Petroleum Engineering

Iranian Journal of Oil & Gas Science and Technology, Vol. 6 (2017), No. 4, pp. 01-17
http://ijogst.put.ac.ir

A Thermal Maturity Analysis of the Effective Cretaceous Petroleum System in the Southern Persian Gulf Basin

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Received: October 28, 2016; *revised*: May 15, 2017; *accepted*: May 22, 2017

Abstract

Commercial hydrocarbon discoveries in the Cretaceous of the southern Persian Gulf basin provide direct evidence that there is an effective petroleum system associated with the Cretaceous series. The revised models of thermal maturity in this region are needed to investigate lateral and stratigraphic variations of thermal maturity, which have not so far been addressed in detail for this part of the Persian Gulf. Such thermal maturity models are required to delineate the existing play assessment risks and to predict properties in more deeply buried undrilled sections. This study uses two dimensional basin modeling techniques to reconstruct maturity evolution of the Cenomanian Middle Sarvak source rock, presumably the most likely source for these hydrocarbons. The results indicate that an estimated 900 meter difference in the depth of burial between the southeastern high and the adjacent trough tends to be translated into noticeable variations at both temperature (135 °C versus 162 °C) and vitrinite reflectance (0.91% versus 1.35%). Since the organic matter in the mentioned source rock is of reactive type II, these could cause a shift of about 18 million years in the onset of hydrocarbon generation over respective areas.

Keywords: Thermal Maturity Modeling, Effective Cretaceous Petroleum System, Cenomanian Middle Sarvak Source Rock, Southern Persian Gulf Basin

1. Introduction

The southern Persian Gulf basin (Figure 1) is a part of the prolific Rub-Al-Khali Basin (US Geological Survey World Petroleum Assessment, Province 2019) with at least three stacked total petroleum systems (Pollastro, 2003). The Iranian part of this basin covers an approximate area of 33500 km^2 and contains more than 8 major producing fields (IOOC unpublished data), including one of the largest gas deposits in the world (Bashari, 2005). Following a comprehensive geophysical study in 2000, a better understanding of the subsurface geology, structural evolution, and sequence stratigraphic development of the area was gained (Farzadi, 2006a; Farzadi, 2006b; Farzadi and

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Hesthammer, 2007; Soleimany and Sàbat, 2010), which served to fuel new exploration activities in this area.

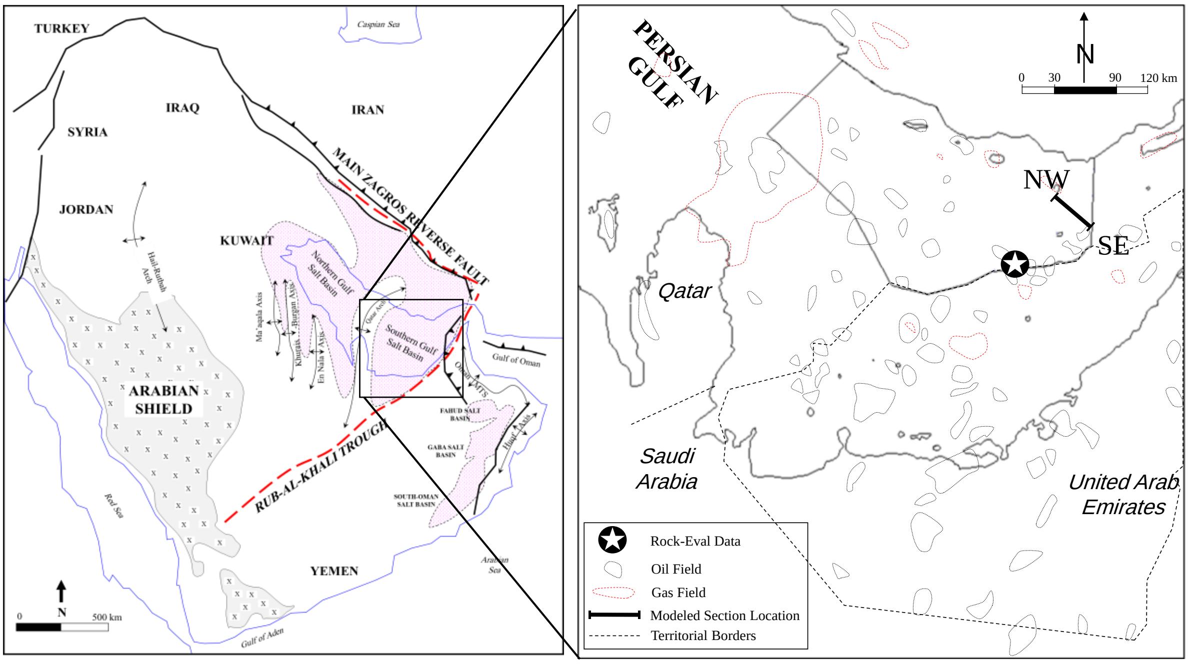

Figure 1

Generalized representation of the main tectonic features (left) and the regional orientation of the modeled section (right) (see Figure 3 for vertical profile of the section).

Basin and petroleum system modeling (BPSM) has proved a versatile technique for locating hitherto undiscovered hydrocarbon deposits through studying the essential elements and processes in multiple dimensions. In addition, many activities, including petroleum play assessments, unconventional resource estimates, and timing of hydrocarbon generation in relation to the trap forming events essentially rely on well-calibrated thermal maturity models (e.g., Grobe et al., 2015). Hence, reliable modeling of thermal maturity conditions in the subsurface is an essential part of petroleum exploration activities. The current study encompasses area to the east of the southern Persian Gulf basin, where thermal maturity aspects are least documented and future exploration activities heavily rely on a refined knowledge about thermal maturation specifics (Figure 1). The aims of the current work are to reconstruct a thermal maturity model along a 2D profile for the Cretaceous petroleum system and the associated source rock (i.e. the Middle Sarvak source rock). Consequently, the modeling results could be applied to defining oil and gas generation windows, making predictions in the more deeply buried undrilled sections, and monitoring variations in the temperature history of the Middle Sarvak source rock across a structural low and the adjacent high.

2. Regional stratigraphic setting and structural framework

The study area is underlain by a thick sedimentary succession with alternating clastics, carbonates, and evaporates, which makes the area particularly prolific for hosting large hydrocarbon deposits. The oldest sediments in the area are believed to be the evaporates, shales, and dolomites of the Late-Precambrian Hormuz Series (Kent, 1979). Generally speaking, there is little data available about the sedimentary history of the Lower Paleozoic in the Persian Gulf region and the sedimentary record is mostly comprised of shales and sandstone with rare carbonates in Devonian and Early Carboniferous (Murris, 1981). During the Permian, carbonate shelf deposits of the Dalan formation were laid under warm, shallow-water conditions. More arid conditions during Mid-Late Triassic formed the evaporate deposits of the Dashtak formation, which marks the end of the carbonate cycles (Figure 2). The Middle Jurassic sediments mainly consist of normal marine organic-rich carbonates (the Surmeh formation) (Alsharhan, 2001) that are capped with extensive evaporates deposited in very shallow conditions (Hith formation) during Tithonian (Alsharhan and Magara, 1994; Lasemi and Jalilian, 2010).

Period	**Epoch**	**Formation name**	**Age (Ma)**	**Petroleum system element**		
				SR	**Res**	**S**
Neogene	Holocene	Seabed	0			
	Pleistocene	Bakhtiyari	0.1			
	Miocene	Mishan	12			
		Gachsaran	15			
Paleogene	Oligocene	Asmari	20			
	Eocene	Jahrum	35			
	Paleocene	Pabdeh	60			
Cretaceous	Upper	Gurpi	63			
		Ilam	80			
		Sarvak	93			
			95.3			
			97.5			
	Lower	Kazhdumi	100			
			106.6			
		Dariyan	115			
			120			
		Gadvan	122			
		Fahliyan	130			
Jurasic	Upper	Hith	146			
		Surmeh	151			
			155			
			160			

Period	**Epoch**	**Formation name**	**Age (Ma)**	**Petroleum system element**		
				SR	**Res**	**S**
	Middle	Surmeh	161			
	Lower	Neyriz	172			
Triassic	Upper	Dashtak	178			
	Lower	Kangan	247			
			251			
Paleozoic	Permian	Dalan	252			
		Faraghan	268			
	Devonian/Carboniferous	Zakeen	295			
	Silurian	Sarchahan	388			
	Ordovician	Paleozoic series	435			
			483			
	Cambrian	Hormuz series	531			
			600			

Figure 2

Generalized stratigraphic column of the Persian Gulf Basin with ages and associated petroleum system elements.

During Cretaceous, three main stratigraphic sequences (Figure 2) are recorded in the Persian Gulf area: the Lower Cretaceous deposits of the Fahliyan, Gadvan and Dariyan formations; the Middle Cretaceous sediments comprising of the Kazhdumi and Sarvak formations; and the Upper Cretaceous deposits of the Ilam, Laffan, and Gurpi formations (Harris et al., 1984; Jordan et al., 1985).

A regional unconformity marks the end of the Cretaceous and the boundary between the Late Cretaceous and Early Tertiary sediments (between Pabdeh and Gurpi formations) (Sharland et al., 2001). Plaeogene in Figure 2 consists of the Pabdeh and Jahrum formations, followed by bioclastic carbonate sediments of the Oligocene Asmari formation. These sediments are followed by evaporate deposition during Miocene (Gachsaran formation). Orogenic folding of the adjacent Zagros during the Late Tertiary resulted in rapid uplift and extensive eroded deposits (Alsharhan and Nairn, 1995), which formed the thick clastic wedge of the most recent time intervals (Figure 2).

The main structural features in the area of study are summarized in Figure 1. The Paleozoic structural deformation is reported in detail for the entire region (Faqira et al., 2009). According to many new findings (Soleimany et al., 2013; Valero et al., 2015), recent deformation episodes of the area included a Late Cretaceous event (producing NNE-SSW trending faults) and a Late Cenozoic event of Zagros Orogeny (reactivating previous folds and causing a new set of NW-SE trending folds). Apart from these events, most of the structures in the Persian Gulf basin are affected by episodic salt movements to varying extents (Jordan et al., 1985).

The paleodepositional settings of the eastern margin of the Arabian plate have been the locus of intra-shelf anoxic basins during several geologic time intervals from Jurassic onward. This resulted in the formation of numerous highly organic-rich strata including the Oxfordian-Kimmeridgian Diyab formation (Alsharhan, 2001), the Mid-Aptian Bab member (Azzam and Taher, 1995; Van Buchem et al., 2011; Maurer et al., 2013), and the Cenomanian-Turonian Shilaif formation (Van Buchem et al., 2002; Peters et al., 2005; Razin et al., 2010). The Upper Jurassic Diyab source unit was deposited under anoxic marine conditions and was recognized as the main source for hydrocarbons existing in the Arab formation (Whittle and Alsharhan, 1996; Al-Suwaidi, 2000; Alsharhan and Scott, 2000). The Bab member is identified as the main source for hydrocarbons existing in the Lower Cretaceous Simsima group (Taher, 1996; Alsharhan et al., 2000), although mixing of the Diyab and Bab oils may occur (Al-Suwaidi, 2000). The Shilaif source rock, which is the focus of this study, is believed to have charged the Mishrif reservoir in many oilfields of eastern UAE (Azzam and Taher, 1993; Gumati, 1993).

3. Previous work

3.1. Oil family classification

In a regional study of 33 oil samples, Rabbani et al. (2014) were able to statistically group the samples into four main families by using 14 source-related biomarker and isotope ratios (Rabbani et al., 2014). The samples were collected from 17 different oilfields across the entire Persian Gulf basin. These authors believe that their Group IV oils (collected from Late Cretaceous reservoirs of the eastern and southern parts of the Persian Gulf basin) have probably originated from mid to Late Cretaceous source rocks. However, no firm evidence is provided to prove genetic relationship between the mentioned oils and the Cenomanian Middle Sarvak source rock.

3.2. Organic geochemistry

In a recent study, rock samples of the Middle Sarvak formation were evaluated from the southern Persian Gulf basin in terms of organic richness, type of organic matter, and depositional setting (Hosseini et al., 2016). Their study has shown good to very good petroleum potential corresponding to types I, II, and II-S deposited under anoxic marine conditions for the Cenomanian Middle Sarvak source rock. According to these authors, an eastward increase in the level of thermal maturation for the Middle Sarvak formation is confirmed by geochemical parameters of extracted organic matter. Although no modeling results are included in their work, a deeper burial toward the Sirri district is mentioned as the main reason for the maturity variation observed.

3.3. Modeling

The thermal maturity of Cretaceous source rocks is extensively studied in the Arabian parts of the Persian Gulf basin, with an emphasis on the timing of petroleum generation and the level of organic transformation (Azzam and Taher, 1993; Gumati, 1993; Taher, 2010). The exact nature and quality of the calibration data is rarely reported by these studies. Therefore, the extrapolation of their results to neighboring areas may give erroneous estimates attached with a large range of uncertainty. As a result, most of the conclusions cited in these studies cannot be readily applicable to nearby areas because, as our study will show, considerable variations might occur over limited geographic distances. This further highlights the importance of constructing maturity models specific to our own region and uses the results for future studies.

In the Iranian sectors, thermal 1D modeling was performed for the Cretaceous petroleum system in the southern Dezful embayment (Opera et al., 2013) and within the Persian Gulf basin (Mashhadi et al., 2015). The latter study is valuable because it provides a general overview of the regional variations in the burial of various source rocks throughout the entire Persian Gulf. However, the importance of local troughs in the evolution of a given petroleum system (e.g., the effective Cretaceous petroleum system) could rarely be reflected in their findings. In addition, according to the latest findings, the organic rich portion of the Middle Sarvak source rock is limited to the southern Persian Gulf basin (Vahrenkamp et al., 2015); hence, the maturity modeling of the Middle Sarvak source rock for wells far to the west of the Persian Gulf basin (Figure 14 in the work of Mashhadi et al. (2015)) would be redundant. In this study, we restrict the modeling results to an area that comprises the organic-rich portions of the Middle Sarvak source rock (see Figure 1). In this way, a deeper perspective could be taken on the maturation behavior of an individual source layer over a 2D transect that encompasses existing deformations (local depressions and uplifts).

4. Methods and input data

Mathematical models are able to make quantitative predictions of geological processes leading to hydrocarbon accumulations. The general geodynamic evolution of the basin is automatically reconstructed by means of backstripping methods, which take into account the progressive sediment compaction based on vertical shear algorithms. Given a realistic heat flow at the base of the model and the thermal properties of each sedimentary unit (e.g. heat capacity, thermal conductivity, radioactive heat generation etc.), a temperature model of the basin can be properly furnished. Possible regions and times of hydrocarbon generation within the basin will be governed by specific kinetic models defined for organic transformations.

For having reliable thermal modeling results, the following effects from several unrelated phenomena should be properly considered: a) the amount of mantellic heat entering the sedimentary package and the amount of temperature defining the upper boundary of the model at the surface; b) local thermal anomalies related to lithofacies variations; c) impact from geological phenomena like formation ages, paleobathymetries, and structural events such as uplift and erosion; and d) observed reading points used for constraining maturity modeling output (in terms of accuracy, type, and number of readings).

Using TemisFlow® software, a two dimensional cross section line was built from depth-converted seismic profiles which convey the thicknesses of existing layers. Formation ages and their lithofacies were carefully defined using the available data. An advanced basement model, comprising of the Upper Continental Crust, Lower Continental Crust, and Mantle (with appropriate lithofacies and thicknesses) was considered underneath the sedimentary package. A constant temperature (≈ 1333 °C) was used at the base of the Upper Mantle, while the surface temperatures were allowed to vary according to the existing database with the intermediate ages taking interpolated values.

The geological grid of the modeled cross section is presented in Figure 3.

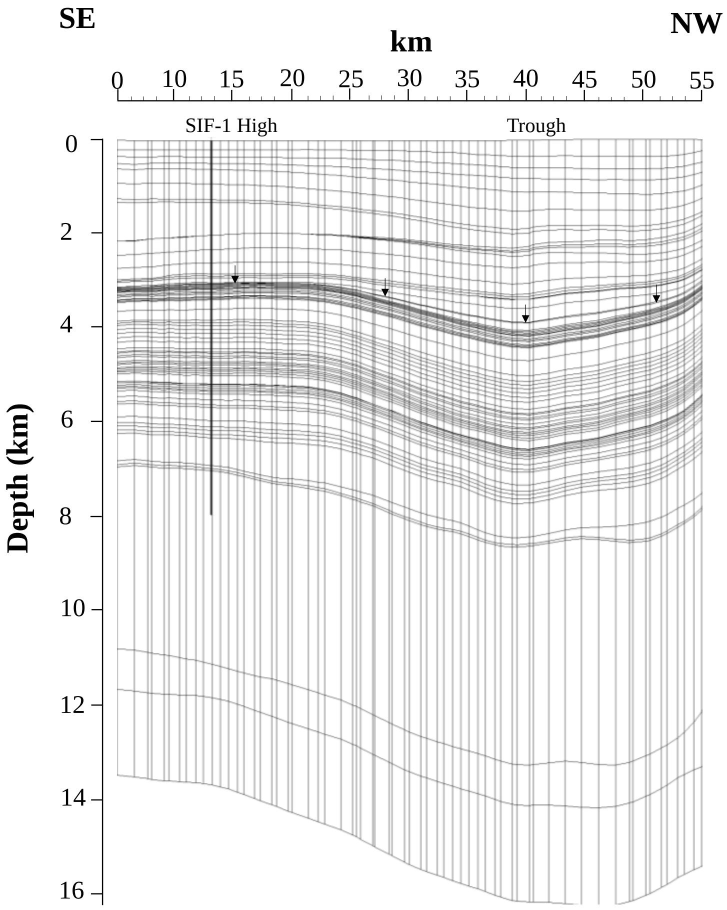

Figure 3
Schematic representation of the modeled section with approximate locations of the studied SIF-1 high and the trough along the section line (see Figure 1 for orientation); arrows indicate the intended source rock level, which is the Cenomanian Middle Sarvak.

Each row in this model represents a unique stratigraphic unit, and the vertical lines define the size of the cells in the model. The section line is oriented specifically to cross through a local trough to the northwest that potentially could act as a favorable petroleum kitchen. Despite the lack of drilling data in the trough, our modeling approach provides valuable information about the maturity evolution of the intended source level within the Cretaceous series. Organic parameters (Table 1) for the Middle Sarvak source rock were obtained from a well shown by the asterisk on Figure 1.

Table 1
Rock-Eval parameters for the Middle Sarvak source rock obtained from a well close to the modeled section (see Figure 1).

Formation	TOC (wt.%)	T_{max} (°C)	S_1 (mg HC/g rock)	S_2 (mg HC/g rock)	HI (mg HC/g TOC)	OI (mg CO_2/g TOC)
Middle Sarvak	5.57	430	4.32	33.19	595.87	15.62
	6.45	436	4.40	38.26	593.18	13.95
	4.13	438	3.31	23.06	558.35	20.34
	2.06	435	2.71	9.55	463.59	44.66
	2.98	436	2.57	15.20	510.07	32.55
	3.13	436	2.67	16.11	514.70	30.35

Formation	TOC (wt.%)	T_{max} (°C)	S_1 (mg HC/g rock)	S_2 (mg HC/g rock)	HI (mg HC/g TOC)	OI (mg CO_2/g TOC)
	1.28	437	2.06	4.88	381.25	87.50
	3.66	436	2.46	19.72	538.80	26.50
	4.38	436	2.86	25.21	575.57	21.23
	3.77	431	3.20	19.62	520.42	27.85
	2.80	433	2.97	14.17	506.07	48.93
	2.54	433	3.45	12.98	511.02	48.03
	2.19	433	2.02	11.53	526.48	46.12
	1.83	436	1.76	10.01	546.99	48.09
	1.87	435	1.64	10.41	556.68	44.92
	2.10	432	1.56	11.76	560.00	48.10
	2.75	434	1.67	16.17	588.00	38.18
	2.71	435	3.47	13.95	514.76	30.26

5. Results and discussion

5.1. Model Calibration

The model is calibrated using the existing temperature and vitrinite reflectance data obtained from nearby wells (Table 2).

Table 2
Vitrinite reflectance and temperature data used for the calibration of the modeled 2D section.

Well	Depth (m)	Vitrinite reflectance (VRo%)	Temperature (°C)
	1517	0.25	
	1688	0.37	
	1734	0.44	
	1874	0.27	
	2033	0.4	
	2075	0.3	
	2151	1.06	
I	2214	0.45	
	2221	0.37	
	2258	0.5	
	2513	0.7	
	2624	0.63	
	2679	0.5	
	2699	0.65	
	3154	0.75	

Well	Depth (m)	Vitrinite reflectance (VRo%)	Temperature (°C)
II	1268	0.332	
	1341	0.347	
	1402	0.44	
	1506	0.455	
III	2123		98
	2588		116
	2123.85		98

The predicted temperatures and maturation profiles are well in agreement with the observed values (Figure 4).

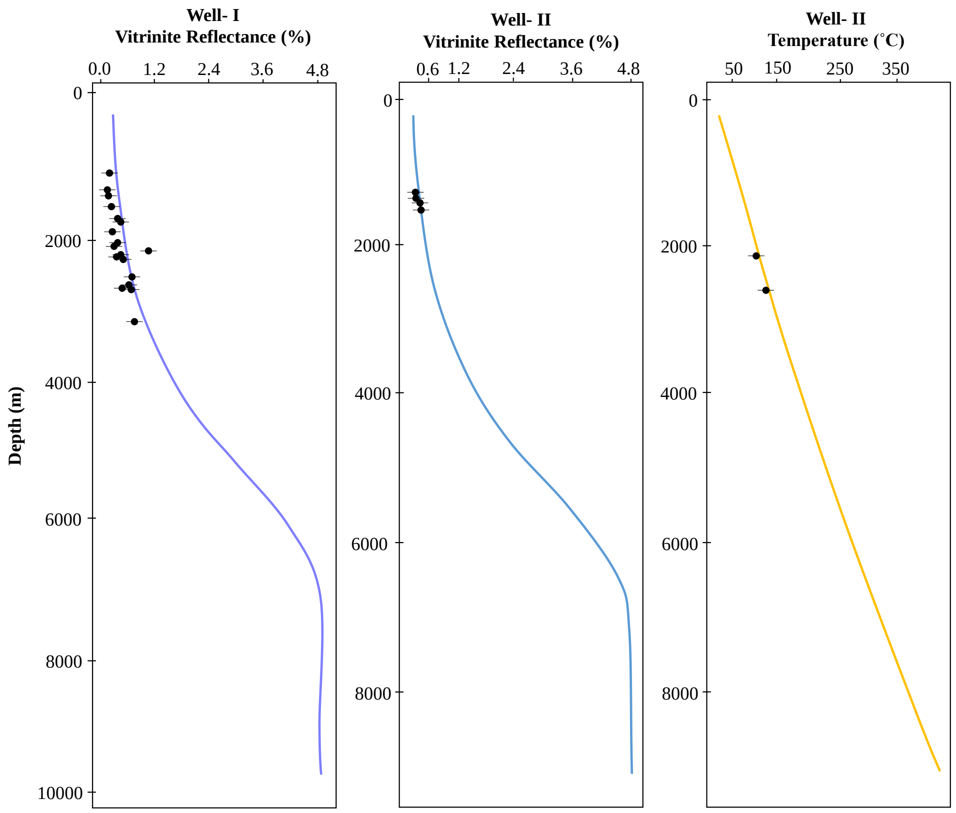

Figure 4
Vitrinite reflectance and temperature calibration profiles for wells close to the modeled section line; modeling predictions (continuous lines) show good agreement with the measured data (points); uncertainty related to each reading point is shown as a bar.

5.2. Thermal maturity

Assuming that the model is satisfactorily calibrated in terms of vitrinite reflectance and temperature, reliable predictions can be made about the level of thermal maturity for candidate stratigraphic units. Representative temperature and vitrinite reflectance models are presented in Figure 5.

Lateral variations are visible in both temperature and vitrinite reflectance in a SE-NW direction as the depth of burial increases for the studied source layer (Cenomanian Middle Sarvak source rock located by arrows on Figure 5).

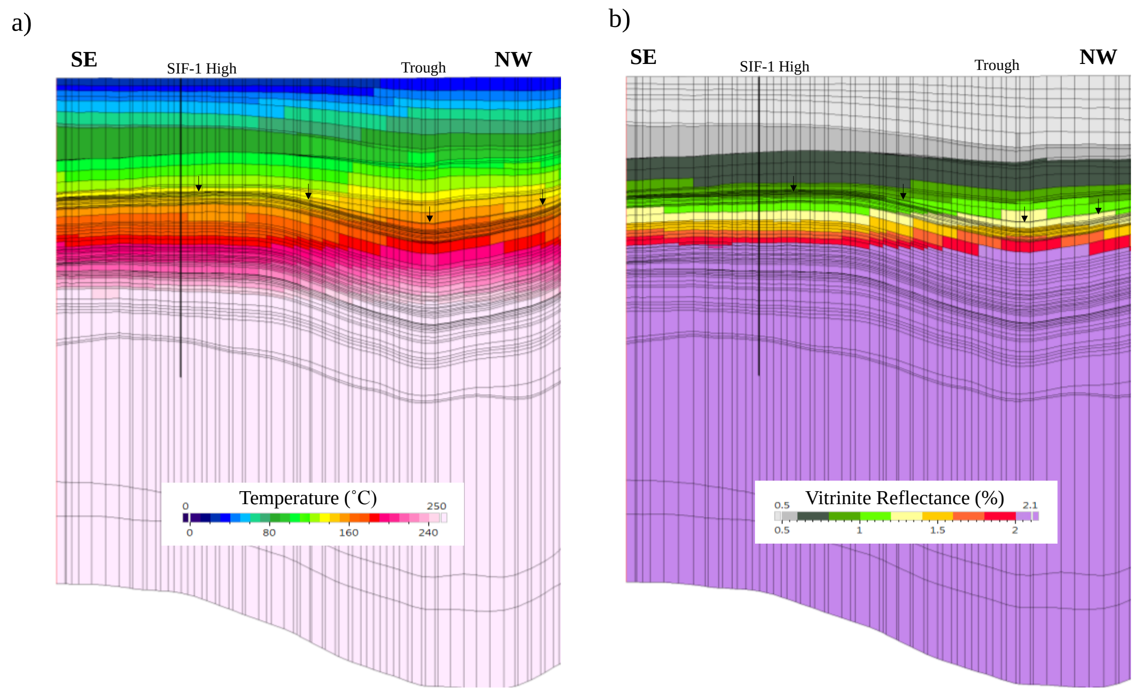

Figure 5

(a) Temperature and (b) vitrinite reflectance distributions from modeling results of the 2D section.

5.3. Hydrocarbon generation and migration

One of the best ways to study the maturation history of source rocks in a basin is by monitoring variations in the transformation ratio of associated organic matter through time. Figure 6 is a preview of the transformation ratio through time for the Middle Sarvak source rock at two different points across the modeled section. Assuming a uniform type of organic matter at a constant thickness for the mentioned source rock, an earlier transformation in the trough relative to SIF-1 high is conspicuous (Figure 6). The early phase of hydrocarbon generation (i.e. equivalent to 10% transformation ratio) happens about 18 million years earlier in the trough compared to the adjacent high (well SIF-1 location) (Figure 6). This example shows that hydrocarbon generation within a source rock may not be a synchronous process (even across horizontal distances around 30 km). The shallower areas in this case would enter the early generation phase when the deeper zones are well into the main phase of generation (Figure 6).

The difference observed in the degree of transformation of kerogen has an impact on the types and masses of hydrocarbons generated. Therefore, the masses of petroleum generated from a single source rock, the dominant phase, and the composition of generated masses all vary at different geographic locations.

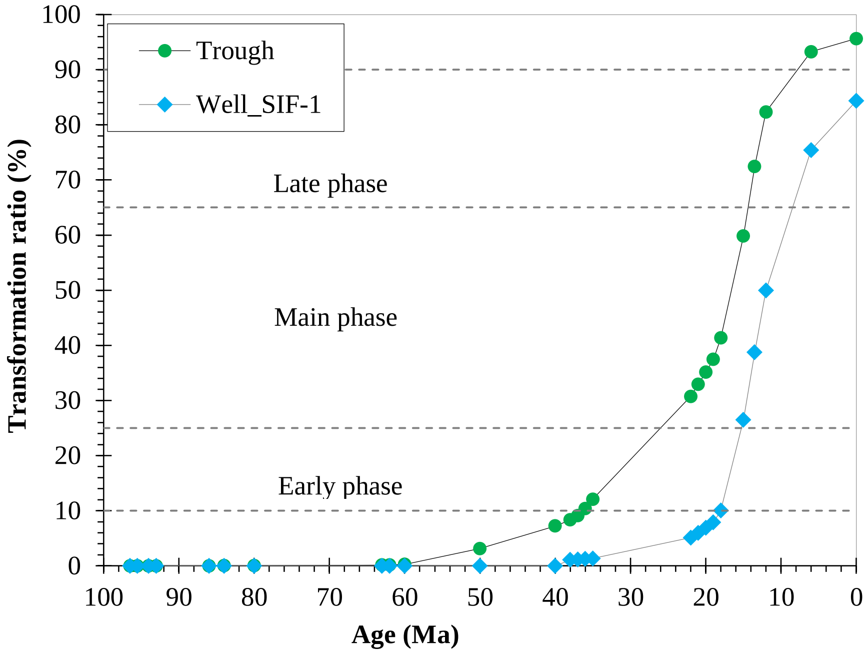

Figure 6

Transformation ratio preview for the Middle Sarvak source rock through time at two different sites (see Figure 3) on the modeled section.

Figure 7 shows the burial history chart reconstructed for cells located in the trough with iso-maturity lines superimposed (dashed lines). With reference to the onset of early generation phase at this locality (i.e. ≈ 38 Ma, Figure 6), it is easy to track the depth and maturation level of source rock at this age using Figure 7. Therefore, it can be concluded that the type of organic matter and its transformation kinetics for the Middle Sarvak source rock do not allow generation at depths shallower than c.a. 2000 m (Figure 7). This finding can be a guide for mapping generative versus non-generative kitchens of the Middle Sarvak source rock in the studied area (assuming uniform organofacies characteristics). The early generation products in the trough would be predominantly heavy oil with minor proportions of normal oil and thermogenic gas as suggested by the model (Figure 7). Progressive burial of the source rock imposes increasingly higher transformation levels, with transformation at present day depths (>4000 m) exceeding 90% (Figure 6) and vitrinite reflectance approaching 1.3% (Figure 7). In these conditions, the normal oil would be cracked to gas (hence the concentration of coke will increase) in the source rock, and the generated masses would be expelled predominantly in the form of thermogenic gas (Figure 7).

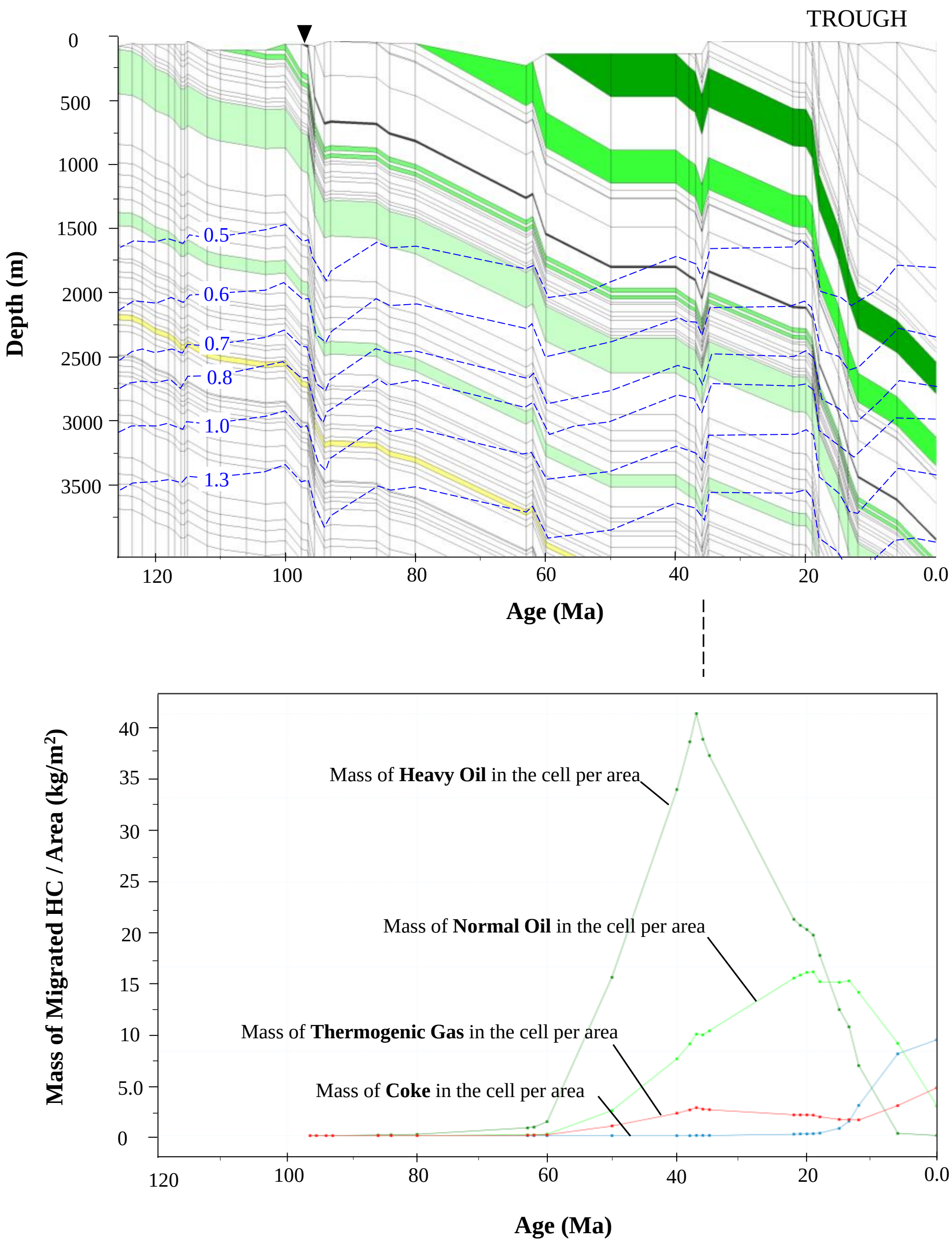

Figure 7
Burial history (top) and the composition of the generated hydrocarbon masses (bottom) from the Middle Sarvak source rock in the trough; the triangle in the upper panel indicates the deposition of the Middle Sarvak source rock.

In the shallower areas towards the SIF-1 high, the early phase of generation starts at about 18 Ma (Figure 6). According to the burial history chart reconstructed for cells located at SIF-1 high, this is the time when the source rock gets buried to depths beyond 2000 m (Figure 8). Therefore, a minimum burial of about 2000 meters seems to be necessary for the beginning of oil generation from Middle Sarvak source rock in the studied area. The main proportion of the early generated masses in the SIF-1 high is in the form of heavy oil with some normal oil, while the present day products are predominantly in the form of normal oil.

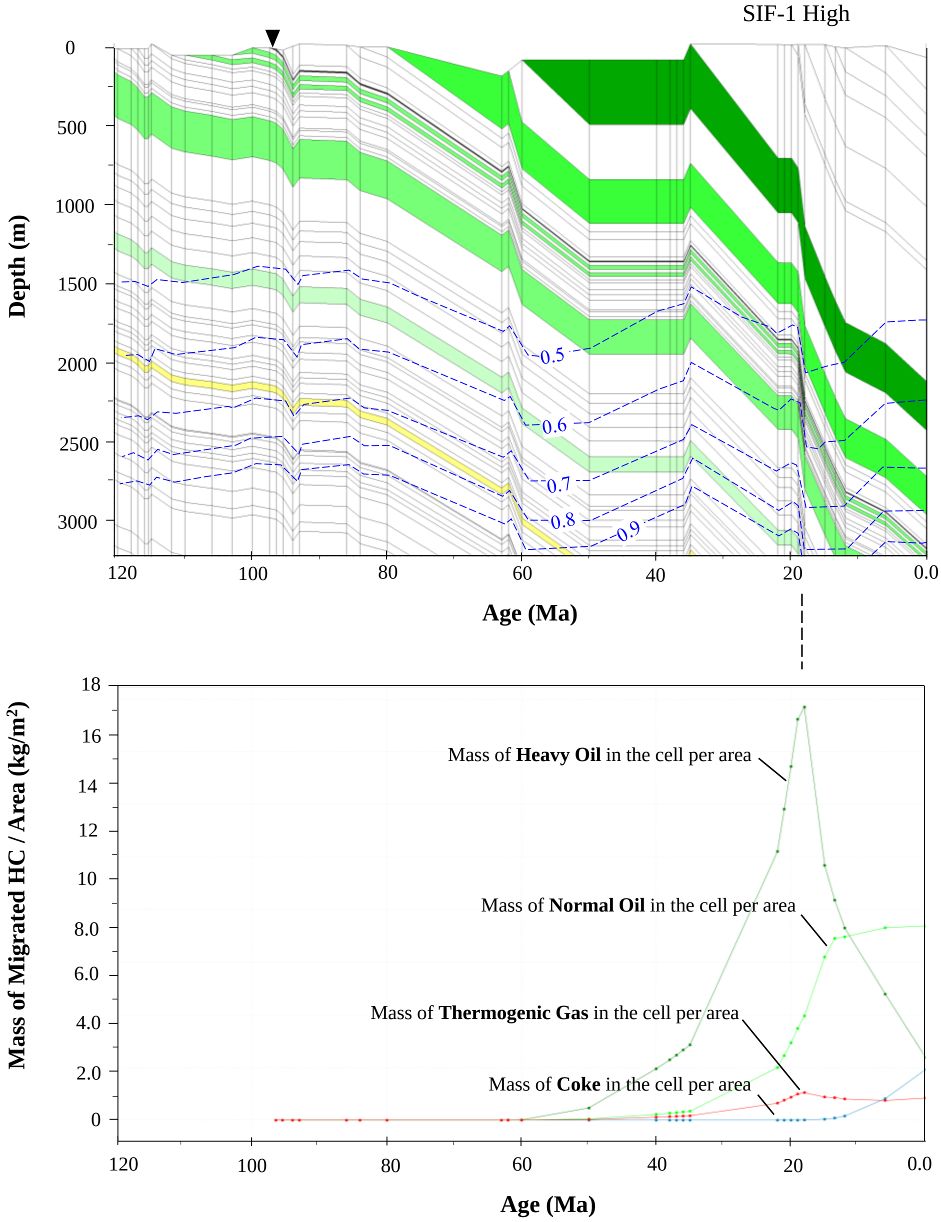

Figure 8
Burial history (top) and the composition of the generated hydrocarbon masses (bottom) from the Middle Sarvak source rock over the SIF-1 (high); the triangle in the upper panel indicates the deposition of the Middle Sarvak source rock.

Implications emerging from the foregoing topics are required to be properly placed within a dynamic framework of petroleum system evolution in the studied area. However, some key points are required to be considered with care:

1. With increasing thermal stress, large concentrations of initial heavy products are cracked into lighter compounds, which will subsequently be cracked into gas molecules. Therefore, depending on the thermal state, a source rock yield may vary from heavy oil to thermogenic gas.
2. The composition of the generated masses is largely governed by the thermal maturity of the associated organic matter. For example, the curve for thermogenic gas has witnessed two peaks

corresponding to early kerogen degradation (primary gas) and oil cracking (secondary gas). These peaks are better visible in the trough (Figure 7) where appropriate maturity conditions are achieved.

3 Despite the relatively short geographic distance between the two points examined in this study (c.a. 30 km, Figure 3), their main transformation products on present day are quite different. The predominant type of present day masses produced is normal oil at SIF-1 high and thermogenic gas within the nearby trough.

4 Most authors believe that petroleum accumulations are average products of source rock generation yields. Within the simple model presented here, assuming charge possibility from both of the discussed sites, multiple trap charge scenarios might exist for any accessible trap. However, for geochemical evaluation purposes, the most favorable geochemical truths will exist in traps that receive charges only from one of the sites mentioned.

5 Timing of trap formation can be coupled to detailed thermal maturity models to provide useful information about charge risking and prospect ranking. Thermal modeling results obtained for the Middle Sarvak source rock by this study can be useful in this regard. Both within the high and the adjacent trough, it is possible to estimate and compare the critical point when a trap is seriously needed to collect petroleum charges emitted from the source rock.

6 The final prospect ranking steps will need to combine charge and trap risking factors (points 4 and 5 mentioned above) with the secondary alteration and seal integrity factors. Eventually, a new zone of interest will get defined either as a high-risk or a low-risk prospect.

6. Conclusions

Modeling the thermal maturation of the Cenomanian Middle Sarvak source rock in this study provided useful information with respect to the timing and masses of hydrocarbons generated. In addition, predictions could be made about the deep undrilled sections in terms of transformation state and generated products. Our results provide valuable information about the burial needed prior to the onset of generation and the predominant composition of the produced masses. An estimated 900 meter difference in the depth of burial between the southeastern high and the adjacent trough is shown to shift the onset of hydrocarbon generation by about 18 million years. Consequently, petroleum with wide ranges of maturities and compositions could be entrapped depending on where on the thermal evolutionary path a trap becomes available to drain products from these sites. Conclusions in this paper are valid under the assumption of a uniform organofacies for the included source rock. Therefore, systematic sampling and geochemical analyses of an adequate number of source rock samples are indispensable for detailed thermal modeling studies in the future. Refined knowledge about the extensions of the Middle Sarvak source rock can be useful for mapping the geographic extents of its active zones in the southern Persian Gulf basin (i.e. burial greater than 2000 m).

Acknowledgements

The authors are grateful to the Iranian Offshore Oil Company (IOOC) for providing the data and permission to publish them. Petroleum Geology and Geochemistry Research Center (PGGRC) of Shahid Chamran University of Ahvaz is also gratefully acknowledged. Constructive discussion and comments from B. Khani, M. Mirshahani, and B. Beyranvand at Research Institute of Petroleum Industry greatly improved the quality of this work. Special thanks are due to Scott Ramos (Infometrix, Bothel) for informative discussions on chemometric analysis of source rock samples, which was required for sample screening and source rock definition in the model.

Nomenclature

2D modeling	: Two dimensional modeling
BPSM	: Basin and petroleum system modeling
HC	: Hydrocarbon
HI	: Hydrogen index
IOOC	: Iranian Offshore Oil Company
Ma	: Million years ago
OI	: Oxygen Index
S_1	: Free hydrocarbons released up to 300 °C within the pyrolysis oven
S_2	: Generative (i.e. remaining) potential
T_{max}	: Pyrolysis oven temperature at maximum hydrocarbon yield
TOC	: Total organic carbon
VRo	: Vitrinite reflectance measured under oil immersion

References

Al-Suwaidi, A. S., Stratigraphy and Geochemistry of Upper Jurassic Diyab Formation, Abu Dhabi, UAE, Society for Sedimentary Geology (SEPM), No. 69, p. 249-271, 2000.

Alsharhan, A. S., Oxfordian-Kimmeridgian Diyab Formation as a Major Source Rock Unit in Southern Arabian Gulf, 18th Annual Meeting Abstracts and Program, The Society of Organic Petrology (TSOP), p. 1-6, 2001.

Alsharhan, A. S., Al-assam, I. S., and Salah, M. G., Stratigraphy, Stable Isotopes, and Hydrocarbon Potential of the Aptian Shuaiba Formation, UAE, Society of Sedimentary Geology (SEPM), No. 69, p. 299-314, 2000.

Alsharhan, A. S. and Magara, K., The Jurassic of the Arabian Gulf Basin: Facies, Depositional Setting and Hydrocarbon Habitat, Canadian Society of Petroleum Geologists, Memoir 17, p. 397-412, 1994.

Alsharhan, A. S. and Nairn, A., Tertiary of the Arabian Gulf: Sedimentology and Hydrocarbon Potential, Palaeogeography, Palaeoclimatology, Palaeoecology, Vol. 114, p. 369-384, 1995.

Alsharhan, A. S. and Scott, R. W., Hydrocarbon Potential of Mesozoic Carbonate Platform-basin Systems, UAE, Society of Sedimentary Geology (SEPM), No. 69, p. 335-358, 2000.

Azzam, I. N. and Taher, A. K., Sequence Stratigraphy and Source Rock Potential of Middle Cretaceous (Upper Wasia Group) in West Abu Dhabi, Society of Petroleum Engineers, SPE 29802, p. 305-317, 1993.

Azzam, I. N. and Taher, A. K., Sequence Stratigraphy and Source Rock Potential of the Aptian (Bab Member) in East Onshore Abu Dhabi: A Model Approach to Oil Exploration, Society of Petroleum Engineers, SPE 25577, p. 475-487, 1995.

Bashari, A., Khuff Formation Permian-Triassic Carbonate in the Qatar-South Fars Arch Hydrocarbon Province of the Persian Gulf, First Break, Vol. 23, p. 43-50, 2005.

Faqira, M., Rademakers, M., and Afifi, A., New Insights into the Hercynian Orogeny, and their Implications for the Paleozoic Hydrocarbon System in the Arabian Plate, GeoArabia, Vol. 14, p. 199-228, 2009.

Farzadi, P., The Development of Middle Cretaceous Carbonate Platforms, the Persian Gulf, Iran: Constraints from Seismic Stratigraphy, Well and Biostratigraphy, Petroleum Geoscience, Vol. 12, p. 59-68, 2006a.

Farzadi, P., Seismic Facies Analysis Based on 3D Multi-attribute Volume Classification, Dariyan Formation, SE Persian Gulf, Journal of Petroleum Geology, Vol. 29, p. 159-173, 2006b.

Farzadi, P. and Hesthammer, J., Diagnosis of the Upper Cretaceous Palaeokarst and Turbidite Systems from the Iranian Persian Gulf Using Volume-based Multiple Seismic Attribute Analysis and Pattern Recognition, Petroleum Geoscience, Vol. 13, p. 227-240, 2007.

Grobe, A., Littke, R., Sachse, V., and Leythaeuser, D., Burial History and Thermal Maturity of Mesozoic Rocks of the Dolomites, Northern Italy, Swiss Journal of Geosciences, Vol. 108, p. 253-271, 2015.

Gumati, Y., Kinetic Modelling, Thermal Maturation and Hydrocarbon Generation in the United Arab Emirates, Marine and Petroleum Geology, Vol. 10, p. 153-161, 1993.

Harris, P., Frost, S., Seiglie, G., and Schneidermann, N., Regional Unconformities and Depositional Cycles, Cretaceous of the Arabian Peninsula, in: Schlee, J.S. (Ed.), Interregional Unconformities and Hydrocarbon Accumulation (Memior 36), American Association of Petroleum Geologists, p. 67-80, 1984.

Hosseini, E., Rabbani, A. R., and Moallemi, A., Source Rock Characterization of the Cretaceous Sarvak Formation in the Eastern Part of the Iranian Sector of Persian Gulf, Organic Geochemistry, Vol. 99, p. 53-66, 2016.

Jordan, C. F., Connally, T. C., and Vest, H. A., Middle Cretaceous Carbonates of the Mishrif Formation, Fateh Field, Offshore Dubai, UAE, in: Roehl, O. P., Choquette, P. W. (Eds.), Carbonate Petroleum Reservoirs, Springer, p. 425-442, 1985.

Kent, P., The Emergent Hormuz Salt Plugs of Southern Iran, Journal of Petroleum Geology, Vol. 2, p. 117-144, 1979.

Lasemi, Y. and Jalilian, A., The Middle Jurassic Basinal Deposits of the Surmeh Formation in the Central Zagros Mountains, Southwest Iran: Facies, Sequence Stratigraphy, and Controls, Carbonates and Evaporites, Vol. 25, p. 283-295, 2010.

Mashhadi, Z., Rabbani, M.R., Kamali, M.R., Mirshahani, M., and Khajehzadeh, A., Burial and Thermal Maturity Modeling of the Middle Cretaceous–early Miocene Petroleum System, Iranian Sector of the Persian Gulf. Petroleum Science, Vol. 12, p. 367-390, 2015.

Maurer, F., van Buchem, F. S., Eberli, G. P., Pierson, B. J., Raven, M. J., Larsen, P. H., Al-Husseini, M. I., and Vincent, B., Late Aptian Long-lived Glacio-eustatic Lowstand Recorded on the Arabian Plate,Terra Nova, Vol. 25, p. 87-94, 2013.

Murris, R. J., Middle East-stratigraphic Evolution and Oil Habitat, American Association of Petroleum Geologists, Special Volumes, p. 353-372, 1981.

Opera, A., Alizadeh, B., Sarafdokht, H., Janbaz, M., Fouladvand, R., and Heidarifard, M.H., Burial History Reconstruction and Thermal Maturity Modeling for the Middle Cretaceous–early Miocene Petroleum System, Southern Dezful Embayment, SW Iran, International Journal of Coal Geology, Vol. 120, p. 1–14, 2013.

Peters, K. E., Walters, C. C., and Moldowan, J. M., The Biomarker Guide: Biomarkers and Isotopes in the Environment and Human History, Cambridge University Press, New York, 2005.

Pollastro, R. M., Total Petroleum Systems of the Paleozoic and Jurassic, Greater Ghawar Uplift and Adjoining Provinces of Central Saudi Arabia and Northern Arabian-persian Gulf, US Department of the Interior, US Geological Survey, 2003.

Rabbani, A. R., Kotarba, M. J., Baniasad, A. R., Hosseiny, E., and Wieclaw, D., Geochemical Characteristics and Genetic Types of the Crude Oils from the Iranian Sector of the Persian Gulf, Organic Geochemistry, Vol. 70, p. 29-43, 2014.

Razin, P., Taati, F., and Van Buchem, F., Sequence Stratigraphy of Cenomanian–Turonian Carbonate Platform Margins (Sarvak Formation) in the High Zagros, SW Iran: an Outcrop Reference Model for the Arabian Plate, Geological Society, London, Special Publications, Vol. 329, p. 187-218, 2010.

Sharland, P. R., Archer, R., Casey, D. M., Davies, R., Hall, S. H., Heward, A. P., Horbury, A. D., and Simmons, M., Arabian Plate Sequence Stratigraphy, Gulf PetroLink, Manama Bahrain, 2001.

Soleimany, B., Nalpas, T., and Montserrat, F. S., Multidetachment Analogue Models of Fold Reactivation in Traspression: the NW Persian Gulf. Geologica Acta: An International Earth Science Journal, Vol. 11, p. 265-276, 2013.

Soleimany, B. and Sàbat, F., Fold Trends and Age of Folding in NW Persian Gulf, Trabajos De Geología, Vol. 29, p. 228-234, 2010.

Taher, A., Delineation of Organic Richness and Thermal History of the Lower Cretaceous Thamama Group, East Abu Dhabi: a Modeling Approach for Oil Exploration, Society of Petroleum Engineers, SPE 36277, p. 65-88, 1996.

Taher, A., Unconventional Oil Exploration Potential in Early Mature Source Rock Kitchens, Society of Petroleum Engineers, SPE 137897, p. 1-13, 2010.

Vahrenkamp, V., Van Laer, P., Franco, B.J., Celentano, M.A., Grelaud, C., and Razin, P., Late Jurassic to Cretaceous Source Rock Prone Intra-shelf Basins of the Eastern Arabian Plate – interplay between Tectonism, Global Anoxic Events and Carbonate Platform Dynamics, International Petroleum Technology Conference, IPTC-18470-MS, Qatar, p. 1-25, 2015.

Valero, L., Soleimany, B., Bulnes, M., and Poblet, J., Evolution of the Nourooz Anticline (NW Persian Gulf) Deciphered Using Growth Strata: Structural Inferences to Constrain Hydrocarbon Exploration in Persian Offshore Anticlines, Marine and Petroleum Geology, Vol. 66, p. 873-889, 2015.

Van Buchem, F., Simmons, M., Droste, H., and Davies, R., Late Aptian to Turonian Stratigraphy of the Eastern Arabian Plate-depositional Sequences and Lithostratigraphic Nomenclature, Petroleum Geoscience, Vol. 17, p. 211-222, 2011.

Van Buchem, F. S., Razin, P., Homewood, P. W., Oterdoom, W. H., and Philip, J., Stratigraphic Organization of Carbonate Ramps and Organic-rich Intrashelf Basins: Natih Formation (Middle Cretaceous) of Northern Oman, American Association of Petroleum Geologists Bulletin, Vol. 86, p. 21-53, 2002.

Whittle, G. and Alsharhan, A. S., Diagenetic History and Source Rock Potential of the Upper Jurassic Diyab Formation, Offshore Abu Dhabi, United Arab Emirates, Carbonates and Evaporites, Vol. 11, p. 145-154, 1996.