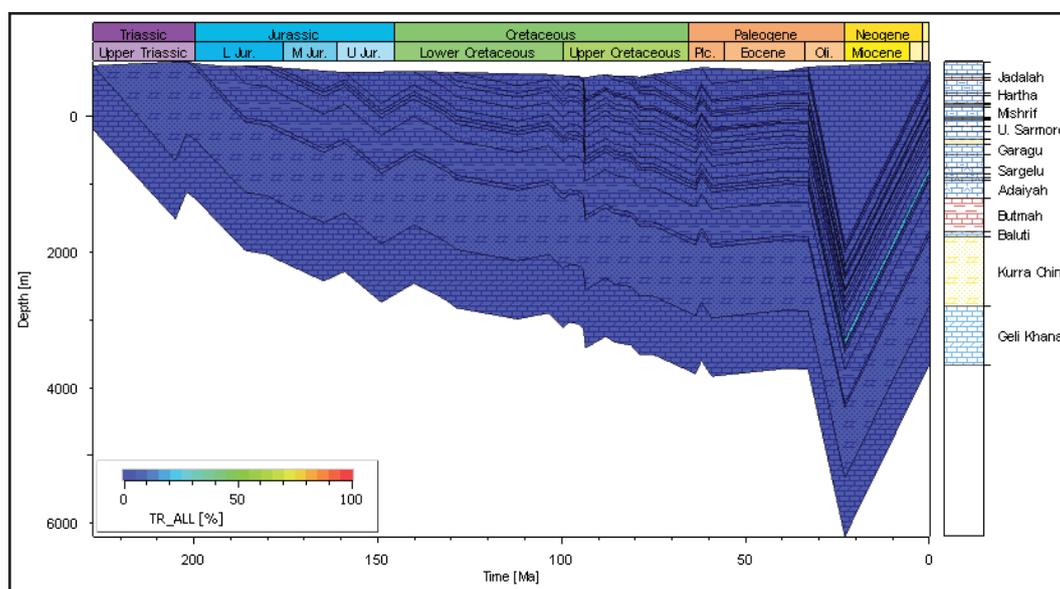


Fig. (4) Burial-history curve at the Qara Chugh-2 location. Location is shown in Figure 1.

Zab-1

The second deep-basin burial-history setting, Zab-1 Well is situated nearly 500m to the west of Zeigawra Well and about 10km to the northeast of Guwair Town near Great Zab River in the Shamamik Plain area of the southern Erbil Governorate (Fig. 1). The ground level is 247m. The well was drilled in 1983 [20]. In the same way, the structural trap occurred here due to an effect of Alpine Orogeny in the Middle Miocene (Fig. 2C). The expelled and migrated oil was preserved in Cretaceous and Tertiary reservoirs. The source rocks younger than Jurassic are still not mature in this area [21].

The history of Zab-1 is unlike that at Qara Chugh-2 in terms of the rapid rates of subsidence/sedimentation during Jurassic when 1930m of deposits were preserved with one hiatus, the same as the break in Qara Chugh-2 at the base of Najmah. Throughout the Cretaceous, the sedimentation rate was a lot slower with five breaks but during Tertiary, 62 Ma to 8.8 Ma the sedimentation rate increased dramatically and a total of 1586m was preserved. The Maximum burial 6250m was occurred around 9 Ma (Fig. 5), after which time uplift and erosion caused the removal of approximately 1100m of the section in this area.

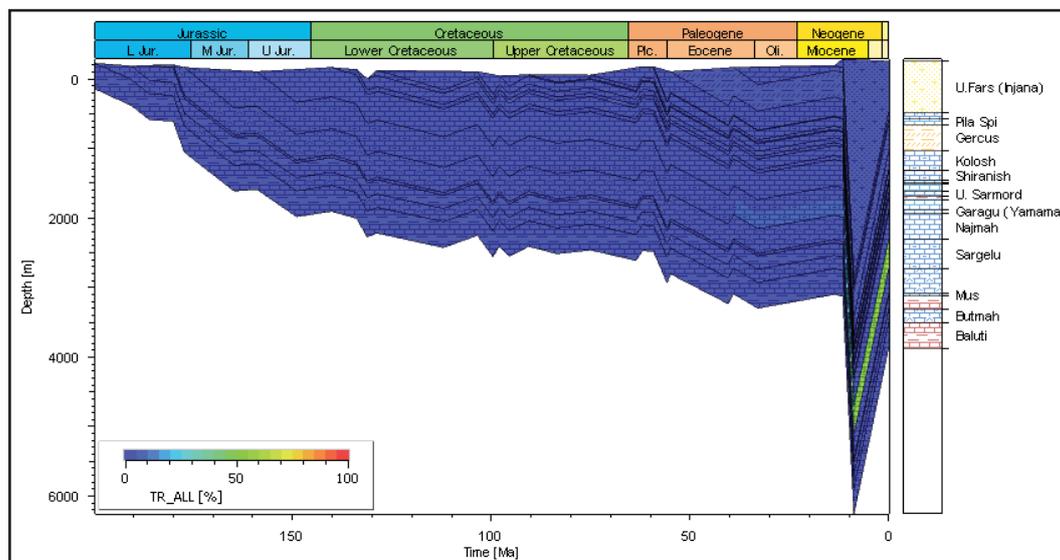


Fig. (5) Burial-history curve at the Zab-1 location. Location is shown in Figure 1.

Guwair-2

Guwair Well is located 25km to the southwest of Erbil and 10km to the southwest of Zab-1 Well (Fig. 1). The well was completed in 1981.

Guwair structure is an elongated surface feature trending NW-SE with the Lower Fars (Fatha) exposed. Both flanks are gently dipping and not affected by faulting. Deep-seated faulting is probably responsible for the major changes in the axis below the Lower Cretaceous [18]. Reverse fault was detected in the Lower Qamchuqa Formation, which could be interpreted as a folded gravity fault [18].

All petroleum system elements have existed by Middle Miocene (Fig. 2D) before the end of Alpine Orogeny in Pliocene. The Middle Miocene Lower Fars (Fatha) Formation which is a seal rock covered the reservoir rocks before oil started to migrate.

The burial history here (Fig. 6) is very similar to that at Zab-1 Well, except that the rate of sediment accumulation was not as rapid during deposition of the Lower Cretaceous formations as at Guwair-2 where this sequence is 200m thicker than the sequence at Zab-1. Although the Tertiary sequence appears to be the same, the thickness of the sequence is about 700m more at Zab-1 due to the presence of Upper Fars Formation at Zab-1 with a thickness of 746m. We estimate that in the last 11.6 m.y., more than 900m of rock has been removed from these areas as Upper Fars

(Injana), Lower Bakhtiari (Mukdadiya), and Upper Bakhtiari (Bai Hassan) Formations are missing. The time of maximum burial 4750m is 11.6 Ma for stratigraphic units at Guwair-2.

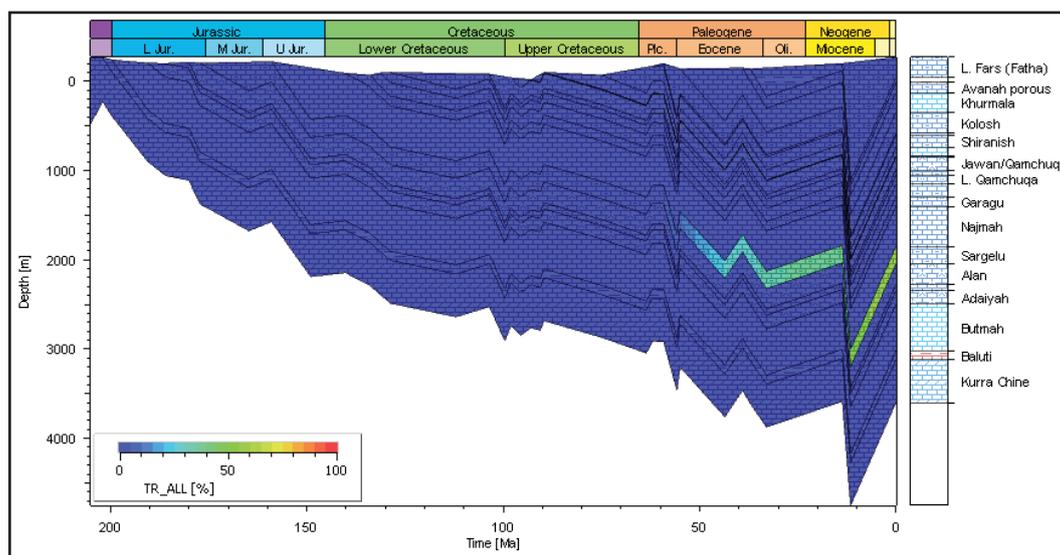


Fig. (6) Burial-history curve at the Guwair-2 location. Data Location is shown in Figure 1.

Shaikan-2

The Shaikhan block is located around 85km northwest of Erbil covering an area of 283km² and is one of the onshore developments. Shaikan-2 Well was drilled nine kilometers southeast of the Shaikan-1 Discovery Well (Fig. 1). The anticlinal trap was formed by Early Eocene (Fig. 2E). The Lower Fars (Fatha) Formation which is a regional cap rock does not exist in this area. Due to a decrease in tectonic impact the oils were preserved in Lower Jurassic Mus Formation (under Alan Formation) and in Middle Jurassic Sargelu Formation's limestone rock (under Barsarin Formation). The Sargelu Formation in this area is a source and reservoir rock at the same time [12]. The Shaikhan-2 represents the shallow depth at which the source rocks were buried (Fig. 7).

The burial history is similar to that of Qara Chugh-2 except for the lack of evidence for the unconformity within the Upper Jurassic at about 164.7 Ma. Therefore, deposition was assumed to have continued uninterrupted until about 142.8 Ma when a

2.6-million-year period of erosion in this area removed an estimated 160m of section prior to renewed deposition of post-Jurassic units.

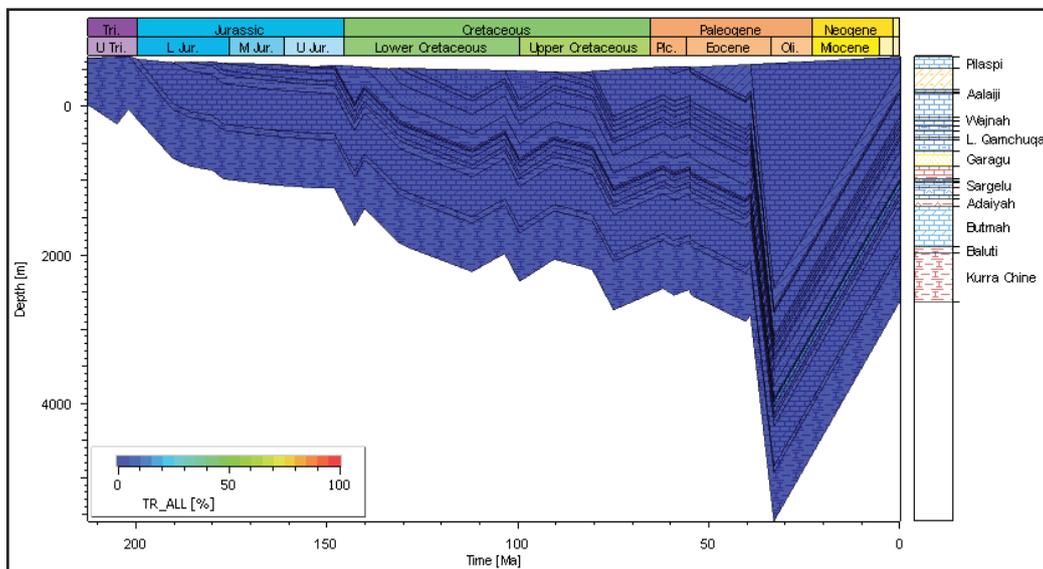


Fig. (7) Burial-history curve at the Shaikhan-2 location. Location is shown in figure 1.

The renewed deposition started from 140.2 Ma to 112 Ma without breaks. Then 199m of sediments of Upper Sarmord from 112 Ma to 103.5 Ma and another 241m of Upper Qamchuqa from 99.6 Ma to 90.6 Ma were eroded. In the last 15.6 m.y. of Cretaceous Period, 255m of rocks was deposited. The total of 220m of rocks may have been removed from this area from 75 Ma to 62 Ma. After deposition of the Aalaji Shale, three episodes of uplift and erosion occurred in this area. The first two erosional events were relatively minor, occurring at about 59.2 Ma and 40.4 Ma during deposition of Khurmala and Pilaspi Formations, respectively. The last hiatus occurred from 33 Ma to Present. The result was the removal of only about 120m of section for the first two breaks but the last erosion above Eocene removed 2900m. It should be noted the rocks on the surface at this well location are latest Eocene in age, the stratigraphical history of this part from 33 Ma to now be built on geologic restoration. The time of maximum burial 5600m is 33 Ma for stratigraphic units at Shaikhan-2.

Petroleum-Generation History:

Timing of oil and gas generation was determined for the five petroleum source rocks at the five burial-history locations. These source rocks are nominated in table 2 as gas- or oil-prone conferring to accessible geochemical rock data and oil-to-source relations [5, 22, 23].

Table (2) Source rocks and type of petroleum potential for burial-history locations.

[Os, Oil from Type-IIS kerogen; O, Oil from Type-II kerogen; G, Gas from Type-III kerogen].

Burial-history location	Source rock				
	Geli Khana	Kura Chine	Baluti	Butmah/Sarki	Sargelu
Taq Taq-1	no data	no data	no data	Os	Os
Qara Chugh-2	O	no data	no data	no data	Os
Zab-1	no data	no data	G	no data	Os
Guwair-2	no data	Os	no data	no data	Os
Shaikhan-2	no data	Os	no data	no data	Os

Oil-prone source rocks

According to kerogen's organic sulfur content, the oil-prone source rocks are categorized into two categories. Oil-prone source rocks which produce high-sulfur oils like Najmah, Naokelekan, Sargelu, and Kurra Chine Formations characteristically contain marine carbonate-or chert -controlled rocks and encompass Type-IIS kerogen (Os in Table 2). In contrast, oil-prone source rocks which produce low sulfur oil like Geli Khana Formation normally comprise of marine detrital source rocks and contain Type-II kerogen (O in Table 2).

The inconsistency between Type-II and Type-IIS kerogen is imperative in describing the timing and range of oil generation from the source rock. Source rocks containing Type-IIS kerogen generate oil at lower thermal maturities and an earlier stage of maturation than regular Type-II kerogen [24, 25]. The source rock kinetic parameters of Phosphoria Formation in the United States were used in earlier basin modeling

analysis [8, 26]. Since the atomic Sorg/C for the Middle Jurassic Sargelu kerogen (0.048) surpasses that of the Early Permian Phosphoria Formation in the western Wyoming in United States (0.045), it is apparent that oil generation started at an earlier time and at lower thermal maturities than documented in earlier basin modeling studies [27]. Throughout the oil generation phase, the gas to oil ratios do not reach 28.3m³/barrel. Likewise, this ratio starts to escalate considerably to initiate the previously generated oil cracking to gas once the thermal stress becomes high enough (≥ 1.17) [28].

The mass of generated gas from source rocks with Type-II and Type-IIS kerogen is significantly smaller than gas generated from the cracking of oil and according to Lewan and Henry [28] the mass is about 3 to 7 times less. Therefore, only gas generation from cracking of produced oil to gas was displayed. Hydrous-pyrolysis kinetic constraints utilized to regulate the timing of gas generation from oil cracking are from Lewan and Ruble [26] and Tsuzuki et al. [29] and are shown in table 3. Immature source rocks have a genetic potential of less than 0.01, and source rocks that have compatibly passed oil generation window and have terminated cracking to gas have a genetic potential of more than 0.99 [30].

Table (3) Hydrous-pyrolysis kinetic parameters used to determine timing of oil and gas generation.

[kcal/mol, kilocalorie per mole; m.y., million years]

Formation	Organic Matter type	Product generation	Atomic Sorg./C	Activation energy (E _o =kcal/mol)	Frequency factor (A _o =m.y. ⁻¹)
Woodford	II kerogen ¹	oil	0.023 ²	52.16	6.51 x 10 ¹⁶
Sargelu	IIS kerogen ¹	oil	0.048 ²	41.52	2.21 x 10 ¹³
-	Crude oil (C15+) ³	gas	-	76.00	3.42 x 10 ³³

¹Lewan and Ruble [26]; ²English et al. [27]; ³Tsuzuki et al. [29]

Gas-prone source rocks

The level of gas generation can be linked to ranks of vitrinite reflectance (%R_o) calculated mathematically from T_{max} values based on Jarvie et al.'s [31] equation. The gas generation from humic coals, Type-III kerogen, starts at vitrinite reflectance of

0.5 %R_o [32] and the end arises at vitrinite reflectance values between 1.8 and 2.0 %R_o [33]. Consequently, EASY %R_o was used to calculate gas generation from Type-III kerogen, with the start and end of gas generation arising at 0.5 and 2.0 %R_o, correspondingly. Throughout this assessment, the conferred generated gas signifies solitary to thermogenic gas.

Discussion:

Maturation History

The measured and calculated vitrinite reflectances (%R_o) are used to determine the thermal maturity's history for each burial-history location. The range of 0.5 to 0.8 %R_o denotes the recommended start to peak of gas generation from Type III kerogen. The %R_o values of 1.10 for peak and 2.0 for the end of gas generation are determined. Only Baluti Formation is considered gas-prone source rock (mostly composed of Type III kerogen) and so vitrinite reflectance (%R_o) may be used to estimate the extent of gas generation from this formation (Fig. 8).

Petroleum Generation History from Source Rocks

The timing and amount of petroleum generation from the known source rocks at the five burial-history locations are listed in table 4 and summarized in figure 8. With the exception of the Qara Chugh-2 and Shaikhan-2 locations, the burial-history curves represent relatively deep parts of the region. As a result, they represent the earliest timing and greatest extent of petroleum generation in the identified source-rock intervals of the region. Toward the west and southwest of these sites, is the time at which petroleum generation arises will be far ahead and the amount of petroleum generation will be scarcer. The place of the Guwair-2 burial-history location in the central part of the south (Fig. 1) and the thickness of overburden over the main source rock of the area, Sargelu Formation which is 2130m, suggest that the timing and extent of petroleum generation will become later and less toward northwest and west due to decrease of overburden thickness in the area and earlier and greater toward the east and southeast. Table 4 shows that Sargelu Formation has entered oil generation at all localities, but entered oil cracking to gas only in Taq Taq-1 and Qara Chugh-2

based on Sargelu Formation's maturity level. Thus, the Sargelu layers in Taq Taq-1 have not consumed 100% of its organic matter potentiality to generate hydrocarbon mainly during six to four million years ago in the Miocene time as stated by Al-Ameri et al. [34].

Rates of oil generation, oil cracking to gas, and gas generation were significantly reduced at low mature areas such as Shaikhan-2, Zab-1, and Guwair-2. The Sargelu Formation in Jabal Kand-1, which is located nearby to Shaikhan-2 has consumed only 70% of its potentiality because of its shallow depth [34] and had passed the -oil window in the Late Eocene to Late Miocene [35].

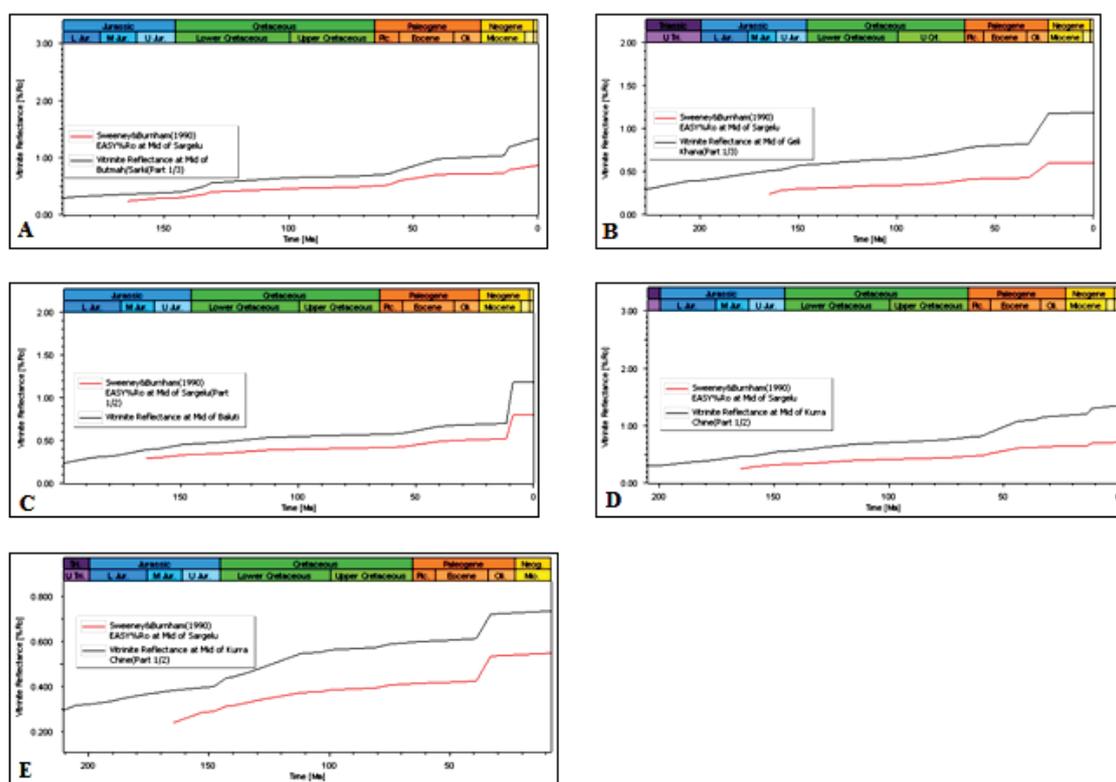


Fig. (8) Vitrinite reflectance curve.

Data used to construct the curve are calculated mathematically from T_{max} values. Location is shown in Figure (1). The red line shows prediction from model scenario [6]. A) Taq Taq-1 location, the steep decline of the curve at 11.6 Ma representing the rapid increase in subsidence/sedimentation rate during deposition of Upper Fars Formation; B) Qara Chugh-2 location, the steep decline of the curve at 23 Ma reflects erosion that was fast. The total of 2600m sediments was eroded during this time

frame; C) Zab-1 location, the steep decline of the curve at around 9 Ma reflects the time when uplift and erosion caused the removal of approximately 1100m of the section in this area; D) Guwair-2 location, the decline of the curve at around 11 Ma reflects the removal of more than 900m of rock in this area; E) Shaikhan-2 location, the steep decline at 33 Ma of the curve reflects the removal of 2900m of section in this area.

The Butmah/ Sarki Formation at Taq Taq-1 entered end of oil generation at 33 Ma and entered the oil cracking to gas at 26 Ma. Kurra Chine Formation in Shaikhan-2 entered oil generation at 46 Ma while starting to generate oil earlier at Guwair-2, 64 Ma. This earlier start to generate oil at Guwair -2 can be linked to the amount of eroded beds, which is the minimum amount among all localities. Baluti Formation at Zab-1 started to generate gas at 120 Ma, but reached peak later at 23 Ma and has not ended yet. At Qara Chugh-2, the Geli Khana entered oil generation at 82 Ma and entered end oil generation at 22 Ma. As anticipated, the most widespread petroleum generation arises at the places where source rocks were deeply buried for instance Taq Taq-1 Well.

The start, peak, and end of oil generation timing (genetic potential of 0.01, 0.50, and 0.99, correspondingly) is presented in (Table 4 and displayed in Figures 3, 4, 5, 6, and 7). Oil generation in Sargelu Formation began as early as 47 Ma at Taq Taq-1, 51 Ma at Guwair-2, 33 Ma at Shaikhan-2, 28 Ma at Qara Chugh-2 and Zab-1. Hakimi et al. [35] determined the time of oil generation in Sargelu Formation at Taq Taq-1 to be 50-48 Ma (1 to 3 m.y.) earlier than the time of oil generation than is determined in this study. This discrepancy may be related to differences of samples' depth that accordingly show different maturity level of samples. The late completion of oil generation at all localities (7, 10, 11, 16, and 22 Ma at Shaikhan-2, Zab-1, Guwair-2, Qara Chugh-2, and Taq Taq-1, respectively) suggests that generation of Sargelu oil was significantly affected by the later Alpine Orogeny-induced structural elements defining the current northern Mesopotamian or by thrusting in the western Zagros thrust belt (22 to 7 Ma).

Table (4) Timing of oil generation for Type-IIS (Sargelu Formation), Type-II, and Type III source rock horizons at five burial history locations.

Source- rock horizon	Oil generation						Oil cracking to gas					
	Start	%Ro	Peak	%Ro	End	%Ro	Start	%Ro	Peak	%Ro	End	%Ro
Taq Taq-1												
Butmah/ Sarki	54	0.70	45	0.90	33	1.18	26	1.67	13	2.12	9	2.77
Sargelu	47	0.50	34	0.63	22	0.72	11	1.69	7	1.76		
Qara Chugh-2												
Geli Khana	82	0.70	33	0.92	22	1.17	13	1.74	5	2.13		
Sargelu	28	0.50	22	0.62	16	0.73	7	1.71	5	1.77		
Zab-1												
Baluti	120	0.50	23	0.70	11	1.20						
Sargelu	28	0.50	18	0.61	10	0.70						
Guwair-2												
Kurra Chine	64	0.69	52	0.93	22	1.19	16	1.72	5	2.12		
Sargelu	51	0.50	33	0.64	11	0.71						
Shaikhan-2												
Kurra Chine	46	0.70	22	0.91	11	1.17	5	1.77				
Sargelu	33	0.50	11	0.66	7	0.72						

[Start, peak, and end of oil generation are represented by transformation ratios of 0.01, 0.50, and 0.99. Values are Ma. Blank cell indicates horizon did not attain transformation ratio].

Oil Cracking to Gas

The start, peak, and end of oil cracking to gas timing (genetic potential of 0.01, 0.50, and 0.99, correspondingly) is displayed in figures 3, 4, 5, 6, and 7. After oil generation ends, the oil cracking to gas does not start immediately and there will be a

pause between them. The duration of this pause is not similar and depends on the type of kerogen that occurs within the rocks as ranges from 6 m.y. for Kurra Chine and Baluti Formations and 11 m.y. for Sargelu Formation.

This discrepancy is related to the thermal-burial history settings. This break is larger for source rocks with Type-IIS kerogen (that is, Sargelu Formation) than for those with Type-II kerogen (that is, Geli Khana Formation). This discrepancy is due to a property of chemical bonds. The oil generation from Type-IIS kerogen takes place prior and at lower thermal maturities than regular Type-II kerogen [24, 25]. Nonetheless, the oils from both kerogen forms have equal kinetic constraints for cracking to gas. This break is also confirmed in the vitrinite reflectance values. Termination of oil generation for Sargelu oil is at nearly 0.73 %R_o, and for the other oil-prone source rocks it is between 1.12 and 1.18 %R_o. The initial cracking of oil to gas for both source-rock types is between 1.67 and 1.77 %R_o (Table 4).

The Zab-1, Guwair-2, and Shaikhan-2 locations have the smallest potential for gas from oil cracking because oils from Sargelu source rock has not been cracked to gas yet. Generally, the order of increasing potentiality of the burial-history sites for gas generation from the cracking of oil is Shaikhan-2 < Zab-1 < Guwair-2 < Qara Chugh-2 < Taq Taq-1.

Gas generation from Source Rocks

The range of gas production from gas-prone source rocks throughout this investigation is directly connected to vitrinite reflectance values based on experimental remarks and not a definite kinetic model. As a result, the timing of gas generation is directly related to vitrinite reflectance values (that is, initiate = 0.5 %R_o, peak = 0.8 %R_o, and termination = 2.0 %R_o), and the burial-history curves for vitrinite reflectance (Fig. 8) compare gas generation from gas-prone source rocks. Table 4 displays the time of gas production for every source rock that is gas prone. In the Zab-1 Well the gas generation occurred from the gas-prone source rock, Baluti formation (Fig. 8C).

Conclusions:

- Results for the base of the Sargelu Formation, a source rock containing Type-IIS kerogen, designate the timing for the initiate of oil generation arose within a wide range, from 51 to 28 Ma, and oil generation ended at all sites by 7 Ma.
- The timing and extent of petroleum generation in the studied area will occur later and less toward northwest and west due to the decrease of overburden thickness and earlier and greater toward the east and southeast.
- Generally, the order of increasing potentiality of the burial-history sites for gas generation from the cracking of oil is Shaikhan-2 < Zab-1 < Guwair-2 < Qara Chugh-2 < Taq Taq-1.
- At Qara Chugh-2 cracking of oil occurred from Geli Khana Formation, and it is still in progress. In the same way, at Shaikhan-2 and Guwair-2 cracking of oil occurred also from Kurra Chine Formation and it has not ended yet.
- In the deepest parts of the region, Taq Taq-1, the production of gas from the cracking of oil initiated at about 26 Ma for Butmah/ Sarki Formation and 11 Ma for Sargelu Formation. Gas generation from oil cracking terminated at these deep sites by nearly 9 Ma for Butmah/ Sarki Formation and has not ended yet for Sargelu Formation.
- The Zab-1, Guwair-2, and Shaikhan-2 locations have the smallest potential for gas from oil cracking because oils from Sargelu source rock have not been cracked to gas yet.

References:

1. L.B. Magoon and W.G. Dow, The petroleum system: From source to trap, AAPG Memoir, chapter 1 (1994) 3–24.
2. G. Banks, Defining Zagros structural domains in the Kurdistan region of northern Iraq, presented to the CSPG Structural Geology Division, Calgary, Western Zagros Oil Company (February 4, 2011).
3. R.C. Bellen, H.V. Dunnington, R. Wetzel, and D.M. Morton, Lexique stratigraphic international, Paris, Vol. III, Asie, Fascicule 10a Iraq (1959), p. 333.
4. International Commission on Stratigraphy, International stratigraphic chart, in: J.G. Ogg, G. Ogg, and F.M. Gradstein, (eds.), A concise geologic timescale, Cambridge University Press (2008).
5. R.A. Abdula, Hydrocarbon potential of Sargelu Formation and oil-source correlation, Iraqi Kurdistan, Arabian Journal of Geosciences, 8 (8) (2015) 5845–5868.
6. R.A. Abdula, Source rock assessment of Naokelekan Formation in Iraqi Kurdistan, Journal of Zankoi Sulaimani, 19 (1) (2017) 103–124.
7. J.J. Sweeney and A.K. Burnham, Evaluation of a simple model of vitrinite reflectance based on chemical kinetics, AAPG Bulletin, 74 (1990) 1559–1570.
8. J.K. Pitman, D. Steinshouer, and L.D. Lewan, Petroleum generation and migration in the Mesopotamian basin and Zagros Fold Belt of Iraq, results from a basin-modeling study, GeoArabia, Gulf PetroLink, Bahrain, 9 (4) (2004) 41–72.
9. T. Buday, The regional geology of Iraq, Vol. 1, stratigraphy and paleogeography, Dar Al-Kutub Publishing House, University of Mosul, Mosul, Iraq (1980), p. 445.
10. A.S. Alsharhan and A.E.M. Nairn, Sedimentary basins and petroleum geology of the Middle East, Elsevier Science B. V., Amsterdam, Netherlands (2003), p. 843.
11. S.Z. Jassim and T. Buday, Late Toarcian-Early Tithonian (Mid-Late Jurassic) Megasequence AP7, chapter 10, in: S.Z. Jassim and J.C. Goff,(eds.), Geology

- of Iraq, first edition, Brno, Czech Republic, Prague and Moravian Museum (2006) 117–123.
12. Gulf Keystone, Internal report, the well report of Shaikhan-2 Well, (unpublished report), Main Office (2015).
 13. R.A.Abdula, S.M., Balaky, M.S., Nurmohamadi, and M. Piroui, Microfacies analysis and depositional environment of the Sargelu Formation (Middle Jurassic) from Kurdistan region, northern Iraq, *Donnish Journal of Geology And Mining Research*, 1 (1) (2015) 001–026.
 14. F.A. Ameen, Biostratigraphy of the Tethyan Cretaceous successions from northwestern Zagros fold–thrust belt, Kurdistan region, NE Iraq, *Arabian Journal of Geosciences*, 7 (7) (2014) 2689–2710.
 15. K.H. Karim, R.K. Al-Hamadani, and S.H. Ahmad, Relations between deep and shallow stratigraphic units of northern Iraq during Cretaceous,” *Iranian Journal of Earth Sciences*, 4 (2) (2012) 75–103.
 16. North Oil Company, Internal report, the final well report of Qara Chugh-2 Well, (unpublished report), Department of Geology (1979).
 17. North Oil Company, Internal report, the final well report of Taq Taq-1 Well, (unpublished report), Department of Geology (1978).
 18. North Oil Company, Internal report, the final well report of Guwair-2 Well, (unpublished report), Department of Geology (1981).
 19. S.N.S. Haddad and M.A. Ameen, Mid-Turonian–early Campanian sequence stratigraphy of northeast Iraq, *GeoArabia*, 12 (2) (2007) 135–176.
 20. North Oil Company, Internal report, the final well report of Zab-1 Well, (unpublished report), Department of Geology (1983).
 21. R.A. Abdula, Organic geochemical assessment of Jurassic potential source rock from Zab-1 Well, Iraqi Kurdistan, *Iraqi Bulletin of Geology and Mining*, 12 (3) (2016) 53-64.
 22. S.F. Naqishbandi, W.J. Jabbar, and A.I. Al-Juboury, Hydrocarbon potential and porosity types of the Geli Khana Formation (Middle Triassic), northern Iraq, *Arabian Journal of Geosciences*, 8 (2) (2015) 739–758.
 23. D.S. Saeed, Organic geochemical characteristic of Lower-Middle Jurassic succession and crude oils from selected wells, Garmian area, Kurdistan region,

- NE Iraq, Master's thesis (unpublished), University of Sulaimani, Iraqi Kurdistan, Iraq (2014), p. 156.
24. M.D. Lewan, Evaluation of petroleum generation by hydrous pyrolysis experimentation, *Philosophical Transactions of the Royal Society of London, Series A* 315 (1985) 123–134.
 25. W.L. Orr, Kerogen/asphaltene/sulfur relationships in sulfur-rich Monterey oils, *Organic Geochemistry*, 10 (1986) 499–516.
 26. M.D. Lewan and T.E. Ruble, Comparison of petroleum generation kinetics by isothermal hydrous and nonisothermal open-system pyrolysis, *Organic Geochemistry*, 33 (2002) 1457–1475.
 27. J.M. English, G.A. Lunn, L. Ferreira, and G. Yacu, Geologic evolution of the Iraqi Zagros, and its influence on the distribution of hydrocarbons in the Kurdistan region, *AAPG Bulletin*, 99 (2) (2015) 231–272/
 28. L.D. Lewan and A.A. Henry, Gas:oil ratios for source rocks containing Type-I, -II, -IIS, and -III kerogens as determined by hydrous pyrolysis, in: T.S. Dyman and V.A. Kuuskraa (eds.), *Geologic studies of deep natural gas resources*, U.S. Geological Survey DDS–67, CD–ROM, (2001).
 29. N. Tsuzuki, N. Takeda, M. Suzuki, and K. Yokoi, The kinetic modeling of oil cracking by hydrothermal pyrolysis experiments, *International Journal of Coal Geology*, 39 (1999) 227–250.
 30. L.N.R. Roberts, M.D. Lewan, and T.M. Finn, Burial History, Thermal Maturity, and Oil and Gas Generation History of Petroleum Systems in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah, Chapter 3, in: USGS Southwestern Wyoming Province Assessment Team, *Petroleum systems and geologic assessment of oil and gas in the southwestern Wyoming Province, Wyoming, Colorado, and Utah*, U.S. Geological Survey Digital Data Series DDS–69–D, U.S. Geological Survey, Denver, Colorado, 1 (2005), p.25.
 31. D.M. Jarvie, F. Mbata, A. Maende, D. Ngenoh, and D.A. Wavrek, Petroleum systems in northwest Kenya, Presented at the annual meeting of the AAPG, Denver, CO., (2001).

32. A.R. Scott, Composition and origin of coalbed gases from selected basins in the United States, Proceedings of the International Coalbed Methane Symposium, The University of Alabama, Tuscaloosa, 9370 (1993) 207–222.
33. M.J. Kotarba and M.D. Lewan, Characterizing thermogenic coalbed gas from Polish coals of different rank by hydrous pyrolysis, Organic Geochemistry, 35 (2004) 615–646.
34. T.K. Al-Ameri, A.A. Najaf, A.S. Al-Khafaji, J. Zumberge, and J. Pitman, Hydrocarbon potential of the Sargelu Formation, north Iraq, Arabian Journal of Geosciences, 7 (3) (2014) 987–1000.
35. M.H. Hakimi, A.A. Najaf, R.A. Abdula, and I.M.J. Mohialdeen, Generation and expulsion history of oil-source rock (Middle Jurassic Sargelu Formation) in the Kurdistan of north Iraq, Zagros folded belt: Implications from 1D basin modeling study, Journal of Petroleum Science and Engineering, 162 (2018) 852–872.