



# Combining biodegradation in 2D petroleum system models: application to the Cretaceous petroleum system of the southern Persian Gulf basin

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## Abstract

Biodegradation modeling is combined with petroleum system modeling along a regional 2D transect from the southern Persian Gulf basin. An advanced basement model was considered in the model that allowed a constant temperature to enter the entire sedimentary column. Modeling results were calibrated against existing temperature and vitrinite reflectance data from nearby wells. Temperature, burial, and charge histories are carefully monitored within the studied section through geological time. Based on our modeling results, biodegradation has been effective along the migration pathway and within the eventual accumulation sites to varying extents. These findings can have practical implications for pre-drill oil quality predictions and accurate geochemical evaluations of oils and reduce offshore oil and gas exploration risks.

**Keywords** Southern Persian Gulf basin · Biodegradation modeling · Cretaceous petroleum system · 2D petroleum system modeling

## Introduction

Biodegradation is a common process in many hydrocarbon reservoirs and can change the physical–chemical properties of petroleum in varying forms and extents (Connan 1984; Head et al. 2010; Head et al. 2003). Measuring the intensity of biodegradation in oil reservoirs has been the focus of many studies since the microbial alteration entails destructive effects on economic value and producibility of the oil (Larter et al. 2003, 2012; Peters and Moldowan 1993; Seifert and Moldowan 1979; Wenger and Isaksen 2002). Various factors controlling the rate of petroleum biodegradation in subsurface reservoirs have been discussed (Adams et al. 2013; Larter et al. 2003).

Integration of biodegradation into the petroleum system models requires linking between petroleum system history (temperature history and residence times, reservoir filling–spilling history, oil mixing, etc.) and other aspects such as reservoir geometry and filling rates and oil composition (Blumenstein et al. 2008). In recent years, enhanced software capabilities have enabled scientists to fully integrate biodegradation within petroleum system models (Adams et al. 2013; Ducros et al. 2016). In this study, we have tried to integrate the biodegradation process in a 2D petroleum system model for the first time in the southern Persian Gulf basin. The study area is a part of the prolific Persian Gulf basin and constitutes several important hydrocarbon fields (Fig. 1). Previously, two main oil families were recognized in this area by the use of chemometric methods and the Cretaceous accumulations were reported to have undergone some levels of biodegradation (Alizadeh et al. 2017). The 2D transect used in this study is located in the east of the area and corresponds to a local depression and its adjacent high (Fig. 1) which captures the Cretaceous petroleum system (Alipour et al. 2017). Timing of hydrocarbon generation from the Middle Sarvak source rock and subsequent migration of expelled products are monitored along the studied section.

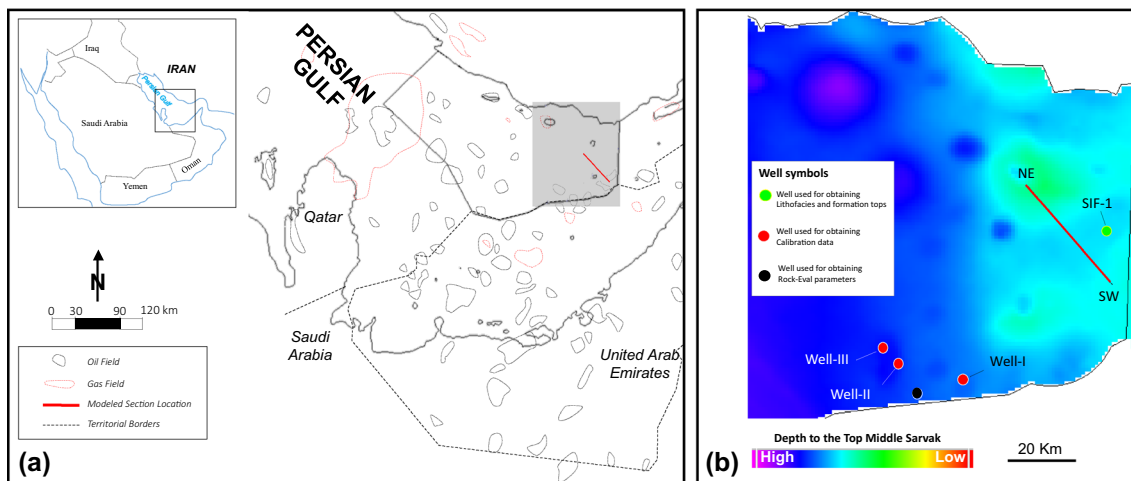
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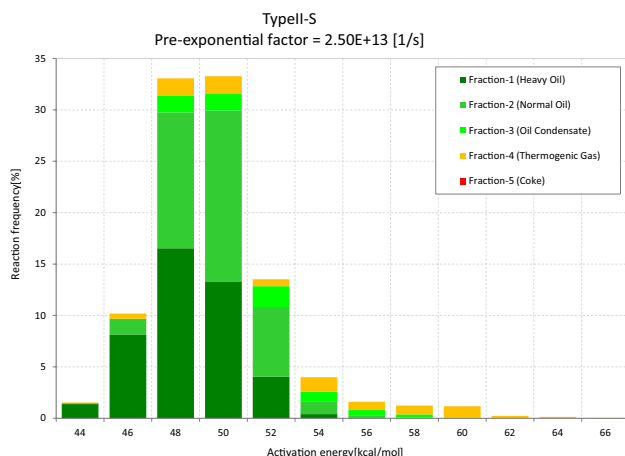
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**Fig. 1** Generalized map of the southern Persian Gulf basin showing the major hydrocarbon fields and block boundaries (a) and geographic location of modeled section shown on a Middle Sarvak depth

map along with nearby wells used for calibration (b). (with modifications from Alipour 2017)



**Fig. 2** Compositional kinetic properties used for modeling thermal transformation of the Middle Sarvak source rock

Consistent with the previous studies (Hosseiny et al. 2016), the hydrocarbon generation behavior of the Middle Sarvak source rock is assumed to mimic that of a reactive type II kerogen (Fig. 2). Biodegradation is monitored along the migration routes and in the eventual accumulation sites. The results of this study can have practical implications for mass balance assessments in future 3D models and for pre-drill oil quality prediction in undrilled structures. These are highly important concerns for offshore exploration and development programs.

## Geological background

The Persian Gulf basin is renowned for holding huge volumes of oil and gas in the Paleozoic through Tertiary sediments and has been studied extensively in recent years (Alipour 2017; Alipour et al. 2017; Alizadeh et al. 2017; Baniasad et al. 2017; Hosseiny et al. 2016, 2017; Rabbani et al. 2014; Saberi and Rabbani 2015). Extremely rich source rocks occur within the stratigraphic framework that upon maturation give rise to highly prolific hydrocarbon systems (Fig. 3).

The essential elements and processes of the petroleum systems lodged in the Persian Gulf basin are influenced by several tectonic pulses that are discussed elsewhere (Alipour 2017; Alipour et al. 2016, 2017). This information is carefully combined with other geological and geochemical data, and a conceptual basin model is constructed in this study, so that the geohistory of petroleum systems could be recreated through time (Hantschel and Kauerauf 2009; Peters et al. 2012, 2017).

Paleogeographic reconstructions during the Upper Cretaceous of the area indicate development of intrashelf basins over the eastern edge of the Arabian Plate (Vahrenkamp et al. 2015). Deposition of organic-rich facies of the Middle Sarvak source rock took place behind the Mishrif rim, which represent favorable carrier/reservoir rock qualities in the area of our study (Al-Zaabi et al. 2010; Henhoefer et al. 2018). The stratigraphy of the Cenomanian Sarvak–Mishrif sequence of the southern Persian Gulf basin has been discussed in more detail recently (Jodeyri-Agahi et al. 2018). In addition, recent geochemical studies on the oils from this basin have highlighted the importance

**Fig. 3** Generalized stratigraphic column of the Persian Gulf basin with ages and associated petroleum systems elements

PERIOD	EPOCH	FORMATION NAME	AGE (Ma)	PETROLEUM SYSTEM ELEMENT			
				Source rock	Reservoir	Seal rock	
NEOGENE	HOLOCENE	SEABED	0				
	PLEISTOCENE	BAKHITIYARI	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				
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							

of the Middle Sarvak organic-rich facies in charging some of the oilfields in the Sirri District (Alizadeh et al. 2017; Hosseiny et al. 2017).

## Materials and methods

Rock-Eval 6 instrument, operated under standard procedure, was used for determining the quantity and quality of organic matter in drill cuttings of the Middle Sarvak source rock obtained from a well nearby to the modeled section (see Fig. 1). In brief, aliquots of pulverized rock samples (about 70 mg) were heated under 300 °C for 4 min to release the free hydrocarbons known as the  $S_1$  peak. The oven temperature was then ramped to 650 °C (25 °C/min rate) to measure the  $S_2$  peak, which represents hydrocarbons released via thermal breakdown of kerogen (Peters 1986).

The temperature at the highest pyrolytic yield is recorded as  $T_{max}$ , which gives an indication of maturation state of the organic matter (Peters and Cassa 1994).

Vitrinite reflectance measurements were made using a Leica P LED4500 microscope at a magnification of 500× under oil immersion and a 546-nm filter. The instrument was calibrated using standard sapphire glasses with 0.494, 0.795, and 1.77 reflectance. Reflectance readings were made in random mode on vitrinite macerals following the ASTM method (D7708-11), and the reported values were arithmetic means of at least 25 measurements per sample.

For modeling the petroleum system evolution along the studied section, a licensed version of TemisFlow® 2015 software was used. Depth-converted seismic profiles were used to build the two-dimensional cross-sectional line. Lithofacies and stratigraphic properties were assigned using available information (Alipour 2017; Alipour et al.

2017). A constant temperature at the base of upper mantle (c.a. 1335 °C) was used to mimic the temperature evolution and generation of hydrocarbons from the source rock. After carefully calibrating the model with respect to existing observation data (temperature and vitrinite reflectance), biodegradation was integrated into this model based on information in the literature (Wellsbury et al. 1997) and using the special module in the TemisFlow® 2015 software (Fig. 4).

## Results

### Model calibration

Similar to the previous studies (Alipour et al. 2017), the two-dimensional model in this study included an advanced basement model underneath the sedimentary package, which comprised of the Upper Continental Crust, the Lower Continental Crust, and the Mantle (with appropriate lithofacies and thicknesses, respectively). A constant temperature of around 1333 °C was considered at the base of the Upper Mantle, and the surface temperatures were allowed to vary according to the existing geological knowledge of the area.

In order to assess the accuracy of model predictions, the best way is to cross check the model against observation data from wells (i.e., model calibration). In this study, temperature and vitrinite reflectance data from three neighboring wells are used for calibration (Table 1 and Fig. 1). The agreement between measured and predicted values is satisfactory (Fig. 5), and therefore, the predictions of the

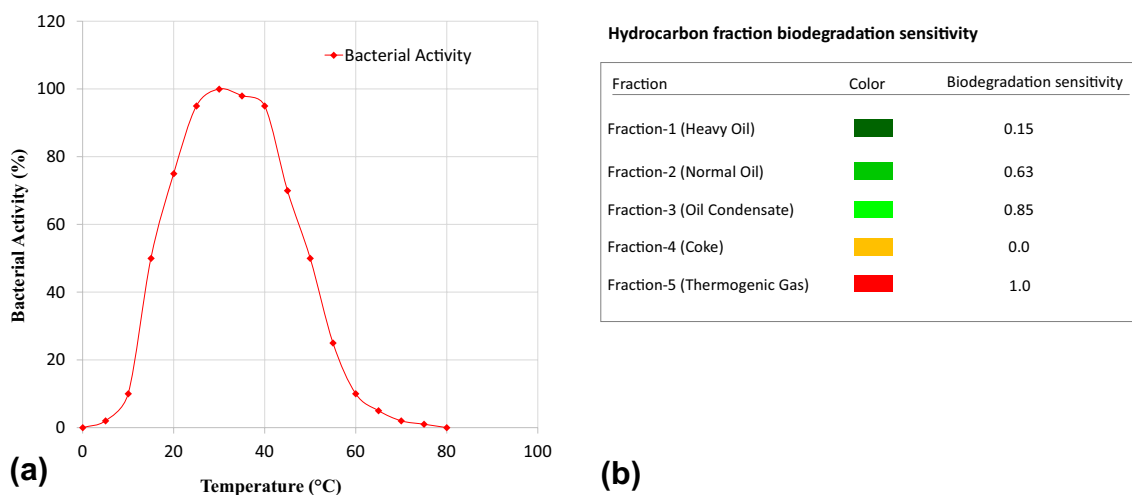
model can adequately represent the natural conditions in the basin.

### Petroleum generation and migration

Kinetic information governing transformation of the organic matter contained in source rocks is critical factor that defines the timing and extent of hydrocarbon generation in basin models (Burnham 2017). As mentioned earlier, in the present study compositional kinetic model corresponding to type II-S kerogen is adopted for the Middle Sarvak source rock (Fig. 2). Modeling results indicate that hydrocarbon generation over the SIF-1 High is delayed relative to the adjacent trough as shown by the calibrated maturity model (Fig. 6) and by the regional variations in the source rock transformation ratio (Fig. 7).

Similarly, expulsion of generated hydrocarbons begins in the trough first; whence, they begin to migrate updip within the porous Mishrif carbonates based on the Darcy's law (Fig. 7). The directions and speed of fluid movement are controlled by lateral and vertical differences in the capillary entry pressure between the different cells, which in turn are controlled by lithofacies properties of each cell.

The updip hydrocarbon migration within the Mishrif carbonates is somewhat influenced by the Laffan Shales as also previously noted in another 2D transects in our study area (Alipour et al. 2016). Wherever these shales are thin or non-existent, migrating hydrocarbons would gain access to the overlying carbonates of the Ilam Formation (Fig. 7). Depending on the existing capillary pressure distributions, the migrating hydrocarbons would shift path from the Mishrif carbonates into the Ilam Formation. However, the net result would be an updip journey toward the SIF-1 High underneath the thick shales of the Gurpi and Pabdeh



**Fig. 4** Graphic illustration of the temperature influence on bacterial activity in the model (a) and the sensitivity of various hydrocarbon fractions for biodegradation (b)

**Table 1** Temperature and vitrinite reflectance data from three wells (see Fig. 1) used for model calibration in this study

Well	Depth (m)	Vitrinite reflectance (VRo%)	Temperature (°C)	
I	309		60.5	
	1811		70.5	
	1812		71.7	
	1998		77.8	
	2043		81.1	
	2339		88.3	
	2716		103.4	
	3464		115.2	
	II	1625	0.39	
		1695	0.28	
1755		0.29		
1795		0.31		
1805		0.29		
1825		0.4		
1895		0.3		
1945		0.36		
1955		0.34		
2080		0.34		
2100		0.33		
2165		0.42		
2195		0.42		
2215		0.45		
2345		0.61		
2355		0.47		
2365		0.62		
2375		0.47		
2385		0.48		
2395		0.48		
2405		0.49		
2412		0.51		
2440		0.51		
2475		0.51		
2495		0.53		
2515		0.54		
2525	0.53			
2535	0.52			
2565	0.55			
2575	0.52			
2585	0.51			
2605	0.53			
2625	0.52			
2640	0.49			
2660	0.53			
2689	0.54			
2703	0.58			

**Table 1** (continued)

Well	Depth (m)	Vitrinite reflectance (VRo%)	Temperature (°C)
III	445.1		55.87
	2312.1		112.24
	2432.1		113.6
	2567.1		114.56
	2801.1		115.93

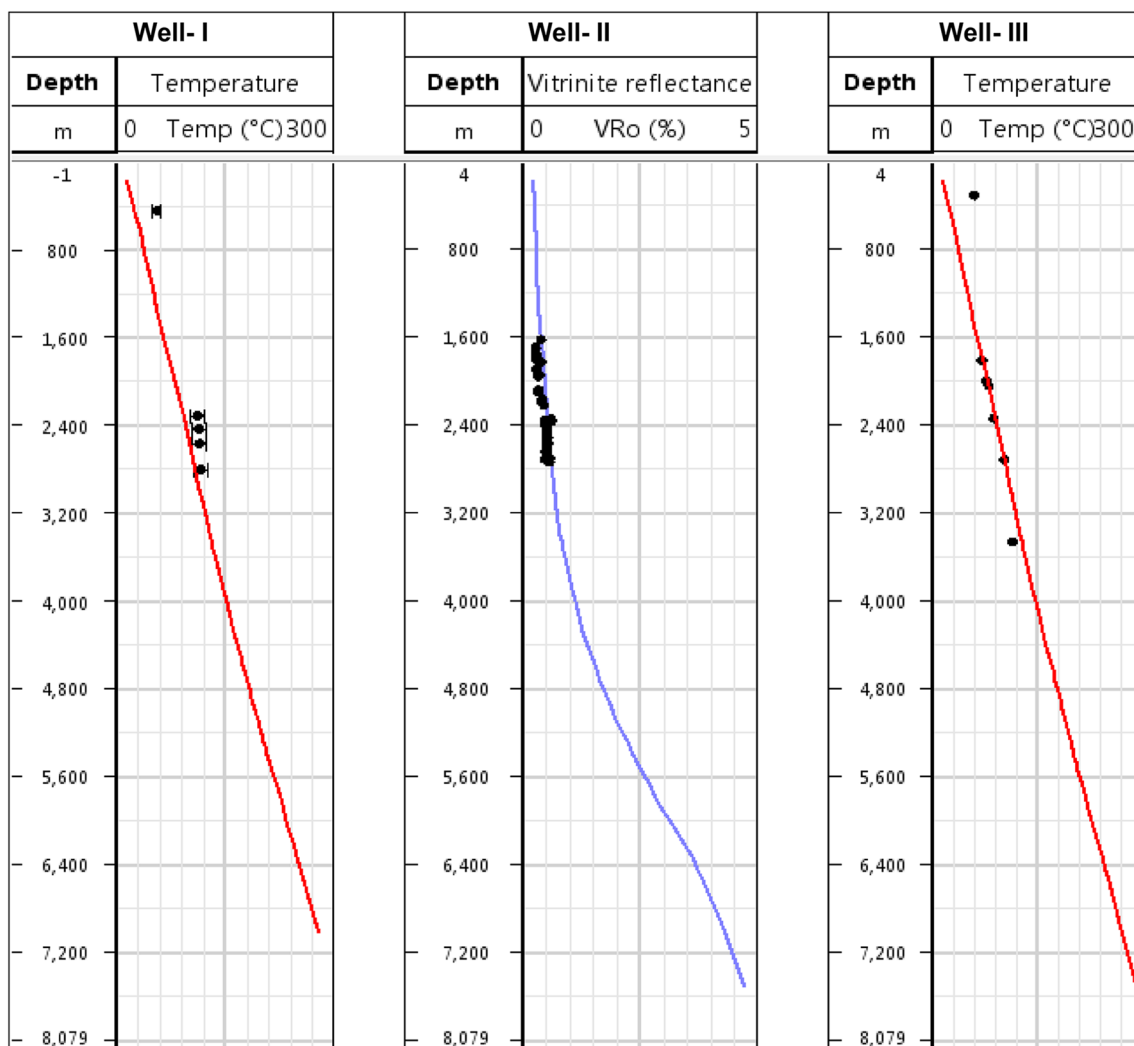
formations (Fig. 7). Therefore, sequence stratigraphic principals seem to define the drainage efficiency of the Middle Sarvak kitchen and hence play a critical role in charging of the potential traps that lie en route.

### Biodegradation

Modeling hydrocarbon migration across the studied section has shown predominantly lateral migration over distances up to 20 km (Fig. 7). Alteration of hydrocarbons along the migration paths is a critical factor that can affect the geochemical properties and economic value of accumulations or set limitations on production/development plans (Larter and di Primio 2005; Palmer 1993; Peters and Moldowan 1993). For this reason, we have attempted to combine biodegradation process with two-dimensional petroleum system modeling in the study area (Fig. 8), where future explorations heavily rely on a refined understanding of the mechanisms controlling occurrence and properties of hydrocarbons. The results indicate that hydrocarbon biodegradation takes place to varying degrees within the Mishrif and Ilam carbonates depending on their burial, temperature, and charge histories. Initial products from transformation of the Middle Sarvak source rock enter the Mishrif Formation, where incipient biodegradation will be operative. However, due to progressive burial, these carbonates become inhospitable for microbial species as temperatures exceed the upper limit of biological activity (i.e., 80 °C) (Fig. 8a). Therefore, biological alteration of hydrocarbons may be restricted to portions of the Mishrif rocks with temperatures less than 80 °C. The shifting of migration pathways from Mishrif to Ilam at the edge of the Laffan shales will restore biodegradation to its former strength, especially as the migration front moves updip toward the SIF-1 High (shallow burial and cooler temperature regimes).

### Discussion

Our results concur with the occurrence of biodegradation along some portions of the migration pathway as well as within the eventual accumulation sites themselves (Fig. 8b,



**Fig. 5** Model calibration profiles based on existing temperature and vitrinite reflectance data from three wells in the study area (see Fig. 1 for locations of wells)

c). Modeling provides important evidences to support these conclusions. The cell histories extracted from the source rock and the reservoir are shown in Fig. 9 for our modeled section. The transformation ratio of the Middle Sarvak source rock has reached values of about 90% at present day (Fig. 9a, b). Generation of hydrocarbons from this source rock began roughly at around 60 Ma with pronounced expulsion at around 20 Ma (Fig. 9b). On the other hand, the reservoir rock has witnessed the arrival of first hydrocarbon charges at around 20 Ma, with predicted temperatures below 80 °C (Fig. 9c). This indicates that the kitchen area dynamics work hand in hand with the trap charge dynamics to define biodegradation occurrence and extent along the studied section.

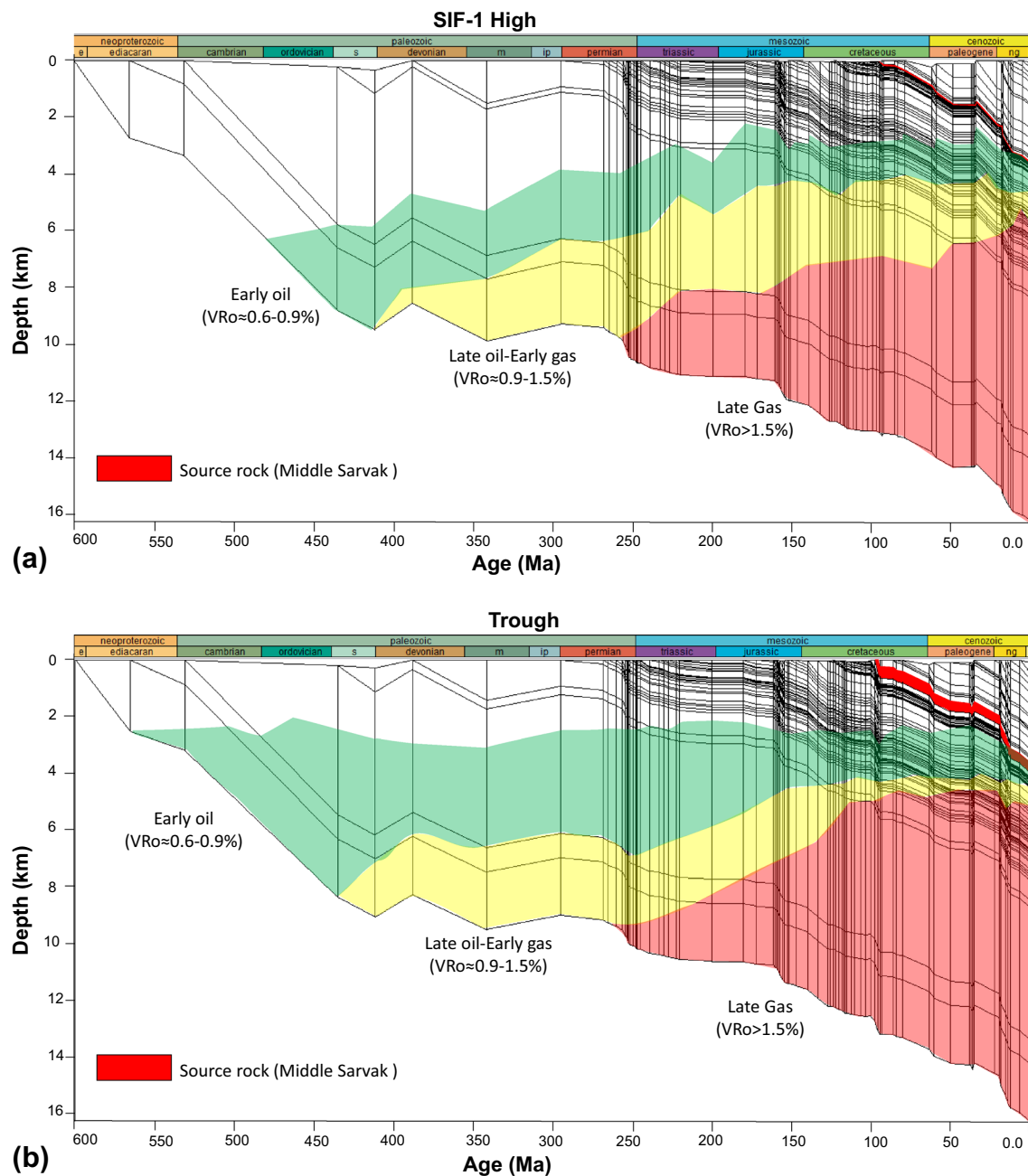
The extents to which the geochemistry of migrating hydrocarbons is affected by these successive phases of biodegradation are not clearly known at present. However,

laboratory simulation studies can provide valuable estimates on compositional modifications resulting from such microbiological processes (e.g., Mishra et al. 2017). Knowledge of these processes is essential for accurate geochemical evaluation of oils from the southern Persian Gulf basin, in particular when mixing of multiple charges occurs (Alipour 2017; Alizadeh et al. 2017).

## Conclusions

Combining biodegradation within 2D petroleum system models is an effective means for understanding the processes controlling the present-day geochemistry of petroleum accumulations. This is particularly useful for offshore hydrocarbon exploration and production, where pre-drill oil quality prediction is highly desired. Application of this

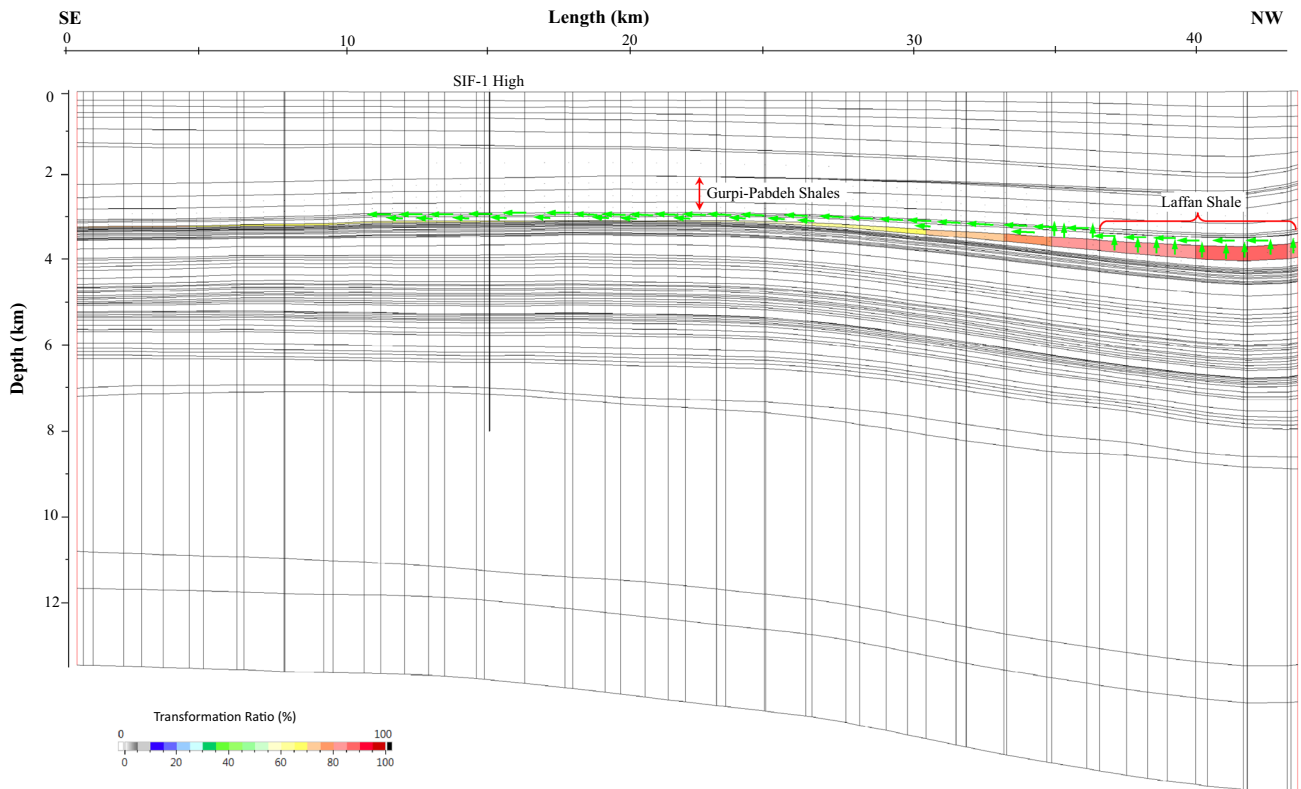




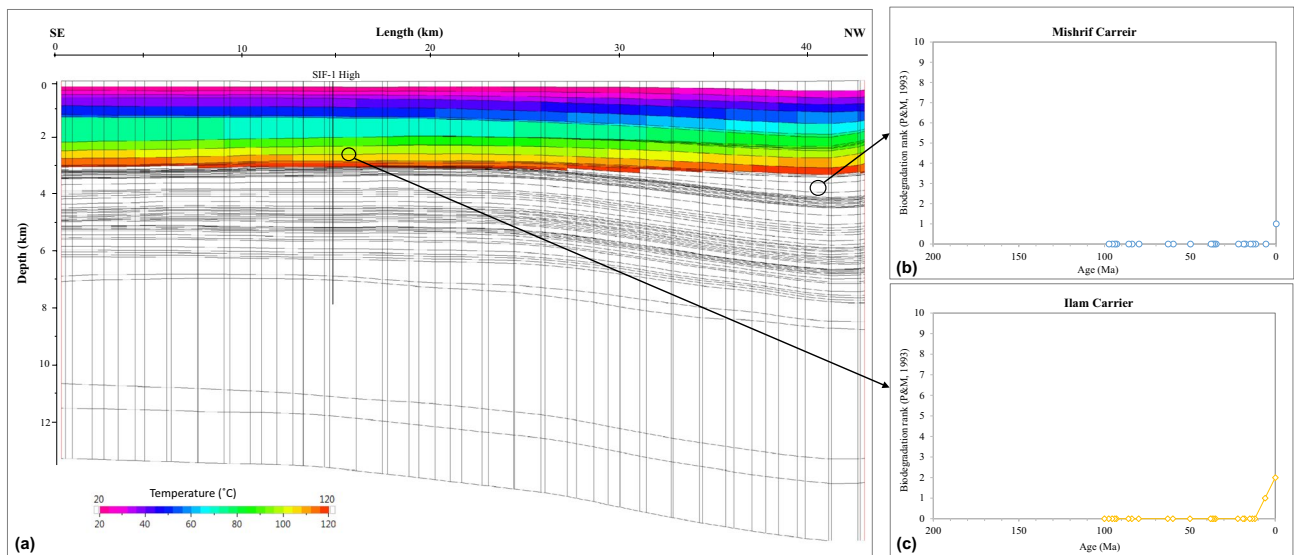
**Fig. 6** Burial history curves with maturity overlays indicating differences in the maturity of the Middle Sarvak source rock in the SIF-1 High (a) and the adjacent trough (b)

technique on a regional 2D transect from the southern Persian Gulf basin indicated that biodegradation can be operative on the expelled hydrocarbons both within their migration path and in the eventual accumulation sites. The sequence stratigraphic architecture of the study area may allow shifting of migration paths between different

carbonate carriers. The net result will be a cumulative influence of biodegradation on individual hydrocarbon charges that reach the accumulation sites. Understanding the occurrence and extents of these processes can help better characterize the associated petroleum systems and reduce exploration risks.

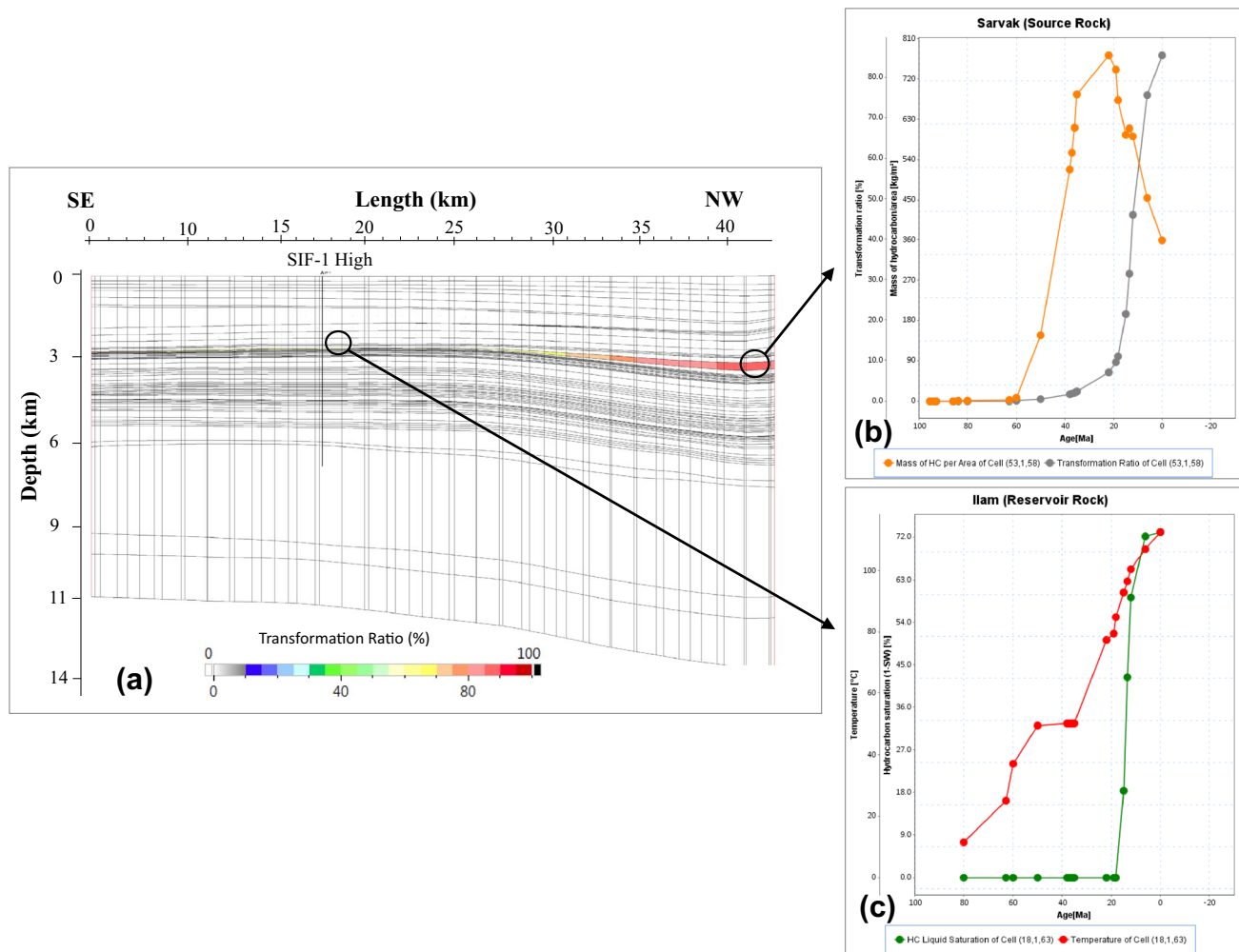


**Fig. 7** Schematic illustration of the migration dynamics along the modeled section showing the early generation in the trough and subsequent migration updip within the porous Mishrif carbonates



**Fig. 8** Temperature model of the studied section (a) and the cumulative biodegradation based on the scale of Peters and Moldowan (1993) for the Mishrif (b) and Ilam (c) carbonates





**Fig. 9** Schematic illustration of the source rock transformation ratio along the modeled section (a), hydrocarbon generation history of source rock in the trough (b), and hydrocarbon charge history of the Ilam reservoir over the SIF-1 High (c)

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