Hydrocarbon generation from candidate source rocks in the Persian Gulf

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Abstract: The main objective of the Petroleum Systems Modeling is to produce a petroleum systems study on the Persian Gulf by using the most advanced petroleum systems modeling techniques, and associated software, available today. This will be based on geological, petrophysical, geochemical and geophysical data in order to predict and estimate of hydrocarbon generation, expulsion time, and reconstruction of the thermal history and source rock maturity over geological time. The following paper covers the 1D modeling of four key Well data from the North-West in the Iranian part of Persian Gulf. Calculated maturities show that the conceptualized Albian Kazhdumi source rock lies in main oil window, though at places in early oil zone also. The Cenomanian Sarvak source lies in early oil and immature zones at present. The timing of HC generation and the onset of expulsion of different sources in all the key wells are evaluated. The Kazhdumi Formation has been HC since Late-Early Miocene (≈10-20 Ma ago) in Well#2 and Well#1 since Eocene (≈50 Ma ago). Also Sarvak Formation has started expelling HC in Well#4 and Well#3 since Miocene (≈10-20 Ma ago) and for Well#2 and Well#1 started expelling since Eocene (≈50 Ma ago).
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Key word: Modeling, Persian Gulf, key well

1. Introduction

Basin modeling is dynamic forward modeling of geological processes in sedimentary basins over geological time spans (Hantschel and Kauerauf., 2009). The aim of this study is to increase the general understanding of thermal history and hydrocarbon potential of the Persian Gulf (Iranian part) main source rocks. For this purpose vitrinite reflectance (%Ro) analyses on samples from four key Wells and 1D numerical simulation performed. The simulation results are presented in detail in this paper. To obtain an overall map of the maturity pattern of this area, vitrinite reflectance data were collected and supplemented with measurements on cuttings and core samples from 4 wells. Based on this data set and on 1D numerical basin modelling, maturity maps for the base of the Kazhdumi and Sarvak (Ahmadi member) formations were constructed. Therefore, core and cuttings from drilled wells were sampled and subjected experimental analyses. As none of the wells was drilled deeper than Lower Cretaceous it was not possible to give evidence on whether or not a source rock is underlying the Neocomian Fahliyan Formation.

2.Geological Background

The Persian Gulf, in Southwest Asia, is an extension of the Indian Ocean located between Iran and the Arabian Peninsula. The Persian Gulf is a part of Arabian plate and its formation was at late Miocene onward. The large scale regional tectonic map suggests that Zagros Mountains and Persian Gulf are parts of the large Arabian continental plate (Ghazban, 2007). The Arabian plate extends from the Red Sea to the Zagros and from the Gulf of Aden to the Taurus Mountains. It consists of Precambrian basement overlain by Tertiary and later volcanics in the west and marine and continental sediments in the east. Its interior lacks any trace of intense late Tertiary deformation. The Mesozoic-Cenozoic sediments in the eastern part of the plate are horizontal or slightly tilted, and they display subdued Late Cretaceous-Eocene structures (Konert et al., 2001) (Figure 1). The Persian Gulf Basin comprises sedimentary rocks of Pre-Cambrian to Quaternary age (Figure 2).

Three major petroleum systems were identified in Persian Gulf after reviewing the available Rock-Eval analysis

2.1Paleozoic petroleum system: It has been postulated that the Early Silurian (Llandoverian) highly organic-rich and radioactive shales (Sarchahan Formation) were the source rocks for the huge Paleozoic oil and gas reserves found in the Arabian Plate with a possible Ordovician and Devonian source rock contribution. In the Persian Gulf, no well drilled deep enough to penetrate the Pre-Devonian sediments, as Well as Early Silurian source rocks (Chehrazi, 2013). Jurassic Petroleum system: Most of the Jurassic petroleum system is driven by a Late

Jurassic source rocks. There are also contributions from sources in Middle and Lower Jurassic.Cretaceous Petroleum system: A) Lower Cretaceous Petroleum System: The principal source rocks are of lower and mid-Cretaceous age. The reservoirs in this system are diverse because the seals are less consistent. B) The Mid-Late Cretaceous–Tertiary Petroleum System: The Kazhdumi (Albian) and Pabdeh (Paleocene-Eocene) formations have been confirmed as the main source rocks of the super-giant oil and gas accumulations of the Zagros fold belt and offshore of southwestern Iran. Asmari, Sarvak (expect Sarvak member) and Ilam formations form the most important reservoirs of this system.

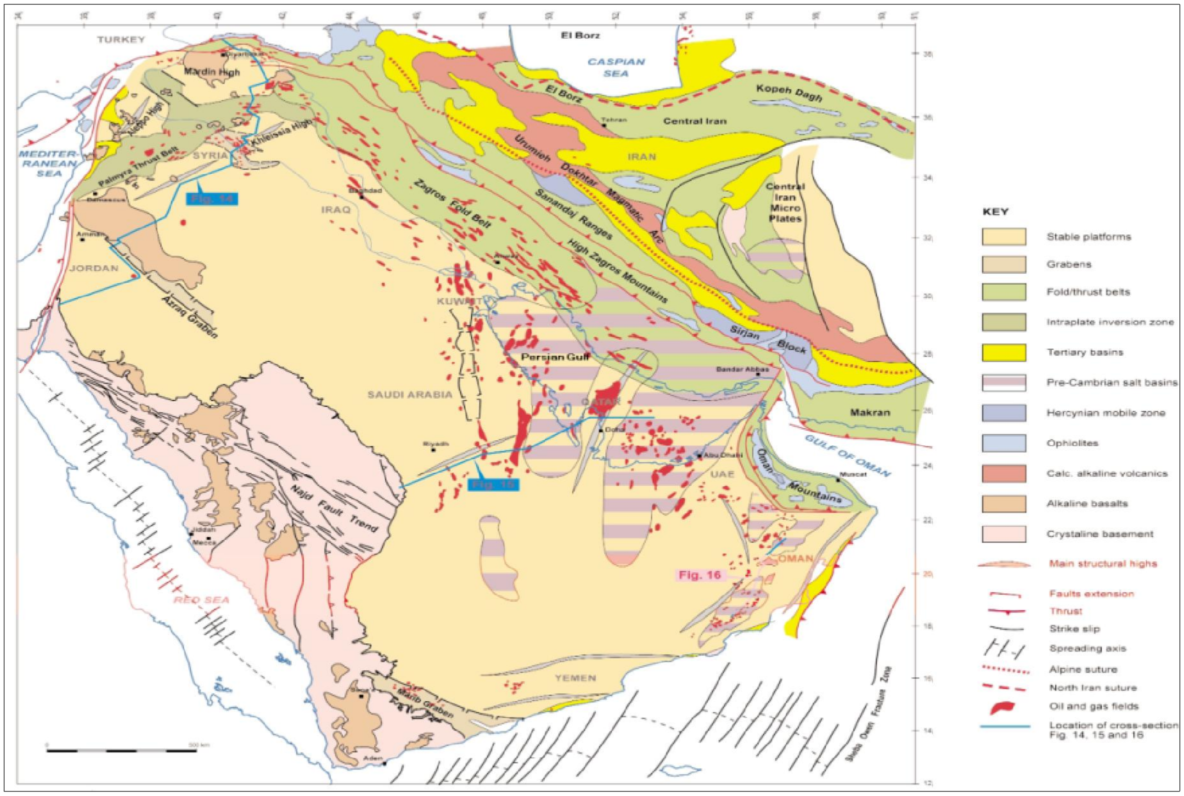

Figure 1. Location and major tectonic elements of the Arabian plate and Iran (Konert et al, 2001).

3. Recommended data

Main information to build the models includes (1) well databases and coordinate or other reference locations of all data; (2) names and age ranges all formation in the model; and (3) lithology and facies characteristics of within the formation (Shabani & Kamali, 2012). By using the very detailed Well reports good quality of the models was obtained. Samples have been taken from cores and cuttings and vitrinite reflectance has been measured in order to establish the present thermal maturity of the source rocks and reconstruct the thermal history of the area. Additional to the maturation of vitrinite, Rock-Eval pyrolysis and other geochemical analysis data (TOC, HI, Kinetics) measurements have been conducted from this stratigraphic interval representing candidate source rocks. These data were used for hydrocarbon 1D modelling study.

4. Methods

4.1Organic petrology and geochemistry

Maturity determination on organic matter provides information about the thermal history of source and non-source rocks in a basin. To estimate thermal maturity of sedimentary rocks the method of vitrinite reflectance measurement is commonly used. Vitrinite is a coalification product of humic substances, which essentially originate from the lignin and cellulose of plant cell walls (Taylor et al. 1998). The optical reflectance of vitrinite increases systematically and irreversibly with increasing thermal stress. In this study vitrinite reflectance measurements were carried out on 40 cutting and core samples from key Wells of the study area. The locations of study area and key wells are shown in Figure 3. Also the Figure 3 shows that key wells locations provide a good distribution for descriptions of source rocks in the study area. The samples are mainly obtained from organic rich sediments including the Kazhdumi (Nahr Ummr) and the Sarvak (Ahmadi member) representing main source formations. These measurements were carried out using a Leitz-MPV-SP microscope. A sapphire glass standard with 0.589% reflectance value was used for calibration. Measurements were determined on polished particulate mounts in the random mode according to Taylor et al. (1998), with an oil immersion objective of 125 magnifications, under light reflectance at a wavelength of 546 nm. Also, the total organic carbon (TOC) content of the sediments has been measured to get information on the concentration of organic matter in the target source rocks.

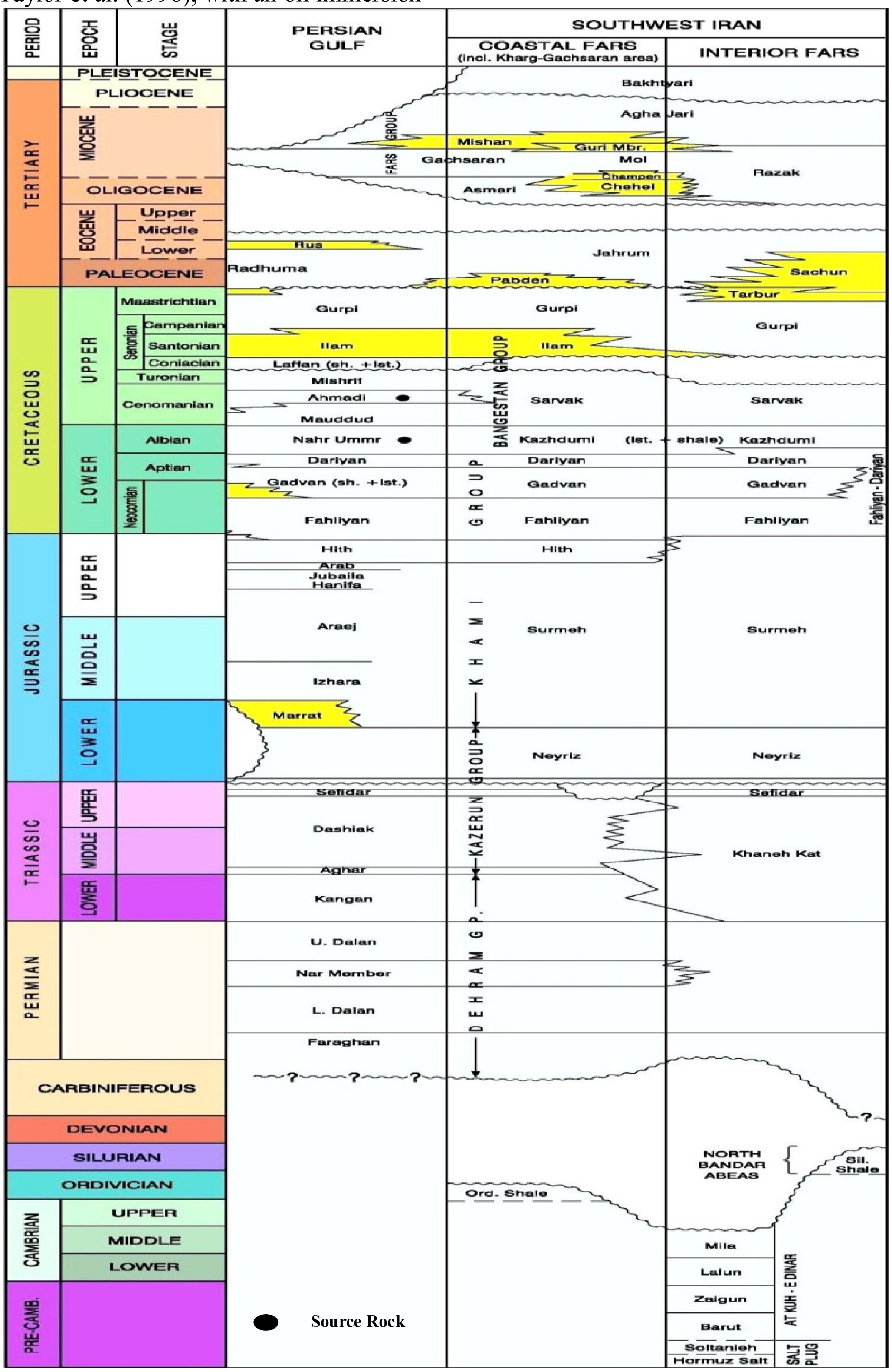

Figure 2. Stratigraphy, source rocks and important events during basin evolution in the study area (Konert et al, 2001).

4.2 Organic matter kinetic analysis

The modeling software programs come with a large number of standard source rock kinetics as well as a licensed range of new kinetics that have been especially developed and calibrated for PVT-controlled property predictions. Nonetheless, certain scenarios might require adjustments to these functions. As part of the modeling software suite the Kinetics Editor helps users predict hydrocarbon generation with maximum accuracy. Clearly defined tables enable users to enter values such as the oil-gas ratio, sorption, frequency factor and activation energy for customizing the primary and secondary reactions of n-component source rock kinetics.

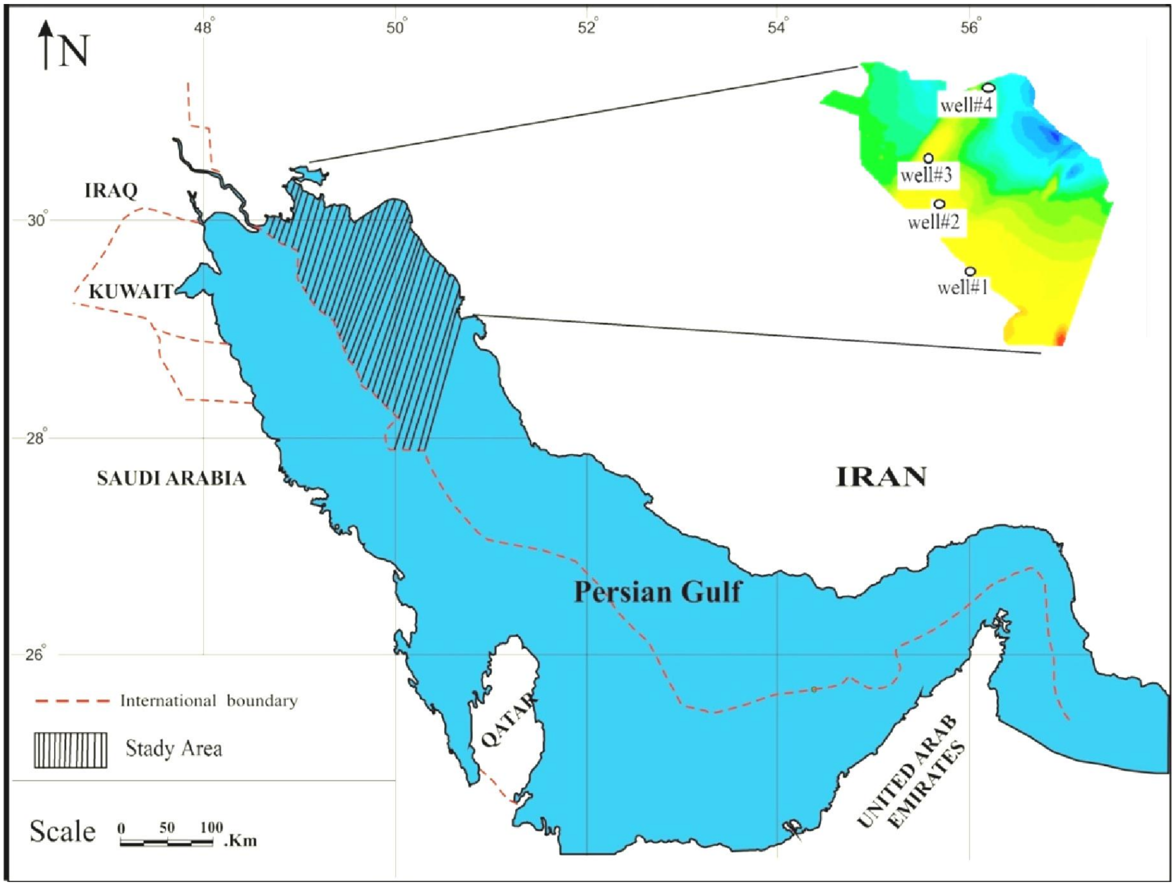

Figure 3. Key Wells location on the study area

4.3 1D Basin Modelling

Geological, geophysical, petrophysical, geochemical and thermodynamic data are used to create a model that can be used to quantify processes at work during the formation of sedimentary basins. Forward modelling thus enables us to obtain results from different geological times during basin evolution and hydrocarbon generation and transformation.

Initially, a conceptual model was created which is based on the observed geological, geophysical, petrophysical and geochemical data. In the conceptual model the basin history is subdivided into an uninterrupted sequence of events (deposition, erosion and hiatus) of specified age and duration. Similarly, structural and tectonic events such as salt movement, folding and faulting have been included. The resulting conceptual model of the basin history provides the numerical ‘‘pattern,’’ both physically and temporally, that describes the essential input for the simulation program (Poelchau et al. 1997). The conceptual model for the numerical modelling in this study is based on Well reports and other useful information relevant the basin evolutions. For the calculation of vitrinite reflectance from temperature histories, the EASY %Ro algorithm of Sweeney and Burnham (1990) was used which is based on reaction organic matter kinetic results. The maturation of

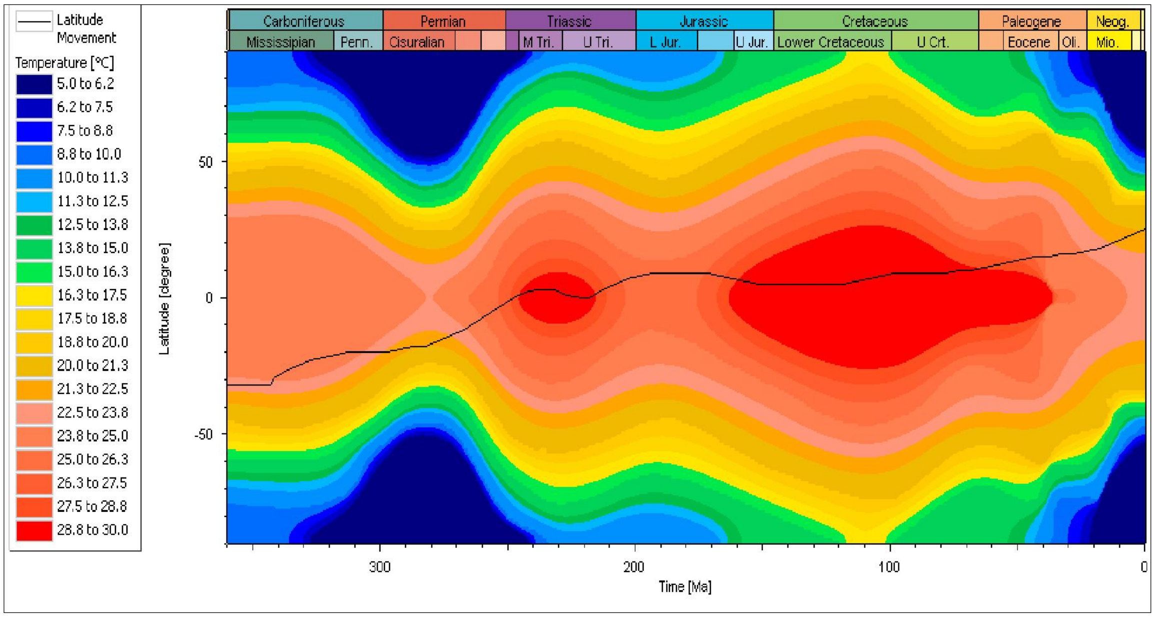

Figure 4: Global mean surface temperature (adapted from Wygrala, 1989)

Table 1. Main Input data used for 1D modelling in Well#1

Formation Name	Thickness [m]	Eroded [m]	Age at Top	Lithology	TOC	HI	PWD	SWIT	HF[mW/m2]
Bakhtiyari-Aghjari	1126		0	Conglomerate (typical)			5	20.2	50
Mishan-Guri	257		12	Limestone (shaly)			30	21.23	50
Gachsaran	365		16	Anhydrite			5	21.81	50
Ghar	33		20	Sandstone (typical)			0	23.1	50
Asmari	70		21	Limestone (ooid grainstone)			25	22.26	55
Jahrum	516	100	35	Limestone (Chalk, typical)			30	23.8	55
Pabdeh	37		50	Marl			100	25.43	55
Gurpi	43		65	Limestone (shaly)			200	25.37	55
Ilam	42		84	Limestone (ooid grainstone)			35	27.73	60
Laffan	29		86	Shale (typical)			40	29	60
Sarvak (Mishrif)	67	150	93	Limestone (micrite)			15	29	60
Sarvak (Sarvak)	5		95	Shale (black)	2	450	40	29	60
Sarvak (Mauddud)	34		98	Limestone (shaly)			20	29	65
Kazhdumi (Shale)	19		100	Shale (black)	1.44	300	70	28	65
Kazhdumi (Dair)	59		102	Limestone (ooid grainstone)			20	29	65
Kazhdumi (Burgan)	14		105	Sandstone (typical)			40	29	65
Dariyan	82	200	115	Limestone (shaly)			20	29	65
Gadvan	97		122	Shale (organic lean, typical)			200	29	75
Fahliyan	504		127	Limestone (micrite)			50	29	75

SWIT; sediment water interface temperature, HF; heat flow, TOC; total organic carbon, HI; hydrogen index, PWD; palaeo water depth

Table 2 Petrophysical parameters of the sedimentary rocks used in basin modelling

Formation Name	Lithology	Grain Density [kg/m3]	Thermal Conductivity at 20(0C) [W/mK]	Heat Capacity at 20(0C) [kcal/kg/K]
Bakhtiyari-Aghjari	Conglomerate (typical)	2700	6.1	0.2
Mishan-Guri	Limestone (shaly)	2730	2.3	0.2
Gachsaran	Anhydrite	2970	6.3	0.18
Ghar	Sandstone (typical)	2720	3.95	0.2
Asmari	Limestone (ooid grainstone)	2740	3	0.2
Jahrum	Limestone (Chalk, typical)	2680	2.9	0.2
Pabdeh	Marl	2700	2	0.2
Gurpi	Limestone (shaly)	2730	2.3	0.2
Ilam	Limestone (ooid grainstone)	2740	3	0.2
Laffan	Shale (typical)	2700	1.64	0.21
Sarvak (Mishrif)	Limestone (micrite)	2740	3	0.2
Sarvak (Sarvak)	Shale (black)	2500	0.9	0.23
Sarvak (Mauddud)	Limestone (shaly)	2730	2.3	0.2
Kazhdumi (Shale)	Shale (black)	2500	0.9	0.23
Kazhdumi (Dair)	Limestone (ooid grainstone)	2740	3	0.2
Kazhdumi (Burgan)	Sandstone (typical)	2720	3.95	0.2
Dariyan	Limestone (shaly)	2730	2.3	0.2
Gadvan	Shale (organic lean, typical)	2700	1.7	0.21
Fahliyan	Limestone (micrite)	2740	3	0.2

vitrinite with increasing thermal stress is described by four parallel proceeding reactions: the generation of water, carbon dioxide, higher hydrocarbons and methane. These reactions cause the decrease of the H/C ratio and the O/C ratio can clearly be correlated with the increase of vitrinite reflectance (%Ro). The calculation of these processes is based on the Arrhenius equation with corresponding reactions that are described by activation energy distributions with the appropriate reaction potential and a constant frequency factor. In the EASY %Ro model the four reactions are integrated in one activation energy distribution that allows the calculation of vitrinite reflectance values between 0.3 and 4.5% VRr. The burial and temperature histories were calibrated by comparing calculated and measured vitrinite reflectance and temperature data from selected wells. Burial and heat flow histories were calculated based on the conceptual model and calibrated for times of maximum temperatures/maximum burial with vitrinite reflectance data. For calibration of present-day heat flow temperature data reported by bottom hole temperatures (BHT) were applied. Input dataset for one of the wells (well#1; deepest well) is shown in Table 1, containing data on thickness, lithology, age, erosion, sediment/water interface temperature (SWIT), basal heat flow (HF) and plaeo water depth (PWD), TOC, HI for each stratigraphic unit. Other data effect to maturity is physical rock properties, the physical properties of the lithologies applied are summarized in Table 2. The sediment/water interface temperatures for all events were calculated by the modelling software after Wygrala (1989) based on the palaeo geographical position of the area and water depth during time of deposition (Figure. 4).

5.Results and discussion

5.1Vitrinite reflectance data

Vitrinite reflectance was determined for 40 cutting samples from Kazhdumi and Sarvak Formations. The samples represent mainly Shale and Marl lithology. Results of the measurements are listed in Table 3.

5.2 Rock-Eval pyrolysis data

Rock-Eval pyrolysis measurements were conducted to get information on quantity and quality of organic matter in source rocks. Rock-Eval pyrolysis information is used for calculation of generated hydrocarbons and volume of generation that have been transformed from organic matter in the source rocks. The main Rock-Eval pyrolysis information in the source rocks are TOC and HI values that are shown in the Table 1.

Table 3. Vitrinite reflectance sample data measured on selected samples from 4 key wells.

Well	Formation	Sample type	Time Unit (Age/ Stage)	Sample No.	Depth (m)	Number of Reading	Ro (%)
Well#1	Kazhdumi	Cutting	Albian	S-985	2106	10	0.47
Well#1	Kazhdumi	Cutting	Albian	S-989	2056	19	0.54
Well#1	Kazhdumi	Cutting	Albian	S-990	2032	16	0.47
Well#1	Kazhdumi	Cutting	Albian	S-992	2020	16	0.51
Well#1	Kazhdumi	Cutting	Albian	S-994	2004	15	0.56
Well#1	Kazhdumi	Cutting	Albian	S-996	1990	12	0.53
Well#1	Kazhdumi	Cutting	Albian	S-997	1986	18	0.61
Well#1	Kazhdumi	Cutting	Albian	S-998	1976	17	0.64
Well#1	Kazhdumi	Cutting	Albian	S-999	1966	18	0.61
Well#1	Kazhdumi	Cutting	Albian	S-1002	1938	21	0.56
Well#1	Sarvak	Cutting	Albian-Cenomanian	S-1004	1908	20	0.60
Well#1	Sarvak	Cutting	Albian-Cenomanian	S-1006	1900	14	0.45
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1008	2960	18	0.69
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1010	2930	12	0.68
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1012	2910	15	0.67
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1014	2890	15	0.66
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1016	2870	15	0.65
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1019	2840	15	0.64
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1021	2820	17	0.62
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1024	2780	19	0.62
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1026	2760	16	0.61
Well#2	Kazhdumi	Cutting	Albian-Cenomanian	S-1028	2740	14	0.6
Well#2	Sarvak	Cutting	Cenomanian	S-1032	2490	13	0.57
Well#2	Sarvak	Cutting	Cenomanian	S-1034	2450	11	0.56
Well#2	Sarvak	Cutting	Cenomanian	S-1035	2420	8	0.55
Well#2	Sarvak	Cutting	Cenomanian	S-1037	2260	14	0.51
Well#3	Kazhdumi	Core	Albian-Cenomanian	GC873-58.1	2329	28	0.47
Well#3	Kazhdumi	Core	Albian-Cenomanian	GC873-60.1	2350	25	0.38
Well#3	Kazhdumi	Core	Albian-Cenomanian	GC873-62.1	2357	27	0.49
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1039	3167	24	0.67
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1041	3154	12	0.63
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1043	3148	13	0.70
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1045	3100	15	0.57
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1048	3086	13	0.60
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1049	3082	11	0.60
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1051	3074	12	0.62
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1053	3064	19	0.62
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1055	3046	18	0.65
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1057	3038	13	0.65
Well#4	Kazhdumi	Cutting	Albian-Cenomanian	S-1058	3020	10	0.57

5.3 Organic matter kinetics analysis

The generation and maturation of HC-components, molecular biomarkers and coal macerals can be quantified by chemical kinetics. Chemical kinetics is formulated using mass balances. It is therefore important to specify and track all chemical reactants of organic matter during the processes of interest (Hantschel and Kauerauf, 2009).

Kinetic parameters analyzed for 2 core samples from Well#2 (Sarvak Fm) and Well#4 (Kazhdumi Fm) key Wells.

Table 4 shown different input parameters using calculation organic matter kinetic types in two key Wells and Table 5 shows main output parameters for generation of oil and gas and applied in our models.

Table 4. Organic matter kinetic parameters

Well	Formation	Activation Energy [kcal/mol]	Frequency Factor [1/Ma]	Initial Ratio [%]	HI	W-Factor
Well#2	Sarvak	53.4	1.12E+27	100	400	0.5
Well#4	Kazhdumi	57	1.82E+28	100	350	0.85

Table 5. Main output parameters applied generation of oil and gas from organic matter

Well	Formation	Tempreture [^{0}C]	Max Generation Rate [mgHC/gTOC/Ma]	Transformation Ratio [%]
Well#2	Sarvak	160	0.217	62
Well#4	Kazhdumi	186	15.4	66

5.4 1D numerical modelling: conceptual model, burial and maturity history

The burial history charts show the temporal extent of the petroleum system. The deposition history can be interpreted and elements like subsidence, uplift and erosion can be shown. selecting different overlays enables further modeling results (e.g. source rock characteristics) to be plotted and interpreted. Since the shapes of the burial histories are strongly defined by the input parameters (e.g. layer thicknesses, erosion events, etc), the plots show different geometries. As the 1D modeling study is mainly interested in the evaluation of the source rock over time, the maturity overlay according to Sweeney & Burnham (1990) has been plotted to the burial histories of the Wells. The early oil window is defined according to Sweeney & Burnham (1990) by a vitrinite reflectance of Ro=0.55%, the main oil window by a reflectance of Ro=0.7% and the late oil window by a vitrinite reflectance of Ro=1%. The maturity overlay according to Sweeney & Burnham (1990) gives a general overview of source rock maturity as expressed by vitrinite reflectance. In the study area, several regional unconformities and hiatuses punctuated the sedimentary succession as a consequence of eustatic sea-level changes and epeirogenic movements. Sedimentation started in the Lower Cretaceous Formations with the deposition of shallow-marine sedimentation. Strong erosion reaching the upper part of the Middle Triassic succession below the Lower Jurassic unconformity was registered. During the Lower Jurassic, a pronounced long-term, sea-level lowstand resulted in a period of erosion and non-deposition marked by a widespread Lower Jurassic hiatus. The Triassic-Jurassic sedimentation was dominated by more than 1000m of carbonate and evaporate deposition, and open marine mixed clastic-carbonate deposits dominated Lower Cretaceous. The Lower Cretaceous is represented by the Fahliyan-Gadvan-Dariyan formations consisting generally massive Oolitic to pelloidal limestones. The Middle Turonian unconformity resulted from both a combination of localized uplift, following initiation of ophiolite abduction on the northeast plate margin, and possibly a global eustatic fall in sea level (Sharland et al., 2001). During the Upper Cretaceous and then since the Oligocene, uplift and erosion characterized the study area as consequence of collision of the Arabian Plate with Laurasia (Zagros orogeny). During the Oligo-Miocene and Pliocene deposition, the study area has been the site of mixed evaporitic, carbonate and clastic sedimentation (Seabed formation). A deep Tertiary foreland basin area has been increasing burial of source rocks in the study area and significant implications of hydrocarbon generation from deeper source rocks. Figure 5 show maturity history plot with calibration by %Ro measurements from core and cutting samples in four key wells. In addition to the Heat Flow effect, the maturity of the source rocks in study area has been controlled by two main subsidence phases corresponding to the Late Cretaceous and Miocene-Pliocene subsidence phases. Variable Heat Flow model has been used during the thermal history of the basin from the Devonian to present-day. The first major thermal event was affected the area concern the Hercynian orogeny uplift following by more than 1000 m of erosion and induced increase of the heat flow at the top of the sediments. The second major thermal event was assigned to the Early- Mid Jurassic uplift (more than 300 m erosion amount assumed) related to Triassic-Jurassic rifting in the Mediterranean Sea. Figure 6 shows some HF graphs for three key wells in geological age after calibration. For the uplift phase during Early- Mid Jurassic increased heat flow values, with a maximum of 100 mW/m2 were applied, decreasing exponentially with time. The reconstruction of the heat flow history was done using measured vitrinite reflectance assuming that vitrinite reflectance can be adequately calculated using the EASY %Ro algorithm (Sweeney and Burnham,. 1990). The calibration of the model leads to a depth/vitrinite reflectance plot that compares measured with calculated data. In Figure 5 the palaeo heat flow and the temperature and maturity calibration data are added to the burial history plot of both wells. The present day basal heat flow is calibrated using measured temperatures in the wells (Figure 6). In all 1D models, the present-day heat flow is in accordance with corrected bottom hole temperatures (BHT) from Well#2, Well#1 and

Well#4 Wells. Best accordance between measured and calculated present-day temperatures was achieved with present-day heat flows in the range of 40–105 mW/m2. Lowest present-day heat flow values resulted for Well#3 and highest values for Well#1(Figure 7).

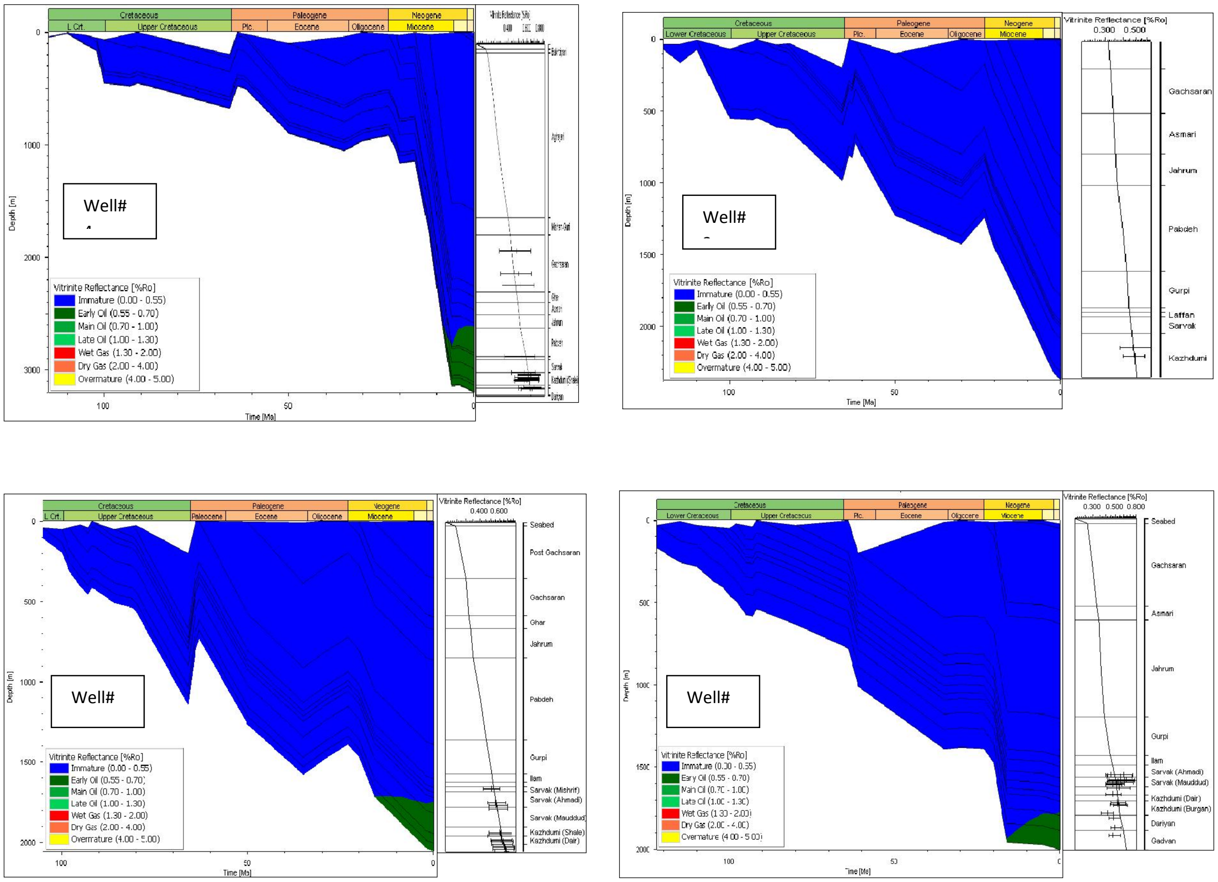

Figure 5: Maturity history plotted on the history matching with calibration using Ro% data in four key wells

5.5 1D numerical modelling: Generation and Transformation Rate

Two source rock layers are considered in this study area, Lower Cretaceous Kazhdumi and Mid-Late Cretaceous Sarvak formations. The maturity history of these source rocks will be discussed respectively. Since maturity is critically controlled by the kinetics of a source rock that discussed above sections. Transformation Ratio (TR) is; represents the quantitative transformation ratio related to total organic carbon and production for the source rocks. The calculations pay attention to the Heat Flow (HF) and burial history as Well as to the assigned kinetics in the facies definition. The ratio ranges between 0% and 100%. Generation Rate (GR) is; calculation of generation rate that takes into account the burial and HF history, the kinetics, the TOC value and the HI (hydrocarbon index).

Figure 8 shows timing of TR &GR factor for Sarvak and Kazhdumi formations in the four key Wells. The timing of generation of hydrocarbons and the onset of expulsion of different sources in all the key Wells are evaluated. The Kazhdumi source intervals in the Well#4 and Well#3 started expelling since Late Miocene(≈10 Ma ago) and Well#2 and Well#1 started expelling since Eocene (≈50 Ma ago) period. And Sarvak source started expelling for Well#4 and Well#3 since Miocene (≈10-20 Ma ago) and for Well#2 and Well#1 started expelling since Eocene (≈50 Ma ago) period (Figure 8).

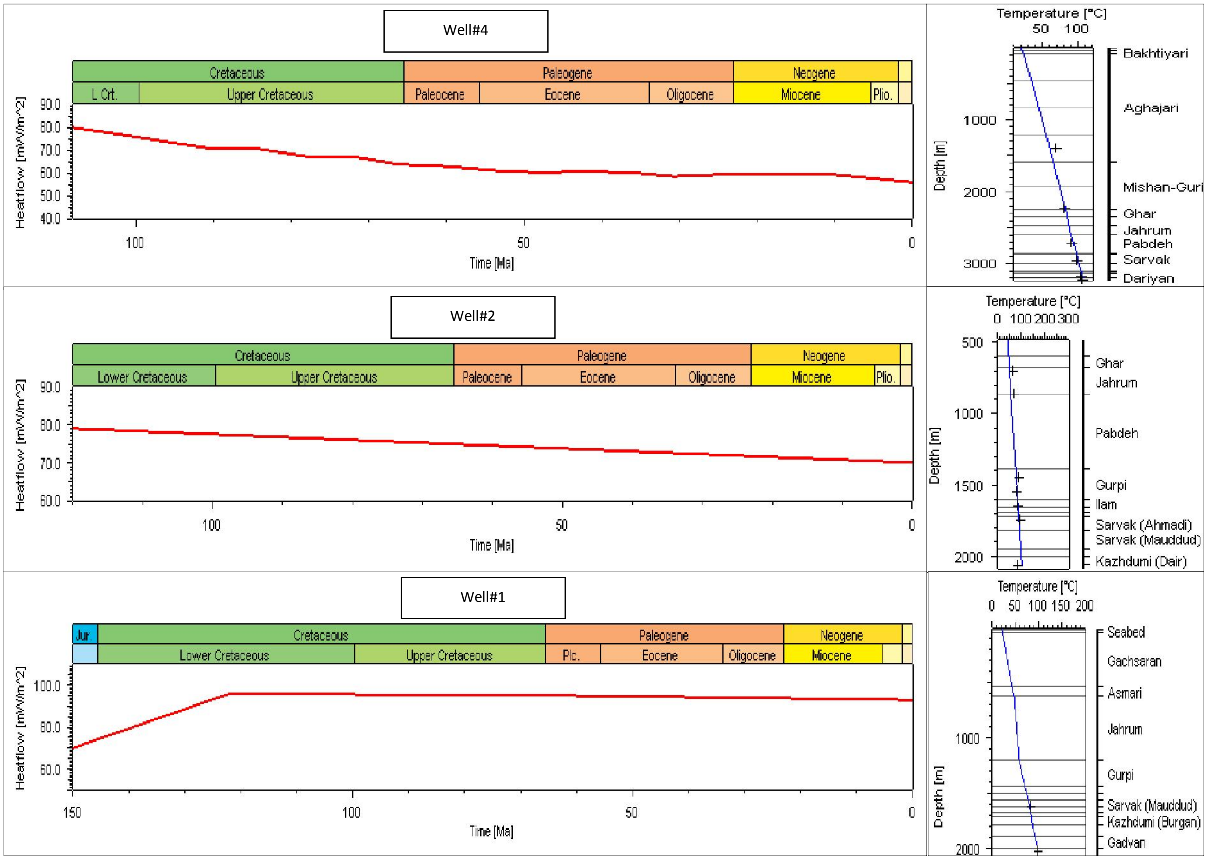

Figure 6: Present day basal heat flow calibrated with measured temperatures in the three

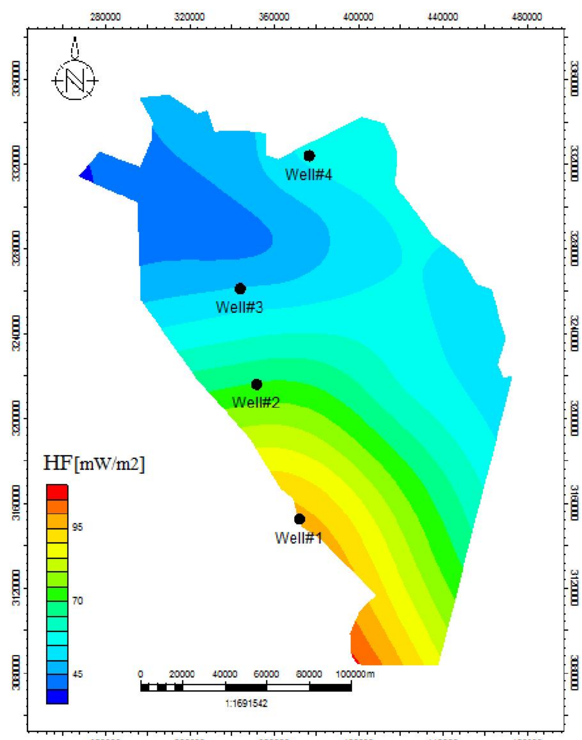

Figure 7: Present day heat flow map in the study area

5.6 Maturity trend

The maturity maps (Figure9; A and B) have been compiled for Kazhdumi and Sarvak formations in the studied area. The principal areas of maturation can also be derived from vitrinite reflectance calculations without consideration of the generated masses, the source rock thickness and the TOC and HI values. These maps are based on a large number of vitrinite reflectance data which were obtained in the framework of this study. Furthermore, numerical basin modeling was applied which helped to interpolate between measured data from different stratigraphic levels.

Maturity of the Kazhdumi Formation is between 0.42 to 0.75% VR and show the trend of increasing from South to north of the studied area and maturity of the Sarvak Formation is between 0.41 and 0.7% VR and increase from South to the North of the studied area. This figure shows that generally, in the studied area, maturity in northern part is generally higher than the southern parts.

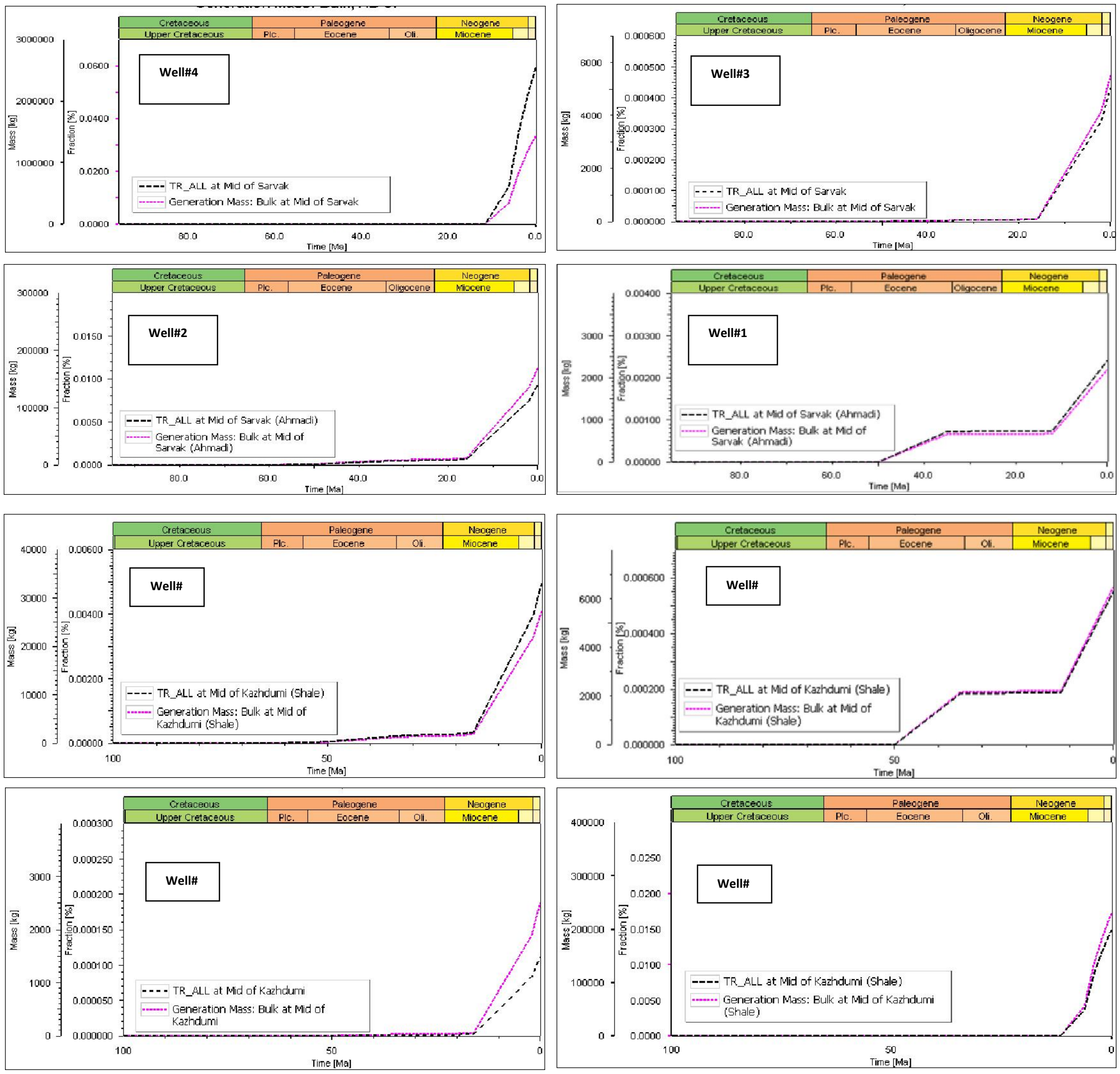

Figure 8: Timing of TR &GR factor for Sarvak and Kazhdumi formations in the four key wells

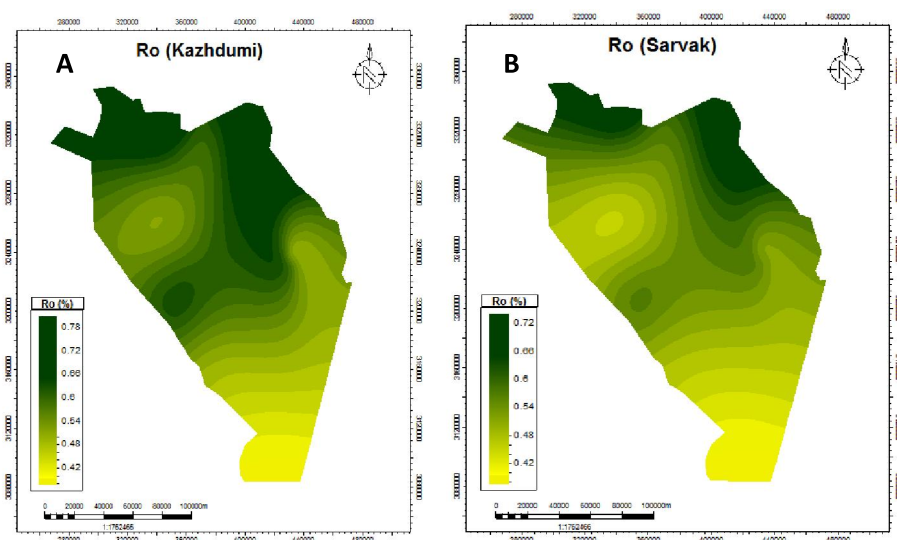

Figure 9: Maturity maps for Kazhdumi (A) and Sarvak (B) formations

6. Conclusions

This study reveals the thermal regime of the N-W part of the Persian Gulf and to describe source rocks burial history.

Four Wells from this have been evaluated: Well#4 Well#1, Well#3 and Well#2. Vitrinite Reflectance data from Well#2, Well#3, Well#1 and BHT temperature values from all three Wells have been used to calculate and calibrate the present day heat flow. Variable heat flow model has been used during the thermal history of the basin from the Lower Cretaceous to present-day. Variable Heat Flow model has been used during the reconstruction of thermal history of the basin from the Jurassic to present-day. Two main tectonic events controlled the thermal history of the studied area: the Hercynian orogeny uplift and erosion which induced the increase of the heat flow at the top of the sediments. The average crustal thickness of 45 km has been used for this study. The present day heat flow varies from 50 mW/m2 to 105 mW/m2 with the highest values in the Well#2 and lowest heat flow values in the Well#3.

Two source rock levels have been considered in this basin modeling study: the Lower Cretaceous Kazhdumi and Cenomanian Sarvak source rocks. The transformation ratio TR is defined as the converted mass fraction of the initial reactant, the transformation ratio TR=0.5 defines the critical point of generation. Some example curves for the kinetics type at three different sedimentation rates show the dependency of the generated petroleum on sedimentation or heating rates. The calculated transformation ratios at present day and paleo-times show how and where most of the petroleum is generated. These can be converted into areas of maturation classes for immature, oil and gas generating, and over mature regions. The principal areas of maturation can also be derived from vitrinite reflectance calculations without consideration of the generated masses, the source rock thickness and the TOC and HI values. The timing of generation of hydrocarbons and expulsion are different in source rocks. The Kazhdumi source intervals in the Well#4 and Well#3 started expelling since Late Miocene(≈10 Ma ago) and Well#2 and Well#1 started expelling since Eocene (≈50 Ma ago) period. And Sarvak source intervals started expelling for Well#4 and Well#3 since Miocene (≈10-20 Ma ago) and for Well#2 and Well#1 started expelling since Eocene (≈50 Ma ago) period. Maturity of the Kazhdumi Formation is between 0.42 to 0.75% VR and show the trend of increasing from South to north of the studied area and Maturity of the Sarvak Formation is between 0.41 and 0.7% VR and increase from South to the North of the studied area. Generally, in the studied area, maturity in north part is higher than the south parts.

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