# Thermal modeling and organic geochemical appraisal of petroleum source rocks within the Aghajari Oilfield, SW Iran

**Bahram Alizadeh[1,2]*, Behzada Khani[1], Majid Alipour[1], Masoud Shayesteh[3], S. Hossein Hosseini[2]**
[1]*Department of Geology, Faculty of Earth Sciences, S. Chamran University of Ahvaz, Iran*
[2] *Petroleum Geology and Geochemistry Research Centre (PGGRC), S. Chamran University of Ahvaz, Iran*
[3] *National Iranian South Oil Company (NISOC)*
**Corresponding author, e-mail: alizdeh@scu.ac.ir*
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**Abstract**
Dezful embayment contains several potential source rocks deposited in tectonically active environments. Existence of various source rocks with different geological ages makes this area one of the most prolific regions throughout the Middle East. The Pabdeh Formation (Lower Paleocene-Eocene), the Gurpi Formation (Santonian-Masstrichtian), the Kazhdumi Formation (Albian) and the Gadvan Formation (Neocomian-Aptian) are among the most favorable source rocks within the embayment. In this study the set of above mentioned source rocks are subject to pyrolysis in Aghajari Oilfield. Results reveal that the Kazhdumi Formation with highest TOC (4.43%) in compare to other probable source rocks has higher hydrocarbon generative potential and is the likeliest source rock responsible for the Asmari and Bangestan reservoirs in the Aghajari Oilfield. Moreover, the pyrolysis of Pabdeh, Gurpi and Gadvan formations show that they are of minor importance as potential source rocks within the studied Oilfield. The burial and thermal history of the Kazhdumi Formation was modeled to infer about the probable time of the hydrocarbon generation. According to Burial history profile and thermal modeling the beginning of the oil window for Kazhdumi Formation was dated at 13Ma. Moreover, the depth of oil expulsion is around 3800m in 9 Ma years ago. Finally the essential element of the petroleum system were identified and modeled.

**Keywords**: *Dezful Embayment, Aghajari Oilfield, Geochemical Evaluation, Thermal maturation, Basin modeling*

## Introduction

Dezful Embayment, one of the most petroliferous basins in the world, bears more than 45 major oil fields often bound up with gas caps. Some Oilfield such as Ahvaz, Aghajari, Gachsaran, Rag-e-Sefid and Marun are among the supergiant oil reservoirs containing between 10 to 50 billion barrels of oil-in-place (Rabbani, *et al*., 2010). The Dezful Embayment formed as a result of Late Cretaceous continental collision between Eurasian (Central Iran) and Persian Plates and Intense structural depression typifies it (Bordenave, 2002). Several potential source rock units with different geological ages were deposited in this tectonically active depression making this area one the most prolific regions in the Middle East (Alsharhan, 1989). Gadvan (Neocomian-Aptian), Kazhdumi (Albian), Gurpi (Santonian-Maastrichtian) and Pabdeh (Eocene) are major source rocks of Cretaceous/Tertiary petroleum system, though each has contributed to the oil reserves in a varying degree (Bordenave, 2002, Alizadeh *et al*., 2012). These source rocks generated around 99% of the Iranian oil reserves onshore trapped in two main reservoirs: the Asmari (Early Miocene) and Bangestan (Cenomanian) reservoirs. These limestone reservoirs contain 330 billion barrels of original oil in place corresponding to more than 7% of the current global reserves (Bordenave and Huc, 1995). The Asmari Formation is a high-energy foraminiferous limestone with a thickness of 250-500 meters and retains extremely favorable reservoir qualities over most of the Embayment. Furthermore, an influential system of fractures near the top most parts of the high-relief anticlines enhances its reservoir characteristics (Rabbani, *et al*., 2010). The Asmari is capped by the thick evaporates of the Gachsaran Formation with effective seal properties. Both the Sarvak Limestone (Cenomanian-Turonian) (300-1000m thick) and Illam Formation (Santonian) (50-200m thick) form the Bangestan reservoir, which in most of the Dezful Embayment is sealed by the thick Gurpi/Pabdeh marls (Motiei, 1995). With a length of 80 km and two separated plunges on Aghajari Formation, this anticline is in alignment with the general structural trend of the Zagros fold belt and is located in the middle part of the Embayment about 120 km southeast of Ahvaz (Fig. 1). The two main reservoir units within the Aghajari anticline are the Asmari Formation and Bangestan Group and are connected by faults (Motiei, 1995).

This study combines the analytical achievements with results from thermal maturity modeling of various petroleum source rocks in the Aghajari Oilfield to judge about the hydrocarbon generative potential and the level of thermal maturity of the studied source rocks.

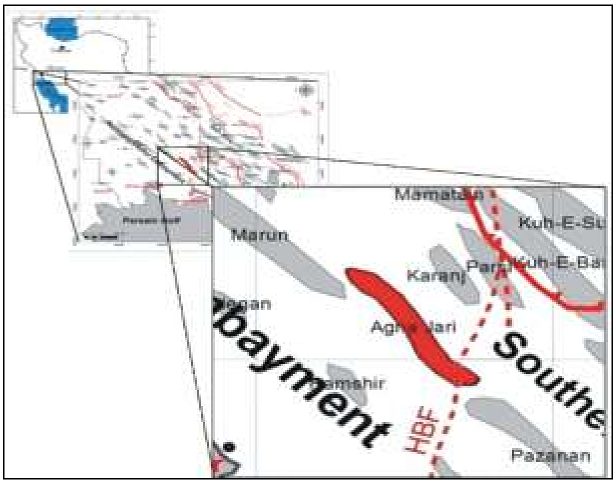

Figure 1: Geographic location and the structural trend of the Aghajari anticline in Dezful Embayment, SW Iran.

**Geology and Stratigraphy**

The Dezful Embayment constitutes a foreland basin with thick post-Oligocene sediments of Aghajari and Bakhtiyari Formation Emerging out at the foot of the uplifting mountain front fault (Sepehr, *et al.,* 2006). In this basin, acting as a major detachment horizon, the Miocene evaporates of the Gachsaran Formation form a very good seal for the Asmari reservoirs. This thick incompetent unit decoupled its overlying folds, which are currently exposed at the surface, from the underlying folds, which host the majority of the hydrocarbons in the Iranian sector of the Zagros (Sepehr, *et al.,* 2006). With the exception of the Devonian and Carboniferrous systems; sedimentation in the Dezful Embayment was nearly continuous and conformable from the Infra-Cambrian to the Pliocene which resulted in composing up to 12000 m thick sediments. The Infra-Cambrian (Vendian) evaporates is followed by the shallow marine carbonate and clastic deposits of the Lower Paleozoic. From Permian and during most of the Mesozoic and up to Lower Miocene the area was part of a broad, shallow carbonate platform. Subsequently the continental red beds, typifies the Mio-Pliocene, followed by thick evaporates. Eventually, during Plio-Pleistocene folding accompanied by syn-tectonic and post-tectonic molasses (Rabbani, *et al*., 2010). The depositional environment of most source rocks in southern Iran are tropical or equatorial dominating calcareous settings. Water-column stratification created anoxic condition during Mesozoic and Cenozoic and source rock units were deposited in intracratonic depressions through high stand. These source rocks contain at least 70% carbonate and are best referred to as argillaceous limestone or as marls (Fig.2). They have excellent source characteristics with TOC values up to 8% and Hydrogen Indexes up to 550 g HC/g TOC (Bordenave & Hegre, 2005).

The Pabdeh Formation was deposited in a NW-SE trending depression parallel to the Zagros Structure during Paleocene-Eocene and Oligocene. It comprises a monotonous sequence of gray marls with a rich planktonic fauna of globorotalia and globigerina. The average TOC values range from 3 wt% in Fars to 7.5 wt% in Lurestan (Bordenave, 2002) (Fig.3).

The Gurpi Formation gradually turns to the purple shales of the overlying Pabdeh Formation and lies by an erosional disconformity on Illam Formation. This formation mainly consists of gray shales and is deposited during Santonian-Maastrichtian (Ghasemi-Nejad & Zare, 2006). This formation has a lower organic content compared to the Pabdeh Formation and has TOC values ranging from 0.5-1.5 wt%.

The Kazhdumi Formation is a succession of up to 300 m of dark gray marls and argillaceous limestone deposited in the Dezful Depression under strictly euxinic conditions during Albian. The contained organic matter is of algal origin and contains up to 5-7 wt% sulfur. Moreover, TOC values vary from 1-11 wt% with average values of 5 wt% in the center of the depression (Bordenave, 2002) (Fig. 4).

The Gadvan Formation is a section of about 170 m of dark gray bioclastic limestone interbedded with gray/green marls, which is deposited from late Neocomian to Aptian (Alavi, 2004). This formation contains lower quantities of organic matter compared to the formerly discussed formations and the TOC values show an average value of 0.16 wt % (Bordenave, 2002).

**Material and methods**

A total of 41 cutting samples from 4 wells were selected to study the Pabdeh, Gurpi, Kazhdumi and Gadvan formations through the Aghajari Oilfield. Quantity, quality and thermal maturity of the organic matter within these formations are determined using the data provided from Rock-Eval 6 pyrolysis method.

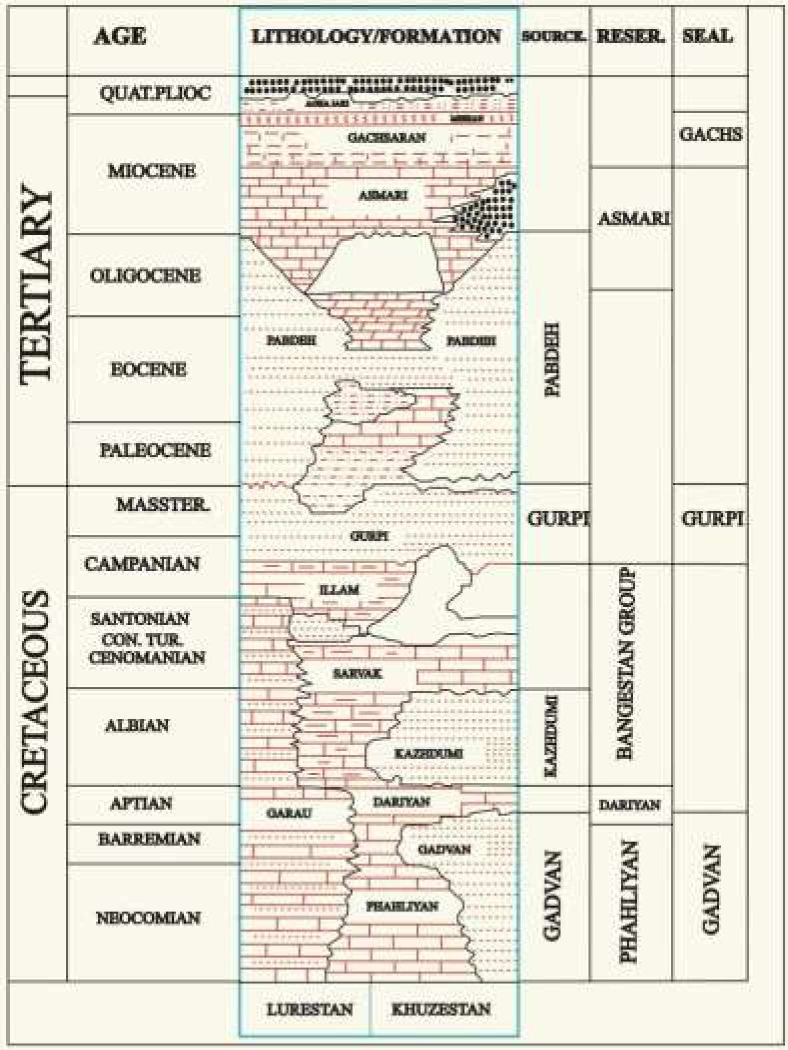


Figure 2: Schematic stratigraphy and source- reservoir-seal relationship for the Dezful Embayment (Bordenave & Burwood 1990).

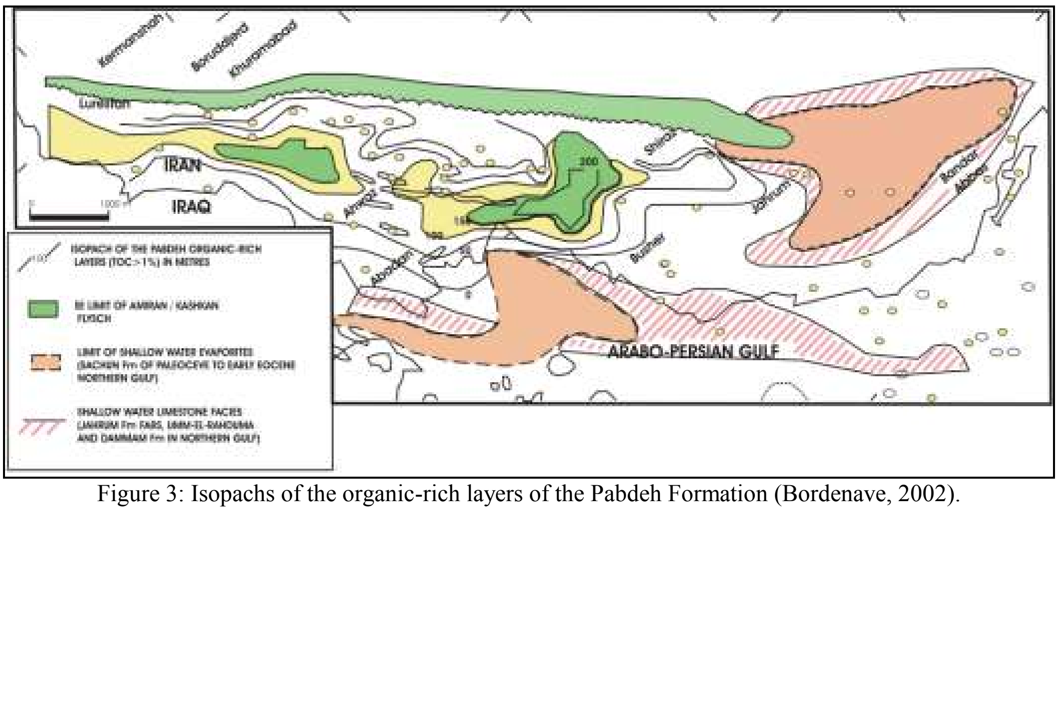


Figure 3: Isopachs of the organic-rich layers of the Pabdeh Formation (Bordenave, 2002).

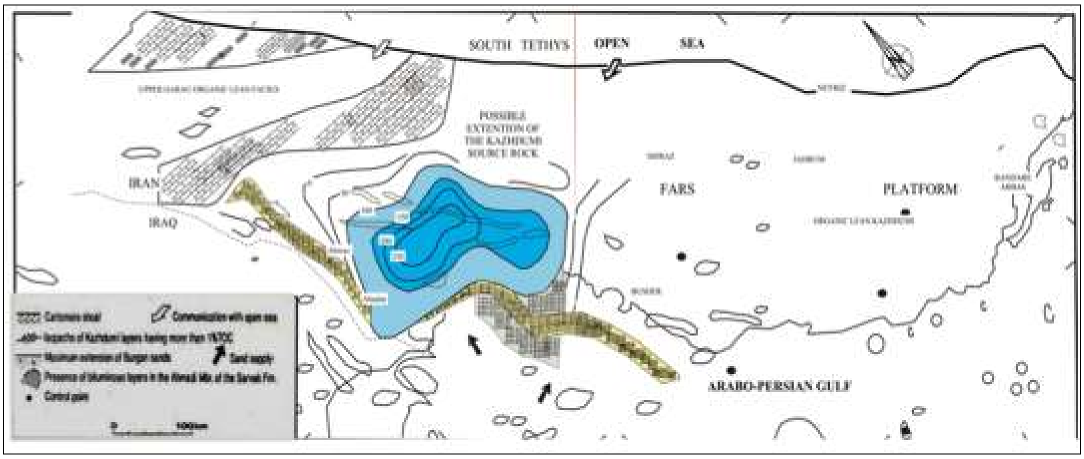

Figure 4: Isopach map of the Kazhdumi bituminous facies (TOC>1%) (Bordenave, 2002).

Selected samples from each formation were crushed using a pestle and mortar and were stored in oven for 24 hours to eliminate moisture. Precisely weighed aliquots of the powdered samples were mounted into crucibles and were analyzed using the method described by Espitalie *et al*., 1997. Moreover, for reconstructing the burial history of the studied formations and determining the time of oil expulsion a PARS BASIN MODELER software was applied in this study.

**Result and discussion**

Results from geochemical analysis of selected samples from studied formations are given in Table 1, while Table 2 presents the average values of various parameters. These data are used for construing the amount, type, thermal maturity and generative potential of the organic matter contained in source rocks.

*Organic Matter Quantity*

Effective hydrocarbon source rocks are characterized to contain a proper amount of the OM, however higher TOC values do not certainly indicate an excellent source rock quality (Hunt, 1996). Since the minimum TOC required for shale source rocks is 0.5 wt% (Tissot & Welte, 1984; Hunt, 1996; Peters *et al.,* 2005), according to the Table 1 and the average TOC values in Table 2 except from one poor source rock (Gadvan Formation) the rest are classified as good (Pabdeh and Gurpi formations) and very good (Kazhdumi Formation) source rocks. However, a fraction of the TOC is inert, which can be measured by plotting the $S_2$ values versus TOC for a source rock (Dahl, 2004). Figure 5 indicates the plotting of the studied samples on these diagrams and Table 3 summarizes the relevant data.

The TOC values of Pabdeh Formation range from 0.20-4.33 wt% with an average value of 1.64 wt%. This Formation will contain 0.51-3.63 wt% TOC after considering the approximately 0.71 wt% inert carbon. For Gurpi Formation the TOC values range from 0.29 to 2.08 wt% with an average of 0.86 wt%. After correcting inert carbon effect, this formation will contain an average TOC value of about 0.76 wt%. Kazhdumi Formation shows TOC values with a range of 0.97-3.26 wt % and an average of 2.26 wt%. By correcting the effect of inert carbon, the average TOC value will become 1.76 wt% for this formation. Lastly, the Gadvan Formation has the lowest average TOC value among the studied formations and correcting the inert carbon leaves an average value of about 0.16 wt % for this formation.

*Organic Matter Type*

Determining the type of the OM in a source unit is a very important step in evaluating petroleum source rocks because it controls the amount and type of the hydrocarbons generated upon thermal maturation (Hunt, 1996; Peters, 1986). Plotting the values of HI versus OI is the most common method used for determining the type of the OM in source rocks. According to these diagrams (Fig. 6), the majority of the samples are plotted as type II kerogen with few samples scattering around type III. The wide range of variation observed in Pabdeh Formation is probably the result of mixing of organic matter from various sources. The OM within the Gurpi Formation seems to be a mixture of marine and terrestrial organic matters (type II and III) as is also supported by the average HI value of 268 (mg HC/g TOC). The OM within the

Kazhdumi and Gadvan formations are type II and type III respectively.

Table 1: Rock-Eval pyrolysis results for selected source rock samples from Aghajari Oilfield.

| Formation | Rock-Eval Data | | | | Calculated Ratios | | | |
|---|---|---|---|---|---|---|---|---|
| | $S_1$ (mg HC/rock) | $S_2$ (mg HC/g TOC) | TOC (wt%) | $T_{max}$ (C°) | HI (mg HC/g TOC) | OI (mg $co_2$/g TOC) | PI | $S_1$+$S_2$ |
| PABDEH | 0.13 | 0.85 | 0.9 | 431 | 94 | 178 | 0.13 | 0.98 |
| | 0.18 | 2.65 | 1.72 | 436 | 154 | 88 | 0.06 | 2.83 |
| | 0.54 | 13.41 | 3.57 | 426 | 376 | 41 | 0.04 | 13.95 |
| | 0.33 | 10.96 | 2.48 | 426 | 442 | 44 | 0.03 | 11.29 |
| | 0.08 | 0.32 | 0.2 | 425 | 160 | 340 | 0.19 | 0.4 |
| | 0.12 | 0.87 | 1.38 | 433 | 63 | 48 | 0.13 | 0.99 |
| | 0.27 | 8.04 | 1.85 | 429 | 435 | 71 | 0.03 | 8.31 |
| | 0.45 | 11.73 | 2.11 | 426 | 556 | 51 | 0.04 | 12.18 |
| | 0.14 | 3.98 | 1.83 | 431 | 217 | 40 | 0.03 | 4.12 |
| | 0.24 | 1.15 | 0.63 | 428 | 183 | 106 | 0.17 | 1.39 |
| | 0.4 | 1.68 | 0.63 | 431 | 267 | 116 | 0.19 | 2.08 |
| | 0.12 | 1.45 | 0.55 | 435 | 264 | 67 | 0.07 | 1.57 |
| | 0.91 | 27.54 | 4.33 | 422 | 636 | 23 | 0.03 | 28.45 |
| | 0.33 | 9.5 | 1.98 | 429 | 480 | 54 | 0.03 | 9.83 |
| | 0.18 | 2.13 | 0.55 | 433 | 387 | 149 | 0.08 | 2.31 |
| GURPI | 0.37 | 6.82 | 2.08 | 425 | 328 | 62 | 0.05 | 7.19 |
| | 0.12 | 2.02 | 0.85 | 430 | 238 | 98 | 0.06 | 2.14 |
| | 0.2 | 4.17 | 1.33 | 430 | 314 | 77 | 0.05 | 4.37 |
| | 0.08 | 0.3 | 0.48 | 433 | 62 | 125 | 0.21 | 0.38 |
| | 0.09 | 0.65 | 0.29 | 437 | 224 | 245 | 0.12 | 0.74 |
| | 0.26 | 3.23 | 0.84 | 430 | 385 | 156 | 0.07 | 3.49 |
| | 0.62 | 3.59 | 0.97 | 429 | 370 | 131 | 0.15 | 4.21 |
| | 0.08 | 1.32 | 0.43 | 430 | 307 | 147 | 0.06 | 1.4 |
| | 0.14 | 1.36 | 0.49 | 431 | 278 | 157 | 0.09 | 1.5 |
| KAZHDUMI | 0.8 | 9.01 | 2.74 | 442 | 329 | 24 | 0.08 | 9.81 |
| | 0.83 | 9.35 | 2.2 | 439 | 425 | 42 | 0.08 | 10.18 |
| | 0.45 | 5.91 | 1.84 | 439 | 321 | 52 | 0.07 | 6.36 |
| | 0.78 | 6.81 | 1.95 | 438 | 349 | 76 | 0.1 | 7.59 |
| | 0.29 | 2.55 | 0.97 | 438 | 263 | 88 | 0.1 | 2.84 |
| | 1.04 | 5.51 | 2.22 | 443 | 248 | 53 | 0.16 | 6.55 |
| | 1.07 | 9.93 | 3.26 | 446 | 305 | 32 | 0.1 | 11 |
| | 0.85 | 14.09 | 4.43 | 443 | 318 | 12 | 0.06 | 14.94 |
| | 0.48 | 3.68 | 1.17 | 441 | 315 | 79 | 0.11 | 4.16 |
| | 0.76 | 8.13 | 2.36 | 437 | 344 | 26 | 0.08 | 8.89 |
| | 0.55 | 6.08 | 1.74 | 438 | 349 | 56 | 0.08 | 6.63 |
| GADVAN | 0.09 | 0.61 | 0.28 | 441 | 218 | 257 | 0.12 | 0.7 |
| | 0.05 | 0.44 | 0.25 | 443 | 176 | 272 | 0.11 | 0.49 |
| | 0.1 | 0.47 | 0.33 | 441 | 142 | 230 | 0.17 | 0.57 |
| | 0.16 | 0.92 | 0.39 | 442 | 236 | 185 | 0.15 | 1.08 |
| | 0.09 | 0.35 | 0.38 | 430 | 92 | 116 | 0.2 | 0.44 |
| | 0.11 | 0.73 | 0.56 | 441 | 130 | 155 | 0.13 | 0.84 |

Table 2: Average values for various Rock-Eval data used for comparing geochemical characteristics of the studied formations.

| Formation | $S_1$ | $S_2$ | TOC (wt %) | HI | PI | $T_{max}$ |
|---|---|---|---|---|---|---|
| **Pabdeh** | 0.29 | 6.41 | 1.64 | 314.2 | 0.08 | 429 |
| **Gurpi** | 0.21 | 2.6 | 0.86 | 278 | 0.09 | 430 |
| **Kazhdumi** | 0.71 | 7.36 | 2.26 | 324 | 0.09 | 440 |
| **Gadvan** | 0.1 | 0.58 | 0.36 | 165 | 0.14 | 439 |

Table 3: Equations of the regression lines over plots of $S_2$ versus TOC.

| Formation | Regression line Equation | $R^2$ | TOC inert |
|---|---|---|---|
| **Pabdeh** | y=0.175x+0.592 | 0.782 | 0.592 |
| **Gurpi** | y=0.262x+0.178 | 0.937 | 0.178 |
| **Kazhdumi** | y=0.220x+0.512 | 0.804 | 0.512 |
| **Gadvan** | y=0.231x+0.229 | 0.197 | 0.229 |

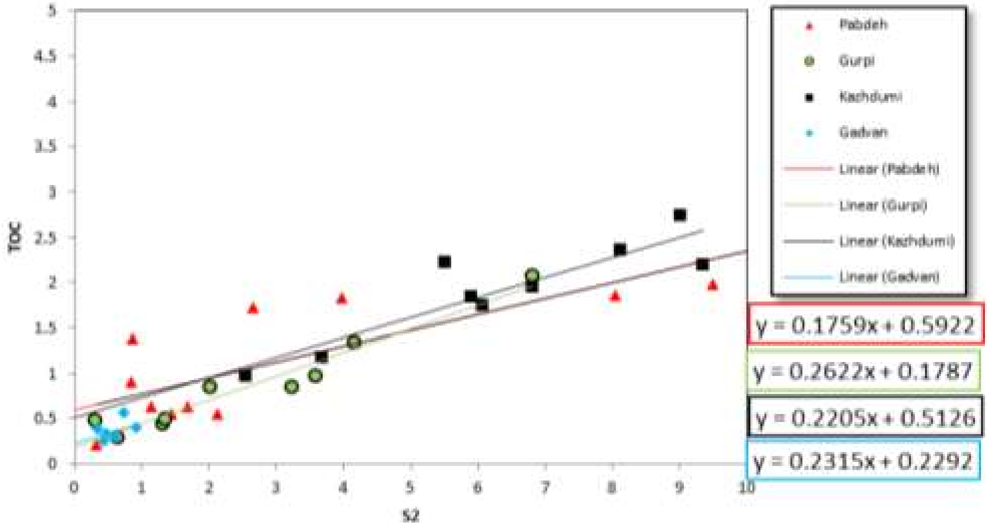


Figure 5: Plots of $S_2$ versus TOC for studied source rocks in the Aghajari Oilfield.

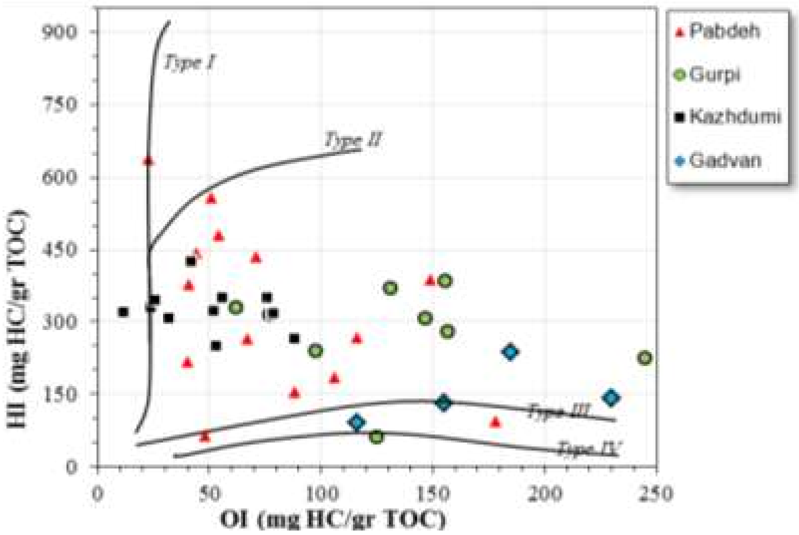


Figure 6. Plots of HI versus OI for studied source rocks indicate that he OM is mainly type II (After Hunt, 1996)

*Thermal Maturity of the OM*

Rock-Eval pyrolysis $T_{max}$ and PI can be used to estimate thermal maturity of the source rock (Peters *et al*., 2005). According to the average PI values in Table 2, the studied formations are in early stages of oil generation with Gadvan Formation exhibiting a relatively higher maturity. Furthermore, plotting $T_{max}$ versus HI vales indicates that, concurrent with their stratigraphic location, Pabdeh and Gurpi formations have a lower maturity than the Kazhdumi and Gadvan formations (Fig. 7).

To indicate the relevant level of oil generation in the studied formations, plots of PI versus $T_{max}$ are used (Fig. 8). This diagram indicates that Pabdeh and Gurpi formations are at the beginning of oil generation window, while Kazhdumi and Gadvan formations have reached the main stage of oil generation.

*Hydrocarbon Generative Potential*

Petroleum generative capacity of source rocks mainly depends on the original quantity (TOC) and quality (HI) of the OM (Peters et al., 2005). Plotting the values of genetic potential ($S_1$+$S_2$) versus TOC values from Rock-Eval pyrolysis is an easy way for determining generative potential of the studied source rocks (Fig. 9). According to these diagrams the samples from Gadvan Formation show lean to poor potential for hydrocarbon generation, while those from Gurpi Formation are fair to good. Moreover, Kazhdumi samples indicate an excellent quality for generation and samples from Pabdeh Formation show a wide range of variation from lean to excellent.

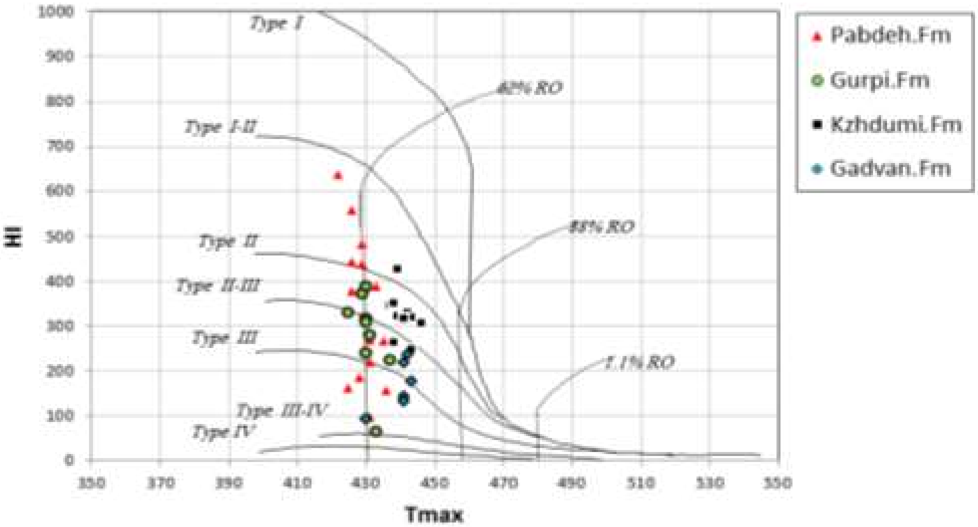


Figure 7: Plot of Hydrogen Index (HI) versus Rock-Eval $T_{max}$ for studied samples indicating that the Pabdeh and Gurpi formations have lower maturity compared to Kazhdumi and Gadvan formations. (After Akinlua *et al*., 2005)

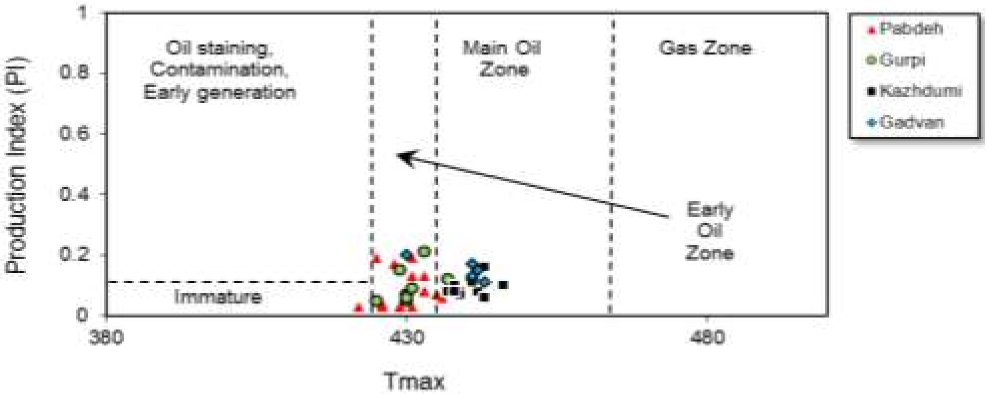


Figure 8: Plots of PI versus $T_{max}$ for studied formations indicating that Pabdeh and Gurpi formations are in the early oil window and Kazhdumi and Gadvan has reached the main oil window (After www.humble-inc.com)

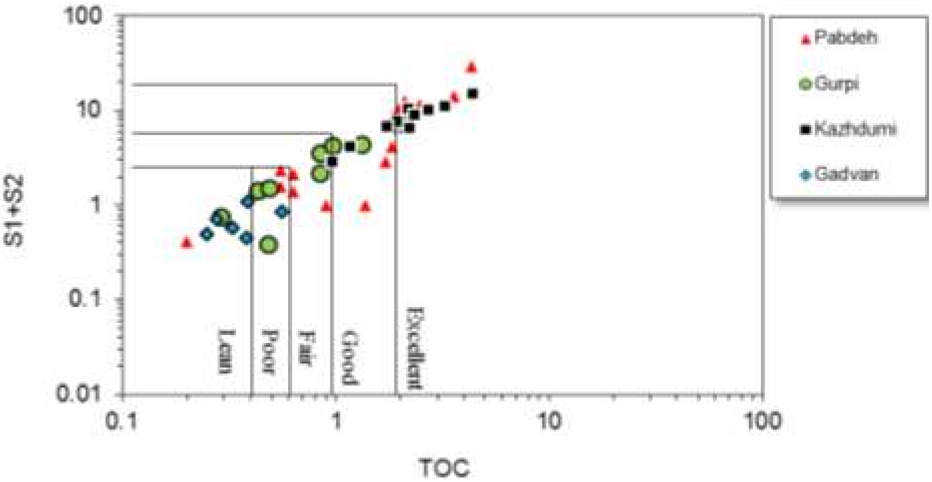


Figure 9: Plotting of values of genetic potential ($S_1$+$S_2$) versus TOC indicates an excellent potential for Kazhdumi Formation (After Huang.*et al*., 2003).

**Thermal Maturity Modeling**

Burial history modeling analyses the cumulative subsidence of selected chronostratigraphic horizons encountered in a well (Lopatin, 1971; Tissot &

Welte, 1984; Falvey & Deighton, 1982). Data required for thermal modeling includes the depths and ages of the formation tops; lithology and water depth for each formation at the time of deposition; the bottom-hole and/or formation temperatures, kerogen type and measured vitrinite reflectance values. The timing of hydrocarbon generation, and the approximate time of migration relative to structure development or trap formation can be predicted using the Lopatin Time Temperature Index or TTI (Lopatin & Bostik, 1973). In our study the Burial history profiles were constructed for well No. 140 and the time of oil expulsion was estimated by thermal modeling (Fig.10 and Fig.11).

Burial history reconstruction in the well 140 of Aghajari Oilfield shows a moderate to steady subsidence from Lower Cretaceous Fahliyan Formation (120 M a) to the Asmari Formation (20 Ma). The average subsidence rate during this long period is around 20 m/Ma. The subsidence rate increased strongly during the deposition of the Gachsaran and the Aghajari formations reaching an average of 350 m/Ma. As shown by the burial history reconstruction and thermal modeling the beginning of the oil window in Kazhdumi formation was dated 13 Ma. The oil expulsion in Kazhdumi formation began at 9 Ma at a depth of 3800 m. Hydrocarbon migration from source rocks (the Kazhdumi and Pabdeh Formations) was enhanced by the syn-orogenic fracturing of reservoir rocks in the Asmari (Asmari Formation) and Bangestan (Sarvak and Illam formations) Reservoirs (Rabbani, *et al*., 2010).

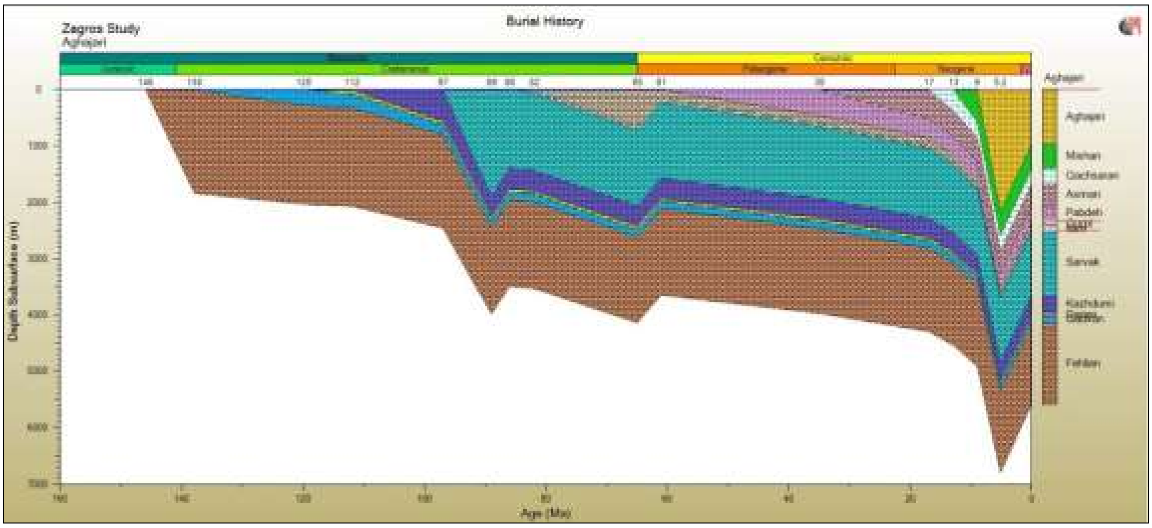


Figure 10: Burial history profile of the Neocomian to Quaternary beds at well 140 in Aghajari oilfield.

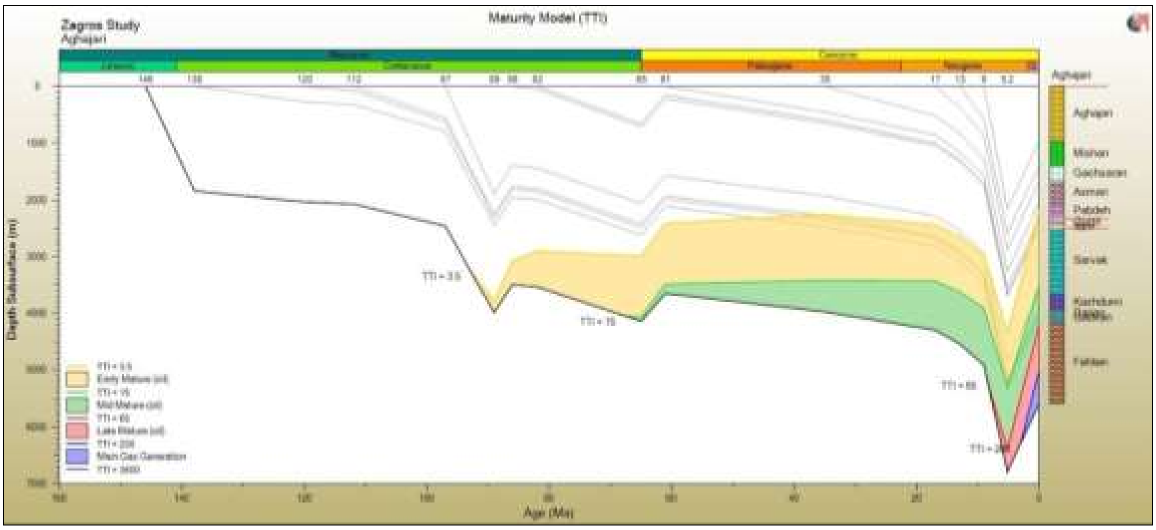


Figure 11: Maturity model of the Neocomian to Quaternary beds at well 140 in Aghajari Oilfield, showing the maturation history of the source rocks.

## Conclusions

Organic geochemical evaluation conducted on possible source rocks in the Aghajari Oilfield identified the Kazhdumi Formation as the effective hydrocarbon source rock. Plotting Rock Eval data for studied source rocks on Tmax versus PI diagrams indicate that Pabdeh and Gurpi formations are at the early oil window, while Kazhdumi and Gadvan formations have reached the peak stage of oil generation. Furthermore, lower average HI value and diagrams of S1+S2 versus TOC indicate that Gadvan Formation is a poor source rock. Therefore, the Kazhdumi Formation remains to be the only source rock responsible for oil accumulations within the Asmari and Bangestan reservoirs. The onset of the oil generation was dated as 13 Ma for the Kazhdumi Formation in burial history and thermal modeling profile. The oil expulsion in Kazhdumi Formation begun around 9 Ma at a depth of 3800 m. The main phase of Zagros folding occurred during the late Miocene and Pliocene. It is believed that migration of hydrocarbons from source rock (Kazhdumi Formation) was enhanced by the syn-orogenic fracturing of reservoir rocks in the Asmari (Asmari Formation) and Bangestan (Sarvak and Illam formations) reservoirs.

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