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PETROLEUM PROSPECTS: SULAIMAN SUB-BASIN, PAKISTAN

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Abstract

The Sulaiman, located on the northwestern margin of the Indian plate, is one of the three sub-divisions of the Indus oil and gas-producing basin which is classed as an Extra-continental Closed Trough Downwarp basin.

The sub-basin in its western part, is filled with a thick sequence of Mesozoic and Cenozoic sediments (over 10,000 meters), whereas moderate thickness of Paleozoic, Mesozoic and Cenozoic sediments (upto 3,500 meters) still remains on its eastern part despite emergence and erosion during its long history of sedimentation. The present synthesis of basin data indicates that all the major requirements for hydrocarbon accumulation are persent—source and reservoir rocks, adequate sedimentation and thermal history, and a large number of traps. As far as the discoveries are concerned, nine gas fields including seven orogenically controlled fields have been discovered. One of the fields is a gaint. The principal gas-collecting reservoir is a reef-shoal type forminiferal limestone of Eocene age. Gas accumulations have also been found in Mesozoic sand reservoirs. Despite a condensate discovery and occurrence of oil seepages, the Sulaiman is generally considered as a gas-prone region. Our studies, however, show existence of sizeable oil potential in addition to gas.

Introduction

The study area is located in central Pakistan and can be divided into three physiographic units which also correspond to major tectonic divisions. These are, from east to west, Punjab platform, Sulaiman depression and Sulaiman foldbelt (Figure 1). It forms middle part of the Indus basin and has been termed as Sulaiman sub-basin. It occupies an area of 142,500 square kilometers, and the thickness of its sedimentary fill exceeds 10 kilometers in the area of maximum subsidence (Figure 2). The history of petroleum exploration in the region dates back to 1885, when drilling of shallow wells commenced at Khattan near Sibi (Figure 3) and between 1885-1892 about 25,000 barrels of oil were produced from thirteen bore-holes drilled in the vicinity of a seepage by the Government of British India. After Pakistan became independent in 1947, the exploration interest in the region revived culminating with the discovery of a gaint gas field in 1952 at Sui (original reserves 8.6 tcf) by Pakistan Petroleum Limited (PPL). So far 24 exploratory wells have been drilled in the area with 8 gas and 1 condensate discoveries (Figure 3). PPL (1952—60) focused its activities in and around the Sulaiman depression and discovered three gasfields, but except Sui, the other discoveries remained dormant due to low methane content and unfavourable market situation. Oil and Gas Development Corporation of Pakistan (OGDC) in 1975—85 also explored the area and discovered one gas condensate (Dhodak) and five gas fields (Pirkoh, Loti, Rodho, Panjpir and Nandpur). AMOCO (1975-76) made a sub-economic gas discovery (Jandran) in the foldbelt region. Shell have twice attempted to explore, firstly as Pakistan Shell Oil Company (PSOC) in 1958-59 and then as Pakistan Shell Petroleum Development (PSPD) in 1980-81 in the platform region but have not succeeded in making a discovery. The seismic exploration and drilling in the sub-basin have remained inadequate and unevenly distributed (Figures 3, 4).

The fields so far discovered have proven reserves of 34 million bbl of oil (condensate) and 14.1 tcf of gas (Table 1). The gasfields of the region have marked variation in their composition as shown in Table 2. Exploration in the past had been slowed down due to lower gas prices. However, with much improved financial package now being offered by the Government of Pakistan, the exploration has gained substantial momentum (Figure 5).

Some of the relevant previous published studies concerning the stratigraphy, tectonics, and petroleum geology of the region include: Nagappa (1959), Tainsh, Stringer & Azad (1959), Williams (1959), Zuberi & Dubois (1962), Rahman (1963), Hunting Survey Corporation Ltd. (1966), Sokolov & Shah (1966), Stoneley (1974), Shah (1977), Stocklin (1977), Powell (1979), Farah & Dejong (1979), Gansser (1981), Kazmi & Rana (1982), Khan & Raza (1986), Banks & Warburton (1988) etc.

In this paper, we synthesize the results from earlier

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geological, geophysical and drilling data generated combined with field studies. Undiscovered petroleum potential of the region has also been indicated based on recent studies of the Hydrocarbon Development Institute of Pakistan (HDIP) in collaboration with Bundesanstalt fuer Geowissenschaften und Rohstoffe (BGR).

Stratigraphy

The Punjab platform forming the eastern part of the sub-basin coincides with the present alluvial plains of the Indus River and its tributaries. The eastern and southern parts of the Sulaiman depression are marked by low, barren hills composed of post-Eocene fluviatile clastics, whereas the northern and western parts of the depression show high relief with rock outcrops of Tertiary carbonates and shales. Mesozoic outcrops comprising limestone, shale and sandstone are the oldest rocks exposed in the Sulaiman foldbelt. Various stratigraphic sequences found in the sub-basin (Figure 6, 7) are described as follows:

Punjab Platform

The stratigraphy in the Punjab platform is known through drilling and seismic surveys (Figures 8,9). The succession is similar to that of the Salt Range to the north. The oldest unit in the sequence is Salt Range Formation, comprising marl, clay-shale, sand-silt, dolomite, gypsum and salt. A maximum thickness of 1053 m of the formation was encountered in Marot-1. The formation thins out westward and becomes more clastic eastward (Figure 8).

Cambrian rocks conformably overlie the Salt Range Formation. The entire sequence is marine and attains a maximum thickness of 500 m. It comprises up-sequence, red santstone (Khewra Formation), greenish grey shale and sandstone (Kussak Formation), creamy dolimite (Jutana Formation) and red sandy claystone and sandstone (Baghanwala Formation).

A major unconformity intervenes the Cambrian and Permian sequences. The Permian sequence, in an ascending order, comprises glacial boulder conglomerate and clay (Tobra Formation), marine sandstone (Dandot Formation), fluviatile sandstone and clay (Warchha Formation), marine clay (Sardhi Formation), marine fossiliferous sandstone (Amb

Table 1. Reservoirs and original recoverable reserves of gas and condensate fields of the sub-basin.

Name	Producing Horizon	Oil/Gas (Status)	Original Recoverable Reserves mmbbl/tcf
Sui (1952)	Eocene	Gas (Producing)	8.624
Zin (1954)	Eocene	Gas (Dormant)	0.100
Uch (1955)	Eocene	Gas (Dormant)	2.550
Rodho (1974)	Paleocene Cretaceous	Gas (Dormant)	0.025
Jandran (1975)	Cretaceous	Gas (Dormant)	0.198
Dhodak (1976)	Cretaceous	Gas/Condensate (Dormant)	34.000/ 0.700
Pirkoh (1978)	Cretaceous	Gas (Producing)	1.906
Nandpur (1984)	Cretaceous Jurassic	Gas (Dormant)	N.A.
Panjpir (1985)	Cretaceous	Gas (Dormant)	N.A.
Loti (1985)	Eocene Paleocene Cretaceous	Gas (Dormant)	N.A.

Formation), fossiliferous limestone with dolomite (Wargal Formation), and fossiliferous limestone with shale and sandstone (Chhidru Formation). The Permian rocks thin out in the west and are truncated against the Tertiary unconformity in northeast (Figures 10, 11).

The Mesozoic sediments were deposited on a westerly tilting platform and are, therefore, thickest on the western side. The Triassic succession comprises, up-sequence, limestone, sandstone and shale (Mianwali Formation), fluviatile sandstone (Tredian Formation and dolomite (Kingriali Formation). The Jurassic rocks overlie the Triassic succession with an unconformity. The succession, in an upward direction, comprises paralic sandstone and shale (Datta Formation), limestone, shale and sandstone (Shinawari Formation), limestone (Samana Suk Formation). The marine sandstone and shale of Chichali Formation (which also go up into Cretaceous) overlie Samana Suk Formation and underlie Paleocene Hangu Formation, both unconformably.

The marine Cenozoic deposits are 400 m thick and like Mesozoic rocks show an increase in thickness westward (Figures 8, 12). Paleocene-Eocene succession comprises foraminiferal limestone, sandstone and

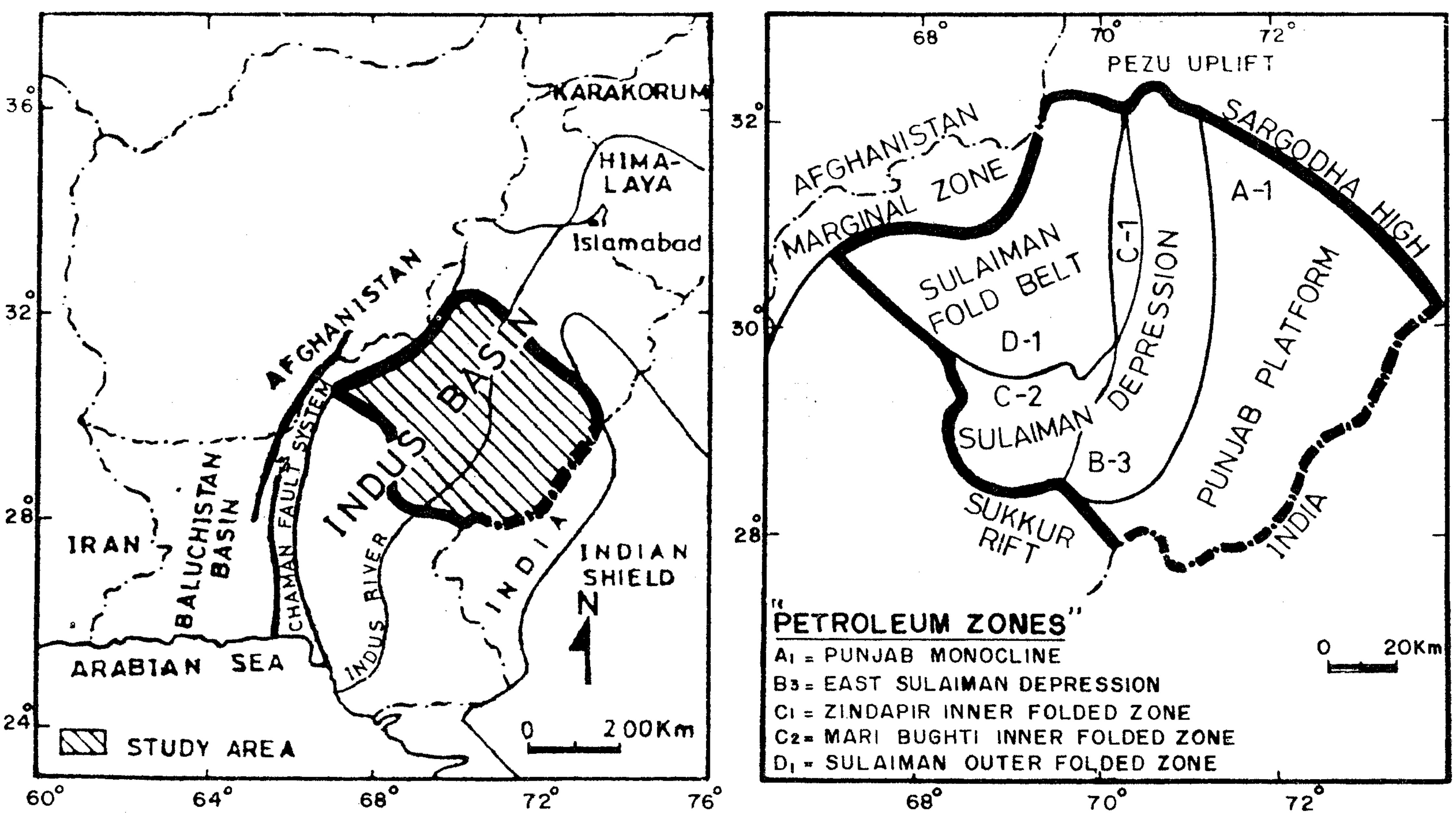


Figure 1. Index map of study area showing tectonic setting and "petroleum zones".

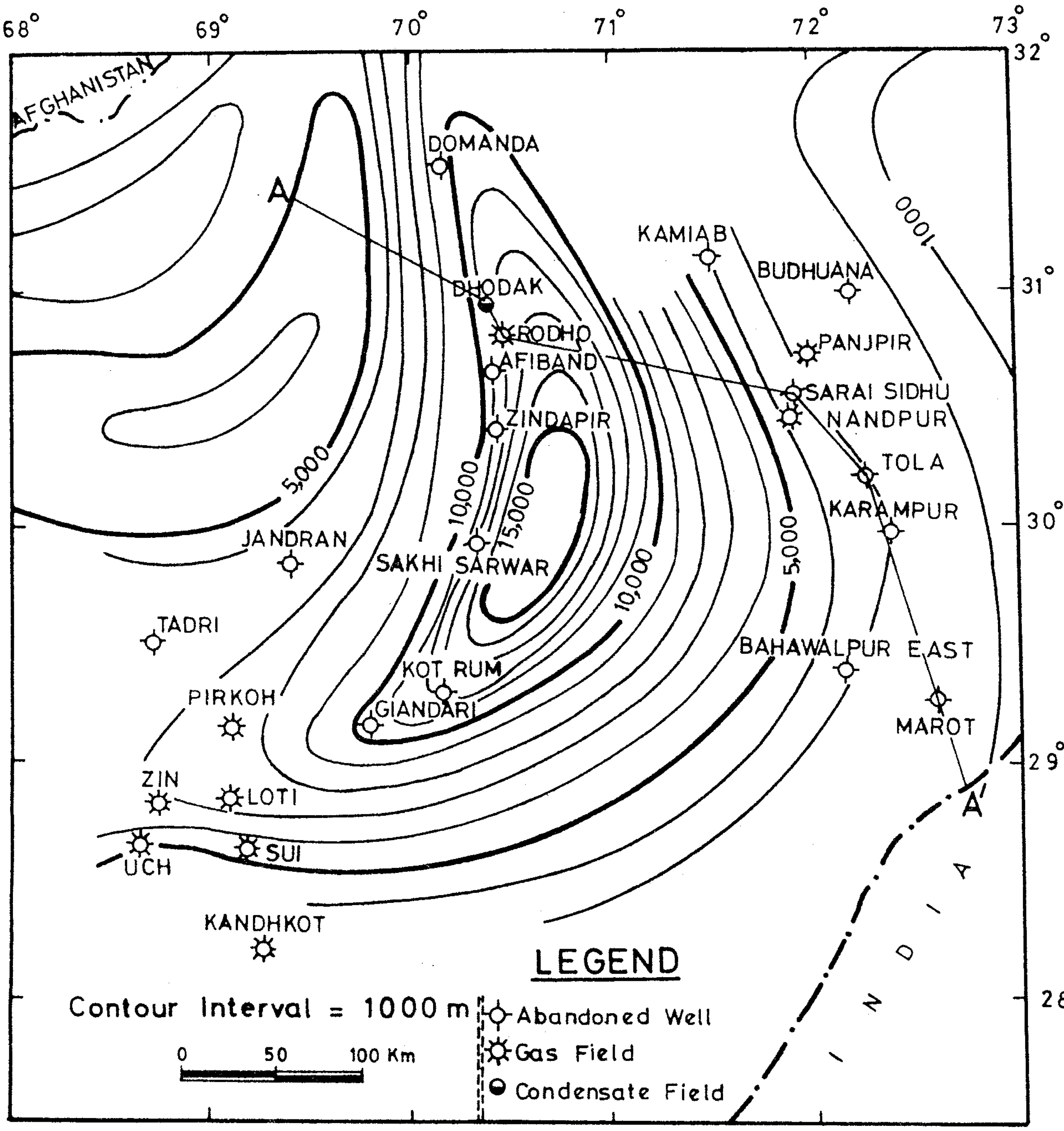


Figure 2. Thickness map of total sedimentary fill in the sub-basin (modified after Kamal, Raza and Chohan, 1982).

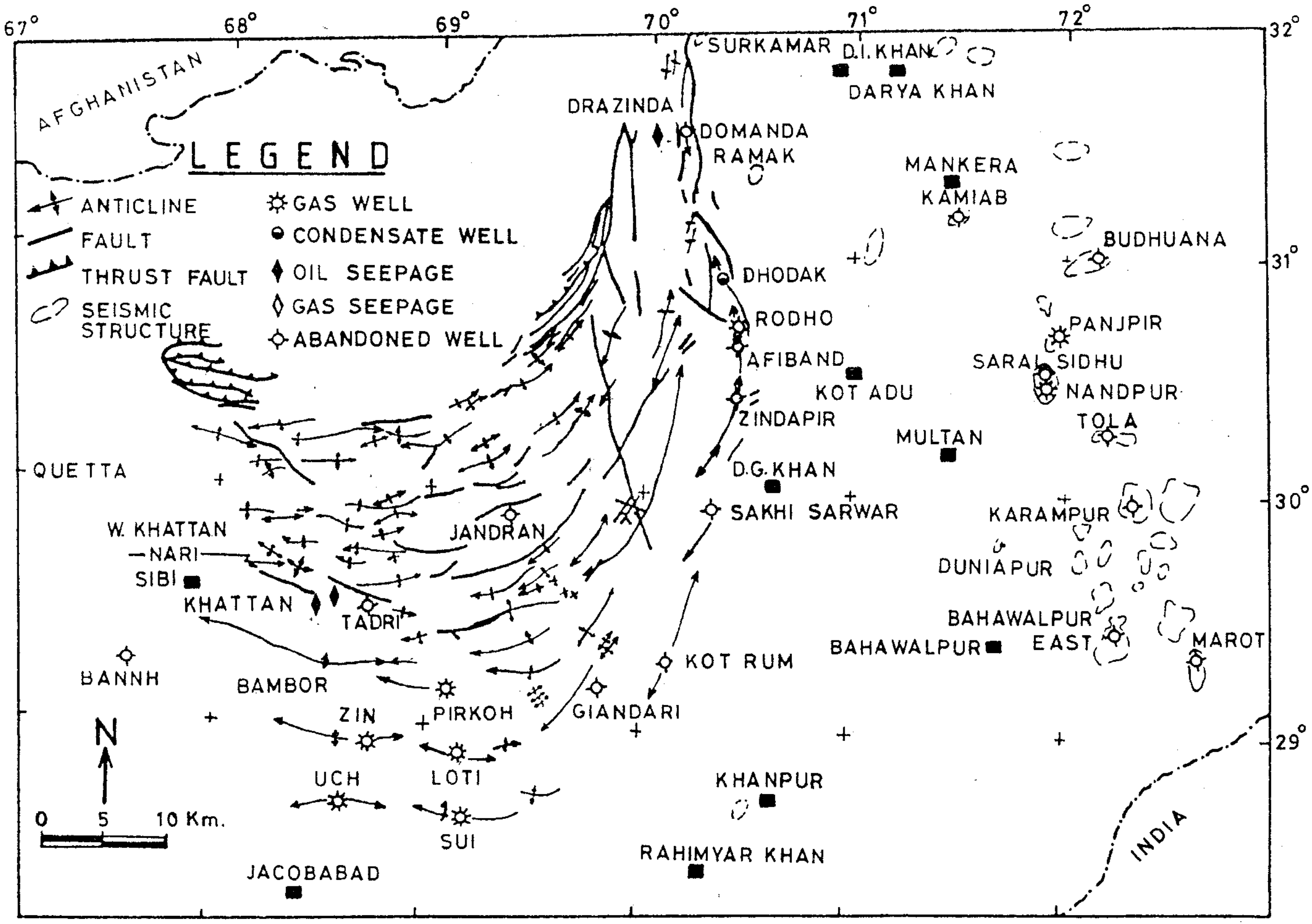


Figure 3. Structural map of the sub-basin showing surface anticlines, faults and seismically delineated structures (modified after Kazmi and Rana, 1982).

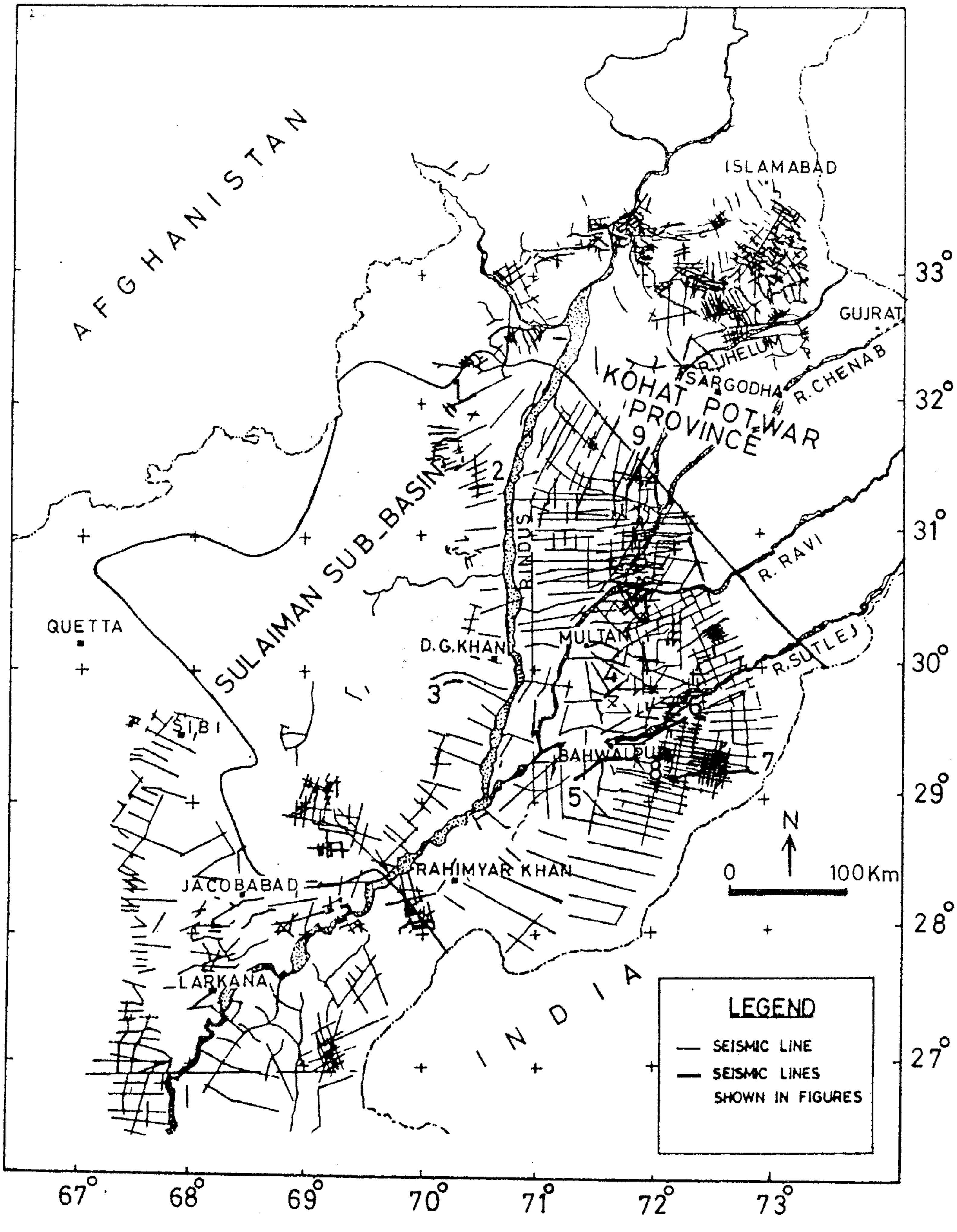


Figure 4. Seismic coverage map (after Ali and Ahmed, 1985, unpublished).

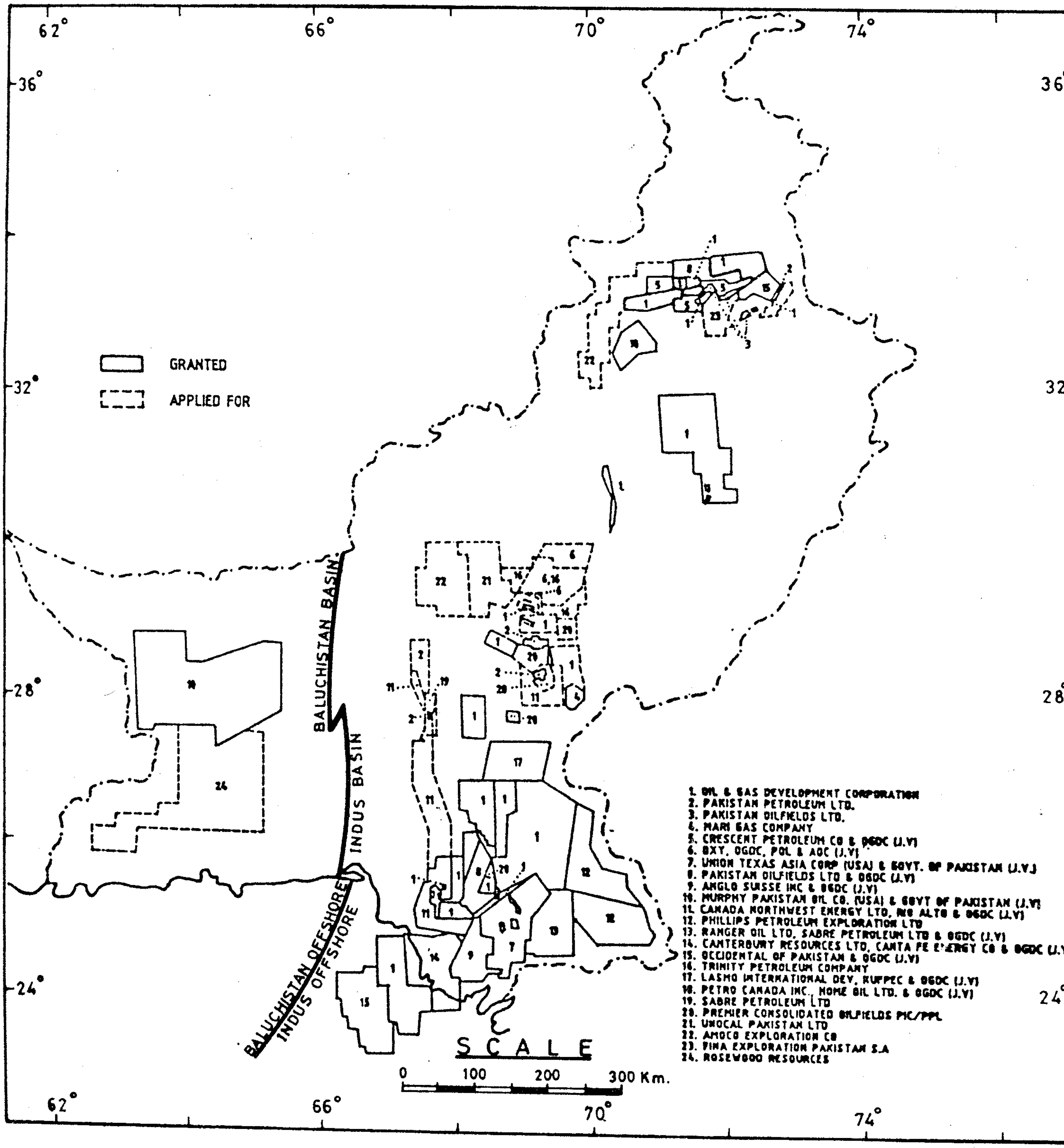


Figure 5. Petroleum concession map of Pakistan as at 1st January, 1989.

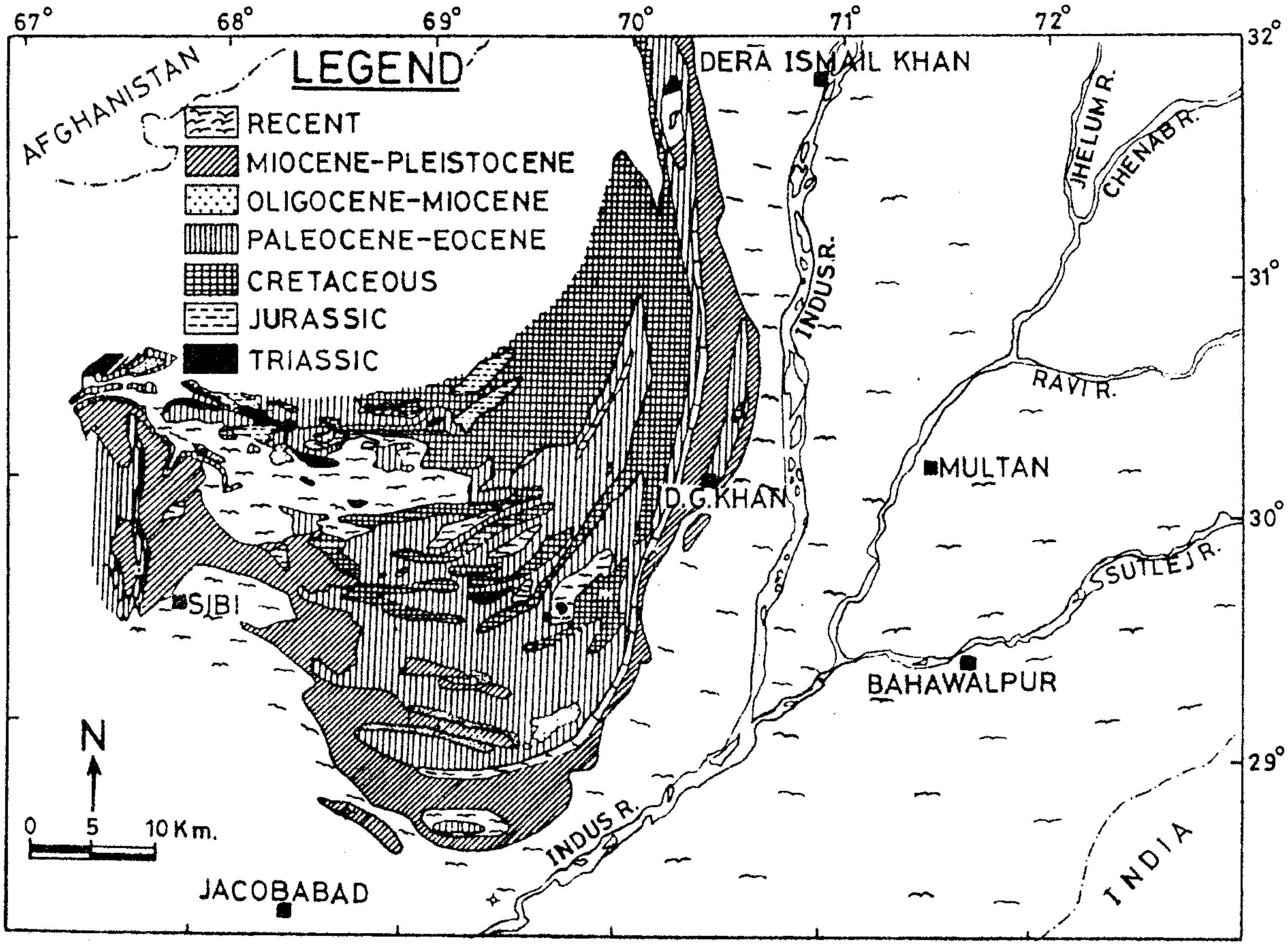


Figure 6. Generalized geological map of the sub-basin (modified after Bakr and Jackson, 1964).

shale (Hangu, Lockhart, Patala, Nammal, Sakesar and Chorgali formations). It is overlain by Neogone fluviatile clastics.

Sulaiman Depression and Foldbelt

In the northern Sulaiman depression, mainly Cenozoic rocks are exposed and the maximum depth of drilling reaches Cretaceous strata. In the Sulaiman foldbelt, rocks from Triassic to Tertiary are exposed. The Mesozoic and Early Tertiary rocks are in excess of 7000 meters (Figure 13). The Triassic rocks comprise shale and limestone (Wulgai formation). The Jurassic strata are made up of limestone and shale (Shirinab formation) and shallow marine limestone (Chiltan formation). The Cretaceous sequence is marine and in ascending order, is composed of shale (Sembar formation), shale and sandstone (Goru formation), limestone (Parh formation) limestone, marl, shale and sandstone (MughalKot formation) and sandstone (Pab formation). The Sembar formation also extends into Jurassic, unconformably overlying Chiltan formation. The Cenozoic sequence is very thick and includes 1700—3700 meters of marine sedimentary rocks (Figure 13). The Paleocene-Eocene rocks comprise sandstone and shale (Khadro formation), foraminiferal limestone (Dunghan formation), marine shales (Ghazij formation) and foraminiferal limestone and shale (Kirthar formation). In southern part of the Sulaiman depression the stratigraphy is slightly different in the Paleocene-Eocene section (Figure 14). There Paleocene rocks comprise limestone, shale and sandstone (Ranikot/Dunghan) and Lower Eocene sequence is dominatly composed of carbonates (Laki formation). The Eocene sequence is unconformably overlain by a thick section of Oligocene and Neogene fluviatile clastics.

Tectonics

Situated on the northwestern margin of the Indian plate, the Sulaiman sub-basin displays a fascinating array of features arising from the collision of the Indian and Eurrsian plates. The Sulaiman alongwith other basins located in the Indian plate was affected by the global tectonic events (Powell, 1979). Fragmentation of Gondwana resulted in separation of the Indian and African segments during Early Jurassic period. Since

Table 2. Composition of gas in some fields of the sub-basin (modified after Tainsh et al, 1959).

Composition of gas	Sui (Eocene)	Uch (Eocene)	Zin (Eocene)	Pirkoh (Cretaceous)	Rodho (Cretaceous/Paleocene).	Panjpir	Nandpur	Jandran	Dhodak
						(Jurassic-Cretaceous)		(Cretaceous)	(Cretaceous)
Methane	88.52	27.3	46.1	81.91	82.78/82.0	52.49	38.40	90.00	79.47
Ethane	0.89	0.7	0.4	0.46	6.20/7.57	0.20	0.21	2.00	7.84
Propane	0.26	0.3	0.15	0.20	2.70/3.75	0.03	0.60		3.57
Butane	0.15	0.1	)	)	)				)
Pentane	0.05	0.1	) 0.15	) 0.06	) 1.87/2.76				) 3.11
Hexane	0.16	0.1	)	)	)				)
Carbon dioxide	7.35	46.2	44.7	6.34	1.80/2.20	5.53	1.67	3.00	1.70
Nitrogen	2.46	25.2	8.5	11.05	4.05/1.52	41.74	59.65	5.00	4.31
Helium	0.02	0.5	0.01						
Hydrogen Sulphide (grains/100 SCF)	92.2	33.5	13.3						
Mercaptan Sulphur (grains/100 SCF)	3.8	10.2	2.3						

then the Indian plate is moving northward. In Paleocene/Eocene time, the Indian plate collided with a block of the Eurasian plate and from Oligocene onward underthrusting of the Indian plate beneath the Eurasian plate continues. As a result, thrust sheets moved from the north and northwest toward south. In the northern Indus basin, infra-Cambrian salt acted as a slippery zone of decollement causing less severe deformation than in the northwestern part of the Indus basin (Sulaiman foldbelt and folded part of the Sulaiman depression) whereas Lower Eocene shales and probably some older shale horizons provided the surface of decollment and resulted in the nappe-like deformation. Transform movement along the Chaman fault (Figure 1) also affected the structures of the Sulaiman foldbelt.

The present day tectonic features of the Sulaiman and its existing folds and faults came into existence during post-Cretaceous orogenic events. The pre-Cretaceous history of the sub-basin is marked by non-orogenic movements.

The sub-basin is bounded on the east by the Indian shield and on the west by the marginal zone of the Indian plate. On the north lie the Sargodha high and Pezu uplift while its southern frontier is marked by Sukkur rift (Figure 1). The marginal zone of the Indian plate has been excluded from the sub-basin in the present study due to our poor knowledge of the complex petroleum geology of the region. The tectonic features of the region under study are described below:

Punjab Platform

The Punjab platform represents the eastern segment of the Sulaiman sub-basin. It is covered by alluvium and forms the Punjab plain.

Tectonically, it is a broad monocline dipping gently towards the Sulaiman depression. The pre-Cretaceous non-orogenic movements tilted the area eastwards during the Paleozoic, and westward from the Mesozoic onwards. The area was relatively less affected by Teritary orogenic movements because of its greater distance from the collision zone. Therefore, tectonic folds and faults are not abundant and the common structural features are either paleotopographic highs or salt pushed anticlinal folds (Figures 15, 16).

Sulaiman Depression

The Sulaiman depression is sub-meridionally oriented large area of subsidence. It becomes arcuate and takes up a transverse orientation along its southern rim. Although the origin of these bent mountains is debatable, yet the most plausible explanation offered so far relates it to plate convergence. The depression was carved during the collision of the Indian and Eurasian plates in post-Eocene time and has developed a large number of tectonic structures (Figure 3). The western flank of the depression is formed by north-south oriented Zindapir folded zone, comprising a chain of large asymmetrical anticlines with steep eastern flanks and gentle western flanks. Some of the structures are quite recent and resulted from the flow of argillaceous, highly pressured Eocene shales (*e.g.* Ramak, Figure 17). Another folded zone, namely Mari-Bugti, is developed on the southern rim of the depression whose folds are transversely oriented. The southern structures in this zone are gently dipping low relief anticlines whereas the northern folds form an orographically uplifted area and are chained with folded part of the Sibi depression.

The eastern flank of the depression is covered by alluvium and fluviatial clastics of Oligocene-Pleistocene age. The eastern flank gently merges with the Punjab platform. The structures in its western part are large tectonic anticlines (Figure 18). The available seismic data in the eastern flank is poor and only a few structural leads are clear. The possibility of stratigraphic traps exists in its eastern part because of the general eastward thinning of the Mesozoic sediments, but further seismic work is needed to confirm it (*e.g.* Figure 12).

Sulaiman Foldbelt

Sulaiman depression gives way in the west to the Sulaiman foldbelt comprising the Sulaiman mountain range. The foldbelt contains a large number of anticlinal structures, but most of them are disturbed and the known prospective reservoirs are often exposed to surface (Figures 3 6). The folds are generally large. Older prospects, fault traps and subthrust structures, merit attention as is the case with foldbelt exploration elsewhere.

Hydrocarbon Potential

For the purpose of evaluating oil and gas

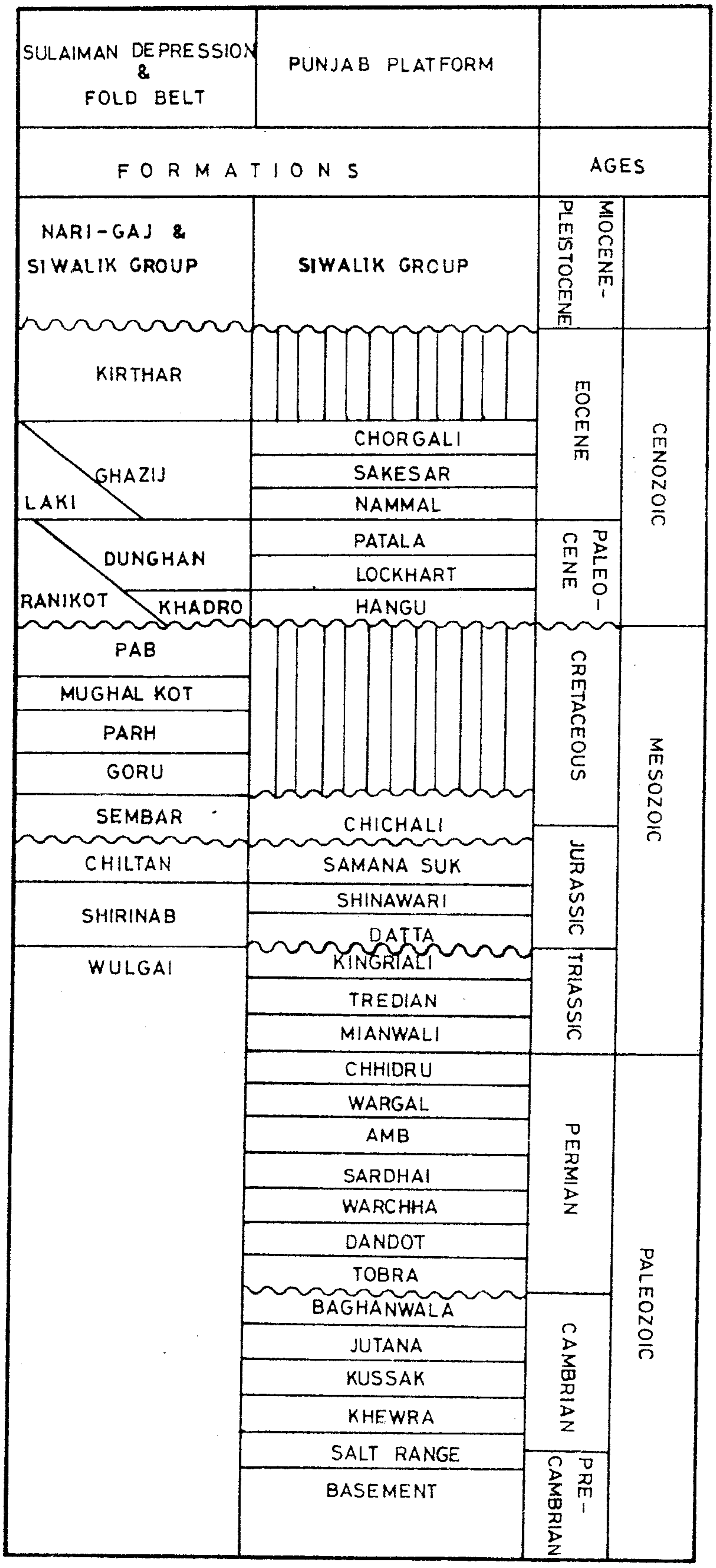


Figure 7. Stratigraphic nomenclature of the sub-basin.

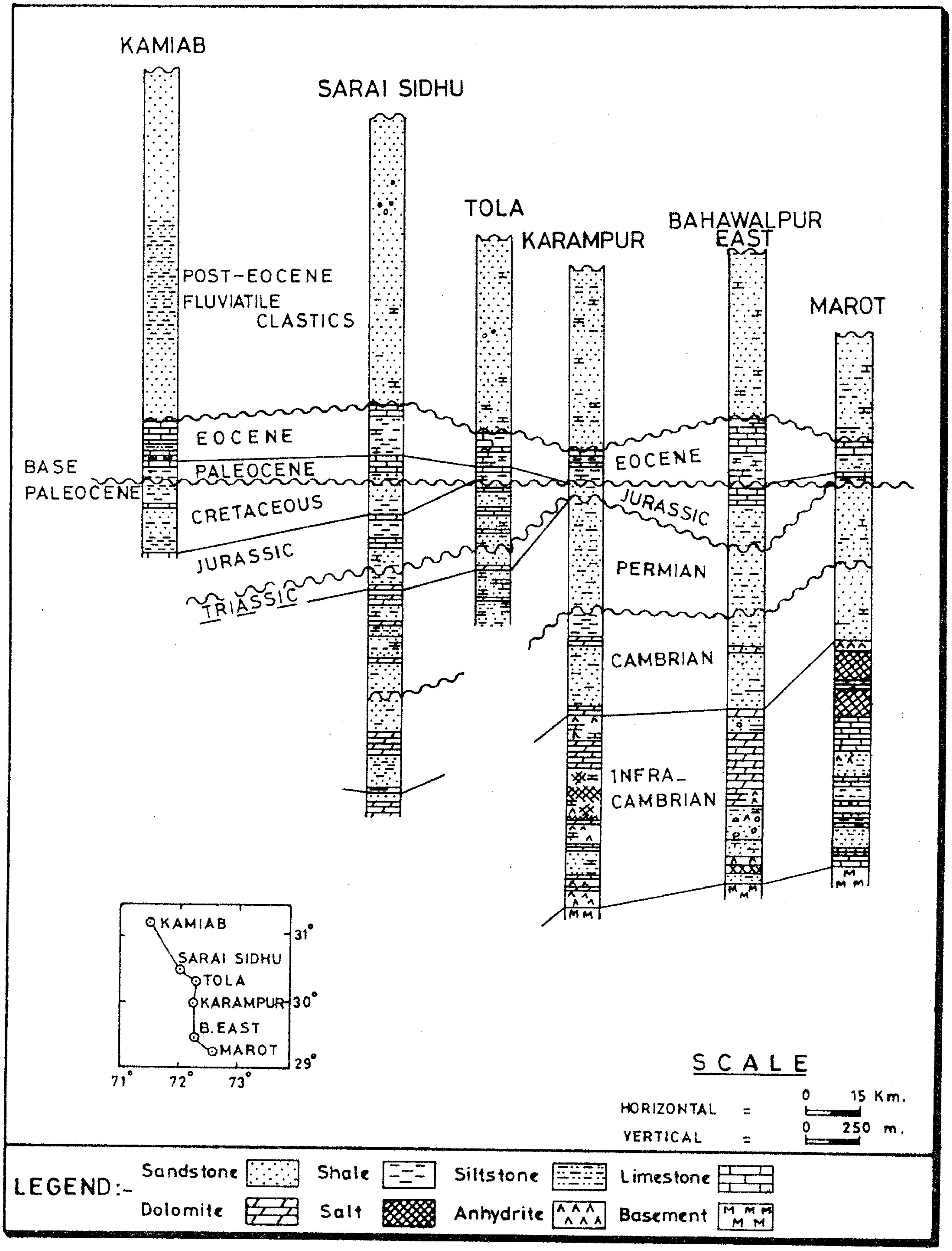


Figure 8. Stratigraphic correlation in Punjab Platform.

potential, the sub-basin is divided into five petroleum zones. These are illustrated in Figure 1 and assessed below:

Punjab Monocline Zone (A-1)

This is a westward dipping gentle monocline overlain by alluvium covering 69,000 sq km. In the subsurface, it contains marine Paleozoic, Mesozoic and Paleogene sediments overlain by Neogene fluviatial deposits. The zone is characterized by regional unconformities (*e.g.*, Figures 8, 10, 11).

Hydrocarbon Habitat

Gas has been discovered in OGDC's Nandpur and Panjpir wells (Figure 3) from the Jurassic and Cretaceous sediments. Good gas shows were encountered in AMOCO's Sarai Sidhu well from the Cretaceous rocks. The source rock studies carried out by Shell (PSPD, 1982) on samples from Karampur indicate: (1) Infra-Cambrian shales (Salt Range Formation) qualify as source rocks in Karampur well and (2) Infra-Cambrian rocks in Bahawalpur well, Permian rocks in Sarai Sidhu and Tola wells, Jurassic rocks in Bahawalpur and Paleocene rocks in Marot well contain shales with adequate organic content but suffer from lack of maturity (probably due to thin overburden).

Recent HDIP-BGR geochemical studies have proven that infra-Cambrian oil from oil show in Karampur well is correlatable to oil from surface oil shale samples of Salt Range Formation from Salt Range.

The geothermal gradient studies carried out by Khan and Raza (1986) indicate low values ranging from 1^{o}-2^{o}/100m. The oil window falls in the lower horizons of the Salt Range Formation and below, which might have been the reason for dry holes in the northern and eastern part of the platform which is close to the Indian shield (Figure 19).

From the above results it can be concluded that generally immature source rocks are present in the zone. The gas discoveries of Nandpur and Panjpir might be related to lateral migration from the Sulaiman depression in the west which is filled with a thick section of Mesozoic and Cenozoic sediments.

Reservoir Rocks

Dolomites of the Precambrian age (Salt Range Formation) with fractured and vuggy porosity, and sandstones of the Cambrian, Permian, Jurassic and Cretaceous with intragranular porosity are potential reservoirs. Mesozoic sands are productive in Nandpur and Panjpir gas fields, and good gas shows are encountered in Sarai Sidhu well from the Cretaceous sands. Table 3 shows average porosities for some of the important reservoirs.

Traps

The sediments in the zone have not experienced much tectonic deformation and the structures are commonly the result of pre-Tertiary non-orogenic movements. A number of paleotopographic highs and salt-induced anticlines have been seismically identified (*e.g.*, Figures 15 & 16) and some of these have been tested by drilling (*e.g.*, Marot & Bahawalpur East). The presence of stratigraphic traps in the area close to the Sulaiman depression where the pinch-out trends of Mesozoic formations have been picked on seismic profiles, holds the key to success in the zone despite failure of Kamiab and Budhana wells which were drilled to test such traps.

Four seismic leads, northeast and southeast of Darya Khan, are available among which the one located east of Mankera having a surface closure of 16.5 square kilometers is the largest and most promising (Figure 3). The feature is older than Tertiary as on the seismic profile the post-Eocene fluviatile sediments appear to be lying flat over it. A large

Table 3. Porosities of various reservoirs in the sub-basin.

AGE	POTENTIAL AND PRODUCING HORIZONS*	LITHOLOGY OF RESERVOIRS	POROSITY %
Eocene	Kirthar (Habib Rahi*)	Limestone	12
	Laki (Sui Upper*)	Limestone	12
	(Sui Main*)	Limestone	14
Paleocene	Dunghan/ Ranikot*	Limestone/ Sandstone	8/12
Creta-ceous	Pab*	Sandstone	12
	Mughalkot	Sandstone	16
Jurassic	Samana Suk*	Sandstone	12
	Datta	Sandstone	14
Permian	Zaluch	Sandstone	19
	Nilawahan	Sandstone	22
Cambrian	Baghanwala	Sandstone	12
	Kussak	Sandstone	23
	Khewra	Sandstone	6

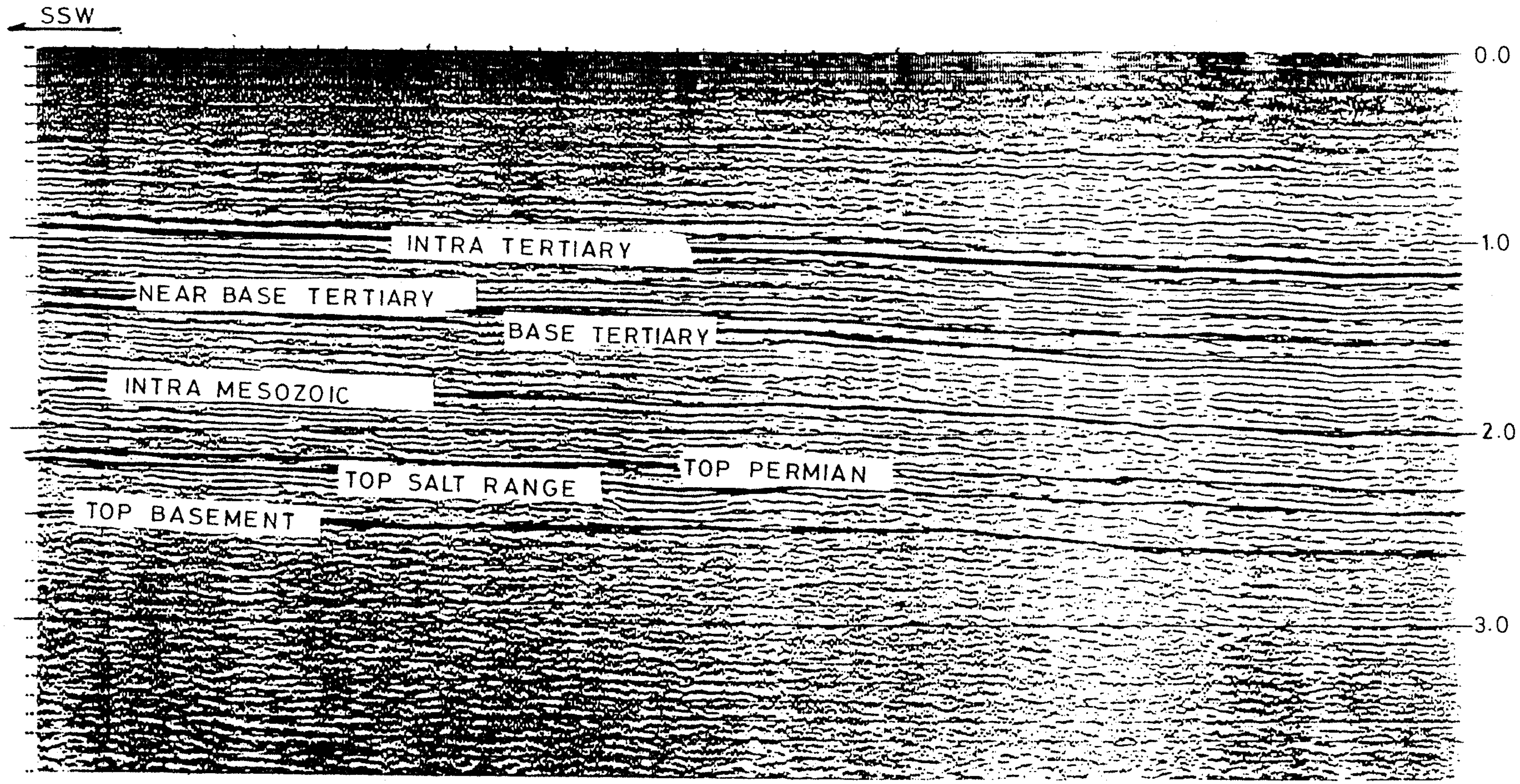


Figure 9. Profile along line 5 showing stratigraphic succession in Punjab Platform (Source: PSPD).

structural lead near Kot Adu, adjacent to the eastern boundary of the Sulaiman depression, can be seismically investigated and developed into a prospect. It is ideally located to receive migrating hydrocarbons from the adjoining Sulaiman depression. A lead mapped by AMOCO, north of Duniapur is a good fault trap and deserves to be developed into a prospect (Figures 3, 20). Another interesting lead identified by AMOCO about 13 kilometers north of Sarai Sidhu well in the vicinity of Basti Waryam is also worth developing into a prospect. A closure picked by seismic survey in the southwest of Khanpur shows reversal at the Permian and Jurassic levels. Further seismic work is required to properly evaluate this feature.

Sulaiman Depression Zone (B-3)

This area is about 25,000 sq km with a great thickness of Mesozoic and Cenozoic sedimentary rocks which decrease in thickness eastward (Figure 21).

Hydrocarbon Habitat

Thick Mesozoic and Early Tertiary marine sediments should contain potential source rocks within thick shale and mudstone section (Figures 22, 23). A number of gas fields and gas seepages reside within Cretaceous-Eocene sedimentary sequence in the adjoining Mari-Bugti and Zindapir zones. Recent HDIP-BGR geochemical studies have indicated that Cretaceous-Paleogene section in the adjoining areas contains potential source rocks which extend to this zone (Tables 4, 5). The summary of the applicable results is: (1) Sembar formation (VR: 3.30, TOC: 1.38), (2) Mughal Kot formation (VR: 1.97, TOC: 0.64), (3) Dunghan-Ranikot formation (VR: 1.74, TOC: 0.49), (4) Ghazij formation (VR: 1.32, TOC: 0.94), (5) Habib Rahi member (VR: 0.40, TOC: 10.95) and (6) Pirkoh member (VR: 0.48, TOC: 4.89).

The average geothermal gradient in the zone is 2.2^{0}/100m and onset of oil window is at 2500m depth. From the above data it may be interpreted that Kirthar (Habib Rahi and Pirkoh mbs) may be the potential source of oil generation.

Reservoir Rocks

Eocene carbonates and Mesozoic sandstones which are producers in the adjoining areas could be the potential reservoirs in the zone.

Table 4. Results of organic geochemical analysis of surface rock samples from Zindapir Inner Folded zone (C-1). Data Source: HDIP-BGR.

Age	Formation	Member	Sample Location	Lithology	VR	TOC	EOM	EOM/TOC	gP	HI
Eocene	Kirthar	Drazinda	Sanghar Lahar	Sh	-	0.24	-	-	-	-
		Pirkoh	Sanghar Lahar	Sh	-	3.95	-	-	22	557
			Vidro Nadi	Marlst	-	3.57	-	-	-	-
			Ramana Thokh	Oil Sh	-	2.56	-	-	11	430
			Bar Nala	Marlst	0.48	1.09	-	-	4	367
				Oil Sn	-	3.47	-	-	21	605
		Sarki	Ramana Thokh	Sh	-	0.14	-	-	-	-
		Habib Rahi	Belab Nala	Oil Sh	-	7.12	6419	90	51	715
				"	-	3.24	3365	104	23	722
			Vidor Nadi	Marlst	-	6.23	-	-	44	706
				Oil Sh	-	6.37	-	-	50	785
			Runghan Lahar	Marlst	-	7.93	-	-	72	909
				Oil Sh	-	9.01	-	-	73	810
			Sanghar Lahar	Oil Sh	-	10.95	9516	87	66	600
				"	-	7.47	-	-	55	736
	Ghazij		Zindapir	Sh	-	0.94	259	29	1.2	128
				"	-	0.24	-	-	-	-
Paleocene	Dunghan/Ranikot		Zindapir	Lst	-	0.70	512	72	3.1	437
			"	Sh	-	0.32	-	-	-	-

Traps

The depression is mainly covered by alluvium and in its western part post-Eocene fluviatile clastics are exposed. The existing seismic profiles are discontinuous over the Indus River and there is a need for river undershooting. The large tectonic anticlines (Sakhi Sarwar and Kotrum) have so far been unsuccessfully tested (Figures 3, 18). Among the available leads, Ramak uplift east of Zindapir zone is the largest and most promising structure (Figure 17). It was recommended for drilling by AMOCO to test petroleum reservoir potential of Oligocene-Miocene sandstones and Middle Eocene limestone. The potential reservoirs are covered by adequate thickness of fluviatile sediments (Siwaliks). The diapirism in the Eocene shales is considered responsible for the uplift as evidenced by the disharmony between the older and younger strata.

The zone is ideally suited for stratigraphic traps due to regional thinning of Mesozoic and Cenozoic sediments eastward, where they are truncated by the younger horizons.

Zindapir Inner Folded Zone (C-1)

The zone having approximately 5,600 square kilometers area comprises north-south oriented fold

Table 5. Results of organic geochemical analysis of surface rock samples from the eastern part of Sulaiman Outer Folded Zone (Zone D-1). **Data source: HDIP-BGR**

Age	Formation	Member	Sample Location	Lithology	VR	TOC	EOM	EOM/TOC	gP	HI
Eocene	Kirthar	Drazinda	Jandola	Sh	-	0.24	-	-	-	-
			Rakhi Nala	Sh	-	0.33	-	-	-	-
		Pirkoh	Rakhi Nala	Marlst	-	4.05	-	-	23	568
				Siltst	0.40	-	-	-	-	-
			Khalgari Nala	Marlst	-	4.89	2168	44	23	470
			Rakhni	Sh	-	3.19	-	-	19	596
			Gumal river	Sh	-	3.83	1276	33	22	574
		Sarkai	Domanda	Sh	-	1.20	-	-	3.3	275
			Toi Nala	Sh	-	1.02	568	56	4.5	441
			Rakhi Nala	Sh	-	0.29	-	-	-	-
		Habib Rahi	Jandola	Sh	-	0.91	-	-	0.69	76
			Rakhi Nala	Siltst	-	1.30	1760	134	9.1	695
				Sh	-	2.55	-	-	13	510
			Khalgari Nala	Oil Sh	-	8.12	7003	86	68	838
				Sh	-	6.47	-	-	38	588
			Toi Nala	Oil Sh	-	4.38	7225	165	43	982
				"	0.40?	2.08	-	-	14	673
			Domanda	Sh	-	2.09	1564	75	13.0	622
				Oil Sh	0.40?	3.36	5609	166	30	890
			Zor Shahr	Oil Sh	-	3.56	4436	125	27	767
			Buri Zam	Oil Sh	-	4.73	5241	111	7.1	150
			Zao River	Oil Sh	-	2.37	1371	58	15	641
				"	-	4.12	3417	83	31	760
Eocene	Kirthar	Habib Rahi	Gumal River	Lst	-	0.85	-	-	5	588
	Ghazij		Rakhi Nala	Sh	-	0.19	-	-	-	-
			Rakhni	Sh	-	0.17	-	-	-	-
			Toi Nala	Sh	1.32	0.21	-	-	-	-
				"	1.27	0.30	-	-	-	-
Paleocene	Dunghan/Ranikot		Rakhi Nala	Sh	1.52	0.49	-	-	-	-
				"	1.74	0.40	-	-	-	-
Cretaceous	Mughal Kot	Fort-Munro	Fort Munro	Sh	>1.5	0.46	-	-	-	-
				"	>1.8	0.39	-	-	-	-
			Rakhi Nala	Marlst	1.07	0.34	-	-	-	-
				Sh	1.19	0.28	-	-	-	-
			Mughal Kot	Siltst	-	0.56	30	5.4	<1	<200
				"	1.43?	0.48	-	-	-	-
			Gat Tangi	Siltst	1.97	0.48	-	-	<1	<200
				Sh	-	0.64	40	6.3	<1	<200
	Goru		Mughal Kot	Sh	-	0.26	-	-	-	-
				"	-	0.27	-	-	-	-
			Gat Tangi	Sh	-	0.19	-	-	-	-
	Sembar		Mughalkot	Sh	3.05	0.68	-	-	<1	<200
				Siltst	3.30	0.74	42	5.6	<1	<150
			Gat Tangi	Sh	-	1.38	56	4.1	<1	<80
				"	3.14	1.24	45	3.6	0.68	55
			Dan Sar	Sh	3.23	1.26	43	3.4	<1	<100

Table 6. Results of organic geochemical analysis of surface rock samples from the western part of Sulaiman Outer Folded Zone (Zone D-1). Data source: HDIP-BGR

Age	Formation	Member	Sample Location	Lithology	VR	TOC	EOM	EOM/TOC	gP	HI
Eocene	Ghazij		Mach	Coal	0.33	54.40	9276	17	115	260
				Sh	0.47	12.20	2664	22	23	189
			Murree Brewery	Sh	1.39	0.32	-	-	-	-
			Sor Range	Coal	0.36	57	11023	19	121	212
				Sh	0.47	10.20	1756	17	18	178
			Duki	Coal	0.54	65.80	13695	21	174	264
				Sh	0.53	0.68	-	-	0.40	59
			Dilkuna	Sh	0.85	0.30	-	-	-	-
Paleocene	Dunghan/ Ranikot		Dilkuna	Lst	-	0.30	-	-	-	-
			Kum Tangi	Lst	-	0.24	-	-	-	-
				Sh	0.94	0.92	408	44	0.38	41
			Siazgi	Siltst	0.43	-	-	-	-	-
Cretaceous	Mughal Kot		Dilkuna	Marlst	-	0.16	-	-	-	-
			Siazgi	Sh	-	0.36	-	-	-	-
	Goru		Dilkuna	Sh	-	5.84	2170	37	30	514
				Siltst	-	0.35	-	-	-	-
			Kum Tangi	Siltst	1.7?	-	-	-	-	-
			Mazar Drik	Sh	-	0.29	-	-	-	-
	Sembar		Mazar Drik	Sh	1.37	1.79	316	18	0.6	34
				"	-	1.44	323	22	0.4	28
			Khum Tangi	Sh	0.62	-	-	-	<1	<160
			Dilkuna	Sh	0.47	1.17	363	31	2	171
				"	-	1.04	300	29	2.6	250

Age	Formation	Member	Sample Location	Lithology	VR	TOC	EOM	EOM/TOC	gP	HI
Cretaceous	Sembar		Qila Saif-ullah	Sh	1.37	0.44	-	-	-	-
				"	-	0.46	-	-	-	-
			Tor Tangi	Sh	0.94	0.74	-	-	<1	<150
				"	1.13	0.95	-	-	<1	<100
			Surkai-zangal	Sh	0.94?	2.06	474	23	1.1	55
				Siltst	-	0.81	-	-	<1	<120
			Old Sang-awi	Sh	-	0.35	-	-	-	-
			Ahmagzai Kili	Sh	-	0.35	-	-	-	-
			Mara Rud	Sh	-	0.08	-	-	-	-
Jurassic	Chiltan		Mara Rud	Lst	1.06?	0.17	-	-	-	-
				"	-	0.13	-	-	-	-
			Tor Tangi	Lst	-	0.15	-	-	-	-
	Shirinab	Spingwar	Tor Tangi	marlst	-	0.22	-	-	-	-
			Qila Saifu-llah	Sh	1.03	0.31	-	-	-	-
				"	1.46?	0.40	-	-	-	-
			Kach Dam	Sh	0.63	0.34	-	-	-	-
				"	2.24	0.38	-	-	-	-
			Mara Rud	Sh	1.07	0.15	168	36	-	-
				"	1.35	-	-	-	-	-
Triassic	Wulgai		Wülgai	Sh	3.20	-	-	-	-	-
				"	2.22?	0.76	41	5.4	<0.2	<30

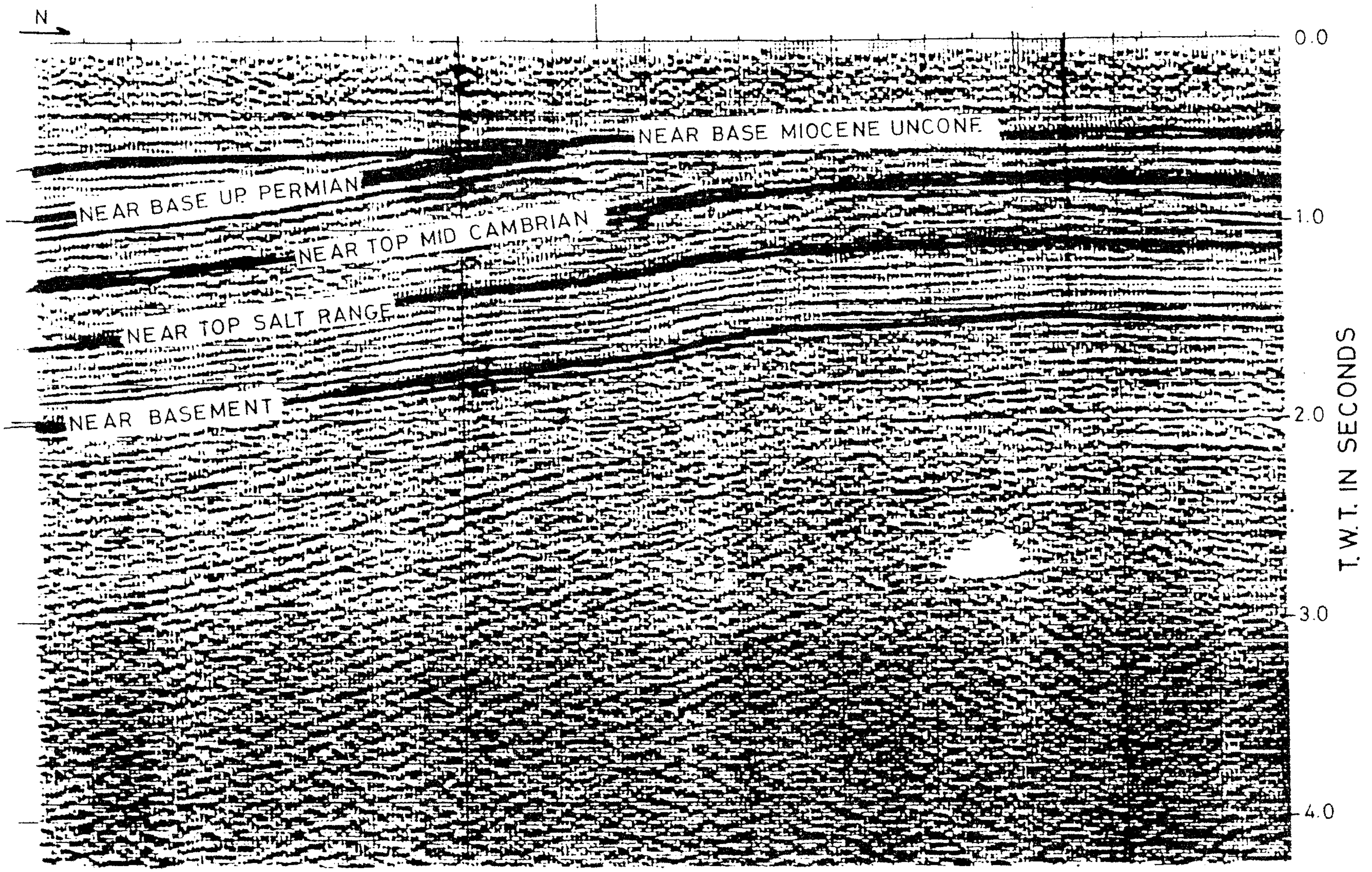


Figure 10. Profile along line 9 showing truncation of Permain strata against Molasse unconformity in Punjab Platform (Source: Gulf Oil).

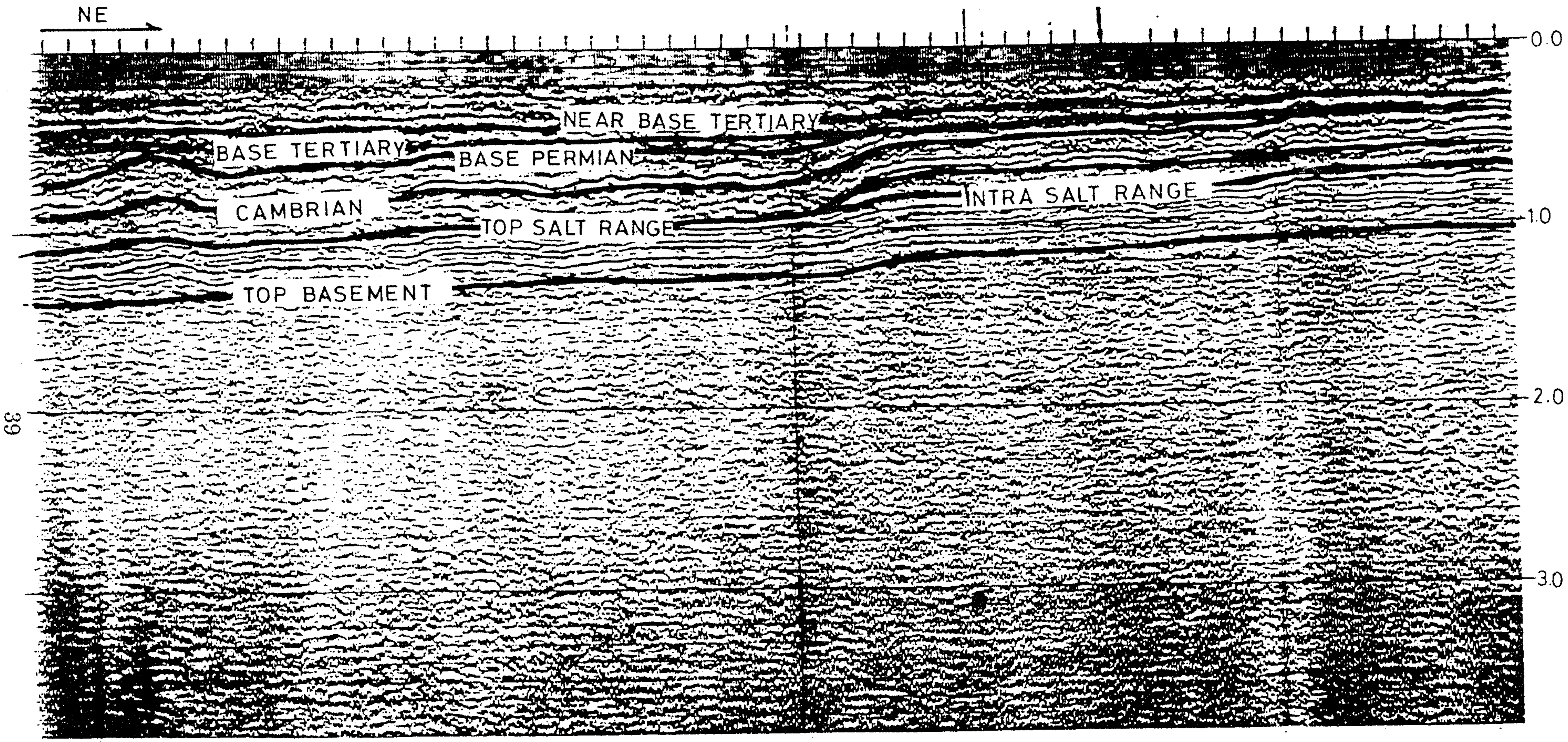


Figure 11. Profile along line 6 showing thinning out and truncation of Cambrian and Permain sediments towards northeast in Punjab Platform (Source: PSPD).

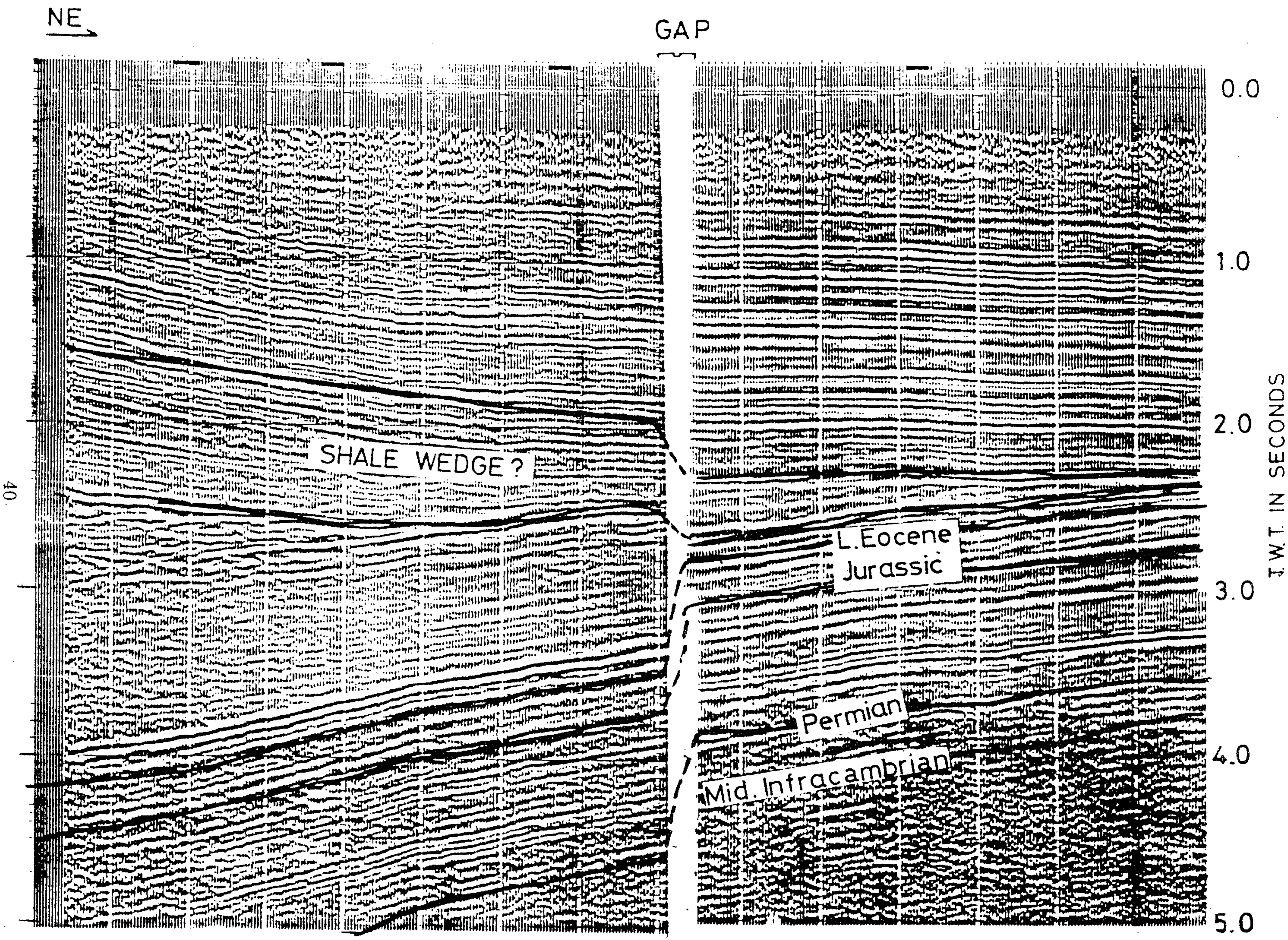


Figure 12. Profile along line 1 showing westerly dip of rock units and their thinning out towards east in Punjab Platform (Source: AMOCO).

Figure 12. Profile along line 1 showing westerly dip of rock units and their thinning out towards east in Punjab Platform (Source: AMOCO).

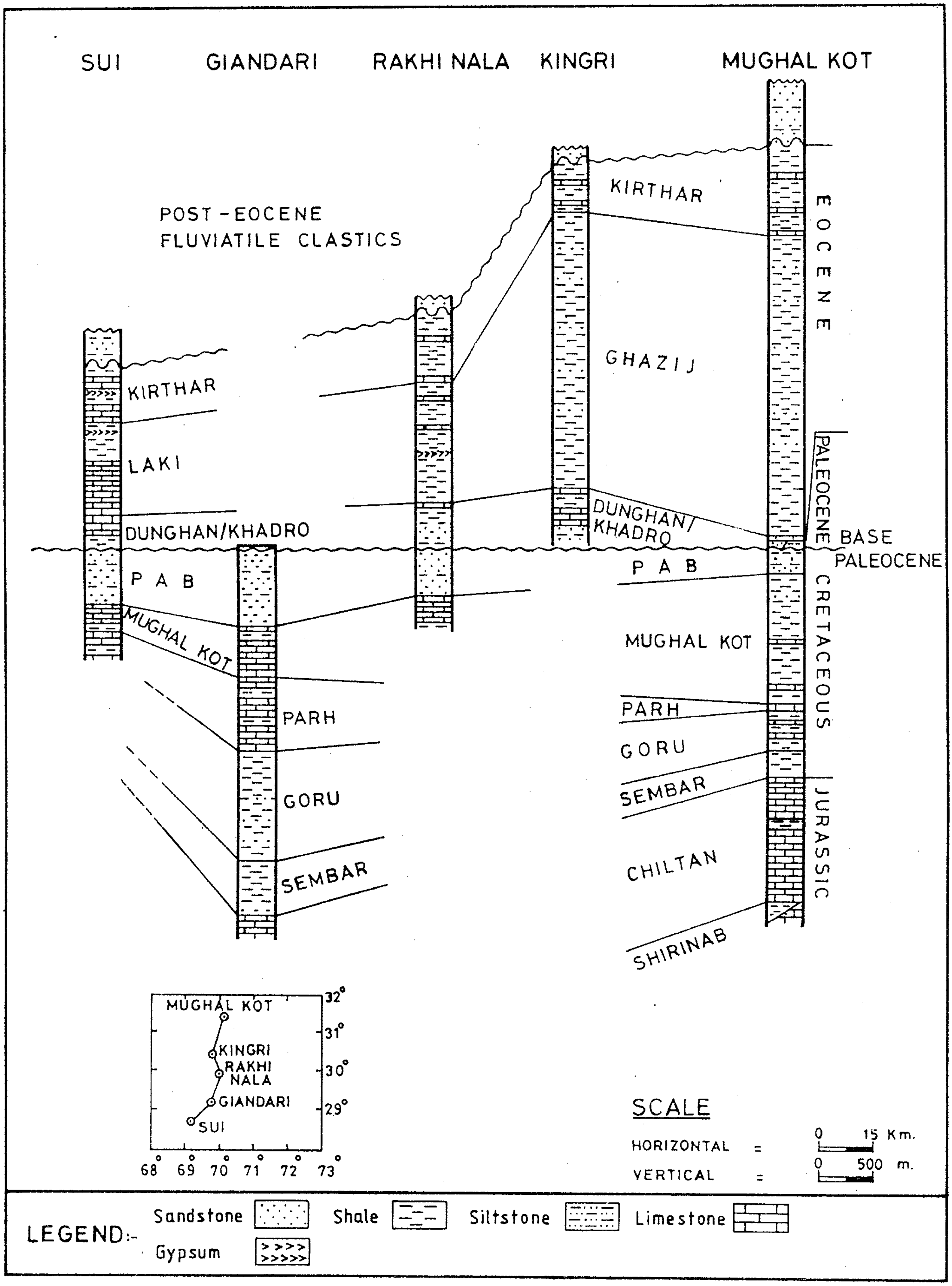


Figure 13. Stratigraphic correlation in Sulaiman Foldbelt.

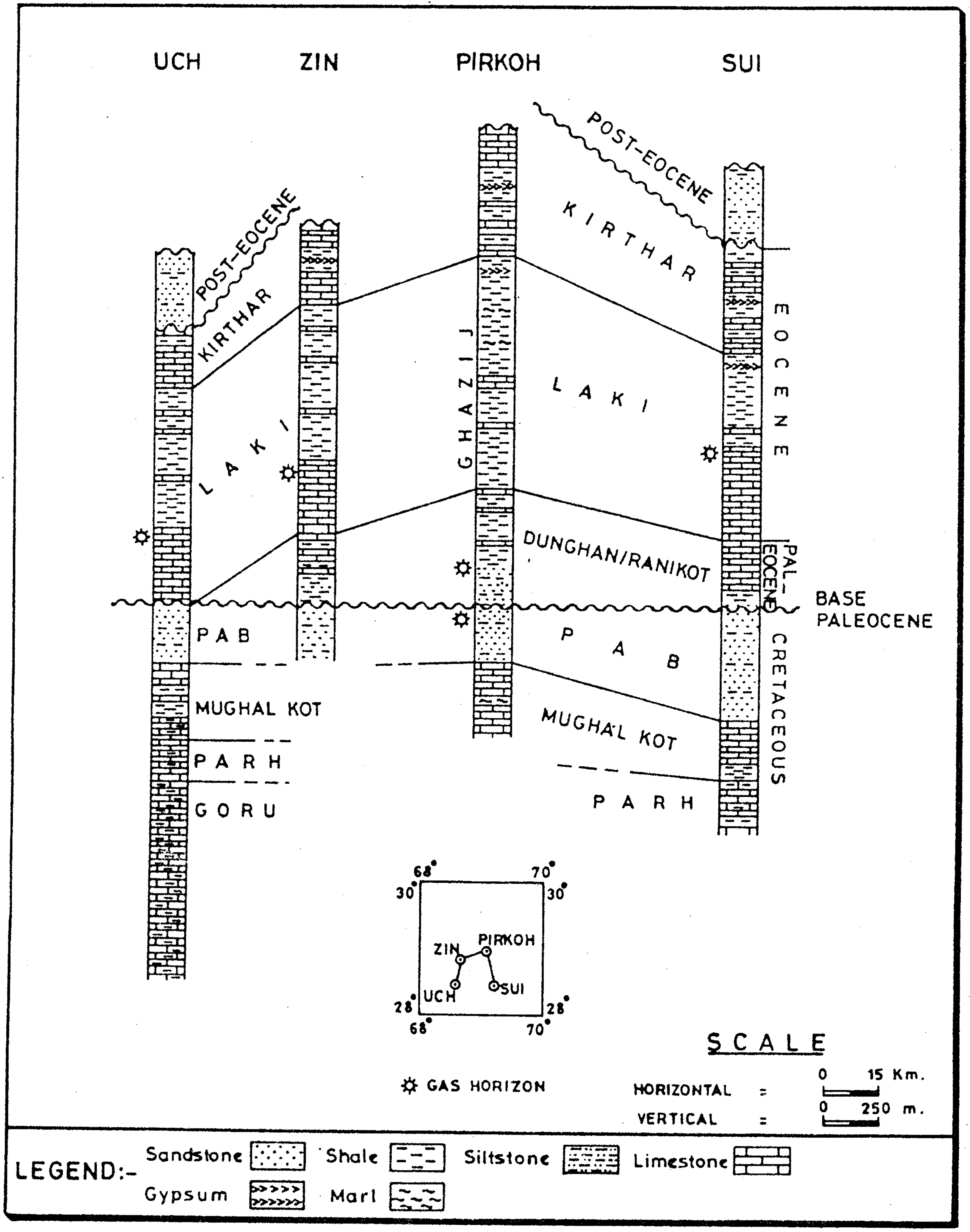


Figure 2 - Stratigraphic correlation in Mari-Bugti Area

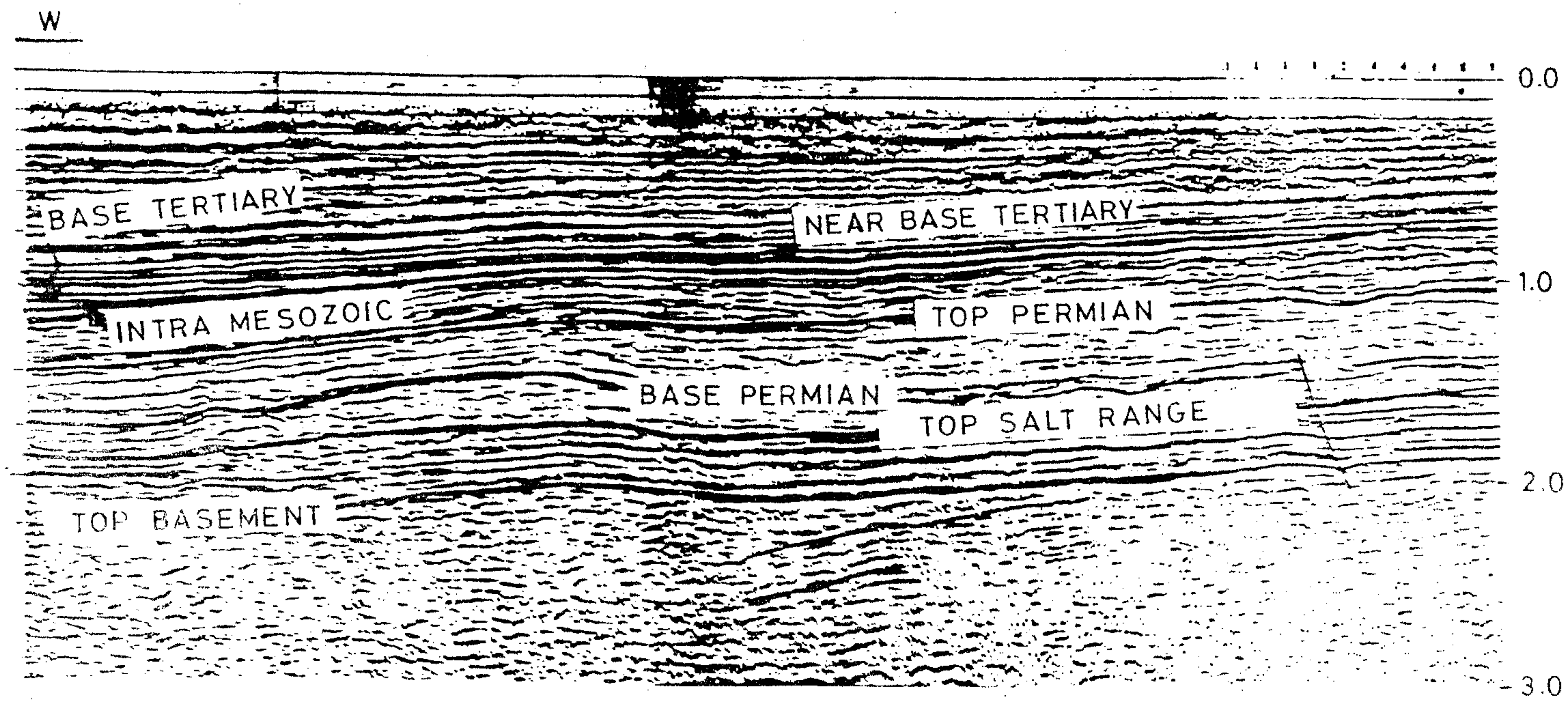


Figure 15. Profile along line 8 showing paleotopographic structure in Punjab Platform (Source: PSPD).

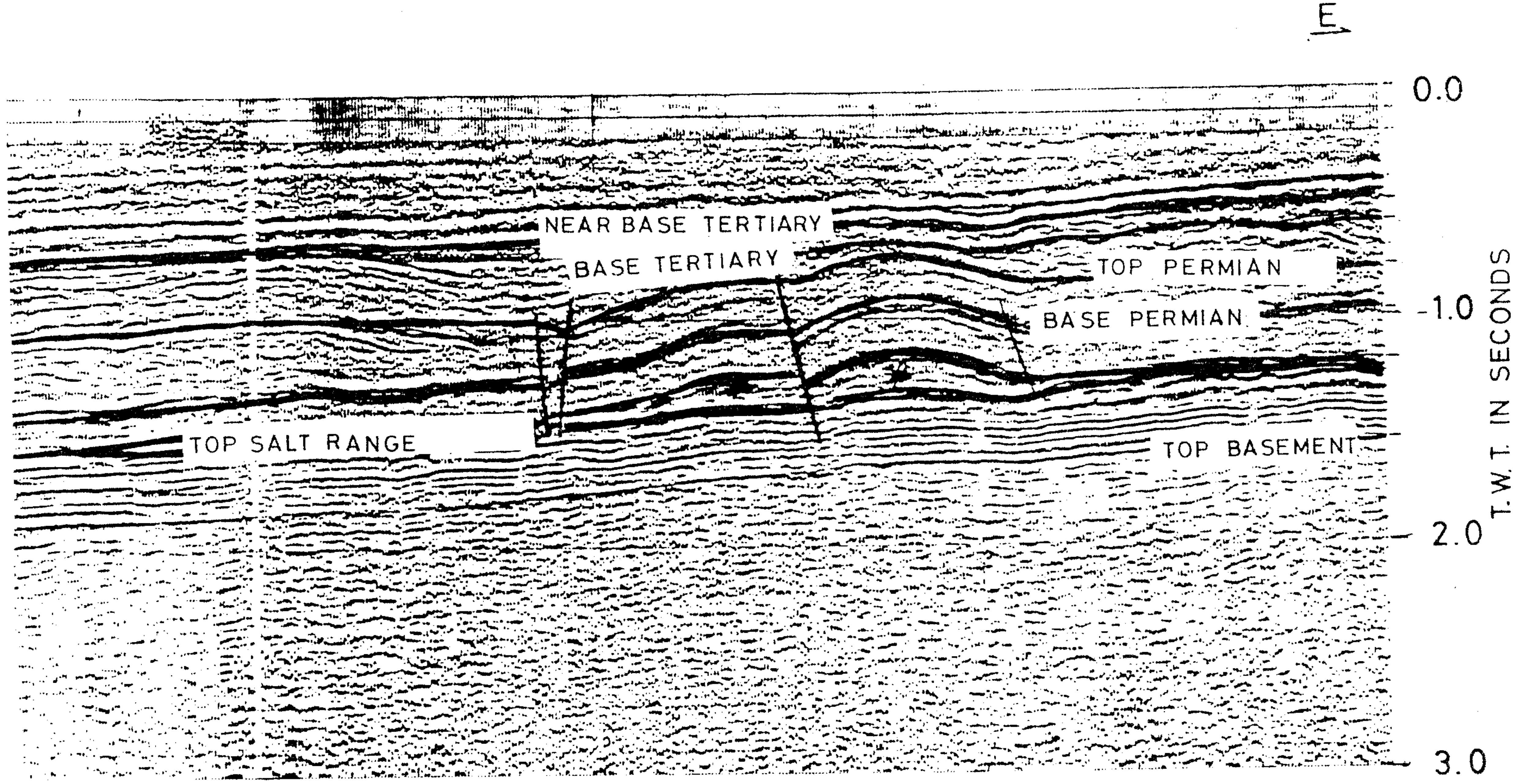


Figure 16. Profile along line 7 depicting salt-induced structure in Punjab Platform (Source: PSPD).

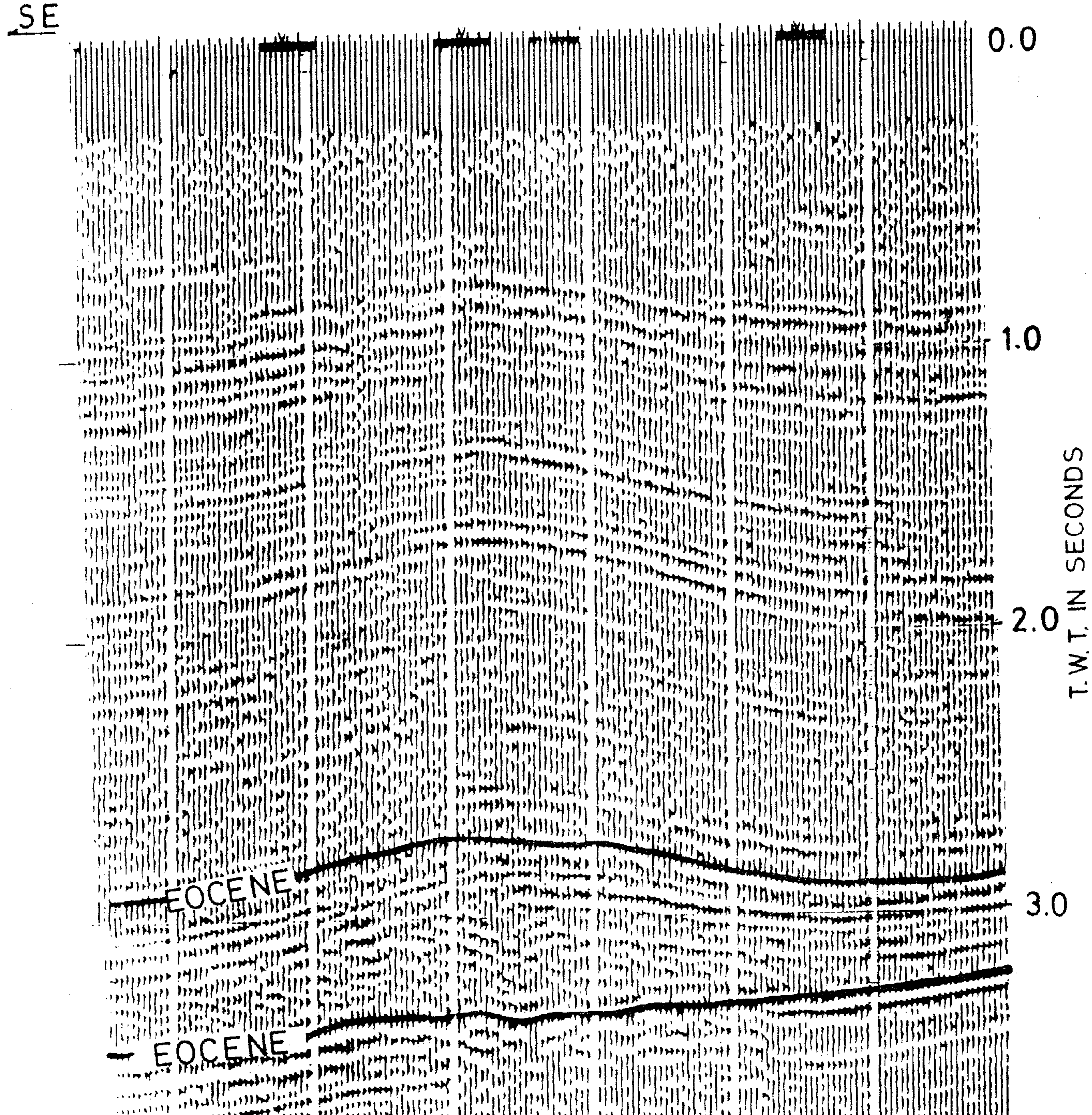


Figure 17. Profile along line 2 showing presence of a large anticlinal structure at Eocene level in northern part of Eastern Sulaiman Depression (Source: AMOCO).

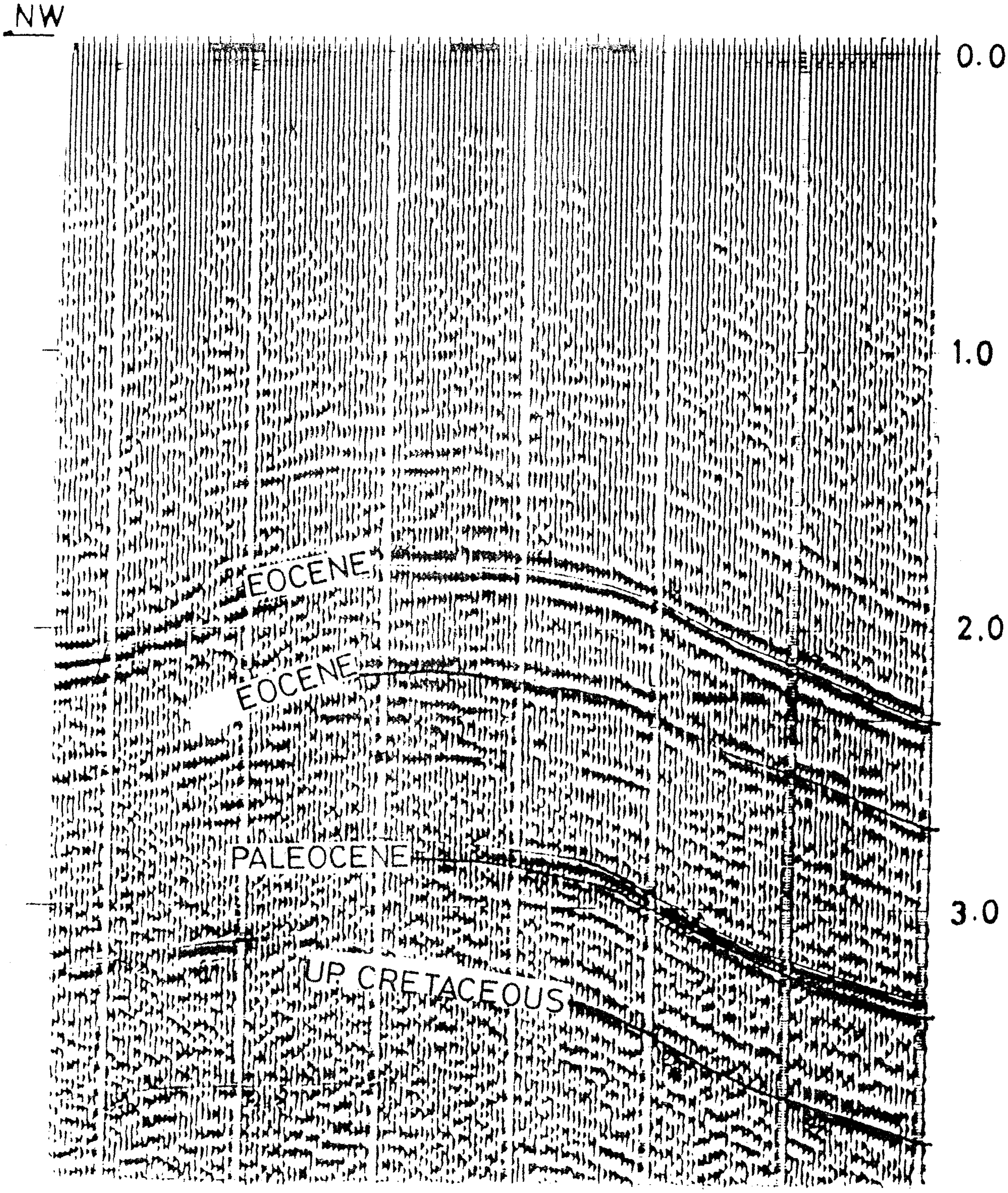


Figure 18. Profile along line 3 showing well formed tectonic anticline in Eastern Sulaiman Depression (Source: AMOCO).

system constituted by four individual anticlines namely, Dhodak, Rodho, Afiband and Zindapir. The anticlines have narrow crests, steep eastern flanks and relatively gentle western limbs. Eocene rocks are exposed in the core of Dhodak, Rodho and Afiband structures, whereas Paleocene and uppermost part of Cretaceous strata are exposed in the core of Zindapir anticline.

Hydrocarbon Habitat

The zone is favourably placed as evidenced by the Cretaceous oil seepage of Mughal Kot located less than 65 km northwest of Dhodak structure, and the Cretaceous gas seepage of Zindapir in the core of Zindapir anticline. The geothermal gradient is on the high side, value in Dhodak well is 2.3°C/100 m and the Eocene, Paleocene and drilled Cretaceous successions are within the oil window. Recent geochemical studies including Vitrinite Reflectance carried out by HDIP-BGR (Table 5) around the area indicate that shales of Early Cretaceous age (Sembar formation) are potential source of hydrocarbons (VR: 3.30, TOC: 1.38).

Reservoir Rocks

Moderately porous sandstone of Pab formation (Late Cretaceous) is the main reservoir in the zone.

Traps

Out of the four available structures, Dhodak and Rodho were productive. The other two *i.e.*, Afiband and Zindapir failed to produce hydrocarbons. Afiband anticline located between gas leaking Zindapir anticline and the first well on Rodho gas field was recently drilled based only on geological information. It merits seismic surveys and additional drilling to fully test its potential. Large Zindapir anticline often referred as a "Sleeping Giant" prior to drilling with some gas shows in the Cretaceous sandy reservoir exposed in the core of the anticline only brought stratigraphic information as it was drilled through nearly most of Mesozoic section.

Mari Bugti Inner Folded Zone (C-2)

The zone contains 5 gas fields, among which Sui having 8.6 tcf original reserves, is ranked among the giants. The zone is characterized by east-west oriented anticlinal systems which gain altitude and structural complications northwards.

Hydrocarbon Habitat

The composition of gas in all the fields is variable (Table 2). Although the zone is gas-prone, yet chances of striking oil exist in structures west and northwest of Pirkoh because of oil seepage of Khattan in Lower Eocene limestone (Figure 3).

HDIP-BGR geochemical studies around the area (Table 6) indicate source rock potential of Cretaceous (VR: 1.37, TOC: 1.79).

The geothermal gradient is generally on higher side in the area. It increases eastward and falls westward. The hot spot is in Giandari well where a value of 4.1°C/100m has been estimated. The oil window in this well lies between 1325—2550m (Cretaceous rocks). The failure of Giandari well might be related to overcooking of source rocks. In Sui field the gradient is 3°C/100m and oil window ranges from 850—3500 m depth (Paleocene-Cretaceous). The gas window in Sui would be below 3500m depth (Early Cretaceous) which hints at a pre-Tertiary source (Figure 19).

Reservoir Rocks

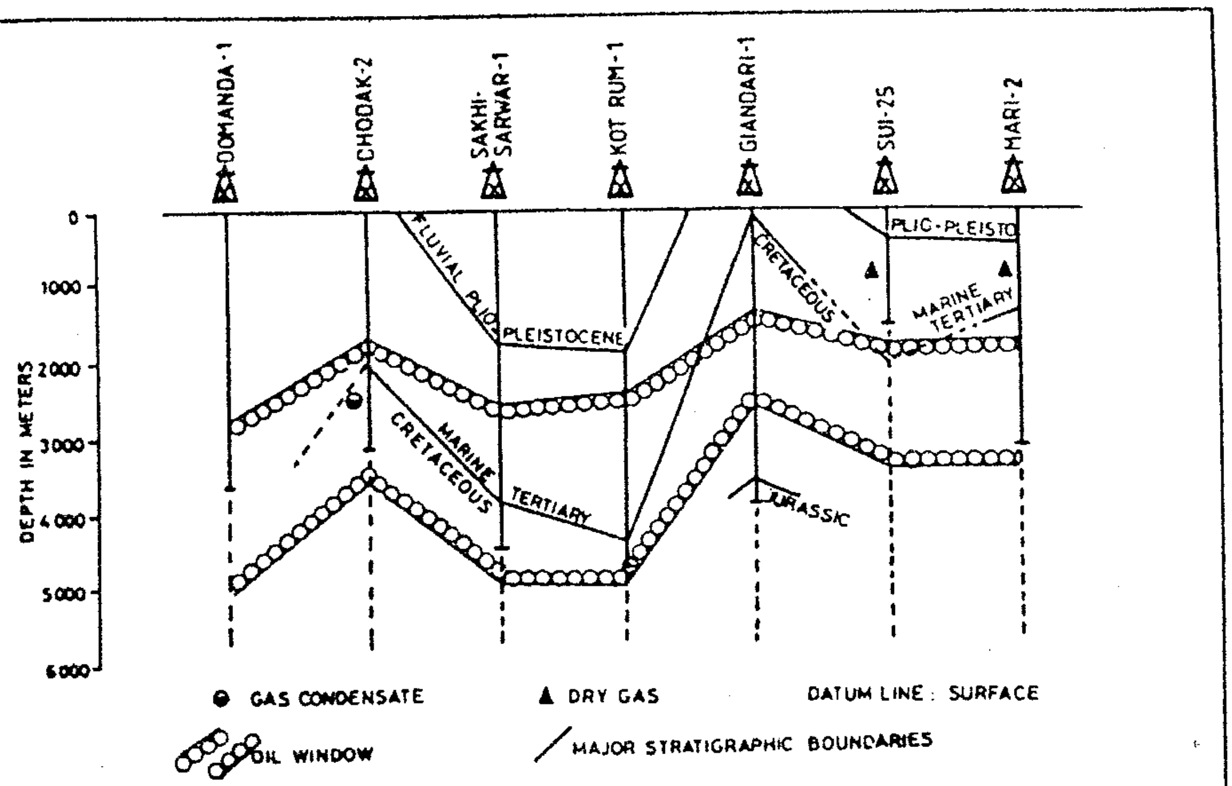
The producing horizon in Sui, Uch and Zin fields is Lower Eocene foraminiferal limestone, which is the most productive gas reservoir in Pakistan and has its maximum development in this zone (Figures 14, 23). In Pirkoh field, sand reservoirs of Paleocene and Upper Cretaceous are productive. The Gas reservoirs in Loti field are Eocene limestone and Upper Cretaceous sandstone.

Traps

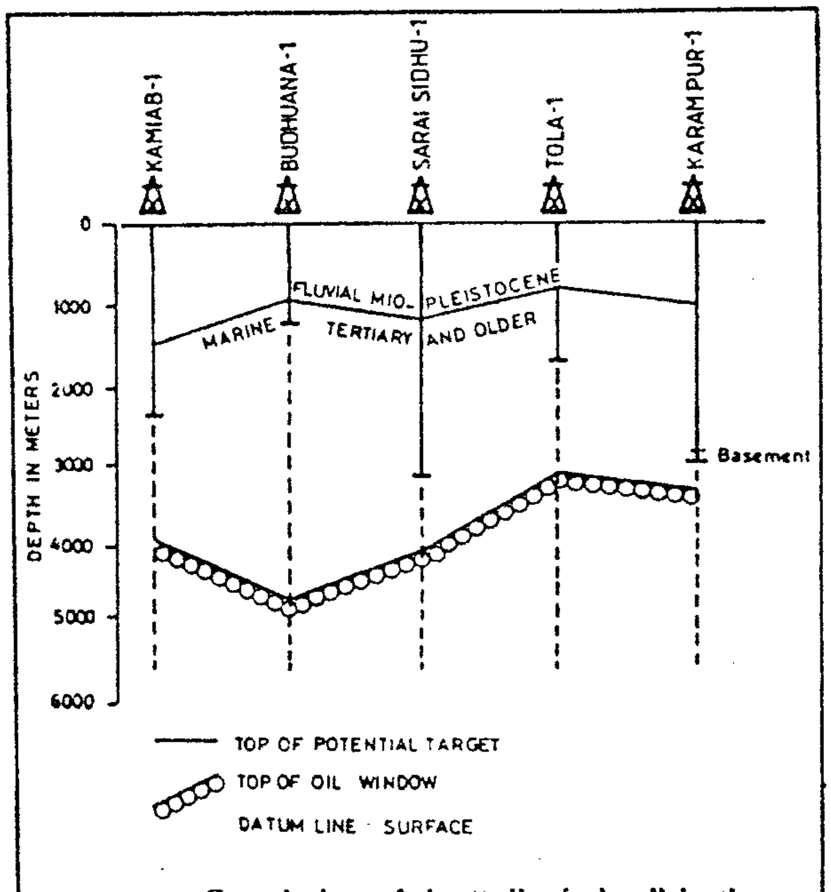
The zone is left with only a few undrilled surface structures. Bambor anticline is the most promising structure which might produce oil.

Sulaiman Outer Folded Zone (D-1)

It is a large zone with a number of anticlinal structures, but with no significant oil or gas discovery



Correlation of the "oil window" in the central part of the Sulaiman region.



Correlation of the "oil window" in the Northern Marginal areas of the Sulaiman region.

Figure 19. Correlation of "oil window" in the sub-basin (after Khan and Raza, 1986).

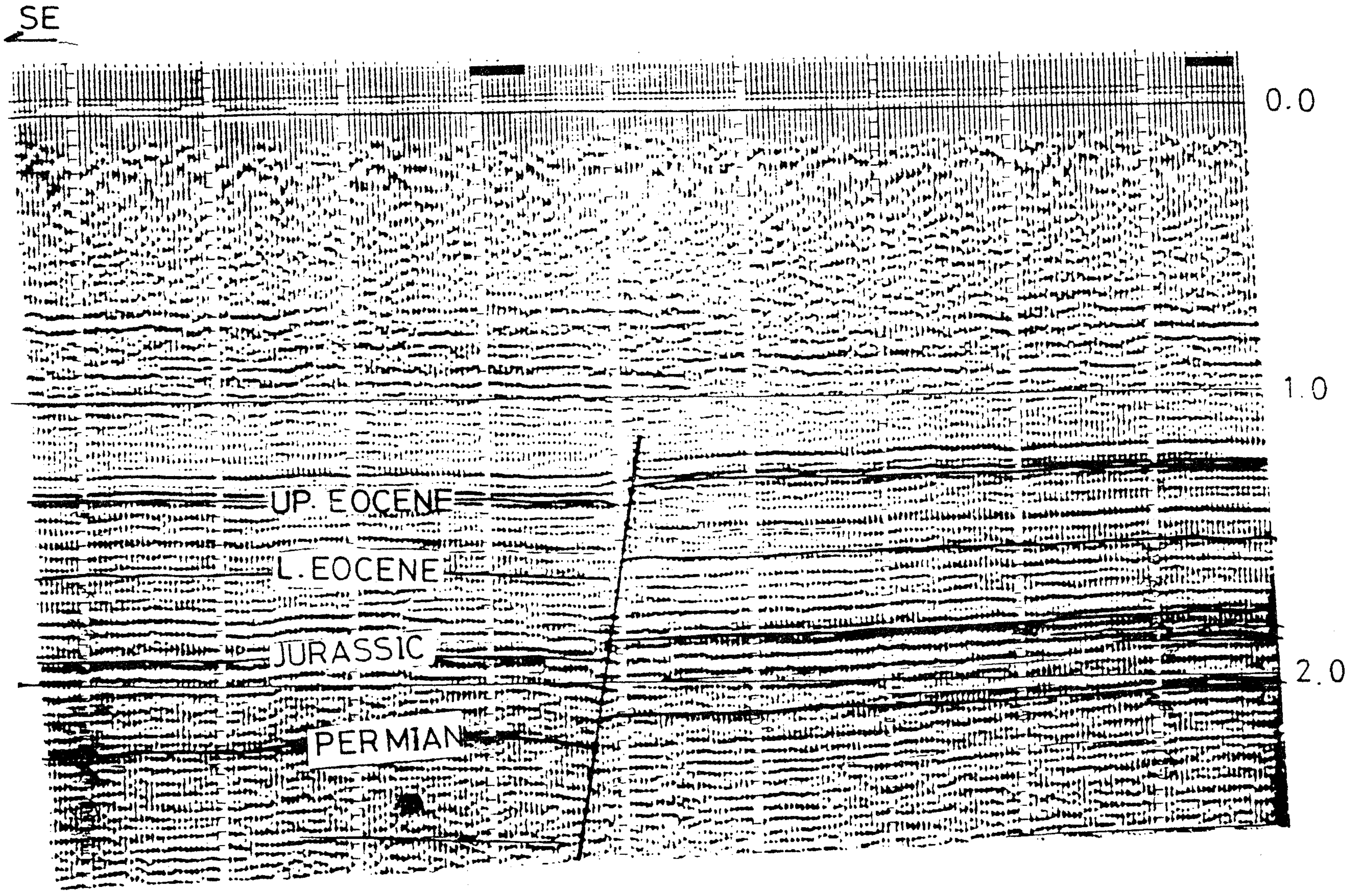


Figure 20. Profile along line 4 indicating fault trap in Punjab Platform (Source : AMOCO).

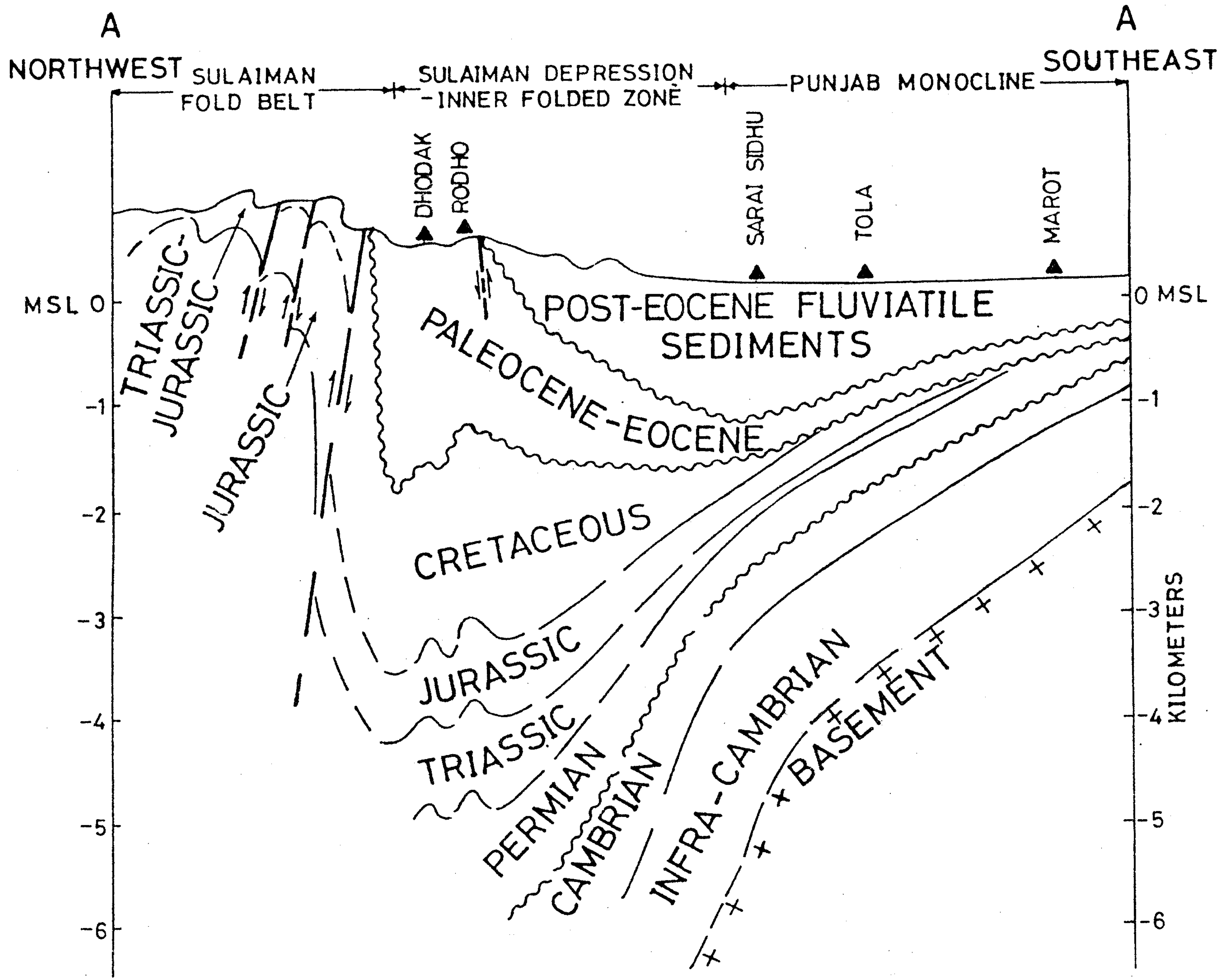


Figure 21. Regional cross section along line AA', Sulaiman region. For location see figure 2.

Figure 21. Regional cross section along line AA', Sulaiman region. For location see figure 2.

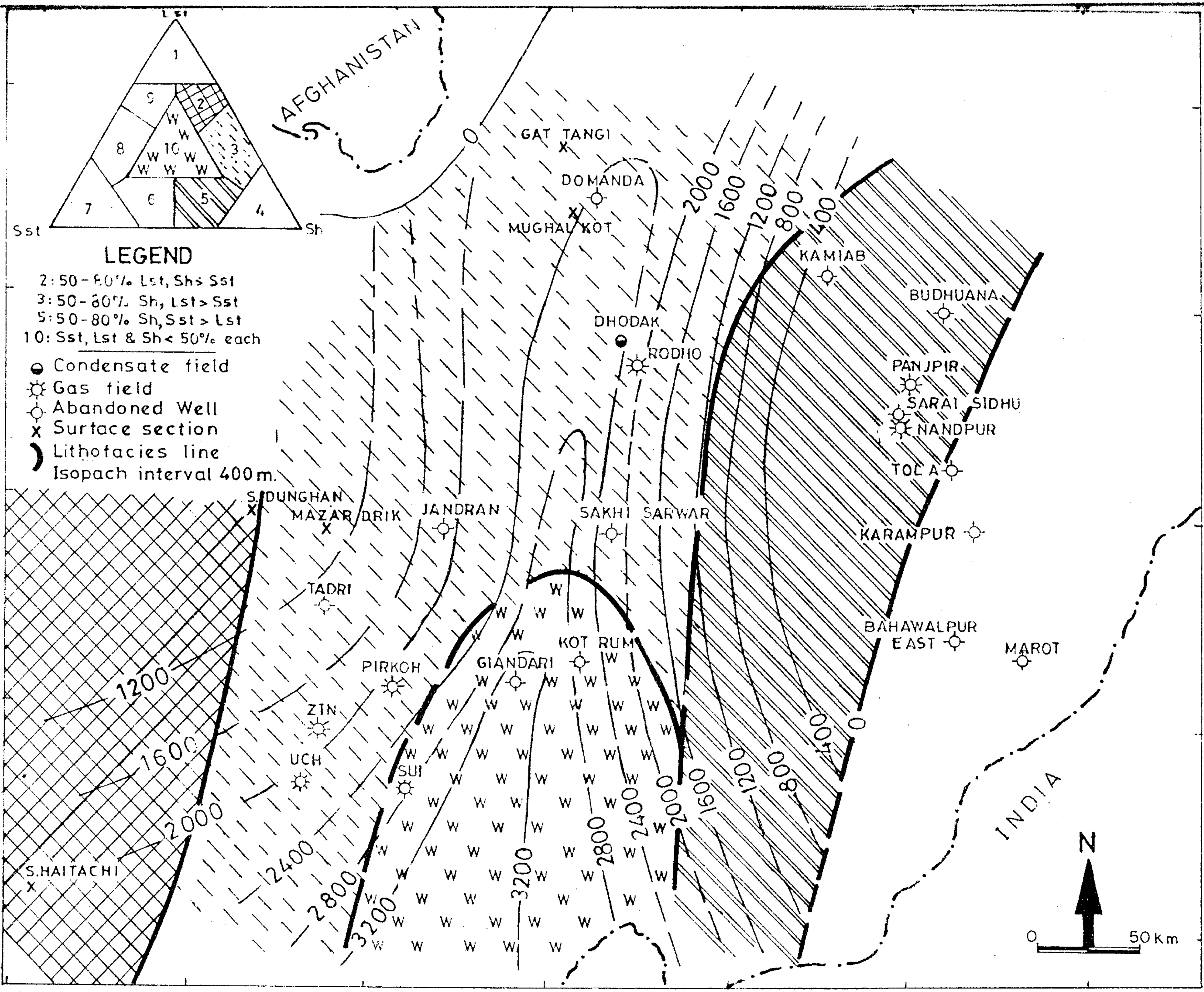
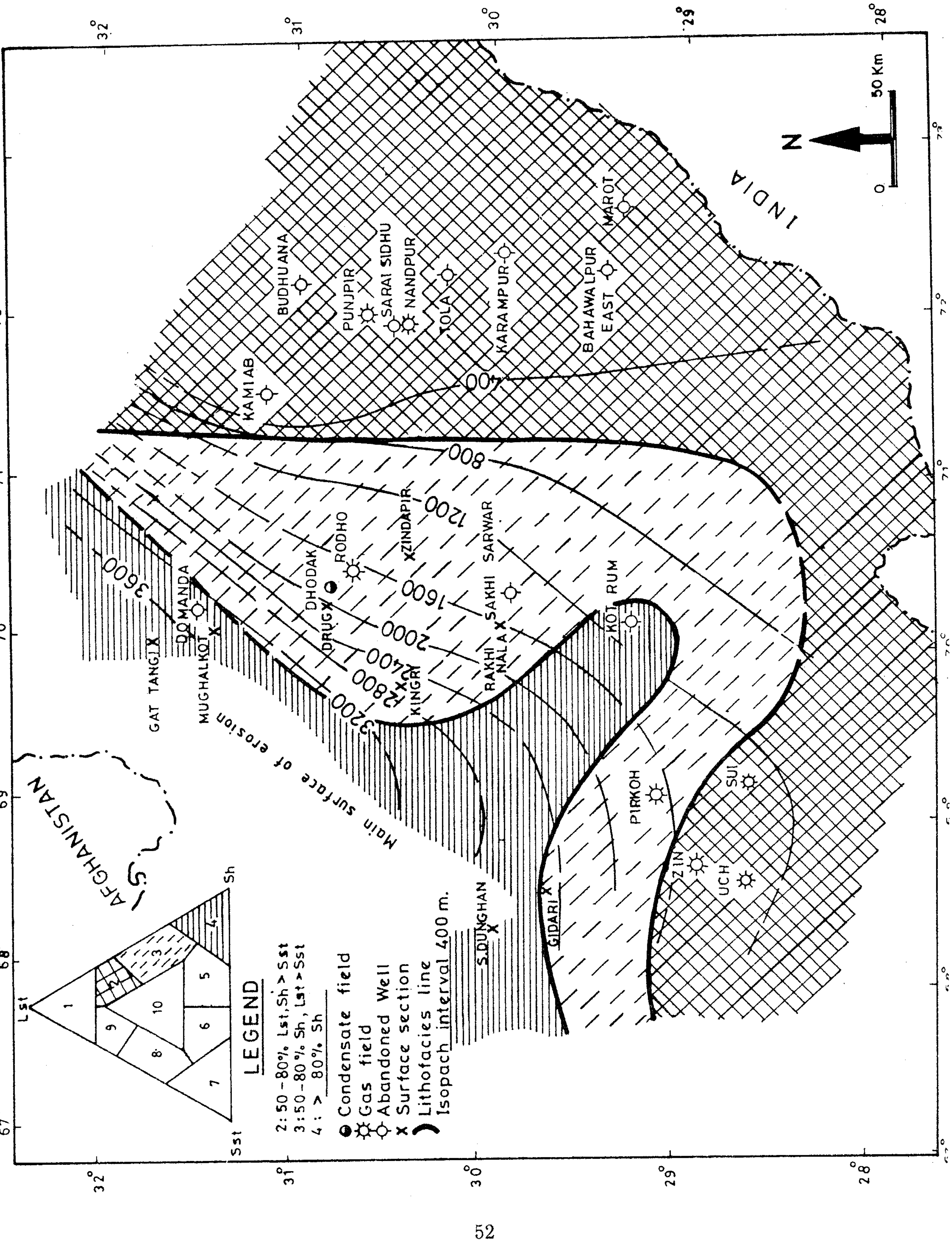


Figure 22. Thickness and lithofacies map of Cretaceous.


LEGEND
2: 50-80% Lst, Sh > Sst
3: 50-80% Sh, Lst > Sst
4: > 80% Sh
Condensate field
Gas field
Abandoned Well
Surface section
Lithofacies line
Isopach interval 400 m.
Lst
Sst
Sh
AFGHANISTAN
INDIA
Main surface of erosion
N
0
50 Km
KAMIAB
BUDHUANA
PUNJPIR
SARAI SIDHU
NANDPUR
TOLA
KARAMPUR
BAHAWALPUR EAST
MAROT
ZINDAPIR
RODHO
DHODAK
SAKHI SARWAR
KOT RUM
DOMANDA
MUGHALKOT
GAT TANGI
DRUG
RAKHI NALA
KINGRI
PIRKOH
SUI
ZIN
UCH
S.DUNGHAN
GIDARI
400
800
1200
1600
2000
2400
2800
3200
3600
67°
68°
69°
70°
71°
72°
73°
28°
29°
30°
31°
32°

to its credit as yet. The sediments are folded, faulted and orographically uplifted, exposing the prospective reservoirs at many places.

Hydrocarbon Habitat

Gas found in Cretaceous rocks in Jandran well and oil seepage of Mughal Kot indicate the generation of hydrocarbons in the zone. Recent HDIP-BGR geochemical studies (Tables 5, 6) indicate that Sembar (VR: 3.30, TOC: 1.38), Mughal Kot (VR: 1.97, TOC: 0.64) and Dunghan/Ranikot (VR: 1.74, TOC: 0.49) formations in the eastern part and Wulgai (VR: 3.20, TOC: 0.76), Shirinab (VR: 2.24, TOC: 0.4), Sembar (VR: 1.37, TOC: 2.06), Goru (VR: 1.7, TOC: 4.84), Dunghan/Ranikot (VR: 0.94, TOC: 0.92) and Ghazij (VR: 1.39, TOC: 12.20) formations in the western part qualify as potential source rocks.

The geothermal gradient study in the northeastern part of the area (Domanda Well) indicates 2.1°C/100m gradient and the oil window between 2600—5000m depth (Upper Cretaceous-Eocene, Figure 19). Therefore, the source of oil is suggested in Cretaceous sediments. In the southern part (Jandran and Tadri wells) the gradient is 2.4°C/100m and the oil window lies between 2300—4400m depth (Jurassic). Hence, source of hydrocarbons in this area could be in Jurassic.

Reservoir Rocks

Jurassic limestone, Cretaceous sandstone and Paleocene-Eocene limestones are considered as potential oil and gas reservoirs in the area.

Traps

The traps in the area are mainly anticlines with dip and fault closures. Some of the promising structures which may be developed into prospects are: (1) Domanda-Drazinda and (2) Surkamar (Figure 3). The Domanda-Drazinda structures have closure against a huge thrust fault and are located on eastern limb of a big syncline. The Surkamar anticline has a well formed closure at Middle Eocene. Middle Eocene limestone reservoir in this structure sourced by Lower Eocene potential source rocks can be productive. The Domanda-Drazinda and Surkamar anticlinal system has in its south Late Cretaceous oil seepage of Mughal Kot and the Rodho-Dhodak Cretaceous gas and condensate discoveries which further enhance its prospects.

The anticlines located in the vicinity of oil seepage, northwest of Pirkoh field *e.g.* Nari, West Kathan, Tarka Rasti, etc., are considered as priority drilling targets.

Resource Estimates

The sub-basin has proven gas reserves of 14.1 tcf and oil (condensate) reserves of 34 million barrels (excluding Nandpur, Panjpir and Loti gas fields whose reserves have not been estimated).

HDIP's internal study (Raza & Ahmed, 1987), on volumetric yield method indicates an ultimate recovery of 11 billion barrel of oil and 80 tcf of gas.

Recently in another internal study of HDIP (Hiller and Ahmed, 1988) based on field and hard laboratory data (Figure 24, Tables 4—6) and in combination with the seismic and well data interpretation the effective generated potential of a part of Sulaiman depression (area east of Domanda Sakhi Sarwar) for the Eocene units (Habib Rahi and Pirkoh limestones) has been cumulatively estimated as 60.3×10^9 barrels of oil. The calculation has been arrived at with the application of mean probabilistic value (m p v).

The chance factors for expulsion, migration, trapping and conservation are set at ranges of 0.4/0.5/0.6, 0.6/0.7/0.8, 0.25/0.55/0.75 and 0.4/0.65/0.85, respectively.

Taking the range of these four chance factors:—expulsion, migration, trapping and conservation into account and applying them to the generated potential, we come up with following mean probabilistic value of oil in place sourcing from:

Habib Rahi limestone	: 6.7×10^9 barrels oil in place
Pirkoh limestone	: 0.4×10^9 barrels oil in place
Together	: 7.1×10^9 barrels oil in place

The recoverable reserves are set with primary recovery at 25%, with secondary recovery cumulative

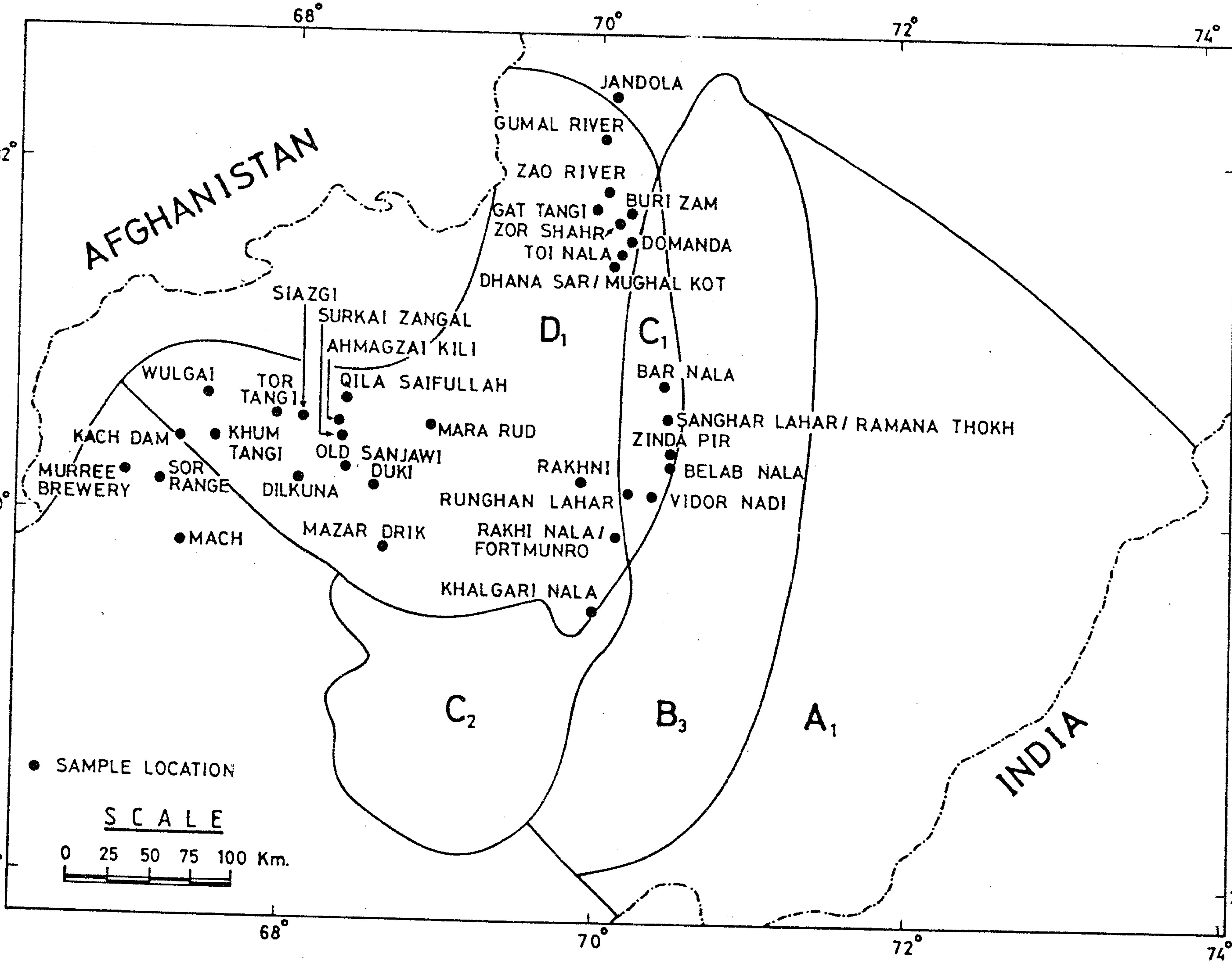


Figure 24. Map showing location of geochemically analysed samples.

at 30% and with ultimate recovery at 40%. This calculates to a mean probabilistic value of reserves of about 2.2×10^9 barrels oil (recoverable).

Conclusions

The Sulaiman sub-basin is the middle part of the Indus oil and gas producing basin, classed as an Extra-continental Closed Through Downwarp basin (Riva, 1983). It is sub-divided into three tectonic features, the Punjab platform, Sulaiman depression and Sulaiman foldbelt. These features have been formed during the Himalyan orogeny in Late Tertiary as a consequence of plate collision.

The Punjab platform has dominantly non-orogenic structures and was subjected to uplift and erosion during Paleozoic and Mesozoic times. It is handicapped by lack of maturity of its source rock, which may have left its reservoirs unfed. There is, however, a strong possibility of lateral migration of hydrocarbons from the Sulaiman depression into the structural features located westwared (*e.g.*, Kot Adu, Duniapur, Basti Waryam).

The Sulaiman depression is the most productive and prospective part of the sub-basin. But there are only a few structures left undrilled in its western flank and southern lobe. The eastern flank of the depression, which merges with the Punjab platform is ideally placed for formation of stratigraphic traps. The area needs further seismic work to develop prospects. The central part of the depression contains maximum thickness of sediments and there is a possibility of overcooking of source rocks in deeper horizons. Furthermore, Mesozoic reservoirs in this part can only be reached by relatively deep drilling.

The Sulaiman foldbelt contains a large number of undrilled anticlinal structures. Additionally, several potential fault traps may also exist. It is regarded as a frontier region due to its difficult terrain, complex tectonic deformation and lack of exploration activity. However, on the basis of our geological knowledge it can be predicted that a number of oil and gas discoveries will be made in this area.

The sub-basin has proven gas reserves of 14.1 tcf and oil (condensate) reserves of 34 million barrels (excluding Nandpur, Panjpir and Loti gas fields whose reserves have not been estimated). The ultimately recoverable reserves are estimated as 11 billion barrel oil and 80 trillion cubic feet gas using volumetric yield method, while genetic potential method for two source rocks only *i.e.* Habib Rahi and Pirkoh members of Kirthar formation, gives a value of 2.2 billion barrel oil. Although there have been more discoveries of gas in the region, possibilities of oil exist in several areas especially northern and southwestern areas.

The sub-basin occupies 142,500 square kilometers of sedimentary area, but only 24 exploratory wells have been drilled, giving the drilling density of only 0.16 per 1000 square kilometers. Thus it leaves a great scope for exploration.

Acknowledgement

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