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Facies Changes and Hydrocarbon Presence in Offshore Indus Basin, Pakistan

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ABSTRACT

Pakistan Offshore Exclusive Economic Zone extends over an area of almost 265,650 sq. km, bordering Pakistan coastline of about 825 km length between Iran border in the west and Indian border in the east. Pakistan Offshore is divided into two major divisions: (i) Offshore Indus basin, and (ii) Offshore Markran basin; having Murray Ridge/Owen Fracture as the dividing line between the two. Offshore Indus Basin lies between Murray Ridge and Indian border and is divided tectonically into three units: (1) An Offshore Depression on the west between Murray Ridge and the Hinge-Line, (2) The Offshore Karachi Trough Platform between the Hinge-Line and Karachi Trough shoreline, and (3) The Offshore Thar Slope Platform or Indus River Deltaic area.

Nine wells were drilled in offshore Indus basin, three wells near Karachi Trough shoreline (Dabbo Creek, Patiani Creek and Korangi Creek), one well on the Platform (Karachi South A-1) and five wells in the Depression (Indus Marine A-1, B-1 and C-1; PakCan-1 and Sadaf-1). Oil and gas shows and traces were recorded in all wells but gas was only discovered in DST-3 Miocene sandstone horizon of PakCan-1 in January 1986 with gas flow rate 3.7 MMCF/day. The presence of gas has opened up vast avenue of further exploration and drilling and confirms the presence of hydrocarbons in offshore Indus basin. Cretaceous sediments become dominantly shaly/marly towards the west from shoreline in offshore Indus basin and are deeply buried. They can be explored and drilled in onshore at comparatively shallow depths. So Paleocene, Eocene, Oligocene and Miocene limestones/sandstones seem to be the main hydrocarbon objectives in offshore Indus basin. Isopachs and facies maps of Eocene Kirthar Formation, Oligocene Nari Formation and Miocene Gaj Formation indicate that Indus river came into existence after Eocene bordering the Sulaiman and Kirthar mountain ranges in the east and built a delta advancing southward resulting in the present position. The maximum thickness of sediments in offshore Indus basin is calculated from seismic sections as greater than 11,000 metres and reflects sedimentation since rifting of the Indian margin in Cretaceous and earlier times. However, the fan sedimentary sequences have been deposited since Oligocene as a consequence of Himalayan uplifts and sea level changes.

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INTRODUCTION

Pakistan holds a special position in the tectonic and geodynamic framework in area between Iran and Central Asia, with a coastline of 825 km length, the Offshore Exclusive Economic Zone of Pakistan extends 265,650 sq.km between Iran and Indian borders (61° 45' to 68° 10'E) and is divided into two main divisions, the offshore Indus basin in the east (23° to 25° N; 66° to 68° E) and offshore Makran basin in the west with Murray Ridge/Owen Fracture as the dividing line between the two. Murray Ridge/Owen Fracture is a submerged high zone in prolongation of the onshore Pab Range (Figure 1). Exploratory efforts in offshore Indus basin comprised of 34,984 km of seismic survey and nine wells, out of which three did not reach objectives due to technical problems while other four appear to have been located on no/inadequate traps though gas shows/traces were recorded in all wells (Figure 2). Difficulties encountered during drilling were mainly due to the over pressures.

A comprehensive pressure study based on well and velocity analyses of seismic was made to identify the over pressured zones. In addition, review and reinterpretation of the seismic data was carried out. These studies indicate that Indus offshore is an extension of Karachi Trough and Thar Slope platform with pressure a function of depth and dependent upon stratigraphy to a small extent only.

EXPLORATION HISTORY

In the Indus offshore, Sun Oil Company carried out single and double seismic survey of 3,816 km in 1961-62, and drilled three near shore wells, Dabbo Creek-1 (1963), Patiani Creek-1 (1964) and Korangi

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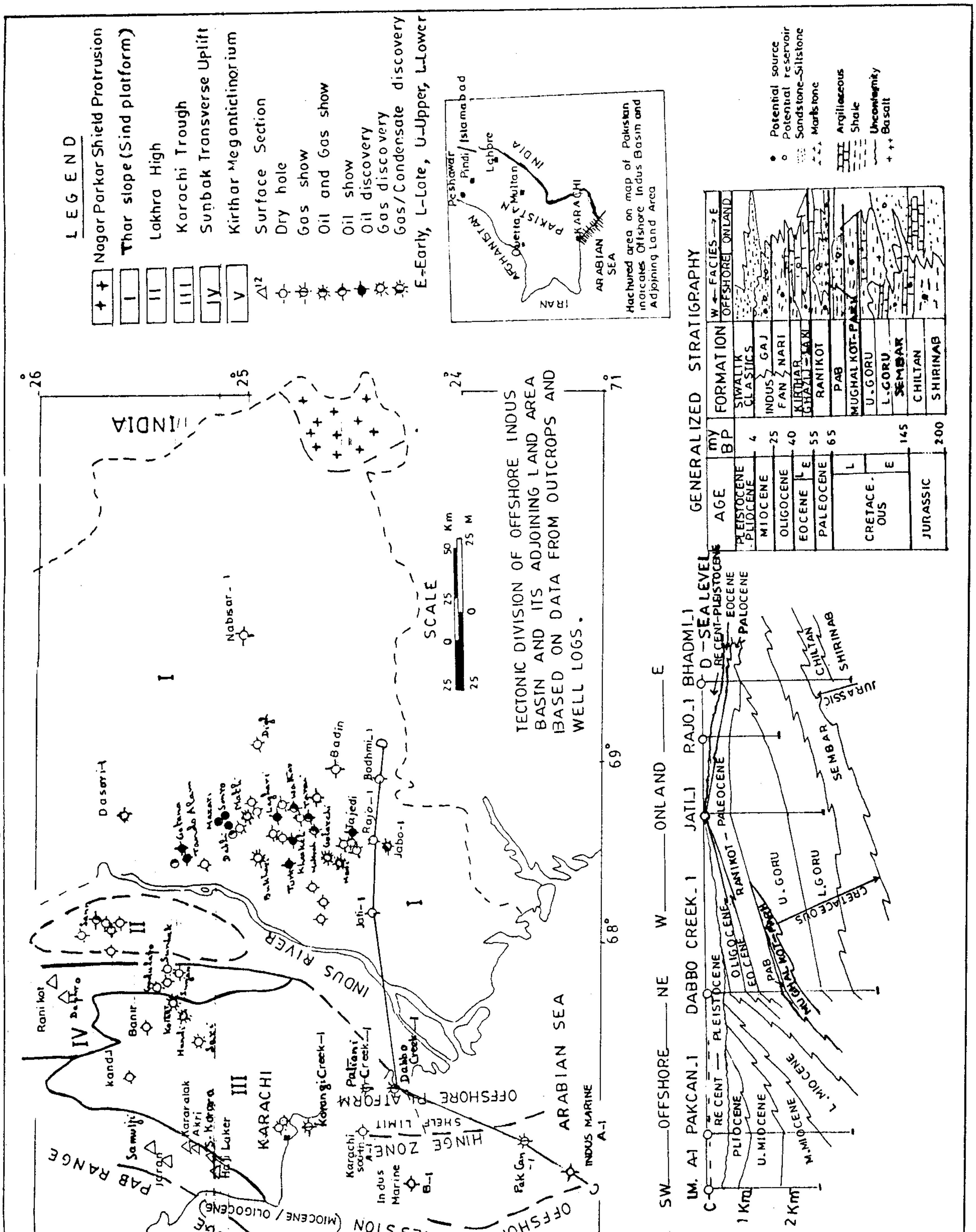


Figure 1– Stratigraphic cross sections along line C-D based on the shown well log locations.

SEISMIC SURVEY

S No	Company	Fold	Year	Length
1.	Sun Oil Co.	(Single and double fold only)	1961-62	3816 Km.
2.	Wintershall	24 Fold	1969-72	9400 Km.
3.	Shell International	12 Fold	1973	506 Km.
4.	Phillips	24 Fold	1977	2557 Km.
5.	Husky	24 Fold	1976-78	2380 Km.
6.	E L F-Acquitaine	24-36 Fold	1977	3004 Km.
7.	OGDC- NORAD	48 Fold	May 1982	1150 Km.
8.	OGDC- PCIAC	60 Fold	APRIL-MAY JUNE 1986	5732 Km.
9.	OXY	60 Fold	1988-89	5685 Km.
10	CANTERBURY	24-28 Fold	1990	754 Km.
			TOTAL	34984 Km.

WELLS DRILLED

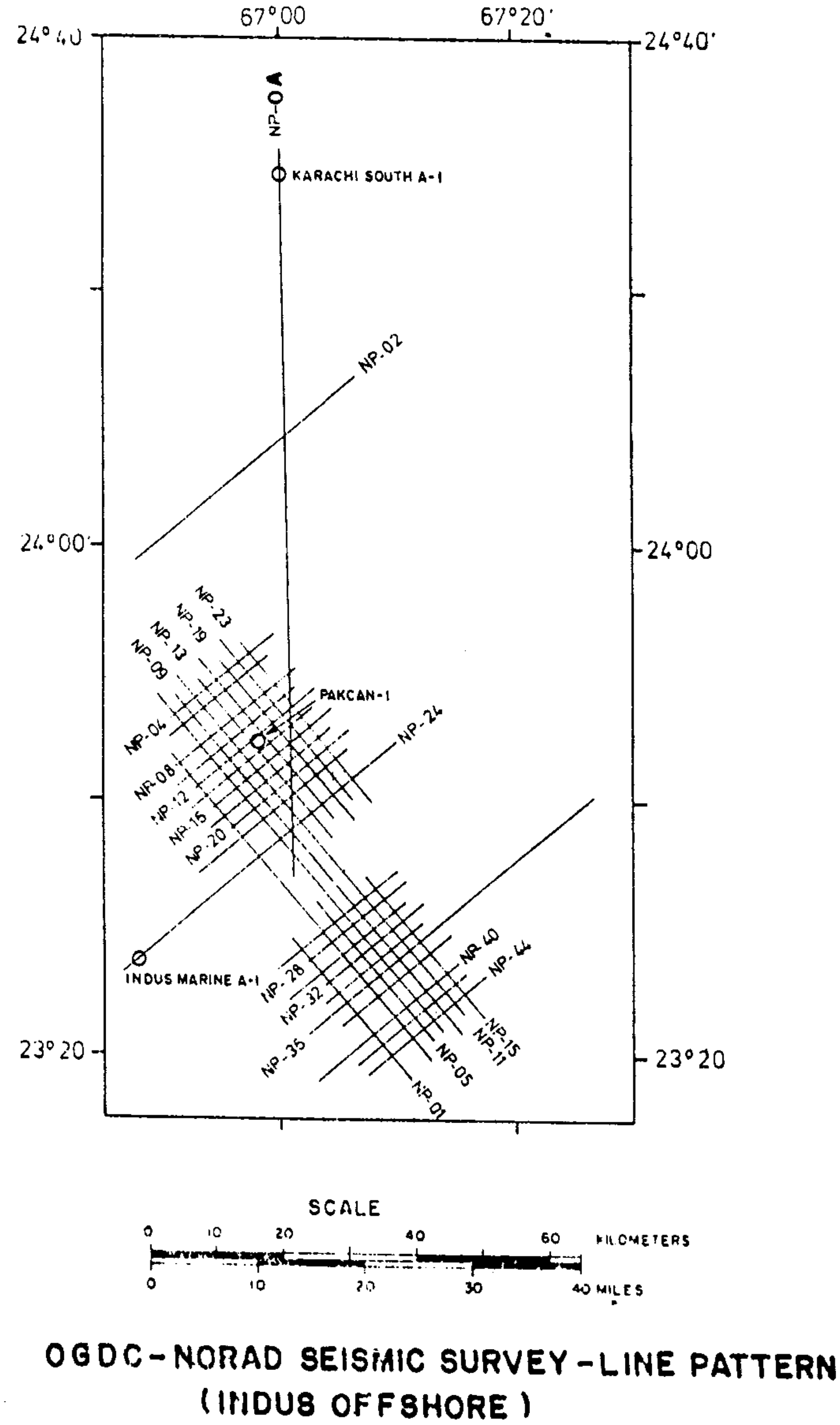
S No	Name of well	Company/Year and location	T.D. in Metres K.B.(Sea level)	Age and formation reached	Remarks
1	Dobbo Creek-1	Sun/1963 24°-20'-02"N 67°-16'-42" E	4354(-4336)	L.Cretaceous Sembar Formation	D & A. Gas shows in Cretaceouse. Drilled on down throw side of fault according to Husky Seismic.
2	Patiani Creek-1	Sun/1964 24°-27'-00" N 67°-17'-30" E	2659(-2643)	U.Cretaceous Mughalkot Formation	D & A. Gas shows in U.Cretaceous. Drilled on the flank of the structure.
3	Korangi Creek-1	Sun/1964 24°-42'-42" N 67°-04'-14" E	4140(-4122)	L.Cretaceous Mughalkot Formation	D & A. Gas shows in Paleogene
4	Indus Marine A-1	Wintershall/1972 23°-27'-27".894 N 66°-48'-25.522" E	2841(-2831)	M.Miocene Gaj Formation	Abandoned due to technical reason after kicking
5	Indus Marine B-1	Winter-shall/1972 24°-15'-02.776" N 66°-45'-20.154" E	3804(-3793)	L.Miocene Gaj Formation	Abandoned due to technical reason after kicking.
6	Indus Marine C-1	Winter-shall/1975 24°-36'-01.111" N 66°-16'-24.073" E	1942(-1932)	L.Eocene Ghozij Formation	Abandoned due to high pressure.
7	Karachi South A-1	Husky/1978 24°-29'-08.3" N 67°-00'-29.7" E	3353(-3338)	U.Cretoceous Mughalkot Formation	D & A. No Structural closure due to absence of fault
8	PakCan-1	OGDC-PCIAC/ 1985-86 23°-44'-33.47" N 66°-57'-35.98" E	3701(-3684)	M/L.Miocene Gaj Formation	DST-3 flowed Gas 3.7 MM Cf/day from 2743-2747 M.Miocene sand-stone interval, confirming the presence of hydrocrbons in the area.
9	Sadaf-1	OXY-OGDC/1989 23°-44'-07.9" N 66°-23'-38.6" E	3980(-3965)	M/L.Miocene Gaj Formation	Failed to encounter the potential reservoir

ABBREVIATIONS

U = Upper, M = Middle, L = Lower, D & A = Dry and abandoned, DST = Drill Stem Test, m = Metre, OXY = Occidental of Pakistan Inc. OGDC = Oil and Gas Development Corporation.

Figure 2– History of seismic survey and drilling in offshore Indus basin, Pakistan.

Creek-1 (1964). Winter Shall A.G. conducted multiple-fold 9,400 km of seismic survey from 1969-72 and drilled three wells: Inuds Marine A-1 (1972), Indus Marine B-1 (1972) and Indus Marine C-1 (1975). Shell International Petroleum carried out multi-fold seismic survey of 506 km in 1973. Phillips Petroleum carried out a pre-licence survey in deep water Indus cone area of 2,557 km length in 1977. Husky Oil digitised and reprocessed Sun Oil's data, and conducted seismic survey on about 2,380 km from 1976-78, and drilled one well (Karachi South A-1) in 1978. ELF-Acquitaine carried out multi-fold seismic survey of 3,004 km in 1977. Reinterpretation of seismic data shows Dabbo Creek to have been drilled on the down thrown side of a fault block structure, Patiani Creek to be located on the northern flank, while the seismic as well as drilling results do not justify the presence of the east bounding fault providing closure for the trap tested by Karachi South A-1. All the three Indus Marine wells were stopped due to technical difficulties without reaching objective reservoirs (Figure 2). The seismic survey of 1,150 km was carried out by OGDC-NORAD in May 1982 (Figure 3a), which provided four drilling sites and some interesting fairways. PakCan-1 well was drilled on the big structural closure during 1985-86 under Canadian Assistance program up to the target depth 3,701 metres and gas flowed at 3.7 MMCF/day from Miocene sandstone in DST-3. Seismic survey of 5,732 km was completed by OGDC-PCIAC during April-May-June 1986 in offshore Indus basin, the interpretation of which revealed number of structural traps including nine reefs at depth approximately 2,800 to 5,400 metres and seven "Bright Spot" at depth from 1,250 to 3,350 metres in sediments ranging in age from Cretaceous to Early Miocene. Occidental and Canterbury carried out 5,685 km and 754 km seismic surveys during 1988-89 and 1990 respectively in the deltaic area of offshore Indus basin. Occidental-OGDC drilled Sadaf-1 exploratory well of total depth 3,980 metres in the area but failed to encounter any potential reservoir.



Figures 3a– OGDC-NORAD seismic survey line pattern, Indus offshore.

TECTONIC SETTING

The Indus offshore is an Atlantic-Type passive Margin which straddles the continental crust of extension of Thar Slope Platform and Kirthar Foredeep and lies between Murray Ridge in the west and the Indian border in the east (23° to 25° N, 66° to 68° E) and is cut in the southeastern corner by the submarine canyon of the Indus river. The basin is divided into two tectonic units namely Offshore Depression in the west and Offshore Platform in the east with hinge Zone/shelf limit as the dividing line between the two (Figure 1). Offshore Depression lies between Murray Ridge and hinge zone i.e. 66° to 67°E, in which post Oligocene sedimentation seems to be nearly continuous. It is represented by mainly thick marine calcareous terrigenous Miocene clastics, a monotonous silty-shaly sequence with lenses of sandstone and bands of limestone. Offshore platform lies between hinge zone and Pakistan shoreline i.e. 67° to 68°E. It may be divided further into two units namely Karachi Trough offshore platform and Thar slope offshore platform or Indus river deltaic area, the boundary between the two is roughly an extension of their onshore boundary (Figure 1). Karachi South A-1 was drilled by Husky almost on the hinge zone. Sun drilled three wells in Karachi Trough offshore platform particularly on shoreline namely Dabbo Creek-1, Patiani Creek-1 and Korangi Creek-1 in which Miocene sediments are mainly sandy limestone of thickness 55,

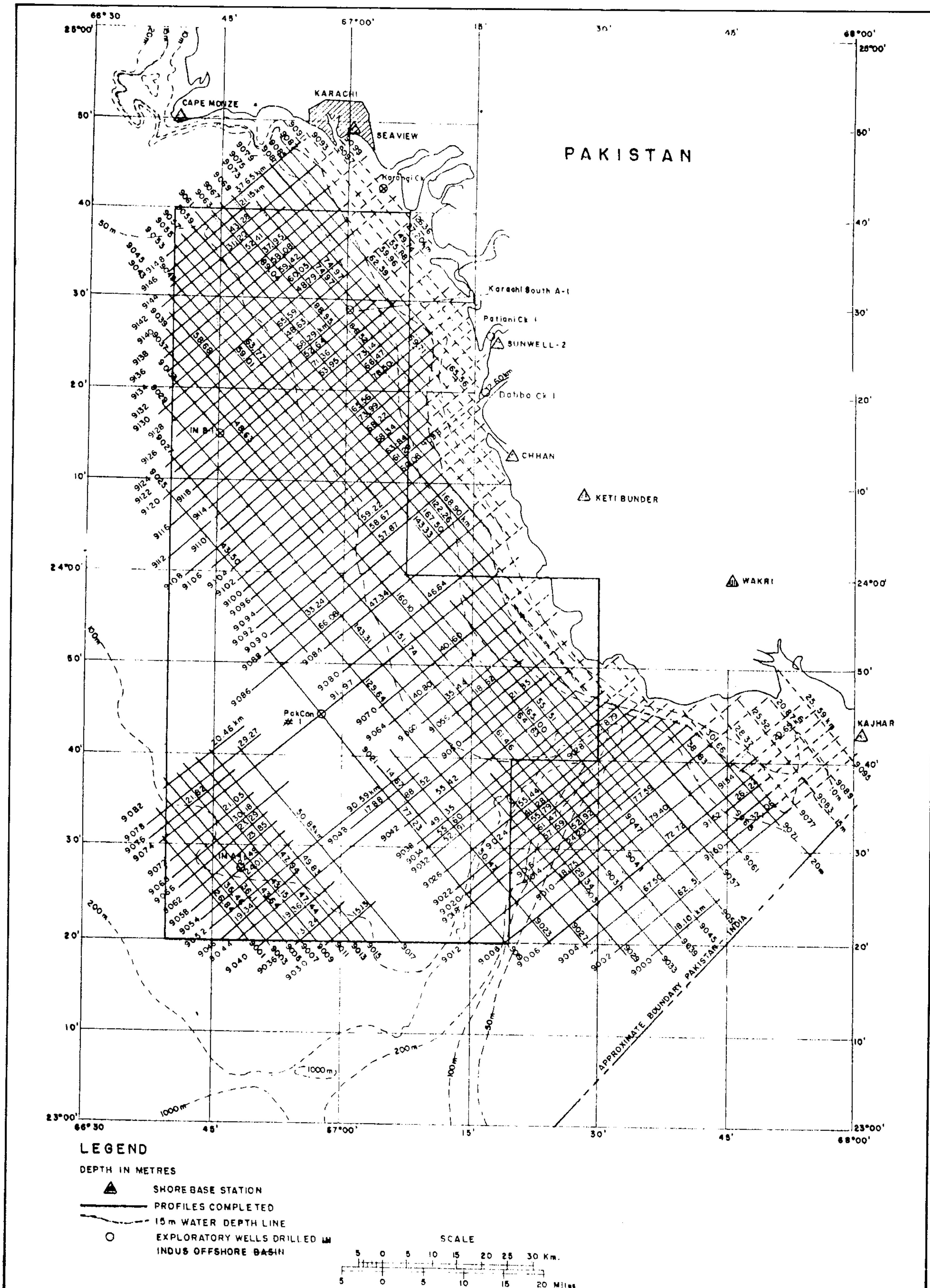


Figure 3b– OGDC-PCIAC seismic survey line pattern, Indus offshore.

66 and 67 metres respectively. These tectonic divisions seem to be valid mainly for Oligocene Nari and Miocene Gaj Formations (Figures-4, 6 and 7).

STRATIGRAPHY

The oldest rocks penetrated by offshore exploratory wells are of Cretaceous age. The Sembar and Goru Formations are early Cretaceous, whereas the Parh, Mughalkot and Pab Formations are late Cretaceous. Early Cretaceous Sembar and Goru Formations are penetrated only in Dabbo Creek-1 well as shown in stratigraphic sections W-E and S-N-E of Figures 8 and 9. They have a thickness greater than 1,860 metres and consist mainly of shaly clastics with few layers of siltstone/sandstone and bands of limestone. Presence of igneous rocks specially basalt is recognized in cores of Sembar Formation of Dabo Creek-1 well (Scull, 1964). Lower Goru sandstone beds produce oil and gas in number of onland wells on Thar Slope platform, drilled by Union Texas and OGDC in its east and northeast directions (Figure 1). Overlying Goru is the Late Cretaceous Parh Formation which is entirely tight carbonate facies of about 136 metres thick. It was also drilled only in the Dabbo Creek-1 well. However, Mughalkot sediments were present in all four wells drilled on the offshore platform namely Dabbo Creek-1, Patiani Creek-1, Korangi Creek-1 and Karachi South A-1 (Figures 8 and 9). The Mughalkot is mainly limestone/marl interbedded with shale. Gas shows were encountered in this formation in the Patiani Creek and Dabbo Creek wells. The uppermost Cretaceouos Pab Formation is mainly a sandy facies and has a maximum thickness of only 51 metres in Patiani Creek and thins westward from Karachi shoreline.

The Ranikot Formation of Paleocene age is present in all four wells drilled on the offshore platform. However, the upper Ranikot is missing except in Patiani Creek-1 wells, where it is about 180 metres thick and consists mainly of interbedded shale and limestone. The lower Ranikot is composed of clastics (sandstone and shale) and layers of basalt and has a maximum thickness of about 1,329 metres in Korangi Creek-1 well, from where it decreases in thickness in the south and west directions (Shuaib, 1982). Ranikot limestone and sandstone beds produce gas in onland Sari and Hundi wells on Karachi Trough in its north (Figure 1).

The Early Eocene Ghazij/Laki Formation was encountered in all four wells drilled on the offshore platform, as well as in Indus Marine C-1 in the western portion of offshore depression near Murray Ridge. It is represented mainly by shaly facies with bands of carbonate rocks and has a maximum thickness of 445 metres in Korangi Creek-1 well, in which gas show was recorded and from where it decreases in thickness in the southward along Karachi offshore (Shuaib, 1982). The Late Eocene Kirthar Formation is present in the four wells on offshore platform and one well Indus Marine C-1 near Murray Ridge. It consists of mainly limestone with layers of shale. The Kirthar Formation has a maximum thickness of about 544 metres in the Korangi Creek-1 and Karachi South A-1 wells along north-south axis about 67°E and from where it decreases in thickness both east and west directions from this axis as shown in isopach map of Kirthar Formation (Figure 5).

The Nari Formation of Oligocene age is present in all the four wells on the Karachi offshore platform and Indus Marine C-1 near Murray Ridge. It consists of mainly argillaceous sandy limestone in the east of approximately 67°E but seems to become dominantly silty-shaly in its west and decreases in thickness eastward from north-south axis of Korangi Creek-Karachi South A-1 wells as shown in the facies and isopach map of Nari Formation (Figure 6).

The Gaj Formation of Miocene age is encountered in all the nine wells drilled in offshore Indus basin and is divided into lower, middle and upper units. Miocene sediment is mainly shaly/sandy limestone along Karachi shoreline wells namely Dabbo Creek-1, Patiani Creek-1 and Korangi Creek-1 of thickness 67, 66 and 54 metres respectively but becomes dominantly silty-shaly clastics in the southwest and also increases in thickness in this direction as shown in the facies and isopach of Gaj Formation (Figure 7). It is evident from stratigraphic sections of wells drilled in offshore Indus basin (Figures 8 and 9) that upper Miocene sediment is missing in the north of offshore Indus basin depression at Indus Marine C-1 and Indus Marine B-1 wells whereas it is present in the south in Indus Marine A-1, PakCan-1 and Sadaf-1 wells. Both upper and middle sediments seem to be missing in the offshore Indus basin platform in the north-east at Karachi South A-1, Korangi Creek-1, Patiani Creek-1 and Dabbo Creek-1 wells. Miocene sediment increases in thickness from north-east to south west in offshore Indus basin but its increase becomes more than 8,000 metres at Indus Marine A-1 position as calculated from seismic section whereas it is less than 100 metres at coastal area in the east and also decreases from depression axis towards Murray Ridge in the west (Figure 7). However, it is mainly lower and middle Miocene sediments which form the enormous thickness in Indus offshore depression area with oil/gas traces and shows (Figures 8 and 9). A study of well cuttings of Miocene sediments from PakCan-1 well was undertaken by OGDC as no core was taken. Five sandy depositional cycles are recognized in predominantly silty-shaly sequences of Miocene sediments at depths approximately 1,683-1,723, 1,831-2,238, 2,693-2,891, 2,963-3,083 and 3,418-3,498 metres from sea level which indicate the changes in sediment-input rates/sea level.

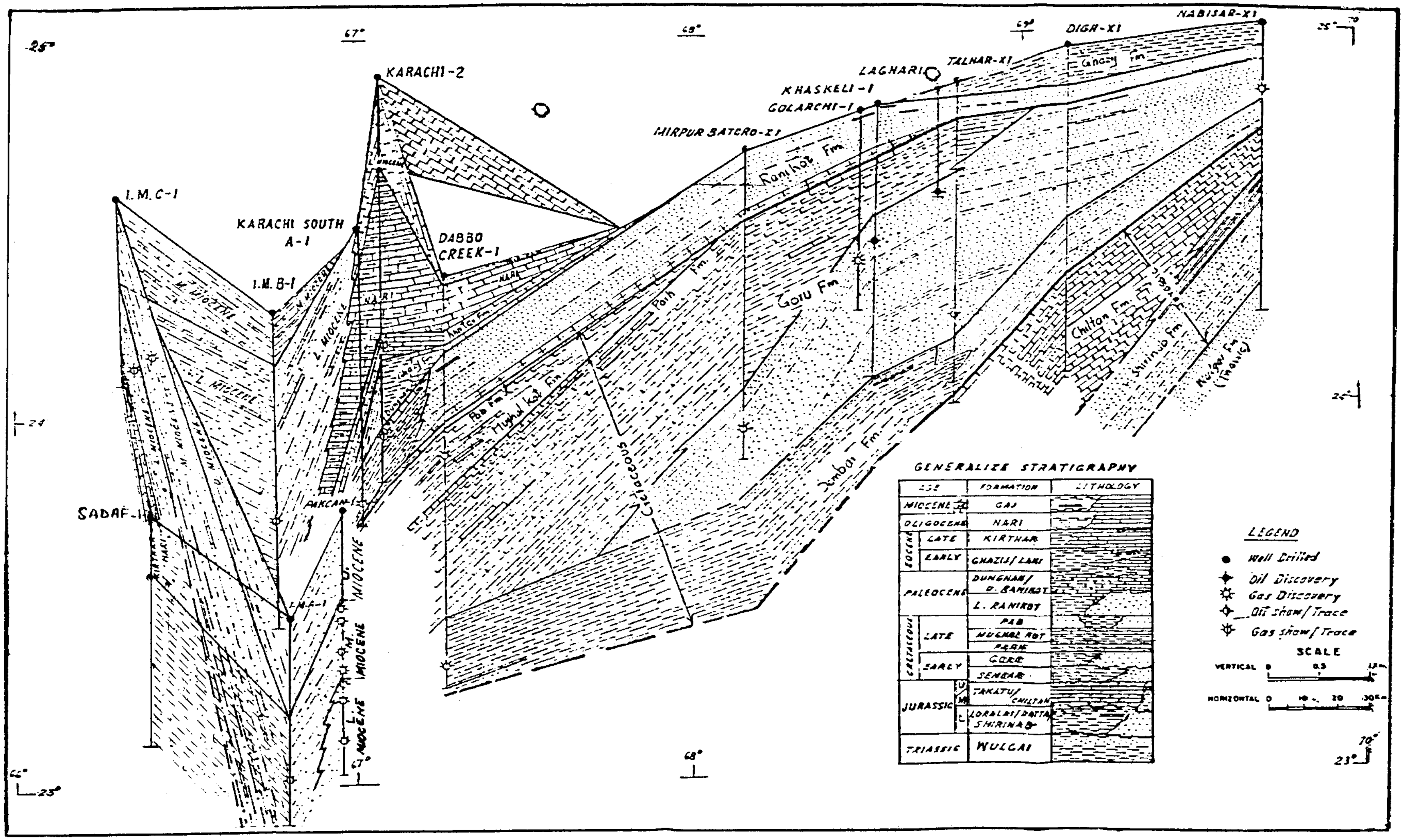


Figure 4– Block diagram showing the correlation of lithofacies and their distribution with positions of oil/gas discoveries and shows/traces in Indus offshore basin and adjoining land area based on well logs (position of wells in Figure 1).

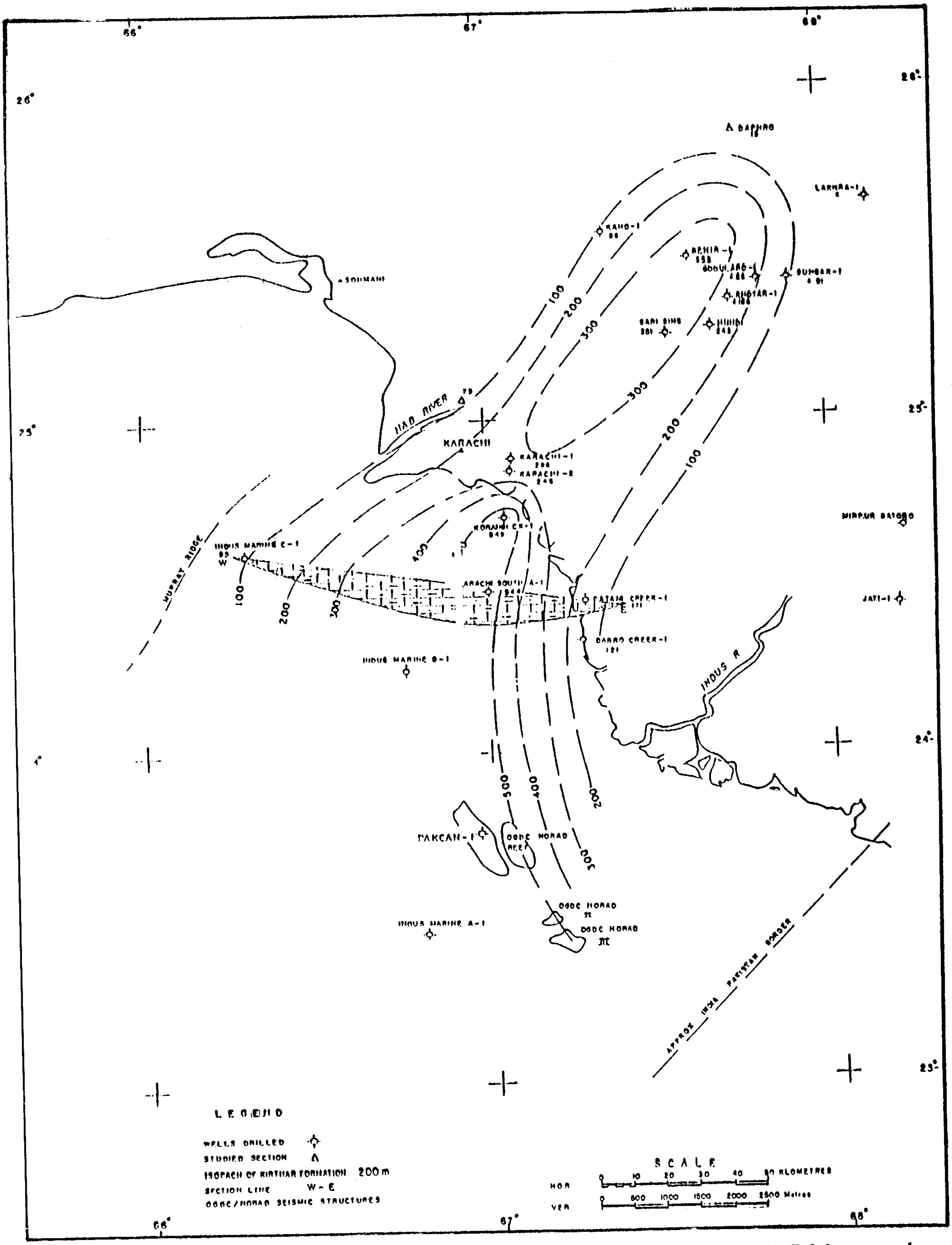


Figure 5– Isopachs and facies of Late Eocene Kirthar Formation in offshore Indus basin and adjoining areas based on well logs and studied sections.

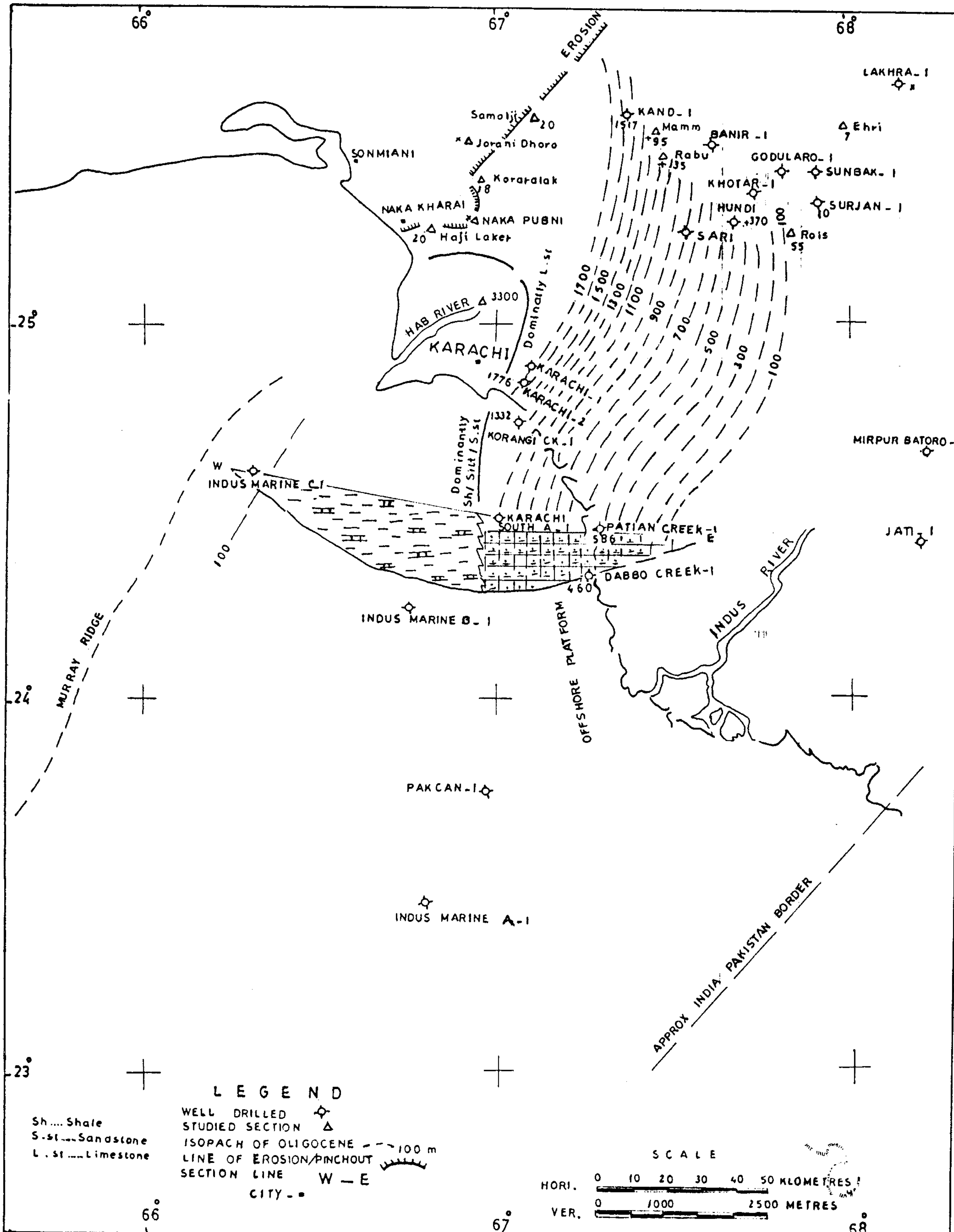


Figure 6– Isopachs and facies of Oligocene Nari Formation in offshore Indus basin and adjoining areas based on well logs and studied sections.

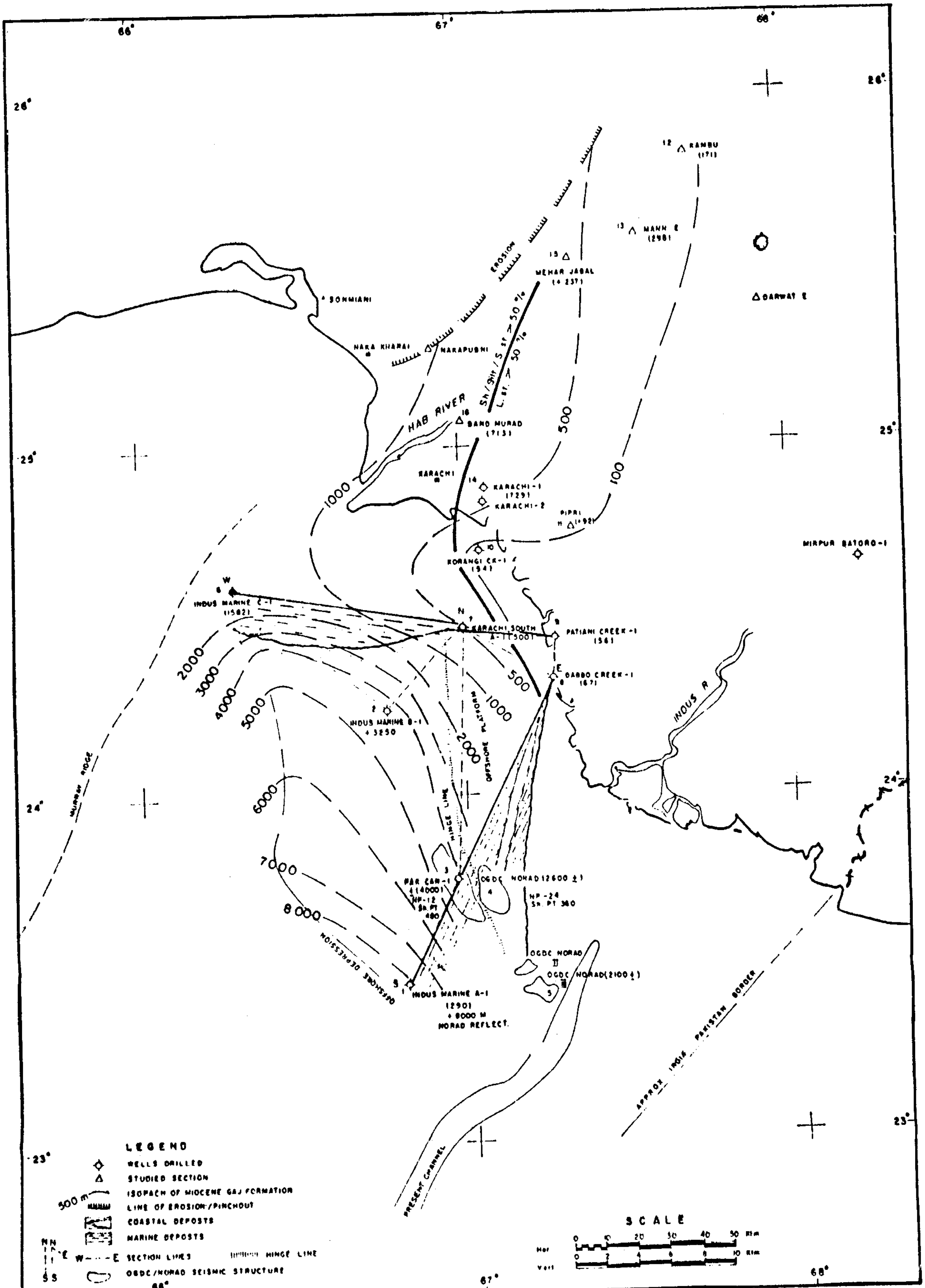


Figure 7– Isopachs and facies of Miocene Gaj Formation in offshore Indus basin and adjoining areas based on OGDC/NORAD reflectors and well completion logs and studied sections.

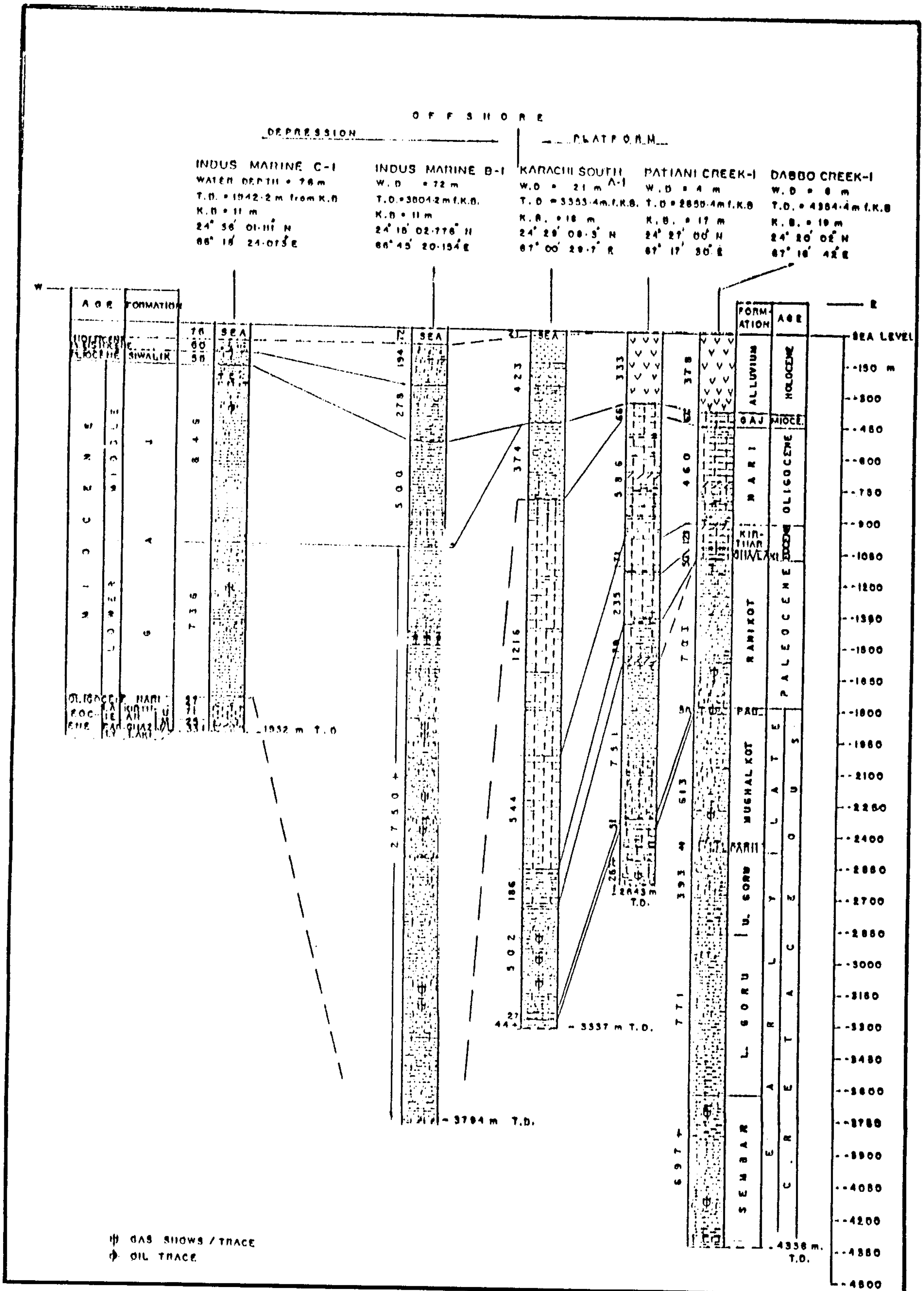


Figure 8– Correlation section of wells in northern area or Indus offshore basin based on well logs; line W-E and well locations are shown in Figure 7).

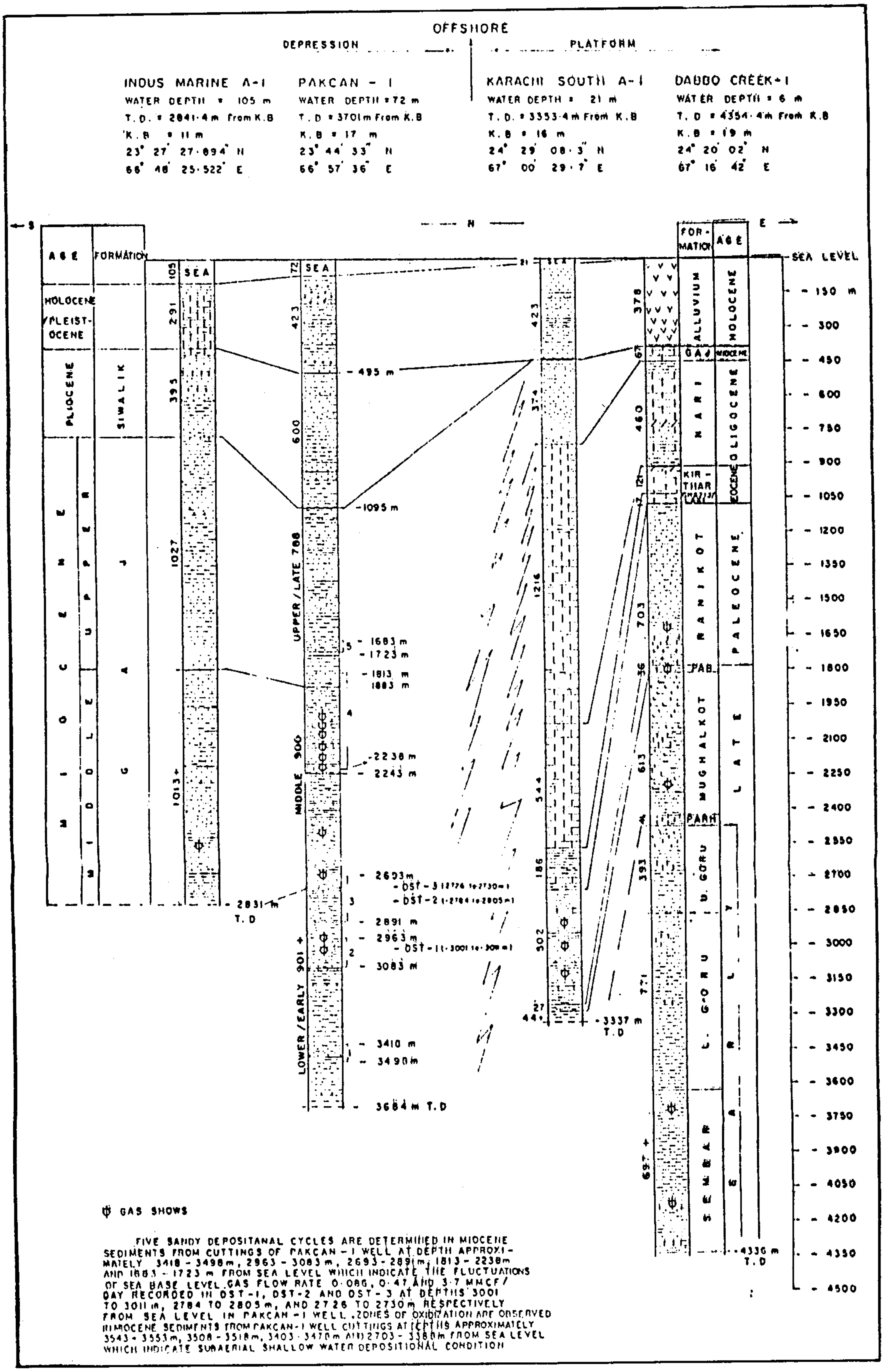


Figure 9– Correlation section of wells in north-eastern area or Indus offshore basin based on well logs; line S-N-E and well locations are shown in Figure 7).

Sandstone is mostly litharenite type, fine to very fine grained, highly micaceous (both biotite and muscovite), moderately sorted, mainly sub-angular quartz, rock fragments and feldspars, cemented by argillaceous-calcareous matrix. Quartz is the dominant detrital constituent and forms about 50%. Among feldspars, the alkalie feldspar is greater than plagioclase feldspar. Biotite shows little or no alternation or de-composition. Miocene sediments are mostly devoid of fossils in PakCan-1 well. However, few micro fossils are recognized (Adams, 1986) and its division into three units (early, middle and late) is mainly based on micro fossils (Figure 9). Zones of oxidation are also observed in Miocene sediment at depths approximately 2703 - 3388, 3403 - 3478, 3508 - 3518 and 3543 - 3553 metres from sea level, the study of which indicates subaerial shallow water depositional conditions of coastal type deposits within marine sediments (Figures 7 and 9). Post Miocene sediments in offshore Indus basin are mainly calcareous fossiliferous clastics of varying thickness (intercalations of clay, silt, and sand with conglomeratic bands) and seem to be of little or no importance from the point of view of hydrocarbon accumulation.

It seems from Figures 5, 6 and 7 that Indus river came into existence after Eocene and built a delta advancing southward and eastward along the Indus trough bordering the Sulaiman and Kirthar mountain ranges. The total area of both the subaerial and subaqueous portions of the Indus river is about the same as that of Mississippi Delta of USA (Coumes and Kolla, 1984). It is estimated that Indus river apparently discharged more than 600 million tonnes of suspended sediments annually untill the late 1940 but since then various man-made structures have greatly decreased that sediment load of the Indus and present discharge is less than 50 million tonnes annually (Million et al, 1984). The maximum thickness of sediments in offshore Indus basin is calculated from seismic sections as greater than 11,000 metres and reflects sedimentation since rifting of the Indian Margin in late Cretaceous and during earlier times. However, the fan sedimentary sequences have been deposited since about Oligocene as a consequence of Himalayan uplifts and sea level changes.

SOURCE ROCKS

Source rock analyses of shale samples from wells drilled in offshore depression area of offshore Indus basin namely Indus Marine A-1, B-1 and PakCan-1 indicate the presence of hydrocarbon maturation in sediments ranging in age from Early to Middle Miocene. Oil/gas shows and traces were also recorded in Middle-early Miocene rocks in these wells (Figures 8, 9 and 10). However, hydrocarbon maturation is observed in sediments ranging in age from Eocene to Miocene in Indus Marine C-1, drilled in the eastern portion of offshore depression near Murray Ridge. On offshore platform, the presence of hydrocarbon maturation in sediments ranges in age from Cretaceous to Oligocene as determined by the analyses of samples from Karachi South A-1, Dabbo Creek-1, Patiani Creek-1 and Korangi Creek-1 wells (Quadri and Shuaib, 1986). So the most likely source rocks in Indus offshore basin seem to be Tertiary shales and carbonates as well as Cretaceous shales.

RESERVOIR OBJECTIVES

Cretaceous Lower Goru sandstone is proved to be oil and gas bearing in number of wells drilled by OGDC and Union Texas in onshore Thar Slope in its north-east and east directions. Paleocene Ranikot sandstone and limestone are also proved to be gas-bearing in Sari, Hundi and Kothar wells drilled by OGDC in onshore Karachi Trough in its north direction (Figure 1). Oil and gas reservoirs were discovered in Bombay offshore of India (Roy Chaudhry and Deshponde, 1982) in its south east direction in Eocene Miocene sandstone and limestone. Therefore, Cretaceous to Miocene sandstone and limestone seem to be the objective reservoirs in Indus offshore basin. However, Cretaceous sediments become dominantly shaly/marly towards the west from Pakistan shoreline in offshore Indus basin and are deeply buried (Figure 4). So Paleocene, Eocene, Oligocene and Miocene sandstone/limestone are the primary objectives for hydrocarbon reservoirs in offshore Indus basin. There are seismic evidences for the presence of reefal build ups of Paleocene-Lower Miocene age at hinge zone/shelf edge. The possible hydrocarbon traps in the offshore Indus basin are large compressional anticlines, drape anticlines, reefal build-ups banks on the hinge zone between platform and depression on very margin of the upper slope where dominant shale sediments can act as source rocks; roll over anticlines against growth faults at the delta front slope; traps associated with distribution and continuity of sandstone reservoirs; fluvial sheet, point bars, deltaic and shore face facies/turbidities related to submarine canyon fan systems.

CONCLUSIONS

Seismic surveys during 1961-78, of reconnaissance to semi-detailed grid have delineated more than fifty six structures; with the assistance of the government of

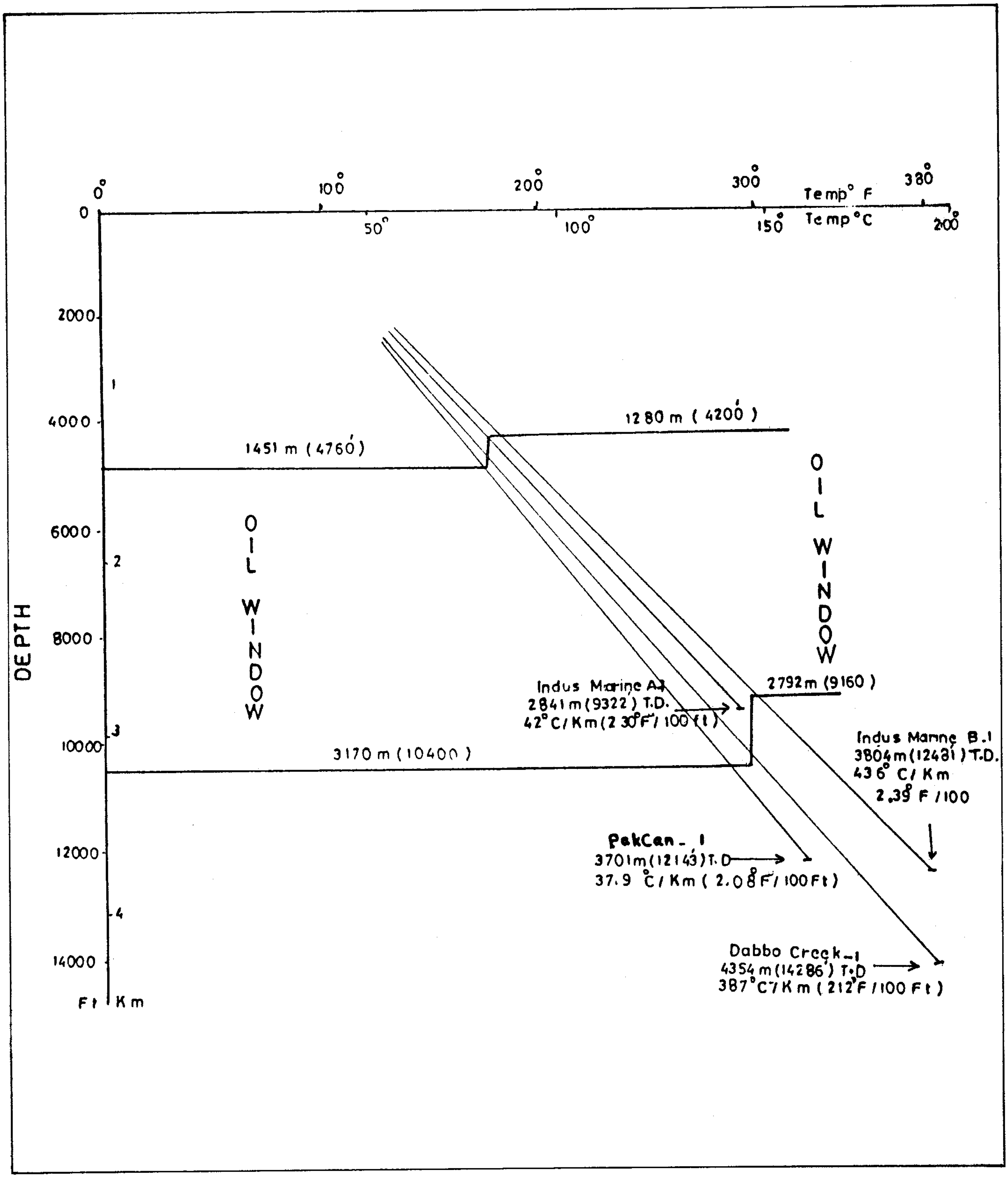


Figure 10– Geothermal gradient and oil window, Indus offshore.

Norway, NORAD-OGDC detailed 1,150 km seismic survey carried out in 1982, which yielded several fair ways, including possible undaform banks and stratigraphic traps in Indus offshore (GECO, 1983). With the assistance of the government of Canada, detailed 5,732 km seismic survey was completed during April to June 1986 in offshore Indus basin, the interpretation of which revealed number of structural traps including nine reefs at the depth approximately 2,800 to 5,400 metres and seven "Bright Spot" at the depth from 1,250 to 3,350 metres in sediments ranging in age from Cretaceous to Miocene. OXY and Canterbury carried out seismic survey of 5,685 km and 754 km during 1988-89 and 1990 respectively in the deltaic area of offshore Indus basin and delineated number of structural traps in Middle-Lower Miocene sandstone beds within dominantly thick silty-clayey sequences. Although tectonic fabrics are different, source and reservoir rocks in the Indus offshore are similar in age, depositional environment and rock type to those present in Bombay offshore of India where oil and gas are already in production in number of wells from sandstone and limestone horizons of Eocene, Oligocene and Miocene age. Nine exploratory wells were drilled in Indus offshore, out of which three did not reach objectives due to technical difficulties while other four appear to have been located on no/inadequate traps though gas traces/shows were recorded in all wells. Gas was discovered in DST-3 Miocne sandstone horizons of PakCan-1 well in January 1986 with gas rate flow 3.7 MMCF/day but was not considered economical to be extracted and was plugged. However, considering the large area of the Indus offshore basin, the number of offshore wells drilled so far represents an insufficient effort of drilling.

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