RESEARCH ARTICLE

Comparative Study on Hydrocarbon Generation in Different Tectonic Zones: A Case Study from the Upper Jurassic Naokelekan Formation at the Imbricated and High Folded Zones, Kurdistan Region, Iraq

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ABSTRACT

The impact of tectonic activities from different tectonic zones on hydrocarbon generation in the Upper Jurassic Naokelekan Formation was addressed in this study. The Upper Jurassic Naokelekan Formation is an important potential of source rocks for hydrocarbon generation that charges most of the Cretaceous and younger reservoirs in the Kurdistan Region, Iraq. A total of 5 rock specimens from the Warte outcrop and 7 cutting samples from Well Bina Bawi-1 were collected for Rock-Eval pyrolysis to investigate the relationship between the ability of the formation to generate hydrocarbons and tectonic activities. The results of Rock-Eval analysis on the analyzed samples showed an average of 2.65 wt% and 0.9 wt% total organic carbon (TOC) for Warte and Well Bina Bawi-1, respectively. Based on the TOC data, the Naokelekan Formation, in general, has a good to very good source rock potential. The qualitative properties of the organic matter (OM) of the formation were inferred from the kerogen types. The Warte section mostly contains type III kerogen that is gas prone, whereas the Well Bina Bawi-1 section contains mixed type I-II kerogen that is oil prone. It should be taken into consideration that the values for the hydrogen index (HI) of the Warte section are unreliable for interpretation of the organic type, because the HI is considerably reduced owing to the high level of thermal maturity. The T_{max} values showed that the Warte section is thermally more mature than the Well Bina Bawi-1 section. The difference in the thermal maturity can likely be attributed to the differential effects of the tectonic activities on the studied areas. Depending on the proximity or distance of the area in relation to the subduction zone, the sediments in the Imbricated Zone were more affected by the tectonic activities than the sediments in the High Folded Zone. Accordingly, the main factors that might have caused a higher thermal maturity in the Imbricated Zone include a high paleo heat flow, overthrusting, and hydrothermal activities.

Keywords: Naokelekan, Imbricated Zone, High Folded Zone, Hydrocarbon generation, Heat flow, Hydrothermal

1. INTRODUCTION

The Upper Jurassic Naokelekan Formation was selected as a potential source rock to address its petroleum generating potential within 2 different tectonic zones, and to discuss the reasons for the differences in the capacity of generating hydrocarbons within the studied sections. A source rock is defined as a rock that has the ability to generate or that has generated movable quantities of hydrocarbons (Law, 1999); thus, the quantity, quality, and thermal maturity of the organic matter (OM) have been documented as the 3 elements that a potential source rock should have. The quality and quantity of the OM are associated with the depositional environment. However, thermal maturity is related to the tectonic history and the geologic structure of the

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sedimentary basin (Law, 1999). Hydrocarbon generation occurs because of the chemical breakdown of kerogen with rising temperature. Thus, temperature and time represent the most significant factors that contribute to the breakdown of kerogen (Allen and Allen, 2013). The Naokelekan Formation is well known as an important source rock within the petroleum systems of the Kurdistan Region. Almost all the Cretaceous and Paleogene reservoirs of this region have been charged by the Sargaleu, Naokelekna, and Chia Gara source rocks (Aqrawi et al., 2010). Wetzel and Morton (1950) in Bellen et al. (1959) described the Naokelekan Formation for the first time from the Imbricated Zone of northeastern Iraq, near the Naokelekan village, Rowanduz district. Stratigraphically, it is overlain by the Barsarin Formation and underlain by the Sargelu Formation (Figure 1). Lithologically, the formation is divided into 3 parts (Bellen et al., 1959; Buday, 1980). The uppermost part is composed of laminated shaly limestones; however, this part is obscured in the type section.

The middle part of the formation comprises hard, dark gray or bluish thick-bedded dolomitic limestones with ammonite traces (it is called the Mottled unit). The lowermost division of the formation is mainly composed of thin beds of bituminous limestone with frequent intercalation between black bituminous and calcareous shales. Bellen et al. (1959) determined the age of the Naokelekan Formation to be Upper Oxfordian–Lower Kimmeridgian. However, Abdula (2016) believes that the age of the Naokelekan Formation should be placed between the Callovian and the Upper Oxfordian. Buday (1980) determined that the depositional environment of the formation is euxinic in a slow subsiding basin. The Naokelekan Formation has been proven to be a potential source rock. The thermal maturity of this formation increases from the west to the east of the Kurdistan Region, from 434°C T_{max} in Amedi to 493°C T_{max} in the Sargelu Village. Therefore, the Naokelekan can be considered as a potential source rock for the generation and extraction of hydrocarbons that have been charged by oil fields in the area (Abdula, 2017). Al-Ameri et al. (2013) believed that the Naokelekan Formation is a potential source rock because the values of TOC, T_{max}, and the hydrogen index (HI) range from 2.75 wt% to 34.92 wt% TOC, 434°C to 447°C, and 11 to 206 mg HC/g TOC, respectively. The best source rock intervals in Well Shorish-1 are Naokelekan (Sachsenhofer et al., 2015). In the Ajil and Balad Oilfields, Rock-Eval pyrolysis data on the Naokelekan samples indicated that it is good to excellent for source rock richness, the kerogen types are type II and mixed type II-III, and that it is thermally in the immature to mature stage (Al-Bayati et al., 2017). Odisho and Othman (1992) and Abdula (2017) concluded that the formation is in the postmature stage in Well Taq Taq-1.

The oil generation started before 134 MA from the Chia Gara, Naokelekan, and the Sargelu source rocks in the Duhok area (Awadh, 2010). The Naokelekan Formation contains a mixture of planktonic, bacterial, and algal OM with a marine origin and the formation is regarded as a very good to excellent source rock in the Ajil and Balad oil fields (El Diasty et al., 2018). Al-Badry (2012) studied the Jurassic formations in the Chia Gara anticline, and, based on his study, the Naokelekan Formation is considered to have a high value of OM content with type I-II kerogen and to be thermally mature and in the oil window.

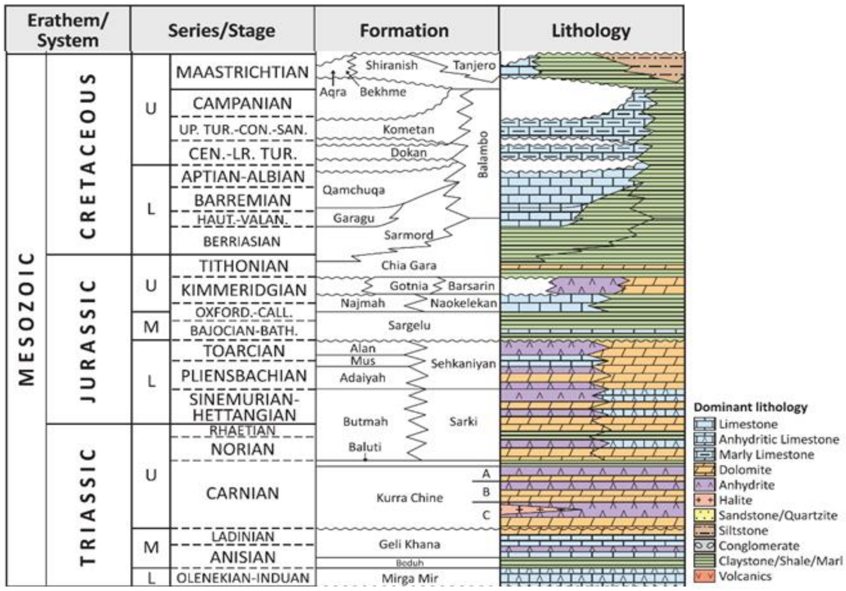

Figure 1. Stratigraphic column of the Mesozoic formations in Kurdistan region, Iraq (English et al., 2015)

2. GEOLOGICAL SETTING

In Iraq, the Late Toarcian-Early Tithonian (Mid-Late Jurassic) Megasequence AP7 is divided into 2 sequences. The lower sequence includes the Sargelu and Muhaiwir Formations, whereas the upper sequence includes the Najmah, Gotnia, Naokelekan, and Barsarin Formations (Jassim and Buday, 2006a). The Late Jurassic Megasequence AP7 of the Naokelekan successions were deposited during a period of isolation of the intrashelf basin of the Mesopotamia Foredeep from the Neo-Tethyan Ocean. It passes laterally toward the central and western parts of Iraq into the Najmah Formation. The Naokelekan Formation overlies the Kimmeridgian-Tithonian supersequence that consists of the evaporitic Gotnia Formation and the limestones and breccias of the Barsarin Formation (Jassim and Buday, 2006a). Regionally, the studied sections are part of the Zagros Fold-Thrust belt that formed during the Late Paleogene and Neogene tectonics (Beydoun, 1993). The Zagros Fold-Thrust Belt is characterized by a northwest-southeast trend that is 300 km wide and 1800 km in length (Alavi, 2004; Alavi, 2007; English et al., 2015). The plate tectonic setting of Iraq can be divided into the following 2 first order segments: the Arabian Plate platformal part and the Shalair terrane of the Sanandaj-Serjan Zone of the Eurasian Plate that is separated by the Zagros Main Thrust (Fouad, 2015). Based on this tectonic division, the Warte section is located within the Imbricated Zone (Figure 2). The Imbricated Zone represents a narrow belt of 15 km in the north and 25 km in the northeast. It is extremely folded and thrusted. Anticlines are displaced by thrusts into imbricates and override synclines (Jassim and Buday, 2006c). In contrast, the second section (Well Bina Bawi-1) is located within the High Folded Zone (Figure 2). The width of this zone is between 25 and 50 km. The folds are commonly asymmetrical and are oriented in a northwest-southeast trend in the northeast, and an east-west trend in the northwestern part of Iraq (Jassim and Buday, 2006c).

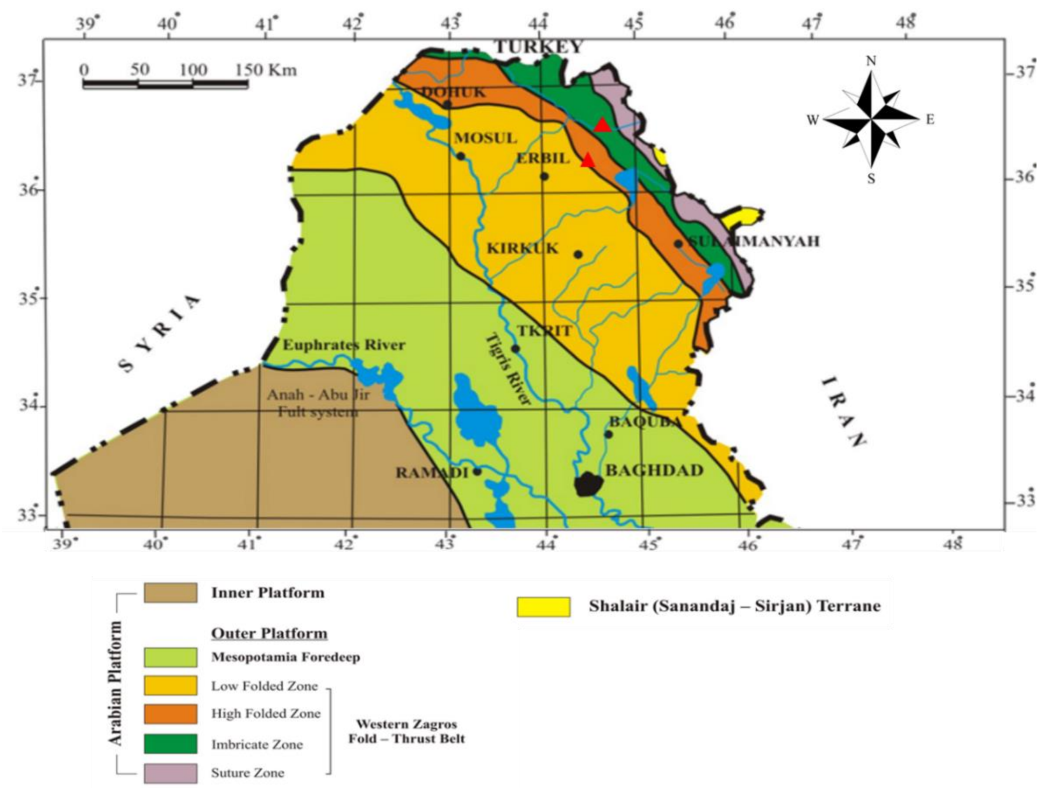

Figure 2. The tectonic divisions of the northern part of Iraq. The locations of the studied sections are indicated by red triangles (modified from Fouad, 2015

3. MATERIALS AND METHODS

The Rock-Eval technique is widely used to assess the hydrocarbon generation potential of a source rock (Espitalié et al., 1977). For this study, 5 outcrop samples and 7 subsurface rock samples were used for Rock-Eval pyrolysis. The examination of the samples was conducted at the Scientific Research Center of the Soran University, Kurdistan Region, Iraq. The samples were first carefully cleaned and crushed to a powder before Rock-Eval pyrolysis. The crushed samples were weighed to between 90 and 100 mg and were subjected to analysis using a Rock-Eval 6 apparatus to determine the amount of TOC, the kerogen type, and the thermal maturity of the OM for each sample. The Rock-Eval pyrolysis provides the S1, S2, S3, and Tmax values directly. By using these parameters, the type and maturity of the OM can be determined. In this study, the measured S1 (mg HC/g rock), S2 (mg HC/g rock), TOC (wt%), and Tmax (°C) parameters and the calculated HI (S2/TOC×100) and production index (PI) (S1/(S1+S2)] parameters were used for interpretation of the data.

4. RESULTS

4.1 Quantity and Quality

The total OM is an indicator of the total amount of OM present in a rock sample. A source rock with a TOC value of >0.5 TOC wt% is regarded as a poor source rock. Values of 0.5 to 1.0, 1.0 to 2.0, 2.0 to 4.0, and >4.0 wt% are interpreted as fair, good, very good, and excellent for source rock richness, respectively (Peters and Cassa, 1994). As indicated in Table 1, the analyzed samples from the Warte section contained TOC values in a range of between 0.24 and 4.61 wt%, with an average value of 2.65 wt%. In Well Bina Bawi-1, the TOC values were in the range of 0.55 to 1.29 wt% (with an average of 0.90 wt%), and based on these values, the Naokelekan deposits can be interpreted as a very good source rock, with increasing values toward the Imbricated Zone.

The S1 value (mg HC/g rock) is the amount of hydrocarbon that has already been generated from a rock sample. It is used as a semiquantitative parameter of source richness (Dembicki, 2017). Values of 0.0 to 0.5, 0.5 to 1.0, 1.0 to 2.0, and >2.0 mg HC/g rock show poor, fair, good, and very good source rock potential, respectively (Peters, 1986). The values of S1 from the studied samples in the Warte section were in the range of 0.11 to 1.56 mg HC/g rock (Table 1). According to the previous S1 values, the analyzed samples indicated a poor quantity of source rock. In contrast, the values of S1 for the Well Bina Bawi-1 samples are in the range of 1.87 to 4.96 mg HC/g rock, representing a good to very good quantity for the source rock potential.

The genetic potential (GP) is the sum of the amount of free hydrocarbon and the quantity of the remaining OM that has not been converted to hydrocarbons (Tissot and Welte, 1984). GP values of <2, 2 to 5, 5 to 10, and >10 mg HC/g rock correspond to poor, fair, good, and very good, respectively, in terms of generation potential (Hunt, 1996). The cross plot between the GP and TOC shows that the samples of both sections have a good hydrocarbon generation potential (Figure 3a).

The S2 value (mg HC/g rock) refers to the amount of hydrocarbon that is produced during thermal cracking of the rock sample. It is commonly used to estimate the generation capacity of the remaining hydrocarbons in the rock sample (Peters and Cassa, 1994). S2 values of 0.0 to 2.5, 2.5 to 5.0, 5.0 to 10.0, and >10.0 mg HC/g rock indicate poor, fair, good, and very good source rock potential, respectively (Peters, 1986). In this study, the S2 values for the Warte section ranged from 3.09 to 13.60 mg HC/g rock, with an average of 6.5 mg HC/g rock, which indicate good to very good petroleum potential. The S2 values for the Well Bina Bawi-1 section were in the range of 3.74 to 9.20 mg HC/g rock, with an average of 6.25 mg HC/g rock, which indicates a good potential source rock (Table 1). The cross plot between the S2 values and TOC shows that the samples of both sections have good hydrocarbon generation potential (Figure 3b).

Table 1: Rock-Eval pyrolysis data for the samples from the Naokelekan formation (the samples' names were given on the basis of the depth from which they were obtained in Well Bina Bawi-1)

Location	Sample number	TOC (wt%)	S1 (mg HC/g rock)	S2 (mg HC/g rock)	HI (mg HC/g TOC)	PP (S1+S2)	T_{max} (°C)	Production index S1/(S1+S2)
Well Bina Bawi-1	1,212	1.29	4.93	9.20	713	14.13	433	0.35
	1,218	1.11	3.44	8.39	756	11.83	430	0.29
	1,232	0.79	2.89	5.72	724	8.61	433	0.34
	1,236	0.88	3.21	6.23	708	9.44	432	0.34
	1,246	0.87	2.85	5.95	684	8.80	435	0.32
	1,260	0.80	2.63	4.65	581	7.28	435	0.36
	1,266	0.55	1.87	3.74	680	5.61	435	0.33
	Average	0.90	3.12	6.27	692	9.39	433	0.33
Warte outcrop	NK1	0.40	0.02	0.27	68	0.29	547	0.06
	NK3	4.00	1.56	10.38	260	11.94	497	0.13
	NK4	2.80	0.67	5.17	185	5.84	506	0.12
	NK6	1.44	0.24	3.09	215	3.33	494	0.07
	NK9	4.61	0.11	13.60	295	13.71	550	0.01
	Average	2.65	0.52	6.50	204	7.02	519	0.08

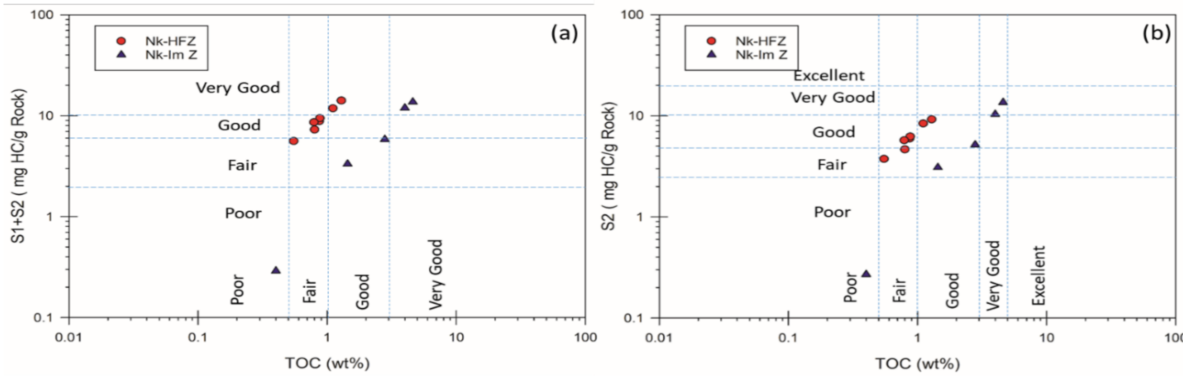

Figure 3. (a) A plot of the petroleum potential (or GP, S1+S2) vs TOC wt%, and (b) S2 vs TOC wt% showing good petroleum potential of the Naokelekan Formation (adapted from Ghori, 2002 and Dembicki, 2017)

The HI is the amount of hydrogen richness in the kerogen that can be generated relative to the amount of OM in the source rock (Dembicki, 2017). The HI value is important to differentiate between various OM source types and the main hydrocarbon products generated (Peters and Cassa, 1994). According to Peters and Cassa (1994), HI values of >600, 300 to 600, 200 to 300, 50 to 200, and values of <50 mg HC/g TOC refer to type I, type II, mixed type II-III, type III, and type IV kerogens, respectively. The analyzed samples from the Warte section indicate that the values for the HI were in the range of 68 to 295 mg HC/g TOC, with an average of 204 mg HC/g TOC, which mainly indicates type III kerogen that is gas prone (Table 1). However, the HI values for Well Bina Bawi-1 ranged from 581 to 756 mg HC/g TOC, with an average value of 692 mg HC g TOC, suggesting mainly type I kerogen that is oil prone (Table 1). A plot of T_{max} vs HI was also used to classify the type of kerogen of the OM in the sediments. As shown in Figure 4, the kerogen types for Well Bina Bawi-1 can be classified as mixed type I-II kerogen, and the samples of the Warte section are considered to be mixed type II-III kerogen. The values of HI for the Warte section cannot be reliably interpreted on the basis of the organic type because the HI value is significantly reduced by an increased thermal maturity (Dembicki, 2017). A cross plot of the remaining hydrocarbon (S2) vs TOC (wt%) can be used to determine the kerogen type (Dembicki, 2017). As shown in Figure 5, samples from Well Bina Bawi 1- are considered as type II kerogen, whereas those of the Warte section belong to type II-III and type III kerogens.

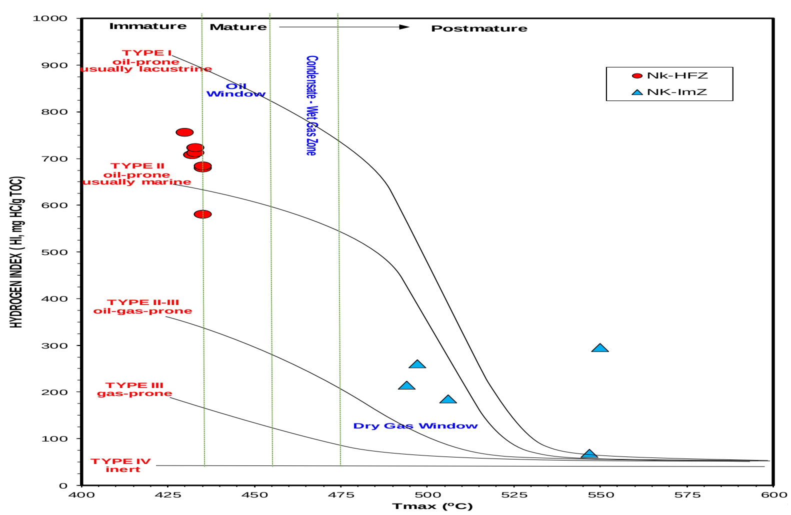

Figure 4. A plot of the HI vs Tmax showing that the samples from Well Bina Bawi-1 are less mature and belong to type II kerogen

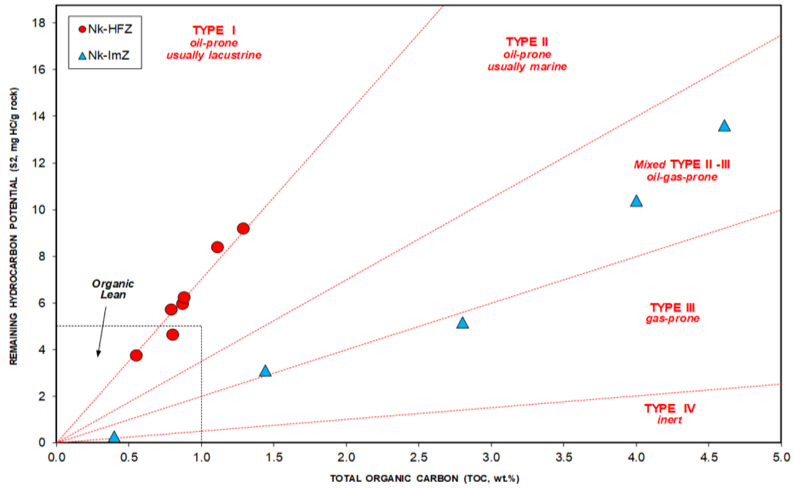

Figure 5. A plot of the TOC (wt%) vs S2 as an indication of the source rock potential of the Naokelekan Formation

4.2. Kerogen maturity

T_{max} is the temperature at which the maximum rate of hydrocarbon generation takes place in a sample during Rock-Eval pyrolysis (Law, 1999). T_{max} indicates the level of thermal maturity of the OM (Peters, 1986). The amount of hydrocarbon within a source rock is strongly linked to the type of OM and its level of thermal maturity (Tissot and Welte, 1984). Based on the kerogen classification diagram constructed using T_{max} vs HI, it was determined that the samples from Well Bina Bawi-1 are in the immature to early mature stage, whereas the Warte samples are in the postmature stage (Figure 4). The PI (S1/S1+S2) is defined as the amount of hydrocarbon that was already generated relative to the total amount of hydrocarbon that could still be generated (Peters and Cassa, 1994). PI in conjunction with T_{max} is commonly used to indicate the type of hydrocarbon generated. As shown in Figure 6, the Warte samples are in the dry gas zone, but the samples from Well Bina Bawi-1 are just inside the early oil window.

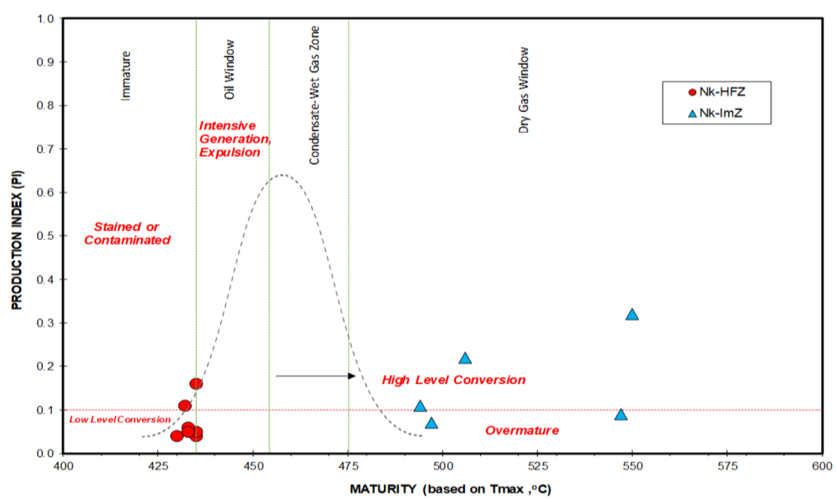

Figure 6. A T*max* vs PI diagram of the Naokelekan. The samples from the Warte section in the Imbricated Zone seem to be more mature than the subsurface samples from the High Folded Zone

5. DISCUSSION

The results of this study are not surprising considering that tectonic events could have played an essential role in the process of hydrocarbon maturation and generation. The simple example of the effect of tectonic events is illustrated in the Wells Shorish-1, and the Bina Bawi-1 fields. The Well Shorish-1 was drilled starting from the top of the Injana Formation, whereas the Well Bina Bawi-1 was drilled from the top of the of Upper Cretaceous Aqra Formation (Awdal et al., 2013; Sachsenhofer et al., 2015). As shown in Figure 7, almost all Cenozoic sediments have been eroded from the Bina Bawi anticline; however, the Low Folded Zone is still covered by a massive thickness of sediments. As mentioned earlier, based on the studies of Odisho and Othman (1992) and Abdula (2017), it was determined that the Naokelekan is in a thermally higher maturity level at Well Taq Taq-l, indicating that it has already generated liquid hydrocarbons. Likewise, based on the study of Sachsenhofer et al. (2015) on the well Shorish-1, the T_{max} values for the Naokelekan Formation are in the range of 454°C to 463°C, which indicate a relatively high maturity. Accordingly, burial depth in Wells Taq Taq-1 and Well Shorish-1 is a significant variable that is affecting the maturity of the OM, but the overburden decreases toward the Bina Bawi anticline and thus a less mature source rock was detected. The top of the Naokelekan is 3067 m below the surface at Shorish-1, whereas the top of the Naokelekan Formation at Well Bina Bawi is less than 1200 m. The reason for a reduced overburden in the Bina Bawai anticline in comparison with the Shorish area can be attributed to the tectonic activities of the area. The northwest Zagros orogenic belt encountered the following 3 main deformation stages: (1) initial hinterland shortening by the Late Middle to Early Late Miocene (~12–10 Ma); (2) frontal Zagros thrust activation by the Latest Miocene (~8 Ma); and (3) Pliocene (~5 Ma) hinterland reactivation and potential out-of-sequence basement (Khoshnaw et al., 2017). Consequently, the Low Folded Zone (e.g., Well Shorish-1) received sediments from the High Folded, Imbricated, and Thrust zones (they were eroded); thus, the OM in the sediments of the Jurassic rocks remained as the underburden and became more mature. In contrast, owing to unroofing of the Bina Bawi area (Bina Bawi anticline), the chance of Jurassic sediments being more mature is less (maturation has possibly ceased since the Late Miocene). Moreover, overthrusting in the Imbricated Zone also may have affected the maturity of the OM in Jurassic source rocks. This is because temperature variations have a key role in influencing the progress of hydrocarbon generation (Barker, 1996). Overthrusting can display very complex temperature histories, because 1 thermal regime is superimposed on top of another. Likewise, the effects of local increases in the thermal maturity on sedimentary OM can be caused by hydrothermal fluids (Barker, 1983; Law et al., 1986).

It is clear that the T_{max} values from the Imbricated Zone are higher than those from the Well Bina Bawi-1 in the High Folded Zone. The data also show that the Naokelekan source rock at the Imbricated Zone has entered into the oil widow before the Zagros thrusting and uplifting. In addition to the overburden, heat flow can be regarded as a significant contributor to the maturation of the OM within a basin. Heat flow may affect the process of maturation of the kerogen in the sedimentary rocks over geological time (Barker, 1996). Allen and Allen (2013) believed that heat flow can be higher in geologically active areas such as active ocean ridges, rifts, and back-arc basins. Owing to the high tectonic activities at the boundary between the Arabian and Iranian Plate over geological time, a high paleo heat flow can be expected in the Zagros Suture in the study area. Pirouei et al. (2019) studied hydrothermal listvenitization and the associated mineralizations in the Zagros Ophiolites in the Rayat area close to Warte. They concluded that the process of listvenitization is related to the impact of the circulation of hydrothermal fluids upward along the fault zones in the Oligocene-Miocene period. Additional evidence is provided in the formation of gossanites, which are rich in sulfide minerals, owing to the hydrothermal activities in the area (Pirouei, 2020). Thus, the occurrence of hydrothermal activities in the area may increase the rate of OM maturation. Although the overthrusting and hydrothermal activities along the tectonic boundary between the Arabian and Iranian Plates are considered as important factors in the maturation of OM, the role of sedimentary overburden must be taken into consideration. On the basis of previous studies, it has been determined that the thermal maturity of OM increases from the east to west of the Kurdistan Region with the east area seemingly being overburdened by a huge amount of sediments compared with the west, and consequently, a higher maturity has been observed in the east of the

Kurdistan Region (English et al. 2015; Abdula, 2017; Edilbi, 2018; Abdula, 2019).

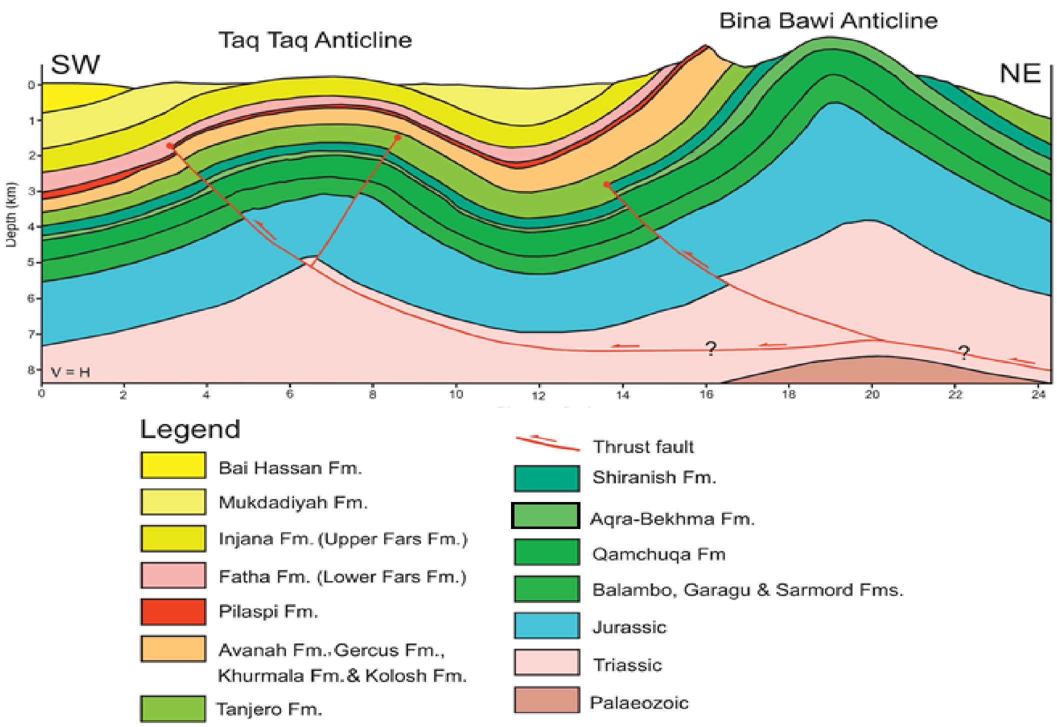

Figure 7. A schematic cross-section of the Bina Bawi anticlines (modified from Awdal et al., 2013)

6. CONCLUSION

The results from the Rock-Eval pyrolysis of the Naokelekan sediments in the Warte outcrop and Well Bina Bawi-1 suggest a good quantity and quality of OM with relation to hydrocarbon generation. OM in the Imbricated Zone in the Warte area is thermally more mature than that in the High Folded Zone in which the Well Bina Bawi-1 exists. The disparity in thermal maturity level is more likely related to the tectonic setting, with the Imbricated Zone possibly having been influenced more by tectonic activities such as overthrusting, paleo heat flow, and hydrothermal processes. Furthermore, the effect of the tectonic activities can also be indicated by the relatively low thermal maturity of the formation in Well Bina Bawi-1 at the High Folded Zone, because the Bina Bawi anticline might have undergone unroofing and thus the OM ceased to mature further.

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