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Influence of Folding on Hydrocarbon Generation: an Example from the Dezful Embayment

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Abstract
One dimensional basin modelling was used to evaluate the maturity of source rocks, the history of oil generation, and expulsion in north Pazanan syncline and Pazanan, Agha-Jari, and Bangestan anticlines in south Dezful Embayment in the Zagros Basin. The oil generation history of source rocks was obtained by using the basin modelling method. Burial history analysis shows an increase in the rate of burial after the Zagros folding, which it was contemporaneous with huge sedimentation. The high rate of burial is more noticeable in the Pazanan syncline, which it plays an important role in the generation of oil from source rocks. The Sargelu, Garau and Kazhdumi source rocks in the Pazanan syncline have reached the gas-maturity stage. Trapped gas in the Pazanan field could be sourced from the syncline.

Key words: Dezful Embayment, Basin modelling, Oil generation, Pazanan anticline, Agha-Jari anticline, Bangestan anticline.

Introduction

The Dezful Embayment with about 60,000 km2 extends over the Zagros Fold Belt in the southwest of Iran [1]. It is a location for extraordinary giant fields such as the Pazanan and Agha-Jari (Fig. 1). A significant proportion of the global hydrocarbon reserve, about 14% [2, 3], is associated with fold and thrust belts; the Dezful Embayment contains 8% of that in carbonate reserves [1].

The Asmari gas reserve of the Pazanan field was discovered in 1936. A small oil reserve was found below the gas zone, and an independent gas column in the Khami Group in 1974 [4]. The Pazanan gas reserve distinguishes it from the adjacent oil fields.

The Agha-Jari field is an oil reserve that was discovered in 1937. It has oil reserves in the Asmari Formation and Bangestan Group, and gas in the Khami Group [5]. The Bangestan field on the mountain front had a gas reserve in the Early Jurassic intervals [6] (Fig. 2).

Basin modelling is used to investigate the oil generation and migration. Petroleum system and basin modelling in the Zagros have been discussed in numerous publications [8-18].

The Zagros orogeny has caused the formation of traps; also, folding has important effects on hydrocarbon generation, migration, and accumulation in the Dezful Embayment [19]. According to the studies which have been carried out by Gussow in 1954 [20] and Bordenave in 2014 [1], hydrocarbon migration and accumulation occurred along the structural trends in the Dezful Embayment. In the Ahwaz, Agha-Jari, Pazanan, and Gachsaran trend, the oil and gas accumulations are explained by differential entrapment [20]. The Zagros folding followed by widespread erosion in structural highs, with deposition of reworked sediments in structural lows and deeply buried of the source rocks [21], which could be pushing the source rocks into the hydrocarbon generation window in the study area.

The origin of the huge gas cap (44 Tcf) in the Pazanan field is difficult to be explained only by considering the main source rock of the area, the Kazhdumi Formation. The gas may have a deeper source such as Sargelu and Garau Formations [6]; the gas has pushed down the oil column until it has reached the spill point in the Pazanan field [6].

The main goal of the present study is to characterize the maturity of source rocks and the history of oil generation. The Zagros orogeny makes different settings of hiatus, erosion, and synorogenic sedimentation in the study area. The influence of these events on source rock maturity and hydrocarbon generation history reveals possible scenarios of gas entrapment in Pazanan instead of oil.

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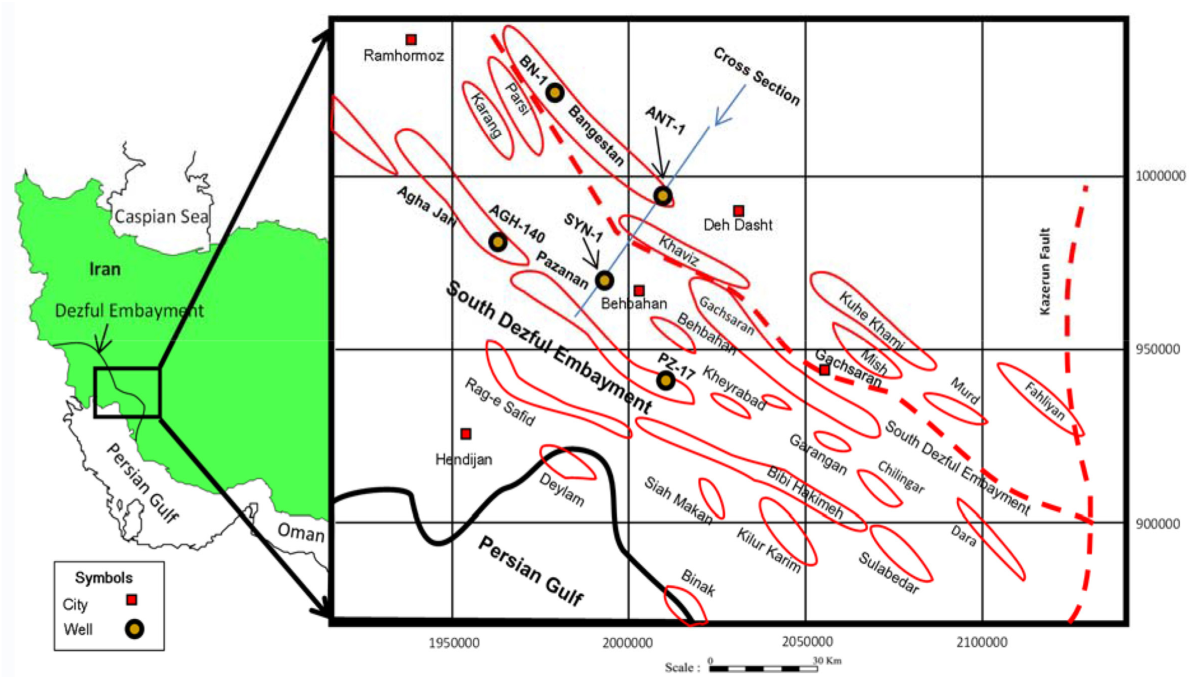

Fig. 1 Location of cross-section and wells of subject in this study.

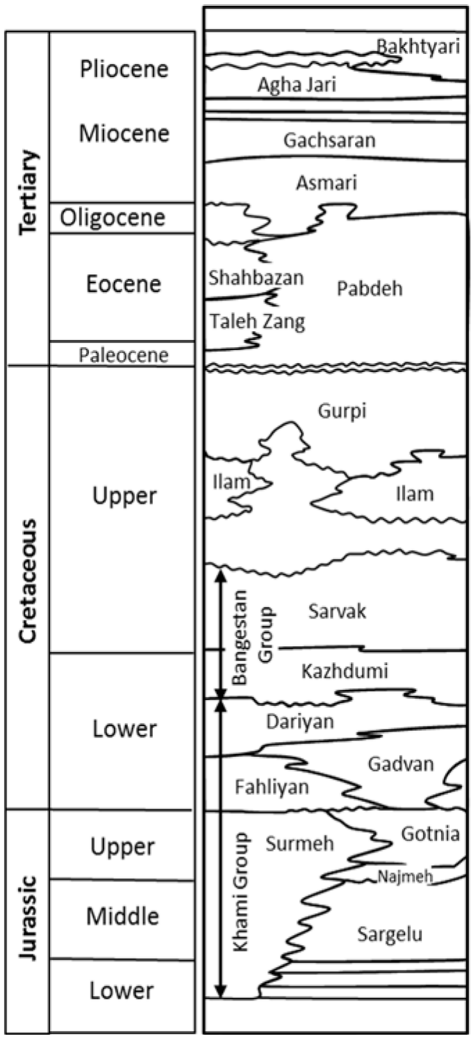

Fig. 2 Stratigraphic column of the Dezful Embayment [After 7].

Geological Setting

The Zagros fold and thrust belt were formed as a result of Neogene convergence between the Arabian Plate and Iranian Block [22-24]. The Dezful Embayment is a saddle [25] that developed after the Upper Oligocene [26]. It consists of thick sedimentary sequences from Precambrian to Holocene with a thickness of about 12 km [27]. The oil wells in the Dezful Embayment reach the Upper Jurassic Gotnia and Surmeh Formations (Fig. 2).

Geological history is dominated by a long term of subsidence and a carbonate-calcareous shale sedimentary regime. It is punctuated by short episodes of epirogenic uplift and nondeposition [28]. During Jurassic-to-Early Miocene, the Zagros basin was part of the Arabo-Nubian platform [29]. The platform was influenced by paleohighs [30] such as Hendijan paleohigh. Also, in areas of slightly higher subsidence, intracratonic basins such as Sargelu Basin were formed [31]. Sedimentation was dominantly high-energy limestone on paleohighs and low energy argillaceous limestone in the depressions [29].

Several source rock units were deposited in intracratonic depressions. The organic-rich sediments were deposited in the anoxic conditions as the result of water stratification. The source rocks are the Sargelu Formation (the Middle Jurassic), the base of the Garau Formation (the Valanginian), the Kazhdumi Formation (the Albian–Cenomanian), and the Pabdeh Formation (the Middle to Late Eocene) (Fig. 2) [9, 31-33].

The Neogene sediments in the area display a broadly upward coarsening. The sediments record the southward migration and progressive uplift of the Zagros mountain belt [34-39]. The Neogene succession passes upwards from Gachsaran sabkha deposits at the base into shallow marine marls (the Mishan Formation). The interval includes tidal flat sediments of the basal part of the Agha-Jari Formation. Finally, the middle–upper Agha-Jari and Bakhtyari Formations are sand and gravel dominated fluvial deposits (Fig. 2) [40].

The Bakhtyari and Agha-Jari deposits are sourced by the erosion of the Zagros Mountain.

Materials and Methods

In this study, Genex software was used, which it was developed by IFP for 1D modelling of oil generation from source rocks. 1D modelling can be used for oil generation simulation via oil or gas well data [41-43]. Data used in the thermal modelling include: the geological ages, depths of formations tops (Table 1), lithology, and water depth of the depositional environment of each formation, geochemical data, the kerogen type, and measured vitrinite reflectance values (Table 2).

The potential kerogen is assigned to the Sargelu, Garau, Kazhdumi and Pabdeh source rocks. The Sargelu and Garau source rocks are buried very deeply (more than 4500 m) in the Dezful Embayment. Little information is available about their characteristics and distributions. A few drilled wells reached the Garau facies such as the Agha-Jari -140 (AJ-140), Pazanan-17 (PZ-17) (Fig. 1). These wells did not reach to the base of the Garau Formation, which it is mostly considered as source rock. The Sargelu and Garau source rocks are drilled in the margin of the Dezful Embayment (e.g. the Bangestan-1 well (BN-1) (Fig. 1 and Table 1). Its characteristics such as thickness were used in the modelling of the studied wells.

Heat flow is a critically important factor in petroleum generation modelling. In this research, several scenarios of constant and variable heat flow values and geothermal gradients were tested. A constant heat flow was used because vitrinite reflectance data matched modelling results properly.

Results and Discussion

Thermal and burial histories were used to investigate oil generation processes at the Pazanan-17 (PZ-17), Agha-Jari -140 (AGH-140), and two synthetic wells. The data for synthetic wells, “Pazanan syncline” (SYN-1), and “Bangestan anticline” (ANT-1) were extracted from the structural cross-section of the geological map [46] (Fig. 3).

Burial histories show the depth of formations as a function of time, and burial lines’ slope represents the rate of sedimentation. The burial histories of the PZ-17 and SYN-1 wells show two peaks of sedimentation rate in the Upper Cretaceous and the Miocene (Fig. 4). The earlier peak of sedimentation was related to the obduction and down warping on the NE edge of the Arabian platform at the end of the Cenomanian [1]. The latter peak of sedimentation was contemporary with Zagros folding time (from 15 Ma to the present time [47]). The high sedimentation rate is obvious in the PZ-17 and AGH-140 wells, and it is intense in the SYN-1 well.

Table 1 Depth, total organic carbon, and age of formations were used in burial history reconstruction.

Formation	Depth (m)					TOC[1]	Age[2] (Ma)
	ANT-1	PZ-17	AJ-140	SYN-1	BN-1		
Bakhtyari				0			0
Lahbari				1272			5
Agha-Jari		0	0	3036			8
Mishan		723	963	4072			9.6
Gachsaran		1222	1391	4583			11.8
Asmari		1963	1666	5119			16.2
Pabdeh		2435	2054.5	5517		2.5	35.1
Gurpi	0	2652	2331	5977			69
Ilam- Sarvak	398	2803	2451.5	6322			84
Kazhdumi	1155	3889	2493	7142		3.0	92
Dariyan	1504	4113	3973.5	7539			110
Gadvan	1554	4164	4020	7589	0		113
Fahliyan	1661	4272	4074.5	7696	118		116.5
Garau	2097	4700	4146	8132	554	2.7	120
Gotnia	2423	5074	5592	8458	880		131
Najmeh	2841	5492		8876	1298		145
Sargelu	2866	5517		8901	1323	5.0	154.6
Base Sargelu	2941	5592		8976	1398		171

1- From Burwood in 1978 [44] and Bordenave and Hegre in 2002 [6], 2- From Koop and Orbell in 1977 [45]. Data in gray cells induced from Bn-1 well information.

Table 2 Vitrinite reflectance was used in modeling of the AJ-140 well (Data from Burwood [44]).

Depth (m)	Ro%	Depth (m)	Ro%
1862	0.48	3700	1.00
1998	0.38	3900	1.04
2036	0.44	3960	0.92
2092	0.41	4040	1.06
2183	0.47	4060	1.13
2222	0.49	4100	1.28
2258	0.50	4325	1.35
2294	0.55	4465	1.09
2338	0.55	4505	1.28
2372	0.59	4660	1.15
2412	0.54	4870	1.06
2468	0.48	5030	1.24
2708	0.52	5125	1.00
3484	0.50	5240	0.97
3560	0.85	5380	1.20
3640	0.83	5465	1.13

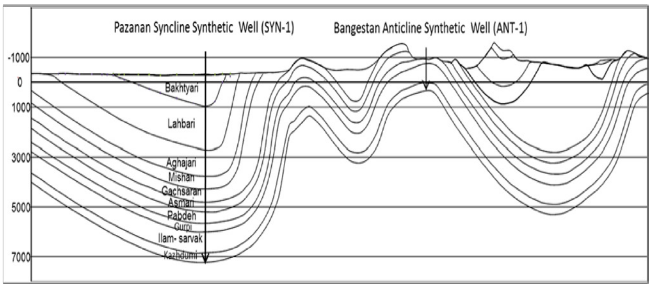

Fig. 3 Cross section and location of the SYN-1 and ANT-1 synthetic wells (after Macked and Akhuri 1970).

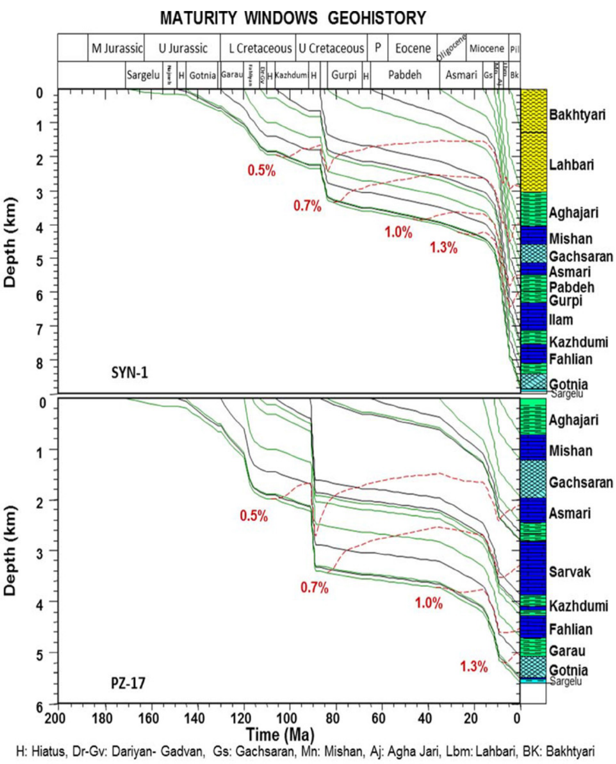

Fig. 4 Burial histories of the SYN-1 and PZ-17 wells.

This high sedimentation rate in burial depth is because of the thick synorogenic sediments (the Agha-Jari and Bakhtyari Formations with a thickness of 4072 m) in the SYN-1 well. Also, there were hiatus and erosion events in the ANT-1 well. As a result of that, the Sargelu Formation is at deeply buried in the SYN-1 well (about 8901 m), while the burial is 2866 m in the ANT-1 well (Fig. 5).

The mantle heat flow of 36 mW/m^2 was selected, because it corresponds to the best fit with measured vitrinite reflectance data of the AJ-140 well from Burwood [44] (Fig. 5). As well as this heat flow was used by Bordenave and Hegre in 2005 [19] and Bordenave and Hegre in 2010 [6].

Sedimentary framework of the Zagros has undergone significant changes in the Neogene [48]. The Zagros folding led to deformation, uplift and erosion of the passive margin sequence in the mountains [49]. After the Zagros folding, intense erosion in structural high of Bangestan anticline followed by deposition of reworked sediments (the Agha-Jari and Bakhtyari Formations) in structural lows. However, the subsidence was more in the Pazanan syncline than Agha-Jari and Pazanan anticlines, as a result, the Bakhtyari Formation only formed in the SYN-1.

The obtained reflectance lines (Fig. 5) show an increases in maturity with burial depth. The maturity of the Sargelu reaches to 2.4 and 1.4 %Ro in the SYN-1 and ANT-1 wells, respectively. Different sedimentation rates at structural settings after the Zagros folding have a significant impact on the burial depth and maturity of the source rocks.

The maturity histories of source rocks show a relatively constant trend before the Miocene at the SYN-1 and PZ-17 wells, (Fig. 6). After the Miocene, it continues at a higher rate at the SYN-1 well. This change in trend occurred from 10 Ma (sedimentation time of the Agha-Jari and Bakhtyari Formations) to the present time. The thickness of the Agha-Jari and Bakhtyari Formations are about 4,072 m at the SYN-1 well, while towards the PZ-17, the Agha-Jari and Bakhtyari Formations thinned (723 m) and disappeared respectively, due to depositional pinch-out [6]. The synorogenic sediments pushed the source rocks into the hydrocarbon generation window in the SYN-1 well.

In the PZ-17 well, source rock maturity is at the oil-maturity stage, while in the SYN-1 well, the Pabdeh source rock passed the peak of oil generation (Ro>0.8%), and other source rocks are at the gas-maturity stage (Fig. 6). According to maturity, the Sargelu, Garau and Kazhdumi organic rich-zone can be the source of gas in the area.

According to kerogen transformation ratio (TR) histories, all source rocks lost the main oil generation potential (TR above 95%) at the SYN-1 well (Fig. 7).

The main phase of the kerogen transformation of Sargelu and Garau occurred in the Upper Cretaceous; it was the Miocene for the Kazhdumi and Pabdeh source rocks.

The expelled hydrocarbon per time of the Pabdeh at the SYN-1 well is contemporaneous with the timing of folding (Fig. 8).

The Pabdeh source rock is currently expelling hydrocarbons, and that expulsion has been going on since 8 Ma. There is an expulsion peak at 4-6 Ma when huge thicknesses of sediments (the Agha-Jari and Bakhtyari Formations) were deposited.

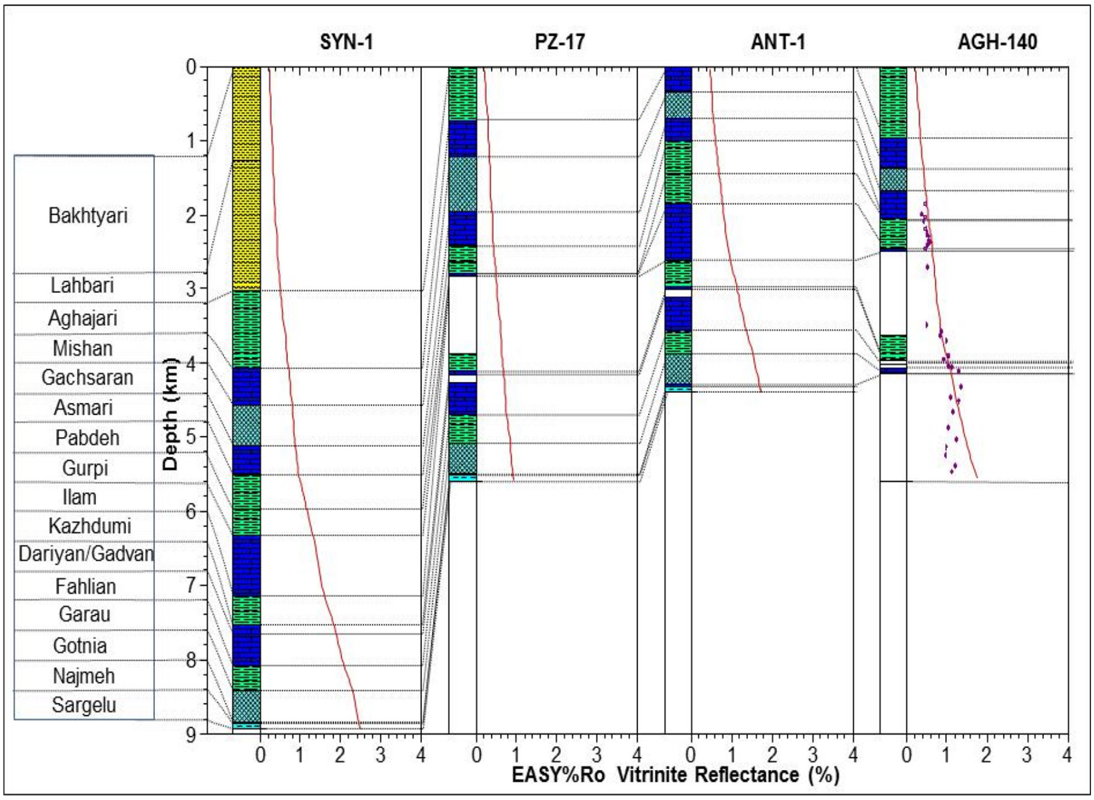

Fig. 5 Correlation and maturity profiles of the SYN-1, PZ-17, ANT-1, and AGH-140 wells.

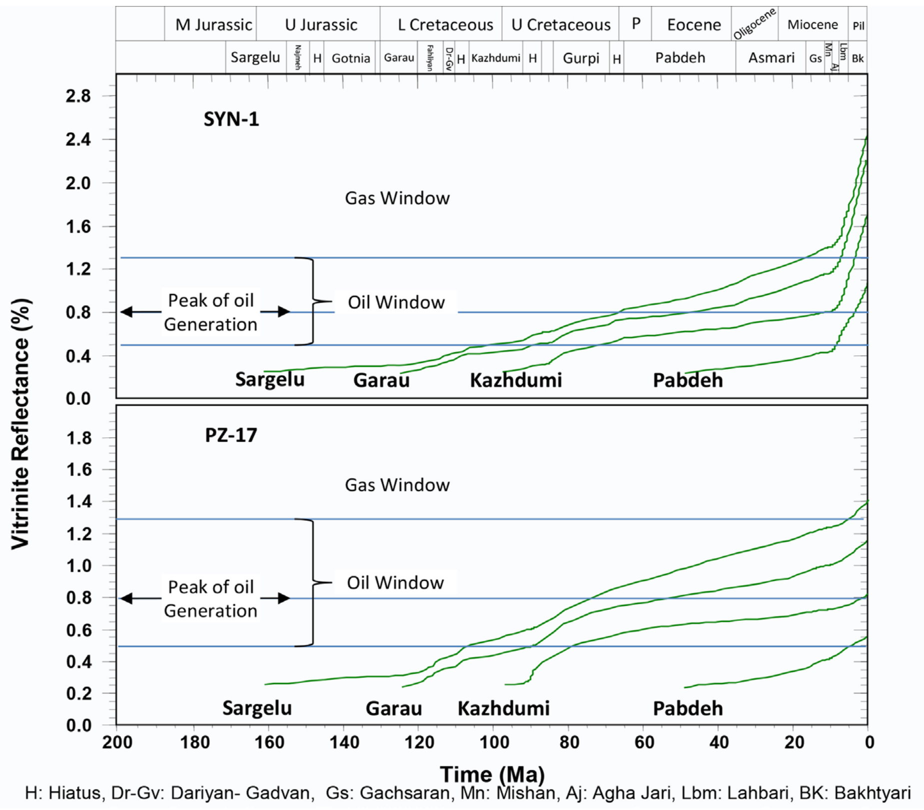

Fig. 6 Maturity history of the source rocks at the SYN-1 and PZ-17 wells.

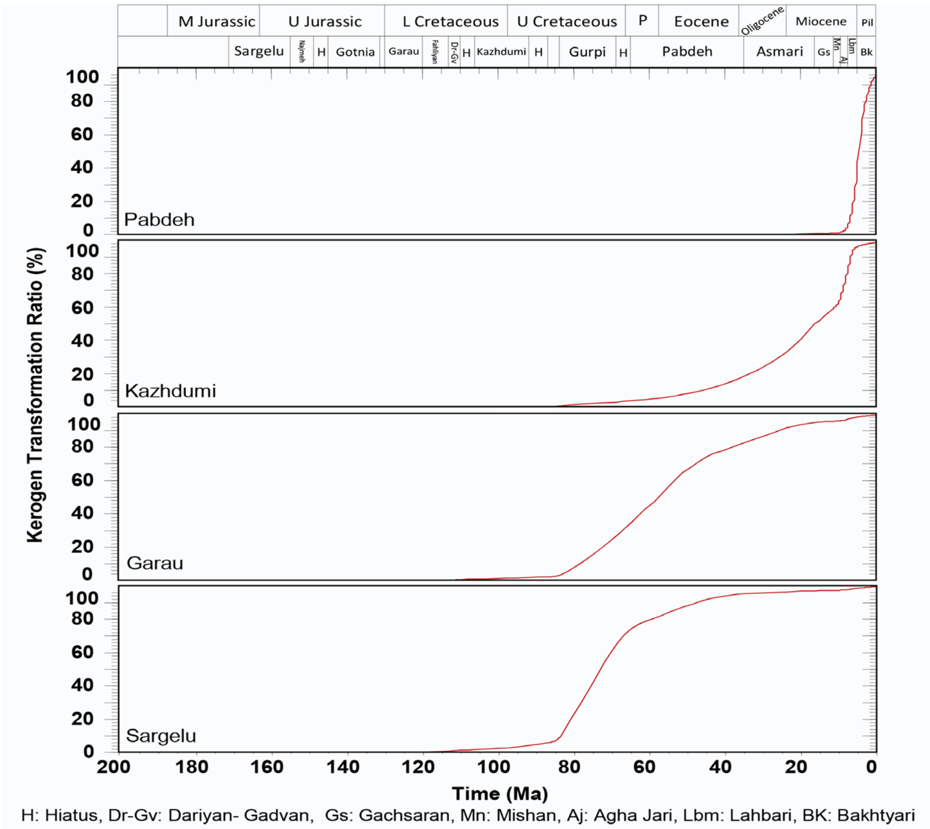

Fig. 7 Kerogen transformation ratio histories of the source rocks at the SYN-1 well.

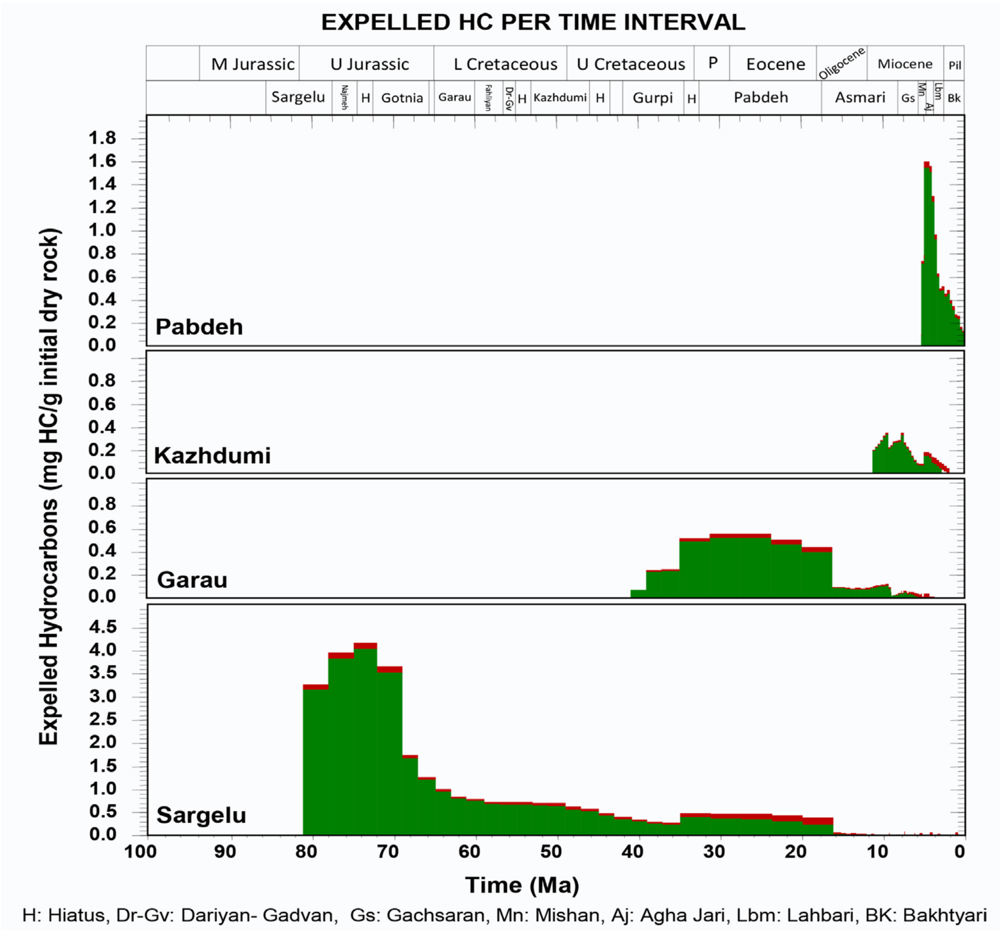

Fig. 8 Expelled hydrocarbon per time of the Pabdeh, Kazhdumi, Garau, and Sargelu source rocks with expulsion saturation of 30% at the SYN-1 well.

The Late Miocene (7-10 Ma) was the main oil expulsion time of the Kazhdumi at the SYN-1 well. These results are in accordance with the findings of Vatandouts et al in 2020 [50], who studied fluid inclusion samples of the Asmari reservoir at three oilfields (the Karanj, Paranj, and Parsi) (Fig. 1). They identified two episodes of oil charging into the Asmari reservoir: 7 to 3.5 Ma and 3.5 to 2 Ma. This oil charging occurred after the migration of oil from the source rocks to the Asmari reservoir.

The Garau source rock expelled oil during the Eocene-to-Miocene period. The main oil expulsion of the Sargelu occurred in the Upper Cretaceous and declined during the Miocene, before the Zagros orogeny. Therefore, there isn't a relationship between hydrocarbon generation of the Sargelu and Garau source rocks and Zagros orogeny.

The quantity of expelled hydrocarbon from the Sargelu, Garau, Kazhdumi and Pabdeh source rocks, are 30, 6, 9.5, and 11 (mg/gr rock) respectively at the SYN-1 well (Fig. 9). The quantity of oil generated from the Sargelu Formation was more than the three other source rocks.

In the study area, oil and gas expulsion and migration in two petroleum systems of the Middle Jurassic (Sargelu), Early Cretaceous (Garau) occurred before the Zagros orogeny. Migration of hydrocarbons occurs to the nearest paleohigh such as Hendijan [19], and after the Zagros folding the hydrocarbon could remigrate to the nearest Zagros anticlines as the Pazanan or Agha-Jari anticlines. The hydrocarbon expulsion in the Kazhdumi and Pabdeh organic-rich zones occurred at the same time as the Zagros orogeny.

Based on previously published studies [e.g. 6, 28, 51, 52], the huge gas cap in the Pazanan field is difficult to be explained only by the oil-prone Kazhdumi or Pabdeh Formations. This study shows that the gas generation of the Garau, Sargelu, and Kazhdumi Formations in the deep of syncline of the Pazanan drainage area is possible. The gas from the Sargelu and Garau sources could have remigrated from the paleohigh reserves. The Kazhdumi gas could have migrated through fractures toward the Asmari Formation.

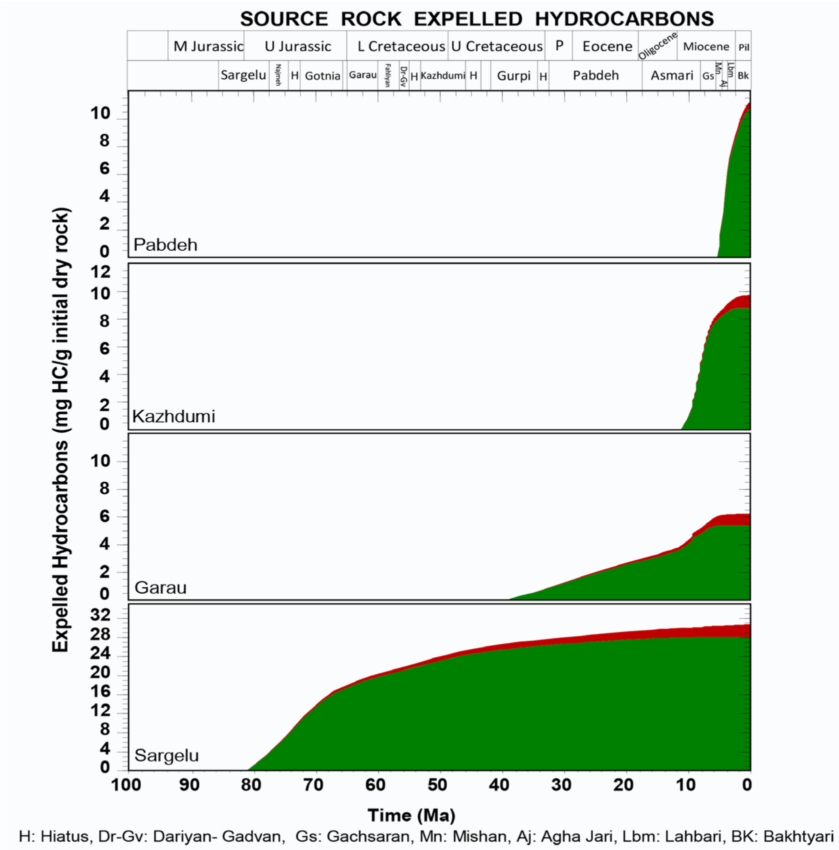

Fig. 9 Source rocks expelled hydrocarbon at the SYN-1 well.

Conclusions

There are two peaks of sedimentation rate during the Late Cretaceous and Miocene-to-the present time. The latter rate occurred at the same time as the folding of layers, and it is greater in the syncline in comparison with anticline settings. The burial histories of the studied anticlines and syncline were similar from the Jurassic-to-Miocene. Furthermore, a significant change in the sedimentation rates caused different maturity histories of source rocks which it is more intense at the Pazanan syncline.

The Zagros folding and synorogenic sediments [49] were responsible for pushing the source rocks into the hydrocarbon generation window. It has a major influence on oil expulsion of the Pabdeh and Kazhdumi with minor influence on Sargelu and Garau source rocks.

Ultimately, according to this study, it is found out that the gas in the Pazanan and Bangestan fields could have originated from the Kazhdumi in syncline. Also, it is possible that gas with Sargelu and Garau origin has remigrated from a paleohigh after the Zagros folding.

Nomenclatures
TR: Transformation ratio

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