




# An integrated approach to evaluate the unconventional hydrocarbon generation potential of the Lower Goru Formation (Cretaceous) in Southern Lower Indus basin, Pakistan

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Southern Lower Indus basin is an oil and gas prone basin, which is important for producing hydrocarbon in Pakistan. Due to limited Rock-Eval pyrolysis data availability in the prospective shale gas basin, the organic facies geochemical characteristics study is a challenging task for researchers. The primary objective of this study is an evaluation of the Lower Goru Formation organic facies hydrocarbon potential by geochemical data and its subsurface facies distribution study by well tops and seismic data. The study area is situated at the Southern Lower Indus basin of Pakistan that is considering the prospective shale gas basin with immense unconventional hydrocarbon potential. In the present study, Rock-Eval pyrolysis data analysis along with the integration of both seismic and well tops data were conducted for investigation of source rock generation potential of organic facies variability within the Lower Goru Formation. The geochemical approaches used in the current study show that the Lower Goru Formation encountered in, bears fair to excellent total organic carbon (TOC) content values of 0.50–3.60% in Well-A and 0.10–4.69% in Well-B. Additionally, the results of Rock-Eval pyrolysis data show that interbedded shales of the Lower Goru Formation contain different types of kerogen (III, II–III, and II) with variable generation potential of oil and gas.

**Keywords.** Lower Goru Formation; organic facies; Rock-Eval pyrolysis; Geochemical characteristics; hydrocarbon potential; Southern Lower Indus basin.

## 1. Introduction

According to the US Energy Information Administration (EIA), the Southern Lower Indus basin of Pakistan bears a world's 9th highest

unconventional resource potential and it contains immense shale-gas potential (105 TCF) which is greater than the collective potential of central Asian countries (El-Sakka *et al.* 2017; EIA 2013). It is still one of the underexplored areas due to lack of

attention of researchers especially up to the level of Lower Goru Formation (Mahmoud 2015). Also, only a very few geochemical studies have been conducted (Nazir 2013). Therefore, an integrated study is required to delineate the potential unconventional targets within shales of Lower Cretaceous (Javaid *et al.* 2017).

At present, state-of-the-art technologies for petroleum exploration has opened new horizons and avenues to reveal unconventional resource potential. Both conventional and unconventional petroleum plays originate from the source rock (McCarthy *et al.* 2011). Shales are considered as the principal source rock for most of the conventional and unconventional petroleum systems. The source rock potential mainly depends upon the geochemical characteristics of organic facies present within the rock (Mani *et al.* 2015). Rock-Eval pyrolysis techniques evaluate the source rock geochemical characteristics (Han *et al.* 2017). The current study presents the detailed geochemical characteristics of the Lower Goru Formation of Cretaceous.

Petroleum system is a fundamental element in exploration of hydrocarbon (McCarthy *et al.* 2011). In a petroleum system (conventional as well as unconventional), a source rock is considered as the primary component of the geological system which is mandatory to produce hydrocarbons. Currently, the source rocks have also become an economic unconventional reservoir (Allen and Allen 2005; Løseth 2011). Therefore, without studying the source rock parameters, other geological studies of the rock are irrelevant (McCarthy *et al.* 2011).

Previous studies show that shales of Lower Cretaceous (Lower Goru Formation) have retained oil and gas potential for exploration and production in the study area which is comparable to the world's, producing shale gas reservoirs (Javaid *et al.* 2017). The Southern Lower Indus basin in Pakistan is enriched with a thick unit of Cretaceous shale acting as a source rock which bears potential to good resource play (Mahmood *et al.* 2018). In several countries, a large volume of hydrocarbon has been extracted from source rocks of Cretaceous (Nazir 2013).

Cretaceous succession is one the important stratigraphic intervals which covers around 52% sedimentary area of Pakistan and its significant part lies in the Southern Lower Indus basin (Nazir and Fazeelat 2017). Biomarkers study of Cretaceous in the study area indicates that the shale units of Lower Goru and Sembar Formations are

potential source rocks from which the hydrocarbon was generated (Nazir *et al.* 2015). In Pakistan, the Cretaceous sequence holds abundant organic matter (OM) which makes it one of the best quality source rocks. Additionally, several studies have indicated that these shales are mature for the hydrocarbon generation and their sufficient thickness has resulted in enormous amount of hydrocarbon reserves (Kadri 1995; Nazir and Fazeelat 2016).

Cretaceous sequence has a huge source rock potential to produce higher than 30,000 barrels of oil and 1200 MMCF of gas per day (Kadri 1993). In Southern Lower Indus basin, around 72% of hydrocarbon production comes from the Cretaceous rocks (Ehsan *et al.* 2018a, b). The hydrocarbon generation potential of the source rock in the study area remains chiefly unidentified due to limited data availability in shales, because in the past, wells were typically drilled at the structural highs to explore conventional resources only (Ahmed *et al.* 2014). Lower Goru Formation is extensively studied by many researchers for conventional reservoir play, but its unconventional resource potential is still unexplored.

The main focus of the current research is on the source rock potential of the Lower Goru Formation and subsurface geological structures using geochemical and seismic data to get a better understanding of hydrocarbon play to increase exploration activity in the study area. Identification of the source rock potential is one of the leading challenges in the Southern Lower Indus basin. Obtaining geochemical data for research purposes is one of the main problems as such dataset are highly confidential or quite expensive to purchase. These are some of the fundamental constraints that has hindered source rock potential evaluation in the study area.

## 2. Geological setting

Pakistan bears moderate potential of recoverable resources of 51 TCF of shale gas of marine origin within the Southern Lower Indus basin (Naseer and Asim 2017). During the Jurassic–Lower Cretaceous, rifting of the Indian Plate from Gondwanaland occurred, which lead to geological structures of the Lower Indus basin (Patriat and Achache 1984). The Southern Lower Indus basin was located on the passive margin setting during the Mesozoic period. The Lower Goru Formation

members consist of sandstone and shale. It was deposited during the Aptian–Albian time in shelf to shallow marine condition under the oxic condition, and the source of sediment supply was uplifted Indian Shield, Jacobabad–Khairpur high and Mari-Khandkot high (Smewing *et al.* 2002; Huang *et al.* 2005).

Tectonic history evidence in the study area fault systems were developed in two different phases of rifting names; the first phase was the Middle to Late Jurassic Kutch rift and the second phase, Upper Cretaceous Cambay rift developed Horsts and Graben's geometry, which were responsible for the accumulation of hydrocarbon in the Southern Lower Indus basin. Hydrocarbon production in the Lower Goru Formation is from mostly fault-bounded structural traps (Memon and Siddiqui 2005). The interbedded shale beds of both Upper and Lower Goru Formations act as a regional seal to Cretaceous reservoirs. The regional north–south trending Jacobabad–Khairpur high in the north of the Southern Lower Indus basin has developed the trapping mechanism in the study area (Berger *et al.* 2009) as illustrated in figure 1.

In the Lower Goru Formation, shale bearing zones with higher values of total organic carbon (TOC) and lower clay contents lie in the close proximity of fault system which is promising for the exploration of unconventional hydrocarbon play (Mahmood *et al.* 2018). Indus basin of Pakistan contains the Cretaceous rocks which are deposited in deltaic to reducing marine environment (Sheikh and Shahid 1999). Marine shales have higher quartz content which will result in increase in brittleness that facilitates the permeability of the reservoir (De Silva *et al.* 2015; Cardott 2012).

The Lower Goru Formation mainly comprised of fine- to coarse-grained sandstone with interbedded shale and siltstone units (Mohsin *et al.* 2010; Munir *et al.* 2011). The formation is further divided into six units including Massive Sand, Talhar Shale, Basal Sand, Lower Shale, Middle Shale and Upper Shale (figure 2, Siddiqui 2016). Lithostratigraphic columns shows the rock units encountered in (a) Well A and (b) Well B (figure 3). These lithological units have porosity which commonly ranges between 5% and 30%. Due to diagenesis, there was a significant loss of the primary porosity within the Massive Sand and Talhar Shale units of the formation. The petrographic studies clearly indicate that the secondary porosity within the formation exists due to dissolution of detrital grains and

authigenic cements (Mohsin *et al.* 2010). Also, Massive Sands are considered as potential candidate for the generation of unconventional hydrocarbon due to the lower permeability (<0.1 md). Depositional sequences present in the formation include several depositional facies such as shoreface barrier bar sands, shoreface tidal channels, Deltaic distributary channel and mouth bar sands, Deltaic heterolithics sands, transgressive tidal channel sands, bioturbated or current-laminated sands, outer shoreface to offshore siltstone-mudstone, offshore mudstones and pelagic shales, slope and base-of-slope sandstone–siltstone, transgressive argillaceous sandstone and transgressive mudstone (Ahmad *et al.* 2004; Ashraf *et al.* 2019, 2020).

In Southern Lower Indus basin, Cretaceous strata lithology is composed mostly sandstone, shale, silt, marl, and limestone (figure 4). On the western side of the basin, predominant lithologies are shale and siltstone and thickness of these units decreases towards the east side. Sandstone is more dominant on the eastern side of the basin (figure 5; Zaigham and Nayyar 2010). Sembar Formation is a leading source rock which is mainly of composed shale, sandstone, silt, and thermally mature on the west side of the basin due to deep burial and less mature towards the east side. In the study area, Lower Goru Formation is a principal reservoir with predominant lithologies that are sandstone lithology with intercalations of shale beds. These shale beds are moderately rich in organic content which can produce oil and gas. Upper Goru Formation is mainly composed of shale, marl, and sandstone. It is organic-rich, but thermally immature and provides a regional seal for underlying Lower Goru Formation (Quadri and Shuaib 1986; Robison *et al.* 1999; Zaigham and Mallick 2000; Wandrey *et al.* 2004; Nazir and Fazeelat 2017).

### 3. Methodology

The hydrocarbon generation potential is dependent upon geological history, sedimentary facies, and burial history of the sedimentary basin (McCarthy *et al.* 2011). Geological data is helpful to understand the geological settings of the basin while seismic data provides information about geological variation in formations. Well logs and seismic data are used worldwide to get information about reservoir properties and subsurface structural traps. Hydrocarbon potential is commonly determined using geochemical data. An integrated

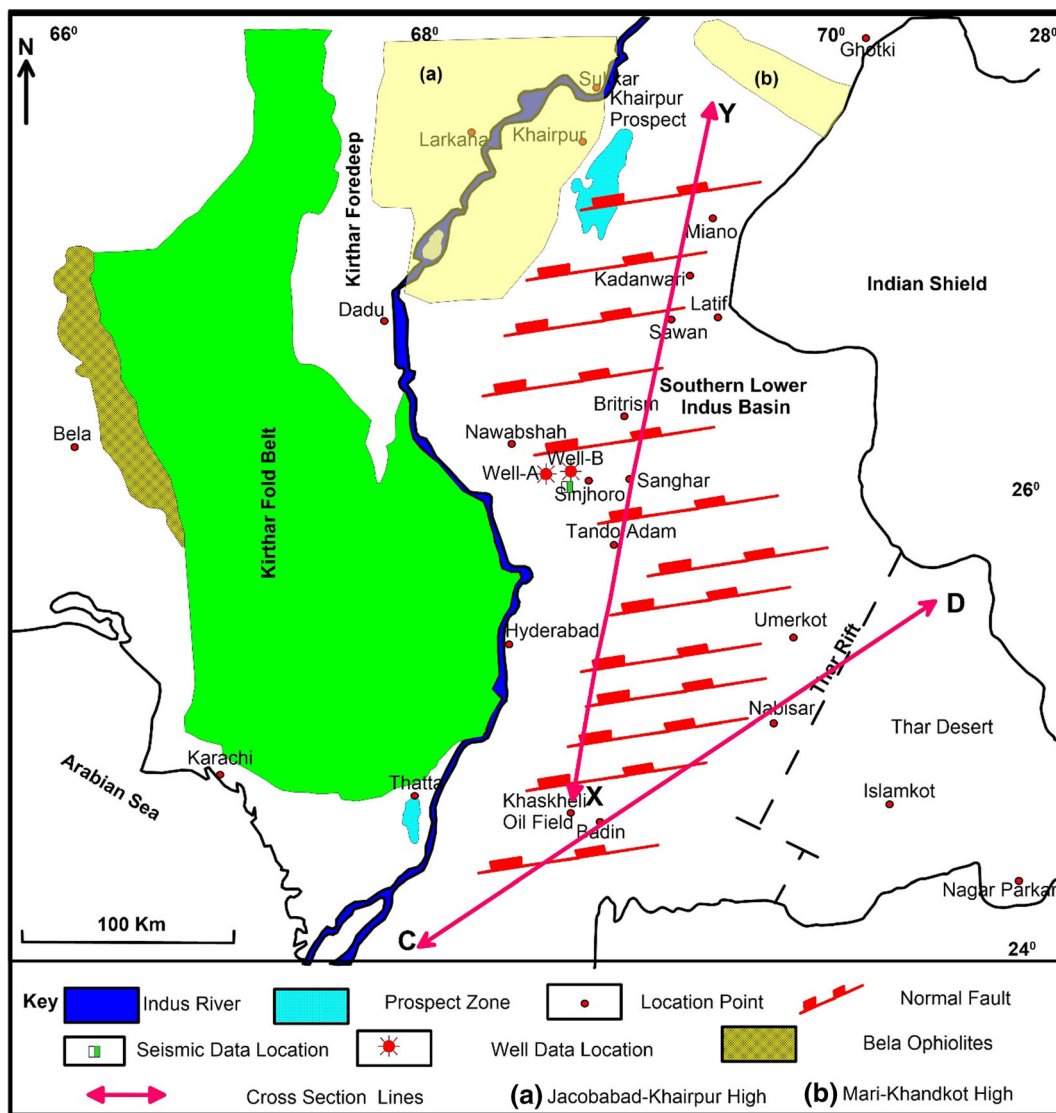


Figure 1. Geological map showing location of Wells A and B in the Southern Lower Indus basin, Pakistan (modified after Zaigham and Mallick 2000).

approach is quite helpful to study the hydrocarbon-bearing structures and generation potential of organic facies. In the present study, the hydrocarbon generation potential of Lower Goru Formation using geological, seismic, and geochemical data.

Using Rock-Eval pyrolysis technique, different direct geochemical parameters including total organic carbon (TOC%) content, pyrolysis temperature ( $T_{max}$ , C°), distillable hydrocarbons present in rock ( $S_1$ , mg HC/g of rock), hydrocarbons generated from pyrolysis of kerogen ( $S_2$ , mg HC/g of rock),  $CO_2$  generated from kerogen pyrolysis ( $S_3$ , mg of HC/g of rock),  $S_2/S_3$ , hydrogen index (HI), oxygen index (OI), generation potential (GP) and production index (PI) were computed. These parameters play an important role in evaluating

the hydrocarbon generation potential of source rocks. The type of kerogen has a significant role in studying hydrocarbon potential of organic facies is also determined using these geochemical parameters.

Well data including well tops at least up to the level of Lower Goru Formation was incorporated in the present study. Also, only those geochemical dataset of the selected wells were used which provide information about TOC,  $S_1$ ,  $S_2$ ,  $S_3$ , and  $T_{max}$ . Geological information was retrieved from the provided maps of Geological Survey of Pakistan (GSP) and other published literature about the study area. Geochemical dataset were obtained from Oil and Gas Development Company Limited (OGDCL), Pakistan for research purposes.

Age		UTP	OGDCL	ENI	OMV/BG	TULLOW	
Late Cretaceous	Goru	'A' Sand	Layer-1	Shale Out			Lower Goru
		Turk Shale	Layer-2				
		'B' Sand	Layer-3				
		Badin Shale	Layer-4				
		'C' Sand	Layer-5				
		Jhol Shale					
		'D' Sand					
Early Cretaceous	Lower	Upper Shale	Upper Sand	'H' Sand	No Significant Sand Body	Lower Goru	
		Middle Sand	Middle Sand	'G' Sand	'C' Sand		
		Lower Shale		'F' Sand			
		Basal Sand	Basal Sand	'E' Sand	'B' Sand		
		Talhar Shale		'D' Sand			
				'C' Sand			
		Massive Sand		'B' Sand			'A' Sand
Late Jurassic	Sembar	Sembar	'A' Sand Sembar	Sembar	Sembar	Pariwar	
Middle Jurassic			Takatu (Obsolete Name Chiltan)			Badesar	
						Baisakhi	

Figure 2. Nomenclature used popular exploration and production companies for the members of Lower Goru Formation (Siddiqui 2016).

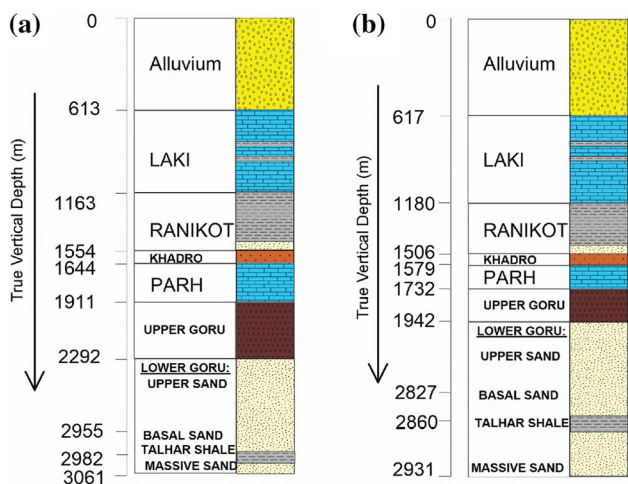


Figure 3. Lithostratigraphic columns showing the rock units encountered in (a) Well A and (b) Well B.

In order to validate the present study, few geochemical parameters and general geology data collected through a literature survey of the study area

(Quadri and Shuaib 1986; Zaigham and Mallick 2000; Ahmed and Chaudhry 2002; Smewing *et al.* 2002; Ahmed *et al.* 2004; Huang *et al.* 2005; Carmichael *et al.* 2009; Berger *et al.* 2009; Shah 2009; Mohsin *et al.* 2010; Sahito *et al.* 2013; Zulfiqar *et al.* 2013; Nazir *et al.* 2015; Naeem *et al.* 2016). Additionally, the previously obtained geological data was incorporated to develop a geological map and stratigraphic column of the study area as illustrated in figures 1 and 4, respectively.

Well correlation is a reliable technique used to determine a relationship between bed boundary, lithology and to develop geological and stratigraphic models to reduce the risk of target well location (Li *et al.* 2004). In the current study, the well formation tops data was utilized to determine the distribution of different formations in the study area by plotting well coordinates data on Google Earth.

A stratigraphic column of the study area was developed using the formation tops details of the previously drilled well as well as the geological time



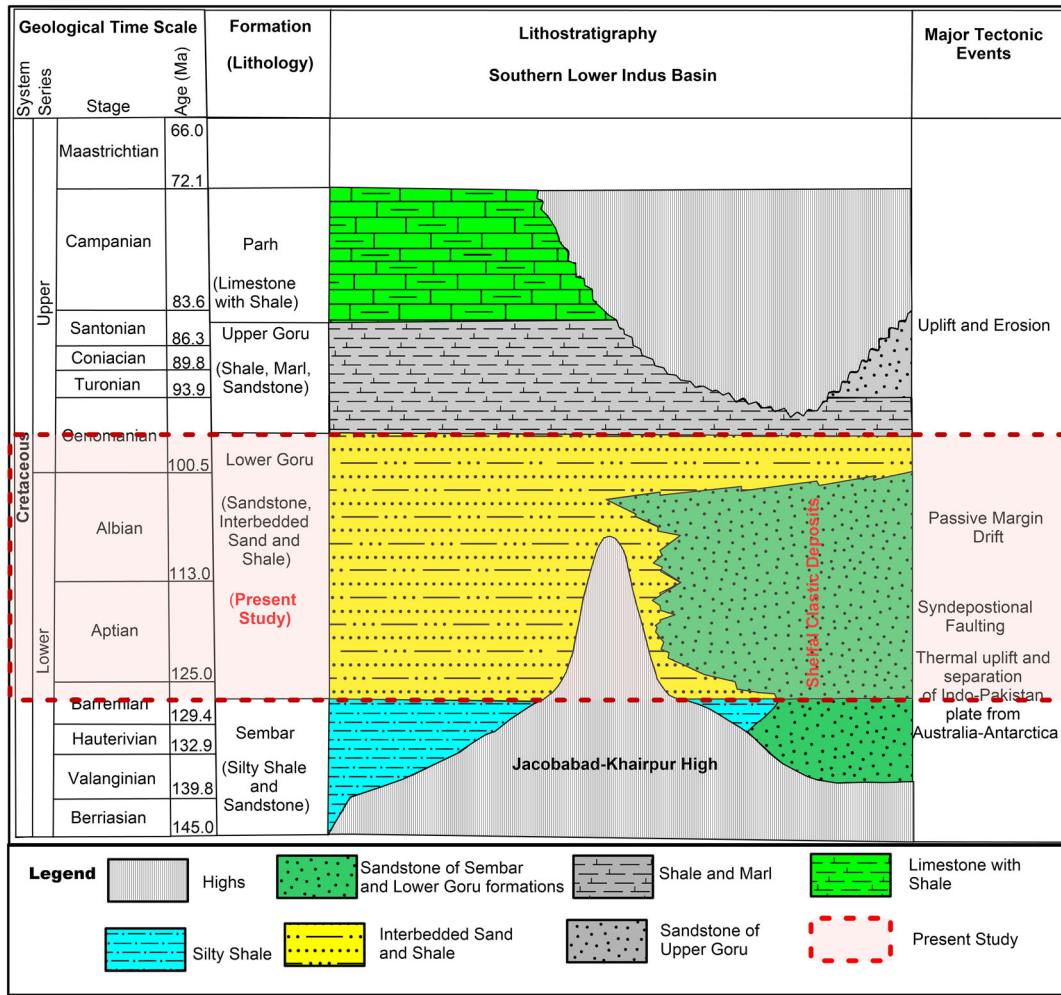


Figure 4. Cretaceous system stratigraphic column of the study area with major tectonic events in the context of the geological history of the basin (modified after Smewing *et al.* 2002).

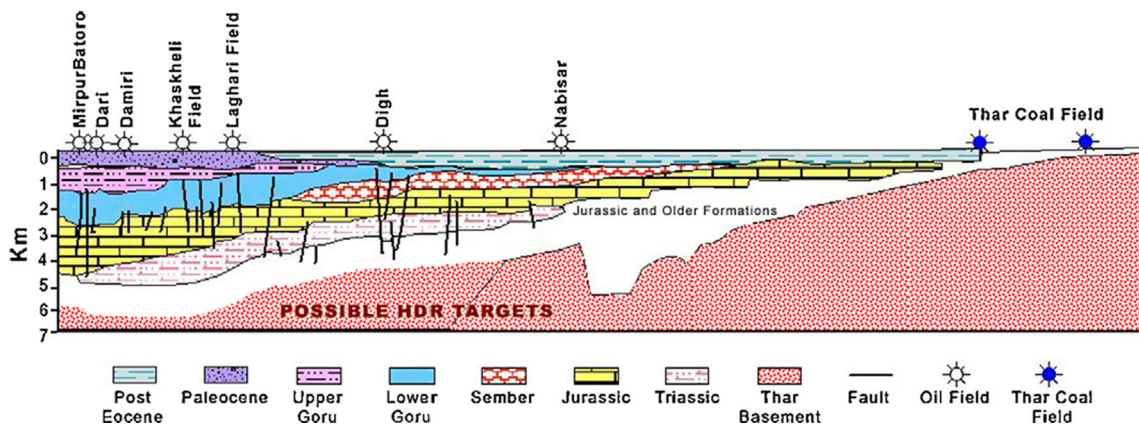


Figure 5. Geologic structural cross-section of Southern Lower Indus basin along the cross-section C-D (figure 1) (Zaigham and Nayyar 2010).

scale reported in Cohen *et al.* (2013). Major tectonic events were added in the context of the geological history of the basin. Also, a systematic evolution model of the Lower Goru Formation was

developed in the framework of the geological literature of the basin. Additionally, a post-stacked time seismic section from Sinjhoru block petroleum concession was used for seismic structural

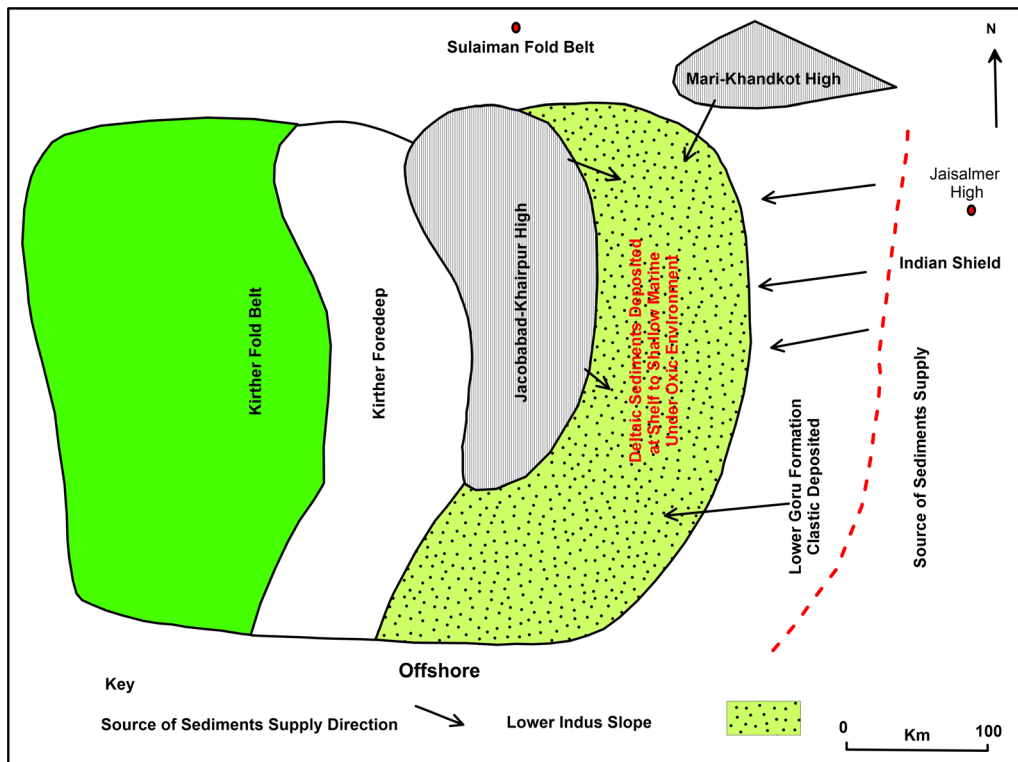


Figure 6. Evolution of the Lower Goru Formation (during Aptian–Albian) and its depositional environment indicates the source of sediments supply was Indian shield (east) and uplift of highs in north (modified after Smewing *et al.* 2002).

description as illustrated in figure 7 adopted from Naeem *et al.* (2016).

The source rock hydrocarbon generating potential is directly associated with organic richness, thermal maturity, and gross volume of the rock (McCarthy *et al.* 2011). Rock-Eval provides organic geochemical data, which are utilized in the petroleum industry to evaluate source rock hydrocarbon potential (Hart and Steen 2015). Organic matter type was determined from Espitalie *et al.* (1984). In the present study, at Well A, available core cutting samples ( $n = 29$ ) of Lower Goru Formation which was encountered at the depth interval of 2550–3192 m were used to evaluate geochemical parameters. The well cutting samples were 2 m in thickness. Also, at Well B, core samples ( $n = 119$ ) of the Lower Goru Formation (1940–3000 m) of variable thickness were utilized. At first, different geochemical parameters including TOC,  $S_1$ ,  $S_2$ ,  $S_3$ , and  $T_{max}$ , were evaluated, which were later used to compute other parameters such as HI, OI, PI, and GP. Vitrinite reflectance ( $R_0$ , %) using relationships described in Jarive *et al.* (2001) such as given in equation (1).  $R_0$  is considered as most widely

accepted and reliable method used to determine the organic maturity of the rock samples (Hakami *et al.* 2016).

$$R_0(\%) = (0.018 \times T_{max}) - 7.16. \quad (1)$$

Generation potential (GP) data are commonly used to classify the source rocks on the basis of two main approaches. Using one approach, source rocks are classified into oil or gas prone facies which is based on Ehinola and Zhu (2008) classification. Secondly, the rocks are categorized into poor to an excellent hydrocarbon generation potential using another approach reported in Hunt (1996). Both these classifications are based on numerical values of GP. These classification schemes were also employed in the present study to evaluate generation potential of Lower Goru Formation as a source rock.

#### 4. Results and discussions

The following section will address each of the parameters and techniques employed in the current study to estimate unconventional resource



potential of the Lower Goru Formation in the Southern Lower Indus basin.

#### 4.1 Geological parameters

Tectonic setting of a basin is a major controlling factor of the source rock geochemistry (Sam 2009). Southern Lower Indus basin is an extensional type basin. During upper Jurassic to Cretaceous, extensional activity was at its peak, and continental break-up tectonic configuration was favourable for deposition of the source rock in the basin. The study area is located on the passive margin (or rifted continental margins) setting, and sediments were most probably deposited on the shelf, slope and marine condition. Uplifted basin sediments were not much transported and deposited nearby interior basins. Evolution model of the Lower Goru Formation during Aptian–Albian is illustrated in figure 6, and its depositional environment indicates the source of sediments supply was Indian Shield (east) and highs (north).

The stratigraphic column representing rock units of Cretaceous present in the study area is illustrated in figure 4. Sembar Formation was deposited in an open marine setting and mainly comprised of silty-shale and sandstone. The silty shale is organically mature, and act as a principle source rock which has charged the Cretaceous reservoir rocks. Sandstone was deposited under shelf condition that has produced both oil and gas according to HDIP (2012). Also, the same findings about Sembar Formation were described in Nazir *et al.* (2012) and it also supports the results obtained from the current study.

Lower Goru Formation is mainly composed of sandstone with interbedded shale. It has produced both oil and gas in the Southern Lower Indus basin and deposited in a passive margin setting. Upper Goru Formation is comprised of shale, marl, and sandstone and acts as a seal rock underlying Lower Goru Formation reservoir. Parh Formation has mainly composed limestone with shale.

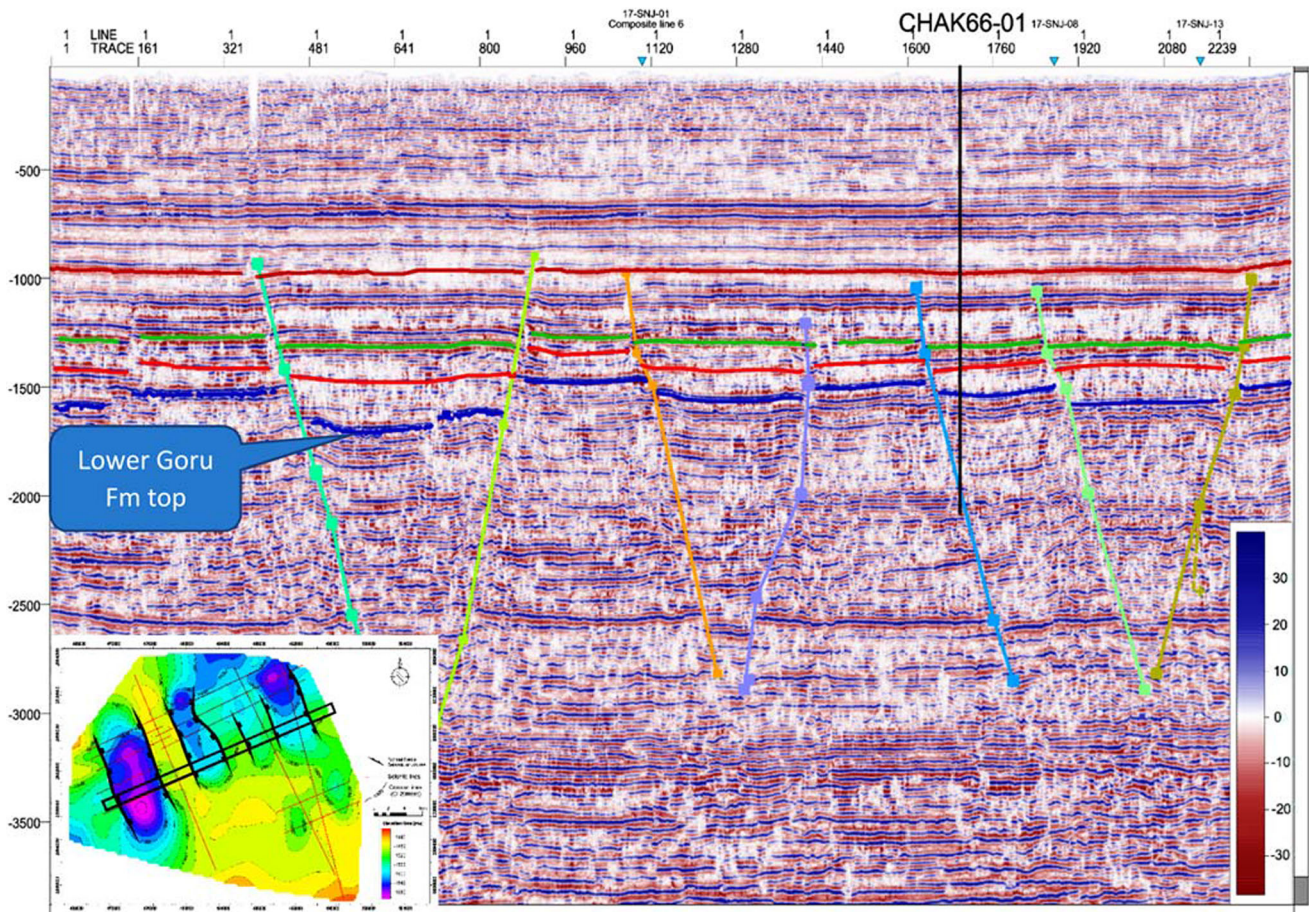


Figure 7. Time-migrated seismic line 20017-SNJ-03 (figure 1) indicating identified horizons and faults (Naem *et al.* 2016).



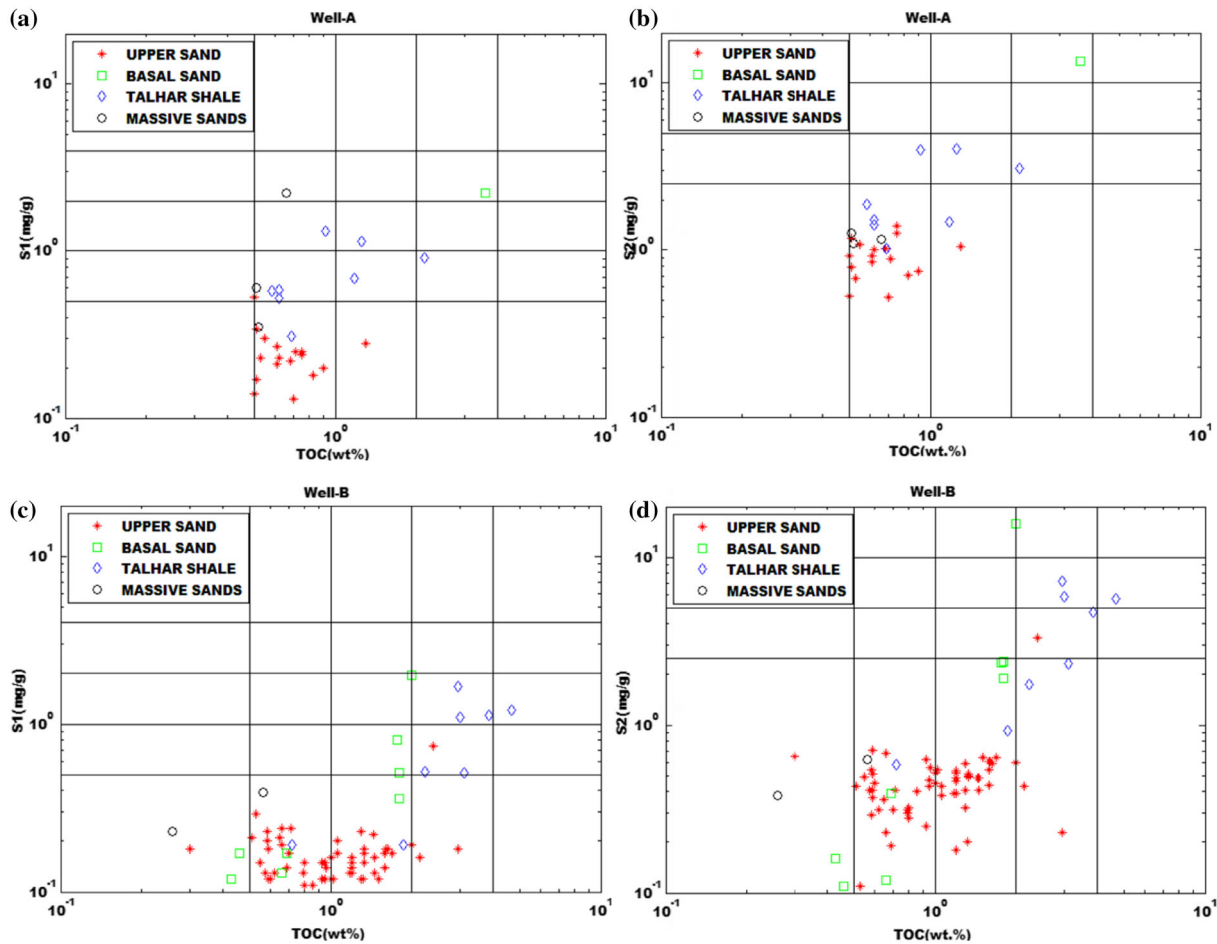


Figure 8. Quantitative and qualitative evaluation of organic matter (OM) in the Lower Goru as a source rock: (a) Plot of  $S_1$  (mg/g) against TOC (%) at Well A, (b)  $S_2$  (mg/g) vs. TOC (%) at Well A, (c) Plot of  $S_1$  (mg/g) against TOC (%) at Well B, and (d)  $S_2$  (mg/g) vs. TOC (%) at Well B.

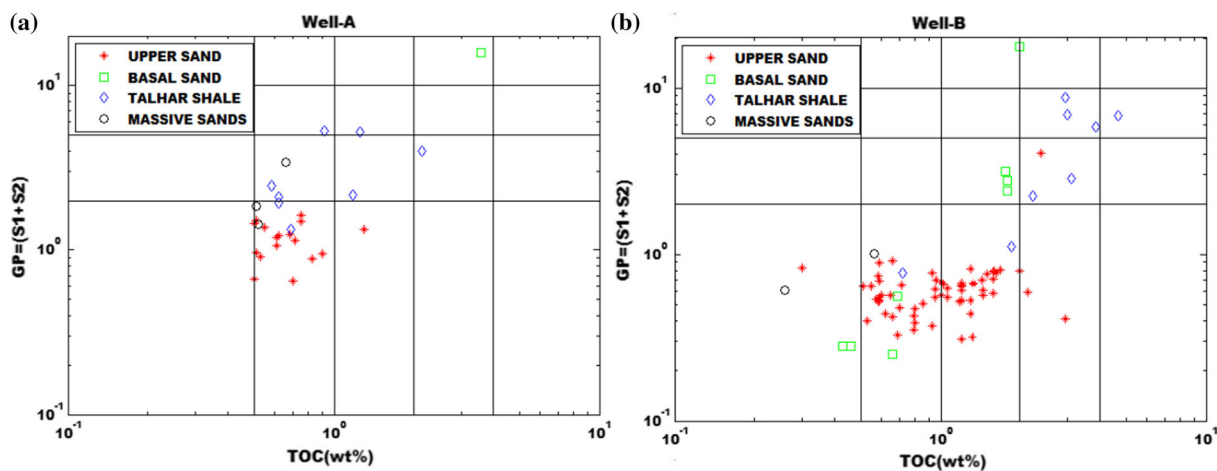


Figure 9. Plot of generation potential (GP) vs. TOC (%) in Lower Goru Formation at (a) Well A and (b) Well B.

The major episode of significant erosion and uplift reported in the study area during Upper Cretaceous. During the Santonian to Danian

(86.3–61.6 Ma), Mughal Kot, and Pab Formation were eroded in the southeastern part of the basin, but these formations are present in the Kirthar

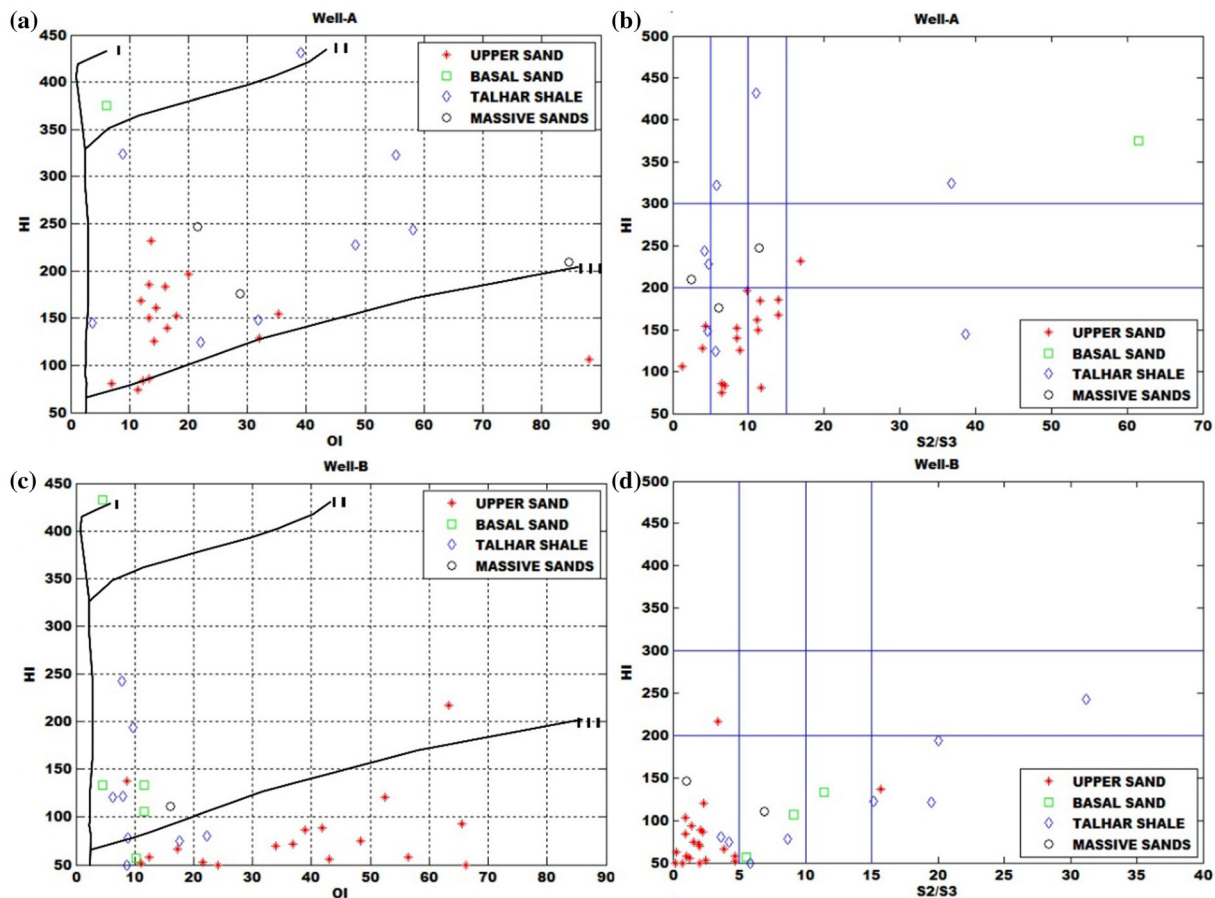


Figure 10. Identification of kerogen types of Lower Goru facies by cross plot analysis: (a) HI vs. OI at Well A, (b) HI vs. S<sub>2</sub>/S<sub>3</sub> at Well A, (c) HI vs. OI of Well B, and (d) HI vs. S<sub>2</sub>/S<sub>3</sub> at Well B.

Fold Belt (Wakefield and Monteil 2002). Another evidence of such activities are the uplift and erosion, which took place as the Indian Plate pass over hot mantle spot and Deccan related uplift and erosion events (Smewing *et al.* 2002; Huang *et al.* 2005). Several other studies including Ahmed and Chaudhry (2002) have reported significant erosion in the study area.

#### 4.2 Subsurface structural interpretation

Reflectors were identified on the basis of prominent adjacency of reflectors from the subsurface interfaces on the seismic lines (Ashraf *et al.* 2016). Using the well tops information at the selected well and generalized stratigraphy of the study area, Lower Goru Formation was marked on the seismic section (Naeem *et al.* 2016). Additionally, faults were identified on the basis of discontinuity in the reflections. Seismic interpretation results indicate that the presence of normal faulting with horst and graben geometry, which is favourable for hydrocarbon entrapment is illustrated in figure 7.

#### 4.3 Rock-Eval pyrolysis data analysis

##### 4.3.1 Source rock quality and quantity

Total organic carbon (TOC) content is used to measure the quantity of organic matter (OM) present in the source rock samples (Peters *et al.* 2005). In general, if its values are high, then we say better source potential of rocks. S<sub>1</sub> and S<sub>2</sub> values are used to characterize source rocks and evaluate the productive hydrocarbon potential of the source rocks, respectively (Peters 1986).

Rock samples were taken between the depth intervals of 2550 and 3192 m from the Upper Sand (2550–2942 m), Basal Sand (2980–2982 m), Talhar Shale (2990–3062 m), and Massive Sand (3110–3192 m) members of the Lower Goru Formation at Well-A. Cross plot of TOC vs. S<sub>1</sub> (Peters and Cassa 1994) clearly indicates that these members have fair to good, very good, fair to very good and poor to good potential, respectively, as illustrated in figure 8(a). At the same well, the cross plot between TOC and S<sub>2</sub> shows that the members of the formation are poor, very good, poor to good and poor to good

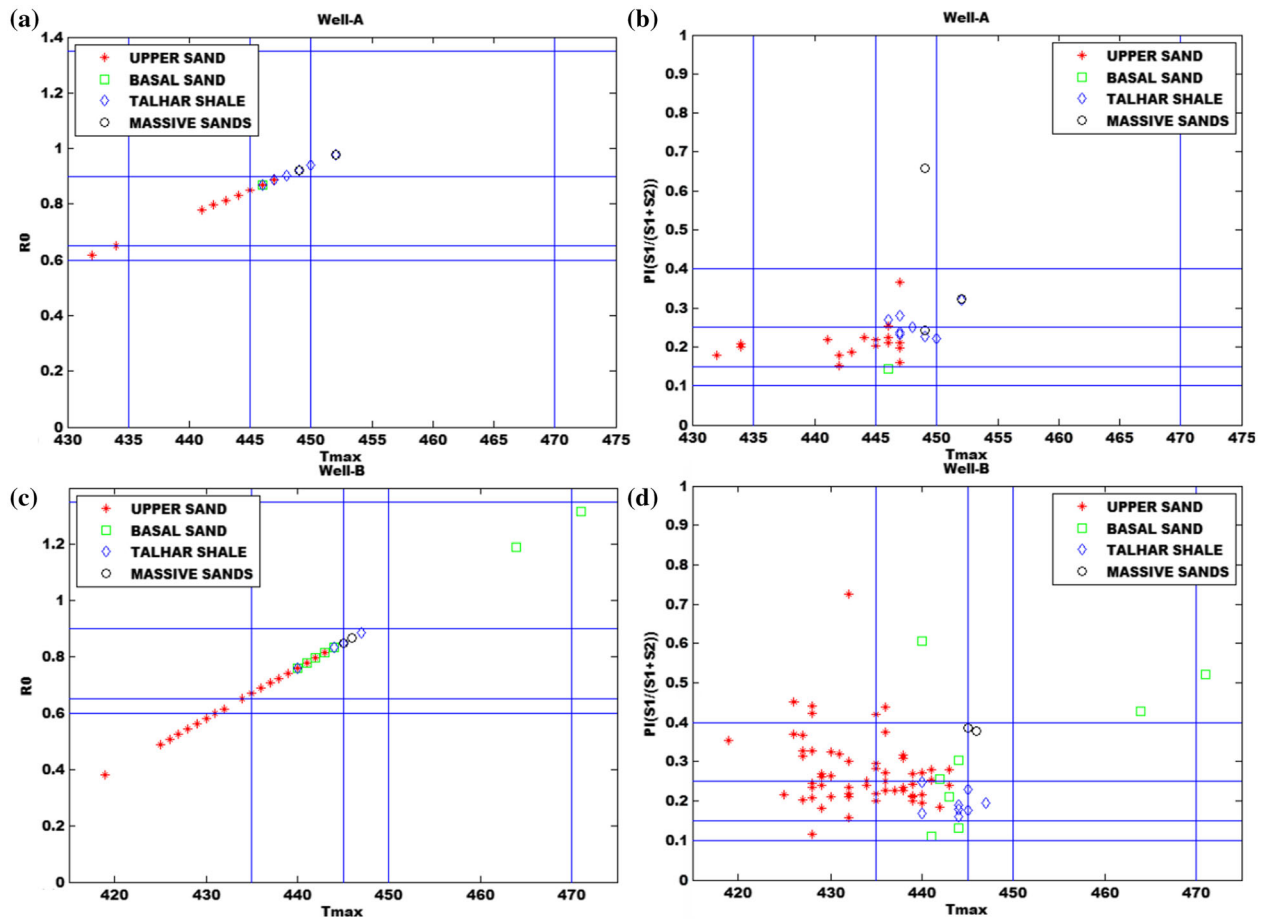


Figure 11. Thermal maturity study using the relationships between  $R_0$  and  $PI$  with  $T_{max}$  on the cross plots: (a)  $R_0$  vs.  $T_{max}$  plot at Well A, (b)  $PI$  vs.  $T_{max}$  plot at Well A, (c)  $R_0$  vs.  $T_{max}$  plot at Well B, and (d)  $PI$  vs.  $T_{max}$  plot at Well B.

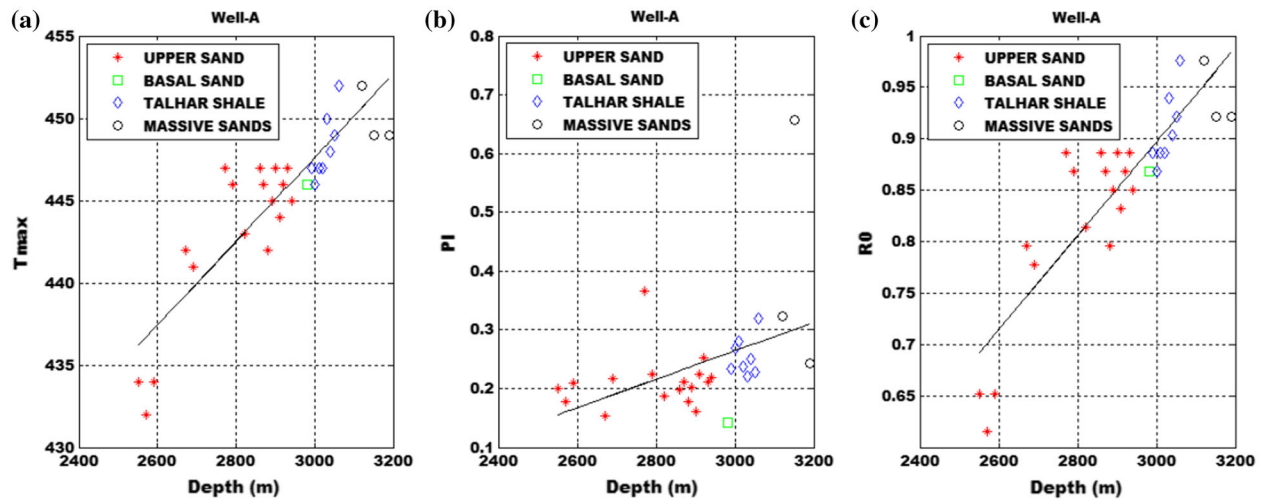


Figure 12. Thermal maturity relationship between  $PI$ ,  $R_0$ , and  $T_{max}$  with depth (m) of Well A.

source, following the classification reported in Langford and Blanc-Valleron (1990), respectively, as depicted in figure 8(b).

Similarly, the samples from the Lower Goru Formation at Well-B were also taken at the

depth levels between 1940 and 3000 m from the Upper Sand (1942–2827 m), Basal Sand (2827–2860 m), Talhar Shale (2860–2931 m), and Massive Sand (2931–3000 m) members of the formation. On the basis of cross plot between



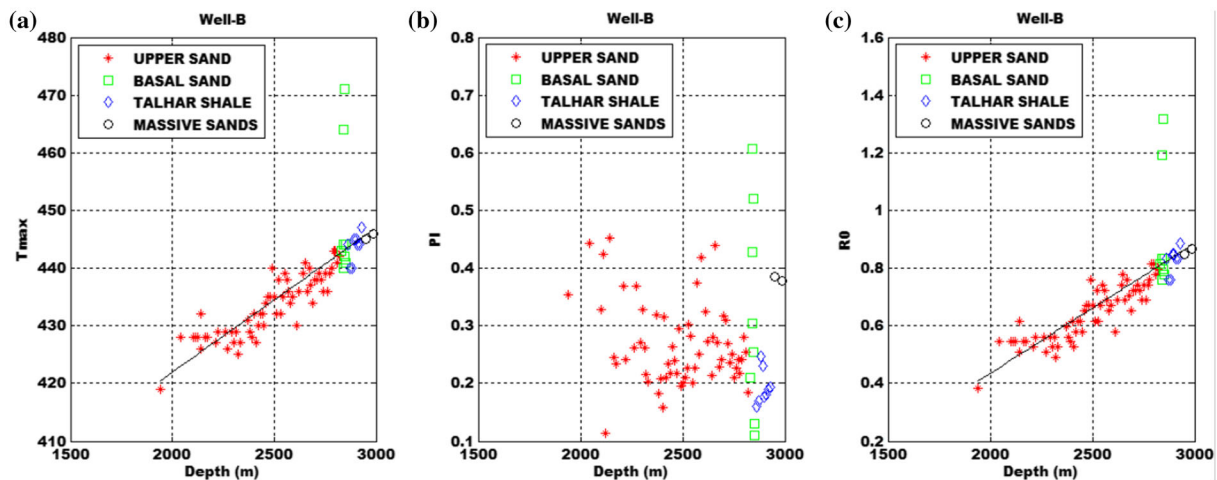


Figure 13. Thermal maturity relationships between  $PI$ ,  $R_0$ , and  $T_{max}$  with depth (m) at Well B.

TOC and  $S_1$ , it was observed that these members bear fair to very good, poor to good, fair to excellent and poor to fair potential, respectively, as illustrated in figure 8(c). The TOC *vs.*  $S_2$  cross plot indicates poor to fair, poor to excellent, poor to very good and poor source potential, respectively, as illustrated in figure 8(d). In a nutshell, it was concluded that Lower Goru Formation bears good source generation potential in the Southern Lower Indus basin which can produce hydrocarbon.

#### 4.3.2 Source rock hydrocarbon generation potential

Generation potential (GP, mg HC/g rock) is the sum of  $S_1$  and  $S_2$ , which is used to evaluate the source rock hydrocarbon generation potential on the basis of its numerical values. The GP values  $> 2$  (mg HC/g rock) show the presence of oil-prone facies, while the lower values ( $< 2$  mg HC/g rock) describe the gas prone facies (Ehinola and Zhu 2008). The cross plot of GP *vs.* TOC indicates that the Upper and Basal Sands have the potential to produce oil as the values of GP ( $> 2$  mg HC/g rock) are greater at Well-A and Well-B, respectively, as illustrated in figure 9(a and b). On the other hand, Talhar Shale and Massive Sands have the ability to produce both oil and gas. Lower Goru Formation has variable GP lies from poor to very good following the classification scheme of Hunt (1996). Upper Sand has poor GP ( $< 1$  mg HC/g rock) which shows that it lacks the potential to produce hydrocarbon. Basal Sand (GP  $> 1$  mg HC/g rock)

has good to very good potential to produce hydrocarbon. Talhar Shale has fair to good GP potential values which indicates that it is capable of generating hydrocarbon, whereas Massive Sands has poor to fair potential to generate hydrocarbon.

#### 4.3.3 Kerogen type

Hydrogen index (HI) *vs.* oxygen index (OI) cross plot is utilized to identify kerogen type of the organic matter. It is considered as a reliable criterion to classify kerogen types of source rocks (Peters and Cassa 1994). In the present study, kerogen types are determined by the cross plot of HI *vs.* OI, which indicates that the Lower Goru has kerogen types I, II, and III. Also, maximum data cluster lies between types II and III, at Well-A and III in Well-B as illustrated in figure 10(a and c). The cross plot of HI *vs.*  $S_2/S_3$  indicates that the Lower Goru has the potential to produce both oil and gas at Well-A and Well-B, respectively, as illustrated in figure 10(b and d).

#### 4.3.4 Thermal maturity

Rock-Eval parameters such as  $T_{max}$ ,  $R_0$ , and  $PI$  are used to determine the thermal maturity of the rock samples (Peters and Cassa 1994; Bozcu 2015). The cross plots of  $R_0$  *vs.*  $T_{max}$  at Well-A and Well-B, respectively, are illustrated in figure 11(a and c). The cross plot of  $PI$  *vs.*  $T_{max}$  at Well-A and Well-B, respectively, are shown in figure 11(b and d). At Well-A, the values of  $T_{max}$  and  $R_0$  indicate that all rock samples are early mature to late mature



Figure 14. Well correlations for Lower Goru facies distribution along the cross-section X-Y (figure 1) in the Southern Lower Indus basin of Pakistan.

(435–455°C and 0.60–1.00, respectively) in the formation. The Lower Goru Formation is also thermally early mature to late mature in Well-B as represented by the values of  $T_{max}$  and  $PI$  (435–455°C and 0.15–0.40, respectively).

The Upper Sand rock samples maturity indicators ( $T_{max}$ ,  $R_0$ , and  $PI$ ) shown that this rock facies is thermally immature to mature (420–445°C, 0.40–0.80, and 0.10–0.40, respectively) at Well-B. Similarly, the production index data shows that the Upper Sand is not sufficiently mature to generate hydrocarbon in the study area. On the other hand, Basal Sand, Talhar Shale, and Massive Sands are thermally peak mature to late mature illustrated by the

values of  $T_{max}$ ,  $R_0$ , and  $PI$  (440–470°C, 0.70–1.30, and 0.10–0.40, respectively) as shown in figure 11(c and d). Overall, the Lower Goru Formation rock samples are thermally mature and produce both oil and gas in both wells.

The thermal maturity depends on burial depth, less buried samples of the Upper Sand are immature, while deeply buried samples are thermally mature. The depth trends of  $T_{max}$ ,  $R_0$ , and  $PI$  increase with increasing depth at Well-A and Well-B as illustrated in figures 12(a–c) and 13(a–c), respectively. At Well-A, a linear trend of depth with other parameters was observed. On the contrary, at Well-B, no significant trend was observed between  $PI$  and depth.

#### 4.4 Well correlation

Well correlation for facies distribution of Lower Goru in the Southern Lower Indus basin of Pakistan is illustrated in figure 14, which indicates facies distribution across the basin. The well correlation profile length is 301.91 km.

### 5. Conclusions

Geological settings of the Southern Lower Indus basin at the time of the Cretaceous were favourable for source rock deposition and also the world's major source rocks were deposited in extensional tectonics. The intraformational shale beds of the Lower Goru Formation and Upper Goru Formation provide regional seals for Cretaceous reservoirs. Evolution of the Lower Goru Formation model and its depositional environment indicate that the source of sediment supply was Indian Shield (east) and uplift of highs (north). The subsurface structural interpretation results show that the Lower Goru Formation has normal faulting with horst and graben geometry.

Upper Sand, Basal Sand, Talhar Shale, and Massive Sands have fair to good, very good, fair to excellent and fair to very good TOC (wt.%), respectively, in both wells. Lower Goru Formation facies have kerogen types I, II, and III, and a maximum cluster of data lies between types II and III. Upper Sand member of the formation is not thermally mature, so it cannot produce oil and gas. Basal Sand, Talhar Shale, and Massive Sands are thermally mature and have the potential to produce hydrocarbon. Basal Sand has potential to produce oil, while Talhar Shale and Massive Sands have the ability to produce both oil and gas. Overall, geochemical analysis study shows that the Lower Goru Formation facies are thermally mature for a generation of unconventional hydrocarbons.

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### Author statement

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