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Sedimentary Environments and Hydrocarbon Potential of Cretaceous Rocks of Indus Basin, Pakistan

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ABSTRACT

Cretaceous rocks of Indus Basin of Pakistan are dominated by clastics with subordinate limestones towards the top. These rocks represent shelf facies and were deposited in deltaic to reducing marine conditions at variable depths. Indications of a silled basin with restricted circulation are also present. Cretaceous fine clastics/carbonates have good source and reservoir qualities. Variable geothermal gradients in different parts of the basin have placed these rocks at different maturity levels; i.e. from oil to condensate and to gas. The potential of these rocks has been proved by several oil and gas discoveries particularly in the Central and Southern provinces of Indus Basin.

Key Words: Cretaceous; Sedimentary Basin; Environments; Petroleum Potential; Indus Basin; Pakistan.

INTRODUCTION

During Cretaceous Period the Indus Basin was part of a broad marine shelf opening westward in a branch of southern Tethys Sea. In the east it was bordered by western margin of the Indian Shield. Nearly all of the sediments were marine and were deposited mostly in a shelf environment sometimes reaching down to bathyal level. During the Early Cretaceous a shallow sea existed throughout the basin. Major tectonic events started during the Late Cretaceous and continued through the Palaeocene. At the close of Cretaceous Period the conditions changed to lacustrine/fluvial. In the opinion of Rizvi et al. (1977) this Cretaceous tectonic instability was responsible for the marked variation in facies both horizontally and vertically.

Mesozoic and Tertiary strata in the Indus Basin of Pakistan, where most of the exploration activities for petroleum have taken place, contain most of oil and gas. Although there are some positive indications of hydrocarbons in the Balochistan Basin, there are no other significant commercial hydrocarbon discoveries in Pakistan (Khan and Raza, 1986).

Cretaceous strata of the Indus Basin having a mixture of lithologies and the possibility of stratigraphic traps in areas of lateral facies change, is considered favourable target horizon (Kadri and Abid, 1975). Several oil and gas seeps through Cretaceous rocks are known from northern and central parts of the Indus Basin and these rocks also have several proven reservoir, source and cap rocks throughout the basin.

TECTONICS AND BASIN DEVELOPMENT

Pakistan lies along part of the Tertiary convergence zone and is involved in the interaction of the Indian, Arabian and Eurasian plates, at the southern extent of the Chaman Transform Fault Zone (Kemal, 1991). Active plate boundaries of various types are exceptionally well exposed (Farah et al., 1984). These plate boundaries and their offshoots give rise to an array of geological features in different sedimentary basins. The Chaman Transform Fault Zone separates the two main convergent boundaries, i.e. continent-island arc-continent collision boundary in the north and an active boundary of oceanic lithosphere subducting between arc-trench gap sediments and continental sediments. Main tectonic segments of Pakistan are shown in figure 1.

The tectonic development of Indus Basin was controlled by the Indian Plate during its northern drift and subsequent collision with the Eurasian Plate. The Indo-Pakistan fragment of Gondwanaland started migrating northward initially at a pace of 3 to 5 cm/yr. The movement increased to over 15 cm/yr between 80 (Cretaceous) to 53 (Palaeocene) m.y. ago (Powell, 1979 and Farah et al., 1984). The rapid northward movement of Indian Plate generated compression in the north, and anti-clockwise rotation produced tension on the western margin. As a result eastern shield was raised, the Indus Basin experienced intense subsidence, the platform was fragmented into grabens and horsts at places and the area experienced extensive volcanic activity. According to Raza et al. (1990) this sort of tectonic setting are ideal for wide-spread deposition of sediments exhibiting a variety of facies (Figure 2).

Pakistan's two main sedimentary basins, Indus and Balochistan, were welded together along Chaman and Ornach strike slip faults, which are large left-lateral strike slip faults oriented approximately N-S, parallel to the motion of the Indian Plate (Nakata et al., 1990). There is yet another newly identified smaller basin named as Kakar-Khorasan Basin (Pishin Basin of Ahmed, 1991). The Sargodha and Nagar Parkar palaeotopographic highs in the Precambrian Indian shield were the main features that controlled the sedimentation in the Proto-Indus Basin until the Jurassic, and the Khairpur-Jacobabad High developed during the Jurassic to Cretaceous/Palaeocene age and divided the Indus Basin into the Northern, Central and Southern sub-basins (Figure 3). Central and Southern sub-basins are collectively designated as Lower Indus Basin.

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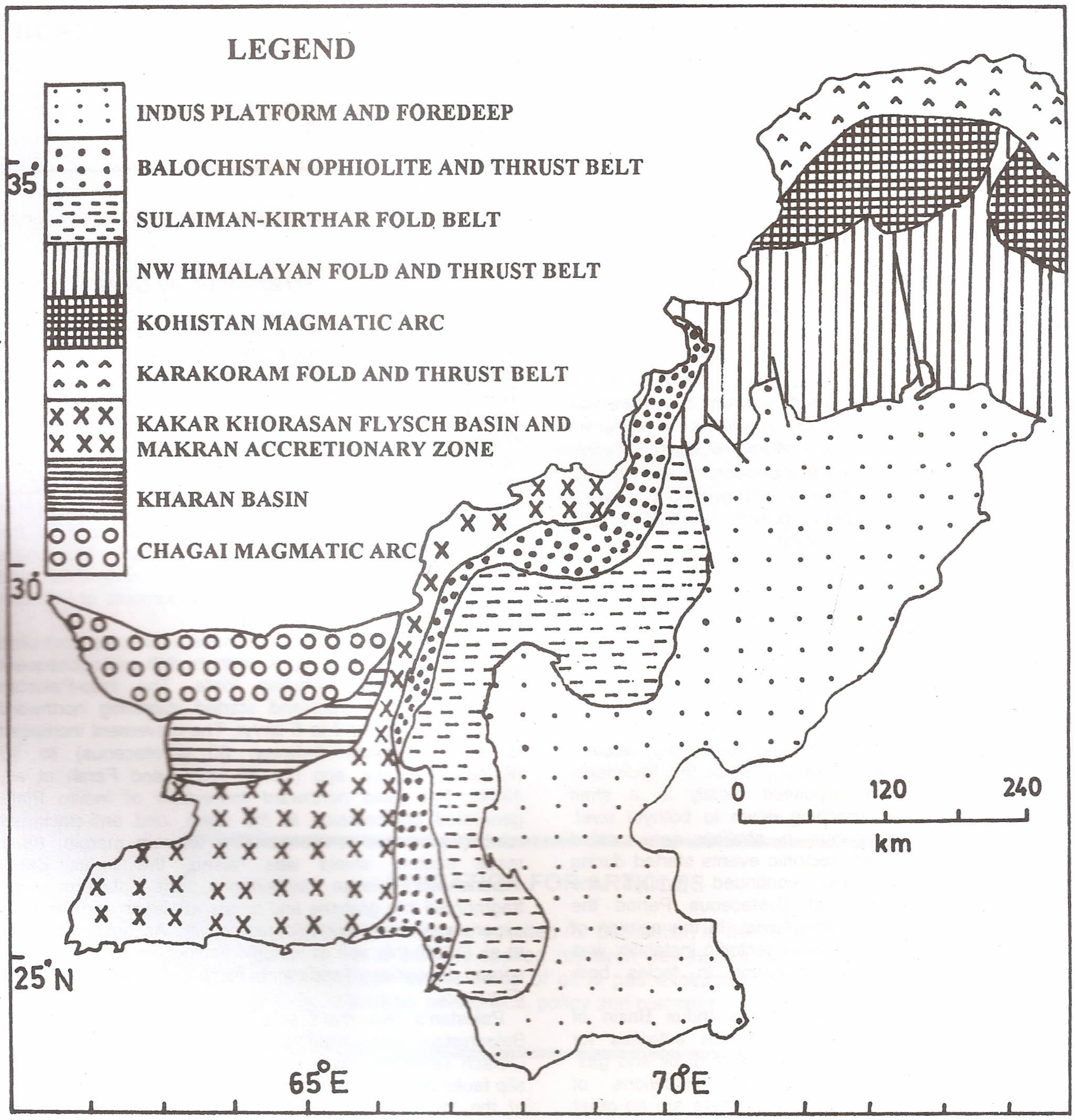

Figure 1- Tectonic segments of Pakistan (Simplified after Kazmi and Jan, 1997).

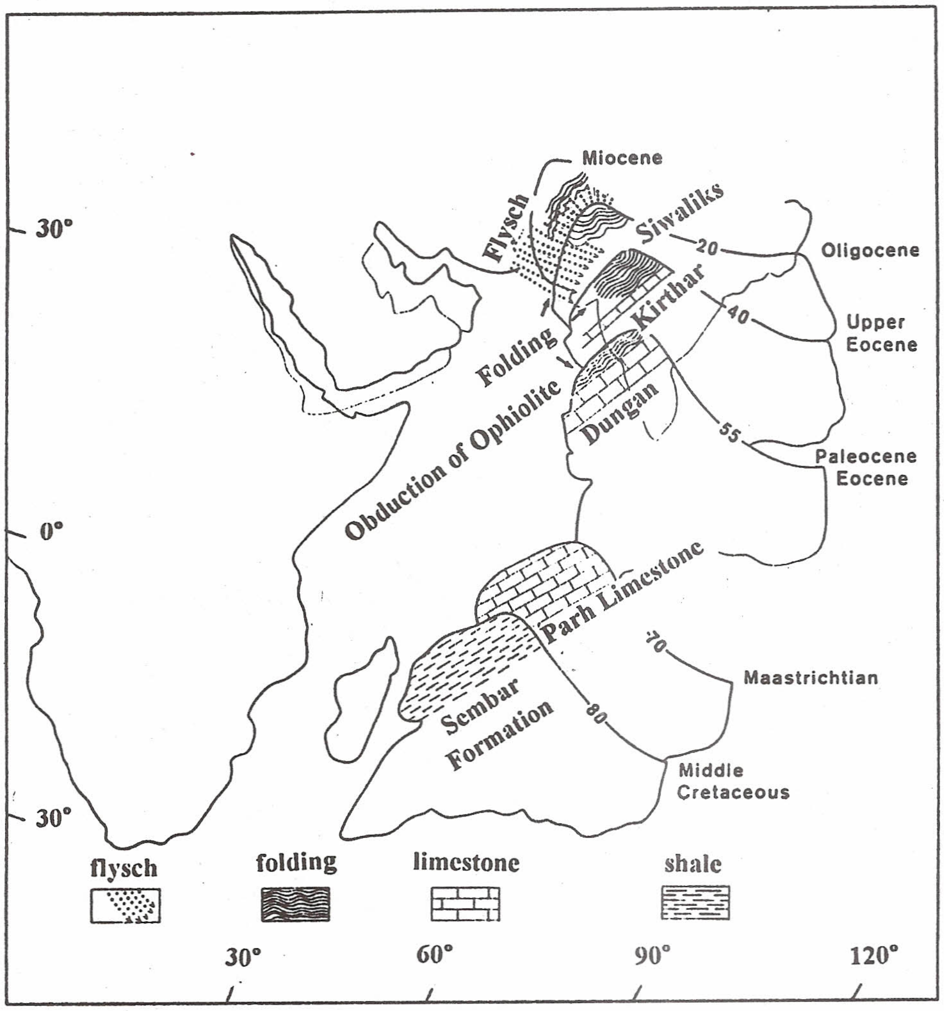

Figure 2- Indian Plate movement and principal sedimentary regimes during the Cretaceous to Miocene (After Bannert et al., 1992).

STRATIGRAPHY

According to Shah (1977) and Iqbal and Shah (1980) Cretaceous sedimentary rocks occur in the Salt Range, Trans-Indus Ranges, Potwar, Kala-Chitta Ranges, Hazara and Kohat area of Kohat-Potwar (Northern) Province and Sulaiman (Central) and Kirthar (Southern) Provinces of Indus Basin. Cretaceous rocks are also present in Axial Belt, Balochistan Basin and northern areas of Pakistan. This strata have been encountered in a number of exploratory wells for oil and gas throughout the Indus Basin. The Lithological and palaeontological details of the Cretaceous Formations are given in Table 1.

THICKNESS

Isopach map (Figure 4) shows the distribution and thickness of Cretaceous rocks of Pakistan. The thinnest isopach intervals are located in the area of present day position of Nagar Parker, Jacobabad, Sanjawi and Sargodha Highs. The thinning can be attributed to subsequent truncation or due to less deposition in tectonically active areas. As a result of post-Cretaceous deformation and subsequent erosion, the Cretaceous sediments were deeply truncated particularly in the Potwar and Indian Platform areas and are absent in eastern part of Indus Platform and eastern Potwar (Rizvi et al., 1977).

In the Lower Indus Basin (Kirthar and Sulaiman Provinces) and adjoining areas of Axial Belt (Balochistan Ophiolite and Thrust Belt, Figure 1), the Cretaceous sediments are several hundred meters thick. The thickness, however, decreases considerably in the Kohat-Potwar Province. The greatest accumulation took place in the Karachi Embayment and is more than 4500 m where the Sembar and Goru formations are up to 3000 m thick but the area appears to be less active during Parh/Mughal Kot time (Companion to Early Maastrichtian). During Pab time (Maastrichtian) this area again became locus of active sedimentation. However, about this time, the Jacobabad High rose and prevented further sedimentation there. Cretaceous sediments thinout gradually east and west of Karachi Embayment. Thick (up to 3000 m) Cretaceous

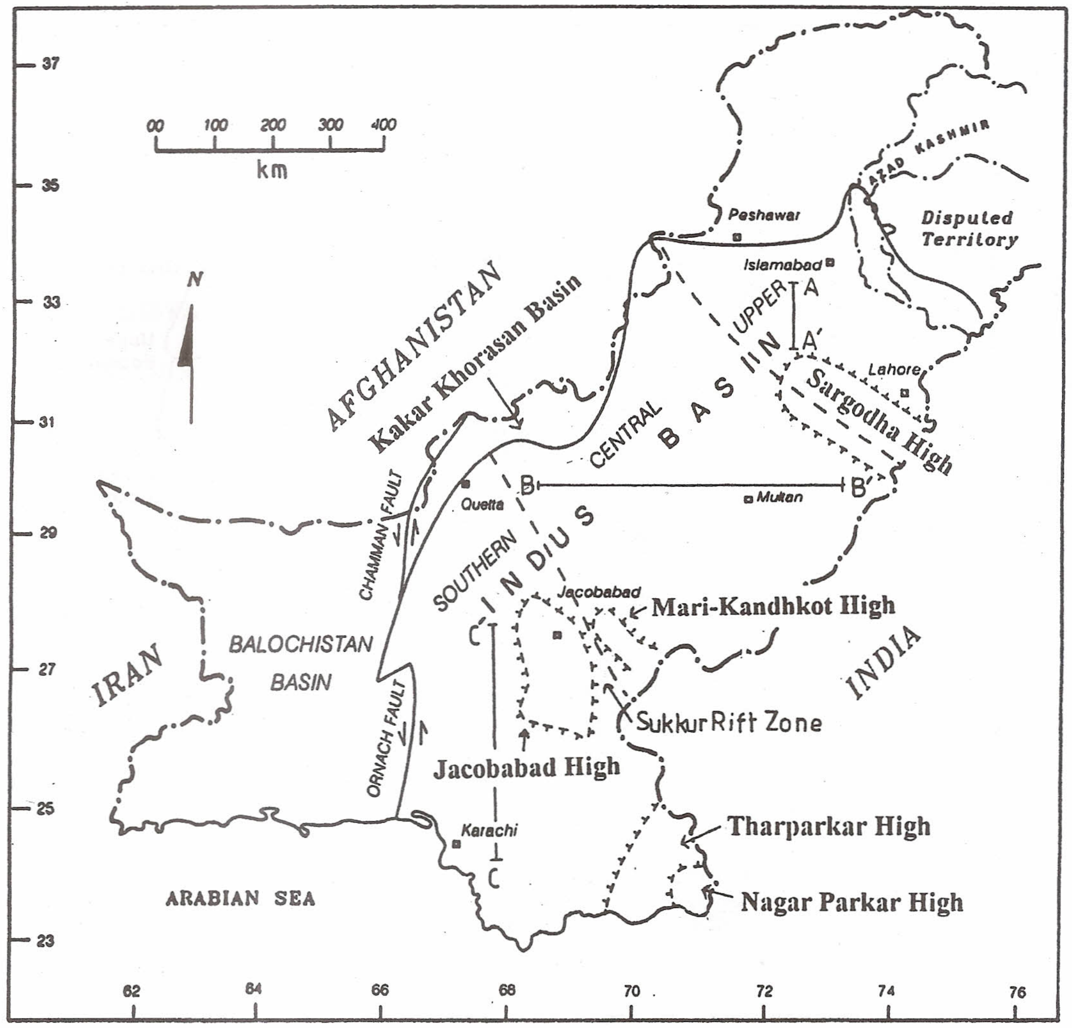

Figure 3- Sedimentary Basins of Pakistan (After Kadri, 1995).

sediments occur in the Sui-Sulaiman Trough and in the Waziristan area Upper Cretaceous strata were also thickly deposited.

SEDIMENTARY ENVIRONMENTS AND HYDROCARBON POTENTIAL

Pakistan has all the requisites for generation and accumulation of hydrocarbons. By the middle of 1997 about 400 exploratory wells had been drilled in Pakistan, which resulted in more than 100 small to moderate size discoveries of oil and gas. The sedimentary basins of Pakistan are composed of rocks ranging in age from Cambrian to Recent. Indus Basin is the most explored region and the Cretaceous rocks have source, reservoir and cap rock characteristics (Figure 5 and Table 2).

Northern Indus Basin

The Neocomian sequence of Kohat-Potwar area is marine, but the Aptian-Albian strata show a change to deltaic sediments that indicate an emergence of this area. This emergence was followed by marine transgression in the later part of the Late Cretaceous, but did not reach the Northern Indus Basin (Shah, 1977). Cretaceous rocks in the sub-basin mainly comprise shale and sandstone (Chichali Formation) and sandstone (Lumshiwal Formation), but in some areas marl and limestone (Kawagarh Formation) are present in the upper part. The Kawagarh Formation is absent in the Potwar Plateau and the Salt and Trans-Indus ranges (Khan et al., 1986).

Chichali Formation is a marine argillaceous and arenaceous facies rich in glauconite and formed in the marginal shallow transgressive seas in a reducing environment, also containing subordinate amount of calcareous sediments (Fatmi, 1966). According to Greensmith (1981) glauconite is formed under shallow marine reducing conditions and warm waters. Demaison and Moore (1980) mention that oil source beds and phosphorites result from upwelling and are present most frequently at low palaeolatitudes at times of Global highstands. These conditions prevailed during deposition of

Table 1. Stratigraphy and fauna of Cretaceous rocks of Indus Basin (Abridge from Iqbal and Shah, 1980).

Formation and Stage	Lithology	Fauna
A. Northern Indus Basin (Kohat-Potwar Province)		
Kawagarh Formation (Coniacian to Campanian)	Dark coloured marl and shale cleaved and calcareous with limestone which is nodular and argillaceous.	*Globutruncana, Heterohelix, Globorotalites*
Lumshiwal Formation (Tithonian-Albian)	This formation mainly consists of light grey sandstone, thick-bedded to massive, current bedded, feldspathic, ferruginous and contains carbonaceous material in the upper part. Shale,silty-sandy and glauconitic beds are present in the lower part	*Gryphaea, Trigonia, Dourilleiceras, Oxytropidoceras, Lemmunoceras, Ammonitoceras*
Chichali Formatin (Late Oxfordian to Neocomian)	This is dark grey, bluish grey, greenish grey, sandy, silty, glauconitic shale with dark green, greenish grey glauconitic sandstone.	*Perisphinctes,Mayaits, Belemnopsis,Hobolites, Aspidoceras, Physodoceras*
B. Central and Southern Indus Basins (Sulaiman and Kirthar Provinces)		
Moro Formation (Maastrichtian)	This formation mainly consists of limestone, marl and shale with minor sandstone and some volcanic conglomerates. Limestones are grey medium-to thick-bedded and argillaceous. The marls are grey to dark grey and the shale is dark grey to greenish grey and calcareous.	*Globotruncana linnei, Lituola, Omphalocyclus, Orbitella, Orbitoides, Siderotites*
Pab Sandstone (Maastrichtian)	This consists of white, cream and brown coloured sandstone, medium-to course-grained, thick-bedded to massive and quartzose; with some cross-bedding marl and argillaceous limestone intercalations and subordinate shale.	*Orbitoides minor*
Fort Munro formation (Late Campanian to Early Maastrichtian)	Limestone, dark grey to black, very hard, thick-bedded, sandy in the upper part, argillaceous in lower part in the northern Sulaiman Province and Axial Belt, whereas in southern part light grey-yellow grey, medium hard, argillaceous slightly calcareous shale is present.	*Omphalocyclus, Orbitoides, Siderotites*
Mughalkot Formation (Campanian to Early Maastrichtian)	Dark grey calcareous mudstone and dark grey shale, calcareous, fossiliferous with intercalations of quartzose sandstone. Light grey argillaceous limestone is also present. Limestone and sandstone are well developed in the northern part of the Sulaiman Province.	*Orbitoides, Omphalocyclus, Siderolites*
Parh Limestone (Cenomanian to Santonian)	Parh limestone is a lithographic, porcellaneous and argillaceous. It is white, cream, olive-green and maroon in colour, and hard, thin-to medium-bedded. Subordinate amount of calcareous shale and marl intercalations are also present.	*Globotruncana ventricosa, G. sigali, G. lapparenti, Pseudotextularia*
Goru Formation (Aptian to Cenomanian)	This consists of light to medium grey, olive-grey interbeds of limestone, shale and siltstone which grades downward into sandstone. Limestone is dominant in lower and upper parts.	*Globigerinelloides, G. caseyi, Retalipora, ticinensis, R. brolzeni, Hibolithes*
Sembar Formation (Tithonian to Neocomian)	Shale, black, silty with interbeds of black siltstone and nodular rusty argillaceous limestone. It is fossiliferous, glauconitic, pyritic and contains phosphatic nodules. In the basal part a sandy shale is developed.	*Hibolithe pistilliformis, H. subfusiformis, Duvalia, Virgalesphinctes*

the Chichali Formation (and also Sembar Formation of Lower Indus Basin). Because of its deposition in reducing environments and fair to good maturity, this formation bears source rock characteristics (Kadri, 1995). In the Attock-Hazara Fold and Thrust Belt the Chichali Formation may also act as source rock, but it is overmature for oil. In the Kala-Chitta Range, however, the Chichali Formation is within the oil window. Potential hydrocarbon reservoirs may occur in the Chichali Formation (Gazanfar et al., 1990).

The petrographic studies of Lumshiwal Formation indicate a change from marine to non-marine environment, and deltaic and prodeltaic conditions resulted in deposition of sandstones during the Aptian to Albian (Shah, 1980). The Formation bears good reservoir characteristics and contains gas in Punjpir and Nandpur gas fields of Central Indus Basin (Kadri, 1995).

The temperature regime in Northern Indus Basin is conducive to oil generation (Figure 6). The average geothermal gradient is about 2 ^{o}C /100 m (Khan and Raza, 1986), and the general range of an oil window is between 2700 to 5700 m (Figure 7). There is an ideal coexistence of source, reservoir and trap in Cretaceous rocks within a favourable geothermal regime (Kadri, 1995).

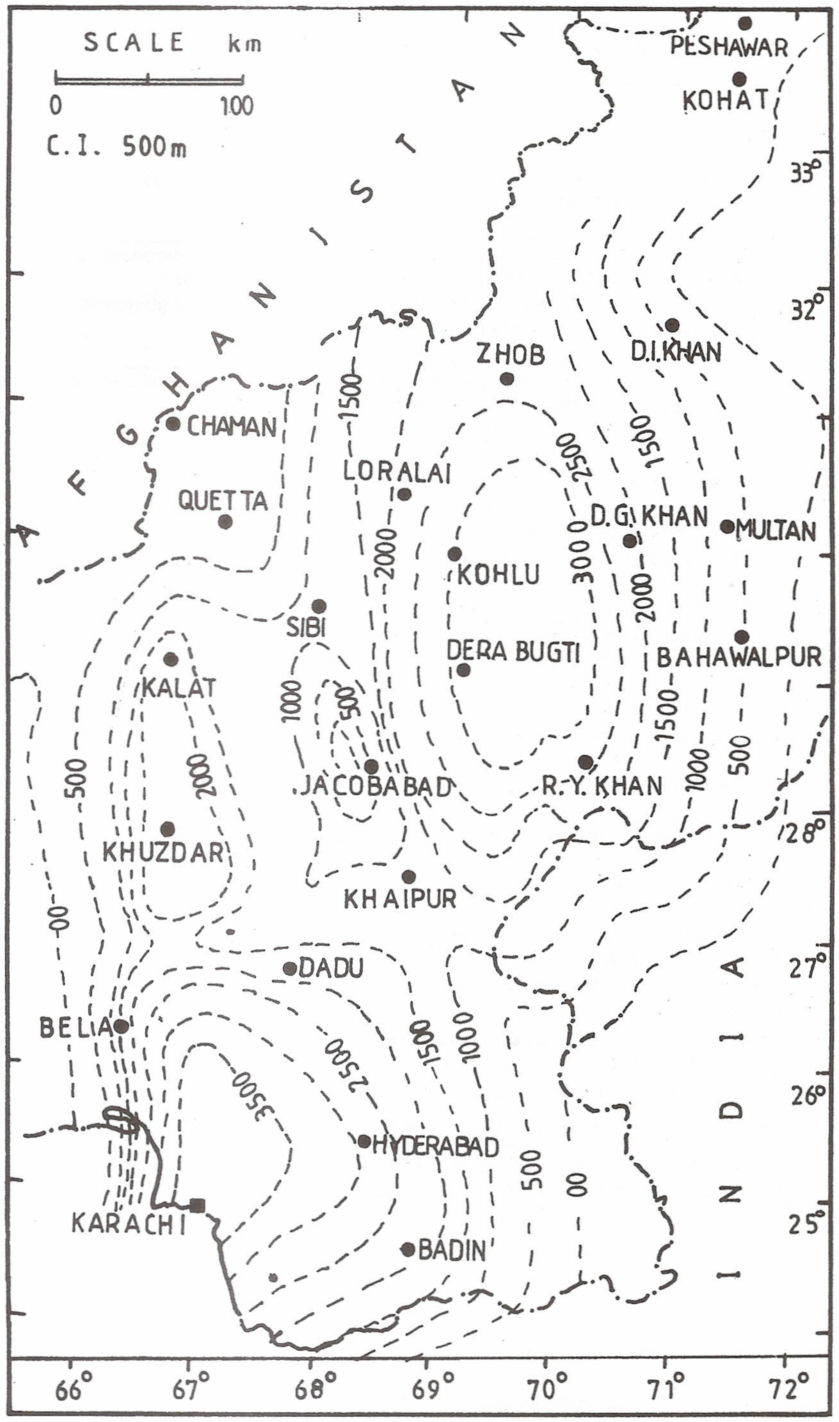

Figure 4- Isopach map of Cretaceous strata of the Indus Basin (After Kadri, 1995).

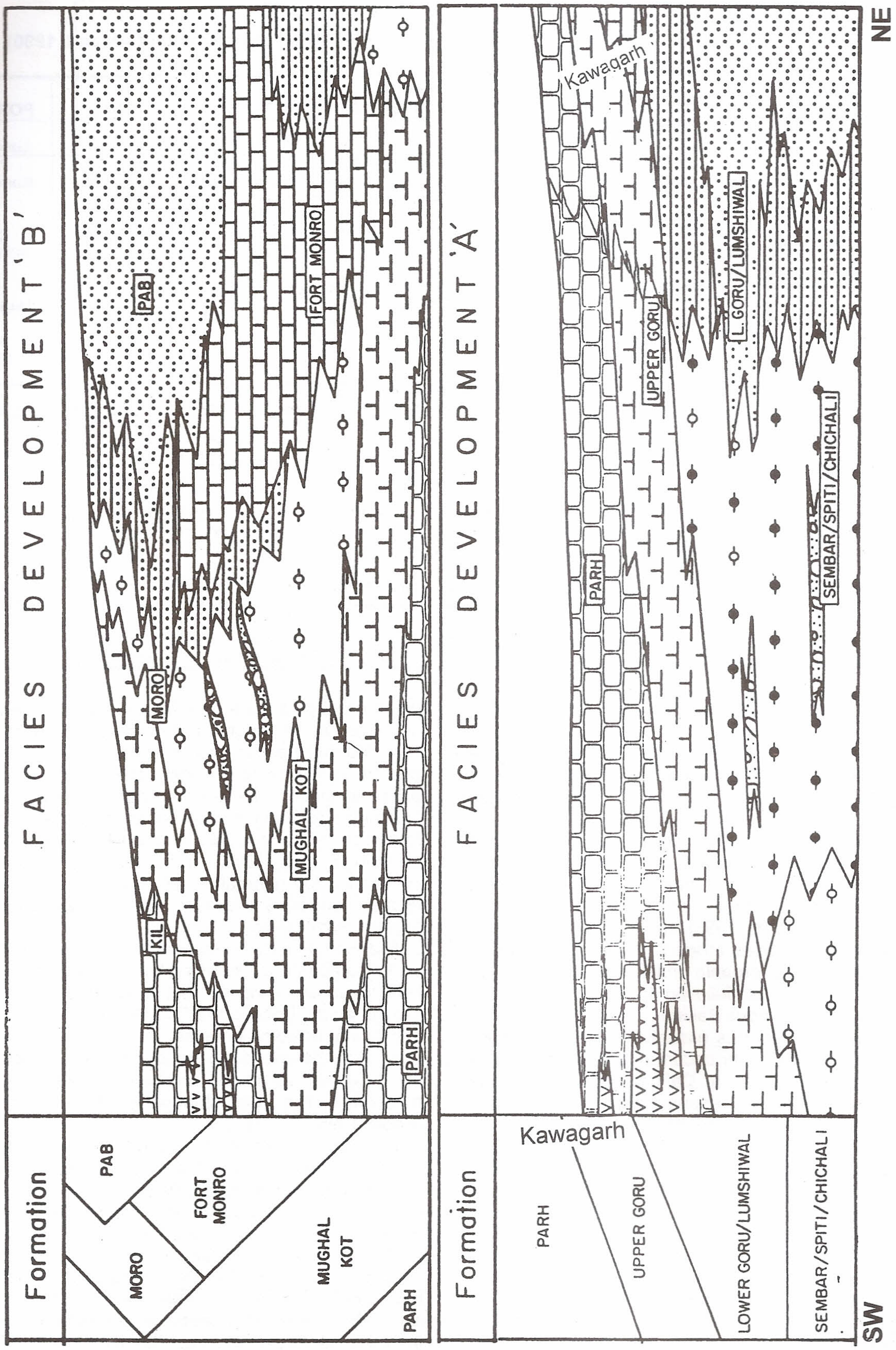

Figure 5- Schematic stratigraphic-cross-section of Lower Cretaceous (A) and Upper Cretaceous (B) (After PHH, 1988).

Table 2. Cretaceous source, reservoir and cap rocks of Indus Basin (Modified after Raza and Ahmed, 1990).

BASIN	SOURCE	RESERVOIR	CAP	MAJOR DISCOVERIES	TOC%	VR%	POROSITY %
Northern Indus Basin	Chichali (sh.)	Lumshiwal (sst.)	Hungu (sh.)				5-10 (Lumshiwal sst.)
Central Indus Basin	Mughal Kot (lst/Marl)	Lumshiwal (sst.)	(sh.)	Sarai Sidhu (Gas), Nandpur (Gas), Panjpir (Gas), Pirkoh (Gas)	0.34-0.64 (Mughal Kot lst.)	1.97 (Mughal Kot lst.)	7.0-12.0 (Lumshiwal sst.)
		Pab (sst.)	Ranikot (sh.)	Bhit (Gas), Dhodak (Cond.)	0.52-4.33 (Sembar sh.)	3.05-3.30 (Sembar sh.)	12.0-17.0 (Chichali sst.)
	Chichali/ Sembar (sh.)	(sst./lst.)	(sh.)	Kadanwari (Gas), Miono (Gas), Khairpur (Gas), Loti (Gas), Kandkot (Gas), Rhodo (Gas)			16.0 (Mughal Kot sst.)
		Pab (sst.)	(sh.)				5.0-15.0 (Pab sst.)
			Ranikot (sst.)				
Southern Indus Basin	Mughal Kot (Lst)	Pab (sst.)	Khadro (sh.)	Khaskeli (Oil), Turk (Oil), Nari (Cond.)	0.07-3.48 (Mughal Kot lst.)	1.13-2.06 (Mughal Kot lst.)	5.0-30.0 (L. Goru sst.)
		(lst.)	(sh./lst.)	Golarchi (Gas), Laghari (Oil), Tajedi (Oil)	1.57-1.72 (Pab sh.)	1.07-1.09 (Pab sh.)	
	L. Goru (sh.)	(lst.)	(sh.) U. Goru (sh.)	Jabo (Gas), Akri (Oil), Ghotana (Gas) and Lashari (Cond.)	2.55 (U. Goru sh.)	1.51 (U. Goru sh.)	
	Sembar (sh.)	L. Goru (sst.)	U.Goru (sh.)	Ghunghro (Oil), Paniro (Oil) and Dhupri (Cond.)	1.72 (L. Goru sh.) 3.0 (Sembar sh.)	1.27 (L. Goru sh.) 0.87 (Sembar sh.)	9.0-36.0 (Sembar sst.)

Central Indus Basin

Cretaceous sediments in Central Indus Basin include the Lower Cretaceous Sembar and Goru/Lumshiwal formations and the Upper Cretaceous Parh, Mughal Kot and Pab formations.

The Sembar and Goru formations possess source reservoir and cap rock properties such as abundant pyrite and carbonaceous matter that indicate reducing depositional conditions and as such may prove to be good source rocks (Shuaib et al., 1993). Only the basinal toe-set facies of Sembar and Goru formation's deltaic sequence appear to be a locus for organic enrichment (PHH, 1988). The Sembar Formation is believed to be the source of hydrocarbons in Central Indus Basin.

The Lumshiwal Formation is essentially of frontal deltaic or shelf type environment. Its occurrence is confined to a small area in the north-east of Central Indus Basin. The formation is an important gas reservoir zone in Sarai Sidhu-I, Nandpur-I and Punjpir-I wells (PHH, 1988).

According to Shuaib et al. (1993) the Parh Limestone contains abundant organic content and seems to have source rock properties. In the Central Indus Basin the Parh Limestone is considered to be the result of deposition in clear deep water of an outer shelf facies. This Formation also has reservoir characteristics, but till late 1997 no oil or gas has been found in Parh Limestone while recently gas is discovered. The Upper Goru is capped in most areas by the Parh Limestone (Kemal et al., 1991).

Limestones of Mughal Kot Formation are mostly compact, argillaceous, carbonaceous and do not have reservoir properties. However, it is rich in organic matter and mostly gives off a strong fetid smell when broken and as such could be good source rock for hydrocarbon generation. Oil seepages at the Mughal Kot gorge are probably generated from Mughal Kot limestones/shales. Sandstones are also present in the eastern portion of Central Indus Basin and possess good reservoir properties. The Mughal Kot Limestone represents shelf facies, and shales of the same formation were deposited in the deeper part of the basin (Shuaib et al., 1993). Indications of silled conditions, necessary for generation of hydrocarbons, are present. Anoxic conditions prevailed enabling the preservation of organic matter (Kadri, 1995).

The Fort Munro Formation represents a thick shallow-water carbonate platform system (Kemal et al., 1991), but limestones are confined mainly to the Sui and Sulaiman Trough areas. Locally, the Fort Munro Formation contains a rich fauna including potential reef building organisms. This fact, plus the existence of the overlying Pab Sandstone which could serve as reservoir, makes the limestone favourable from the standpoint of petroleum potential (Kadri, 1995).

The Pab Sandstone crowns the Cretaceous sequence in the Central Indus Basin. It is mainly of shoreface origin and as such has a widespread distribution and uniform internal characteristics. It has proven to be an important gas reservoir at Pir Koh and Rodho fields as well as condensate-gas at Dhodak field (Shuaib et al., 1993). In the Central Indus Basin the Pab Sandstone is considered to have been deposited in shallow-water, not far from shore line. In the Mughal Kot seepage area most of the oil comes from the contact of the Pab Sandstone with the overlying Palaeocene Ranikot Formation. The Pab Sandstone is considered to have no source potential.

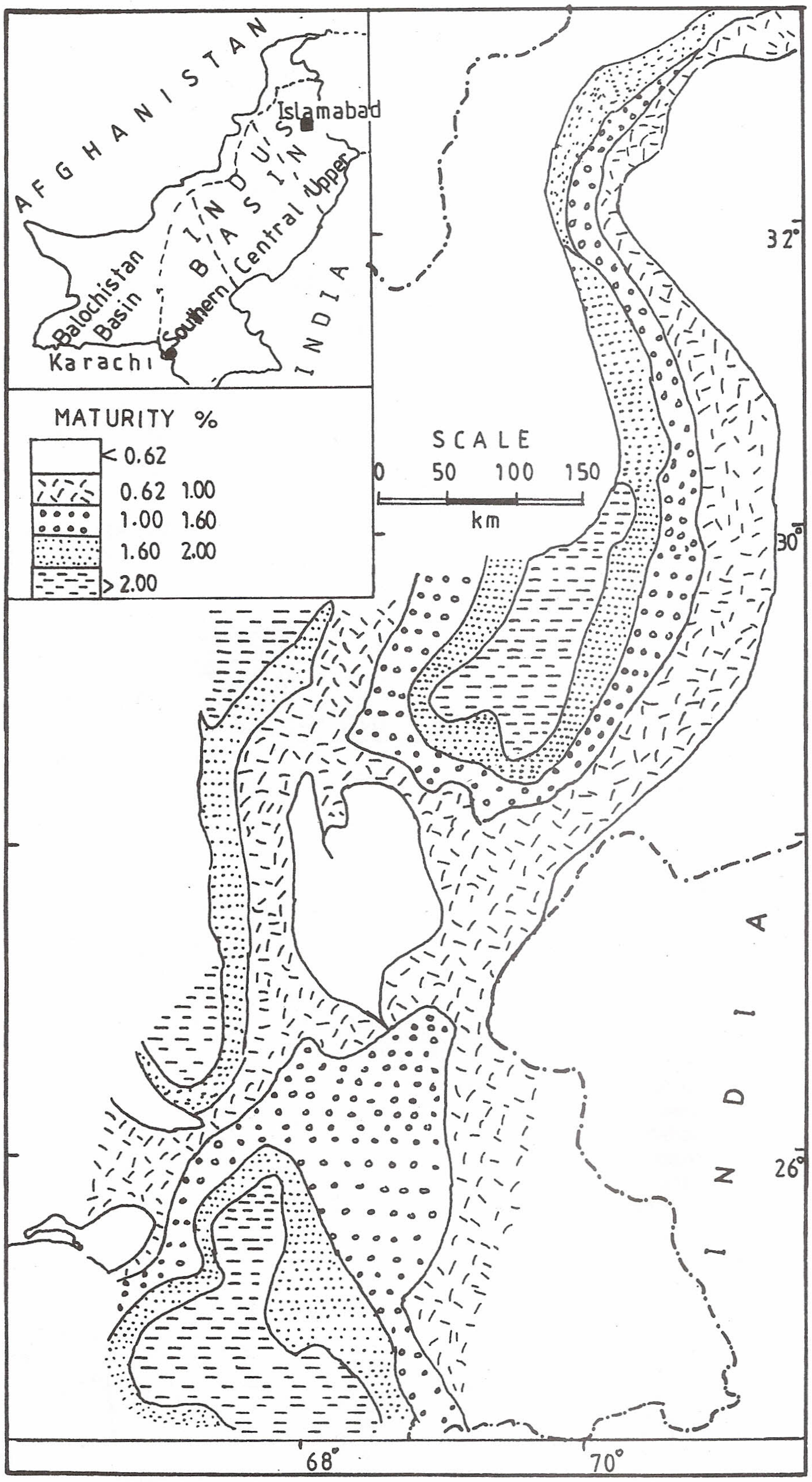

Figure 6- Map showing base Cretaceous maturity of the Indus Basin at present day (After Kemal, 1991).

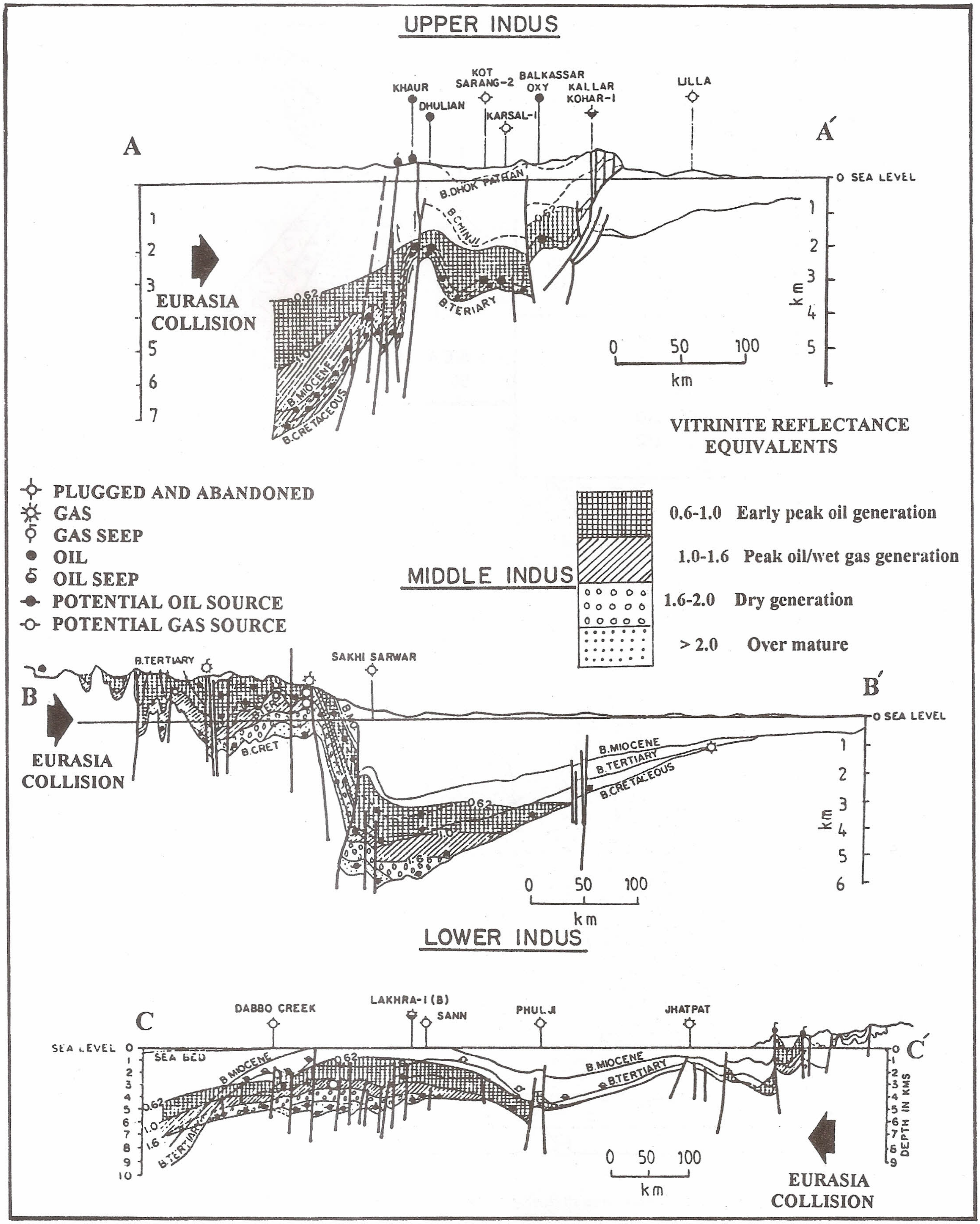

Figure 7- Maturity profiles of Indus Basin (After Kemal, 1991).

The Source rock potential in the Central Indus Basin in the Sembar and Mughal Kot formations has been proven geochemically confirmed (Raza and Ahmed, 1990). The temperature regime in Central Indus Basin ranges from 1.4 to 4.1 °C/100 m (Av. 2.4 °C/ 100m). In Central Indus Basin condensate has been encountered in Cretaceous sediments in the Dhodhak structure where the gradient is 3.2 °C/100m. The oil window ranges between depths of 1700 and 3350 m in Lower Eocene to Lower Cretaceous sediments. Towards the north and south of the Dhodak well, the gradient falls to 2.1 °C/100m at the Domanda and Sakhi Sarwar structures. The range of oil window in these wells is between 2600 and 5000 m falling in the Eocene to Upper Cretaceous sequence. In the Sui gas field an average gradient of 3 °C/100m prevails, while in individual wells, values of 2.83 to 3.1 °C/100m have been calculated. In both these field, the window lies below the gas producing horizons somewhere in Cretaceous sediments (Khan and Raza, 1986).

Southern Indus Basin

Nearly all of the oil and gas production (30,000 barrels of oil and 1200 million cubic feet gas per day) from Lower Indus Basin is directly attributed to Cretaceous sources (Kadri and Khan, 1994). In the Southern Indus Basin the Cretaceous sediments range from shale deposited in deep depression overlain by bar-type sands in the basal part, through deep and shallow marine limestones, into thick sandstone in the upper part (Raza et al.,1990).

Several oil and gas discoveries in Southern Indus Basin have been made, most of which are concentrated in the platform area (Badin block) where Cretaceous sandstones contain small traps associated with normal faulting. The structures in Badin area can be categorized in two regions 1) products of rifting extending from adjoining Indian Rift Basins 2) product of compression associated with plate convergence (Raza and Ahmed, 1990).

Cretaceous rift features in northern part of Southern Indus Basin of Pakistan are generally grouped “Sukkur Rift Zone” which comprises a graben flanked by two horsts. These features partly extend into India and host oil and gas fields on both sides of the border. The main graben (Cambay Graben) is formed in the Indian side. Rapid facies changes (Bhuj and Dhrangadhra formations in India) are noticed in Cretaceous section due to effect of rifting in the south (Ahmed and Ahmed, 1991). Stratigraphic prospects exist in the western part of the Indian Kutch Basin (south of Cambay) and in offshore basins. Mid-Jurassic reefal carbonates and Lower Cretaceous deltaic sediments are the main exploration objectives (Biswas, 1982). The Sembar and Lower Goru are by far the most important potential source and reservoir in the Southern Indus region (PHH, 1988).

The Sembar Formation is considered to have been deposited on a broad shelf, gently sloping westward off the Indian Shield. According to North (1985) anoxic regions occur preferentially off the west side of continents in lower latitudes. Some silling may have existed and circulation would therefore have been restricted. Numerous good source rock determinations as well as gas and oil shows have been reported from the Sembar, which suggest the presence of reducing conditions. The Sembar Formation is the source of hydrocarbons in Badin Platform field (Kadri, 1995). Sandstones of Sembar Formation represent a secondary, intermediate depth objective for hydrocarbon exploration. These sandstones probably represent aggradational (or minor progradational) deposits that were laid down in minor stillstands of sea level which occurred during worldwide Early Cretaceous sea level rise (Hussain et al., 1991). In the Badin rift sub-basin, in the Southern Indus Basin, organic rich Sembar shales, deposited during Late Jurassic to Early Cretaceous, act as source to overlying good quality Lower Cretaceous Lower Goru sandstone reservoirs (Hassan, 1994). The Upper Cretaceous Upper Goru claystone/marl provide an excellent seal. The discovery of oil in the Badin Block in the Khaskheli field confirmed the presence of optimum condition for hydrocarbon exploration in southern Pakistan (Hassan, 1994).

The Lower Goru is composed of inter-bedded sandstones and shales deposited in a deltaic to shallow marine environment (PHH, 1988). The sandstones are predominantly quartzitic, fine- to medium-grained, with fair to good sorting. These sandstones are shallow marine laterally extensive bar-type deposits (Ahmed and Ashton, 1982). The potential of Lower Goru seems to be high in view of discovery of various oil and gas reservoirs. The sandstone facies of prograding delta-front is widely distributed with 4/1 sand/shale ratio, which is considered as ideal reservoir-source combination. In eastern part of Karachi depression and offshore these shales are within oil and gas window. The Upper Goru may act as cap rock over underlying formations (Raza et al., 1990).

The Upper Goru is capped in most areas of the Southern Indus Basin also by the Parh Limestone, a thin carbonate ramp deposit (Kemal et al., 1991). The micritic nature of the limestone indicates deposition far from source areas of clastic sediments, a factor which probably accounts for overall thinness. Its widespread distribution results from a general transgression of the sea during early Late Cretaceous. The unit is highly fossiliferous. Gas deposits has been reported in the northern part of the Central Indus Basin.

The limestones of Mughal Kot Formation was deposited mainly in shallow water and its thinning indicates deposition on shelf areas or along developing positive trends (Kadri, 1995). Gas shows were recorded from Mughal Kot Formation in wells Patiani Creek-I and Dabbo Creek-I. Indications of silled conditions are present in Karachi depression. The formation shows good source rock potential and is within oil window in offshore platform and Karachi depression (Raza et al., 1990).

The thick interbedded quartzose sandstones and shales of the Pab Sandstone were deposited in the Central and Southern Indus basins, which represents delta plain or shallow water environments (Kemal, 1991). The Pab Sandstone is areally the most restricted of the Cretaceous formations, and extends from Karachi to the Kirthar Range. The thickest sequence of the Pab Sandstone accumulated adjacent to Axial Belt in the area north and north-west of Karachi. Over 1200 m was deposited in a narrow northwest-southeast oriented basin. The eastward thinning from this depression is accompanied by an increase in thickness of the underlying Mughal Kot Formation, due to lateral gradation (Kadri, 1995). The Pab Sandstone is considered to have been deposited in shallow water. Pab Sandstone forms petroleum reservoirs at PirKoh, Loti, Dhodak and Rhodo fields in Central Indus Basin.

Geochemical studies indicate source rock potential in Sembar and Lower Goru formations in the Southern Indus Basin (Raza and Ahmed, 1990). The temperature regime is variable in the Southern Indus Basin, probably due to mixed compressional-extensional tectonics, and the associated lava flows. The average geothermal gradient is 2.45 °C/100m. In the Southern Indus Basin gas shows were recorded in Palaeocene (Bara) and Cretaceous (Goru) structures. Geothermal gradient in Lakhra-I was high (3.3 °C/100m), the oil window being much shallower (1650-3200m). The geothermal regime and stratigraphic structures, are very encouraging, with a probability of gas condensate or gas prospects in deeper (Cretaceous and below) horizons, given the right type of source rock. In Badin Block, the Nabisar, Digh, Badin and Patar wells have an average geothermal gradient of 2.1-2.3 °C/100m. The oil-producing and prospective Cretaceous rocks (which are also established source rocks of the contained oil) are not present within oil window in Nabisar, Digh and Badin wells, the wells have not produced. However, oil shows were encountered in the Patar well, since the Cretaceous rocks were present in the oil window. The Talhar, Tarai and Khaskheli wells exhibit range of average geothermal gradient from 2.65-3.1 °C/100m. The source rocks of Cretaceous age (Sembar and Lower Goru formations) exist within the range of oil window, and the area thus has a high potential for oil generation. In the Karachi region (Dabbo Creek wells), the potential source rock (Sembar shales) appears to be over-cooked as it occurs in a temperature zone deeper than 163 °C. In the Badin block, Cretaceous-Palaeocene basaltic lava-flows seems to have caused higher geothermal gradient in the western part (Figure 8). In those areas on the Badin block where potential source rocks are present within the oil window, oil accumulations have been found (Khan and Raza,1986).

CONCLUSIONS

1. During Cretaceous Period, the Pakistani branch of Tethys Sea, a broad marine shelf, was a silled basin with high biological productivity in which oxic and anoxic layers enabled preservation of organic matter.
2. Cretaceous rocks are developed in the Indus Basin and represent mostly shelf facies. There is a facies change both vertically and horizontally caused by the successive transgression and regression phases due to regional tectonic activity during the Cretaceous. This facies change is responsible for the entrapment of hydrocarbons in Southern Indus basin.

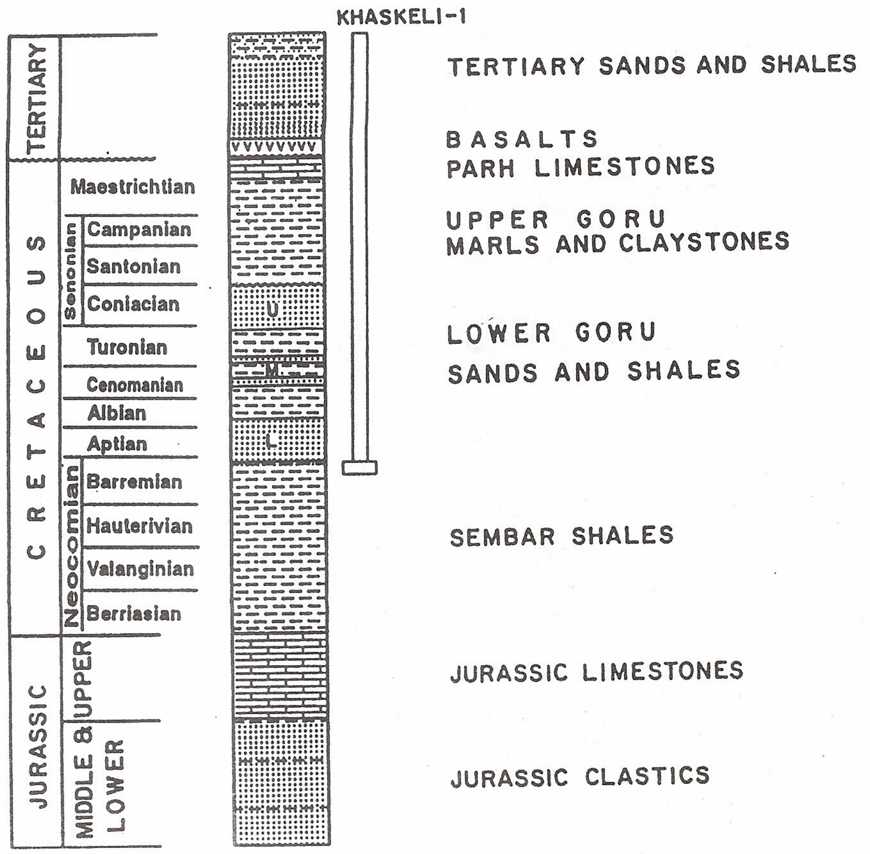

Figure 8- Generalized stratigraphic section of Badin area (After Ahmed and Aston, 1982).

3. Basinal toe-set facies of Sembar /Goru Formations of deltaic sequence in the Central Indus Basin appear to be locus for organic enrichment. Sembar and Goru/Lumshiwal formations were deposited in reducing conditions and possess properties of source, reservoir and cap in a favourable geothermal regime.
4. In the Central Indus Basin Parh Limestone is deposited in deep outershelf environment, have source/reservoir properties and gas discovery is made from this formation.
5. The Mughal Kot Formation (limestones) of the Central Indus Basin represents mostly a shelf facies, with deeper shales and subordinate sandstones. Indications of silled basin are present. Limestones of this formation could be good source rock while sandstones possess good reservoir properties.
6. Petroleum potential of shallow shelfal limestone of the Fort Munro Formation seems to be favourable in Sui and Sulaiman troughs.
7. The Pab Sandstone of shore-face origin is a proven reservoir in Central Indus Basin.
8. In Central Indus Basin Lower Eocene to Lower Cretaceous sediments fall within oil window.
9. Both divergent and convergent structural as well as stratigraphic traps are present in Badin Block of Southern Indus Basin.
10. In southern Indus Basin the Sembar Formation was deposited on a broad shelf in reducing conditions with some silling in the basin and restricted circulation. In Badin Platform field the Sembar shale is believed to be the source and sandstone represent a secondary intermediate depth objective for hydrocarbon exploration.
11. In Badin area , the Lower Goru sand acts as a good reservoir rock. The potential seems to be very high in view of the discovery of various oil and gas fields. These sands are shallow marine bar-type predominantly quartzitic. The Goru shale shows characteristics of source rock and falls within oil window.
12. The Mughal Kot Formation in Southern Indus Basin shows good source potential as it is within oil window in Karachi depression and offshore areas. In these areas indications of silled basin are present.

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