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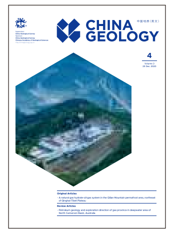

Exploration prospects of oil and gas in the Northwestern part of the Offshore Indus Basin, Pakistan

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A B S T R A C T

Oil and gas resources are short in Pakistan and no commercially viable oil and gas sources have been yet discovered in its offshore areas up to now. In this study, the onshore-offshore stratigraphic correlation and seismic data interpretation were conducted to determine the oil and gas resource potential in the Offshore Indus Basin, Pakistan. Based on the comprehensive analysis of the results and previous data, it is considered that the Cretaceous may widely exist and three sets of source rocks may be developed in the Offshore Indus Basin. The presence of Miocene mudstones has been proven by drilling to be high-quality source rocks, while the Cretaceous and Paleocene–Eocene mudstones are potential source rocks. Tectonic-lithologic traps are developed in the northwestern part of the basin affected by the strike-slip faults along Murray Ridge. Furthermore, the Cretaceous and Paleocene–Eocene source rocks are thick and are slightly affected by volcanic activities. Therefore, it can be inferred that the northwestern part of Offshore Indus Basin enjoys good prospects of oil and gas resources.

1. Introduction

The sea area (Arabian Sea) of Pakistan is comprised mainly of the Offshore Indus Basin, Makran Accretionary Prism, and Oman Abyssal Plain. The former two areas have been explored for oil and gas resources for nearly 60 years, with a total of 18 wells being drilled. As a result, only a small amount of natural gas was obtained in the Miocene sandstones of the Offshore Indus Basin during the drilling of Well Pakcan 1, with no commercial oil and gas resources being discovered (Shuaib SM, 1982; Shuaib SM et al., 1999). The eastern part of the Offshore Indus Basin has been extensively surveyed, achieving a density of exploration grid of up to 4×8 km on average and up to 2×4 km in some areas. In contrast, the northwestern part has been less surveyed, with a density of exploration grid of only 16×16 km. In this paper, to identify the oil and gas resource potential and to make a breakthrough in oil and gas exploration in the northwestern part, the potential and prospects of the oil and gas resources in the northwestern part of the Offshore Indus Basin are explored based on the comprehensive research of the regional geological features and the geological conditions and reservoir formation of oil and gas.

2. Regional geological background

The sea area of Pakistan stretches across three plates. It can be divided into five tectonic elements according to the distribution features of Paleogene strata, namely Makran Accretionary Prism, Oman Abyssal Plain, Murray Ridge, Offshore Indus Basin, and Saurashtra High (Fig. 1), which consist of the tectonic framework of alternate uplift and depression from north to south (Smith GL, 2013; Kopp C et al., 2000; Jiang KX et al., 2016; Malod JA et al., 1997). The

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Makran Accretionary Prism is a part of the Eurasian Plate (Liu B et al., 2020; Zhang Z et al., 2020), the Oman Abyssal Plain is a component of the Arabian Plate, and the Offshore Indus Basin is a part of the Indian Plate. The Indian Plate is separated from the Arabian Plate by the NE-SW-trending right-lateral strike-slip fault of Murray Ridge.

As the second-largest submarine fan in the world, the Indus Fan can be further divided into three major submarine fans, namely the upper fan, the middle fan, and the lower fan. The Offshore Indus Basin lies in the upper fan, with the area accounting for about 90% of the total area of the upper fan. It was concluded from previous survey and research results that the Offshore Indus Basin was mainly comprised of Cenozoic strata, with a maximum thickness up to 11000 m (Kolla V et al., 1987; Clift P et al., 2002; Daley T et al., 2002); during the Paleocene–Eocene, carbonate platform and its related organic reef developed on the top of Deccan volcanic seamount (Shahzad K et al., 2018; Khurram S et al., 2019) and deep-sea shale was deposited in the depression area between the carbonate platforms; during the Oligocene –Quaternary, hugely thick sediments developed in the Indus Fan, while large-size channel –levee sediments developed during Miocene–Holocene (Mchargue TR and Webb J, 1986; Droz L et al., 1991).

Fourteen wells have been drilled in the Offshore Indus Basin, Pakistan up to now, including three wells located in the deep-water area, namely Anne 1x, Pak-G2 1, and Kekra 1. The remaining 11 wells are located in the shallow shelf. Among them, only a small amount of natural gas was obtained in the Miocene sandstone during the drilling of Well Pakcan 1, while other wells are dry wells (Jiang KX et al., 2016), including the latest Well Kekra 1 completed in June 2019 (Table 1; Fig. 2). Pakistani experts and the oil companies considered that these were mainly attributed to insufficient hydrocarbon charge and poor quality of reservoirs.

3. Cretaceous strata widely developing in the offshore Indus Basin

Indus Basin is the largest sedimentary basin and oil and gas energy base in Pakistan, and the Cretaceous strata in this basin serves as both important source rocks and key reservoirs (Huang ZX et al., 2005; Zaigham NA and Mallick KA, 2000; Li LT et al., 2015; Lin WD, 2008; Clift P et al., 2002; Chen X et al., 2017a; Yang JF et al., 2019). Among the Cretaceous, the shale of the Lower Cretaceous Sembar Formation are the main source rocks (TOC: 1.72%–2.55%, R_o: 1.27%–2.06%), while the sandstones of the Lower Cretaceous Lower Goru Formation serve as the main reservoirs. Therefore, it is of great significance to find out whether the Cretaceous exists in the Offshore Indus Basin.

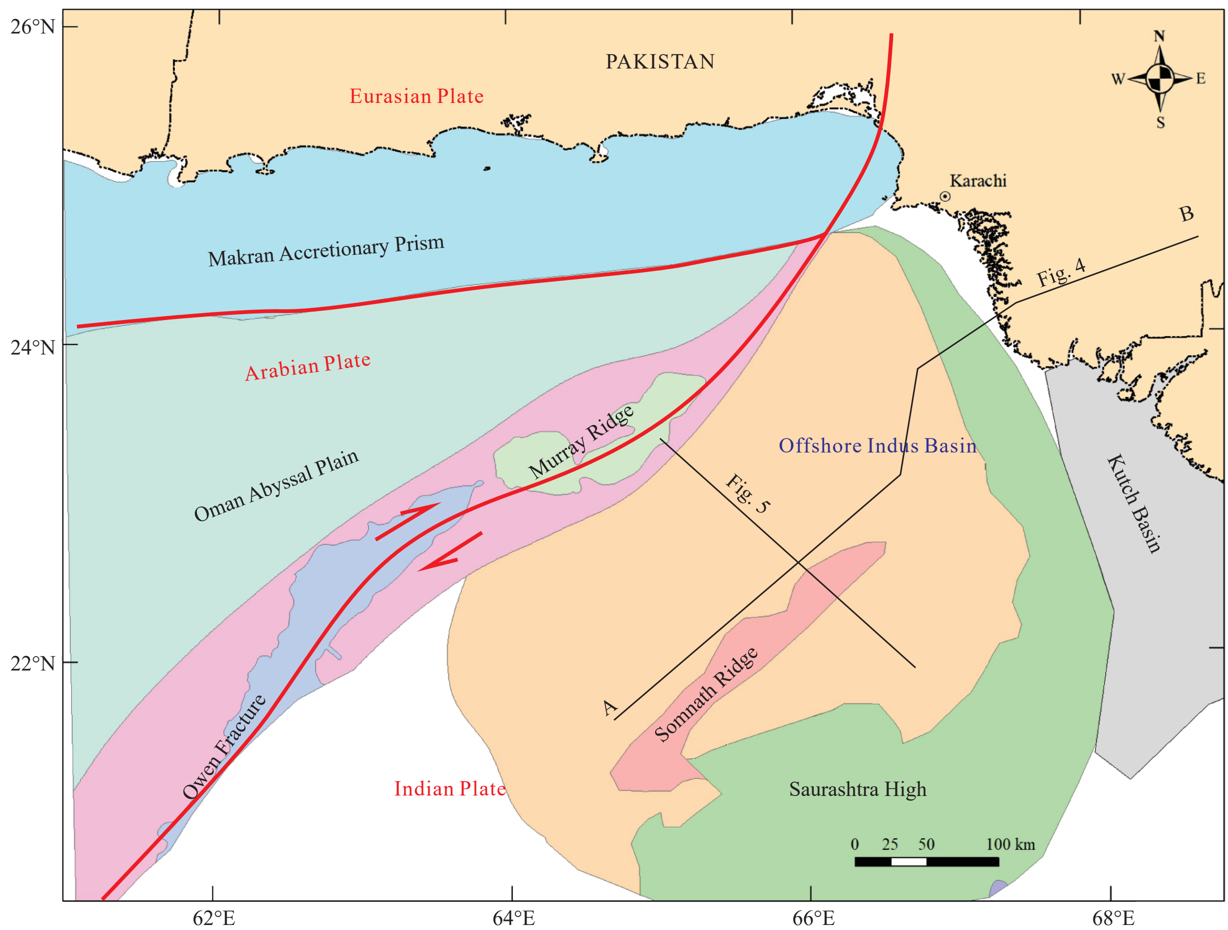

Fig. 1. Geotectonic location of Pakistan Sea area (modified from Smith GL, 2013).

According to the comprehensive analysis of the drilling data of the sea area, onshore-offshore stratigraphic correlation, and seismic interpretation results, the Cretaceous was believed to widely exist in the Offshore Indus Basin for four major reasons. First, Cretaceous shale was discovered beneath Deccan volcanic rocks during the drilling of wells Karachi South A-1 and Dabbo Creek 1 located in the northern shelf region of the Offshore Indus Basin (Khurram S et al., 2019) (Fig. 3). Second, the Cretaceous was discovered by drilling to be widely distributed in the onshore area of the

Table 1. Oil and gas drilling results in the sea area of Pakistan.

No.	Well name	Operator	Year	TD/m	Result and reasons
1	Dabbo Creek 1	Sun	1963	4354	Drill off structure
2	Patiani Creek 1	Sun	1964	2659	Drill off structure
3	Korangi Creek 1	Sun	1964	4140	Possible seal failure
4	Indus Marine A-1	Wintershall	1972	2841	Poor reservoir quality
5	Indus Marine B-1	Wintershall	1972	3804	Mechanical failure
6	Indus Marine C-1	Wintershall	1975	1942	High formation pressure
7	Jal Pari 1A	Marathon	1976	2007	High formation pressure
8	Karachi South A-1	Husky	1978	3353	Poor reservoir quality
9	Pakcan 1	OGDC	1985	3701	Edge of sand body
10	Sadaf 1	Occidental	1989	3980	Lack of charge
11	Shaikh Nadin 1	Canterbury	1992	1679	Gas show
12	Pasni 1	OPC	1999	3569	Reservoir not encountered
13	Gwadar 1	OPC	2000	3810	Reservoir not encountered
14	Pak-G2 1	Total	2004	4750	Lack of charge
15	Pasni X-2	PPL	2005	4000	Reservoir not encountered
16	Anne 1x	Shell	2007	3268	Reservoir not encountered
17	Shark 1	Eni	2010	3503	Lack of charge
18	Kekra 1	Eni	2019	5693	Lack of charge

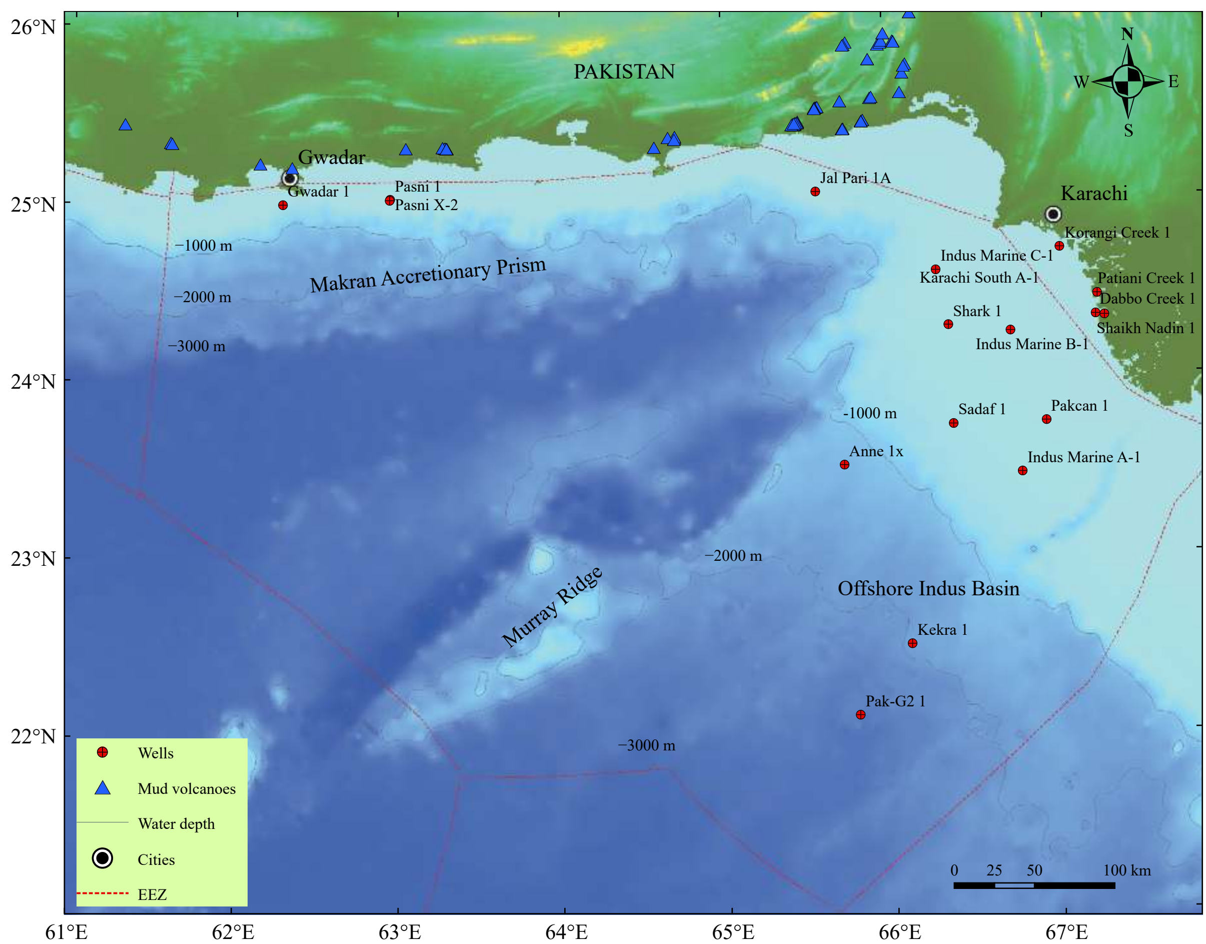

Fig. 2. Location and drilling results of 18 offshore wells in Pakistan.

Indus Basin (Carmichael SM et al., 2009) (Fig. 4), with a large thickness of about 3000 m (Chen X et al., 2017b; Chen X et al., 2017c). Third, the Cretaceous in Kutch Basin, which is closely adjacent to the eastern part of the Offshore Indus Basin, thickens toward the sea area (Biswas SK, 1982). Meanwhile, natural gas was discovered in the Cretaceous sandstones during the drilling of two wells (GK-39 1 and GK-22C 1). Finally, as indicated by the latest interpretation results

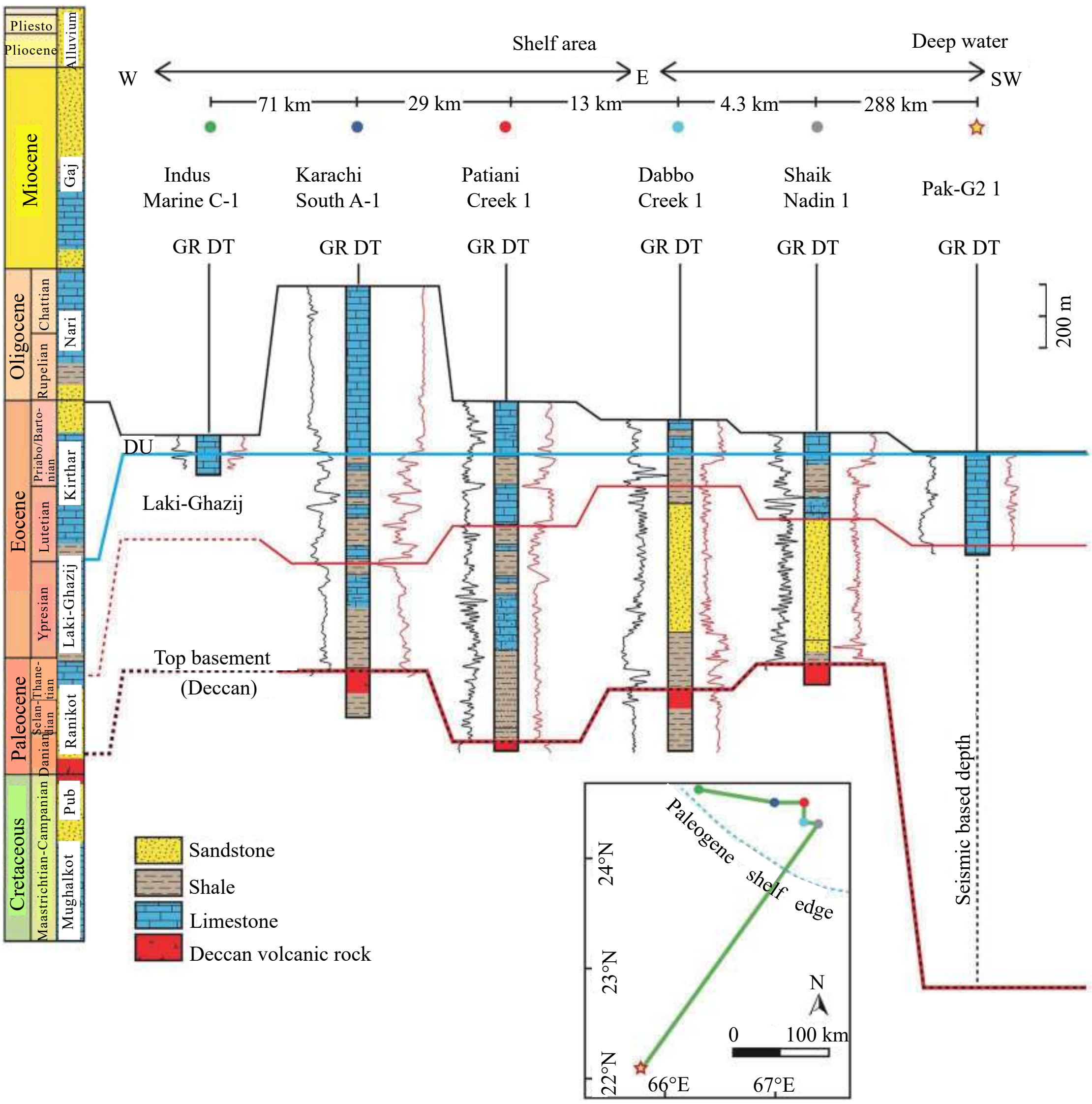

Fig. 3. Cretaceous shale discovered during the drilling of wells Karachi South A-1 and Dabbo Creek 1, while Paleocene-Eocene limestone discovered during drilling of Well Pak-G2 1 (after Khurram S et al., 2019).

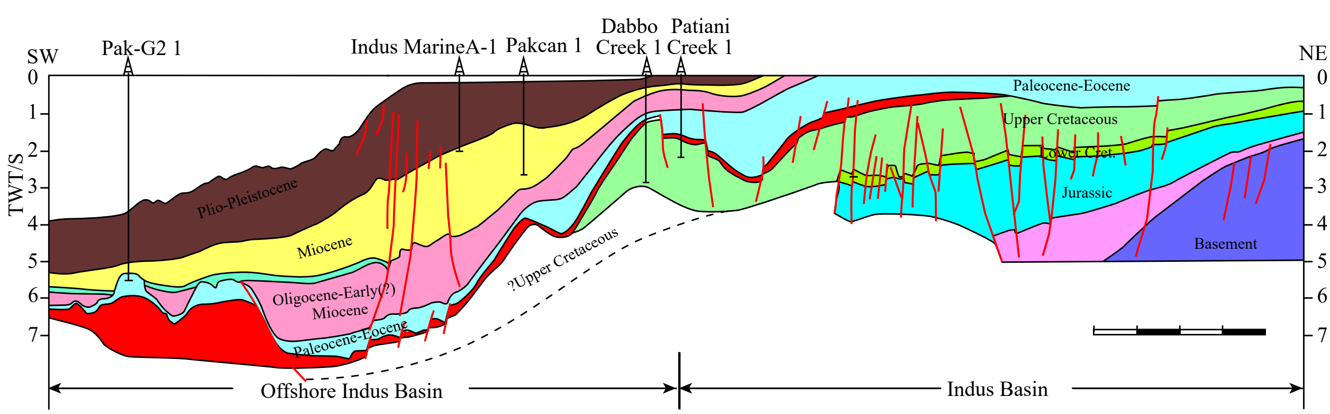

Fig. 4. Onshore-offshore stratigraphic correlation in Pakistan discovered by drilling (after Carmichael SM et al., 2009) (Location of the profile see Fig. 1).

of seismic data, there is a set of weakly continuous seismic reflection signals with medium–weak amplitude beneath the Paleocene–Eocene Series, with the two-way travel time of the signals ranging 1000–2000 ms. The strata featuring the seismic reflection signals were preliminarily interpreted to be the Cretaceous (Fig. 5). It can be seen from Fig. 5 that the Cretaceous tends to thicken toward the northwestern part of the basin on the side of the strike-slip fault zone of Murray Ridge.

4. Geological conditions of oil and gas in the northwestern part of the Offshore Indus Basin

4.1. Favorable hydrocarbon generation conditions

Three sets of source rocks, namely the Cretaceous, Paleocene–Eocene, and Miocene source rocks are believed to possibly exist in the Offshore Indus Basin according to the comprehensive analysis of the drilling data and onshore-offshore stratigraphic correlation results (Table 2; Fig. 6) (Yang JF et al., 2019; Chen X et al., 2017b; Chen X et al., 2017c; Syed AA et al., 2011; Gaedicke C et al., 2002; Qian K et al., 2017; Wang WG, 2014). Among them, the Miocene source rocks have been proven present by drilling of Well Pakcan 1, with a mudstone thickness of 300 m, an average TOC up to 2%, and an average R_o of 0.8% (Carmichael SM et al., 2009). Therefore, they are of high quality. The potential source rocks include Cretaceous mudstones and the Paleocene–Eocene mudstones interbedded with coal seams. As for the former, the TOC is up to 3%–3.5%, R_o ranges 1.27%–2.06%, and the types of organic matter include Ⅱ and III (Aadil N et al., 2014; Sheikh N et al., 2017). As for the Paleocene and Eocene mudstones interbedded with coal seams, the TOCs are up to 3% and 3.7%, respectively, and R_o ranges 1.01%–1.11% (Biswas SK, 1982). In terms of the lithology and TOC of Paleocene–Eocene source rocks in the Indus Basin and Kutch Basin (Table 2), the Indus Basin is mainly comprised of shale, while Kutch Basin contains coal seams besides shale. Moreover, the abundance of organic matter in the Indus Basin is slightly higher than that in the Kutch Basin. Therefore, it can be inferred that the types of organic matter in Paleocene – Eocene mudstones in the Indus Basin may be slightly more favorable than those in Kutch Basin. Since Type-Ⅲ organic matter was found in the Paleocene–Eocene mudstones by drilling of offshore Well KS1-1, it is believed that the organic matter in two sets of potential source rocks in the Offshore Indus Basin is of Type-Ⅱ and Type-Ⅲ and thus is both matured.

As indicated by previous interpretation results, the sedimentary center of the Paleocene–Eocene mudstones is located in the northwestern part of the Offshore Indus Basin (Jiang KX et al., 2016), with a maximum thickness of about 900 m (Fig. 7). Meanwhile, the interpretation results of seismic data in this study show that the Cretaceous thickens toward the northwest (Fig. 5). Therefore, the northwestern part of the Offshore Indus Basin features thick source rocks and thus boasts favorable hydrocarbon generation conditions.

4.2. Favorable reservoir conditions

There are two sets of proven reservoirs in the Offshore Indus Basin as indicated by the drilling data, namely the widely distributed Miocene channel sandstones and locally distributed Paleocene–Eocene reef limestone. According to drilling data of Well Pakcan 1, the Miocene reservoirs are comprised of medium to fine-grained sandstones and siltstones and a small amount of coarse-grained sandstones and inequigranular sandstones, with a thickness of 2–50 m. The sandstones are loose to medium-hardness, and thus it can be inferred that the intergranular pores are developed. As indicated by the analysis of physical properties, the Miocene

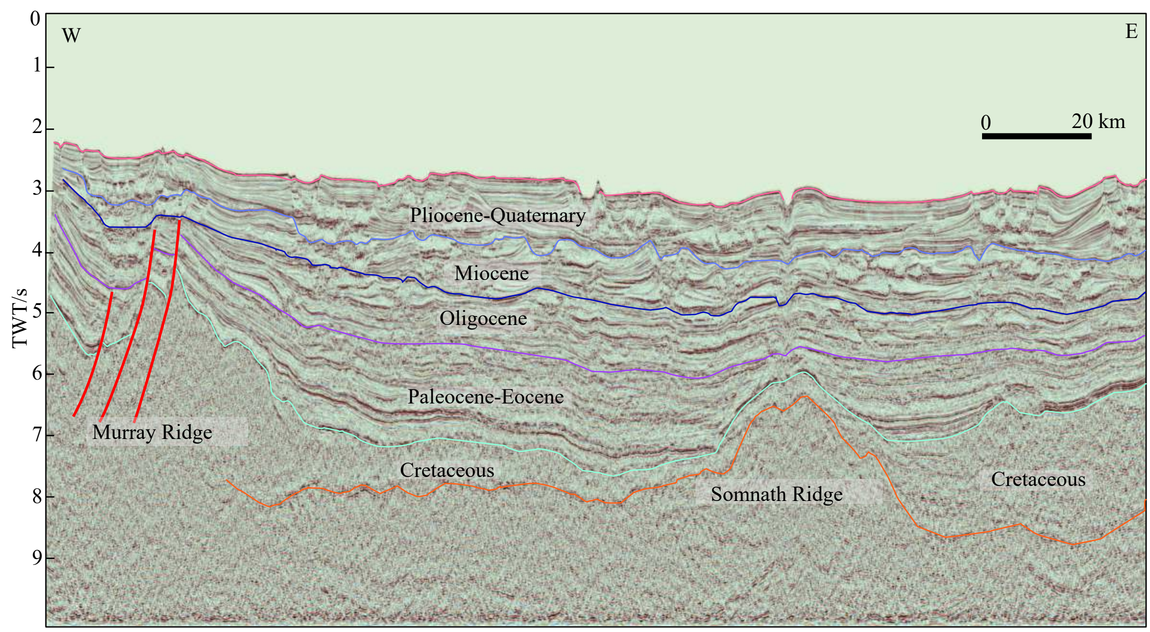

Fig. 5. NW-SE-trending seismic interpretation profile across the Offshore Indus Basin (Location of the profile see Fig. 1).

reservoirs feature a porosity of 15%–20% and thus are favorable reservoirs. In addition, according to the analysis of core data of wells Indus Marine A-1 and Indus Marine B-1, the Miocene sandstones feature a porosity and permeability of mainly 20%–25% and 100–500 mD, respectively. Therefore, they are favorable reservoirs. The Paleocene–Eocene reef limestone or shoal limestone have been proven to be present by the drilling of wells Pak-G2 1 and Kekra 1. According to the drilling data of Well Pak-G2 1, the carbonate reservoirs consist of the bioclastic limestone, bio-framework reef limestone, and packstones, with bio-framework pores and intergranular pores developing. As indicated by the analysis of physical properties, the porosities of the Paleocene and Eocene reservoirs are 27% and 26%, respectively, and thus the two kinds of reservoirs are favorable reservoirs. The reef limestone discovered by the drilling of Well Pak-G2 1 is about 350 m thick on the seismic profile, and the porosity of the Eocene limestone discovered by the drilling of Well Kekra 1 is 20%–28% (Table 3).

According to the results of analogy with Kutch Basin adjacent to the sea area and the onshore Indus Basin, it is very possible that Cretaceous sandstone reservoirs exist in the Offshore Indus Basin. The evidence is as follows. Firstly, 22 offshore wells have been drilled in Kutch Basin up to now, among which oil and gas were discovered in four wells and natural gas was discovered in Cretaceous sandstones in two wells, namely GK-22C 1 and GK-39 1. The two wells were drilled in 1995 and 2001, respectively and their recoverable reserves of natural gas in Cretaceous sandstones are up to 168.8×10^6 m^3 and 472×10^6 m^3, respectively. The reservoirs discovered by the two wells are both composed of sandstones of delta–neritic facies, with a porosity of 18%–25% and a permeability of mainly 32.8–1000 mD. Therefore, they are both favorable reservoirs. Secondly, the Cretaceous sandstones in the onshore Indus Basin are also a set of important reservoirs. They feature high sorting degree and rounding, with an average porosity of 20% and a permeability of mainly 10–4000 mD. Therefore, three sets of reservoirs may exist in the Offshore Indus Basin, and thus the basin features favorable reservoir conditions in general. It can be seen from the latest interpretation results of seismic data (Fig. 5) that, with the Somnath volcanic platform (also called Somnath Ridge) as a boundary, the Cretaceous of the Offshore Indus Basin thickens toward the eastern and western sides. Meanwhile, the Cretaceous reservoirs in the northwestern may enjoy more favorable reservoir conditions since the northern part is far away from the Somnath volcanic platform.

4.3. Tectonic-lithologic traps developing

The Offshore Indus Basin is located on a passive continental margin. It features weak tectonic activities, with a few faults and folds developing besides a small number of normal faults developing in the continental shelf subject to gravity. However, a number of tectonic-lithologic traps are developed in the northwestern part of the Offshore Indus Basin owing to uplifting and strike-slipping of the adjacent Murray Ridge.

As indicated by the interpretation results of seismic data, there are four types of traps in Offshore Indus Basin, namely drape anticlines, wide and gentle anticlines, faulted anticlines, and lithologic traps. The northwestern part of the basin is adjacent to the strike-slip fault zone of Murray Ridge. Therefore, the fault carrier system in this region is more developed than that in other areas, which is favorable to the

Table 2. Onshore-offshore correlation of source rocks in the Offshore Indus Basin and its adjacent areas.

Basin/Well No.	Era		Lithology	TOC/%	Type	R_o/%	Remarks
Indus Basin	Lower Cretaceous (primary)	Sembar	Shale	3.5	II and III	0.87	
		Upper Goru		2.55–1.72	II and III	2.06–1.27	
	Upper Cretaceous		Shale and mudstone	1.28–1.72		1.07–1.29	
	Paleocene		Shale	1.19–6.89		1.01–1.11	
	Eocene		Shale	9.75		1.44	
	Oligocene		Shale	0.86		0.94	
Kutch Basin	Lower Eocene		Shale and lignite of lagoon facies	0.58–3.7	II and III	>1.1	Well GKH–1
	Paleocene		Calcareous shale and lignite seams	0.35–3	II and III		Thin
	Cretaceous		Shale interbedded with coal seams	0.1–10.65	III and II	<0.5	
	Upper Jurassic–Lower Cretaceous (primary)		Shale	0.5–3	III and II	0.34–0.49	
Pakcan 1	Lower Miocene		Mudstones	0.55–3.24/2		0.6–0.9	
Bombay Basin	Paleocene–Lower Eocene (primary)		Shale and coal seams	>0.5–1.0			
	Oligocene		Shale	≥1			
KS1–1	Paleocene–Eocene (primary)		Shale and mudstones	3–4.5%	III		Black shale (about 3 m)
Offshore Karachi	Paleocene		Mudstones		III		

Notes: Data from Jiang KX et al., 2016; Yang JF et al., 2019; Chen X et al., 2017b; Chen X et al., 2017c; Syed AA et al., 2011; Gaedicke C et al., 2002; Qian K et al., 2017; Wang WG, 2014.

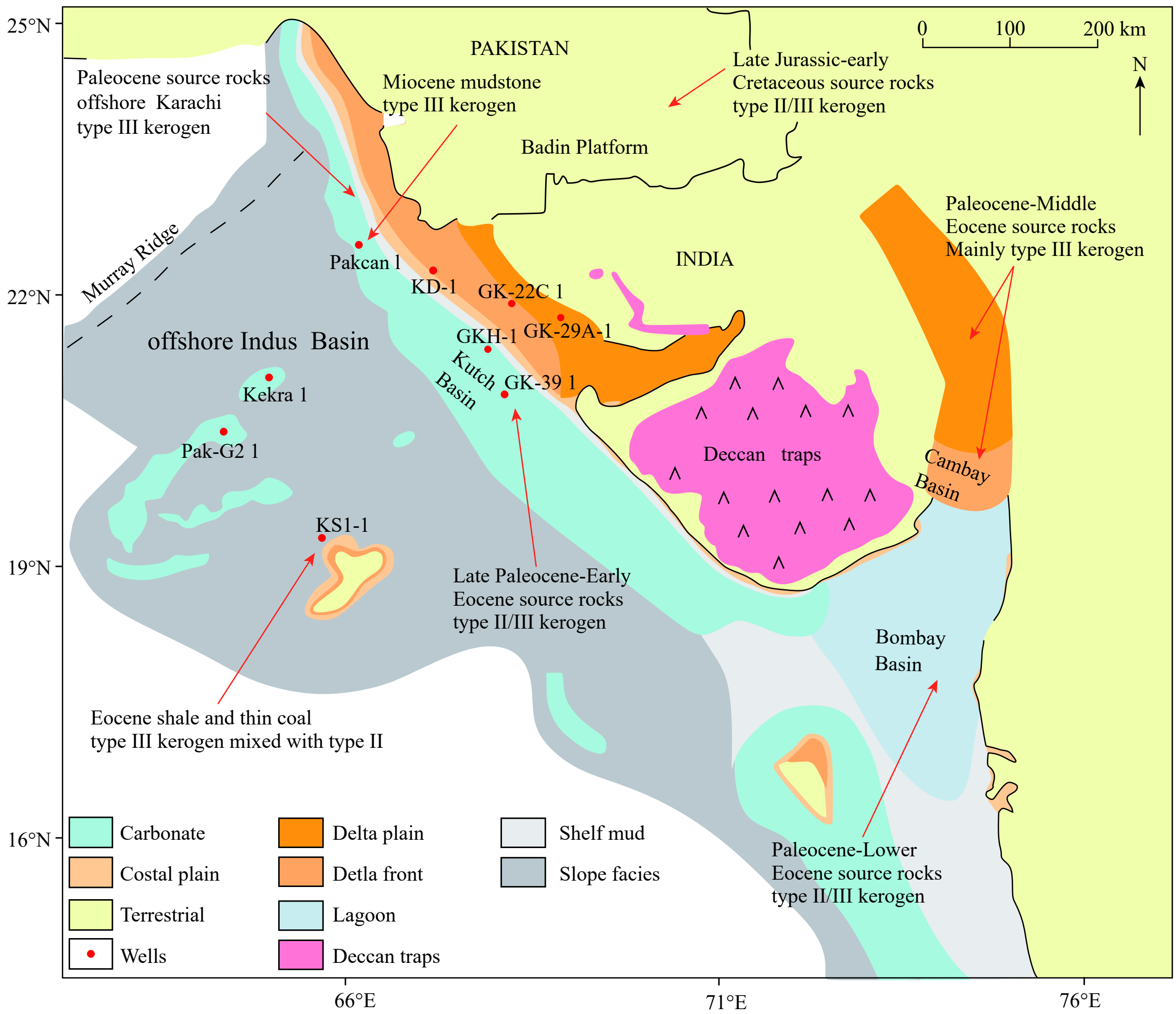

Fig. 6. Sedimentary environment of source rocks in the Offshore Indus Basin and its adjacent areas in the Paleocene–Eocene (modified from Jiang KX et al., 2016).

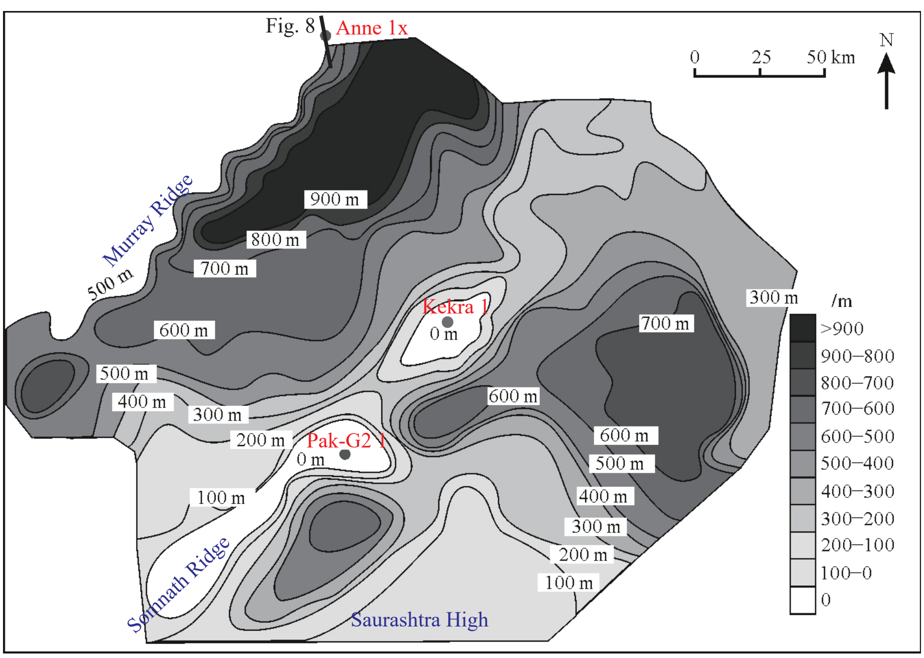

Fig. 7. Isopach map of Paleocene–Eocene mudstones in the Offshore Indus Basin (after Jiang KX et al., 2016).

Table 3. Onshore-offshore reservoir correlation in the Offshore Indus Basin and its adjacent areas.

Basin /Well No.	Era	Lithology	Thickness/m	ϕ/%	K/mD	Remarks
Offshore Indus Basin	Miocene	Fan delta Sandstones	10–20 on average	18–25, with an average of 22	100–500, with an average of 514	Pakcan 1
	Eocene	Reef limestone				Pak-G2 1
	Eocene	Reef limestone		20–28		Kekra 1
Indus Basin	Lower Eocene	Limestone	234.7	4–30	4	
	Paleocene	Sandstones	90	10–25		
	Cretaceous	Sandstones	100–150	15–22		
Kutch Basin	Cretaceous Naliya and Bhuj Formations	Sandstones of fluvial – delta – neritic facies	Net thickness: 30	25	High permeability	GK-39 1
				18	32.8	GK-22C 1
	Lower Paleocene	Fluvial sandstones		20–25	100–1000	GK-29A-1
	Lower Eocene	Limestone	Total/net: 50/15			KD-1
Bombay Basin	Miocene	Limestone		18–35	50–500	
	Upper Eocene	Limestone		14–22	20–1000	

transport of the Cretaceous and Paleocene–Eocene oil and gas to the Eocene carbonatites and/or Miocene channel sandstones.

Actually, the seismic profile passing through Well Anne 1x in the northwestern part of the Offshore Indus Basin (Fig. 8) shows obvious anticline structure, as well as clear bright spots and gas leakage. Unfortunately, the well was not drilled on the top of anticline structure; however, it can be inferred that the top of the anticlines has good oil and gas prospects. A number of tectonic-lithologic traps related to the strike-slip faults of Murray Ridge have been determined in the northwestern part of the basin according to seismic interpretation up to now, and they are inferred to enjoy good oil and gas prospects.

5. Discussion

According to the statistics of the drilling data, the volcanic activities were weak in the onshore area of Pakistan at the end of the Cretaceous. As a result, the erupted Deccan basalts in the same period are thin in general. Moreover, they gradually thin from south to north until they disappear. Therefore, the Deccan basalts have a small impact on onshore oil and gas resources. However, two large volcanic activities occurred in the sea area of Pakistan (Chatterjee S et al., 2013), and the volcanic platforms formed divide the Offshore Indus Basin into two parts, namely the northwestern part whereby the Paleocene–Eocene Series serves as the sedimentary center and the southeastern part that was much impacted by volcanoes (Fig. 7). The two volcanic activities include: (1) Basalt eruption of Somnath Ridge (about 70 Ma), and (2) basalt eruption of Deccan-Reunion (Reunion mantle plume, about 65 Ma). Based on the research into the features of volcanic basement of the Offshore Indus Basin, Calvès G et al. (2010) argued that (Fig. 1) the basalt eruption of Somnath Ridge was attributed to the formation of the volcanic basement in the southeastern part of the Offshore Indus Basin, which is mainly located in Somnath Ridge and Saurashtra High, about 305 km long and 155 km wide, and cover an area of 45000 km^2. The igneous basement is composed of a series of deeply-buried shield volcanic rocks, with a maximum thickness up to 7 km. Moreover, a set of pyroclasic sediments are developed on its periphery and slump deposits are developed in its depression area. According to the interpretation results of seismic data, in the depression area of the southeastern part of the basin adjacent to the Somnath Ridge and Saurashtra High, the Deccan basalts are distributed in the marine-facies strata of the upper Cretaceous –Paleocene in a laminated form (Khurram S et al., 2019). In contrast, the northwestern part of the Offshore Indus Basin is far away from the Reunion mantle plume, and therefore, the Deccan basalts pose a small impact on it. In addition, according to the research by Calvès G et al. (2010), the geothermal gradient of the Cretaceous–Paleogene distributed along Somnath Ridge is low and only 33℃/km, while that of the Cretaceous –Paleogene distributed in sedimentary center is high and up to 37℃/km –55℃/km, aiding the maturity of the source rocks.

Overall, the Cretaceous–Eocene in the southeastern part of the Offshore Indus Basin may contain much pyroclasic matter, thus hindering the development of source rocks. Therefore, it can be concluded that the southeastern part has gloomy oil and gas prospects. However, the northwestern part of the basin is far away from the developing area of volcanic rocks and is close to the strike-slip fault zone of Murray Ridge, and thus faults are developed. This facilitates the transport of the oil and gas in deep Cretaceous and Paleocene –Eocene to the Miocene channel sandstone reservoirs. Therefore, it can be inferred that the northwestern part has good oil and gas prospects.

6. Conclusions

(i) It is concluded that the Cretaceous may widely exist in the Offshore Indus Basin according to the comprehensive research of land-sea stratigraphic correlation, stratigraphic correlation revealed by offshore drilling, and the latest interpretation results of seismic data.

(ii) The northwestern part of the Offshore Indus Basin boasts favorable geological conditions of the oil and gas in general, with three sets of source rocks and three sets of reservoirs being developed. Among them, the Cretaceous and Paleocene –Eocene source rocks with high sedimentary

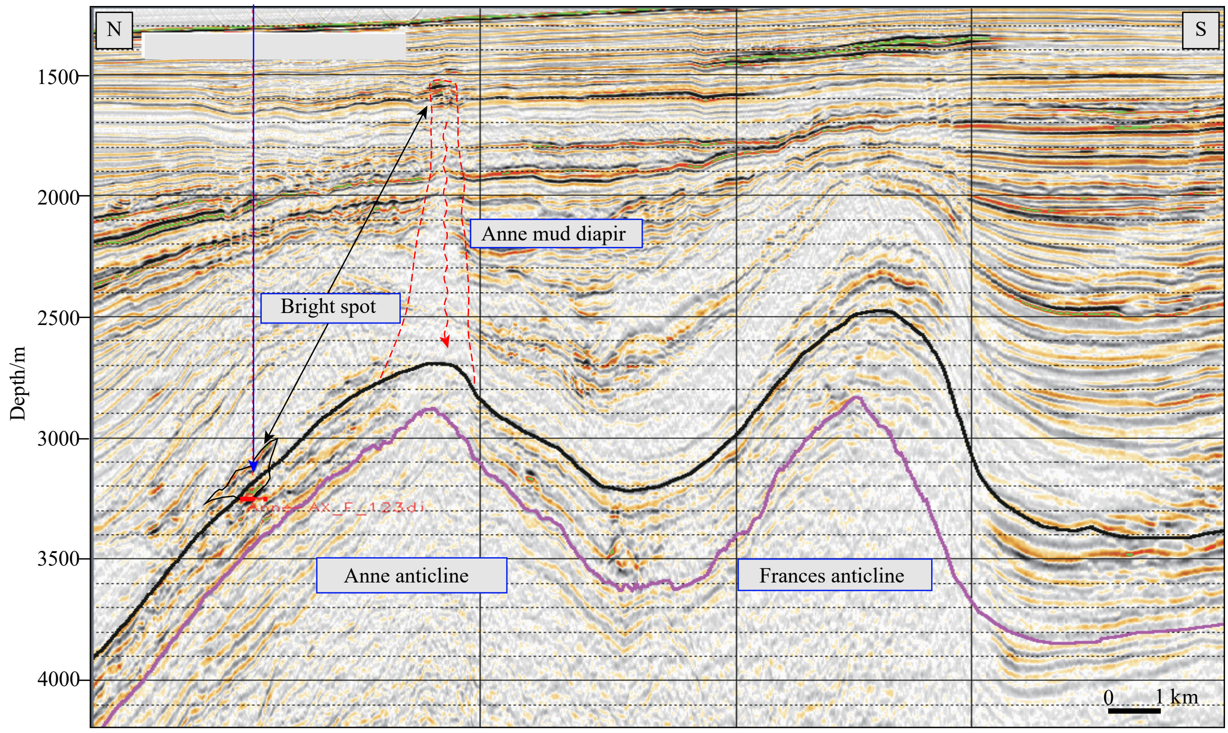

Fig. 8. Seismic profile passing through Well Anne 1x in the northwestern part of the Offshore Indus Basin (Well location see Figs. 2 and Fig. 7; after Carmichael SM et al., 2009).

thickness show great hydrocarbon-generating potential and hydrocarbon storage capacity since they are far away from Somnath Ridge.

(iii) The northwestern part of the Offshore Indus Basin is closely adjacent to the hydrocarbon-generating depression, and a number of fault-related tectonic-lithologic traps are developed in this region. Furthermore, it is slightly affected by volcanoes. Therefore, it can be inferred that the northwestern part of the Offshore Indus Basin has good oil and gas prospects.

CRediT authorship contribution statement

Jian-ming Gong conceived of the presented idea. Jing Liao drew all the figures. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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