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Quantitative assessment of the petroleum generation potential of Early Cretaceous source rock in the northern part of Mari-Kandhkot High, north Sindh and southern Punjab, Pakistan

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ABSTRACT

A source rock study and thorough petroleum system modelling have been performed as part of an exploration evaluation programme in one of the blocks in the northern part of the Mari-Kandhkot High (northern Sindh and southern Punjab) to determine the potential of Early Cretaceous sources and evaluate petroleum generated volumes in cubic feet gas per sq. km. The primary source rock in this region are the shales of the Early Cretaceous Sembar Formation (Berriasian-Valanginian, 145-132 Ma), while the Lower Goru Formation (Albian-Aptian, 125-113 Ma) shales can be considered the second most efficient source due to their high organic content.

Our study database involved 10 wells in the study area, where detailed source rock analyses were carried out on 106 samples in the Maluk -1, POGC Sabzal X-1, and Sara -1 wells, and the Total Organic Carbon (TOC) on seven additional wells was calculated through the Δlog R method. Study has determined, the mixed Type-II and Type-III kerogen, the TOC in the Sembar Formation ranges from 0.06% to 2.15%, with an average of 1.0%, and vitrinite reflectance (Ro) ranges from 0.7% to 1.95%. As a secondary source rock in the region, the Lower Goru Formation primarily contains Type-III organic matter, with TOC averaging 0.9% and Ro ranging from 0.80% to 1.45%. Depending on the quantity and quality of organic matter, oil generation depth ranges from 2200 to 2700 metres at temperatures between 100^{o} and 125^{o} C, whereas the minimum depth at which gas generation begins is 3000 metres at a temperature of approximately 125^{o}C.

According to the results of the petroleum system modelling, the first hydrocarbon generation reached maturity at 53 Ma and peaked at 25 Ma, with a potential to generate 60–80 bcf/sq km of gas.

In our paper, we discussed the results of the organic geochemical analysis of the Lower Goru and Sembar formations from the Early Cretaceous, and we presented maps of the thickness of the organically rich layers, the distribution of thermally mature areas, and the intensity of hydrocarbon expulsion. These maps may offer future operators interested in exploring the area substantial data by supporting them understand the geological history of a source rock.

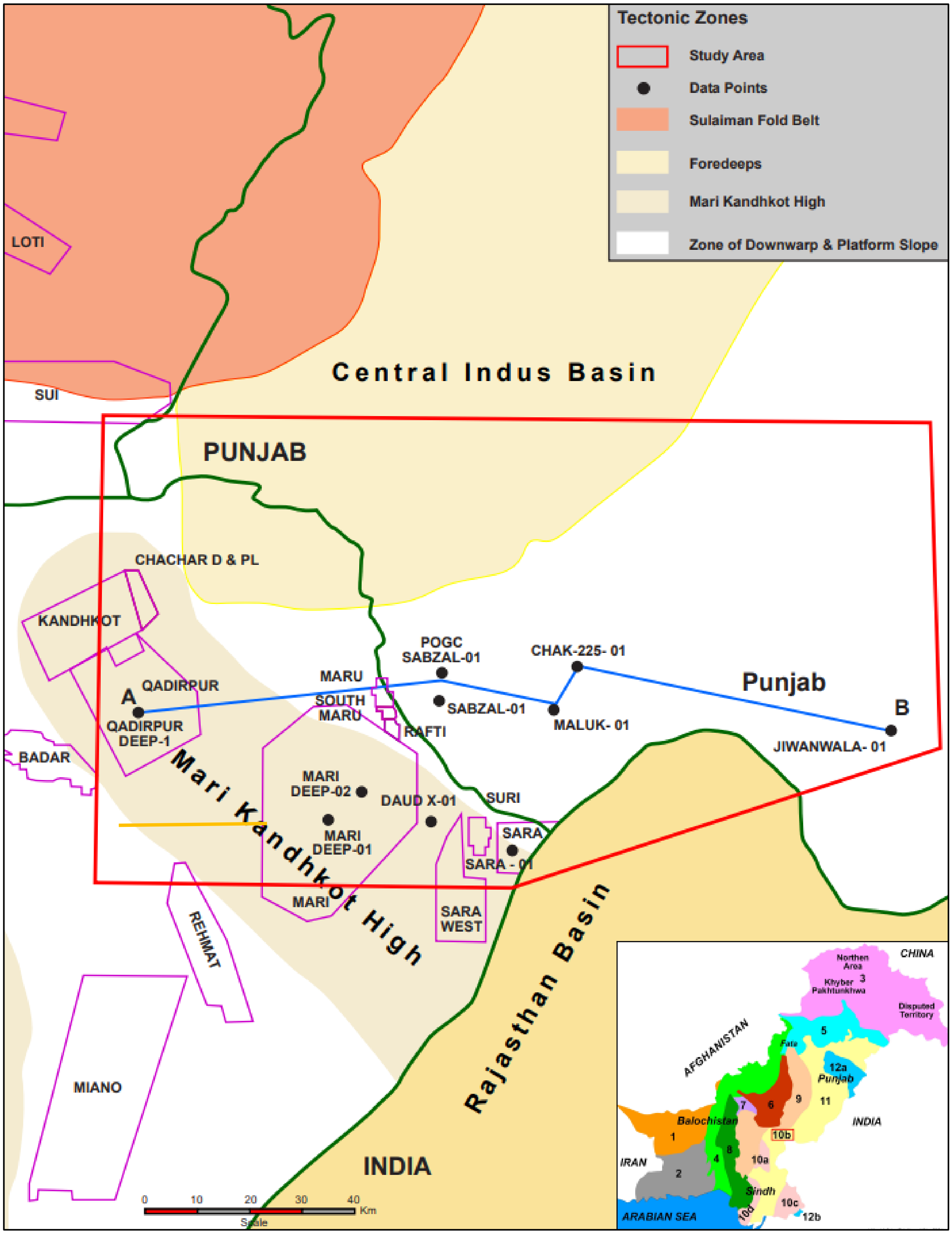

Figure 1. Location map of the study area, the southwestern part lies on the Mari Kandhkot High. Map in inset, showing the major tectonic features of Pakistan. 1: Chagai Volcanic Arc & Cal-Alkaline Magnetic Belt. 2: Makran Flysch Basin, 3: Karakoram – Himalayan Fold belt 4: Bela Chaman Kurrum Fault and Ophiolite belt 5: Himalayan Fold belt 6: Sulaiman Trough, 7: Sibi Trough 8: Kirthar Fold Belt, 9: Foredeeps 10: Zones of Upwarp 11: Zones of Downwarp & Platform slope 12: Buried Ridges.

1. INTRODUCTION

The success of petroleum exploration largely depends on the insight of the source rock in the basin. In the Indus Basin of Pakistan, it is widely believed that the Early Cretaceous sedimentary marine sequences, consisting of Sembar and Goru formations, have adequate source potential to generate a commercial quantity of petroleum (Figure 1). Siddiqui et.al, (2014); has reported 1.5-4.7% TOC in Pakistan in Early Cretaceous Sembar / Goru formation whereas Nazir et.al, (2011), Ahmad et.al, (2012); and Qayyum et.al, (2016) reported as high as 9.5% TOC. However, no published work is available that may confirm the source of hydrocarbon correlation and quantification of the generation potential of these sequences. Therefore, it relies mainly on the fact that the Early Cretaceous sequence has reasonable volumes of TOC with adequate thermal maturity for generation, as found in wells in our study area. Despite the scarcity of wells in the southern part of Punjab that have drilled to the Cretaceous, we will present the results of a detailed geochemical analysis that we have carried out in two different laboratories on the well cuttings of Maluk -1, POGC Sabzal-1, and Sara -1. The resistivity and acoustic logs of 10 wells were also used to calculate TOC by a method proposed by Passey and Creaney (1990). These wells are Qairpur Deep 1, Chak 255-1, Jiwanwala -1, Mari Deep-1, Mari Deep-2, Daud X-1, Sara-1, OGDCL Sabzal-1, POGC Sabzal -1, and Maluk-1

2. EXPLORATION HISTORY

The Mari-Kandhkot High, northern Sindh, and southern Punjab is the part of the central Indus basin on the western extension of the Rajasthan basin (Figure 1), which has remained a site for active exploration since the last decade of the nineteenth century. It was reported that the Government of British India had drilled the first well near Sukkur in 1891. However, details of this well have not been available, nor was this information confirmed from any exploration and production (E&P) company sources. The E&P companies had acquired 2D and 3D seismic data over the large area of the study and had drilled several exploratory wells (Table 1). The biggest gas field in this area was discovered from Habib Rahi Limestone (HRL) of the Middle Eocene age in 1957 when Stanvac drilled Mari-X1 well. In 1997 Mari Gas Company Limited (MGCL) discovered gas from sandstones of the Cretaceous with combined estimated recoverable gas reserves of 10,500 Billion Cubic Feet (BCF) from HRL, Cretaceous, and other Eocene reservoirs. In 1990 Qadirpur (discovered and operated by OGDCL) and in 1994, Sara (27 BCF) and Sara West both operated by Tullow oil were also discovered from Eocene Basal Ghazij sands and Lower Goru formation, respectively (Pakistan Energy Yearbook, 2018). Qadirpur gas field has 4,560 BCF estimated recoverable gas reserves and has been producing since 1995, whereas Sara, Suri, and Sara West gas fields were relatively small. Sara and Suri gas fields had completed the production and were abandoned after depletion. Table 1 provides the summarized information about the wells drilled in the area.

This area is known for the occurrence of higher Carbon dioxide (CO_2) and Nitrogen

(N_2) from both Eocene and Cretaceous reservoirs, with the calorific value from 560 to 815 British Thermal Units (BTU).

Exploration drilling in district Rahim Yar Khan was carried out by OGDCL (Dandhi-1, Sabzal - 1, Maluk 1, and Chak 255), Polish Oil and Gas Company (POGC Sabzal-1), and Pakistan Petroleum Limited (PPL Daud-X1, Sadiqabad X-1, and Sadiqabad X-2 and Cholistan X-1). All the wells drilled in district Rahim Yar Khan, Punjab, were dry, whereas many gas fields were found in Ghotki district, Sindh, including giant Mari and Qadirpur fields.

3. GEOLOGICAL SETTING AND STRATIGRAPHY

The Mari-Kandhkot High, northern Sindh and southern Punjab is the part of the central Indus basin on the western extension of the Rajasthan basin (Figure 1). The general northwestward down warping of the shelf has been proven by the data of wells and seismic and has also confirmed the presence of sediments over the Pre Cambrian basement (not penetrated in any well in this area) covering the Phanerozoic with existence of unconformities which resulted due to either non deposition or uplifting and erosion. Jurassic age carbonates of Chiltan formation was the oldest sediment penetrated in the study area (Figure 2(b)). The depth of sediments varying from few kilometers to more than 7 kilometers with increasing trend towards north and northwest. Tectonically, the study area was a part of Indian plate which had pronounced and observable drift, rift and collision events during Early Jurassic, Cretaceous and Tertiary respectively. In subsurface, failed rifting phase has more dominant structural imprints than other events which led to form titled fault blocks; Sukkur Rift, consisting of Mari Kandhkot High, Pano Aqil Graben and Jacobabad-Khairpur High are located towards south. Petroleum occurrence has also been closely associated in the traps formed due to the rift related normal fault blocks which have been routinely targeted for hydrocarbon exploration by E&P companies in the area.

The limestone of Late Jurassic Chiltan Formation and sands in Early to Middle Cretaceous Sembar and Lower Goru formations are the main reservoirs as proven by hydrocarbon shows and discoveries in the study area. The marl and clays in Late Cretaceous Upper Goru formation provides the regional seal while clays and shales within Sembar Formation and Lower Goru Formation are believed to be the local seals. Figure 2(b). The general northwestward down warping of the shelf has been proven by the data of wells and seismic and has also confirmed the presence of sediments over the Pre Cambrian basement (not penetrated in any well in this area covering the Phanerozoic. Around 1500 to 2500m thick cover from Late Cretaceous Upper Goru to recent deposits provides sufficient burial for source rock to be mature to generate hydrocarbon at commercial scale.

The Mari-Kandhkot High is the horst block probably formed because of failed extensional rift between the Madagascar and the Indian Plate in the Jurassic to Late-Middle Cretaceous. The hydrocarbon generation, migration and accumulation started in the Middle Paleocene, achieved critical moment by early Miocene resulting

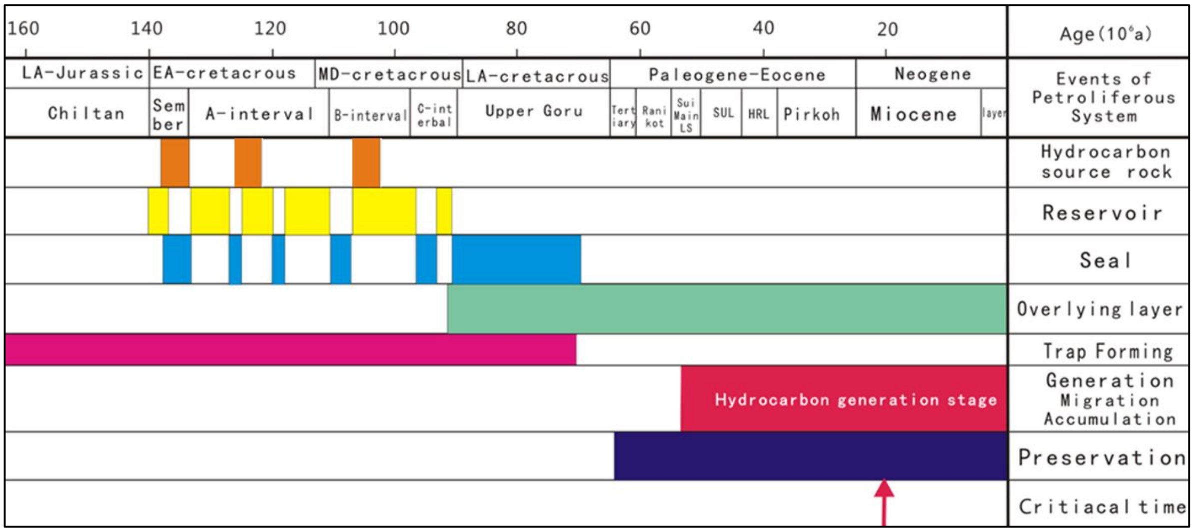

Figure 2(a). Petroleum system model showing major reservoirs seal pairs, trap timing and generation, migration, accumulation and preservation timing.

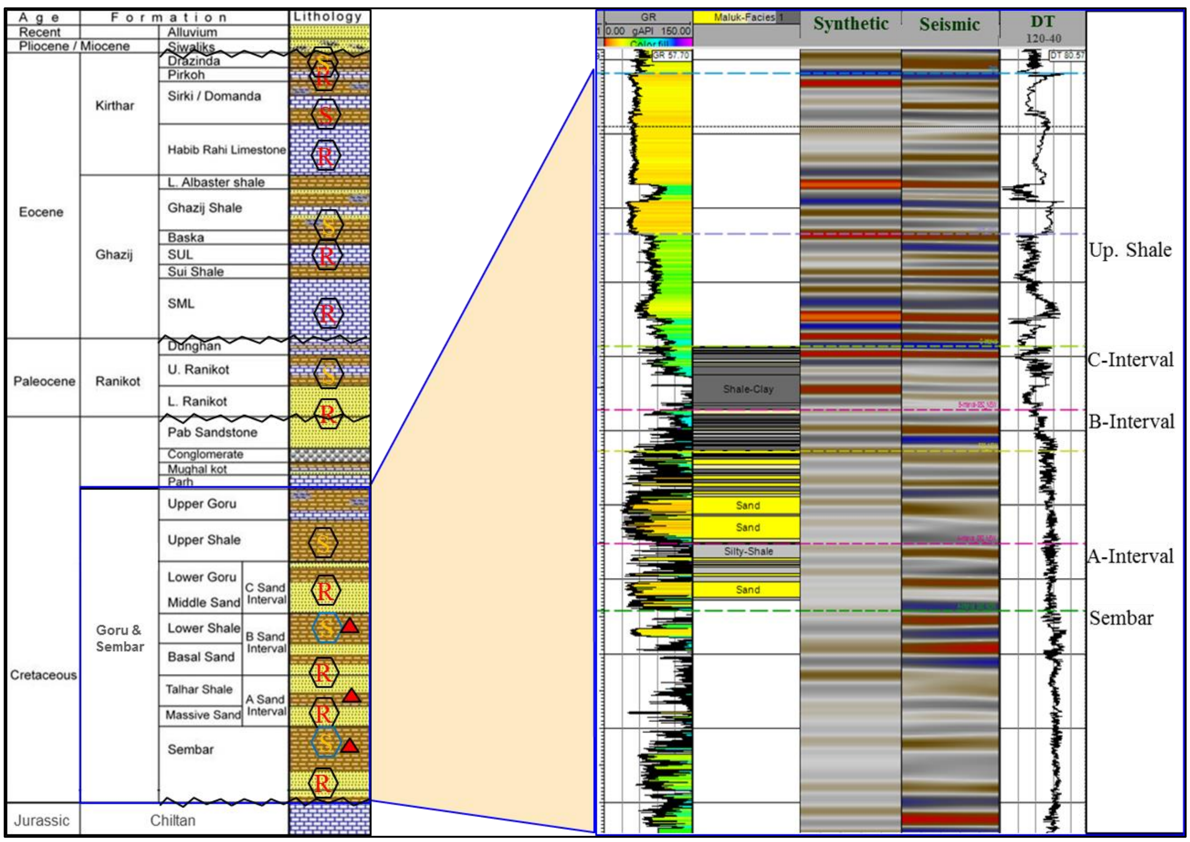

Figure 2(b). Generalized stratigraphy of the study area highlighting the significance of source rocks, reservoirs and seal rocks, (left). standard GR log, sonic log and a typical synthetic and seismic display showing the seismic signatures of A, B and C sand units of Lower Goru and top of Sembar Formation of Early Cretaceous age (right).

Table 1 Exploratory wells drilled in the study area. Mari and Qadirpur are the major gas. So far reservoir of Tertiary and Creteceous age found to be productive. NP: No present. PP: partially penetarted Red font: Information to be updated/unknown

Sr. No.	Well name	Operator	District	Year	TD (m) @ Formation	KB elevation AMSL (m)	Primary Target	Secondary Target	Well initial Flow rate (Reservoir)	Top Lr. Goru (m)	Bottom LG (m)	Thickness of Lr. Goru (m)	Top Sembar (m)	Bottom (m)	Thickness of Sembar (m)	Early Cretaceous (Lr.Goru Sembar) sediments Thickness (m)	Well Status	Remarks
1	**Mari-X1**	STBC	Ghotki	1957	3386 @ Sembar	73	Tertiary Carbonates	Mesozoic Clastics	4.4 MMSCFD gas (Kirthar/HRL)	1889	3331	1442	3331		55+	1497+	Discovery	Sembar PP
2	**Kandhkot-1**	PPL	Jacobabad	1959	2079 @Fort Munro	73	Fort Munro		2.5 & 1 MMSCFD gas (SUL & SML)	NP	NP	NP	NP	NP	NP	NP	Discovery	
3	**Mari-X7**	ESSO	Ghotki	1966	785 @HRL	76	HRL		FLOW RATE	NP	NP	NP	NP	NP	NP	NP	Discovery	
4	**Dhandi-1**	OGDC	Rahim Yar Khan	1984	1646@ Pab	77	HRL	SML/Pab		NP	NP	NP	NP	NP	NP	NP	P&A	
5	**Mari-E1**	MPCL	Ghotki	1986	800 @ HRL	77	Eoc		FLOW RATE	NP	NP	NP	NP	NP	NP	NP	Discovery	
6	**Mari-E2**	MPCL	Ghotki	1986	799 @ HRL	72	Eoc		FLOW RATE	NP	NP	NP	NP	NP	NP	NP	Discovery	
7	**Mari-E3**	MPCL	Ghotki	1986	802 @ HRL	76	Eoc		FLOW RATE	NP	NP	NP	NP	NP	NP	NP	Discovery	
8	**Qadirpur-1**	OGDC	Jacobabad	1990	1566 @ Pab	76	SML		FLOW RATE	NP	NP	NP	NP	NP	NP	NP	Discovery	
9	**Qadirpur-X2**	OGDC	Sukkur	1991	1587 @ Pab	79	Pab		FLOW RATE	NP	NP	NP	NP	NP	NP	NP	Discovery	
10	**Ghotki-1**	OCCIDENTAL	Sukkur	1993	1600 @ Pab	79	???			NP	NP	NP	NP	NP	NP	NP	P & A	
11	**Kashmore-1**	OGDC	Jacobabad	1993	2714 @Dunghan	79	Dunghan			NP	NP	NP	NP	NP	NP	NP	P&A	
12	**Sara-1**	TULLOW	Ghotki	1994	3185 @ Chiltan	103	HRL/SML	Chiltan	17.75/0.6 MMSCFD (Basal Ghazij Sand/ SUL)	1563	2601	1038	2601	3143	542	1580	Discovery	
13	**OGDCL Sabzal-1**	OGDC	Rahim Yar Khan	1994	3185 @ Chiltan	71	HRL\SML	Pab\Lr. Goru\Sembar		2550	3611	1061	3611	3640	29+	1090+	P&A	Sembar PP
14	**Chachar-1**	TULLOW	Kashmor	1995	1802 @ SML	78	SML		FLOW RATE	NP	NP	NP	NP	NP	NP	NP	Discovery	
15	**Sara West -1**	TULLOW	Ghotki	1996	3045 @ Lr. Goru	88	Lr. Goru\SML\Ghazij	SUL	25.6 MMSCFD gas (Lr. Goru-B Sand)	1938	3045	1107+	NP	NP	NP	NP	Discovery	
16	**Mari Deep-1**	MPCL	Ghotki	1997	4116 @ Chiltan	69	Lr. Goru	Chiltan\SML	23.9 MMSCFD gas & 85 BBL condensate (Lr.Goru-B Sand)	1873	3220	1347	3220	3936	716	2063	Discovery	
17	**Mari Deep-2**	MPCL	Ghotki	1997	3906 @ Sembar	71	Lr. Goru	Sembar	15 MMSCFD gas & 60 BBL condensate (Lr.Goru-B Sand)	1898	3196	1298	3196	3906	710+	2008+	Discovery	Sembar PP
18	**Suri-1**	TULLOW	Ghotki	1997	1249 @U.Goru	86	SML			NP	NP	NP	NP	NP	NP	NP	Discovery	
19	**Daud X-1**	PPL	Ghotki	1998	3285 @ Sembar	89	Lr. Goru	SML/HRL		2018	3184	1166	3184	3285	101+	1267+	P&A	Sembar PP
20	**Chak 255- 1**	OGDC	Rahim Yar Khan	1999	3004 @ Sember	81	Lr. Goru	Pab\SML		2099	3000	901+	NP	NP	NP	901+	P&A	Lr. Goru PP
21	**Jiwanlwala -1**	OGDCL	Rahim Yar Khan	1999	2106 @ Shirwari	131	Chiltan	Goru/Sembar		876	1665	788	A	A	A	A	P&A	
22	**Khan-1**	TULLOW	Sukkur	2000	1370@U.Goru	87	???			NP	NP	NP	NP	NP	NP	NP	P & A	
23	**Khairgarh-1**	TULLOW	Khairpur	2000	1400 @U.Goru	78	U Goru			NP	NP	NP	NP	NP	NP	NP	P & A	
24	**POGC Sabzal -1**	POGC	Rahim Yar Khan	2001	3530 @ Sembar	81	Lr. Goru\Pab\Ranikot	SML\Dunghan		2462	3508	1046	3508	3555	46+	1092+	P & A	Sembar PP

Sr. No.	Well name	Operator	District	Year	TD (m) @ Formation	KB elevation AMSL (m)	Primary Target	Secondary Target	Well initial Flow rate (Reservoir)	Top Lr. Goru (m)	Bottom LG (m)	Thickness of Lr. Goru (m)	Top Sembar (m)	Bottom (m)	Thickness of Sembar (m)	Early Cretaceous (Lr.Goru Sembar) sediments Thickness (m)	Well Status	Remarks
25	**Mari SML-1**	MPCL	Ghotki	2005	1268 @ Ranikot	78	SML	Pirkoh	6.0 MMSCFD gas at SML & Pirkoh	NP	NP	NP	NP	NP	NP	NP	Discovery	
26	**Maluk -1**	OGDC	Rahim Yar Khan	2007	3682 @ Sembar	74	Lr. Goru	Sembar		2075	3084	1009	3084	3682	602+	1611+	P&A	Sembar PP
27	**Qairpur Deep 1**	OGDCL	Ghotki	2007	4696@ Chiltan	78	Lr. Goru\Sembar	Pab\Parh		2740	4074	1334	4074	4706	632	1966	P&A	
28	**Bhitai-1**	MPCL	Ghotki	2007	1202 @ Ranikot	0	Eoc		11.32 MMCFD	NP	NP	NP	NP	NP	NP	NP	Discovery	
29	**Reti-1**	OGDC	Ghotki	2008	770 @ HRL	75	Pirkoh	HRL	2.6 MMSCFD (Pirkoh)	NP	NP	NP	NP	NP	NP	NP	Discovery	
30	**Watayo-1**	MPCL	Ghotki	2008	1182 @SML	80	SML			NP	NP	NP	NP	NP	NP	NP	P & A	
31	**Maru-1**	OGDC	Ghotki	2009	794 @ HRL	75	Pirkoh	HRL	1.4 MMSCFD gas (Pirkoh)	NP	NP	NP	NP	NP	NP	NP	Discovery	
32	**Rafay-1**	PEL	Sukkur	2009	3672 @ Lr. Goru	78	Lr. Goru	Nil		NP	NP	NP	NP	NP	NP	NP	P & A	
33	**Chak 216 West-1**	OGDC	Rahim Yar Khan	2010	1590 @ Ranikot	76	Pirkoh	HRL/SML		NP	NP	NP	NP	NP	NP	NP	P&A	
34	**Chak 205**	OGDC	Rahim Yar Khan	2010	1645 @ Ranikot	82	Pirkoh	HRL/SML		NP	NP	NP	NP	NP	NP	NP	P&A	
35	**Seher-1**	OGDC	Ghotki	2010	1535 @Ranikot	90	Pirkoh	HRL/SML		NP	NP	NP	NP	NP	NP	NP	P&A	
36	**Qadirpur PK-1**	OGDC	Ghotki	2010	865 @Sirki	75	Pirkoh	Nil		NP	NP	NP	NP	NP	NP	NP	P & A	
37	**Maru South**	OGDC	Ghotki	2011	~ 800(Pirkoh/HRL)	77	Pirkoh	Nil	2.5 MMSCFD gas (Pirkoh)	NP	NP	NP	NP	NP	NP	NP	Discovery	
38	**MGP-1**	MPCL	Ghotki	2013	551 @ Pirkoh	75	Pirkoh		1.9 MMCFD	NP	NP	NP	NP	NP	NP	NP	Discovery	
39	**MPX-1**	MPCL	Ghotki	2013	667 @Sirki	75	Pirkoh		1.7 MMCFD	NP	NP	NP	NP	NP	NP	NP	Discovery	
40	**MP-1**	MPCL	Ghotki	2013	553 @ Pirkoh	83	Pirkoh		2.5 MMCFD	NP	NP	NP	NP	NP	NP	NP	Discovery	
41	**Maru East**	OGDC	Ghotki	2014	~ 800(Pirkoh/HRL)	76	Pirkoh	Nil	2.67 MMSCFD gas (Pirkoh)	NP	NP	NP	NP	NP	NP	NP	Discovery	
42	**Ismail-1**	OGDCL	Ghotki	2015	840 @ Pirkoh	79	Pirkoh	Nil		NP	NP	NP	NP	NP	NP	NP	P&A	
43	**Sadiqabad X-1**	PPL	Rahim Yar Khan	2016	1040 @ Pirkoh	85	Pirkoh	Nil		NP	NP	NP	NP	NP	NP	NP	P & A	
44	**Sadiqabad X-2**	PPL	Rahim Yar Khan	2016	1039 @ Pirkoh	84	Pirkoh	Nil		NP	NP	NP	NP	NP	NP	NP	P & A	
45	**Shahbaz-1**	MPCL	Ghotki	2016	1180 @SML	87	SML	SUL	10.87 MMCFD	NP	NP	NP	NP	NP	NP	NP	Discovery	
46	**Khamiso-1**	OGDC	Sanghar	2016	753 @Sirki	76	Pirkoh		2.9 MMSCFD gas (Pirkoh)	NP	NP	NP	NP	NP	NP	NP	Discovery	
47	**Shaheen-1**	MPCL	Ghotki	2017	1175 @SML	79	SML	SUL	12.334 MMCFD	NP	NP	NP	NP	NP	NP	NP	Discovery	
48	**Tipu-1**	MPCL	Ghotki	2017	3944 @ Sembar	NR	L Goru	Sembar	21.4 MMSCFD gas (L Goru)	?	?	?	?	?	?	?	Discovery	
49	**Qadirwali-1**	OGDC	Ghotki	2017	2950	0	Cre			NP	NP	NP	NP	NP	NP	NP	P & A	
50	**Sheikhan Bhutta-1**	OGDC	Rahim Yar Khan	2018	3300@Chiltan	92	Goru			?	?	?	?	?	?	?	P & A	
51	**Umair-1**	OGDC	Ghotki	2018	785 @	79	Eoc		2.47 MMCFD	NP	NP	NP	NP	NP	NP	NP	Discovery	
52	**Qadirpur Deep -X1**	OGDC	Ghotki	2018	1454 @ SUL	0	L Goru & Sembar	Nil		NP	NP	NP	NP	NP	NP	NP	P&A	
53	**Parwaz-1**	MPCL	Ghotki	2019	1237	0	Eoc			NP	NP	NP	NP	NP	NP	NP	Testing	

expulsion and migration of hydrocarbon that might have continued till recent depending on the source rock richness and maturity in different sub-regions within study area Figure 2(a).

4. SAMPLE AND METHODS

The source rock geochemical study was conducted to ascertain the Early Cretaceous source potential for a better understanding of the petroleum system maturity and its effectiveness in one of the areas where Pakistan Petroleum Limited (PPL) is actively exploring hydrocarbon. One hundred six (106) samples from zones of interest were collected from three (3) wells and sent to one local laboratory for initial screening for the TOC and Rock-Eval Pyrolysis, selected samples for the vitrinite reflectance (Ro). Another batch of samples was selected for detailed analysis based on the initial results for Ro. Moreover, samples of POGC Sabzal -1, Maluk-1, and Sara- 1 were sent to another international laboratory to determine organic matter abundance, organic source type, and thermal evolution. The results of these wells are summarized in Table 2. Based on source rock profiling of 3 wells (Maluk-1, POGC Sabzal-1, and Sara-1), wells logs of all available wells were used to determine organic richness using Passey and Creaney's (1990) method.

The Ro of POGC Sabzal-1 and Maluk-1 obtained from two different laboratories showed variation in thermal maturity from low maturity or low intensity Ro 1-1.2% to higher maturity or higher intensity Ro 1.7%-1.95% (Figure 3d and Table 3). We have introduced an additional medium intensity scenario for thermal maturity, which estimates the gas generation potential from the source rock in this area. This study was based on petroleum system modeling to determine the potential of hydrocarbon generation from the Early Cretaceous source rock. The results facilitated the preparation of the quantifiable hydrocarbon expulsion maps in the study area.

Log evaluation for TOC and maturity

We have also undertaken source rock analysis on the Resistivity and Acoustic logs by the method proposed by Passey and Creaney (1990) on available logs data of Qadirpur Deep -1, POGC Sabzal-1, OGDC Sabzal-1, Maluk -1, Chak 255-1, Jiwanwala-1, Daud X-1, Mari Deep-1, Mari Deep-2, and Sara-1 wells.

The formula is as follows;

$TOC=\triangle logR\times 10a$

Where, $a=2.297-0.1688LOM$

Δlog R – the difference between the acoustic curve and resistivity curve;

LOM – the organic matter maturity, reflecting the obtained organic matter maturity through analyzing quantitative samples (Ro analysis) or evaluating burial and thermal evolution histories.

The calculation formula of Δlog R is: Δ Δlog R = 1g (RT/RT baseline) +0.02 * (Δt – Δt baseline)

Where RT – resistivity (Ω•m); Δt – tested Ac (μs/m); RTbase line – the baseline value of Resistivity curve in the non-source rock interval; Δt baseline –the baseline value of Ac curve in the non-source rock interval.

The standard well is selected with sufficient geochemical data and high-quality logging data. The calculated Δ log R of the standard well by logging data is calibrated with laboratory-measured TOC. The TOC calculation model is presented as:

$$\text{TOC measured} = k \times \Delta \log R + \Delta \text{TOC}$$

Where k is the organic carbon conversion coefficient; ΔTOC is the basic TOC content value in the source rock. The TOC measured is calibrated by the TOC values obtained through laboratory experiments to confirm the accuracy. If the accuracy is proved high enough, the model is applied to calculate the TOC of other wells.

We have used POGC Sabzal -1 as a standard well for Lower Goru Formation. This well has the maximum penetration of the sediments, better geochemical data, and logging data, whereas Maluk-1 was used as a standard well for Sembar Formation. Figure 6 shows the east-west cross-section passing through Maluk-1 and POGC Sabzal-1, standard wells for the Sembar and Lower Goru formations, respectively, with well-matched calculated TOC and tested TOC.

Hydrocarbon generation and expulsion dynamics

Oil and gas generation amount and rate were calculated by solving the hydrocarbon generation kinetics equation established based on the geological/ burial history model, thermal history inversion, source rock organic matter type, organic carbon content, source rock thickness, and distribution in the area. The petroleum system modeling software (Trinity and PetroMod) workflow were used for modeling the hydrocarbon generation and expulsion calculations. This software applies the equations described in simple kinetic models of petroleum formation (Pepper and Corvit, 1995, Pepper and Dodd, 1995). The hydrocarbon generation dynamics and hydrocarbon conversion curves representing fair to medium rich source rock in the study area are shown in Figure 10.

Well Results

The values obtained from geochemical analysis of the three wells, i.e., POGC Sabzal -1, Maluk-1, and Sara- 1, concluded that the Early Cretaceous Sembar Formation could be designated as the principal thermally mature source rock which had generated hydrocarbon, whereas Lower Goru Formation can be designated as the second important source rock.

Figure 3(a-d) and Table 2 represent the summarized geochemical analysis results of POGC Sabzal -1, Maluk-1, and Sara- 1

Sara-01

Lower Goru Formation has TOC ranging from 0.20% to 1.22%, average 0.83%; S1+S2 ranges from 0.11-2.75mg/g, average 1.12 mg/g; Hydrogen Index (HI) is from 29 to 211 mg/g, average 114 mg/g. Lower Goru is a gas-prone source rock having kerogen type III with a medium abundance of organic matter.

The Tmax ranges from 427℃ to 435℃, average 432℃; Vitrinite reflectance (Ro) ranges from 0.47% to 0.50%, average

0.48%; the S1/TOC is between 1.7mg/g to 15.0mg/g, average 7.6mg/g. Based on the thermal maturity analysis, Lower Goru Formation falls in the early maturity stageFigure 3(a-d).

Sembar Formation has TOC`s ranging from 0.23% to 2.14%, average 1.16%; S1+S2 ranges from 0.53mg/g to 10.33mg/g, average 2.56 mg/g; HI is from 87 mg/g to 453 mg/g, average 175 mg/g. Sembar is a gas-prone source rock of mixed kerogen type II - III with a medium abundance of organic matter.

The Tmax is from 419℃ to 436℃, average 432℃; Ro is between 0.50 and 0.78%, averagely 0.56%; the S1/TOC is between 1.7 mg/g to 29.9 mg/g, average 12.3 mg/g. Therefore, based on the thermal maturity analysis, Sembar Formation falls in the early maturity stage Figure 3(a-d).

Early Cretaceous sedimentary marine sequences, consisting of Goru formation, achieved early maturity in Upper Cretaceous at ~ 1800m depth, main oil generation in Paleocene at ~ 2500m depth, and Wet gas window in Early Eocene Figure 4(a).

Maluk-1

Lower Goru Formation has TOC ranging from 0.20% to 1.56%, average 0.87%; the S1+S2 ranges from 0.14 mg/g, to 3.10 mg/g, average 0.94 mg/g; HI from 44 mg/g to 167 mg/g, average 80 mg/g. Lower Goru is a gas-prone kerogen type III source rock with a medium abundance of organic matter.

The Tmax is from 419℃ to 436℃, average 432℃; Ro is between 0.8% and 1.0%, average 0.9%; the S1/TOC is between 5.5 mg/g to 58.0 mg/g, average 18.1 mg/g. Based on thermal maturity analysis, the Lower Goru Formation source falls in the oil maturity stage.

Sembar Formation has TOC ranging from 0.06% to 2.15%, average 0.92%; S1+S2 is from 0.08 mg/g to 4.52 mg/g, average 1.33 mg/g, the range of HI is from 42 mg/g to 209 mg/g, average 133 mg/g. Sembar is a gas-prone, kerogen type III source rock with medium organic matter abundance.

The data of Tmax obtained was from 400ºC to 436℃, average 426℃; Ro is between 0.7% and 1.3%, average 1.0%; the S1/TOC is between 7.7 mg/g and 48.4mg/g, average 20.9mg/g. Therefore, based on thermal maturity analysis, Sembar Formation falls in the oil maturity stage Figure 3(a-d), 4(b) & 5.

Early Cretaceous sedimentary marine sequences, consisting of Sembar and Goru formations, achieved early maturity in Upper Cretaceous at ~ 2000m depth, main oil generation in Paleocene at ~ 2500m depth, wet gas window in Early Eocene, and main gas generation phase in Oligocene at ~3100m depth. Figure 4(b)

POGC Sabzal-1

Lower Goru has TOC ranging from 0.21% to 3.00%, average 1.00%; S1+S2 is 0.02 mg/g -3.71 mg/g, average 1.47 mg/g; HI is from 5 mg/g to 287 mg/g, average 115mg/g. Lower Goru is a gas-prone, kerogen type III source rock with a medium abundance of organic matter. The Tmax is from 410 ℃ to 438℃, with an average of 430℃. Ro is between 0.81% and 1.87%, average 1.50%; the S1/TOC is between 2.9

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mg/g and 40.8 mg/g, average 21.7 mg/g. Based on thermal maturity analysis, Lower Goru Formation falls in the wet gas maturity stage.

Sembar Formation has TOC ranging from 0.53% to 0.95%, average 0.73%; S1+S2 from 0.22 mg/g to 1.22 mg/g, average 0.62 mg/g; HI from 23 mg/g to 98 mg/g, average 55 mg/g. Sembar is a gas-prone kerogen type III source rock with a medium abundance of organic matter. The data of Tmax obtained from pyrolysis was 410ºC to 438℃, an average of 430ºC. Ro is between 1.74% and 1.95%, average 1.87%; the S1/TOC is between 13.1 mg/g and 30.5mg/g, average 23.5mg/g. Based on thermal maturity analysis, Sembar Formation falls in the wet gas maturity stage Figure 3(a-d).

Early Cretaceous sedimentary marine sequences, consisting of and Goru formation, achieved early maturity in Paleocene at ~ 2000m depth, main oil generation in Paleocene at ~ 2500m depth, wet gas window in Early Eocene, and main gas generation phase in Oligocene at ~3100m depth. Figure 4(c).

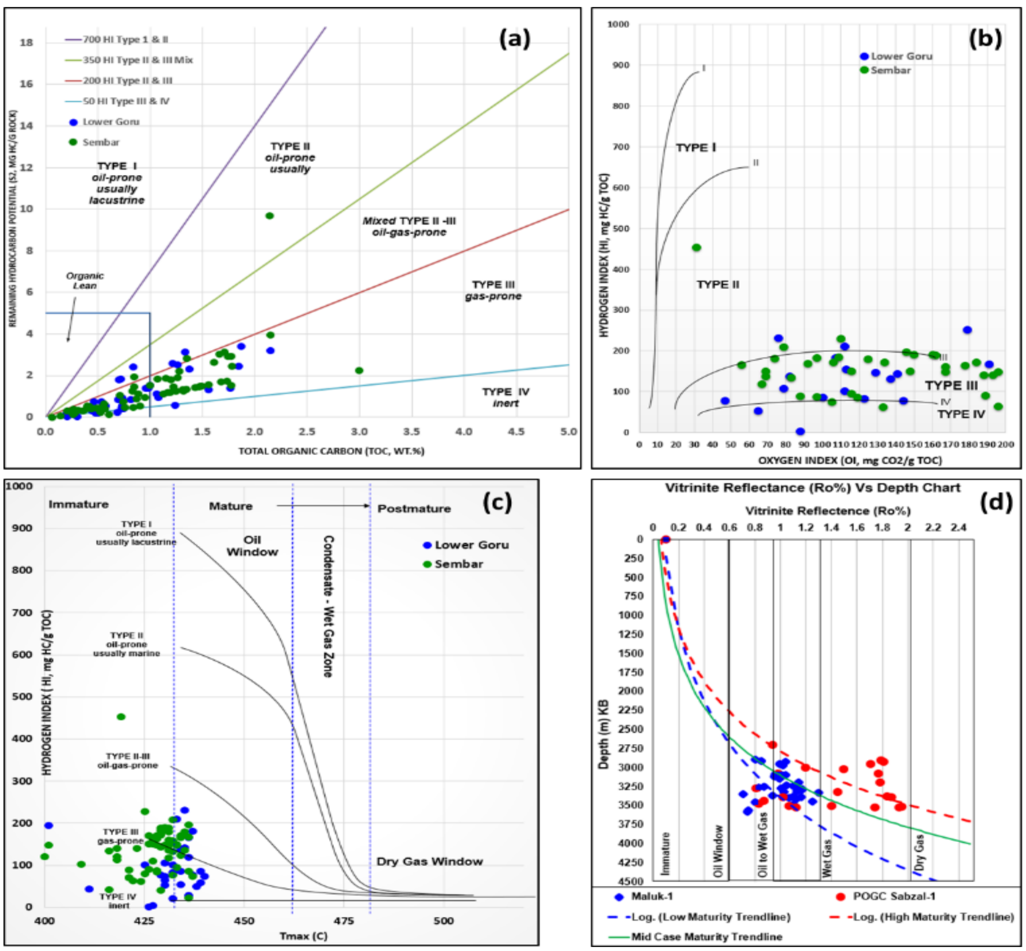

Figure 3 (a to d) a) chart showing TOC vs remaining hydrocarbon potential (S2,mgHCg/g rock) b) chart with Oxygen Index (OI) Vs Hydrogen Index (HI) Cross-plots c) Tmax vs Hydrogen Index d) vitrinite reflectance Vs depth for all samples.

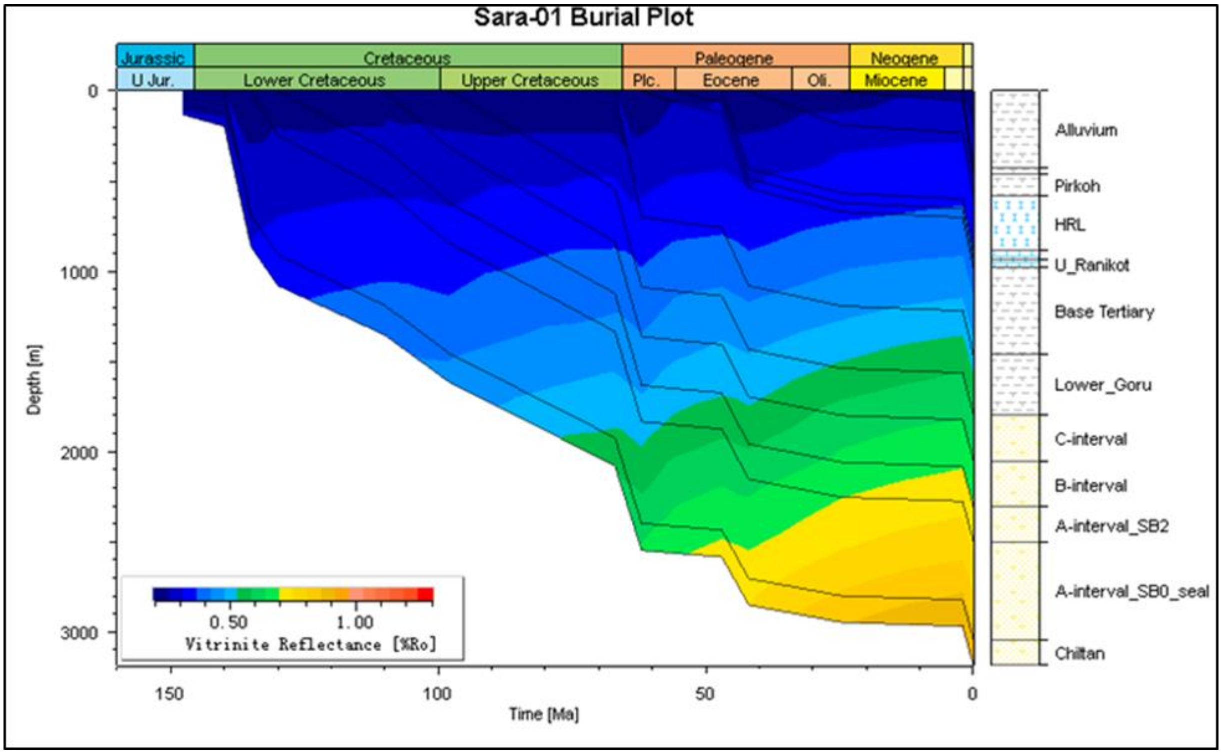

Figure 4(a): Burial Histrory and maturity plot at Sara-01 well.

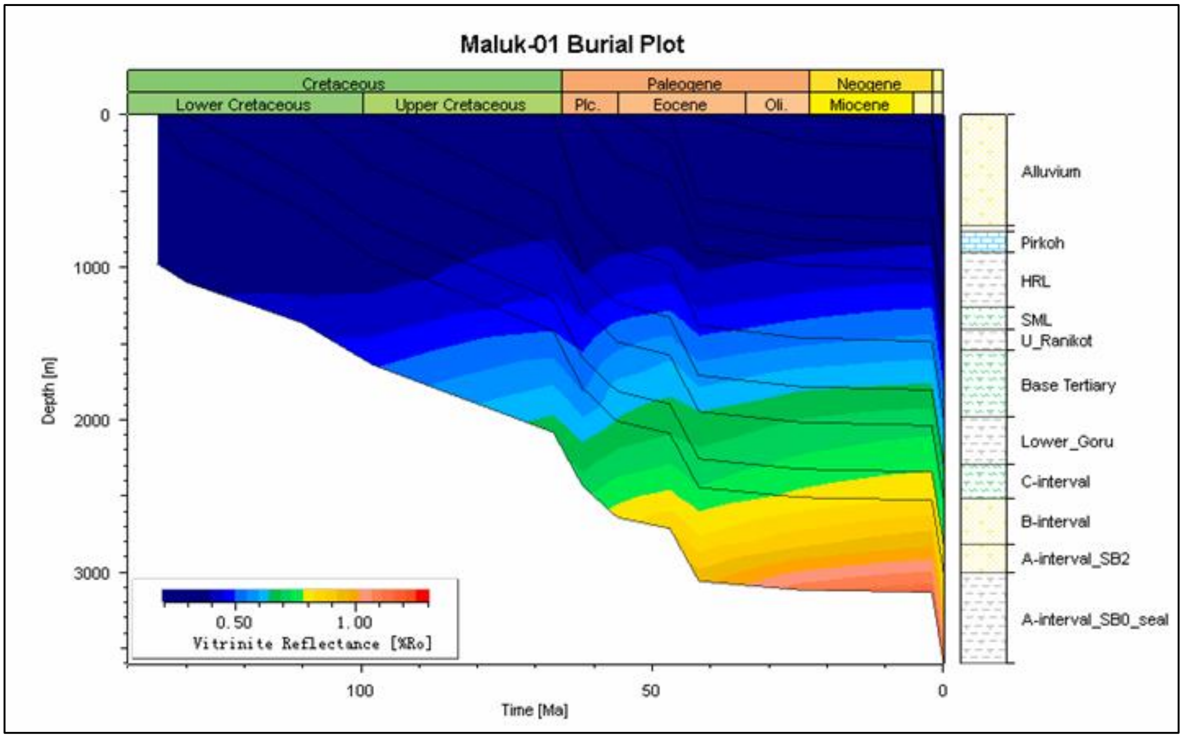

Figure 4(b): Burial Histrory and maturity plot at Muluk-01 well

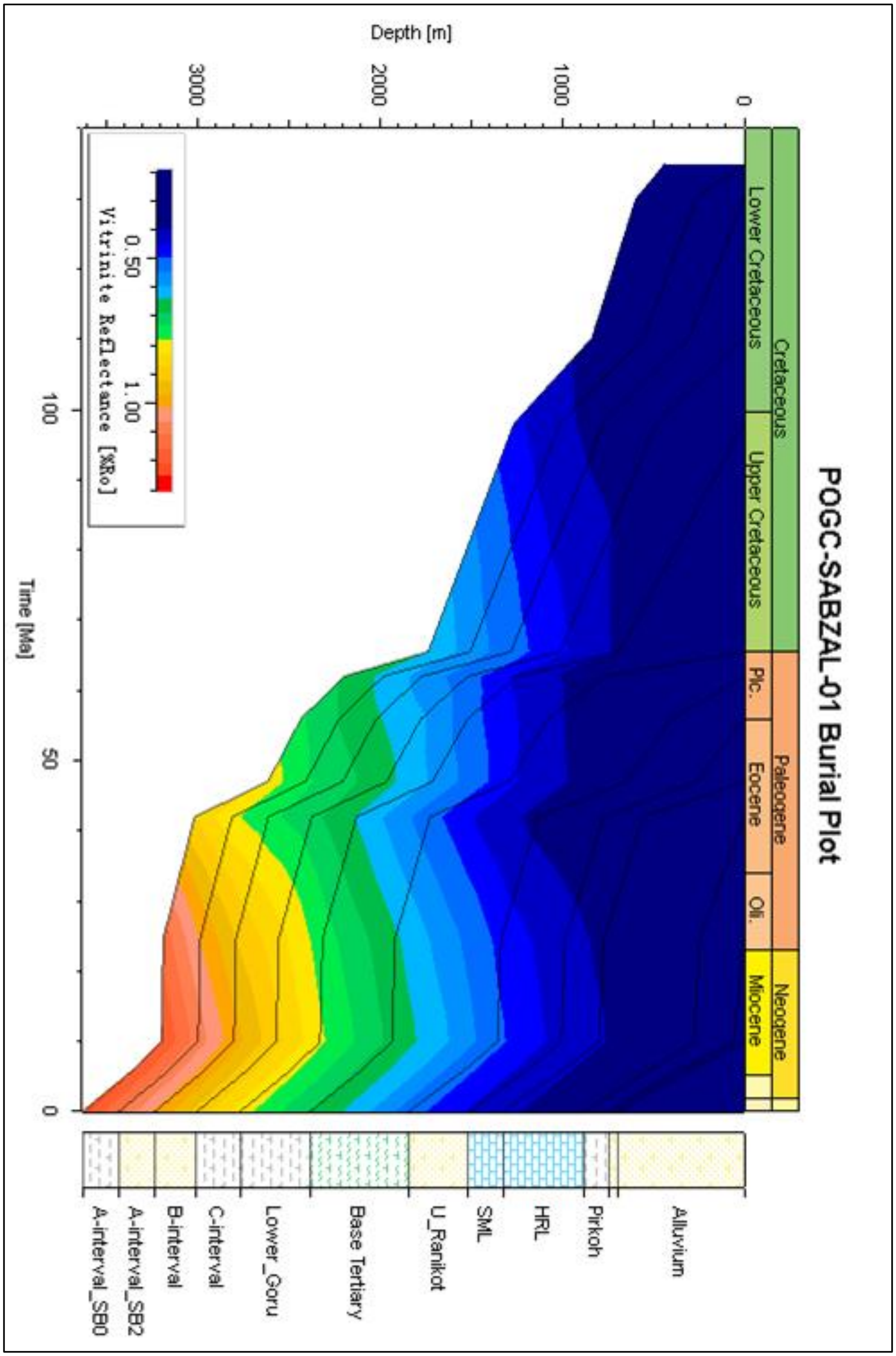

Figure 4(c): Burial Histrory and maturity plot at Sabzal-01 well.

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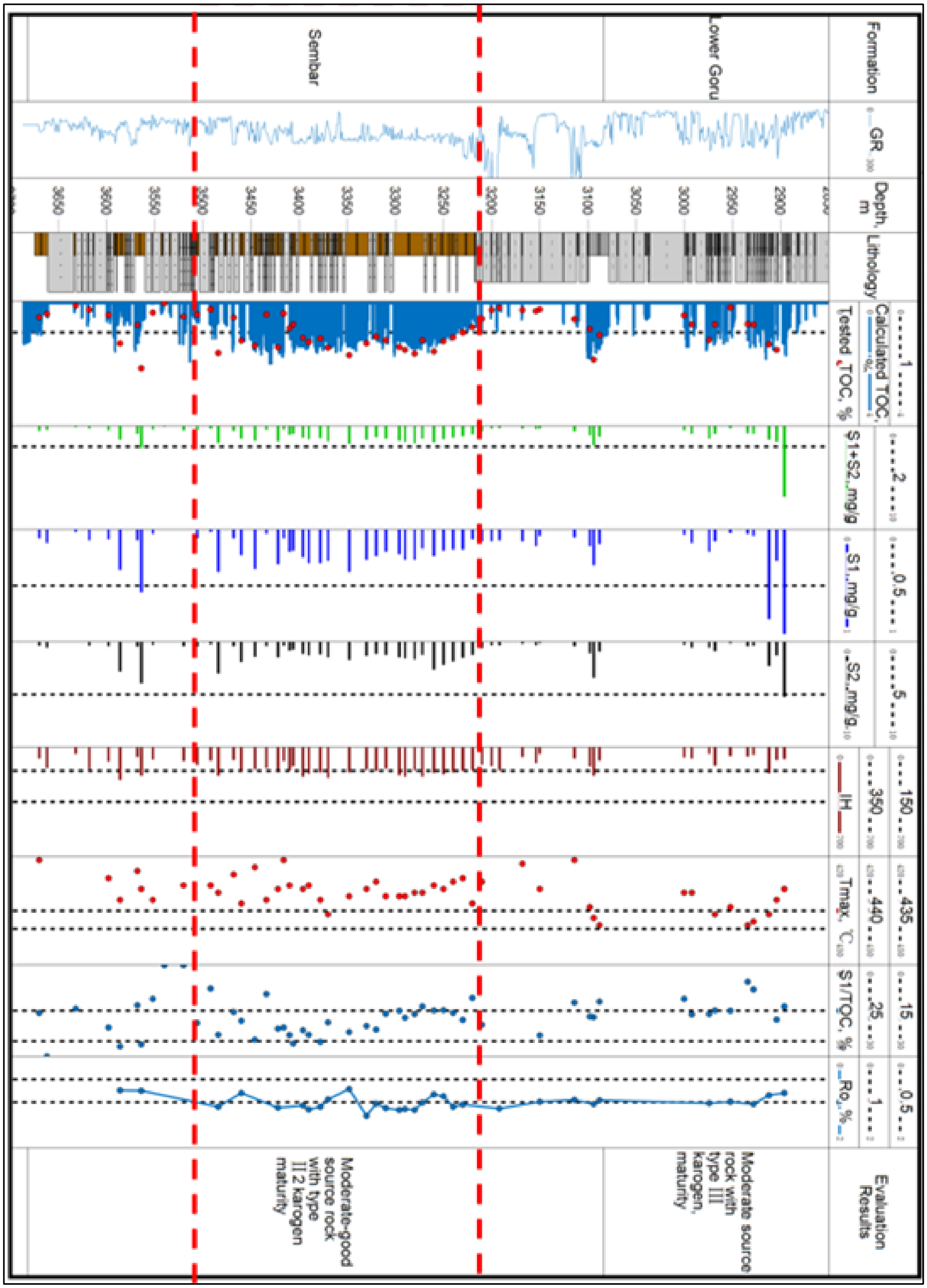

Figure 5. Geochemical profiling of source rock evaluation for Maluk-1

Table 2. Summary of TOC and Pyrolysis results from 3 wells from study area.

Formation	Lower Goru						Sembar					
Wells	TOC Range (%)	S1+S2 mg/g	HI mg/g	Avg. TOC (%)	Avg. S1+S2 mg/g	Avg. HI mg/g	TOC Range (%)	S1+S2 mg/g	HI mg/g	Avg. TOC (%)	Avg. S1+S2 mg/g	Avg. HI mg/g
Sara-01	0.20-1.22	0.11-2.75	29-211	0.8	1.1	114.0	0.23-2.14	0.53-10.33	87-453	1.2	2.6	175.0
Maluk-01	0.20-1.56	0.14-3.10	44-167	0.9	1.0	80.0	0.06-2.15	0.08-4.52	42-209	0.9	1.3	133.0
POGC Sabzal-01	0.21-3.0	0.02-3.71	5-287	1.0	1.5	115.0	0.53-0.95	0.22-1.22	23-98	0.7	0.6	33.0

Table 3. Hydrocarbon generation potential from Early Cretaceous source rock scenarios based on the variations of vitrinite reflectance data and depth of oil and gas window and generation

Maturity Scenario	Low Intensity	Medium Intensity	High Intensity
Ro range	1 - 1.2	1.2 - 1.5	1.7 – 1.95
Depth (m) of oil window	2600-2700	2500-2600	2200-2300
Depth (m) of dry gas window	3700-3800	3300-3400	3000-3100
Generation Potential (bcf/Km2)	10-20	60-80	140-160

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5. DISCUSSION

The laboratory measurements in 3 wells and calibrated logs data modeling of 11 wells of the source rock for Early Cretaceous Sembar and Lower Goru Formation have established the presence of reasonably good TOC in both horizons. To resolve the complication, which arises from the two different laboratories' Ro data of Maluk-1 and POGC Sabzal-1, we have preferred to apply the middle point case to predict the most optimal case maturity model and also used for assessing the gas generation volumes in the study area, (Table 3 & Figure 3d)

The study area is located towards the northern flank of the Mari Kandhkot High, where depth at the Cretaceous level increases more than its southern flank. Hence, the eastern part of the study area becomes shallower. The formation seems to have been deposited under open marine environmental conditions (Quadri & Shuaib, 1986). East-west cross-section (Figure 6) of wells Jiwanwala-1, Chak 255-1, Maluk-1, POGC Sabzal-1, and Qadirpur Deep-1, displaying the lateral distribution of the Sembar and Lower Goru formations. Sembar Formation is absent in the easternmost Jiwanwala-1, whereas the westward thickness of this formation increases and exceeds 600m. The Sembar Formation also deepens from east to west, and in Qadirpur Deep-1 was encountered below 4050m, whereas the relatively older Jurassic Chiltan Formation was at 1650m in Jiwanwala-1.

Based on Ro data of POGC Sabzal-1 (Ro 1.4% -1.8%) and Maluk-1 (Ro 0.71%-1.1%), maturity increases westward from early oil to gas (Figure 3). Considering the increasing depth of Early Cretaceous burial

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westward from 750m to more than 4500m towards north and northwestward. (Figure 7) the increasing depth trend has a significant implication for the occurrence and effectiveness of the source kitchen and generation potential, which establishes the most optimal exploration area. This area has good potential that may contribute to the generation, expulsion, up-dip migration, and accumulation of any valid trap at Cretaceous or shallower reservoirs.

The gross thickness of the Lower Goru Formation in the study area is from 700 to 1400m, whereas the thickness of the zones having TOC, 0.5% to 2%, is up to 700m thick. The eastern part of the study area has the least source potential than the central and western parts. (Figure 8)

The gross thickness of the Sembar Formation is up to 750m, whereas the thickness of the zones having TOC, 0.5 to 2%, is up to 250 thick in the central part of the area, whereas the eastern part has the least source potential (Figure 9). Ro results obtained during our study suggest that source rock maturity in the Sembar Formation has formed a significantly closer and distinct trend as observed in the structural trend vis a source rock thermal maturity increases towards the west and northwest (Figure 7 & Figure 10). The oil and gas conversion from their source kerogen was estimated to start at 90 and 125ºC, respectively, and reached its maximum limit at 175ºC and 210ºC in our study area (Figure 11). The gross thickness of the Sembar Formation is up to 750m, whereas the thickness of the zones having TOC, 0.5 to 2%, is up to 250 thick in the central part of the area, whereas the eastern part has the least source potential (Figure 9). Ro results obtained during our study suggest that source rock maturity in the Sembar Formation has formed a significantly closer and distinct trend as observed in the structural trend vis a source rock thermal maturity increases towards the west and northwest (Figure 7 & Figure 10). The oil and gas conversion from their source kerogen was estimated to start at 90 and 125ºC, respectively, and reached its maximum limit at 175ºC and 210ºC in our study area (Figure 11).

As discussed earlier, increasing maturity and depth towards the west and northwest are reflected in the intensity of oil and gas expulsion. Based on middle values of Ro (1.2%-1.5%), we have estimated that the expulsion intensity, 60 to 80 BCF/Km2 for gas and 4 to 7 million barrels (MMbbl) oil per Km2 is possible. (Table 3, Figure 12 and 13). Due to the non-availability of the wells data, the northwestern part of the study area demonstrates slightly exaggerated expulsion intensity from the source rock (Figure 12). Low and high expulsion intensity on various Ro values is summarized in (Table 3).

Several unsuccessful exploratory wells have been drilled in the north of Mari-Kandhkot high in the closer vicinity of the mature source kitchen. The well failures reasons may be attributed to the absence of effective traps in the Cretaceous and ineffective hydrocarbon migration pathway for Tertiary reservoirs..

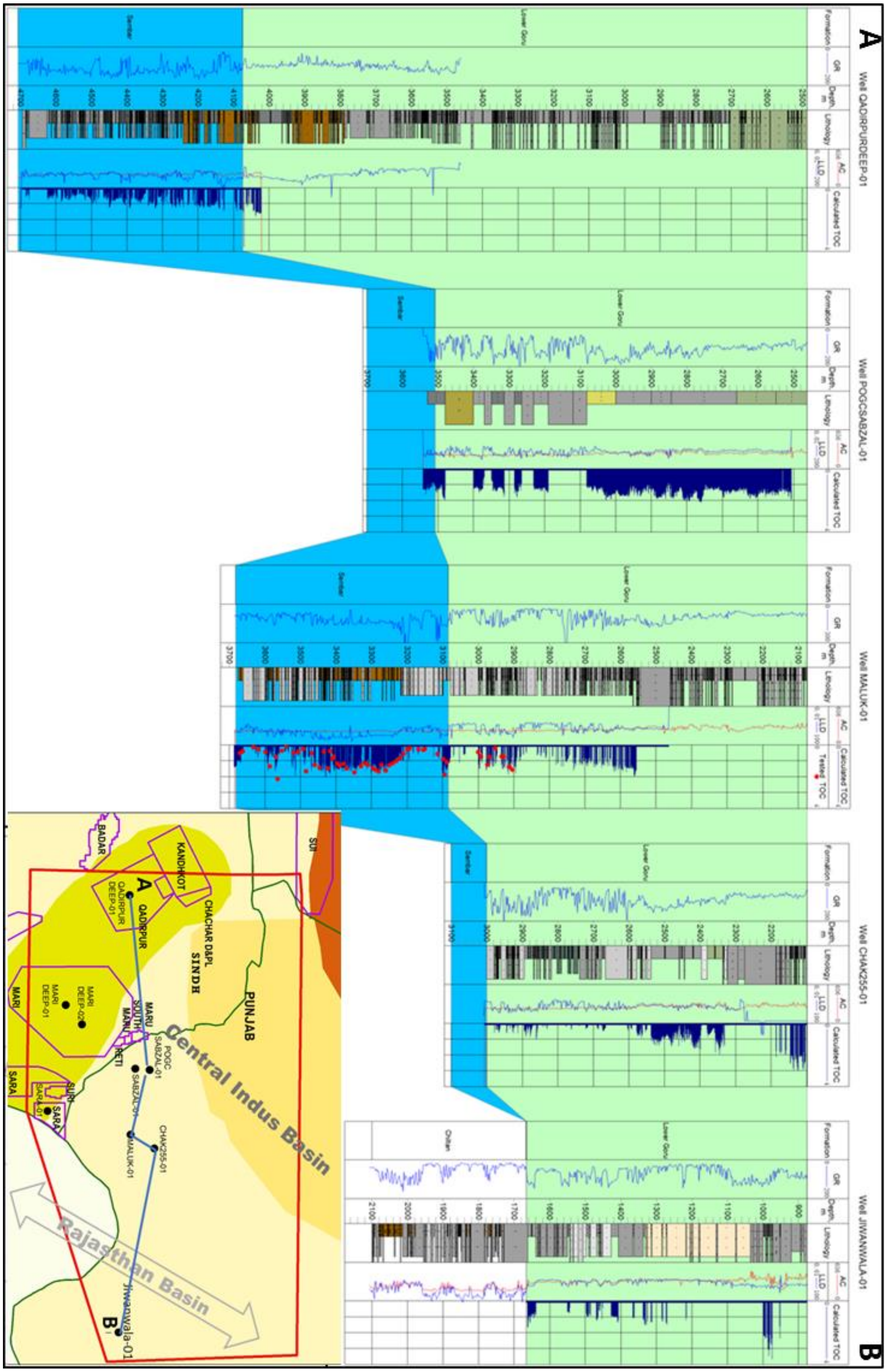

Figure 6. East West Cross-section showing distribution of Sembar and Lower Goru formations in the wells.

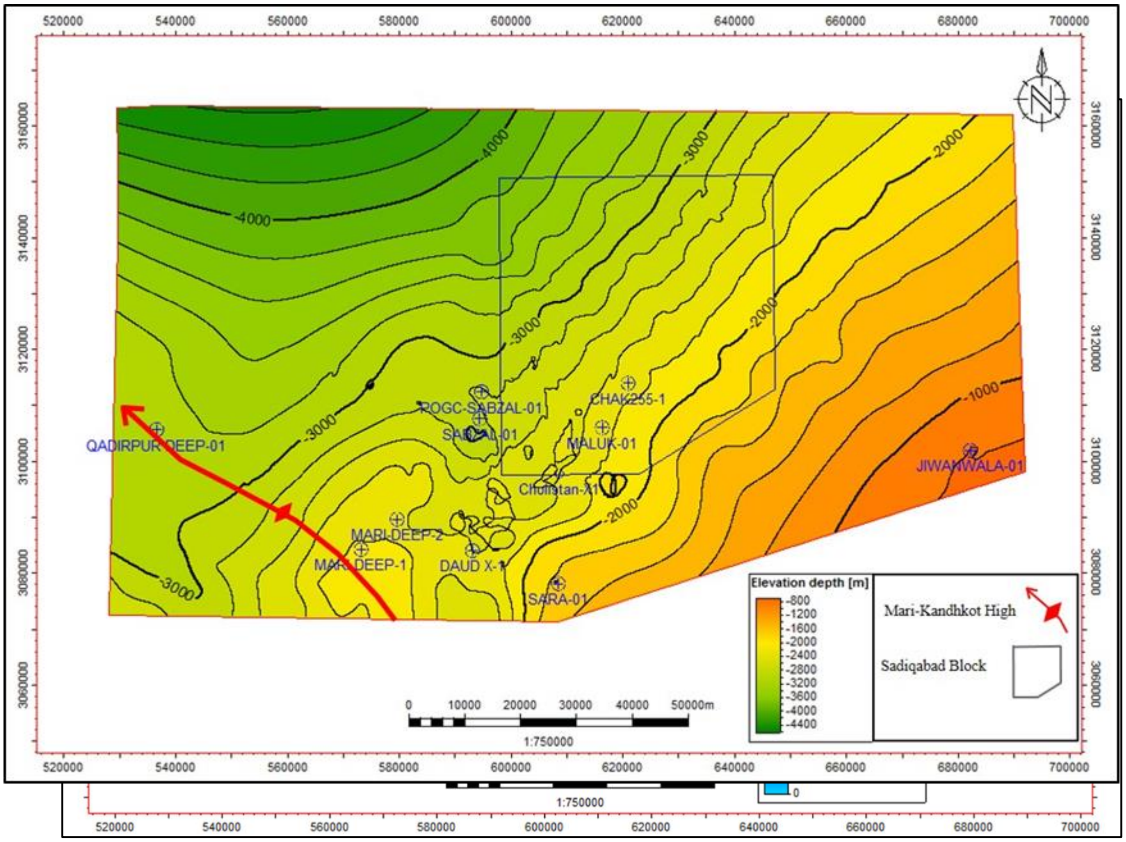

Figure 8. Lower Goru source rock thickness map for TOC (0.5-2%) overlain by gross Lower Goru thickness. (C.I: 25m).

Figure 7. Depth structure map on top of Lower Goru formation C interval of Early Cretaceous whereas pre Early Cretaceous levels structural trend remains the same. Depth increases northwestward and shallowing at eastern part of study

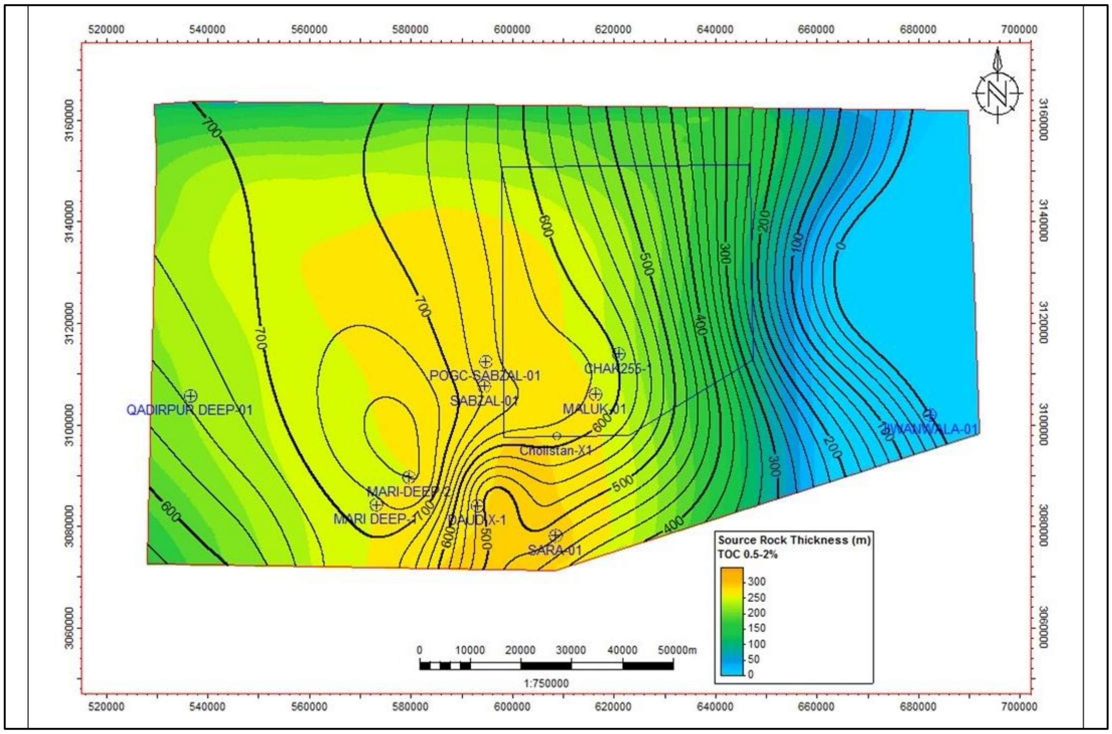

Figure 9. Sembar source rock thickness map for TOC (0.5-2%) overlain by gross Sembar thickness contours (C.I: 25m).

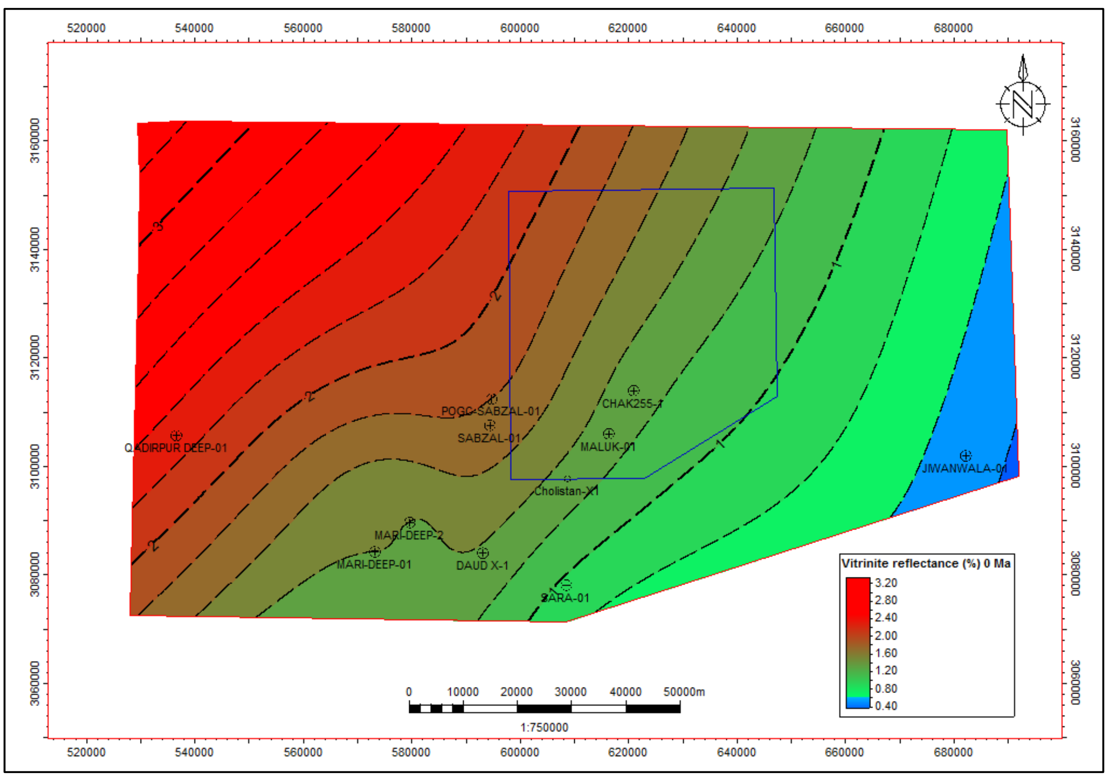

Figure 10. Map showing thermal maturity of Sembar Formation.

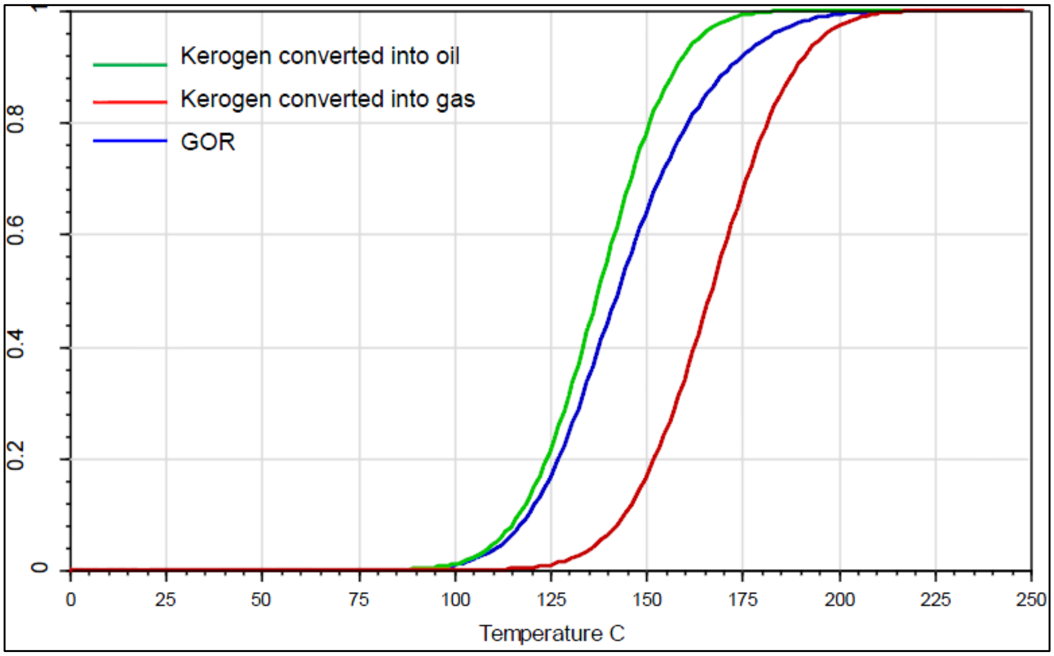

Figure 11. Hydrocarbon generation dynamics and hydrocarbon conversion curves for source rock.

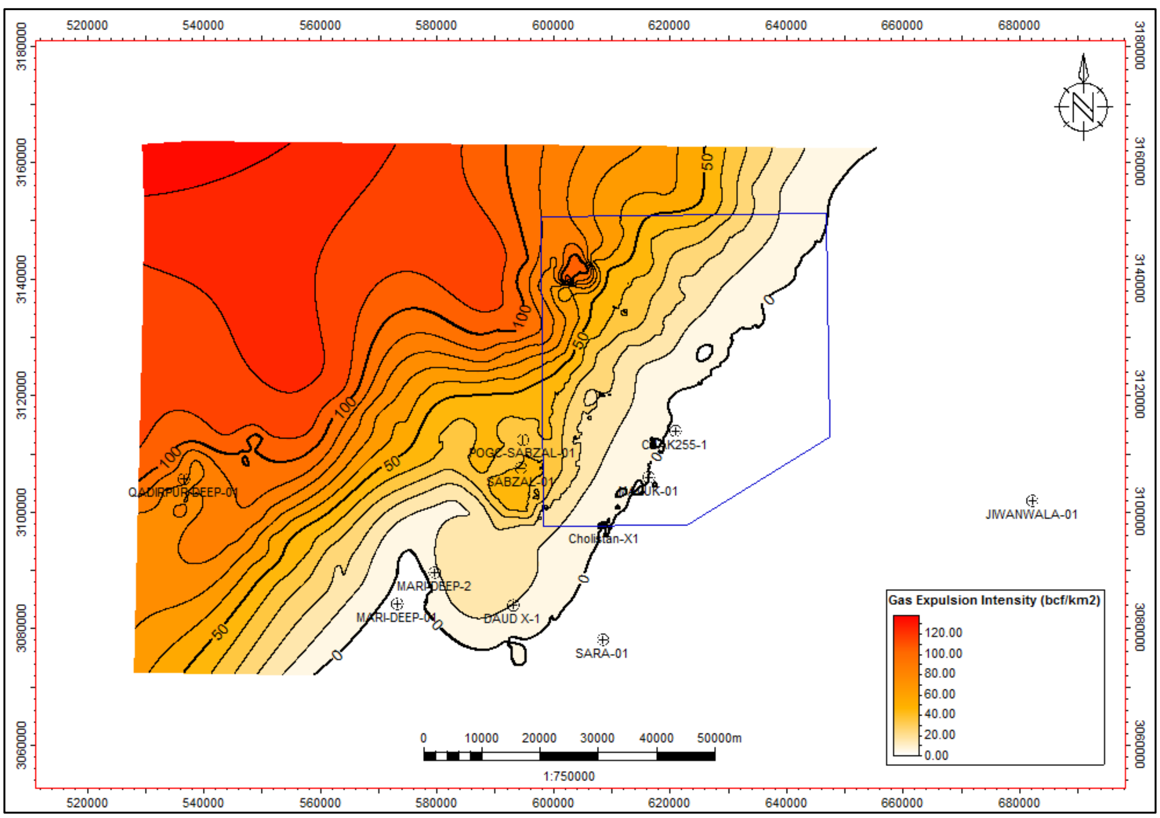

Figure 12. Gas expulsion intensity map from source rock by Time ~ 0 Mya (C.I: 10 bcf /Km2). Nearly 90% of generated gas has been already expelled out of source rock at present day. This map is based on optimized maturity data.

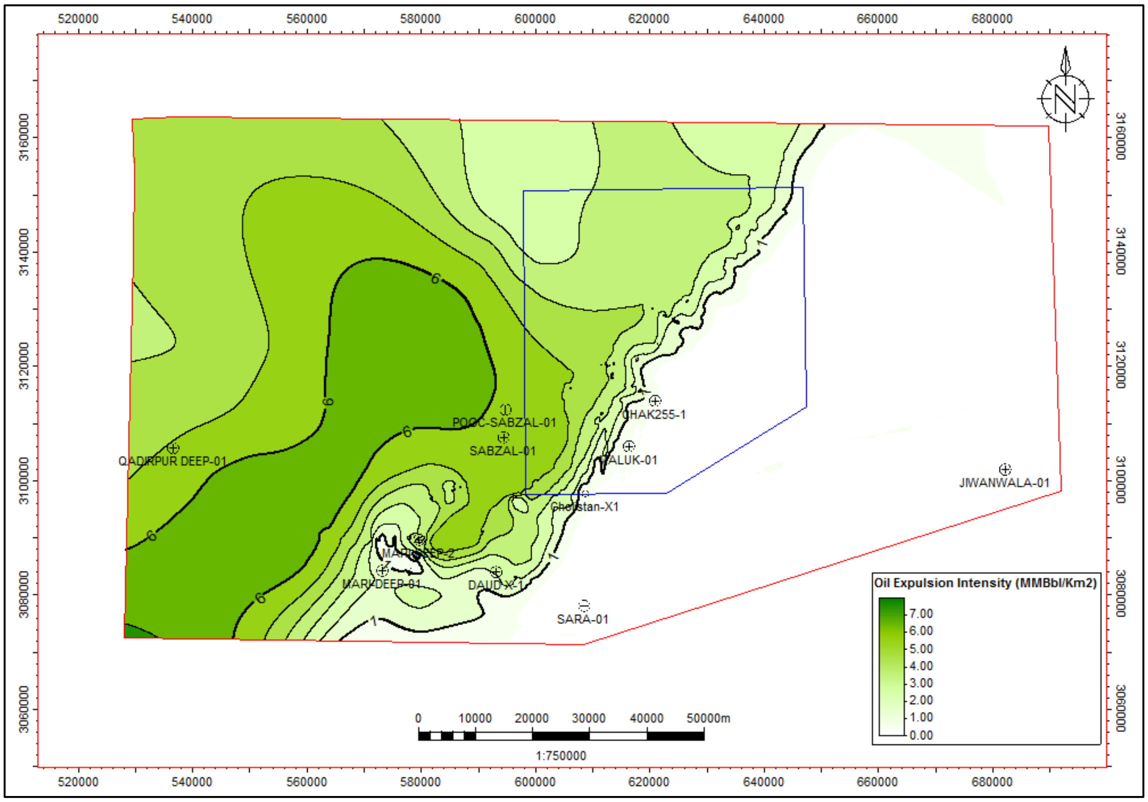

Figure 13. Oil expulsion intensity map from source rock by Time ~ 0 Mya (C.I : 1 MMbbl /Km2) The oil expelled is not very intense, Oil expulsion vs generation might be low as some oil still have been absorbed in source rock. This map is based on optimized maturity data.

6. CONCLUSIONS

The geochemical and logs evaluation analysis from samples of 10 wells of Lower Goru and Sembar Formation have shown a positive indication of the presence of thermally mature source rock, particularly in the west and northwest. Lower Goru Formation contains mainly Type III organic matter, contributing to this area's gas generation. Sembar Formation has a distinctively better prospect to be considered as a principal, and has better effectiveness, as the source rock than Lower Goru Formation, which contains mixed type II and III organic matter. The most promising area, closer to the mature source kitchen, lies in the west. In contrast, the eastern part has limited generation potential, mainly due to shallower depth where overburden did not provide an adequate thermal blanket for the source for maturation. The oil and gas conversion from their source kerogen is estimated to start at 90ºC and 125ºC, respectively, and reached its maximum limit at 175ºC and 210ºC in our study area. The area's source has an expulsion intensity of 60 to 80 BCF/km2 for gas and 4 to 7 MMbbl/Km2 of oil.

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