PETROLEUM GEOLOGY OF PAKISTAN

IQBAL B. KADRI

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Published (1995) by Pakistan Petroleum Limited,
PIDC House, P.O. Box No. 3942,
Dr. Ziauddin Ahmed Road
Karachi - Pakistan.

Designed, produced and printed by
Ferozsons (Pvt.) Ltd.,
32, Shahrah-e-Bin Badees (Empress Road),
Lahore - Pakistan.

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Foreword

The publishing of this book Petroleum Geology of Pakistan is a significant contribution to the petroleum industry of Pakistan, there has long been a need for such a standard reference volume. Iqbal Kadri is to be congratulated for having recognized this need and undertaken the task to fill the void. This book is more a practical guide than an academic treatise, for it talks to the professional who will be walking the outcrop, shooting the seismic, delineating the prospect, planning the exploratory drilling or sitting on the well rather than those in research. For the students of the Earth Sciences who plan to enter the industry, it characterizes the elements of source, seal, reservoir, migration and structure that they will need to consider in constructing the petroleum plays of the future.

This book is largely based on the personal experience of the author rather than being a digest of the work of others. In Pakistan there has been a scarcity of published information on the results of the oil company's exploration. It is regrettable that so little has found its way into print in professional papers. It required someone with a broad spectrum of knowledge and experience in Pakistan, to take what has been made public and put it in a basin or country wide context. The industry is fortunate to have a person such as Kadri to pull it all together.

Iqbal Kadri has been a friend and colleague for almost thirty years and I have always admired his keen perception and his devotion to exploration. He has dedicated his career to the application of geology to the search for petroleum and other minerals in Pakistan. Now he has recorded his experience so as to pass on to others the benefits of his know-how. A large part of the credit for my own success in finding oil in the Province of Sindh is due to insights provided by Kadri. He fired my imagination, he shared his enthusiasm and he infected me with an obsessive conviction that there is a habitat for oil in Pakistan. I hope that others can use this book as a data base and continue the search for Pakistan's hidden resources.

The motivation to explore for oil in the largest sense is, of course, the hope for economic gain. This is what drives nations and companies to invest. On the individual scale however, there is another dimension, it is the thrill of discovery. For a geologist, walking an outcrop that perhaps no other geologist has ever seen or sitting on a wildcat well and being the first to set eyes on the oil stained cuttings of a new oil pay, is a heady reward in itself. The romance of exploration and the thrill of discovery are powerful driving forces. To those of you who are driven by these forces, I say 'treasure this book and good luck'.

HERBERT A. YOUNG
SITARA-E-QUAID-E-AZAM (SQA)
465 West Road, Cutchogue,
New York 11935,
USA.

Acknowledgments

I wish to acknowledge the support and encouragement of my friends and colleagues which impelled me over the years whilst I worked on this manuscript.

I would specially like to thank young Moin Raza Khan without whose dedication, commitment, research and analysis it would not have been possible for me to complete this book.

My sincere thanks to Rifat Haider who coordinated, chain-smoked and cheerfully kept us all in order during the process of finalisation of the manuscript.

Acknowledgment is also due to Nusrat Kamal Siddiqui for editing of the text and illustrations, to Ayub Khan Kundi and Nausheen Ahmad as well as Mausuf Ahmad for their assistance in the finalisation of the chapters on legal framework and the economics of Exploration and Production.

Thanks are also due to A. M. Malick for reviewing the manuscript, Pervez Jamula and A. Samad respectively for transcribing the text and drafting the illustrations.

I am grateful to Masrur Ahmad for his critical review of the manuscript and also for the inspiration and support provided to me during our long association.

I am also indebted to the Board of Directors of Pakistan Petroleum Limited, and particularly Hamid Masood Sohail, Managing Director, for sponsoring this publication.

In the end my heartfelt gratitude to my wife, Mumtaz for bearing with me and to my children for their belief in my efforts.

IQBAL B. KADRI
October, 1994
Karachi.

1
Introduction

The petroleum exploration and production (E&P) industry in Pakistan has now entered the adolescent age, conscious of its future and aspiring for its rightful place to play a dominant role in national development. This, therefore, seems a particularly appropriate time to reflect on Pakistan's past exploratory endeavours, its achievements, and to project its petroleum potential for the future.

Ever since the world energy crisis of early 1970s, indigenous energy resource development has been consistently given high priority by every Pakistan Government of the day. This policy is more than likely to be followed well into the future. The up trend in the oil and gas exploration activity, as a consequence, has resulted in several recent discoveries. The prospectivity of the different basins of Pakistan has, therefore, attracted worldwide attention. A new Petroleum Policy announced by the Government in March 1994, provided further liberal incentives to explorers, producers, refiners and marketing companies, which reflects the dynamics of the current exploration scene in Pakistan.

One of the most important prerequisites of an effective exploration programme is availability of an exploration data base. This is all the more important in the case of developing countries with petroleum potential and less explored basins such as Pakistan. It is felt that despite liberalised Government policies, one of the reasons for lack of sufficient exploration activity in Pakistan has been the dearth of published information on its petroleum potential and related facts. Recognizing this need the Ministry of Petroleum & Natural Resources, Government of Pakistan has recently undertaken the task of organizing and disseminating geological information. This is an important step towards further accelerating petroleum exploration in Pakistan.

To promote and regulate exploration after independence in 1947, the Petroleum Production Rules were promulgated in 1949. Very limited published literature on geology applied to petroleum was available to meet the specific needs of the fledgling petroleum industry of Pakistan in the early fifties. Some excellent geological literature, published by institutions such as Geological Survey of Pakistan (GSP) and authors, mainly dealing with stratigraphy / paleontology / structural geology etc., was available and formed the basis of early Petroleum exploration. The oil companies undertook grass roots studies and geological geophysical data collection. These investigations met the immediate needs of the industry and also provided opportunities for Pakistani geoscientists to learn the trade. However, the data acquisition and assimilation process was often time consuming and could not be integrated satisfactorily in the limited time due to large areas of investigation, structural / stratigraphic complexities etc. This frequently resulted in delayed completion of exploration activities. In some instances exploratory wells, drilled without assimilation of all the available information, proved abortive causing large tracts of prospective acreage being downgraded such as Southern Indus Basin (Badin area), offshore Indus, Makran Basin, the Punjab Platform and certain areas of the Potwar–Kohat Basin. Most of these areas have subsequently proved to be oil/gas bearing with commercial potential. Initial understanding of basin architecture was based mainly on surface geological features (structural and stratigraphic) as the subsurface information was lacking for the alluvium covered and offshore areas. The evolutionary process, through which the oil/gas industry progressed in Pakistan, is clearly seen during the period from sixties through eighties. This is reflected in the introduction of modern seismic data acquisition techniques, seismic stratigraphy, basin modeling, source rock studies, satellite imagery, plate tectonics and geodynamic concepts as well as increase in the level of exploratory drilling onshore and offshore. In the last two decades some excellent studies and research papers on petroleum geology of Pakistan have been published by several foreign and Pakistani organizations like the Hydrocarbon Development Institute of Pakistan (HDIP).

In this book, published information has been synthesized and the scope of petroleum geology enlarged for providing students and the oil industry with a hands–on approach to applied petroleum geology, operational environment, economics and the fiscal/legal regime for petroleum exploration in Pakistan.

It has been observed, particularly in the petroleum industry, that geoscientists with background of specific disciplines in earth sciences or related engineering applications, tend to restrict their observation to their field of specialization. However, geology applied to petroleum exploration has to embrace other sciences and engineering subjects to achieve successful economic results.

The contents of this book include sections on the tectonic framework, sedimentary basins and their evolution. The geological formation descriptions include their distribution, facies, depositional environment, source/reservoir rock potential, stratigraphic correlation, log response, drilling characteristic etc. For easy reference, list of selected publications is provided with most of the sections and a complete bibliography at the end.

This book is intended to stimulate interest in Pakistan's Petroleum Geology and is the author's humble contribution to Pakistan's future exploration effort as it is ushered into the 21st century.

2

History of Petroleum Exploration

ONSHORE

The search for oil in South Asian Subcontinent dates back to the early days of oil exploration in other parts of the world. The initial exploration activity was carried out in the vicinity of hydrocarbon seepages; the first exploratory well was drilled by the Punjab Government near an oil seepage at Kundal (Khisor Range, NWFP) in 1866, just seven years after the world's pioneer well in Pennsylvania (USA) drilled by Col. Drake. Similarly, during 1885–1892, thirteen wells were drilled near Khattan oil seepage (southeast of Quetta) in Balochistan which produced about 25,000 barrels of heavy oil. Exploration was undertaken at that time by the Government but lack of significant success halted further effort. In 1912, a syndicate was formed which later became Attock Oil Company (AOC) of U.K. and undertook extensive geological surveys in the Potwar area of northern Pakistan. This resulted in the first commercial oil discovery at Khaur (North Potwar, Punjab) in 1915 in Miocene and Eocene reservoirs. This field had produced about 4 million barrels of oil up to 1990 and is still on production. At the same time Burmah Oil Company (BOC) of U.K., which was active in the eastern part of the subcontinent, carried out extensive geological investigations including gravity surveys in different parts of the region which later became part of Pakistan. BOC drilled an exploratory well Chandragup-1 (Makran Coast), in Balochistan in 1916, to a total depth of 810 meters near an active mud volcano but without success.

The following two extracts from old geological reports and memoirs provide interesting historical information which indicate that the region had attracted the attention of explorers as a potential oil bearing area.

Quote 'SINDH Kukrani Dome–Field work was undertaken in 1874–77 by Messrs. Blanford and Fedden.' **Unquote**

Quote 'In 1915 H. T. Mayo of the B.O.C. visited the Harnai Valley to ascertain whether any anticlinal structures suitable for the retention of oil could be found in the Ghazij Shales. He examined Kipaz Mand and mapped the structure on 1" scale but did not consider it to be worth testing.' **Unquote**

As a result of combined effort of BOC and AOC, Dhulian (1936), Joya Mair (1944) and Balkassar (1946) oil fields were discovered in the Potwar area establishing the potential of the highly fractured Eocene limestone.

After the inception of Pakistan in 1947, the Government issued the Pakistan Petroleum (Production) Rules (1949) under which several fiscal and other incentives were granted to oil companies to encourage and accelerate petroleum exploration activities. Thereafter BOC and AOC established Pakistani Companies, Pakistan Petroleum Limited (PPL) and Pakistan Oilfields Limited (POL) respectively and transferred exploration activities to these Companies.

In 1952, a well drilled by Pakistan Petroleum Limited (PPL) on the Sui structure (located in Balochistan Province), in Central Indus Basin, made the maiden discovery of large reserves of natural gas in the Sui Main Limestone of Early Eocene age. The original recoverable gas reserves were estimated to be 8.624 trillion cubic feet (TCF) equivalent to about 1 billion barrels of oil. The discovery of Sui Gas Field was the first milestone in the search for hydrocarbons in Pakistan.

Following the natural gas discovery at Sui, several foreign oil companies took active interest in carrying out exploration in Pakistan. The Government of Pakistan entered into 'Profit Sharing' Petroleum Concession Agreements with Standard–Vacuum Oil Company (1954), Hunt International Oil Company (1955), Shell Oil Company (1956), Sun Oil Company (1957) and Tidewater (1958), all of USA. This led to further exploratory drilling in prospective areas. Further discoveries of natural gas were made during 1954–59 at Zin, Uch, Mazarani (PPL) in Balochistan and Khairpur (PPL), Mari (Stanvac), Kandhkot (PPL) in Sindh, all in Eocene limestone reservoirs. During the same period Karsal Oil Field (1956) in Potwar area was discovered by PPL/POL.

During 1956–59, thirty five exploratory wells were drilled and this could be described as a period of extensive exploration in Pakistan. However, because of lack of oil discoveries and since the natural gas discoveries with commercial production potential could not be developed for exploitation (the natural gas industry was then in its nascent stage and there was limited gas market), exploration activities sharply declined in early 1960s. Government of Pakistan then decided to participate directly in the search for oil and gas and established the state oil exploration company, Oil & Gas Development Corporation (OGDC) in September, 1961 with the assistance of USSR. OGDC's first success was the small gas discovery at Sari Singh (Sindh, 1965), which was followed by discovery of oil at Toot (Potwar, Punjab, 1968), gas at Hundi (Sindh, 1970), Rodho (Punjab, 1972) and Kothar (Sindh, 1973) and gas / condensate at Dhodak (Punjab, 1977). During this period POL discovered oil at Meyal (Potwar, Punjab, 1968) and American Oil Company (AMOCO) discovered a small gas accumulation at Jandran (Balochistan, 1975).

The Central and Southern Indus basins had been regarded as gas prone areas until early 1981 when Union Texas Pakistan (UTP), subsidiary of a USA Company, discovered oil at Khaskeli (Sindh) in the Lower Goru Sandstone of Cretaceous age. This opened a new oil province outside the traditional oil province of the Potwar in the north. After Sui, the discovery of oil in the Southern Indus Basin was the second milestone in the search for hydrocarbons in Pakistan. This led to a boom in exploration activity in Southern Indus Basin, resulting in several oil discoveries in an area regarded heretofore as of low potential for liquid hydrocarbons. This area attained the distinction of contributing more than 50% of the total oil production of the country by early 1990s.

The first natural gas discovery in the Punjab Platform was made by OGDC at Nandpur in 1984 followed by Panjpir (1985) in Cretaceous / Jurassic reservoirs.

In 1989, LASMO (of U.K.) made a gas discovery in Lower Goru Sandstone (Cretaceous) at Kadanwari, south of Khairpur–Jacobabad High, thus bridging a wide gap between PPL's Kandhkot Gas Field (1959) in the north and OGDC's Bobi Oil Field (1988) in the south.

Up to 1993, 92 oil and gas fields (39 oil, 33 gas and 20 oil / gas) had been discovered in various basins of Pakistan (Fig. 2.1).

OFFSHORE

Offshore Indus consists of the sedimentary package deposited by the Indus River system draining the Himalayan mountains. The Indus River is about 2,900 kms long and travels about 1,200 kms in the plains after leaving the high mountains with the total drainage area of 966,000 sq. kms. The river has, therefore, developed a basin which is one of the single largest offshore basins in the world.

This basin is analogous to other producing basins of the world in terms of geological setting e.g. Mississippi Delta, (Gulf of Mexico, USA), Niger Delta (Nigeria), Mahakam Delta (Indonesia), Mackenzie Delta (Canada), Gipsland Basin (Australia) etc.

Exploration in the Indus Offshore started in 1961 when Sun Oil Company (USA) carried out seismic surveys and then drilled three nearshore wells, Dabbo Creek-1 (1963), Patiani Creek-1 (1964), and Korangi Creek-1 (1964).

Wintershall (Germany) conducted 9,400 kms of 24 fold seismic surveys during 1969–72 and drilled three wells, Indus Marine A-1 (1972), Indus Marine B-1 (1972) and Indus Marine C-1 (1975). Phillips Petroleum carried out 2,280 kms of 24 fold seismic survey (1977) in deeper part of the basin. Husky (USA) conducted about 2,380 kms of 24 fold seismic survey during 1976–78 and drilled one well, Karachi South A-1 (1978).

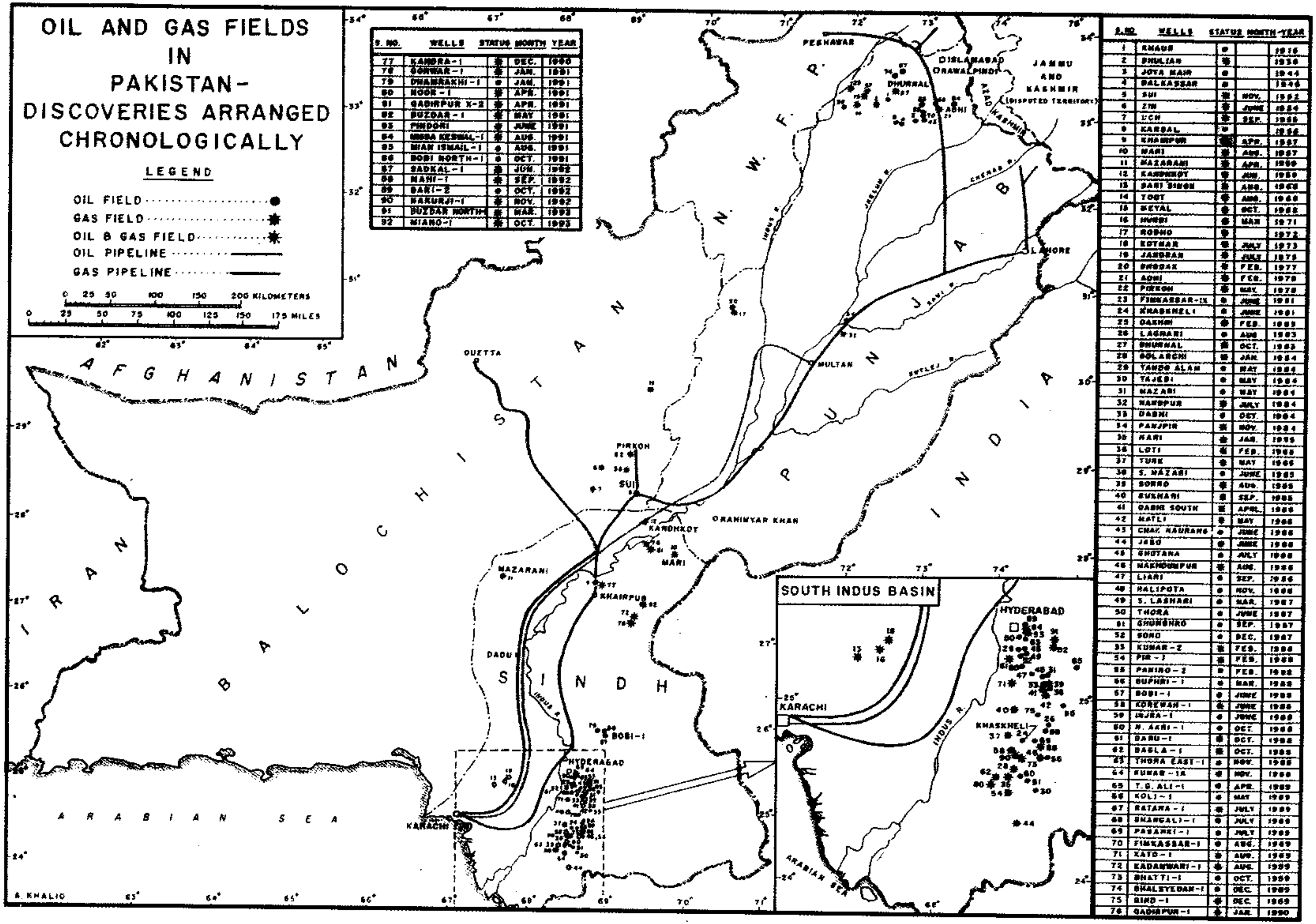
All these seven Indus Offshore wells, drilled till 1978, did not test movable hydrocarbons, although gas shows were reported in most wells. Seismic survey of maximum (48) fold coverage was acquired in 1982 by OGDC-NORAD (a Pakistan–Norway collaboration). On the basis of this seismic data a well Pak Can-1 was drilled with Canadian assistance for OGDC in 1986 and tested natural gas, albeit with uneconomical production potential by offshore standard.

Occidental (USA), after conducting modern seismic in their Indus Delta Exploration Licence, drilled a well Sadaf-1 (1989); however, the well turned out to be located in a thermally immature region.

In Makran offshore, the only well, Jal Pari 1-A, was drilled by Marathon (USA) in 1976-77 after conducting extensive seismic surveys. The well was abandoned due to uncontrollable overpressures.

SUMMARY

A total of 301 exploratory wells (since 1866) had been drilled till 1992 (290 onshore and 11 offshore) in the sedimentary basins of Pakistan – 827,365 sq. km (611,307 sq. km onshore and 216,058 sq. km offshore). On the basis of exploratory drilling, Pakistan is considered one of the less explored basins with exploratory well density of five wells for more than 10,000 sq. km. In other basins which are generally similar in geological



S. NO.	WELLS	STATUS	MONTH	YEAR
1	KHAUR	●		1915
2	DHULIAN	✱		1936
3	JOYA MAIR	●		1944
4	BALKASSAR	●		1946
5	SUI	✱	NOV.	1952
6	ZIN	✱	JUNE	1954
7	UCH	✱	SEP.	1955
8	KARSAL	●		1956
9	KHAIRPUR	✱	APR.	1957
10	MARI	✱	AUG.	1957
11	MAZARANI	✱	APR.	1958
12	KANDHKOT	✱	JUN.	1959
13	SARI SINGH	✱	AUG.	1965
14	TOOT	✱	AUG.	1968
15	MEYAL	✱	OCT.	1968
16	HUNDI	✱	MAR	1971
17	RODHO	✱		1972
18	KOTHAR	✱	JULY	1973
19	JANDRAN	✱	JULY	1975
20	DHODAK	✱	FEB.	1977
21	ADHI	✱	FEB.	1978
22	PIRKOH	✱	MAY	1978
23	FIMKASSAR-1X	●	JUNE	1981
24	KHASKHELI	●	JUNE	1981
25	DAKHNI	✱	FEB.	1983
26	LASHARI	●	AUG.	1983
27	DHURNAL	✱	OCT.	1983
28	DOLARCHI	✱	JAN.	1984
29	TANDO ALAM	●	MAY	1984
30	TAJEDI	●	MAY	1984
31	MAZARI	●	MAY	1984
32	NANDPUR	✱	JULY	1984
33	DABHI	●	OCT.	1984
34	PANJPIR	✱	NOV.	1984
35	KARI	✱	JAN.	1985
36	LOTI	✱	FEB.	1985
37	TURK	✱	MAY	1985
38	S. MAZARI	●	JUNE	1985
39	SONRO	✱	AUG.	1985
40	BUKHARI	✱	SEP.	1985
41	DABHI SOUTH	✱	APRL.	1986
42	MATLI	✱	MAY	1986
43	CHAK NAURANG	●	JUNE	1986
44	JABO	✱	JUNE	1986
45	GHOTANA	●	JULY	1986
46	MAKHDUMPUR	✱	AUG.	1986
47	LIARI	●	SEP.	1986
48	HALIPOTA	●	NOV.	1986
49	S. LASHARI	●	MAR.	1987
50	THORA	●	JUNE	1987
51	GHUNGHRO	●	SEP.	1987
52	SONO	●	DEC.	1987
53	KUNAR-2	✱	FEB.	1988
54	PIR-1	✱	FEB.	1988
55	PANIRO-2	●	FEB.	1988
56	BUPHRI-1	●	MAR.	1988
57	BOBI-1	●	JUNE	1988
58	KOREWAH-1	✱	JUNE	1988
59	INJRA-1	●	JUNE	1988
60	N. AKRI-1	●	OCT.	1988
61	DARU-1	✱	OCT.	1988
62	BAGLA-1	✱	OCT.	1988
63	THORA EAST-1	●	NOV.	1988
64	KUNAR-1A	✱	NOV.	1988
65	T.G. ALI-1	●	APR.	1989
66	KOLI-1	●	MAY	1989
67	RATANA-1	✱	JULY	1989
68	BHANGALI-1	●	JULY	1989
69	PASAHKI-1	●	JULY	1989
70	FIMKASSAR-1	●	AUG.	1989
71	KATO-1	✱	AUG.	1989
72	KADANWARI-1	✱	AUG.	1989
73	BHATTI-1	●	OCT.	1989
74	BHALSYEDAN-1	●	DEC.	1989
75	RIND-1	✱	DEC.	1989
76	QADIRPUR-1	✱	JAN.	1990

S. NO.	WELLS	STATUS	MONTH	YEAR
77	KANDRA-1	✱	DEC.	1990
78	SONWAR-1	✱	JAN.	1991
79	DHAMRAKHI-1	●	JAN.	1991
80	NOOR-1	✱	APR.	1991
81	QADIRPUR X-2	✱	APR.	1991
82	BUZDAR-1	✱	MAY	1991
83	PINDORI	✱	JUNE	1991
84	MISSA KESWAL-1	✱	AUG.	1991
85	MIAN ISMAIL-1	●	AUG.	1991
86	BOBI NORTH-1	●	OCT.	1991
87	SADKAL-1	✱	JUN.	1992
88	MAHI-1	✱	SEP.	1992
89	BARI-2	●	OCT.	1992
90	NAKURJI-1	✱	NOV.	1992
91	BUZDAR NORTH-1	✱	MAR.	1993
92	MIANO-1	✱	OCT.	1993

Figure 2.1 Oil & Gas fields of Pakistan

setting and petroleum potential, such as Western Canada, Gulf Coast of the United States and North Sea, the well density is several times higher than in Pakistan. In India density of drilling in the sedimentary basins averages 12 wells per 10,000 sq. km compared to a world average of about 100 (Ref. PETROMIN, The Asia's Oil & Gas Magazine, June 1992). However, even limited exploratory drilling in selective basins

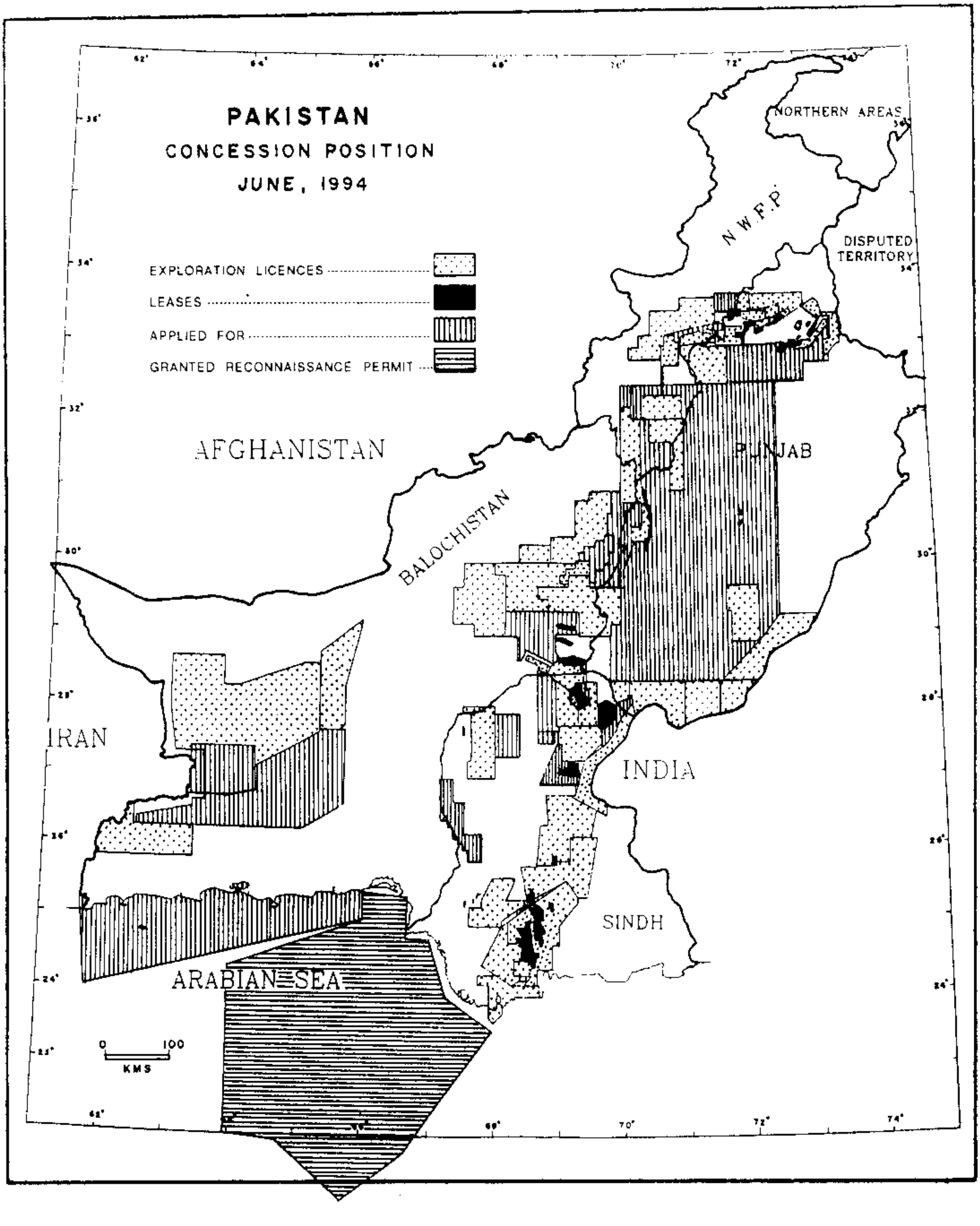


Figure - 2.2 Pakistan; Concession Position, June 1994.

CRUDE OIL RESERVES AS ON JUNE 30, 1993

Unit: Million US Barrels

	FIELD	Operator Company	Original Recoverable Reserves	Cumulative Production	Balance Recoverable Reserves
1.	Khaur	POL	4.310	4.184	0.1260
2.	Dhulian	"	41.400	41.360	0.0400
3.	Joyamair	"	10.450	6.782	3.6680
4.	Meyal	"	42.500	35.292	7.2080
5.	Toot	OGDC	15.800	11.454	4.3460
6.	Dhodak (c)	"	16.200		16.2000
7.	Fimkassar	"	30.000	4.912	25.0880
8.	Dakhni (c)	"	12.440	1.230	11.2100
9.	Tando Alam	"	20.160	8.999	11.1610
10.	Ghotana	"	0.400	0.166	0.2340
11.	Chak–Naurang	"	4.700	2.175	2.5250
12.	Lashari South (c)	"	0.230		0.2300
13.	Thora	"	11.210	7.868	3.3420
14.	Sono	"	8.650	3.823	4.8270
15.	Lashari Centre	"	5.270	3.250	2.0200
16.	Bobi (c)	"	9.760	0.738	9.0220
17.	Kunar	"	14.020	0.758	13.2620
18.	Daru	"	0.260		0.2600
19.	Pasakhi	"	9.370	4.972	4.3980
20.	Bhal Syedan (c)	"	0.198	0.069	0.1290
21.	Lashari East [1)]	"		0.037	
22.	Buzdar (c)	"	0.081		0.0810
23.	Missakaswal	"	34.730	2.394	32.3360
24.	Dhamrakl	"	1.370		1.3700
25.	Sadkal (c)	"	0.738		0.7380
26.	Buzdar North (c)	"	0.210	0.008	0.2020
27.	Meyun Ismail [1)]	"		0.256	
28.	Khaskheli	UTP	8.196	8.078	0.1180
29.	Laghari	"	20.261	18.375	1.8860
30.	Dabhi	"	4.445	3.161	1.2840
31.	Tajedi	"	0.464		0.4640
32.	Golarchi (c)	"	0.196	0.136	0.0600
33.	Nari	"	0.399	0.032	0.3670
34.	Turk & Turk deep (c)	"	1.322	0.839	0.4830
35.	Mazari	"	14.745	13.087	1.6580
36.	South Mazari	"	10.902	5.344	5.5580
37.	Sonro (c)	"	0.950	0.356	0.5940
38.	Halipota	"	0.432	0.286	0.1460
39.	Liari	"	5.429	3.953	1.4760
40.	Ghungro	"	0.787		0.7870
41.	Duphri	"	0.105		0.1050
42.	Matli	"	0.311	0.248	0.0630
43.	North Akri	"	1.487	0.196	1.2910
44.	Paniro	"	0.197		0.1970
45.	Dabhi South	"	0.047		0.0470
46.	Bhatti (c)	"	0.617	0.072	0.5450
47.	Bukhari	"	1.651	0.414	1.2370
48.	Jabo	"	0.014		0.0140
49.	Kato	"	0.141		0.1410
50.	Khorewah	"	0.698	0.002	0.6960
51.	Koli (c)	"	0.179		0.1790
52.	Mukhdumpur	"	0.237	0.060	0.1770
53.	Rind (c)	"	0.062		0.0620
54.	Mahl	"	0.209		0.2090
55.	Bari	"	2.531	0.121	2.4100
56.	Pir	"	0.007		0.0070
57.	Dhurnal	OXY	50.940	43.856	7.0840
58.	Balkassar [2)]	"	34.015	32.493	1.5220
59.	Ratana (c)	"	12.000		12.0000
60.	Bhangali	"	1.840	1.720	0.1200
61.	Adhi (c)	PPL	10.221	3.601	6.6200
	TOTAL: Million Barrels		**480.494**	**277.157**	**203.630**
	Million TOE		***64.46***	***37.18***	***27.32***
Of which:					
	POL Total:		98.66	87.618	11.042
	OGDC Total:		195.797	53.109	142.981
	UTP Total:		77.021	54.76	22.261
	OXY Total:		96.795	78.069	20.726
	PPL Total:		10.221	3.601	6.82

Table - 2.1 Crude oil reserves as on June 30, 1993
(Source: Directorate General Petroleum Concessions)

NATURAL GAS RESERVES AS ON JUNE 30, 1993

Unit: Trillion Cubic Feet

	Non-associated Gasfields	Operator Company	Original Recoverable Reserves	Cumulative Production	Balance Recoverable Reserves
1.	Adhi	PPL	0.11600	0.02392	0.09208
2.	Kandhkot	"	0.78300	0.13016	0.65284
3.	Khairpur	"	1.00000		1.00000
4.	Mazarani	"	0.01859		0.01859
5.	Sui	"	8.62400	5.44926	3.17474
6.	Mari	MGCL	6.30000	1.21063	5.08937
7.	Bhai Syedan	OGDC	0.00330	0.00052	0.00278
8.	Bobi	"	0.04224	0.00122	0.04102
9.	Buzdar	"	0.00810		0.00810
10.	Dakhni	"	0.25500	0.02637	0.22863
11.	Daru	"	0.01301		0.01301
12.	Dhodak	"	0.58140		0.58140
13.	Hundi	"	0.05940	0.01632	0.04308
14.	Jandran	"	0.08230		0.08230
15.	Kothar	"	0.01180	0.00020	0.01160
16.	Loti	"	0.27695	0.06122	0.21573
17.	Nandpur	"	0.29600		0.29600
18.	Nur	"	0.00608		0.00608
19.	Panjpir	"	0.03350		0.03350
20.	Pirkoh	"	1.80000	0.40184	1.39816
21.	Qadirpur	"	3.97873		3.97873
22.	Rodho	"	0.01300		0.01300
23.	Sari	"	0.03900	0.01370	0.02530
24.	Uch	"	4.05000		4.05000
25.	Zin	"	0.10000		0.10000
26.	Ratana	OXY	0.35000		0.35000
27.	Bhatti	UTP	0.03494	0.00007	0.03487
28.	Bukhari	"	0.06794	0.01835	0.04959
29.	Dabhi	"	0.01631	0.00373	0.01258
30.	Dabhi South	"	0.00372		0.00372
31.	Golarchi	"	0.05536	0.03636	0.01900
32.	Halipota	"	0.00218	0.00053	0.00165
33.	Jabo	"	0.00280		0.00280
34.	Kato	"	0.00474		0.00474
35.	Khorewah	"	0.09975	0.00019	0.09956
36.	Koli	"	0.01483		0.01483
37.	Mahi	"	0.01308		0.01308
38.	Matli	"	0.05555	0.03561	0.01994
39.	Mukhdumpur	"	0.02366	0.00465	0.01901
40.	Nakurji	"	0.02565		0.02565
41.	Nari	"	0.00727	0.00527	0.00200
42.	Pir	"	0.00142		0.00142
43.	Rind	"	0.00150		0.00150
44.	Sonro	"	0.01784	0.00651	0.01133
45.	Tando Ghulam Ali	"	0.00390		0.00390
46.	Turk	"	0.11356	0.08151	0.03205
47.	Turk Deep	"	0.03171		0.03171
48.	Kadanwari	LASMO	0.72800		0.72800
	ASSOCIATED GASES *		0.56153	0.38090	0.18063
	TOTAL: TCF		**30.72864**	**7.90904**	**22.81960**
	Million TOE		***578.23***	***171.29***	***406.94***

Table - 2.2 Natural Gas reserves as on June 30, 1993
(Source: Directorate General Petroleum Concessions)

of Pakistan has resulted in the discovery of about 500 million barrels of oil and 31 TCF of gas until mid 1993 (Tables 2.1 and 2.2). Large areas of Pakistan's petroliferous basins still remain geological frontier and hold promise for the future in view of the multiple habitats for petroleum generation and accumulation.

In 1989, the Government of Pakistan introduced the block/bidding system and 43 blocks were offered internationally for competitive

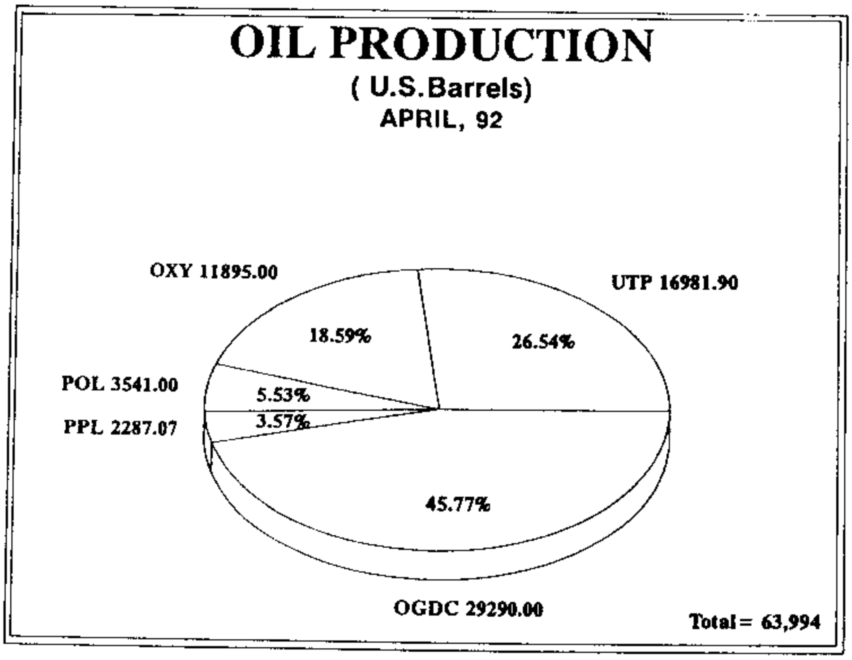


Figure - 2.3 Oil Production (after OGDC, 1992)

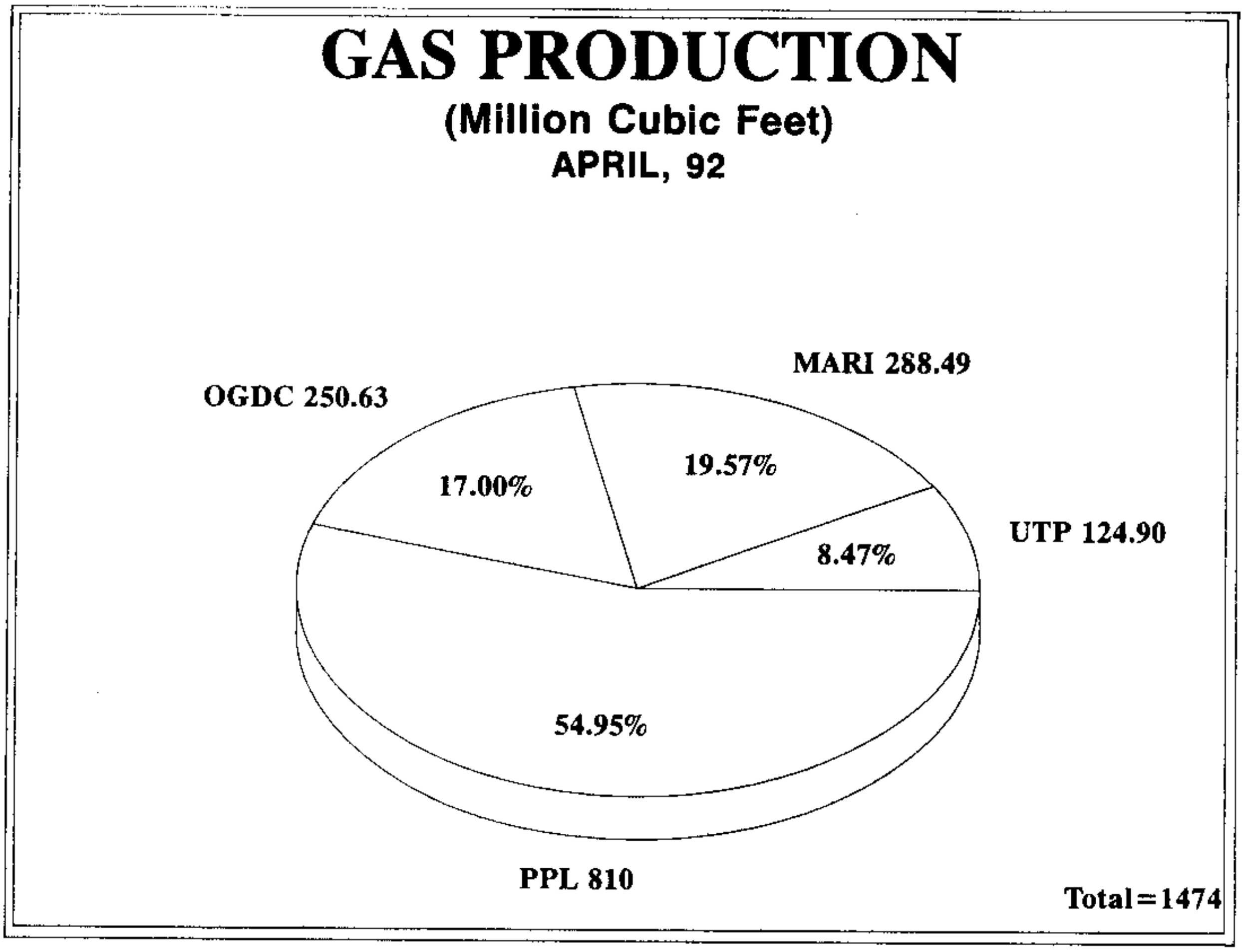


Figure - 2.4 Gas Production (after OGDC, 1992)

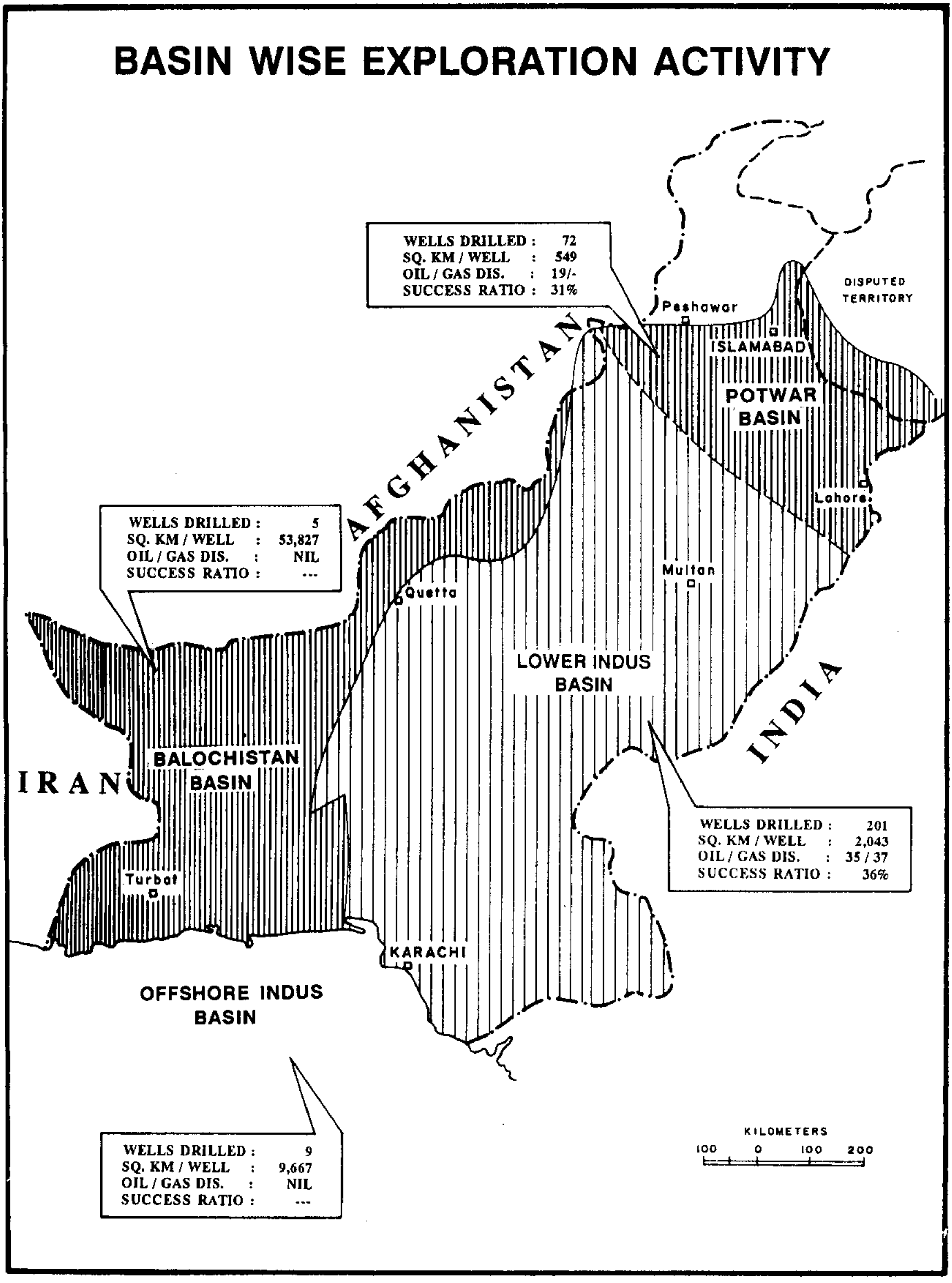


Figure - 2.5 (a) Relative wells density and success ratios in different basins

BASINWISE
EXPLORATION DRILLING RECORD
(1947 - 1993)

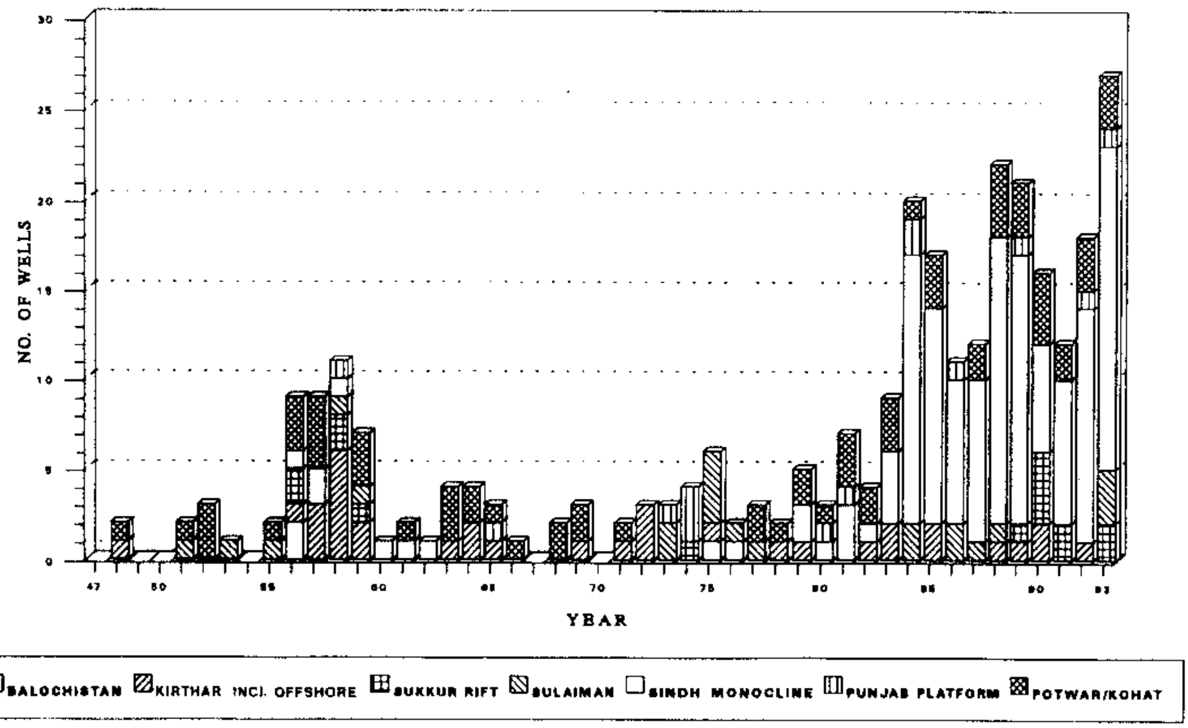


Figure - 2.5 Pakistan,Basinwise Exploratory Drilling record (1947 - 1993)

EXPLORATORY/DEVELOPMENT
DRILLING ACTIVITIES
(1947-1993)

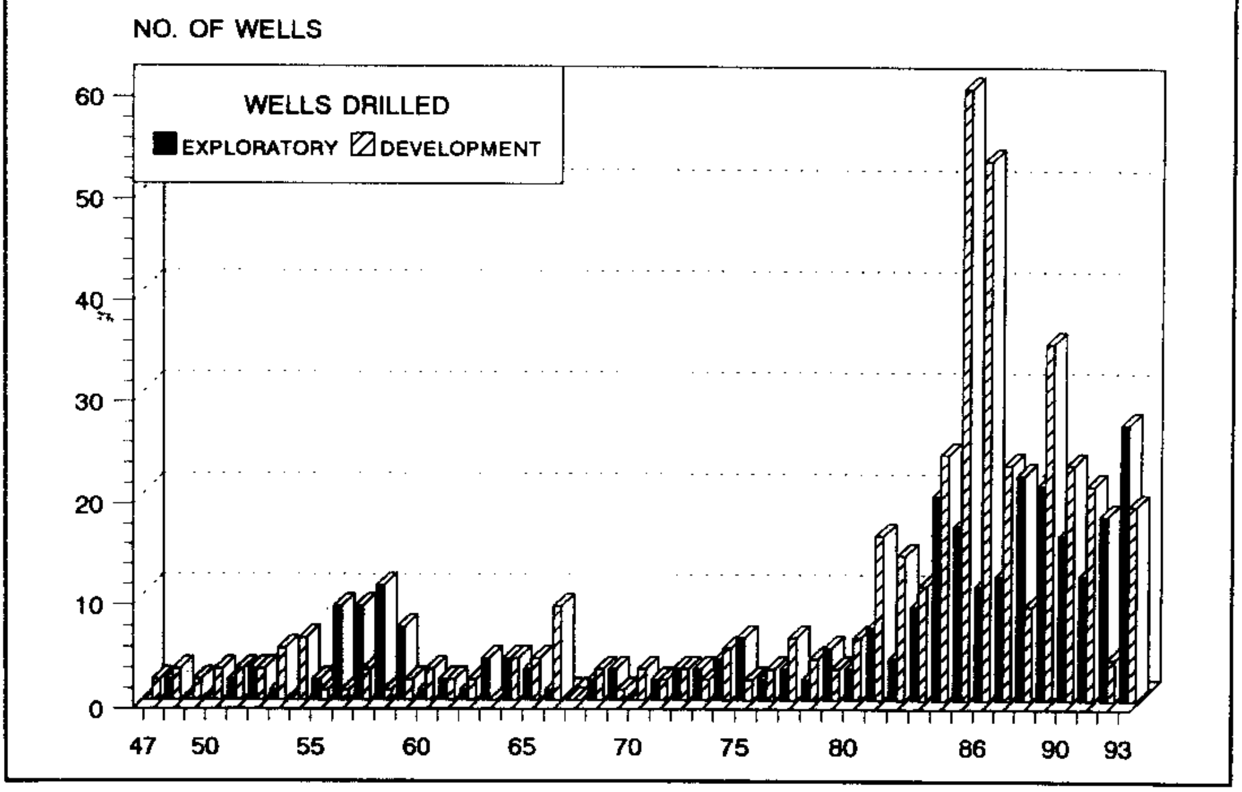


Figure - 2.6 Exploratory/Development drilling activities (1947-1993)

EXPLORATORY DRILLING
PAKISTAN
1948-92

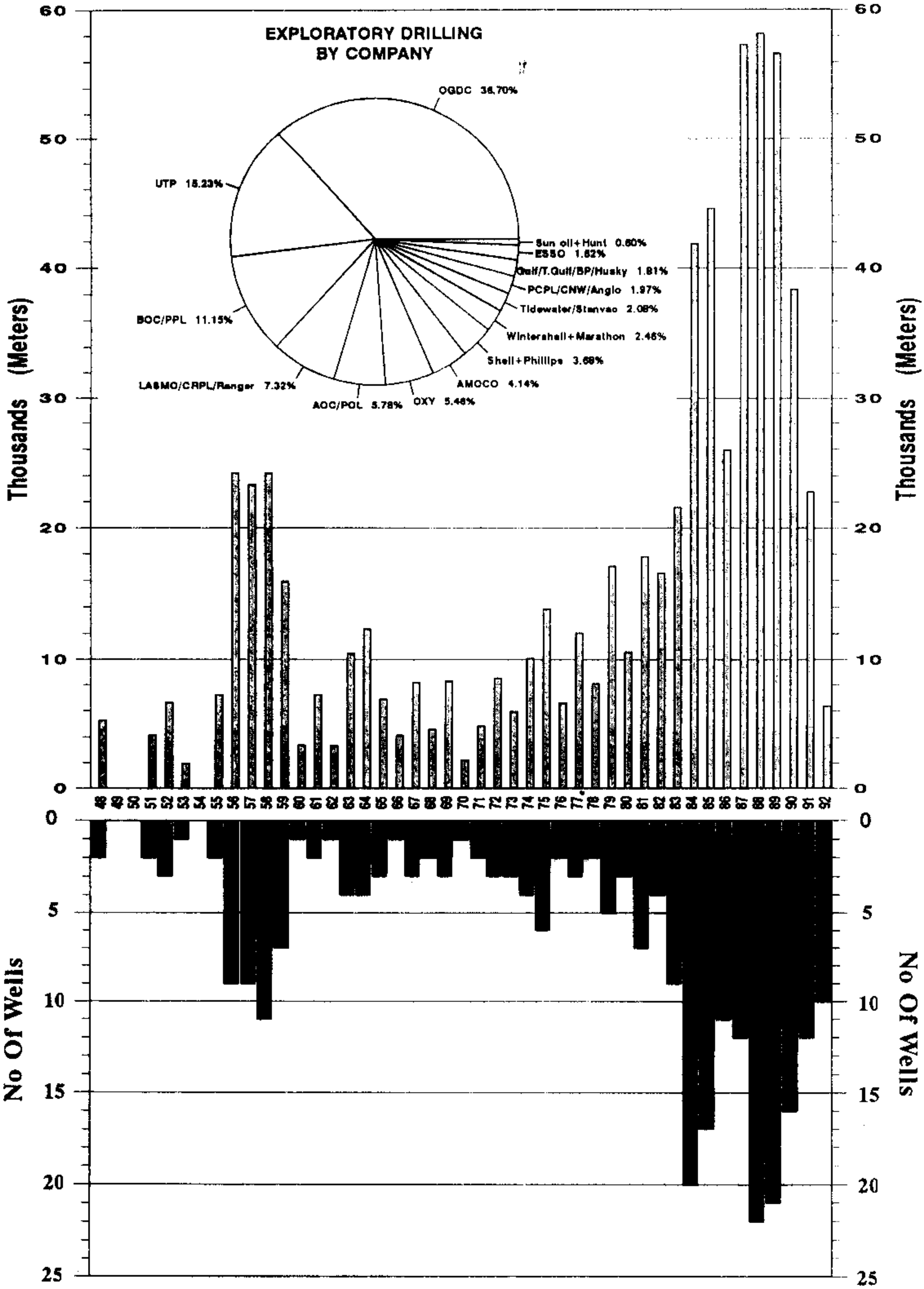


Figure - 2.6(a) Exploratory Drilling Pakistan (1948 - 92)

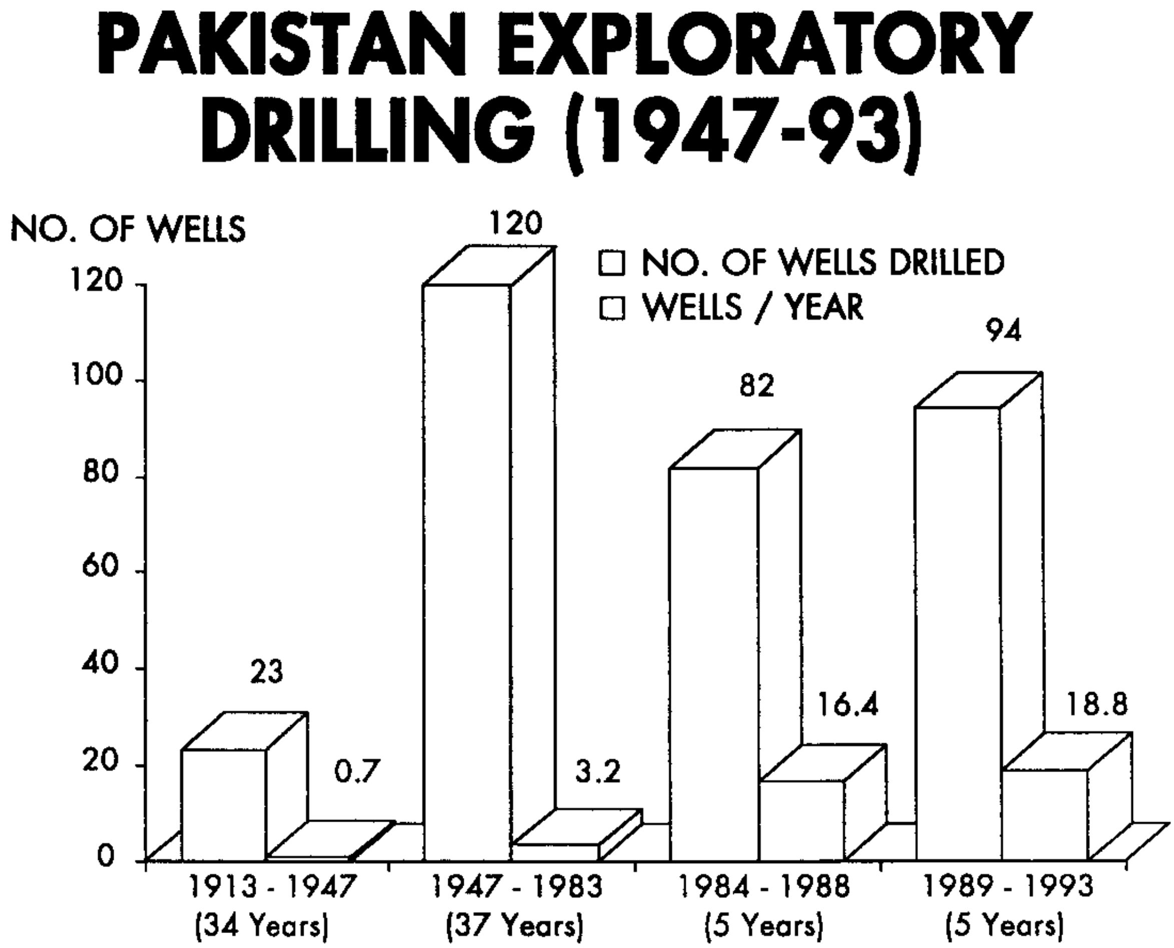


Figure - 2.6(b) Exploratory Drilling (1947 - 93)

bidding (36 onshore and 7 offshore). The second round of bidding for seventeen blocks was announced in 1993.

Total area under Concession was about 155,000 sq. km in April, 1992 and 54 Exploration Licences were held by 23 companies. Fig. 2.2 shows the concessionary trend and Figs. 2.3 and 2.4 show the total oil and gas production (April, 1992) respectively.

The exploration activity in different basins has been directly proportional to the discoveries made therein. Fig. 2.5 shows basin/yearwise relative density of exploratory drilling and Fig. 2.5(a) shows the relative well density and success ratios in different basins.

Fig. 2.6 shows yearwise relative exploratory / development drilling activity. Fig. 2.6(a) shows exploratory drilling by companies from 1948 to 1992. For oil/gas production history refer to Fig. 25.1. Fig. 2.6(b) shows the drilling trend.

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3

Tectonic Framework

Tectonic understanding of a region is a continuous process which evolves as more and more relevant evidence becomes available for integration. The initial understanding of Pakistan's basin architecture and tectonic framework was presented by Zuberi and Dubois (1962) and is shown in Fig. 3.1.

Modern concepts of plate tectonics and availability of satellite remote sensing data integrated with field geology and seismic data have led to a better understanding of the sedimentary basins of Pakistan. According to Farah et al (1984), active plate boundaries of various types are exceptionally well exposed in Pakistan. These plate boundaries and their offshoots give rise to fascinating array of features (Fig. 3.2) in different sedimentary basins. The simplified interpretation of tectonic zones of Pakistan is shown in Fig. 3.3.

Tectonics of Pakistan is characterised by two active convergent boundaries:

1. In the northeast there is an active continent–island arc-continent collision boundary, the west end of the Himalayan orogen;
2. In the southwest, there is an active boundary of oceanic lithosphere subducting beneath arc-trench gap sediments and continental sediments, the oceanic part of the Arabian plate passing under the Makran arc-trench gap and Afghan microplate.

These two convergent boundaries are connected by a very large displacement north-south, left lateral strike-slip faults of the Chaman Transform Zone. (Fig. 3.2).

The following main tectonic segments in Pakistan have been adopted and briefly discussed.

1. Northern Collision Belt
2. Subduction Complex Association of Balochistan
3. Chaman Transform Zone
4. Ophiolites and Ophiolitic Melanges
5. Platform Areas

NORTHERN COLLISION BELT

The Northern Collision Belt of Pakistan is a part of the Alpine–Himalayan orogeny which has been considered to be the prototype of mountain belts produced by continental collision. This belt comprises areas representing the stratigraphy of Upper Indus Basin.

The main features (Fig. 3.4) of the Northern Collision Belt from south to north are the following (Yeats & Lawrence, 1984):

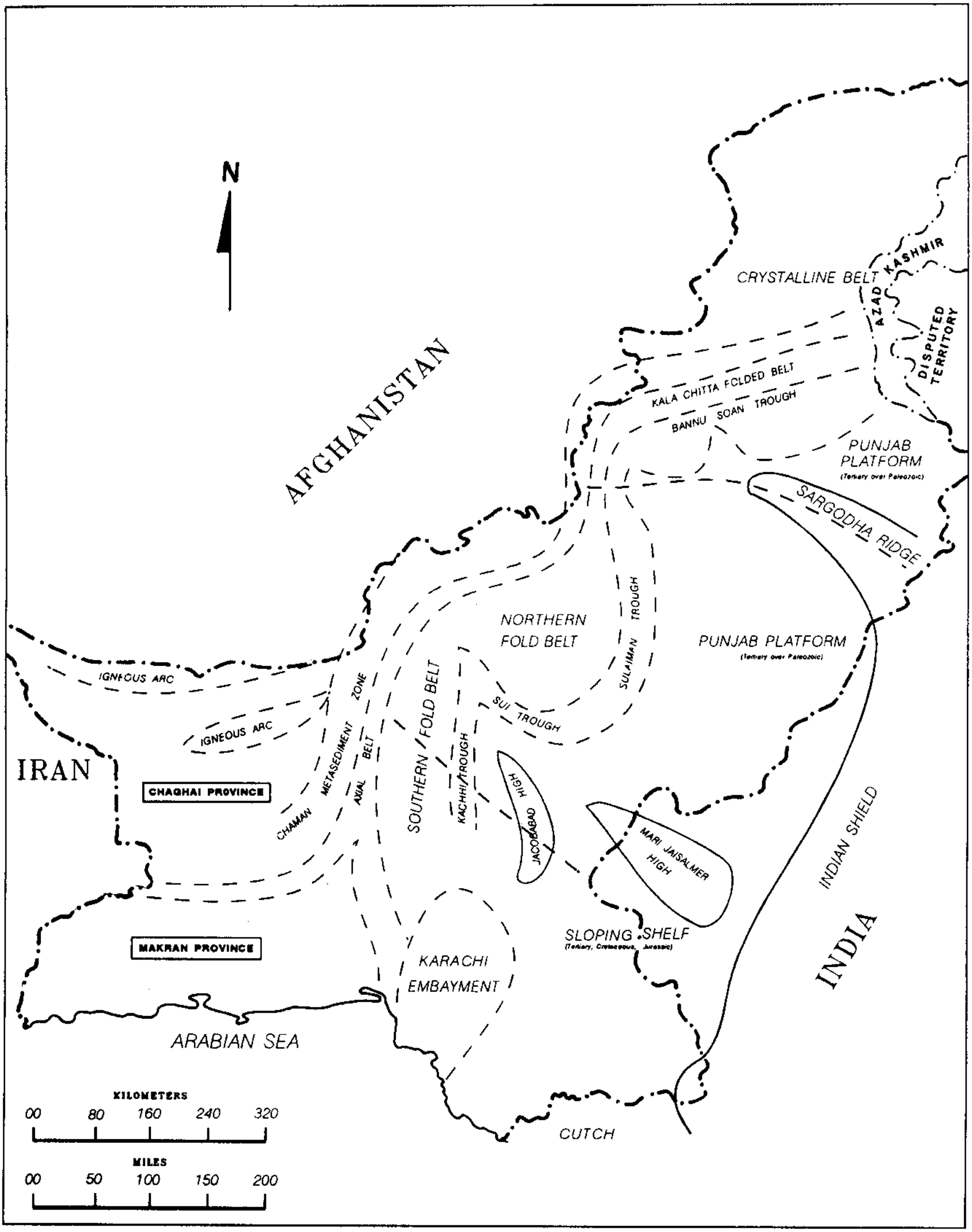

Figure - 3.1 Basin Architecture, Pakistan (after Zuberi & Dubois, 1962)

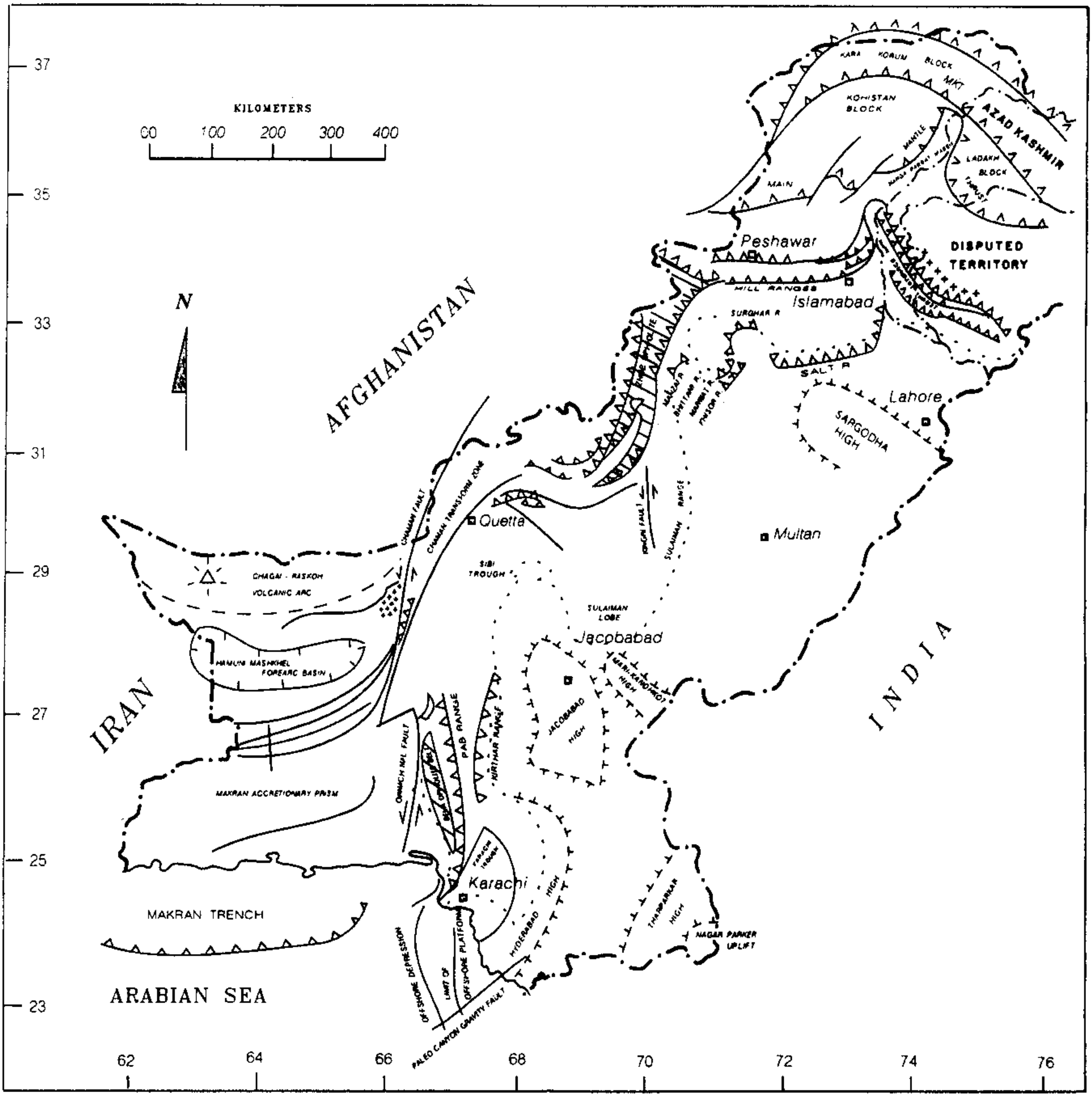

Figure - 3.2 Tectonic Framework of Pakistan (after Abul Farah et al,1984)

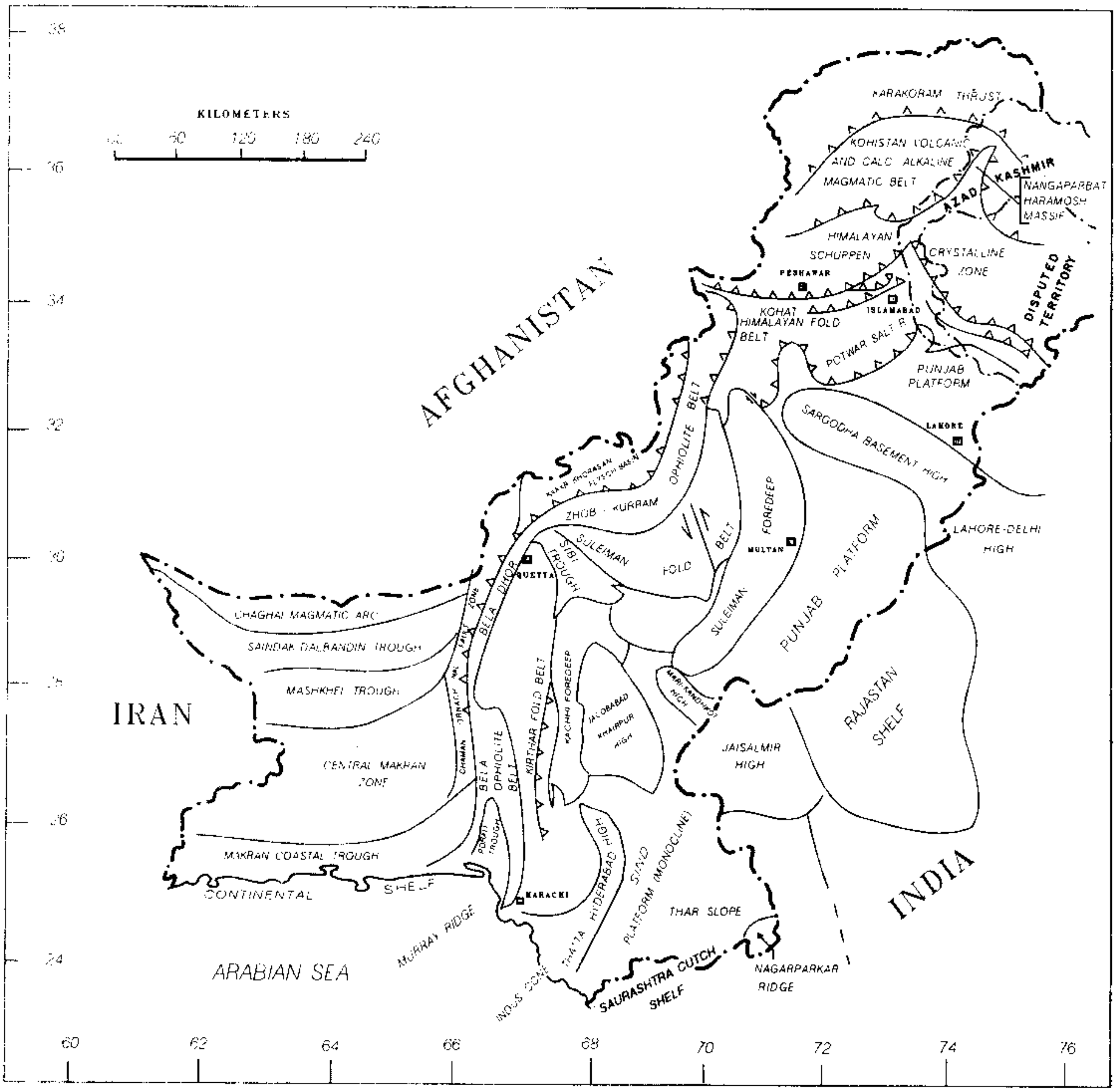

Figure - 3.3 Tectonic Zones of Pakistan; Simplified Interpretation. (after "Facts & Figures",OGDC,1992)

a) Indian Foreland
b) Salt Range
c) Potwar and Kohat Plateau
d) Hill Ranges
e) Plio-Pleistocene Basins
f) Southern Kohistan
g) Nanga Parbat Massif
h) Karakorum Block

INDIAN FORELAND

Rocks of the Indian Shield are reportedly exposed in Pakistan only at Nagar Parkar and Kirana Hills (Fig. 3.2). The Kirana Hills are part of the east-southeast trending Sargodha Ridge (Fig. 3.1) of raised continental crust. The similarity of the stratigraphy between the Karampur and Kundian wells, drilled south and north respectively of the Sargodha Ridge, suggests that these wells were drilled in what was originally a single basin (Fig. 3.5). Thus the ridge may post-date rather than pre-date the depositional sequence found in these wells. The ridge may be analogous to the outer swell commonly developed by breaking of the lithosphere, seaward of a subduction zone.

Salt Range

Salt Range and Trans-Indus Salt Range (Fig. 4.6) are the surface expressions of the leading edge of a decollement thrust in which the crystalline basement is not involved. The zone of decollement appears to have been provided by the evaporites of the Eocambrian Salt Range Formation which underlies the Salt Range and the Potwar Plateau to the north. This Eocambrian

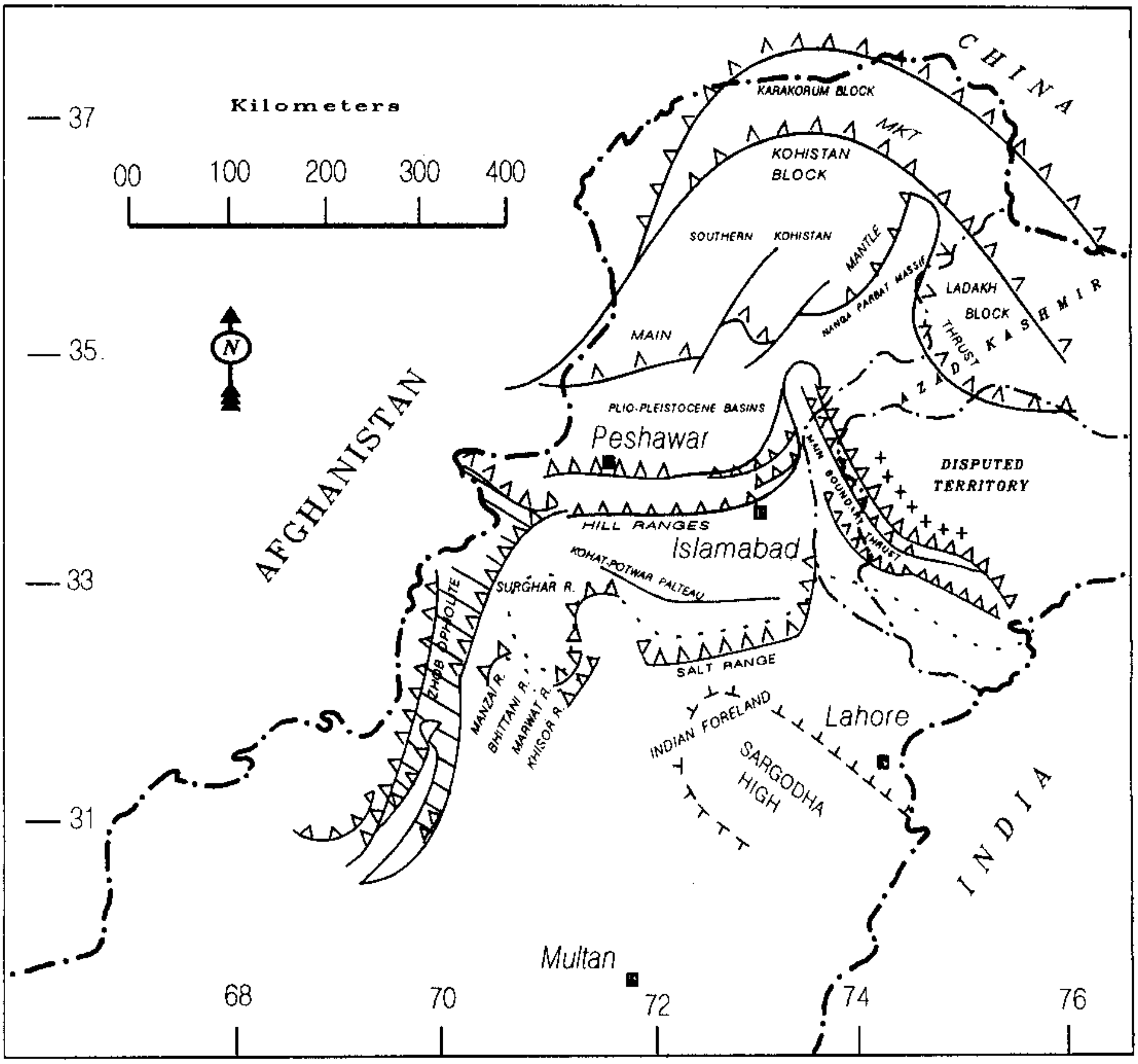

Figure - 3.4 Tectonic Elements of Northern Pakistan

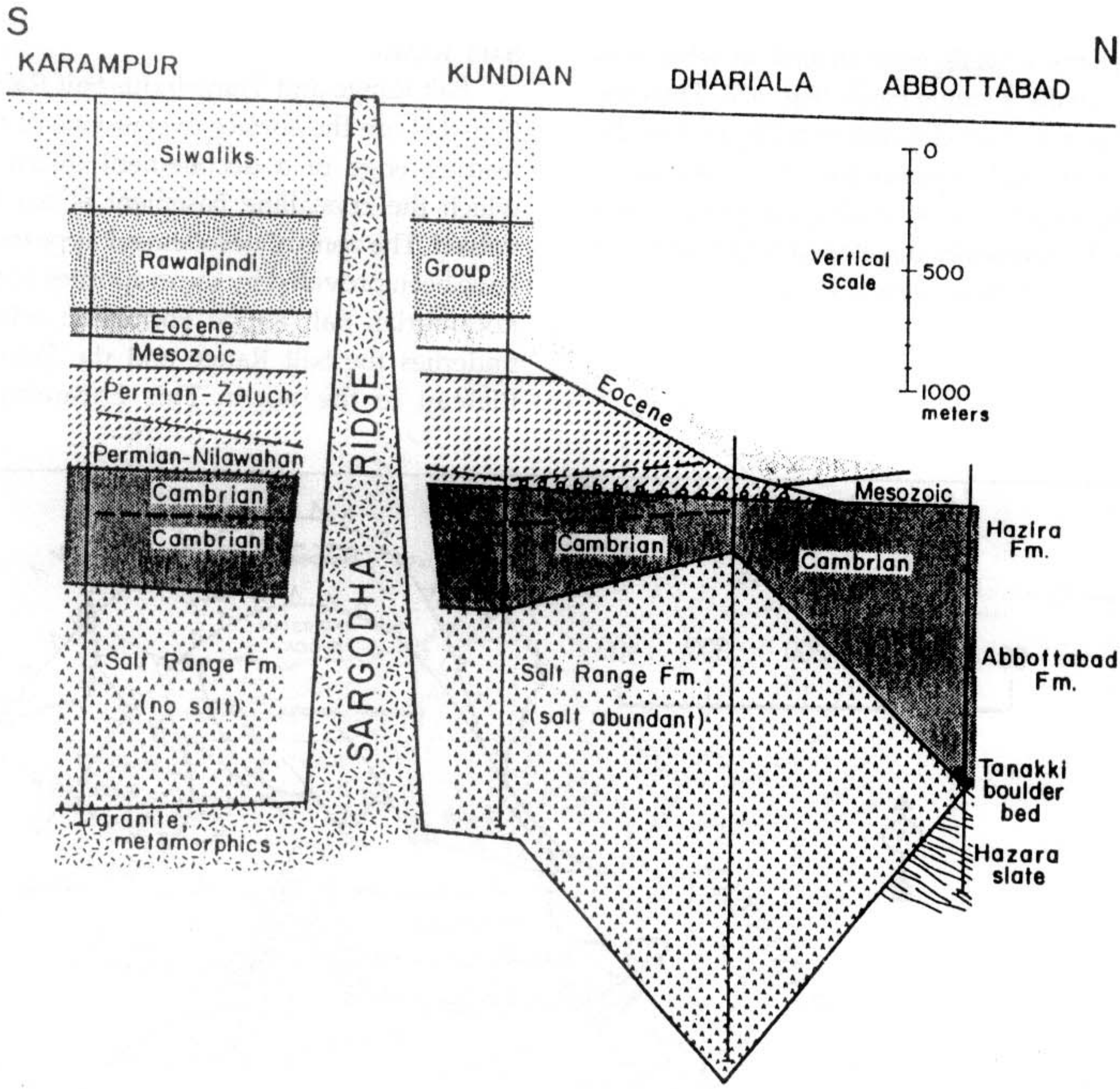

Figure - 3.5 Stratigraphic correlation section from Punjab plains (left) to Hazara region (right). No horizontal scale. All are exploratory well sections except Abbottabad. (after Lawrence and Yeats, 1984)

evaporite sequence is an effective zone of decoupling, allowing thrusting to extend more than 100 km south of Main Boundary Thrust (MBT) without involving basement.

Potwar and Kohat Plateau

The area is located north of Salt Range and Trans-Indus Salt Range culminating in the Parachinar–Kala Chitta Fold Belt. Structurally Potwar Plateau comprises the northern folded zone and the platform zone while the Kohat Plateau consists of Kohat Eocene Salt Zone and Bannu Depression. The Kohat Plateau structures differ from those of the Potwar Plateau largely on account of the higher salt detachment horizon (Eocene) in the Kohat Area, against that of Precambrian in Potwar.

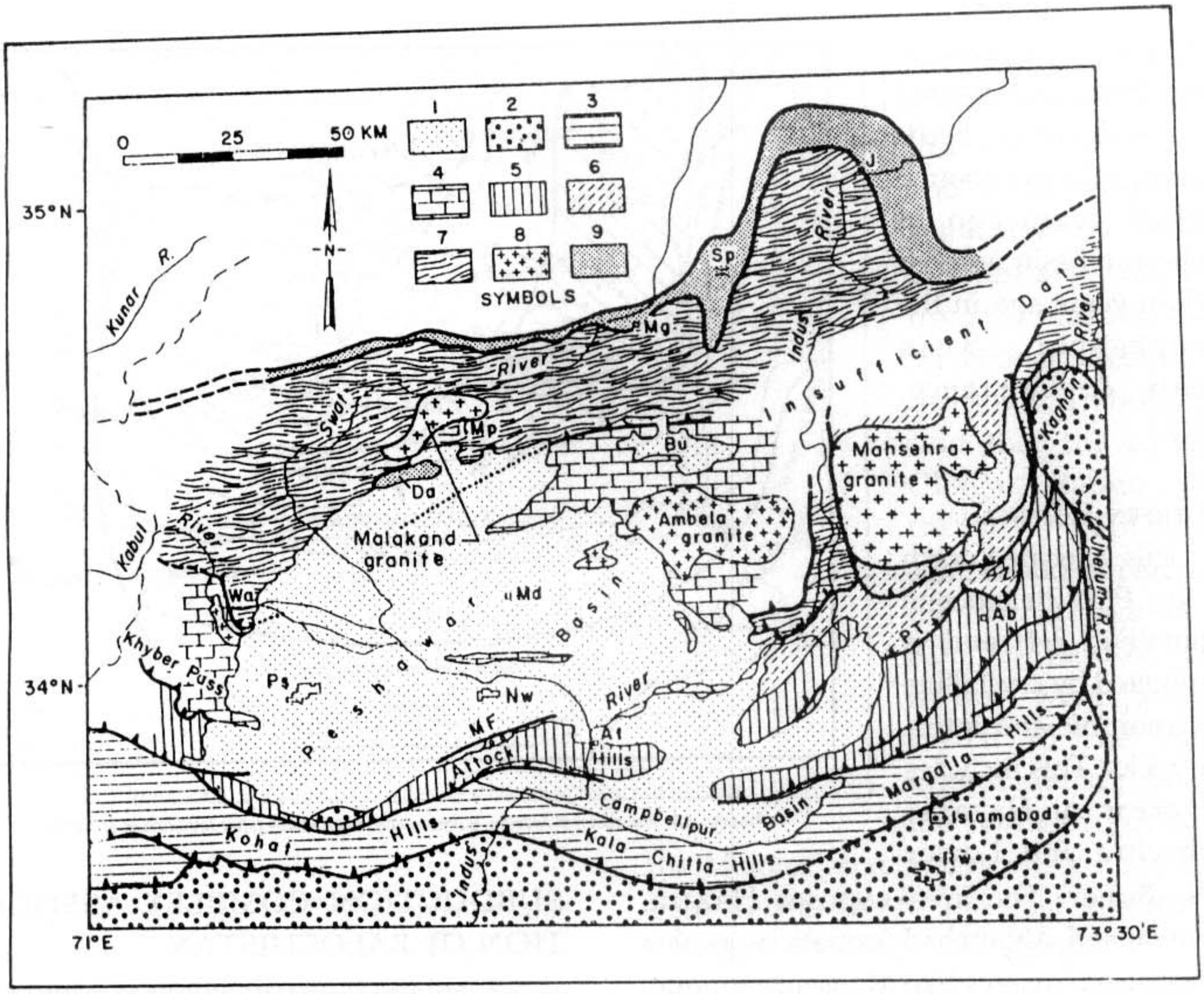

Figure - 3.6 Tectonic sketch of northwestern Pakistan from the Hill Ranges to Southern Kohistan. Geologic Units 1) quaternary of Plio-Pleistocene basins, 2) Murree and Siwalik strata, 3) Mesozoic and Cenozoic rocks with stratigraphic affinities to the Sulaiman Range, 4) Late Precambrian to Paleozoic Sedimentary rocks with stratigraphic affinities to Kashmir, 5) Late Precambrian and lower Paleozoic rocks with stratigraphic affinities to the lesser Himalaya, 6) Tanawal-type metamorphic rocks and included lower Paleozoic gneisses, 7) Salkhala-type metamorphic rocks and included lower Paleozoic gneisses, 8) Alkaline granitic rocks of Ambela, Warsak, and Malakand, 9) Suture Zone complex included ophiolite of the Main Mantle Thrust. Locations: Da=Dargai Klippe, Mp=Malakand Pass, Mg=Mingora, Sp=Shangla Pass, J=Jijal, Wa=Warsak, Ps=Peshawar, Md=Mardan, Nw=Nowshera, Bu=Buner, PT=Panjal Thrust, Ma=Mansehra, Ab=Abbottabad, MF=Manki fault, At=Attock, Rw=Rawalpindi. (Modified after Lawrence and Yeats, 1984)

Hill Ranges

Similar to the Salt Range, Hill Ranges form the major uplift where rocks from just above the detachment are brought to the surface. These consist of a pair of low, interrupted mountain chains extending from the Hazara–Kashmir syntaxis to Sulaiman Range.

Plio-Pleistocene Basins

Campbellpur and Peshawar Basins (Fig. 3.6) are two major currently active geomorphic features in northern Pakistan. These basins were formed at the expense of southern Kohistan in the north and Hill Ranges in the south. Unlike Potwar Plateau and Kohat Plateau which are loci of active degradation at present, these Plio-Pleistocene basins are filled by meandering and braided river sediments. Sedimentation began about 3 million years ago in Peshawar Basin and 1.8 million years ago in the Campbellpur Basin (Yeats & Lawrence, 1984).

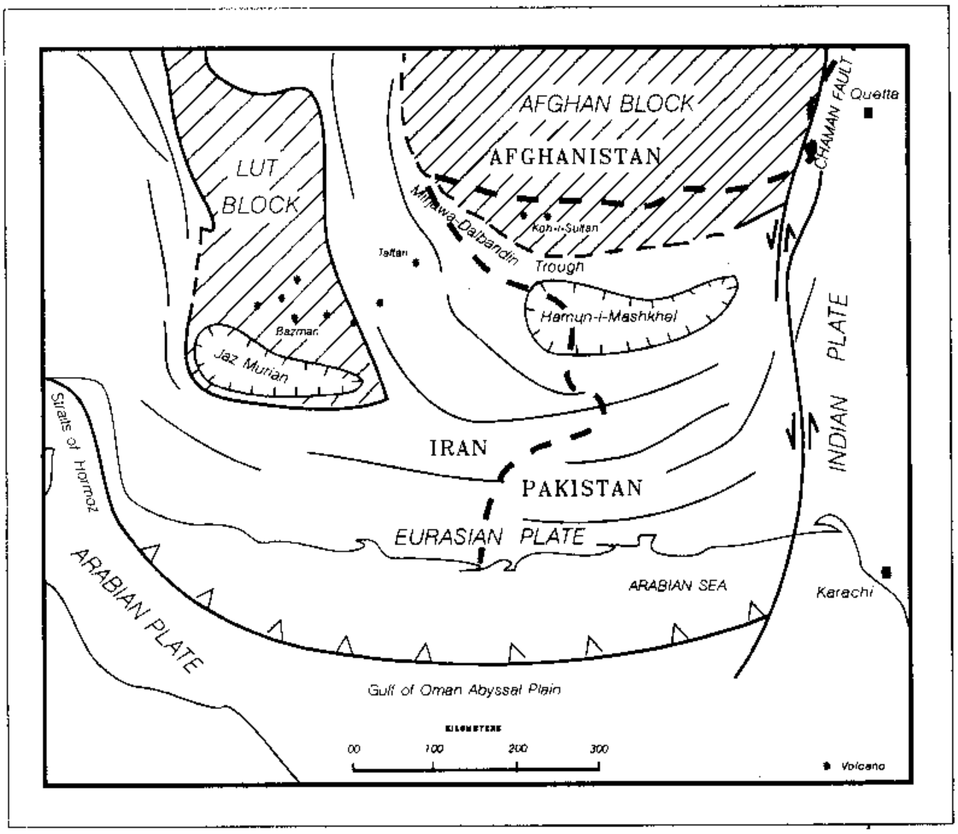

Figure - 3.7 Interaction of Arabian, Eurasian and Indian Plates (after Arthurton et al ,1978)

Southern Kohistan

This is located north of the Plio-Pleistocene Basins(Fig. 3.4) and is dominated by crystalline metamorphic and intrusive rocks. This includes the areas of Hazara–Mansehra and Lower Swat–Buner. The area exposes Hazara, Tanawal and Abbotabad formations as also the intrusive masses like Mansehra granite, Ambela granite and Malakand granite (Fig. 3.6).

Nanga Parbat Massif

This is characterised by the rocks which are extensively magmatized by Himalayan age metamorphism and cross-cut by small Tertiary tourmaline granite intrusive bodies. This massif is a narrow northward extension of the crystalline rocks deep into the Kohistan–Ladakh andesitic arc terrain and represents the western end of the Precambrian slab of the High Himalaya (Fig. 3.4).

Karakorum Block

This is located north of Main Karakoram Thrust (MKT, Fig. 3.4), and is a terrain of Gondwana affinities which was sutured to Eurasia.

SUBDUCTION COMPLEX ASSOCIATION OF BALOCHISTAN

A subduction–convergence zone with an unusually wide and subaerially exposed arc-trench gap is situated west of Chaman–Ornach Nal faults (Fig. 3.8). The general geologic setting is typical of a subduction zone complex except for a very wide arc trench gap. An Andean type andesitic arc in the Chagai Hills, Ras Koh and Saindak area exists in the north of Hamun-i-Mashkel Fore-Arc Basin. Hamun-i-Mashkel (Fig. 3.7) is a wide area of Quaternary cover in Balochistan desert which can be regarded as Fore-Arc Basin. This is followed by Makran Ranges in the south which expose thick extensive flysch deposits of Late Paleogene/Early Neogene age. This may be regarded as Makran accretionary prism. The subduction zone is extended far in the south under the ocean.

According to a different school of

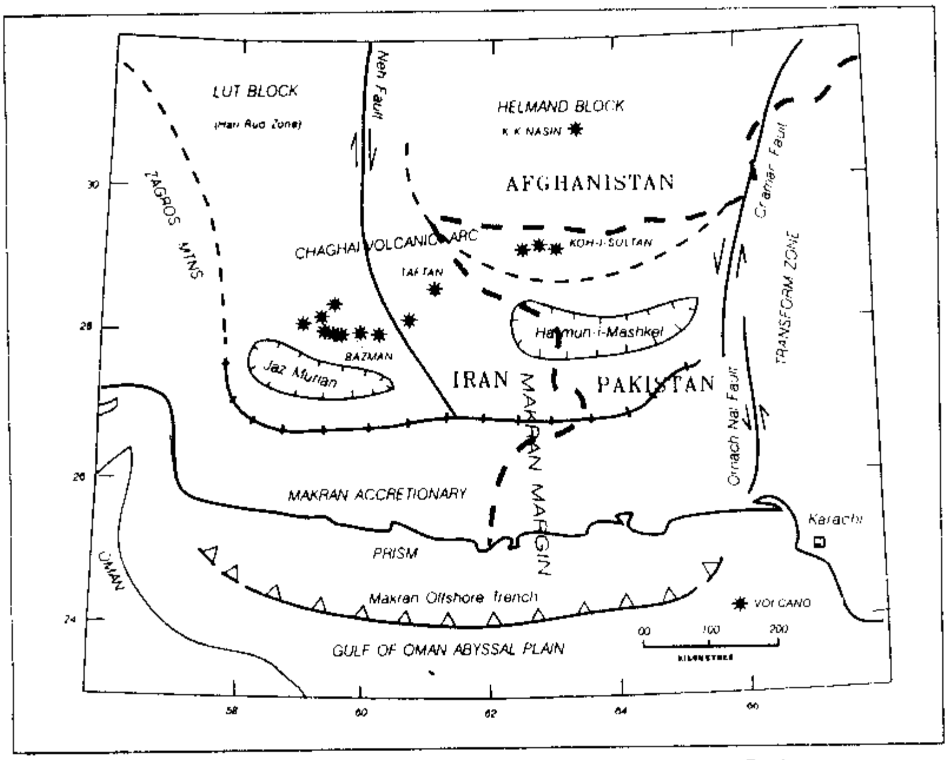

Figure - 3.8 Subduction Complex Association of Balochistan Basin

thought (Kanomori, 1977) the present subduction zone has migrated from near the southern margin of Ras Koh where it began in the Late Cretaceous with a long mid Cenozoic pause. During this pause, huge submarine fan of flysch was constructed and provided the southward driving force to this subduction zone to give rise to wider arc-trench gap.

Volcanic-Plutonic Arc of Chagai

The Chagai volcanic arc (Fig. 3.8) is the northern most subduction associated feature exposed in Pakistan. It is convex towards south and extends for about 500 kms in east-west direction and 150 kms in a north-south direction. This andesitic volcanic arc is associated with ultramafic rocks of Ras Koh Range. These two are divided by Mirjawa–Dalbandin Trough (Fig. 3.7) formed through Paleogene. In the north, Ras Koh Range is in tectonic contact with the gently folded Mesozoic–Tertiary sequence of the Chagai Volcanic Arc (Fig. 3.8) and in the south it is separated by zone of Quaternary deposits from the Makran Trench accretionary deposit further south. Thus it can be said that the rocks of Chagai Range were thrust southward, against and in part, over the northern side of Ras Koh. The Ras Koh rocks, in turn were probably thrust to the south, against and in part, over the northern portion of the Makran accretionary wedge. The three belts terminate to the east against the Chaman Transform boundary.

Makran Margin

This is the accretionary wedge of sediments developed between a buried offshore trench and Quaternary volcanoes and regarded as the arc-trench gap. Arabian Plate, which is subducting beneath the Makran Margin, dips gently northwards. The exposed rocks of the ranges are youngest at the coast and generally become older to the north. Makran margin is characterised by broad synclines separated by sharp thrust–faulted anticlines. Pakistani Makran is bounded between two strike–slip fault systems (Fig. 3.8); to the west the Neh faults of Hari Rud Zone and to the east the Chaman Transform Zone.

According to Jaccob & Quittmeyer (1979) Makran Margin presents many interesting features. The trench gap measures

400–600 kms across, about twice the width of a typical gap, and the shallow dipping zone is weakly developed extending to a depth of only 80 kms. They have brought out three points about this margin.

1. The Makran Margin is an active plate boundary with ongoing subduction at a rate of about 5 cm/year,
2. The subduction model implies that a large part of southern Makran is under-lain by a mobile oceanic basement, and
3. The Makran subduction margin is one of the most interesting places to study the subduction processes of accretion and consumption in an arc-trench gap because of subaerial exposure.

CHAMAN TRANSFORM ZONE

This is the most important tectonic feature (Fig. 3.2) controlling the evolution of the structural style and Post-Oligocene deposition in Pakistan.

This zone is mainly characterized by strike slip faulting with minor thrust components. It connects the Makran Convergent Margin in the south with Himalayan Convergence Zone in the north.

The width of the transform zone varies from north to south. It is 100 kms wide in the south; narrows to 30–40 kms between Khuzdar and Quetta; widens abruptly to over 200 kms in Zhob Thrust Belt and then narrows gradually towards the Kabul Block in the north. The rock type of this zone is the Khojak Flysch of Oligocene/Miocene age. The eastern edge of the zone is marked by continental margin type Mesozoic rocks of Lower Indus Basin and the obducted ophiolites of Las Bela and Muslimbagh/Zhob. Hence this zone represents the basin formed at the expense of continent-island / arc-continent collision.

The eastern margin of the transform zone is formed by the Quetta region along which the sediments of the Khojak Flysch Belt came into contact with the Mesozoic and Cenozoic platform sediments of the Indian subcontinent. The line is formed by a series of faults. From north to south these include the region from Zhob Thrust to the Ornach-Nal Fault (Fig. 3.2).

There is an internal convergence zone east of Chaman Transform Zone near Quetta-Loralai-Barkhan, achieved by southward decollement thrusting of the sedimentary sequence as a result of combined northward and westward convergence and counter clockwise rotation of the Indo-Pakistan subcontinent with Eurasia.

ZONE OF OPHIOLITES AND OPHIOLITIC MELANGES

The eastern edge of the transform zone is associated with ophiolites which are believed to have been obducted upon the sediments of the margin of the Indo-Pakistan subcontinent. These are Zhob, Waziristan, Muslimbagh and Bela ophiolites (Fig. 3.3).

Bouger gravity anomalies of the Muslimbagh area indicate that the flysch deposits are underlain by continental crust and not by the oceanic crust, suggesting the extension of Indian Plate far into the north up to Chaman Fault.

Bela ophiolites were emplaced as a result of oblique convergence between the Indian Plate and the Neo-Tethys giving rise to an emergent zone of tectonically mixed continental and oceanic rocks. It appears (De Jong & Subhani, 1979) that during the Late

Cretaceous a volcanic island arc was formed on the shelf of the western margin of Indo-Pakistan subcontinent. Later the products of erosion of the island arc were pushed together along with the basement (Mor Range) towards the Indo-Pakistan Platform. Thereafter the counter clockwise rotation of Indian Plate resulted in the formation of triangular Porali Trough (Fig. 3.3).

PLATFORM AREAS

Platform Areas are the eastern most features of Pakistan. These are relatively much stable areas where generally monoclinal strata rest atop crystalline basement (Indian Shield). Cambrian to Siwaliks aged rocks seem to onlap against this basement. There seems to be no activity related to the basement. However, the overlying strata are affected by the plate collision. Platform areas form south-eastern part of Lower Indus Basin.

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4

Sedimentary Basins and their Evolution

In terms of genesis and different geological histories, Pakistan comprises two main sedimentary basins (Fig. 4.1), Indus Basin and Balochistan Basin, which evolved through different geological episodes and were finally welded together during Cretaceous/Paleocene along Ornach Nal/Chaman Strike slip faults. There is yet another newly identified smaller basin, termed as Kakar–Khorasan Basin (Fig. 4.1) also referred to as Pishin Basin (Ahmed, 1991), which carries its own geological history for most of its development. This basin came into existence due to the interaction of Indian and Eurasian plates and is classified as Median Basin. The development of Balochistan Basin has been partly dealt with in Section-3 and has been discussed in detail in Section-17.

The geological history of the Indus Basin goes back to Precambrian Age. The Paleotopographic features, shown on the gravity map of Pakistan (Fig. 4.2), influenced, to a large extent, the depositional processes throughout the basin development. These features also marked the limit of the basin and its divisions. The ongoing tectonic processes further enhanced and modified the configuration and gave rise to some new ones creating an array of modern basins. Fig. 4.3 is the gravity map of Southern Indus Basin.

The main feature which controlled the sedimentation in the proto-Indus Basin up to Jurassic was Precambrian Indian Shield whose topographic highs exist in the form of Kirana Hills (Sargodha High) and Nagar Parkar Ridge. It is the Sargodha High which is considered to be a divide between Upper Indus Basin and Lower Indus Basin (Fig. 4.1). The Early Jurassic saw the first breakup of the supercontinent Pangea which disturbed the equilibrium.

Following is the classification of Indus Basin:

Upper Indus Basin:	Kohat sub-Basin
	Potwar sub-Basin
Lower Indus Basin:	Central Indus Basin
	Southern Indus Basin

Generalized stratigraphy of these basins is shown in Fig. 4.4 and the depositional environments of various formations in Pakistan are shown in Fig. 4.5. In addition to these, two modern basins are also recognised which are Peshawar Basin and Campbellpur Basin. Another term, Siwaliks Basin signifies all the trough areas in Indo-Pakistan subcontinent; formed at the expense of Himalayan Orogeny, they received tectonic shed of positive areas. However, these trough areas have also undergone deformation and

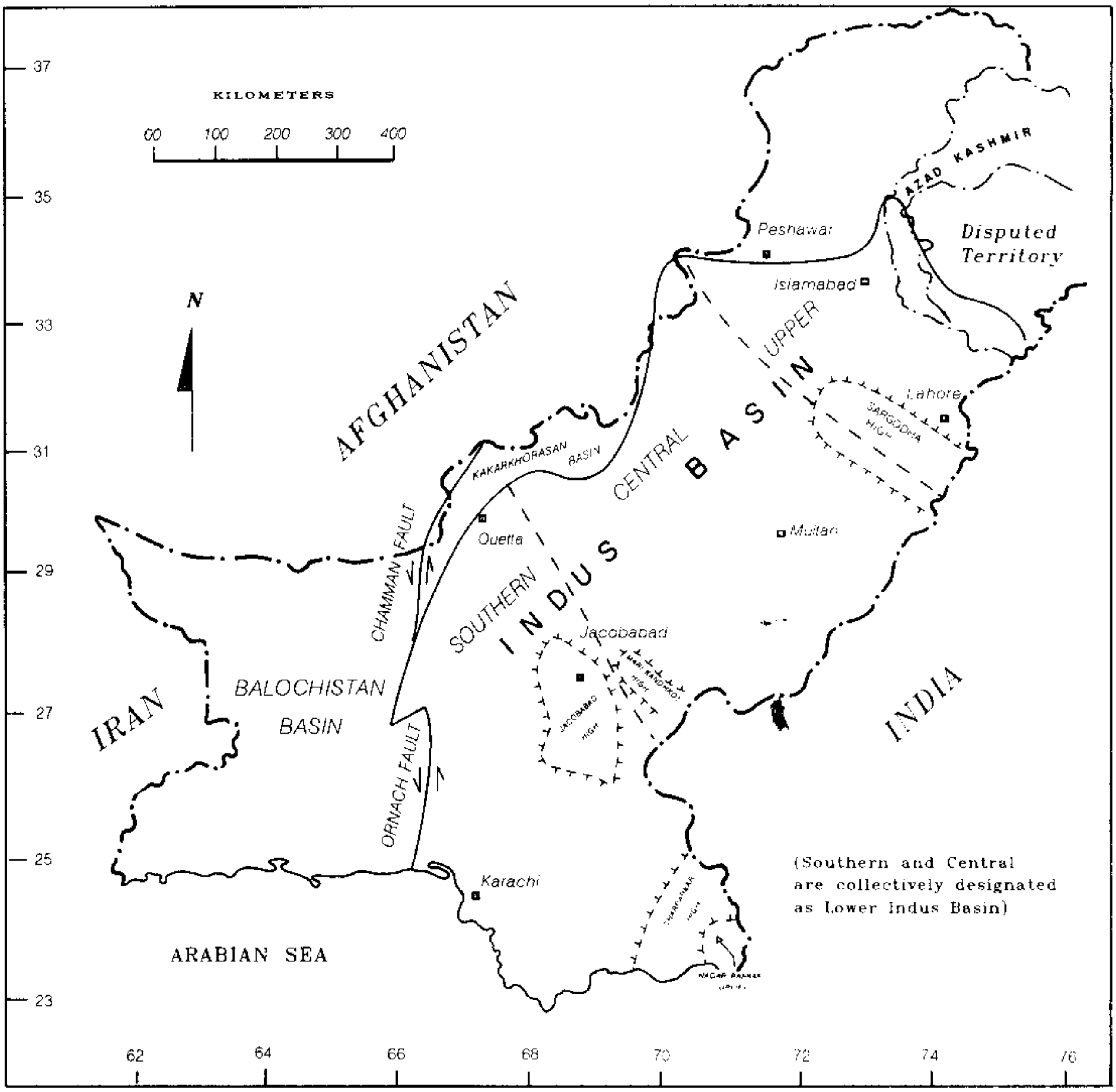

Figure - 4.1 Sedimentary Basins of Pakistan (after Abul Farah et al, 1984)

destruction losing their integrity.

Another major feature of basement topography, as seen on gravity data, is Khairpur–Jacobabad High and its associated structures which grew through Jurassic and Cretaceous/Paleocene ages and divided the Lower Indus Basin further into two basins namely Southern and Central Indus basins (Fig. 4.1).

UPPER INDUS BASIN

This basin is located in the northern Pakistan and is separated from the Lower Indus Basin by Sargodha High (Fig. 4.1). The northern and eastern boundaries coincide with the Main Boundary Thrust (MBT) – the southern most of the major Himalayan thrusts. The MBT runs through the Margala Hills, Kala Chitta and Kohat Ranges. West-

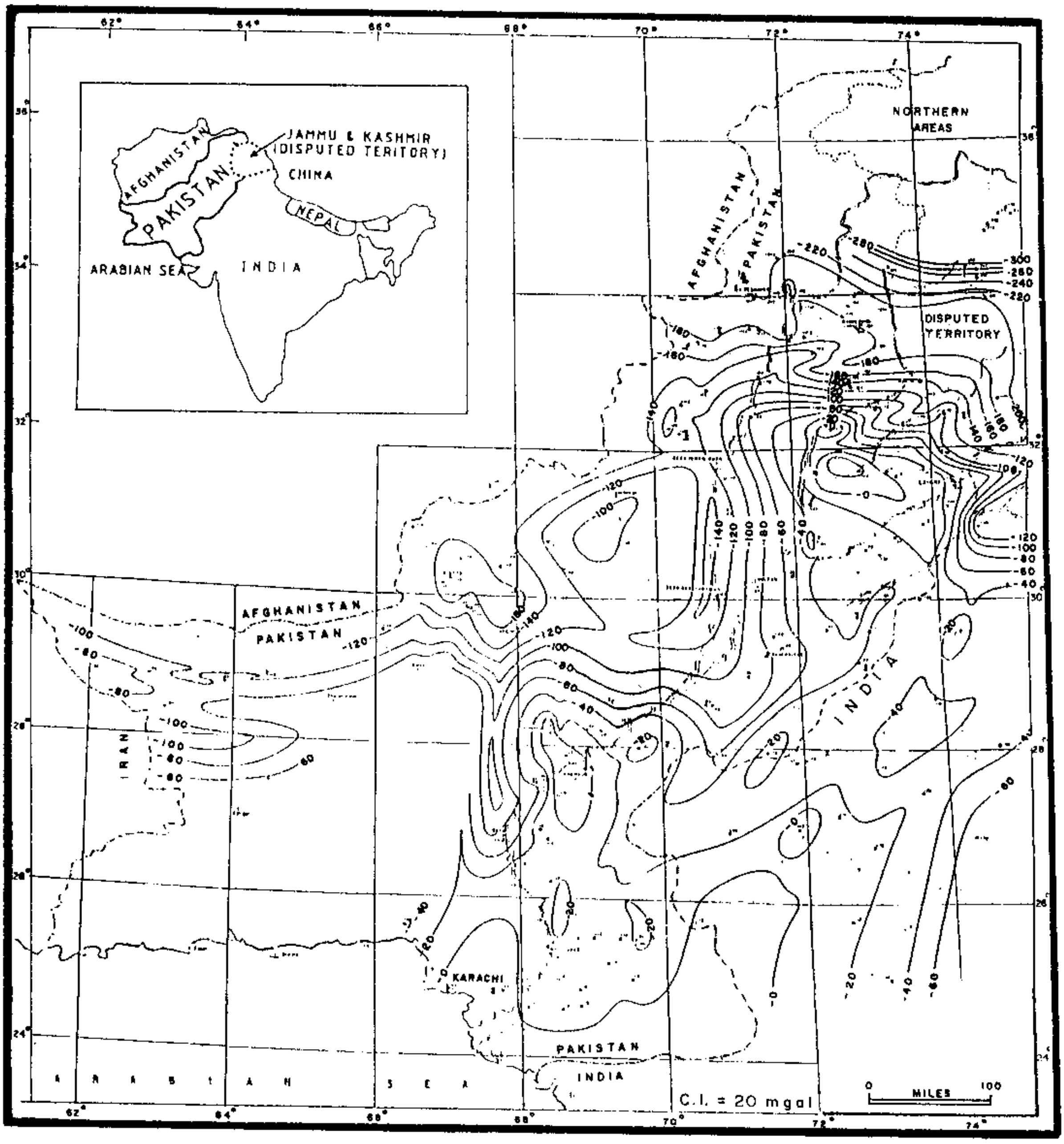

Figure - 4.2 Bouguer Anomalies In Pakistan

ern boundary of the basin is marked by an uplift of Pre-Eocene sediments and eastward directed thrusting to the west of Bannu.

The basin is further subdivided into Potwar, to the east and Kohat, to the west, by river Indus (Fig. 4.6). Regardless of the small size of the Potwar and Kohat sub-basins they depict important facies variations.

Potwar sub-Basin preserves the sediments from Precambrian to Quaternary age in the subsurface and all of these are exposed in the Salt Range – a southernmost

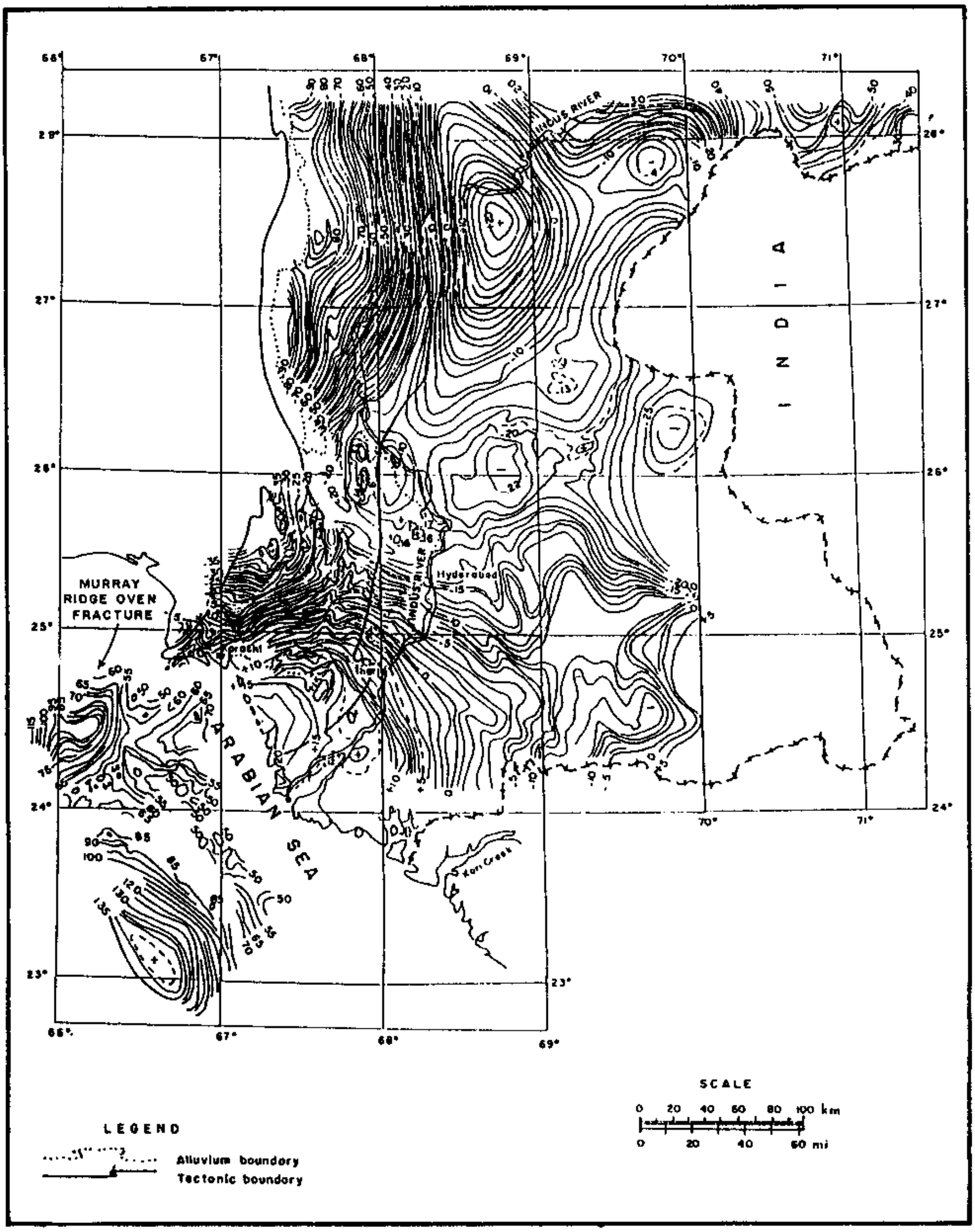

Figure - 4.3 Bouguer Anomalies (m gal), Southern Indus Basin (after Quadri and Shuaib, 1986)

thrust. The Trans-Indus Ranges in south of the Kohat sub-Basin (Fig. 4.6) expose sediments from Cambrian to Pliocene age.

Both Kohat and Potwar sub-basins are characterized by an unconformity between Cambrian and Permian. Mesozoic sediments are also exposed around the basin rim. However, their presence is governed by Pre-Paleocene erosion which progressively cut into the older sequence from the Trans-Indus Ranges in the west to East Potwar through Salt Range.

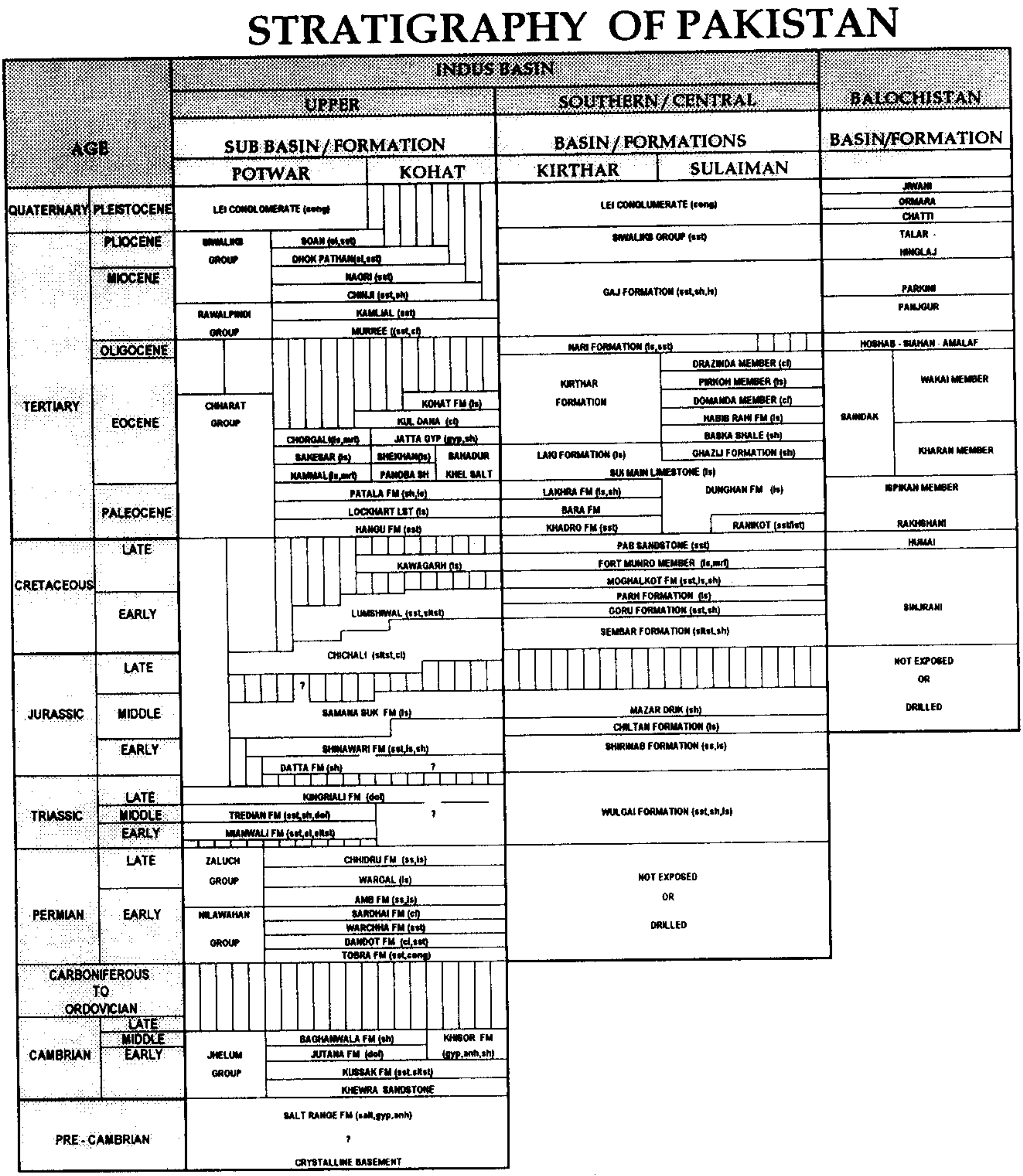

Figure - 4.4 Stratigraphy of Pakistan

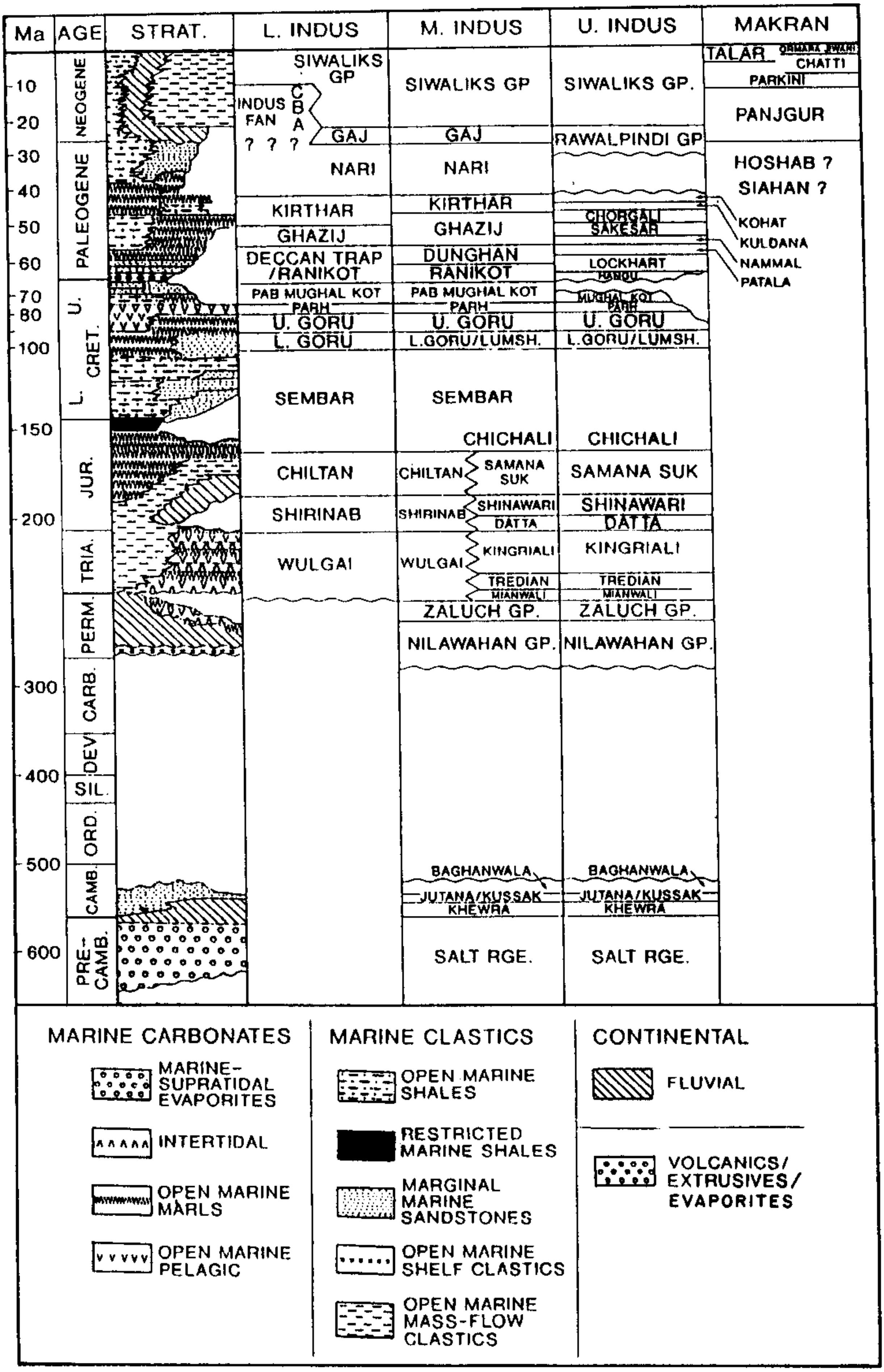

Figure - 4.5 Depositional environments of various formations in Pakistan

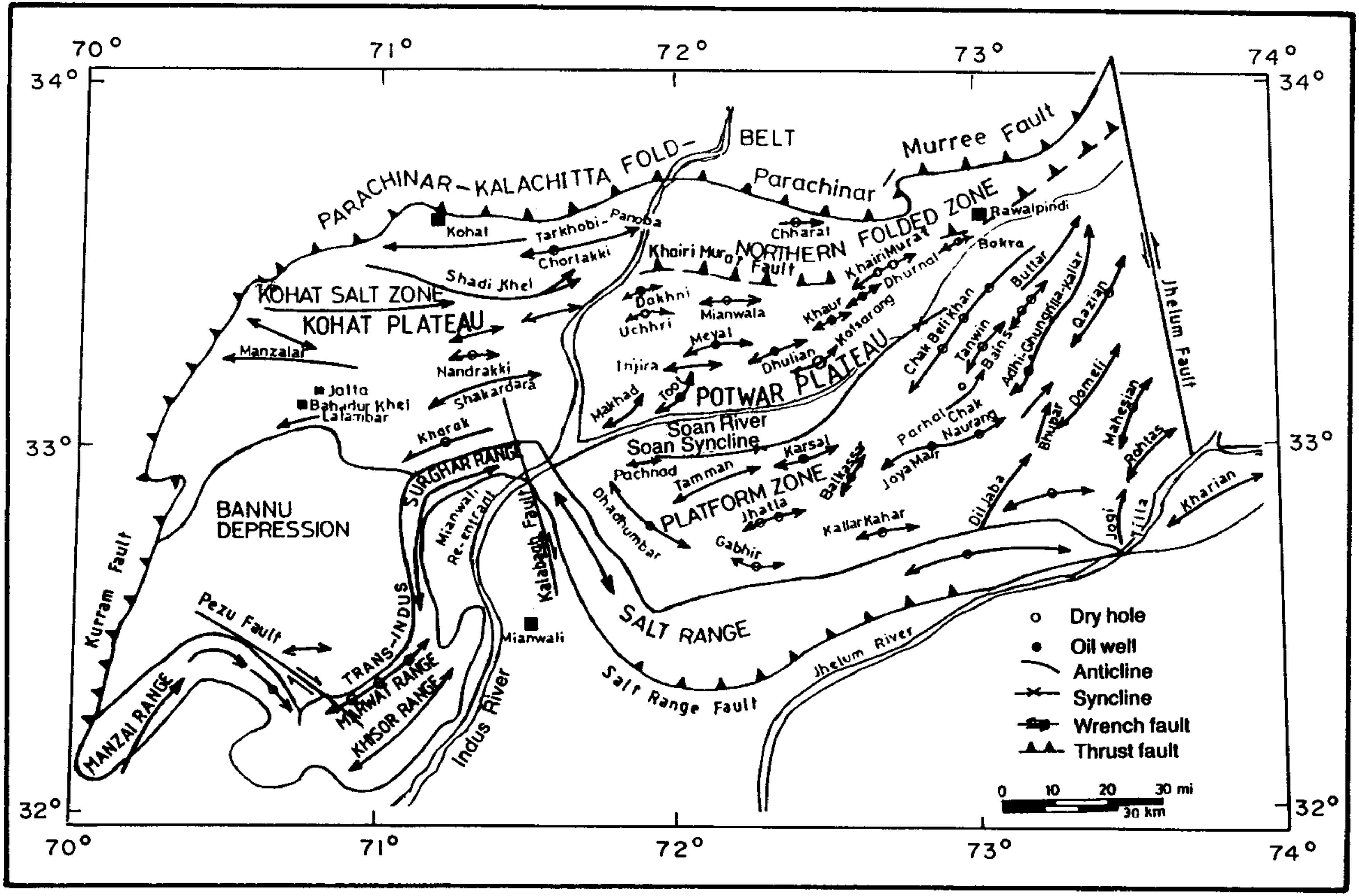

Figure - 4.6 Structural Map of Kohat-Potwar Depression (after Khan et al. 1986)

In the Kohat sub-Basin, west of the Potwar sub-Basin, Eocene through Siwaliks strata are involved in a complex fold and thrust belt in which Eocene Salt occupies the cores of many of the anticlines. Moreover, Paleocene and Eocene stratigraphy is more complete in Kohat sub-Basin.

The Upper Indus Basin stratigraphy is shown in Fig. 4.4.

LOWER INDUS BASIN (SOUTHERN AND CENTRAL INDUS BASINS)

Different classification schemes have been given to this basin by various experts. In this book the scheme being used is as follows:

Central Indus Basin: (Sulaiman sub-Basin, After Raza et al, 1984)
- a. Punjab Platform
- b. Sulaiman Depression
  East Sulaiman Depression
  Zindapir Inner Folded Zone
  Mari Bugti Inner Folded Zone
- c. Sulaiman Fold Belt

Southern Indus Basin: (After Quadri & Shuaib, 1986)
- a. Thar Platform (Sindh Monocline)
- b. Karachi Trough
- c. Kirthar Foredeep
- d. Kirthar Fold Belt
- e. Offshore Indus

The Central and Southern Indus basins are separated by Jacobabad and Mari–Kandhkot highs (Fig. 4.1) together termed as the Sukkur Rift (Raza et al, 1989). The latter has acted as a basin divide since Jurassic times. On gravity and magnetic anomaly data these Highs represent a very deep subsurface wedge of upper mantle or oceanic crust. The Highs have been active since Jurassic times and at least up to Paleocene, as Paleocene strata are missing along the crest and its surrounding areas. The stratigraphy of Lower Indus Basin is shown in Fig. 4.4.

CENTRAL INDUS BASIN

The basin is separated from Upper Indus Basin by the Sargodha High and Pezu uplift in the north. It is bounded by Indian Shield in the east, marginal zone of Indian Plate in the west, and Sukkur Rift in the south (Fig. 4.7). The oldest rocks exposed in this basin are of Triassic age (Wulgai Formation) while the oldest rocks penetrated

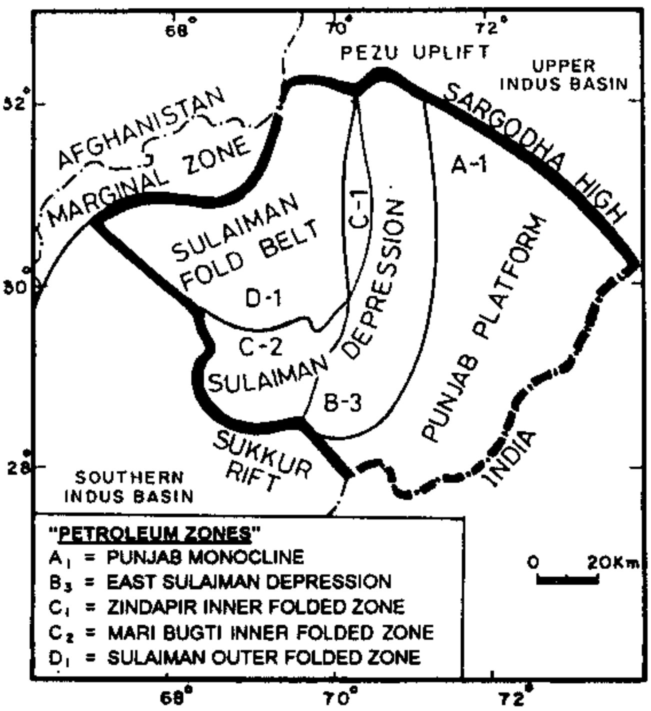

Figure - 4.7 Central Indus Basin and the subdivisions into Petroleum zones. (after Raza et al, 1989)

through drilling are of Precambrian Salt Range Formation on Punjab Platform. The depth to the basement is about 15,000 meters in the trough areas. Pre-Himalayan non-orogenic movements have resulted in prolonged uplifts/sea regression causing unconformities which have led to the large gaps in succession.

Precambrian rocks are largely missing from the basin, although Precambrian shield rocks are evident along the rim of the Indian Plate. Cambrian aged shallow marine rocks are recorded in Karampur well (Shell, 1958). The basin comprises, from east to west, three main units (Fig. 4.8) on the basis of the topography of Indian Shield and later development, as follows (Raza et al, 1989):

a. Punjab Platform
b. Sulaiman Depression
c. Sulaiman Fold Belt

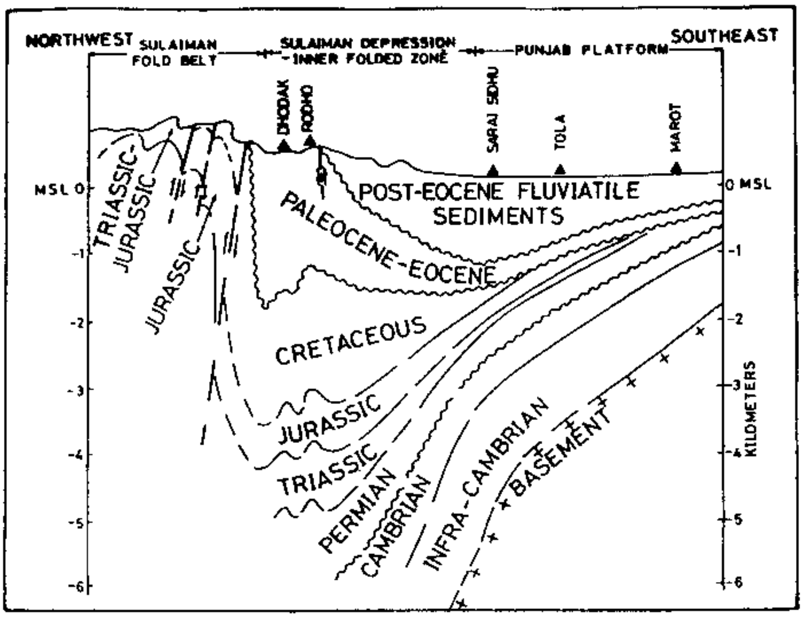

Figure - 4.8 Regional Cross Section, Sulaiman Region (after Raza et al, 1989)

Punjab Platform

This unit marks the eastern segment of Central Indus Basin and shows no surface outcrops of sedimentary rocks. Tectonically, it is a broad monocline dipping gently towards the Sulaiman Depression. The Pre-Cretaceous non-orogenic movements tilted the area eastward during the Paleozoic and westward since Mesozoic resulting from the collision of Indian and Eurasian plates.

Punjab Platform is tectonically the least affected area because of its greater distance from collision zone. However, this presents larger stratigraphic variations; Cambrian and Permo-Carboniferous(?) strata appear to onlap against the Sargodha High.

A number of wells have been drilled on this platform. The stratigraphic sequence established on the basis of these wells revealed some of the most significant stratigraphic pinchouts in Pakistan.

Sulaiman Depression

This depression is clearly indicated on gravity data and is a longitudinally oriented area of subsidence; it becomes arcuate and takes up a transverse orientation along its southern rim. Like many other features, this depression was also formed as a result of the collision between two plates. The western flank of the depression includes Zindapir Inner Folded Zone while Mari Bugti Inner Folded Zone lies in the south; to the east it merges into Punjab Platform. On seismic evidence the area shows some buried anticlines (e.g. Ramak) which may have been formed at the expense of flow of Eocene shales. The stratigraphy in the depression area is more complete.

Sulaiman Fold Belt

This is a major tectonic feature in the proximity of collision zone and, therefore, contains a large number of disturbed anticlinal features. Unlike the Upper Indus Basin, the decollement zone in this part was possibly provided by shales.

In the Lower Indus Basin the oldest rocks (Triassic-Wulgai Formation) are exposed in this region.

The most important lithostratigraphic variations observed in Sulaiman Depression and the Fold Belt are in Paleocene/Eocene. This period marks the facies changes from north to south and east to west. The reason for this variation is believed to be the presence of a number of new basins at that time, created due to the collision of plates and their irregular and non-uniform coalescence.

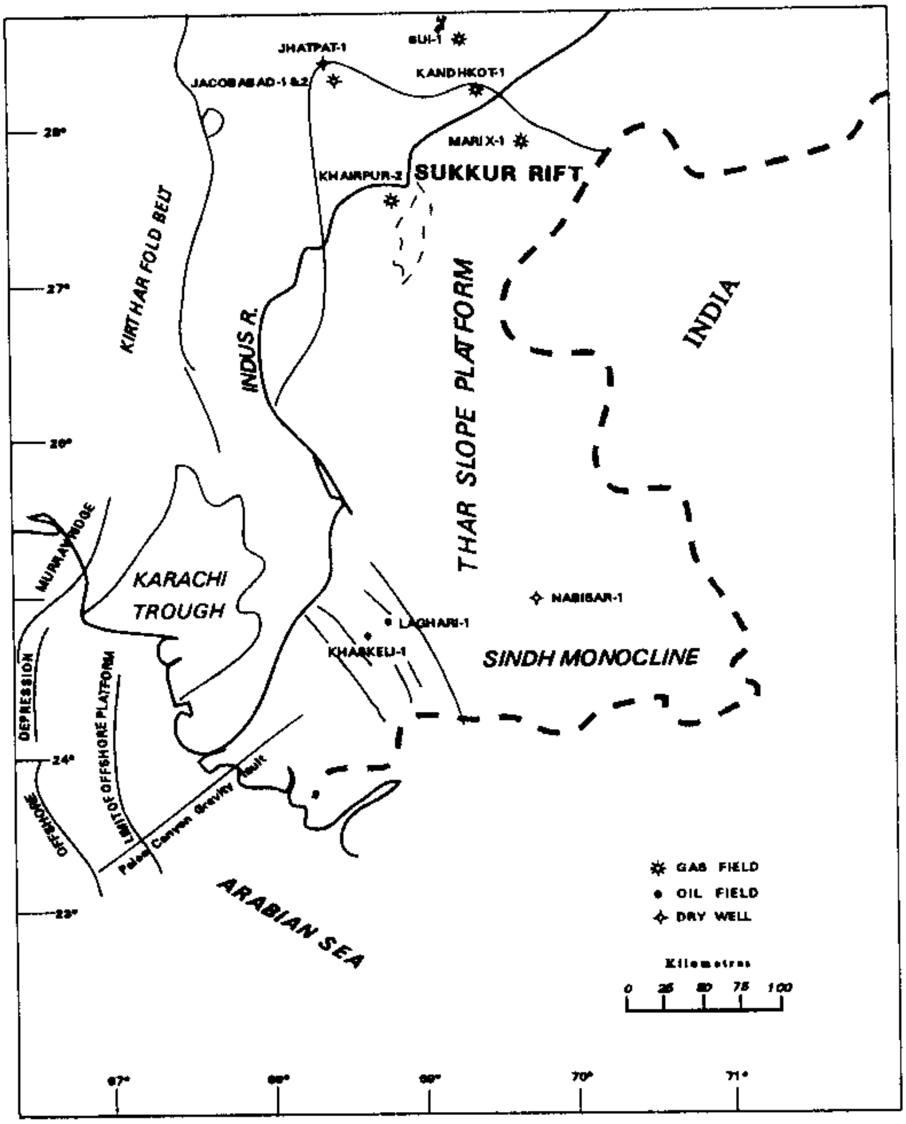

Figure - 4.9 Structural Setting of Southern Indus Basin (Modified after Quadri & Shoaib, 1986)

SOUTHERN INDUS BASIN

This basin (Fig. 4.9) is located just south of Sukkur Rift – a divide between Central and Southern Indus basins. It comprises the following four main units:

a. Thar Platform
b. Karachi Trough
c. Kirthar Foredeep
d. Kirthar Fold Belt
e. Offshore Indus

The platform and trough extend into the offshore Indus.

The Southern Indus Basin is bounded by the Indian Shield to the east and the marginal zone of Indian Plate to the west. Its southward extension is confined by offshore Murray Ridge–Oven Fracture plate boundary.

The oldest rocks encountered in the area are of Triassic age (Jhat Pat and Nabisar wells). Central and Southern Indus basins were undivided until Lower/Middle Cretaceous when Khairpur–Jacobabad High became a prominent positive feature. This is indicated by homogeneous lithologies of Chiltan Limestone (Jurassic) and Sembar Formation (Lower Cretaceous) across the High. Sand facies of Goru Formation (Lower-Middle Cretaceous) are also extending up to Kandhkot and Giandari area. This is further substantiated by Khairpur and Jhat Pat wells located on the High. In Khairpur-2 well, significant amount of Lower Cretaceous and Paleocene is missing while in Jhat Pat-1, the whole Cretaceous and Paleocene are absent with Eocene directly overlying Chiltan Limestone (Jurassic). Paleocene facies south of the High are quite different from those in north and are dominated by clastic sediments derived from the positive areas (Khairpur–Jacobabad High and Nabisar Arc).

Thar Platform

It is a gently sloping monocline analogous to Punjab Platform (Fig. 4.8) controlled by basement topography. The sedimentary wedge thins towards the Indian Shield whose surface expressions are present in the form of Nagar Parkar High. It differs from the Punjab Platform in that it depicts the buried structures formed due to extension tectonism resulting from the latest counter – clockwise movement of the Indian Plate. It is bounded in the east by Indian Shield, merges into Kirthar and Karachi Trough in the west and is bounded in the north by Mari-Bugti Inner Folded Zone. A strati-structural cross-section constructed through Thar Platform, Karachi Trough and Offshore Indus (Fig. 4.10) clearly shows the strati-

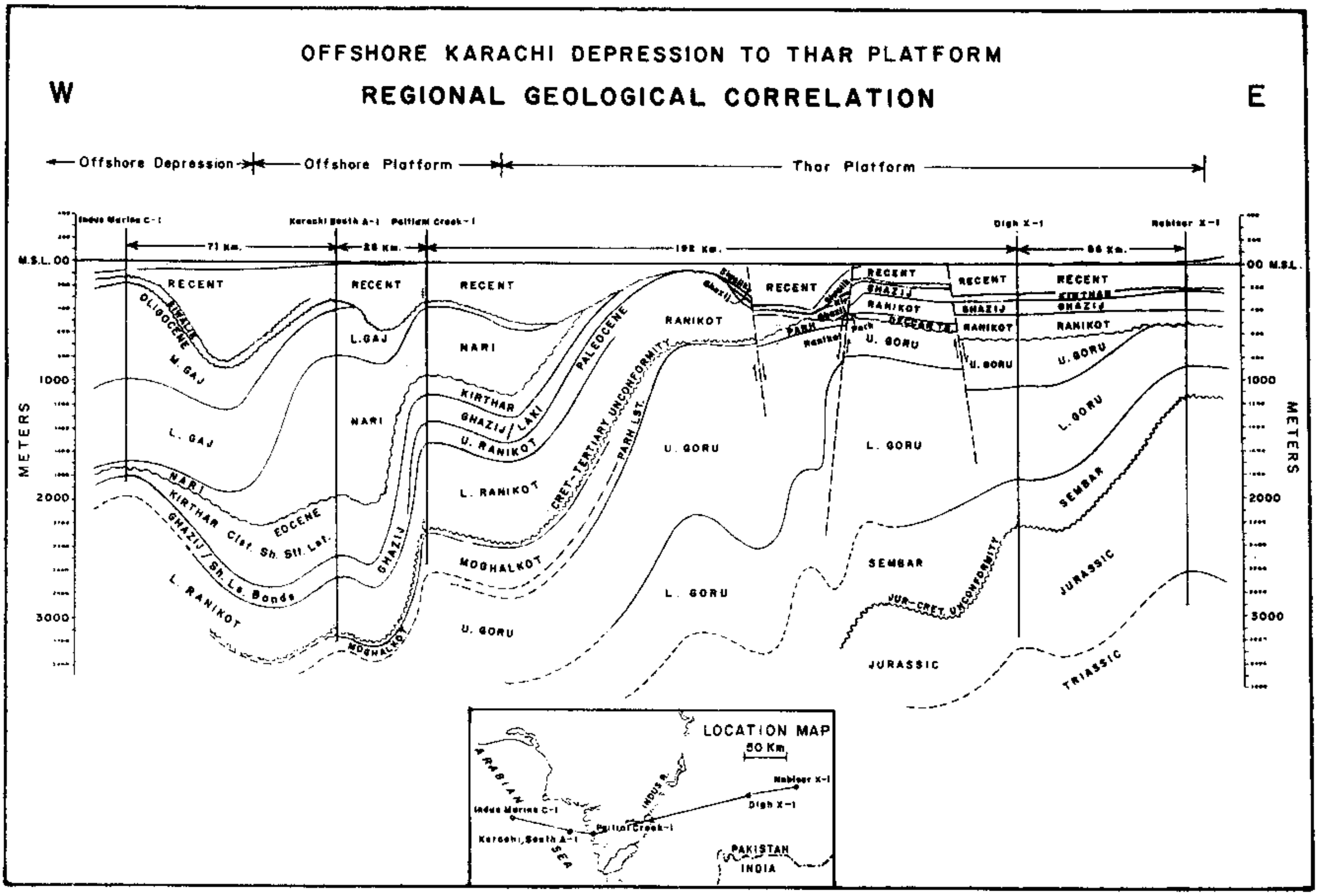

Figure - 4.10 Offshore Karachi Depression to Thar Platform, Regional Geological Correlation graphic and structural variation across the two sub-basins. The Platform marks very good development of Early/Middle Cretaceous Sands (Goru) which are the reservoirs for all the oil/gas fields of Union Texas Pakistan and Oil Gas Development Corporation in this region.

Karachi Trough

It is an embayment opening up into the Arabian Sea. The Trough is characterised by thick Early Cretaceous sediments and also marks the last stages of marine sedimentation. It contains a large number of narrow chain like anticlines, some of which contain gas fields (Sari, Hundi & Kothar). The Early, Middle and Late Cretaceous rocks are well preserved in the area. It has been a trough throughout the geological history. The Upper Cretaceous is marked by westward progradation of a marine delta.

The most interesting feature of Karachi Trough is the reportedly continued deposition across the Cretaceous / Tertiary (K/T) boundary wherein Korara Shales were deposited, the basal part of which represents Danian sediments. This localized phenomenon probably represents a unique example where no hiatus in sedimentation occurred at the end of Cretaceous era. Elsewhere in Pakistan, a break in deposition marked by laterites, bauxites, coal etc. is a common feature across the K/T boundary.

Kirthar Foredeep

Kirthar Foredeep trends north-south which has received the sediments aggregating a thickness of over 15,000 meters It has a faulted eastern boundary with Thar Platform. It is inferred that the sedimentation had been continuous in this depression. However, from the correlation of Mari, Khairpur and Mazarani wells it appears that the Upper Cretaceous would be missing in the area. Paleocene seems to be very well developed in the depression but is missing from Khairpur–Jacobabad High area. This depression, like Sulaiman Depression, is the area of great potential for the maturation of source rocks.

Kirthar Fold Belt

This north-south trending tectonic feature is similar to Sulaiman fold belt in structural style and stratigraphic equivalence. Rocks from Triassic to Recent were deposited in this region. The configuration of the Kirthar fold belt also marks the closing of Oligocene–Miocene seas.

The western part of the Kirthar fold belt adjoining the Balochistan basin, which marks the western edge of the Indus basin, is severely disturbed. This western margin is associated with hydrothermal activities which resulted in the formation of economic mineral deposits of Baryte, Fluorite, Lead, Zinc and Manganese.

Offshore Indus

This area forms the part of passive continental margin and appears to have gone through two distinct phases of geological history (Cretaceous–Eocene and Oligocene-Recent). Sedimentation in offshore Indus region started from Cretaceous time. However, deltaic and submarine fan sedimentation has occurred since middle Oligocene time with the inception of Proto-Indus System.

Offshore Indus is divided into Platform and Depression along a Hinge Line in close proximity and parallel to 67°E Longitude (Fig. 4.11). Offshore Platform is divided into

Karachi Trough and the Thar Platform's deltaic area by a line which divides Karachi Trough from Thar Slope onshore (Fig. 4.11).

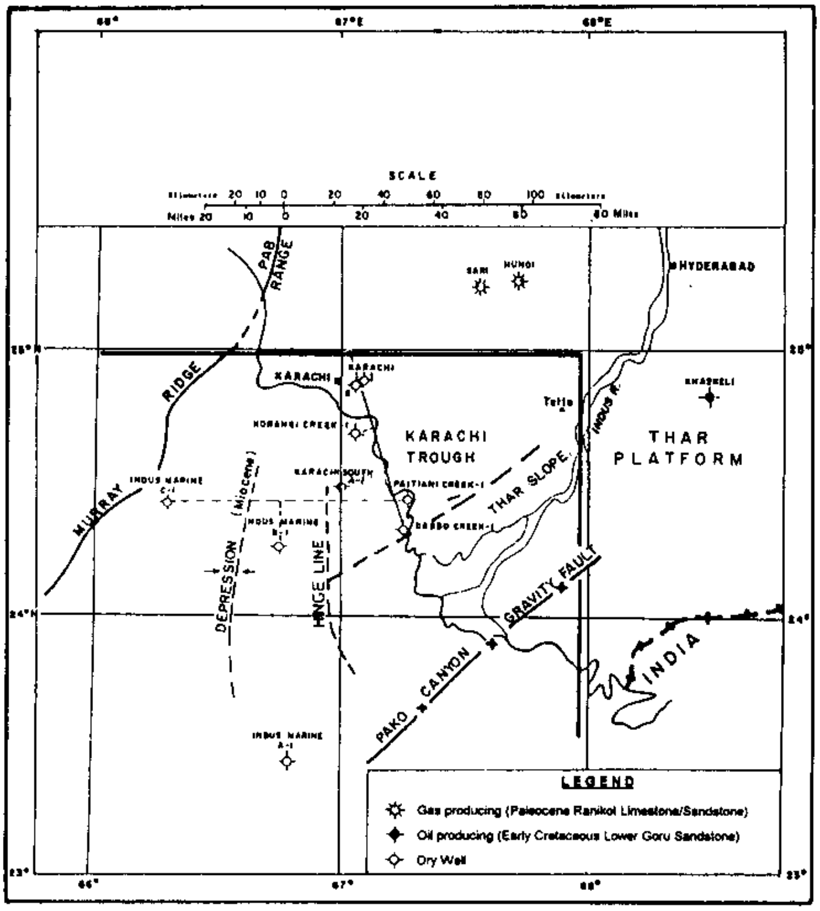

Figure - 4.11 Structural Setting of Southern Indus Basin and offshore area (after Quadri, 1980)

KAKAR KHORASAN BASIN (PISHIN BASIN)

This basin (Fig. 4.1) has been recently recognized as separate entity from Indus and Balochistan basins in that it has evolved through different geological processes and has an independent tectonic style.

The basin is located between Chaman Fault in the north and northwest and obducted ophiolitic margin of Indian Plate in the south. In the north it extends (about 50%) into Afghanistan and is known there as Kundar–Urgun Basin.

This median basin was formed between the leading edges of Indian and Eurasian Plates during the course of their coalescence and the Tertiary sedimentary fill is probably underlain by oceanic crust or very thin continental crust. This is confirmed by the presence of ophiolites at its southern margin and presence of Precambrian basement in the north in Helmund and Kabul blocks.

Since the basin is very young, most of the sedimentary sequence is dominated by younger (Post-Eocene) flysch similar to the corresponding stratigraphic units of Balochistan Basin.

BALOCHISTAN BASIN

In view of its different geological history and tectonic setting the Balochistan Basin (Fig. 4.1), has been dealt in detail in Section-17.

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5

Stratigraphic Nomenclature

The surface stratigraphic units in the area now constituting Pakistan have been studied since the late 19th century, particularly in the northern and central parts of Pakistan. The published records date as far back as 1853 (Flemming), 1864 (T. Oldham), 1878 (Wynne) and 1892 (R. Oldham). After the turn of the century further work was carried out by the then Geological Survey of India: Pinfold (1918), Cox (1930), Gee (1928–1934), Davies and Nuttal (1927–40), Eames (1951-52), Pascoe (1964), Krishnan (1968) and Wadia (1919 and 1975). Subsequently the Geological Survey of Pakistan (GSP) in collaboration with the Government of Canada, under the Colombo Plan and with the United States Geological Survey (USGS) carried out systematic geological mapping in 1953–56 and 1960 respectively.

Other workers and agencies also revised, renamed and adopted different stratigraphic correlations. More than 40 names have been proposed over the years for the various stratigraphic units, only in the Eocene. In some instances various authors and agencies have used same formation names for different geological ages.

Stratigraphic Committee of Pakistan was established in 1960 to standardize the stratigraphic nomenclature of Pakistan. This Committee constituted members from various national and international geological bodies including oil companies.

With the availability of subsurface data (including the offshore area) obtained by various oil companies through geophysical surveys and exploratory drilling, new formations' names have been introduced in the literature, e.g. Sui Main Limestone (Eocene), Sindh Trap (Paleocene) etc.

Practical difficulties and complications arise in the use of surface and subsurface names mainly in the Tertiaries and Mesozoic formations. Nomenclature adopted for this book is based on 'A Guide to the Stratigraphy of Pakistan' Volume 35, published by the Geological Survey of Pakistan (1980). Tables 5.1 through 5.6 illustrate the heterogeneity of nomenclature used by various authors and agencies and its evolution over the years for different basins/regions. Lower Indus Basin, Upper Indus Basin, Balochistan Basin, Axial Belt and the Northern Montane area which falls north of the Main Boundary Thrust (Fig. 3.4) and mainly exposes metamorphic and crystalline rocks.

LOWER INDUS BASIN

AGE	MEDDLICOTT (1864)	WYNNE (1877)	NOETLING (1903)	VREDENBURG (1909)	PILGRIM (1910)	MORRIS (1938)	GEE (1946)	EAMES (1952)	HUNTING (1961)	WILLIAMS (1961)	PASCOE (1963)	IN CURRENT USAGE (1992)
PLEISTOCENE MIOCENE-PLIOCENE	Upper Siwalik Sub-Himalayan System	Dandot SS Red Zone Mari Group			Boulder Conglomerate Tatrot & Pinjor Dhok Pathan Nagri Zone or Nagri Stage Chinji Zone Siwalik System Murree Series	Sheri Ghasha Fm. Marwat Formation Karghocha Fm	Kalabagh Conglomerate	Alternation Beds Chinji	Dada Conglomerate Urak Group) Sibi Group)	Gaj Formation	Estuarine Passage Beds Lower Gaj Upper Gaj	LEI CONGLOMERATE (Gill 1952) SOAN FORMATION DHOK PATHAN FM. (Cotter 1913) NAGRI FORMATION (Lewis 1937) CHINJI FORMATION (Lewis 1937) SIWALIK GROUP KAMLIAL (Cotter, 1913) MURREE FORMATION GAJ FORMATION
OLIGOCENE									Urak Group) Sibi Group)			NARI FORMATION MOMANI GROUP
EOCENE			Kirthar Series Laki Series					Shales with Alabaster Rubbly Limestone Green and Nodular Shales Ghazij Shales Upper Rakhi Gaj Shales	Brahui LS Tiyon Formation Laki Group (Tiyon Formation) Gidar Dhor Group)	Ghazij Formation		KIRTHAR FORMATION LAKI FORMATION GHAZIJ FORMATION (Chat Beds- Nagappa 1959) SML '(TAINSH ET AL 1959)
PALEOCENE				Upper Ranikot Lower Ranikot Upper Ranikot Lower Ranikot				Lower Rakhi Gaj Shales Zinda Pir Limestone Gorge Beds Venericardia Shales	Dab Formation Dungan Group Rattaro Thar Formation Bad Kachu Jakker Group Gidar Dhor Karkh Group Lower Ranikot Fm	Dungan Formation Ranikot Formation Khadro Formation		DUNGHAN FORMATION LAKHRA FORMATION (AHMED & GHANI 1971) BARA FORMATION (Ahmad & Ghani 1971) KHADRO FORMATION RANIKOT GROUP
CRETACEOUS				Limestone with Hemipneustes Hemipneustes Limestone Belemnite Shales				Orbitoides Limestone and Shales	Moro Formation (Dangan & Jamburd Groups) Pab Sandstone Parh Group Parh Series	Somalji Trail Fort Munro LS Member Mughal Kot Fm. Parh Limestone Goru Formation Sembar Formation		MORO FORMATION PAB SANDSTONE FORT MUNRO FM MUGHAL KOT FM PARH LIMESTONE GORU FORMATION SEMBAR FORMATION
JURASSIC				Massive Limestone					Chiltan Limestone Shirinab Fm.	Takatu Limestone Sulaiman LS Group		CHILTAN LIMESTONE SHIRINAB FORMATION

Table - 5.1 Stratigraphic nomenclature adopted by different Authors - Lower Indus Basin

CHART SHOWING ROCK STRATIGRAPHIC CORRELATION AND NOMENCLATURE AS USED BY DIFFERENT OIL COMPANIES FOR LOWER INDUS BASIN

AGE	PAKISTAN PETROLEUM (1952)	PAKSIATN SHELL OIL (1965)		STANDARD-VACUUM (1961)	IN CURRENT USAGE (1992)
		KIRTHAR BASIN	SULAIMAN BASIN		
PLEISTOCENE	Siwalik	Manchar	Siwalik	Siwalik GR	LEI CONGLOMERATE (Gill 1952) SOAN FORMATION
MIOCENE-PLIOCENE	Gaj FM	Gaj FM	Siwalik	Gaj FM	DHOK PATHAN FM. (Cotter 1913) NAGRI FORMATION (Lewis 1937) CHINJI FORMATION (Lewis 1937) KAMLIAL (Cotter 1913) MURREE FORMATION GAJ FORMATION
OLIGOCENE	Nari FM	Nari FM	Nari FM	Nari FM	NARI FORMATION MOMANI GROUP
EOCENE	Kirthar Laki: Sui Upper LS Ghazij Shale Sui Main LS	Kirthar FM Laki FM	Kirthar FM Ghazij FM	Kirthar FM Ghazij FM Dunghan FM	KIRTHAR FORMATION LAKI FORMATION GHAZIJ FORMATION (Chat Beds- Nagappa 1959) SML (Tainsh et al 1959)
PALEOCENE	Ranikot FM Cardita Beaumonti	Ranikot FM Cardita Beaumonti Zone	Dunghan FM Quartzose SS FM	Dunghan FM Ranikot FM	DUNGHAN FORMATION LAKHRA FORMATION BARA FORMATION (Ahmad & Ghani 1971) KHADRO FORMATION
CRETACEOUS	Pab FM Orbitoides Zone Parh FM Belemnite Shale FM	Pab FM Orbitoides Zone Parh FM Belemnite Shale FM	Nishpa FM Parh FM Belemnite Shale FM	Khadro FM Pab SS Ft.Munro Mughal Kot FM Parh LS Goru FM Sembar FM	MORO FORMATION PAB SANDSTONE FORT MUNRO FORMATION MUGHAL KOT FORMATION PARH LS GORU FORMATION SEMBAR FORMATION
JURASSIC Upper Middle Liassic	Jurassic LS	Chiltan FM Mor FM	Chiltan FM	Takatu] Sulaiman Anjira FM } LS. Group Loralai LS] Spingwar FM	CHILTAN LIMESTONE SHIRINAB FORMATION
TRIASSIC		Juner FM		Wulgai FM	

Table - 5.2 Stratigraphic Correlation and nomenclature as used by different Oil Companies for Lower Indus Basin

UPPER INDUS (POTWAR-KOHAT-SUB BASIN)

AGE	WYNNE (1877)	WAAGEN (1891)	MIDDLEMISS (1896)	NOETLING (1903)	PILGRIM (1910)	DAVIES (1930)	GEE (1945)	EAMES (1952)	FATMI & KHAN (1966)	AHMAD & KHAN (1990)	TEICHERT (1966)	HUSSAIN (1967)	PASCOE (1963)	MEISSNER ET AL (1968)	CALKINS & MATIN (1968)	LATIF (1970)	MISCELLANEOUS	IN CURRENT USAGE (1982)
PLEISTOCENE		Kalabagh Beds					Kalabagh Conglomerate										Lei Conglomerate (Gill 1952)	LEI CONGLOMERATE (Gill 1952)
MIOCENE-PLIOCENE					Tatrot & Pinjor Dhok Pathan Nagri Zone or Nagri Stage Chinji Zone Siwalik System Murree Series			Murree/Kamlial Beds Chinji									Sheri Ghasha Fm Morris(1938) Marwat Formation Morris(1938) Karghocha Fm Morris(1938) Kamlial (Cotter, 1913)	SOAN FORMATION DHOK PATHAN FM (Cotter 1913) NAGRI FORMATION (Lewis 1937) CHINJI FORMATION (Lewis 1937) SIWALIK GROUP KAMLIAL FORMATION MURREE FORMATION GAJ FORMATION
EOCENE	Kuldana Beds Hill Limestone Green Clay		Kuldana Series Nummulitic Series			Shekhan LS	Sakesar LS Nammal Limestone Badrar Beds Kohat Series Kohat Saline Series Green Clay & SS	Kohat Shales Nummulitic Shales Kohat Limestone Sirki Shales Lower Chharat Series Gypsiferous Beds Upper Shekhan LS Middle Shekhan LS Lower Shekhan LS Panoba Shales					Chorgali Beds	Mami Khel Clay Jatta Gypsum Bahadur Khel Salt		Kuldana Fm Lora Formation Margala Hill LS	Nammal Marl (Danilchik, 1967) Passage Beds (Pinfold, 1918)	SAKESAR LIMESTONE NAMMAL FORMATION KOHAT FORMATION KULDANA FORMATION CHORGALI FORMATION JATTA GYPSUM MARGALA HILL LS BAHADUR KHEL SALT SHEKHAN FORMATION PANOBA SHALES
PALEOCENE	Hill Limestone	Nummulitic Fm	Nummulitic Series			Patala Shales Lokhart LS Hangue Shale Hangu SS Dhak Pass Beds	Kharabad LS	Tarkhobi Shales Tarkhobi LS		Langrial Iron Ore Horizon						Kuzagali Series Mari Limestone Mari LS	Dhak Pass Fm (Danilchik, 1967)	PATALA FORMATION LOCKHART LS HANGU FM
CRETACEOUS			Giumal SS			Sublithographic LS Main SS Series	Lumshiwal SS		Darsamand LS	Durban LS					Sepu LS	Chanali LS	Kawagarh Marls (Attock Oil)	KAWAGARH FM LUMSHIWAL FM CHICHALI FM
JURASSIC						Samana Suk FM L Samana Beds Samana Beds	Baroch LS Variegated Stage		Shinawari FM						Daulatmar LS	Sikhar LS	Kioto Ls (Cotter 1933) L Part of Kioto Ls " Red Clay Zone (Misc Oil Cos) Datta Formation (Danilchik, 1967)	SAMANA SUK FM SHINAWARI FM DATTA FORMATION
TRIASSIC		Ceratite Beds Bivalve LS Topmost LS & Dolomite Beds					Kingriali Dolomite Tredian FM Kingriali SS Mianwali Series		Chak Jabbi LS Kala Chitta LS Bagh LS								Kioto Ls (Cotter 1933)	CHAK JABBI LS KINGRIALI FM TREDIAN FM MIANWALI FM (KUMMEL, 1966)
PERMIAN	Lavender Clays Olive Series Eurydesma Beds Conularia Beds	Chhidru Beds Middle Productus LS Amb SS Beds Middle Speckled SS Speckled SS		Chhidru Group Productus LS The Wargal Group U part of Warchha Group Warchha Group Lavender Clays Dandot Group			Sardhai FM Speckled SS Talchir Boulder Bed or Talchir Stage Nilawahan Series				Wargal LS Amb Formation Zaluch Group Salt Range Boulder Beds	Warchha SS	Lavender Clay Stage					ZALUCH GROUP CHHIDRU FM WARGAL FM AMB FM NILAWAHAN GROUP SARDHAI FM WARCHHA SS DANDOT FM TOBRA FM
ORDOVICIAN TO CARBONIFEROUS										A B S E N T								
CAMBRIAN	Pseudomorph Salt Crystal Zone Obolus Beds or Siphonotreta Beds Purple SS Series	Neobolus Beds		Bhaganwala Group Jutana Stage Kussak Group Khewra Group			Gypsiferous Series					Khisor Gypsiferous Beds	Baghanwala Stage				Salt Pseudomorph Shales (Holland, 1936) Magnesian SS (Fleming, 1859)	KHISOR FORMATION BAGHANWALA FM JUTANA FORMATION KUSSAK FORMATION KHEWRA SANDSTONE
PRE-CAMBRIAN	Saline Series						Punjab Saline Series										Khewra Trap (Khewraite)	SALT RANGE FM (Asrarullah 1967)

Table - 5.3 Stratigraphic nomenclature adopted by different Authors - Upper Indus Basin

BALOCHISTAN BASIN

AGE	BLANFORD (1872)	VREDENBURG (1901)	AHMED (1951)	CROOKSHANK & HERON (1955)	HUNTING (1961)	ASRARULLAH (1967)	IN CURRENT USAGE (1992)
PLEISTOCENE		Gwadar Stage		Sub-Recent Shelly Limestone	Kamerod FM Kech Conglomerate Haro Conglomerate Jiwani FM Ormara FM		BOSTAN FM HARO CONGLOMERATE JIWANI FM GWADAR FM
MIOCENE		Hinglaj Series			Hinglaj Group Diz Formation Talar SS Greshak Group Parkini MS Chatti MS	Sandstone Stage Lower Mudstone Stage	HINGLAJ FM
OLIGOCENE	Makran Series	Khojak Shales and Flysch Makran System Hinglaj Series) Gwadar Stage) Talar Stage)			Nauroz FM Turbat Group Dalbandian Assemble Amalaf FM		KHOJAK FM MAKRAN GROUP AMALAF FM
EOCENE		Kirthar Stage	Eriklag LS		Kharan LS) Robat LS) Pishi Group) Washap FM)		KHARAN FM SAINDAK FM
PALEOCENE		Cardita beaumonti beds Volcanic Flysch Ranikot FM	Bunap FM		Ispikan Conglomerate Juzzak FM Gidar Dhor Group		ISPIKAN CONGLOMERATE RAKHSHANI FM
CRETACEOUS		Hippuritic LS			Humai FM Kuchakki Volcanic Group		HUMAI FM SINJRANI VOLCANIC GROUP

Table - 5.4 Straigraphic nomenclature adopted by different Authors - Balochistan Basin

AXIAL BELT

AGE	BLANFORD (1872)	WYNNE (1877)	VREDENBURG (1901, 1904, 1906, 1909)	AHMED (1951)	HUNTING (1961)	WILLIAMS (1959)	CALKINS ET AL (1968)	STAUFFER (1968)	LATIF (1970)	TAHIRKHELI (1970)	IN CURRENT USAGE (1982)
MIOCENE-PLIOCENE			Hinglaj Series		Hinglaj Group) Diz Formation) Talar Sandstone) Greshak Group) Parkini Mudstone) Chatti Mudstone						HINGLAJ FORMATION
OLIGOCENE	Makran Series		Khojak FM) Flysch) Nauroz FM Turbat Group Pishi Group Dalbandian Assemblage Makran System Hinglaj Series) Gwadar Stage) Talar Stage) Cretaceous-Eocene Flysch		Amalaf FM						KHOJAK FM MAKRAN GROUP AMALAF FM
EOCENE	Eocene LS) L.Kirthar Shales)		Black Nummulitic LS Ghazaband LS L.Kirthar Shales Upper Kirthar Massive LS Spintangi LS Nari Khojak Series		Nisai Group Nimargh LS Wad LS Wakabi LS Wakai LS Khude LS Kasria Group Upper parts: Jakkar & Jamburo Groups						NISAI FM
PALEOCENE			Cardita beaumonti beds Volcanic Flysch Ranikot FM Siwalik Group	Bunap FM	Ispikan Conglomerate Rakhshani FM Juzzak FM) Gidar Dhor Group) Pishi Group						ISPIKAN CONGLOMERATE RAKHSHANI FM
CRETACEOUS					Bela Volcanic Group						BELA VOLCANIC GROUP
TRIASSIC					Alozai Group Shirinab FM Windar Group	Wulgai FM					WULGAI FM
PERMIAN			Permian of Balochistan								PERMIAN OF BALOCHISTAN
CARBONIFEROUS-PERMIAN								Khyber LS		Shakhai FM	SHAKHAI FM KHYBER LS
SILURIAN-DEVONIAN								Ali Masjid FM Shagai FM Misri Banda Quartzite Nowshera FM Kandar Phyllite	L.Carboniferous Rocks near Nowshera		ALI MASJID FM SHAGAI FM PIR SABAK FM MISRI BANDA QUARTZITE NOWSHERA FM KANDAR PHYLLITE
ORDOVICIAN-SILURIAN		Attock Slate						Attock Slates Khyber Slates Landikotal Slates		Khattak LS Manki Slate Shahkotbala FM	ATTOCK FM LANDIKOTAL FM
CAMBRIAN		Below the Trias Tanol Group					Abbottabad FM Tanawal FM		Abbottabad Group		ABBOTTABAD FM TANAWAL FM
PRE-CAMBRIAN		Attock Slates					Tanawal FM		Hazara Group		HAZARA FM

Table - 5.5 Stratigraphic nomenclature adopted by different Authors - Axial Belt

NORTHERN MONTANE AREA (North of the Main Boundary Thrust)

AGE	LYDEKKER (1878)	MIDDLEMISS (1910)	HAYDEN (1915)	WADIA (1931)	SCHIEFER (1957)	SCHNEIDER (1957)	IVANAC, ET AL (1951)
CARBONIFEROUS-PERMIAN	Panjal System	Volcanic Greenstone and Agglomerate Slate	Sarikol Slate	Panjal Volcanic Series	Chalt Schiefer-series	Pasu Slate	Darkot Group Chalt Schist & Greenstone Complex Darkot Group
SILURIAN-DEVONIAN							
CAMBRIAN							
PRE-CAMBRIAN				Salkhala Series			

AGE	PASCOE (1959)	CALKINS ET AL (1969)	STAUFFER (1968)	OFFIELD & ABDULLA (1969)	IN CURRENT USAGE (1992)
CARBONIFEROUS-PERMIAN			Baltit Group Chalt Schist		PANJAL FM & AGGLOMERATE SLATE PASU SLATE BALTIT GROUP CHALT SCHIST SARIKOL SLATE
SILURIAN-DEVONIAN	Devonian of Chitral				DEVONIAN OF CHITRAL
CAMBRIAN					CAMBRIAN SYSTEM OF THE NORTHEAST
PRE-CAMBRIAN				Salkhala FM	SALKHALA FM

5.6 Stratigraphic nomenclature adopted by different Authors - Northern Montane Area

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6

Precambrian

The oldest rocks in Pakistan are of Precambrian age, which form the basement for the lower Paleozoic sediments and in certain cases serve as the source of terrigenous clastics for the younger rocks in adjoining areas.

The Precambrian rocks exposed in Pakistan can be genetically divided into three main groups.

1. Isolated granitic outcrops piercing out of the sedimentary cover are believed to be parts of the Indian Shield; these are Nagar Parkar granite exposures in southeastern Sindh and Kirana Hills in the Punjab Plains.

   The exposure in the south, near Nagar Parkar, is granite with intrusion of basic igneous rocks. The pink granite is mainly composed of coarse grained orthoclase and quartz with few dark minerals.

   The exposure in the north, near Sargodha in the Kirana Hills, is predominantly composed of grey slate, red and grey quartzite with minor amount of conglomerates. The absolute age for the Kirana group is estimated to be 870 $\pm$40 million years which is late Precambrian.

   Sargodha High is defined by exposed basement rocks of the Kirana Hills and by a series of positive gravity anomalies. There are three basic interpretations for the Sargodha High:

   a) it is caused by flexure due to the Tertiary underthrusting of the Indian Plate beneath Eurasia (Yeats & Lawrence, 1984),
   b) it is an older basement feature similar to Aravalli Range of India (Farah et al 1977), and
   c) it is an expression of a recently activated intracontinental thrust (Le Fort, 1975).

2. Metamorphic rocks/metamorphosed sediments are exposed in and around Hazara, Kashmir and further north. The southern limit of these sediments (Hazara Formation) is somewhere around Attock and Peshawar Basin where they are mainly composed of slate and phyllite with minor occurrence of limestones and graphite layers. Some thick bedded fine-medium grained sandstone is also present. Gypsum is also present in south-

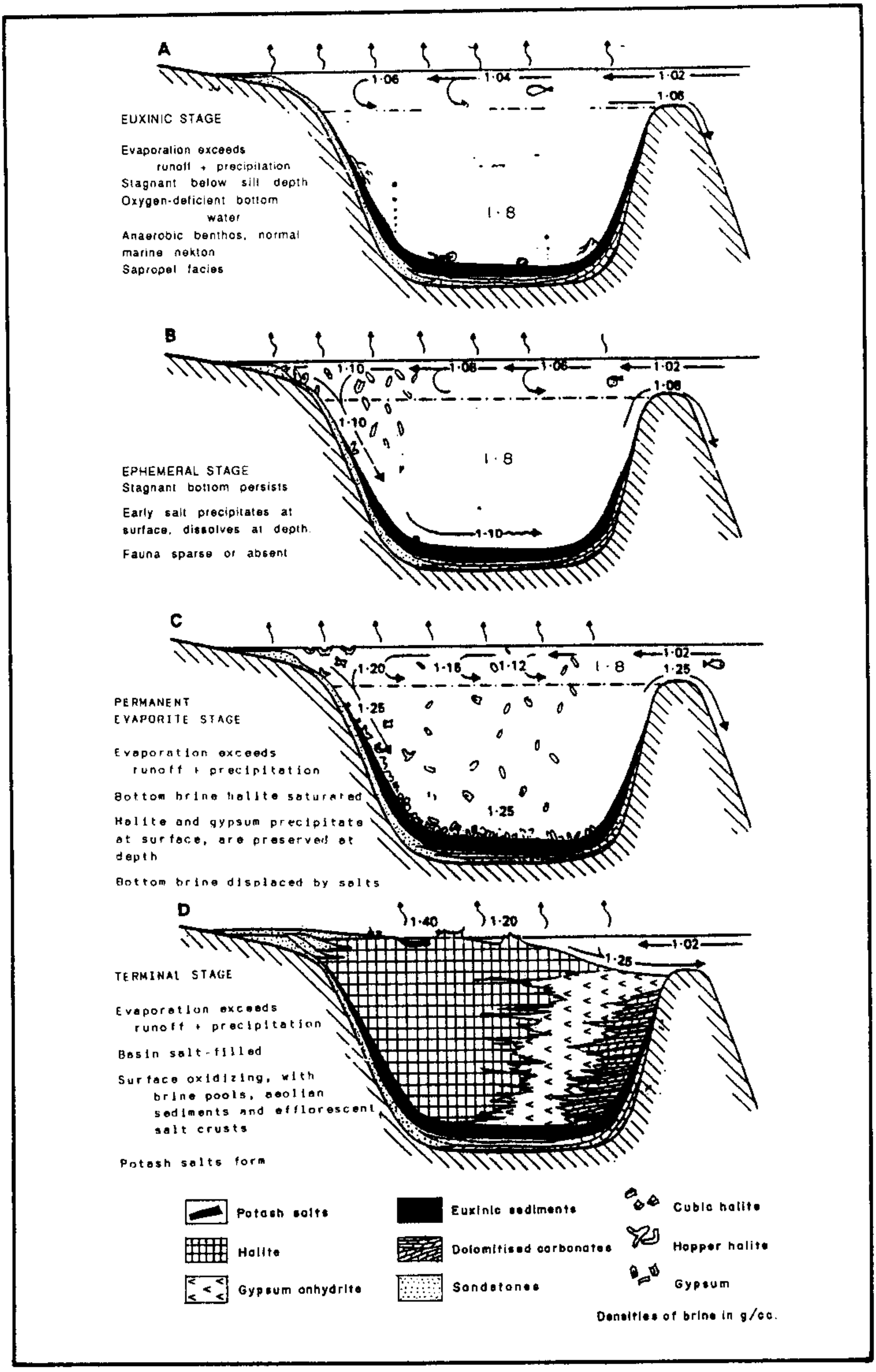

Figure - 6.1 A Depositional Model for the Saline Series (after Schmalz, 1969) ernmost Hazara and Azad Kashmir. The age is determined between 765 ± 20 and 950 ±20 million years.

In the north-eastern part of Pakistan, Salkhala Formation has been described as Precambrian. The formation extends from Kashmir to the Karakoram Range. The formation is mainly slates with prominent graphite beds interbedded with marble and also includes quartzite, garnet-biotite-quartz schist and talc schist at various places. The thickness varies from 1,800 meters to 3,000 meters in the Kashmir area.

3. Evaporitic sediments known as 'Salt Range Formation' are composed mainly of salt (Halite), gypsum, anhydrite, dolomite with intercalation of shales. Depositional model for this sequence is shown in Fig. 6.1. This is the only formation in the Precambrian which bears some petroleum potential; hence it has been treated in more detail in the succeeding paragraphs. The extension of the formation further south beneath Sulaiman Range is yet to be confirmed by deep drilling to the basement. Some authors (Gorin et al, 1982) believe that the Salt Range Formation is of limited extent and is only confined to the Upper and Central Indus basins. This hypothesis is acceptable since thinning of the formation is observed southwards in all exploratory wells drilled in eastern part of Central Indus Basin. The formation is correlatable chronologically and lithologically to the Hormuz series and Huqf Group of Iran.

SALT RANGE FORMATION (SALINE SERIES)

Regional Distribution

The formation is exposed along the outer periphery of the Salt Range from Kalabagh in the west to the eastern Salt Range. Both Precambrian and Cambrian ages have been assigned to the Salt Range Formation on the basis of superposition as there is no definite paleontological evidence available. However, its age is referred to as Eocambrian by recent authors. In the subsurface the Salt Range Formation has been encountered in Potwar (Dhulian, Adhi). Gypsiferous deposits of possible Eocambrian age, in the Hazara district north of Main Boundary Thrust (MBT), indicate that the original evaporite basin may also have extended substantially further north. Towards south its occurrence is not yet proved due to comparatively thicker overlying sedimentary cover. However, recent studies indicate possibility of a salt decollement surface overlain by Sulaiman Range and further south by Kirthar Range. This inference is based on the unique structural style and arrangement of lobes and orocline in aforesaid ranges (low surface slope, large width of the fold-and-thrust belt and the gentle folding at the front of the Sulaiman Lobe and Karachi Arc). However, no definite conclusions can be drawn regarding the presence of the evaporites in the Sulaiman and Kirthar ranges, unless more direct evidence is available.

In the Punjab plains the Salt Range Formation extends to at least 29° N latitude, south of Sargodha High, as confirmed by its thin occurrence in some exploratory wells. Fig. 6.2 is a cumulative isopach map of this formation.

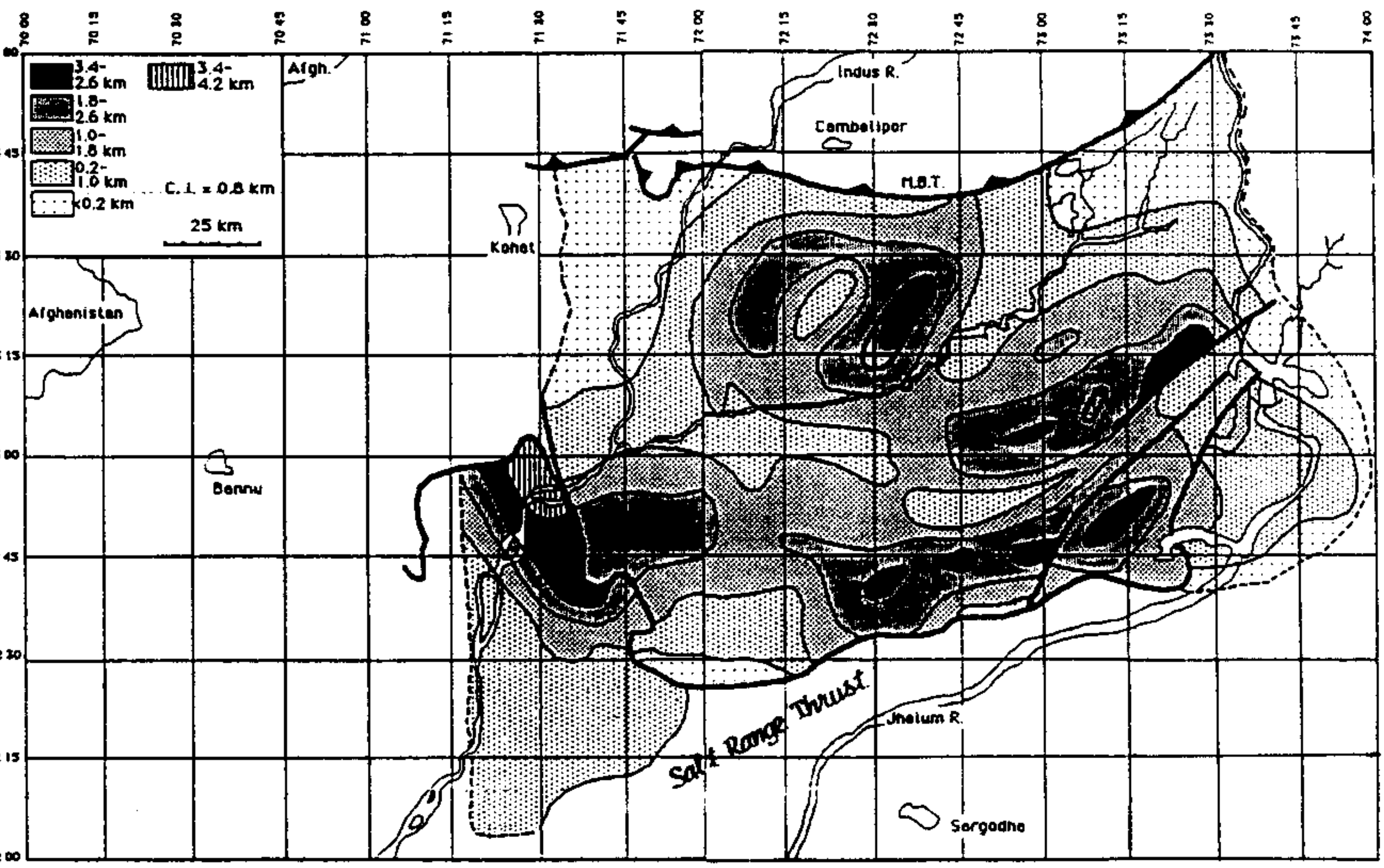

Figure - 6.2 Cumulative thickness isopach of Eocambrian Salt Range Fm (SRF). This shows the total thickness of the formation above basement, and the limits (dashed lines) assumed in determining average thickness of this formation over the area. Thickness of SRF in front of the Salt Range is thin, and was not included in the calculation due to its small contribution. (After Leathers, 1987)

Regionally, the Hormuz evaporites sequence that lies at the base of Zagros Fold Belt is coeval and was possibly once connected laterally to the Pakistan deposits (Ala, 1974; Jackson et al, 1980). Similarly, the large Siberian evaporite basin is a temporal equivalent to the Pakistan basin (Zarkov, 1981).

The Salt Range Formation (or Saline Series) consists of largely a mass of unstratified halite in areas north of the Sargodha High with thin dolomite beds, capped by gypsum and anhydrite. South of the Sargodha High the Salt Range Formation consists of largely dolomite with lesser thickness of halite, anhydrite and gypsum.

Stratigraphic division of Salt Range Formation in Khewra Gorge is as follows:

STRATIGRAPHY

Sahwal Marl Member (oldest member)

1. Dull red marl beds with some salt seams and 10 meters thick gypsum bed on top; (more than 40 meters).
2. Bright red marl beds with irregular gypsum, dolomite beds and 'Khewra Trap'; (3-100 meters).

Bandar Kas Gypsum Member

Massive gypsum with minor beds of dolomite and clay; (more than 80 meters).

Billanwala Salt Member

Ferruginous red marl with thick seams of salt; (more than 650 meters).

CONTACT

The base of the Salt Range Formation is known from wells (Karampur, Bahawalpur East, Warnali, Lilla and Marot) drilled by Shell in Salt Range and Punjab Platform. In Karampur Well the formation is overlying metamorphic rocks of probable Precambrian age. The contact on ditch samples can be recognised with change from sedimentary rocks (anhydrite) to metamorphic rocks. On electric logs there is a marked shift in SP and increase in resistivity values.

The upper contact with the Khewra Sandstone appears to be transitional. Shift in the resistivity values is observed as the Khewra Sandstone has lower resistivity than the Salt Range Formation.

DECOLLEMENT

One of the most important features of Salt Range Formation is its behaviour as a zone of decollement between underlying rigid basement and overlying platform sequence.

The entire sedimentary sequence has been carried southward by a shallow-dipping thrust along this decollement (Fig. 6.3). Salt Range itself is the surface topographic expression of this great thrust sheet riding up and over a basement normal fault. Crustal shortening of as much as 24 Km have occurred in the Eastern Salt Range/ Potwar Plateau since 5.5 Ma.

Thickness of the salt also plays an important role in the amount of internal deformation. In Eastern Salt Range/Potwar Plateau the salt wedge locally thins (Fig. 6.2), thus influencing the internal deformation.

THICKNESS

The thickness of the formation at the type surface section in the Khewra Gorge is more than 825 meters. In the subsurface, (Dhariala well) maximum thickness encountered is about 2,100 meters.

LITHOLOGY

The formation exhibits varied lithology, dominantly composed of reddish brown to maroon gypseous marl. Interbedded with thin layers of gypsum, dolomite, clay, salt marl and thick seams of rock salt. Thin intercalation of kerogen shales, or oil shales, have been found in the Salt Range Formation. They consist of thin bedded dark grey to black papery shales with minor siltstones and dolomites. These shales are rich in organic matter and have a faint kerosene odour when freshly broken. Dolomites are generally light grey, flaggy and cherty.
The thickness of the rock salt beds is up to 600 meters; gypsum beds are up to 46 meters thick and are white to light grey and massive. A trachy basalt trap, called the 'Khewra Trap' or 'Khewrite' is present in some localities, consisting of decomposed radiating needles of a light colour mineral, probably pyroxene.

SOURCE AND RESERVOIR ROCK CHARACTERISTICS

Numerous hydrocarbon shows have been observed in cores and ditch samples of wells drilled in the Salt Range Formation (Dhariala, Kallar Kahar, Karampur). However, the oil is very heavy and viscous and

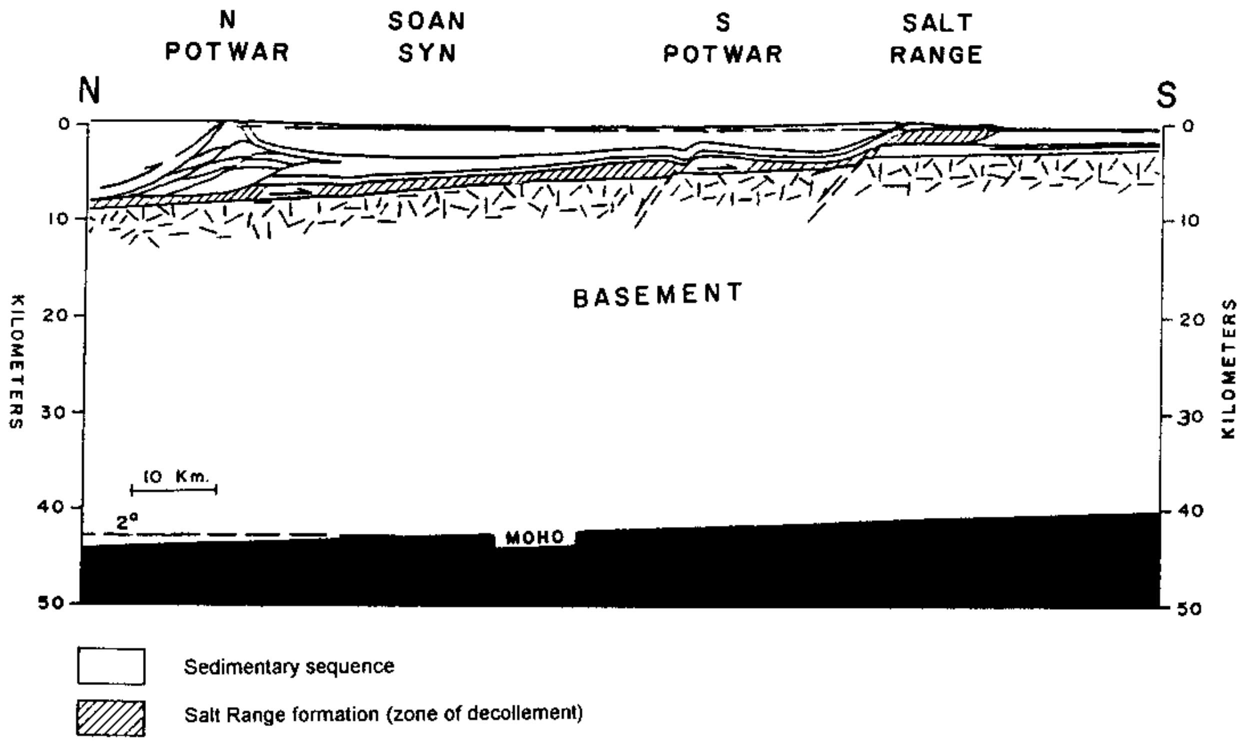

Figure - 6.3 Southward thrusting of sedimentary sequence over the gently northward dipping basement. Ramping is provided by down to north normal faults in basement.

not considered commercial. Heavy asphaltic oil and bituminous material were also encountered in fractured anhydrite and dolomite beds in the formation.

The oil shales of the formation, associated with the upper dolomites, are rich in organic matter; freshly broken surface of these shales have faint kerosene odour. These shales are considered as a potential hydrocarbon source. The best quality occurs in the top most part of the formation in Eastern Salt Range, with total organic carbon (TOC) value of about 30% and oil yields of more than 20%. Silled and reducing basin conditions favourable for generation of oil were locally present at that time. The gas-condensate in the Cambrian in Adhi Field support the generation of some of the components of hydrocarbons from the Precambrian source.

Fractured dolomite in the formation can form a suitable reservoir in the right setting with a cap or seal to prevent migration. Possibility of entrapment of hydrocarbons in the overlying formations also exists, provided the hydrocarbons have not been destroyed during the hiatus of Ordovician to Carboniferous times. This hiatus is represented by a major unconformity in Pakistan.

Seismic Characteristics

Although the seismic coverage is somewhat sparse, reflection seismic surveys have indicated that the Salt Range Formation may be present in both the Kirthar and Sulaiman Foredeeps. Depending on the Salt tectonics the characteristics of the reflections vary considerably.

Drilling Characteristics

Only at some locations of the Punjab

Plain (in the foothills of the Salt Range) and the Kohat-Potwar Depression some wells have been drilled into the Precambrian.

The main drilling problems are commonly associated with the evaporite sequence, and are enlarged hole size, high mud viscosity etc.

Contact between the siltstone in basal Khewra Formation and the Salt Range Formation is recognizable by the reduction in the rate of penetration in the latter formation. Bouncing of the bit is also experienced due to alternation of hard and soft beds. There is a distinct rise in the salinity of mud when the Salt Range Formation is penetrated, requiring continuous treatment of mud with additives.

In the Punjab Plains no high formation pressures have been encountered while drilling the Salt Range Formation. Normally mud weight of 1.55 - 1.65 sp. gr. is required for drilling the formation. Partial losses of circulation have also been observed and can be cured with conventional loss of circulation material (LCM).

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7
Cambrian

REGIONAL DISTRIBUTION

Rocks of Cambrian age, collectively known as Jhelum Group, are extensively exposed along the southern boundaries of Kohat - Potwar Basin in the Salt and Khisor ranges forming arcuate belts. Cambrian rocks were encountered in subsurface in Potwar in several wells, (Dhariala-POL, 1952, Adhi-PPL, 1978) and presumably extend up to Kala Chitta area. The rocks are present around the periphery of the Precambrian exposures of Kirana Hills. Cambrian sediments are expected to underlie most of Punjab Plain east of River Indus and south-eastwards beyond the latitude of Karampur well. There is every likelihood that Cambrian rocks are present in the Sulaiman Basin to the west of River Indus. On the basis of surface and subsurface evidence Cambrian sediments are considered to occupy a total area of about 250,000 sq. km. (Fig. 7.1).

TECTONICS AND DEPOSITIONAL SETTINGS

During Cambrian time a warm shallow marine (shelf) environment existed. This is based on the position and setting of Greater India during that time. Evidence indicates that Greater India was situated adjacent to Australia and Antarctica and widely separated from Iran, Afghanistan, Tibet and other microcontinents to which it is joined now.

Cambrian strata exposed in Trans-Indus and Potwar indicate lagoonal to restricted marine conditions. Deposition of shallow water clastics and evaporites took place in the lagoonal areas and marine limestone in the shelf areas.

CONTACTS AND UNCONFORMITIES

Continuous sedimentation, except a minor hiatus at top Khewra Sandstone typically marked by a well rounded/sorted quartz gravel bed, has been documented throughout the Cambrian and there is no major evidence of tectonic activities. The Jhelum Group represents different cycles of sedimentation beginning with mixed non-marine and marine sandstone and ending with the lagoonal Baghanwala/Khisor Formation (Fig. 7.2).

The Jhelum Group is conformably underlain by the Salt Range Formation of probable Precambrian age. It has an unconformable contact with the overlying Tobra Formation (Permian). However, top Cambrian marks a widespread unconformity with different formations of the Jhelum

CAMBRIAN DISTRIBUTION

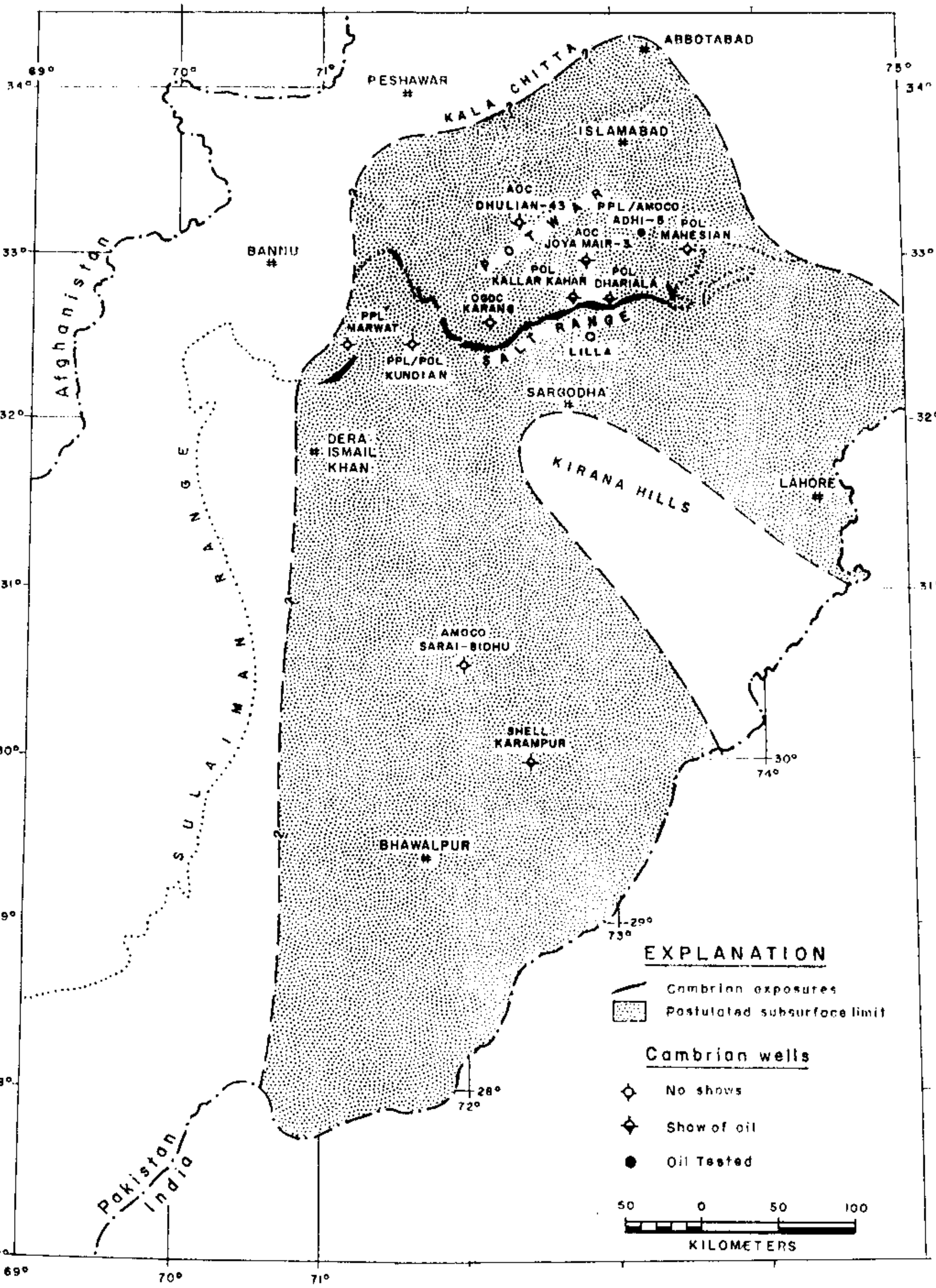

Figure - 7.1 Cambrian Distribution

Group underlying the Nilawahan Group of Permian age in different localities/stratigraphic positions (Fig. 9.4). The significant lithological change preceding and following the Cambrian make the upper and lower contacts very easy to recognize, both in field and on wireline logs. Early Permian sediments mark the onset of fluvio-glacial to glacio- marine/lacustrine conditions which gave rise to laminitic/diamictitic facies of

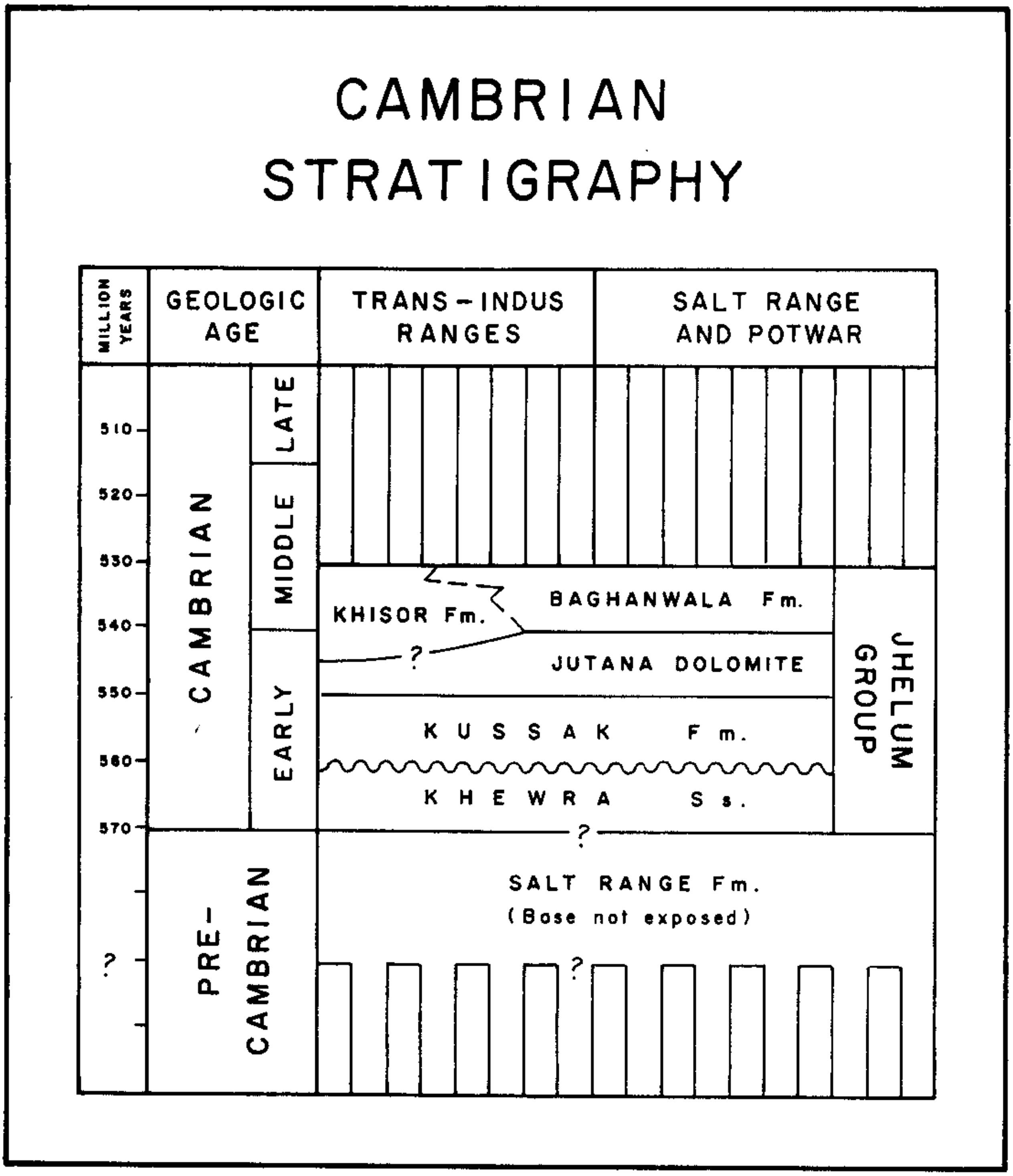

Figure - 7.2 Cambrian Stratigraphy

the Tobra Formation. Base Permian is very easy to pick on Density-Neutron logs. This widespread unconformity can also be seen clearly on dipmeter logs. The typical response of Salt Range Formation is low resistivity across the salt and is also reflected on the Density Neutron logs.

Since Khewra, Kussak, Jutana, and Baghanwala or Khisor formations also represent different cycles of sedimentation, their contacts can also be resolved on modern suites of logs by careful observation.

LITHOSTRATIGRAPHIC DIVISIONS

In Upper Indus Basin the Cambrian is collectively known as Jhelum Group and is represented by following formations.

Jhelum Group

Khisor Formation (Khisor Range)	Middle Cambrian
Baghanwala Formation (Salt Range)	Middle Cambrian
Jutana Formation	Early to Middle Cambrian
Kussak Formation	Early Cambrian
Khewra Formation	Early Cambrian

Some authors include upper part of Salt Range Formation in Early Cambrian based on faunal evidence. But the faunas are probably not in-situ and may have been transported from the overlying Cambrian formations.

Fig. 7.3 shows the stratigraphic succession of the Jhelum Group as exposed in the Khewra-Dandot area of the Eastern Salt Range. Fig. 7.4 is an isopach and distribution map of the Jhelum Group in the Upper Indus Basin. The individual formations of the Jhelum Group are described below in more detail.

Khewra Sandstone

The Khewra Sandstone (formerly known as Purple Sandstone) is a distinct lithological unit exposed in the Salt Range and encountered in various wells in Potwar area and in the Punjab Plain. It probably extends to the Kohat area also and its stratigraphic equivalents could be seen in Abbotabad area with similar lithological characteristics.

The thickness at the type locality in the Eastern Salt Range is about 150 meters; it varies from 200 meters in Western Salt Range to about 70 meters in Khisor Range. On the basis of subsurface data it appears that thickness decreases southward. The lower contact of Khewra Sandstone with the Salt Range Formation can be easily recognized on ditch samples and on electric logs because of change in lithology from interbedded siltstone and argillaceous sandstone to anhydrite/gypsum of the Salt Range Formation.

The upper contact with the Kussak Formation is disconformable in most of the sections exposed in the Salt Range and is marked by a thin conglomerate band. In the subsurface, the lithology changes from brown or purple, well sorted sandstones of Khewra to greenish grey, highly micaceous shales, intercalating thin siltstone/sandstone of the Kussak Formation. This can be easily recognized by change in character on electric logs across the contact.

The Khewra Sandstone can be divided into three units. The lower unit, often called the 'maroon shale group', consists of thin bedded, dark red to purple, argillaceous siltstone, with intercalations of dark purple shales. Occasionally argillaceous sandstones are present. The middle unit is a thin bedded to flaggy, purple to brick red sandstone.

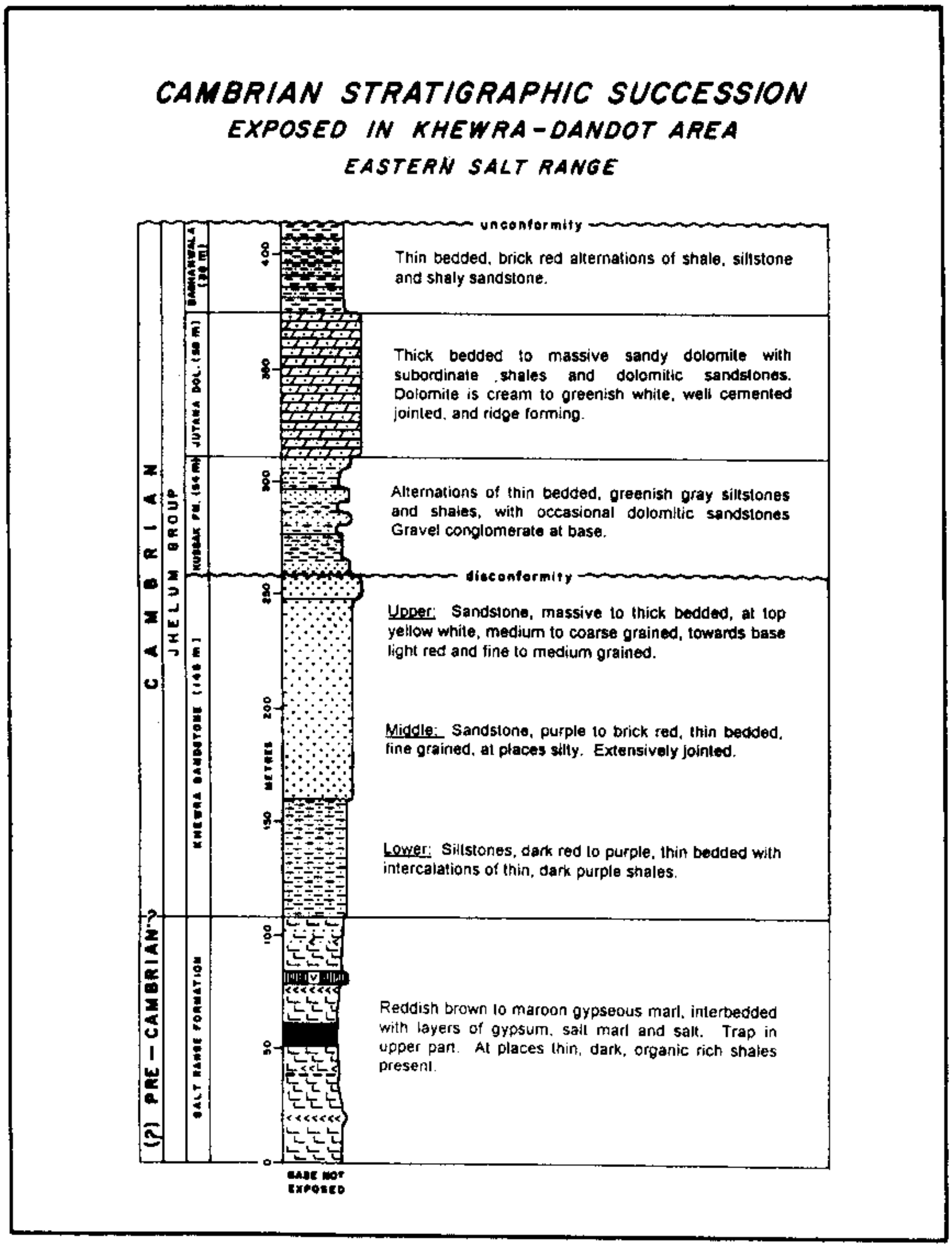

Figure - 7.3 Cambrian Stratigraphic Succession Exposed in Khewra - Dandot Area

It is generally micaceous, fine grained and silty at the base; the grain size increases towards the top. The upper unit consists of light red to yellowish white sandstone which is medium hard to friable. It gets coarser towards the top.

The formation was probably deposited in an arid continental environment, possibly under varying near-shore to aeolian conditions as can be seen from frequency of cross laminations, ripple marks, sun cracks and such surface marks as rain drop prints, worm burrows and fucoid impressions.

Kussak Formation

The formation is widely distributed throughout the Salt and Khisor ranges. In the subsurface the formation is recognized in the Potwar area and in the Punjab Plain up to at least 30° N latitude.

The thickness of the formation is variable; at the type locality in the Eastern Salt Range it is about 70 meters thick and thins in the northwest toward Adhi area. Further northward it is truncated and the Khewra directly underlies the Permian unconformity. Thickest deposits are found in the Punjab Plain where thickness of more than 200 meters is recorded in wells.

The contact of Kussak Formation with the underlying Khewra Sandstone is disconformable. A thin well-marked yellowish white quartzite conglomerate bed is present

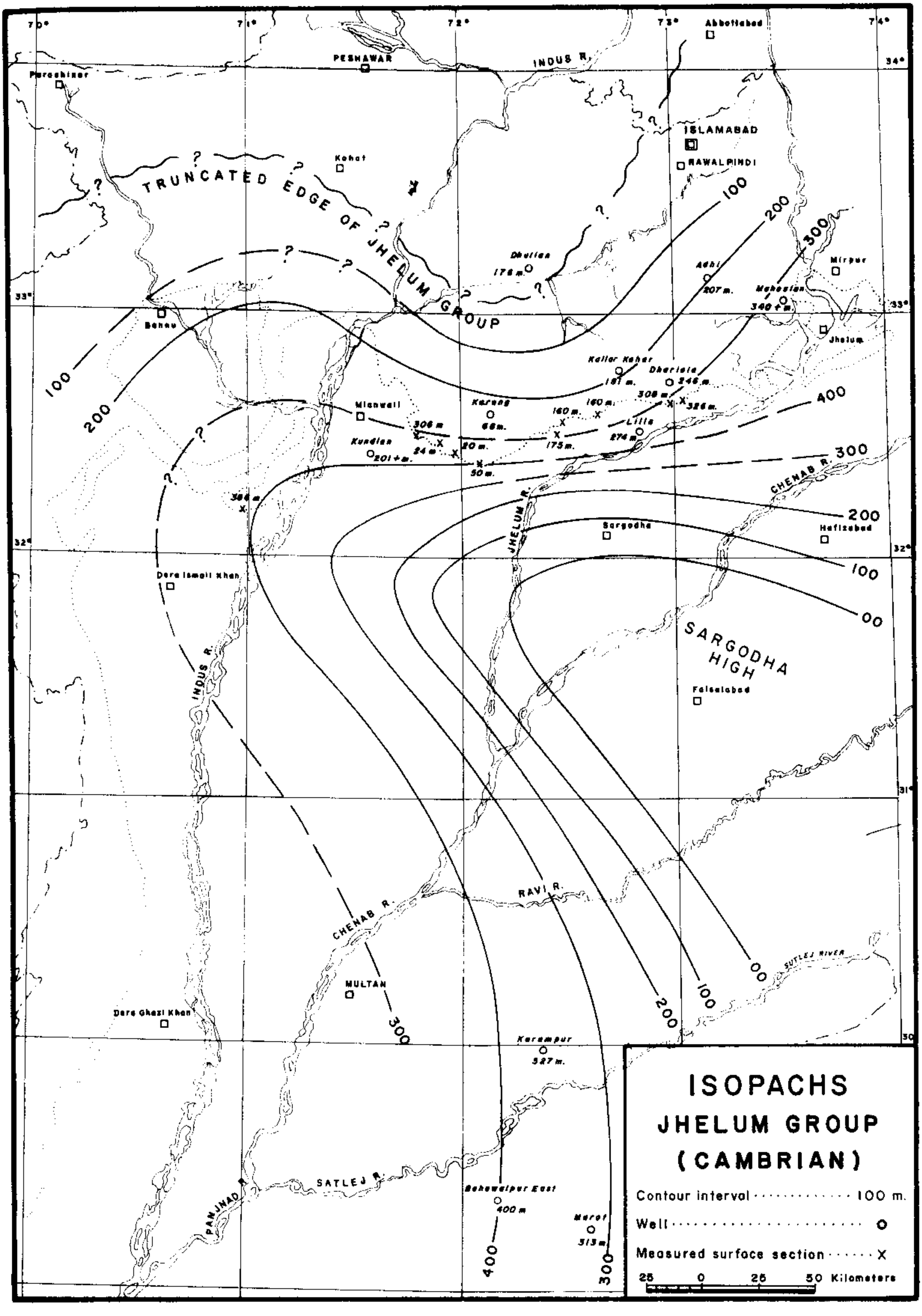

Figure - 7.4 Isopachs,Jhelum Group (Cambrian) at the base of the Kussak Formation.

The white conglomerate consists of granule to sand sized clasts. Sorting is fair-good and seems to be a result of a high energy environment of deposition.

The Kussak Formation is conformably overlain by the Jutana Formation, which is a sandy dolomite. This change in lithology can be easily recognised on Gamma Ray logs.

The formation consists of interbedded silty shales and quartzose sandstone with some sandy dolomite. The shales are greenish grey, non calcareous, silty and micaceous. The sandstones are dirty white to greenish grey, dolomitic, glauconitic and highly micaceous. The dolomites are creamy white to light brown, argillaceous, glauconitic, micaceous, and ferrugenous with rare bituminous coatings. However, in the lower part the shales are black to dark grey. The gritty sandstone bands occur towards the base; the sand is brownish grey, medium hard to friable and coarse grained.

Jutana Formation

The formation is exposed in the Eastern Salt Range area but is absent in the Western Salt Range. It is present in subsurface in the Potwar area (Adhi, Kallar Kahar and Dhariala), but is absent in the Mahesian and Joya Mair wells.

Thickness at the type locality in the Eastern Salt Range is about 75 meters; this is the maximum recorded thickness. It thins toward west to 45 meters in the Khisor Range. Thinning is pronounced toward south, where the wells show very thin deposits of Jutana Formation in the Punjab Plain.

The lower contact with the Kussak Formation is conformable and distinct. The upper contact with the overlying Baghanwala Formation is also conformable. It can be recognized on electric logs by the lower resistivity and higher SP values as compared to the overlying Baghanwala Formation. In areas where the Tobra Formation unconformably overlies the Jutana, the contact is strictly marked with a change from sandy dolomite to conglomerate.

The Jutana Formation is mainly dolomite, with interbedded shales and sandstone. The dolomites are dirty white, light green, hard, micaceous, sandy, pisolitic and glauconitic toward the base. The sandstones are whitish grey, fine grained, well sorted, dolomitic, silty and glauconitic. The shales are greenish grey, glauconitic and highly micaceous, occasionally ferrugenous and thinly bedded.

The formation was probably deposited in a shallow marine to near shore environment, as glauconite has been observed throughout.

Baghanwala Formation

The exposures of Baghanwala Formation are present in the Eastern Salt Range only; the formation is truncated westward by the overlying Permian unconformity. In the subsurface the formation extends up to Bahawalpur area, at least up to 30 degrees N latitude. It is not encountered in the foothills of the Salt Range and is absent in most of the Potwar region. The formation shows very rapid changes in thickness due to truncation by the Permian unconformity. It is up to 110 meters thick in the Eastern Salt Range and thins toward the west. In the Dandot area the formation is 38 meters thick. It is present in subsurface in the Punjab Plain.

The lower contact with the Jutana Formation is conformable. The upper contact is unconformable with the overlying Tobra Formation of Permian age. The contact is easily recognizable where encountered in the subsurface or in surface exposures due to the distinct change in lithology from Baghanwala shales to Tobra conglomerates. It is also very clearly defined on electric logs.

The Baghanwala Formation consists of red colour shales, siltstones and sandstones. The basal part has more silty and sandy intercalations. The shales are of bright red colour, micaceous and occasionally glauconitic. Salt pseudomorph structures are commonly found.

The presence of salt pseudomorphs and absence of fossils indicate that the depositional environment was probably lagoonal in an arid climate.

Khisor Formation

Khisor Formation outcrops in Khisor Range only and is stratigraphically equivalent to Baghanwala/Jutana Formations (Fig. 7.2). Subsurface evidence indicates that it is also present in the Marwat Range. The thickness in Khisor Range is of the order of 170 meters

The formation consists of a sequence of dolomite and anhydrite / gypsum. The lower part consists of massive white gypsum with thin beds of white crystalline dolomite and the upper part consists of shales with fine crystalline dolomites and white gypsum. Lesser amounts of dolomitic shale, siltstone and sandstone are also present. Shales contain appreciable amount of organic matter.

Its upper contact with the Tobra Formation is unconformable and marked by sudden appearance of diamictites. This contact is easily discernible on electric logs.

This formation was deposited in a very shallow marine environment under slightly less restricted conditions to a silled basin.

SOURCE ROCKS

Shales of Khewra, Kussak and Jutana formations are of lacustrine to marine origin and contain woody, coaly to variously amorphous (with significantly woody herbaceous) kerogen which are capable of generating paraffinic to normal crude and gas. A thick sequence of organic rich shales is also present in the Khisor Formation–the upper most Cambrian in Khisor Range. This sequence was deposited in a semi-silled basin which is very suitable for abundance and preservation of organic matter. The maturity level of these strata is very high for their present depth, indicating their original deep burial and then removal of much of the overburden by upthrusting along the boundary faults of Salt and Trans Indus ranges. There are indications that hydrocarbons were generated in Cambrian source rocks.

The time of hydrocarbon generation, migration and the presence of suitable structural and stratigraphic traps, need further study in the search for oil in Cambrian reservoirs.

RESERVOIR ROCKS

Khewra is the main potential Cambrian reservoir, with possibilities in the Kussak and Jutana formations also.

Khewra Formation is generally divided into three units. The basal unit consists of thin bedded, partly shaly, fine to medium grained sandstone with thin clay beds. These represent the products of arid environment to marginal marine environment. The upper and middle units of the formation are moderately porous and display intergranular primary porosity which ranges from 10-12 %. The uniform grain size and moderate sorting of the sandstone indicates its excellent reservoir nature. The sandstone also displays fracture and jointing which may contribute to increase in effective permeability. Oil is produced in Potwar area from Khewra Sandstone at Adhi. Prior to the oil discovery at Adhi (1978) only dead oil shows from the Cambrian had been reported.

Kussak Formation is generally tight. However, hydrocarbon indications are reported both on ditch sample (fluorescence) and log evidence.

The Jutana Formation also has reservoir potential and hydrocarbon indications are reported in some wells in the Potwar.

Log Response

Since most of the Cambrian rocks are terrigenous/clastic deposits, the matrix and clay parameters are rather difficult to resolve. Hence, the logging tools which respond to matrix parameters are very important. Water resistivity (free and bound) is also an important parameter which needs to be resolved through careful log analysis, especially in the lower part of the Khewra. Typical Rw values in the Khewra Sandstone reservoir range between 0.02 to 0.04 ohm-m indicating the average salinity of 120,000 ppm Nacl. While calculating water saturations the presence of clay must not be disregarded as its bound water can significantly affect the final output. Similarly high gamma ray does not always mean high shale content and, therefore, gamma ray spectroscopy tool is recommended to differentiate between shales and high gamma ray micaceous sands.

SEISMIC CHARACTERISTICS

Seismically the Cambrian sequence deposited in Trans Indus-Potwar Basin is too thin to be resolved in terms of individual units. However, a weak reflector corresponding to top Khewra Sandstone is generally found to be very consistent over a wide range in the Potwar Basin. The top Salt Range Formation reflector can also be mapped consistently as its character is fairly strong and consistent because of high acoustic contrasts.

Seismic facies of Cambrian sediments are characterized by variable, locally high, but normally low to moderate amplitude. The reflectors have low continuity and moderate to narrow frequency.

DRILLING CHARACTERISTICS

Due to the hard, sandy and abrasive nature of the Cambrian formations, drilling rate is usually low and ranges from 0.25 - 1.5 m/hr. It can be improved by using optimum hydraulic parameters and hard formation drill bits.

While drilling in Khisor Formation, which contains thick sequences of anhydrite and gypsum, mud treatment with suitable additives is essential in order to prevent dissolution of formation calcium.

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8
Ordovician, Silurian, Devonian and Carboniferous

The strata belonging to these geological periods are not present in the peninsular part of India and Pakistan. They are confined to the northern most borders of Himalayas (Fig. 8.1) and to upper Mayanmar (Burma). The Himalayan occurrences of these rock groups are restricted also to the northern most or Tibetan zone of Himalayas, where a broad belt of marine fossiliferous sedimentary rocks extends from the western extremity, Hazara and Kashmir, through Spiti, Garhwal and Kumaon to Nepal, Sikkim and Bhutan.

The absence of these rocks from most of Pakistan is very important geological phenomenon as it constitutes nearly three fourths of the Paleozoic history of earth.

Ordovician sediments have long been known from Kashmir, notably from the Marahum Syncline. Ordovician sediments embracing most stages from Tremadocian to Ashgillian are now known from several localities in Afghanistan. Talent and Mawson (1979) report latest Silurian age for Kandar Phyllite only near Nowshera; upper strata in the region are believed to be of Early Devonian age. Stauffer (1968) suggested Late Silurian to Early Devonian age for Nowshera Limestone.

There are several occurrences of Devonian outcrops in Chitral and Peshawar districts. The most important sections of middle to Late Devonian rocks outcrop on Kuragh Spur and Shogram in Chitral. Likewise thick carbonates of the Nowshera Formation (Fig. 8.2) have been described and interpreted in terms of reef buildup in Early Devonian times. Rocks of Carboniferous age exist in Pakistan south of Indus suture and its westward extensions.

The stratigraphic succession of these formations is described in the following paragraphs. Name of the authors of the various formations have been shown in parentheses. Formation thicknesses wherever reported have been mentioned.

STRATIGRAPHY

NORTHERN MONTANE AREA

SILURIAN - DEVONIAN

Devonian of Chitral (Pascoe 1959).

There are several occurrences of Early Devonian (Lochkovian) rocks on either side of the Mastuj valley in the Barum-Reshun-Kuragh region. A shallow marine (shelf)

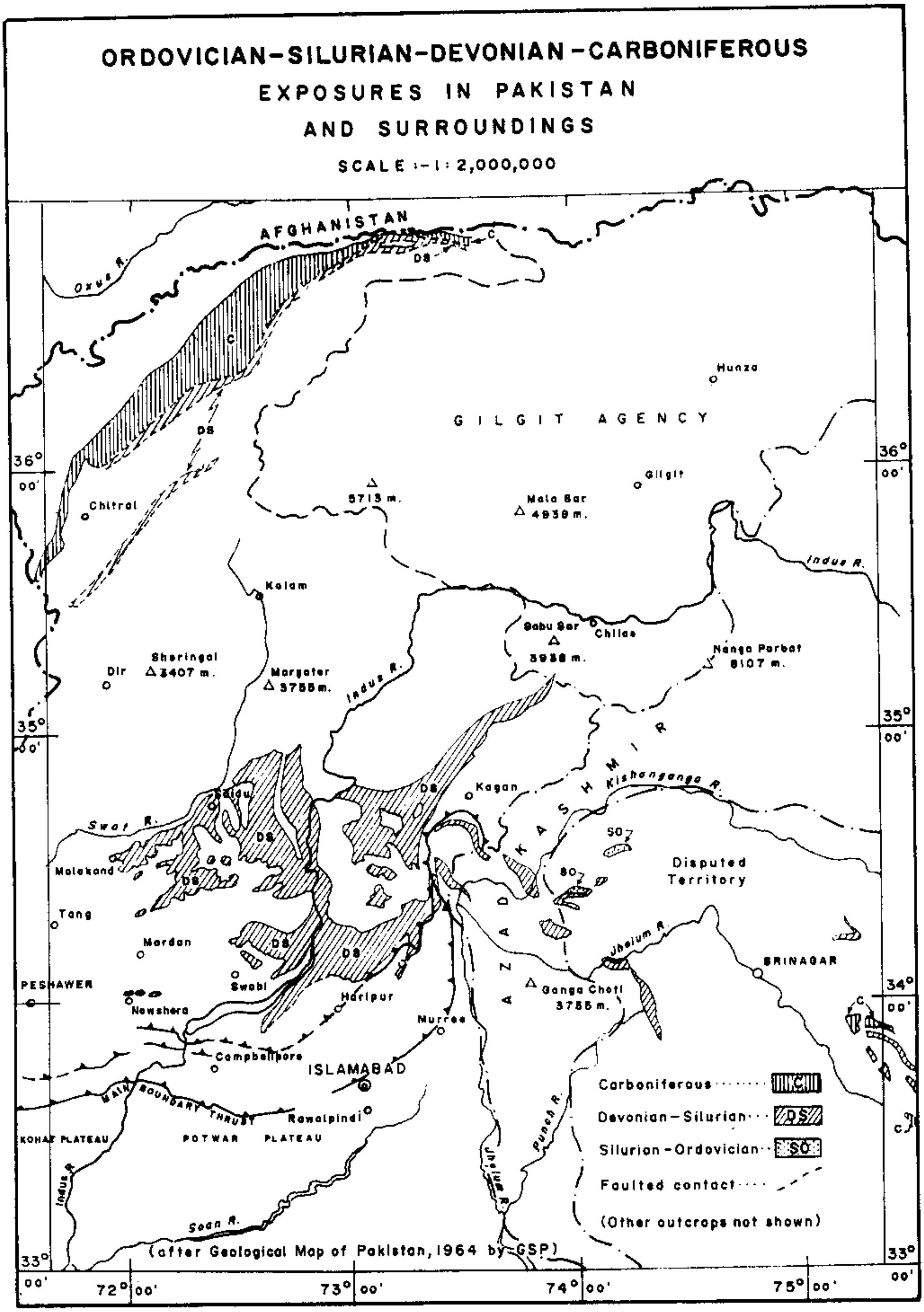

Figure - 8.1 Ordovician - Silurian - Devonian - Carboniferous Exposures in Pakistan and surroundings

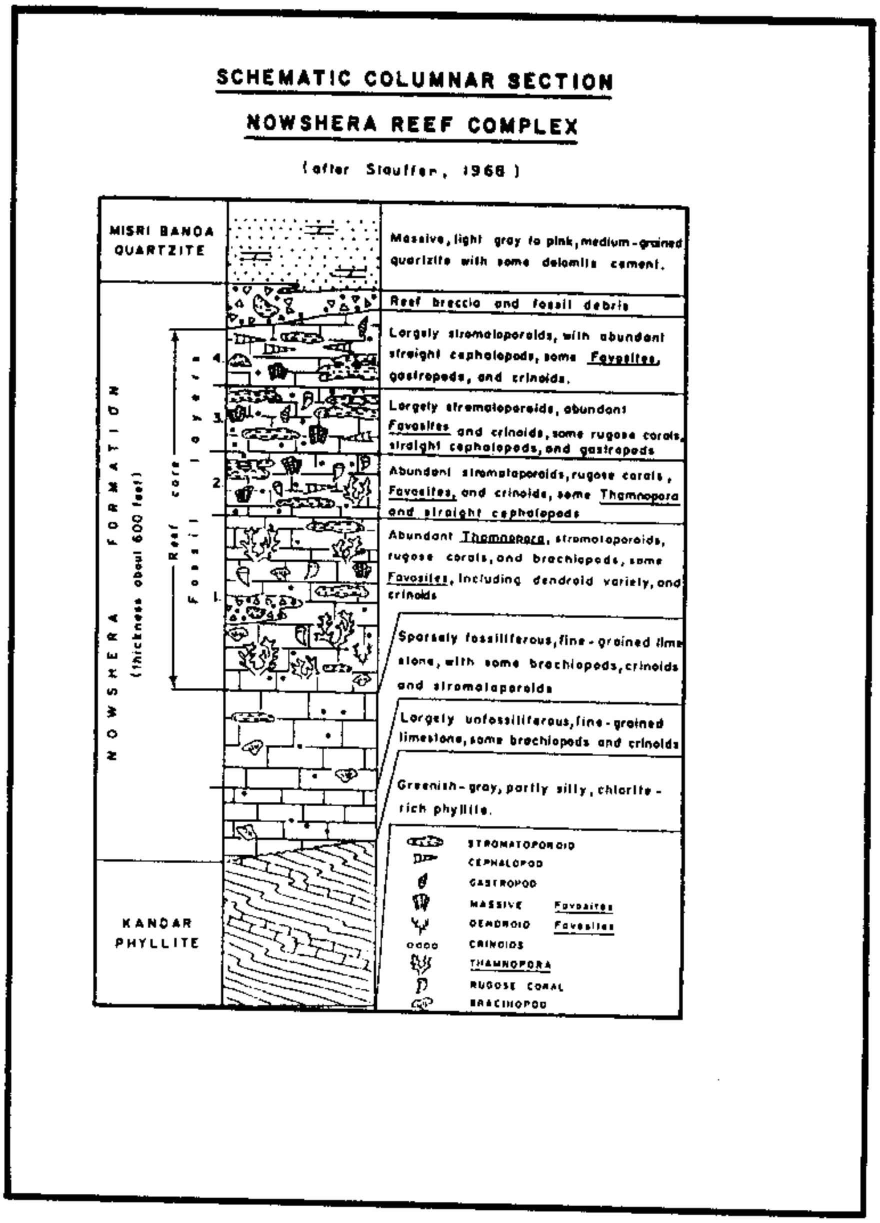

Figure - 6.2 Schematic Columnar Section, Nowshera Reef Complex (after Stauffer, 1968)

paleoenvironment is indicated from the abundant Devonian fossils present in the crystalline limestones of northern montane area.

CARBONIFEROUS - PERMIAN

Sarikol Slate (Hayden 1915)
Thickness not given.

The rocks outcrop from Chinese Turkestan to Chitral. These are predominantly slates with subordinate quartzites, limestones, calcareous beds and some volcanic rocks.

Darkot Group (Ivanac, Traves, King 1956)
Thickness not given.

Widespread occurrences are found from Darkot to Chitral. It contains slates, limestones, quartzites, conglomerates, schists, marbles, gneiss and volcanics. In Yasin valley (northwest of Gilgit) it consists of fossiliferous shelf limestones. Intensity of metamorphism increases eastwards.

Chalt Schist (Stauffer, 1968) – 95 meters

It contains quartz biotite schists, also sandstones, quartzites, green schists, crystalline limestones, marbles and conglomerates.

Baltit Group (Stauffer, 1968) – 66 meters–Outcrops south of the Karakorum Batholith. It consists of schists, amphibolites, coarsely crystalline marbles, micaceous quartzites, and gneissose lenses.

Pasu Slate (Deiso, 1963; Schneider, 1957)
Thickness not given.

Outcrops in the north along the Karakorum Batholith. This unit comprises slates, quartzites and limestones.

Panjal Formation and Agglomerate (Middlemiss, 1910)

Thickness not given.

Outcrops around apex of Kashmir Syntaxis. This formation contains volcanic greenstones, low grade metamorphic carbonaceous agglomerate slates, sandstones, conglomerates, shales, phyllites, and amphibolites. Metamorphic lava flows and tuffs of intermediate mafic composition are indicated by volcanic greenstone.

AXIAL BELT

ORDOVICIAN – SILURIAN

Landikotal Formation (Stauffer, 1968) - 3,330 meters

The lithology of this formation is marked by a variable assemblage of slate, phyllite, quartzite, dolomite, limestone and some basic igneous rocks. Dykes are also abundant.

Attock Formation (Tahirkheli, 1970) – 397 meters

This contains three units. The lowest unit consists of sandy crystalline limestones, sandstones/slaty shales and dolerite sills. The middle unit comprises phyllites, slates and slaty shales with lenticular sandy bands and limestone pockets. The upper unit is crystalline limestone with numerous dolerite intrusions.

SILURIAN - DEVONIAN

Kandar Phyllite (Stauffer, 1968) – 5,000 meters

The formation is composed of chloritic phyllites with interbeds of crinoidal limestones in the upper part (Fig. 8.2).

Nowshera Formation (Stauffer, 1968)

This formation is mainly composed of limestones and dolomites (Fig. 8.2). This has been subdivided into three units which are Reef core, Carbonate reef breccia/talus, and Unfossiliferous carbonates. Reef core is correlated with the Early Devonian of Chitral.

Misri Banda Quartzite (Stauffer, 1968) – 500 meters

This consists of massive quartzites with calcareous cement and occasional dolomite lenses. The quartzite outcrops along the entire length of Nowshera reef complex and overlies Nowshera Formation (Fig. 8.2).

Pir Sabak Formation (Latif, 1970)

Thickness not given.

The lower part of the formation is thick bedded dolomitic limestone; the middle part is thin to thick bedded limestone of light grey colour and the upper part is grey limestone, coarse grained and partly dolomitised.

Shagai Limestone (Stauffer, 1968) – 2 meters

The formation is exposed about 1 Km northeast of Shagai Post. Its lower part, in most places, is medium to thin bedded while the upper half is massive. The formation is very fine grained and is thought to be its diagnostic character.

Ali Masjid Formation (Stauffer, 1968) – 34 meters

Its type section is near the village of Ali Masjid, Khyber Pass. The formation consists of shale, siltstone, sandstone, quartzite and limestone. The diagnostic features at the type locality are red coloured shale and an alteration of various lithologies.

CARBONIFEROUS - PERMIAN

Khyber Limestone (Stauffer, 1968) – 1,300 meters

Its type section is located near the village of Ali Masjid, Khyber Pass. The formation at the type locality is predominantly limestone with negligible argillaceous and arenaceous partings: the limestone frequently grades into marble and dolomite.

Shakhai Formation (Tahirkheli, 1970) – 25 meters

The formation is exposed near Shakhai Village about 16 Km west of Nowshera. It consists of thin bedded to massive dolomitic limestone with thin bedded quartzite and slaty shale at the base.

STRATIGRAPHIC ANALYSIS

Since scattered outcrops of Ordovician rocks are present throughout the Kashmir and Axial Belt, it is interpreted that a widespread carbonate platform existed offshore northern Pakistan (north of MBT) in that time while the megacontinent containing India continued to exist in southern latitudes. This was followed by a global cooling period associated with widespread glaciation which reduced the coral faunas and carbonate development. This glacial episode ended in the earliest Silurian with a corresponding glacio-eustatic sea level rise.

Most of the Silurian is considered to be marked by extensive epeiric sea situated in the low latitudes of surrounding Pangea. Cosmopolitan nature of the Silurian fauna and their contents confirm the continued existence of megacontinent and the presence of the shelf seas and their widespread nature. Carbonate reefs and evaporites are exposed in the Northern Montane-Axial Belt areas, notably in the Nowshera region. This sedimentary record is largely missing from the rest of Pakistan but it is plausible that similar conditions were widespread.

This period of transgression was followed by a widespread regression during the Devonian, indicating a widening of the continental platform. It is understood that the Laurasia and Gondwana super-continents were closer to each other during the Middle Devonian and continued to converge throughout the rest of the Devonian. Ural Mountains in Russia are an example of this continental collision. This was also associated with the opening of 'Paleo-Tethys' and the generation of oceanic crust. Final collision between Laurasia and Gondwana occurred in the Middle Carboniferous causing the Hercynian Orogeny.

The continental collision is noted by the presence of basic volcanics in Karakorum District. Black shales and mudstones were deposited in this region while thick marine shales were deposited to the east, representing the infill of miogeosynclinal basins. Collision was accompanied by the opening up of centre and western part of Paleo-Tethys giving rise to the deposition of shales which is now known as Chitral Slates.

HYDROCARBON POTENTIAL

The rocks belonging to this period seem to be mostly thermally associated and have lost their original characters. Hydrocarbon potential of most of the stratigraphic sequence of this period, therefore, is very low due to high level of metamorphism throughout. Furthermore, since these strata exist at the collision zone, structures are highly crushed and are allochthonous. However, possibility of finding reservoir characteristics in these rocks can not be ruled out as hydrocarbons have been discovered in hard rocks in various regions of the world.

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9

Permian

Rocks of Permian age are found in the Kohat-Potwar province in the Upper Indus Basin and in the Axial Belt. In the Lower Indus Basin, Permian sediments have been encountered in wells drilled in the Punjab Plains down to latitude 29°N. In the subsurface, Permian rocks have been encountered in the Potwar in a number of wells including Dhurnal, Dhulian and Adhi, and probably extend up to Kalachitta area. The southeastern limit is defined by the Precambrian (basement) exposures of Kirana Hills. Permian sediments outcrop only along the escarpments of Salt and Trans-Indus ranges.

The Permian sediments are expected to underlie most of the Punjab Plains. There is every likelihood that Permian rocks are present in the Sulaiman Basin also. This is substantiated by the fact that west of River Indus Permian sediments were encountered in Marwat-1 well (Marwat Range) and are exposed in Khisor Range with westerly dips. On the basis of surface and subsurface evidence Permian sediments are considered to occupy an area of about 200,000 sq. kms. The distribution of Permian rocks is shown in Fig. 9.1.

TECTONICS AND DEPOSITIONAL SETTINGS

In Indus Basin, Cambrian was followed by regional uplift and break in sedimentation and erosion, which prevailed until the end of Carboniferous. The Permian epoch marks the breakup of Gondwanaland into its fragments and thus the end of Gondwanaland sedimentation.

At the time of the onset of Permian, conditions were generally cold and mostly fluvio-glacial environment prevailed all over the Kohat-Potwar and Lower Indus Basin. Subsequently the climatic conditions generally became warmer and environment changed to continental and then to shallow marine thus marking the great sedimentological diversity.

In the Central Indus Basin, Permian is recorded in Karampur, Bahawalpur East and Marot wells (Shell); one of the wells encountered Permian boulder beds. Early Permian glacial environment can, therefore, be extended at least down 29 degrees latitude.

LITHOSTRATIGRAPHIC DIVISIONS

The Permian strata in the Upper Indus Basin have been divided into two groups viz. the Nilawahan Group and the Zaluch Group, as under:

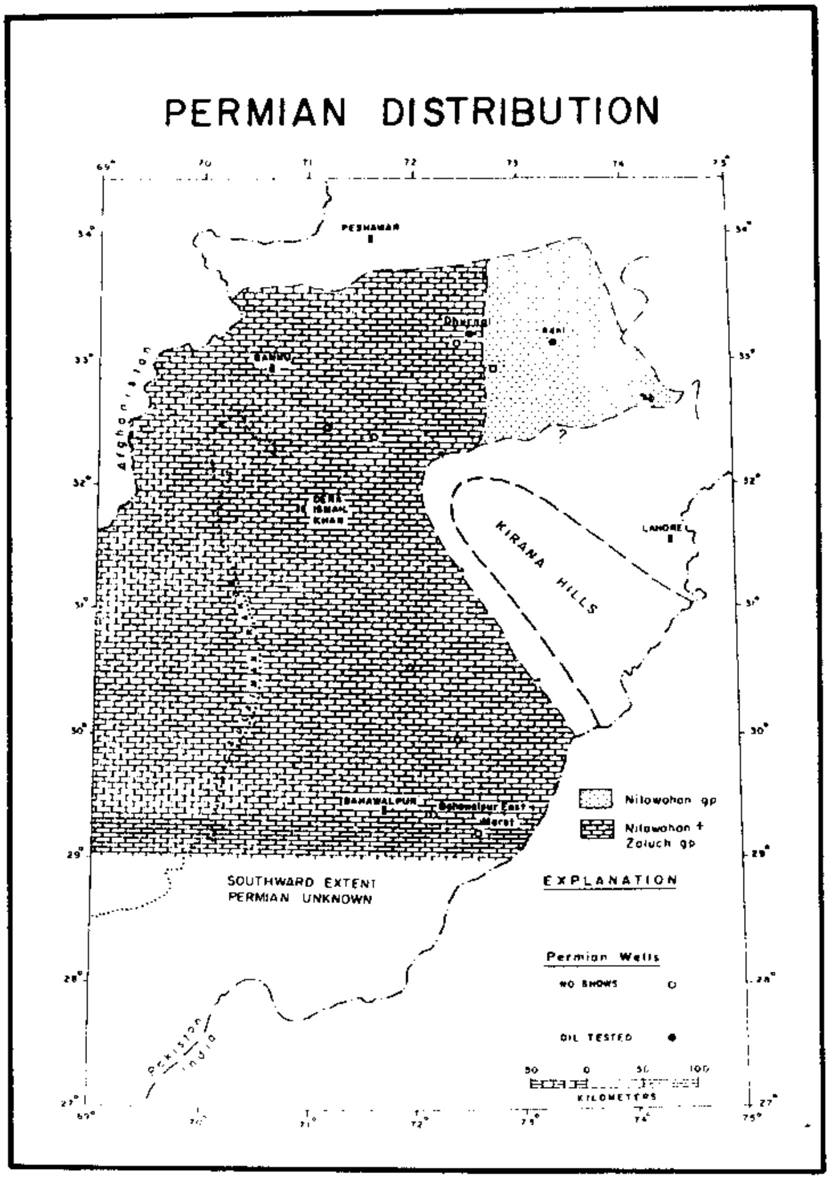

Figure - 9.1 Permian Distribution

Nilawahan Group (clastics)	Sardhai Formation
	Warcha Sandstone
	Dandot Formation
	Tobra Formation
Zaluch Group (carbonates & clastics)	Chhidru Formation
	Wargal Limestone
	Amb Formation

Fig. 9.2 depicts the Permian stratigraphic succession exposed in Saiyiduwali/ Luna Algad sections of Khisor Range and Figure 9.3 represents the same in the Salt Range.

NILAWAHAN GROUP

TOBRA FORMATION

The Tobra Formation refers to the lowest formation of the Nilawahan Group. It is widespread in the Kohat-Potwar province. Surface exposures are present from eastern Salt Range to Khisor Range. It is present in subsurface in the Potwar and the Punjab Plains (in the Bahawalpur East & Karampur wells) but was not encountered in Punjab Plains in the foot hills of Salt Range (Warnali & Lilla wells; Shell, 1982-83) where Siwaliks directly overlie the Cambrian.

The lower contact of the Tobra Formation with the Bhaganwala Formation (Cambrian) is unconformable; it can be easily recognised on ditch samples and electric logs. The upper contact with the Dandot Formation is (gradational) conformable. The contact can be recognised with change in lithology from black and dark brown siltstone to greenish sandstone of Dandot Formation. In the Western Salt Range and in Khisor Range, however, the Dandot Formation is absent and Warcha Sandstone is directly overlying the Tobra Formation. The contact between the two is sharp and can be recognised in the field.

Thickness of Tobra Formation varies

considerably. In outcrops in Western Salt Range it is more than 140 meters which is the maximum recorded thickness of the formation. In the Eastern Salt Range it is about 30 meters and in subsurface the thickness varies from 10 meters to 25 meters.

The Tobra Formation comprises boulders, cobbles, pebbles and gravels of acid igneous rocks in a silty, sandy and argillaceous matrix. The conglomeratic sandstones are pinkish white to yellowish white, friable and poorly cemented. Pebbles and gravels are mainly pink granite and occasionally metamorphic rocks. Matrix is silty and argillaceous. The siltstones are light grey, sandy and highly micaceous. The shales are dark grey to greenish grey.

The upper and lower parts consist of more sandy matrix while in the middle more silty and argillaceous matrix is observed in surface exposures.

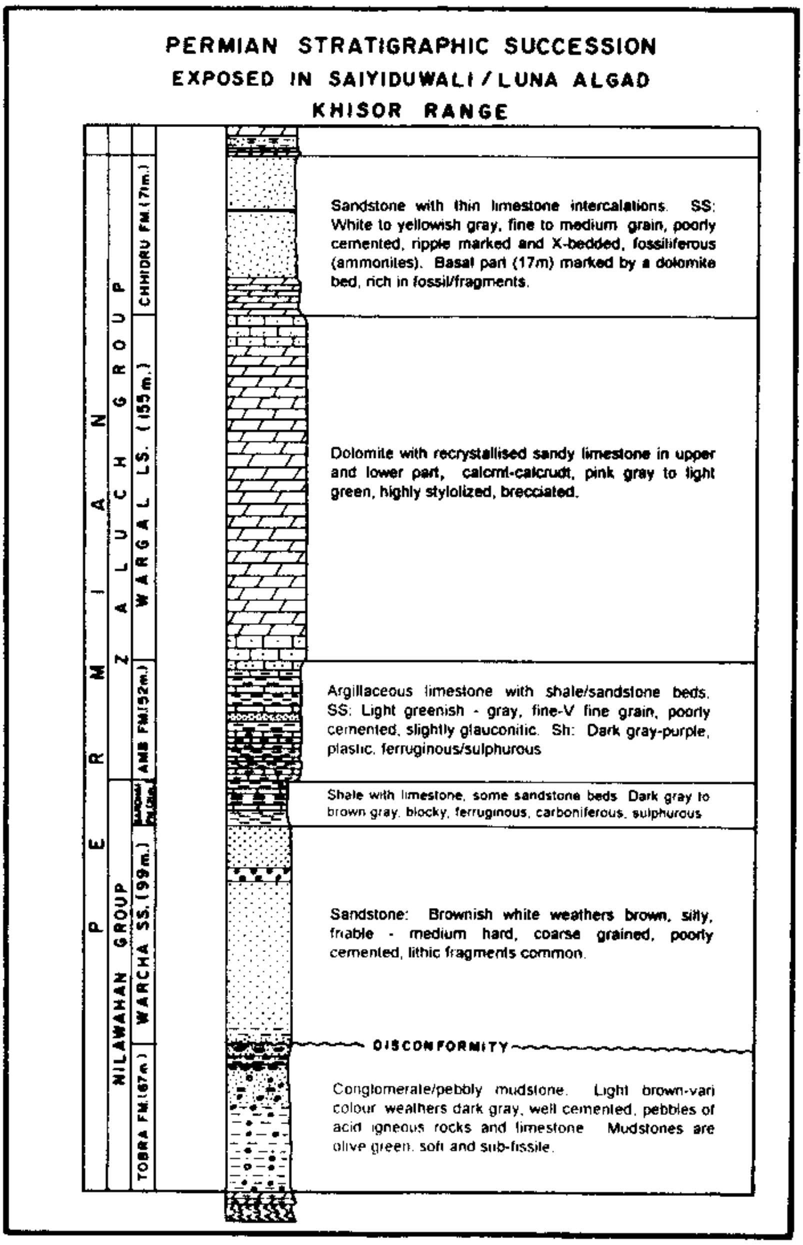

Figure - 9.2 Lithostratigraphic Column of Permian in Khisor Range

The Tobra Formation was mostly deposited in glacio-marine/lacustrine environment which occasionally became shallow marine at places. The heterogeneous mixture, striated and faceted surface of boulders and silty matrix suggest transportation by fluvio-glacial agents. It appears that igneous fragments were derived from the Kirana Hills and Rajhastan (India), while slate fragments were derived from the metamorphic zone of northern Pakistan.

At places this formation depicts very good reservoir characteristics with presence of primary and development of dissolution porosity. Moreover, sandstones of the formation are fractured in vertical and horizontal directions.

Dandot Formation

The Dandot Formation is well exposed in the Eastern Salt Range and thins out westwards. It is not found in Western Salt Range and Khisor Range. In subsurface the formation is present in Kallar Kahar and

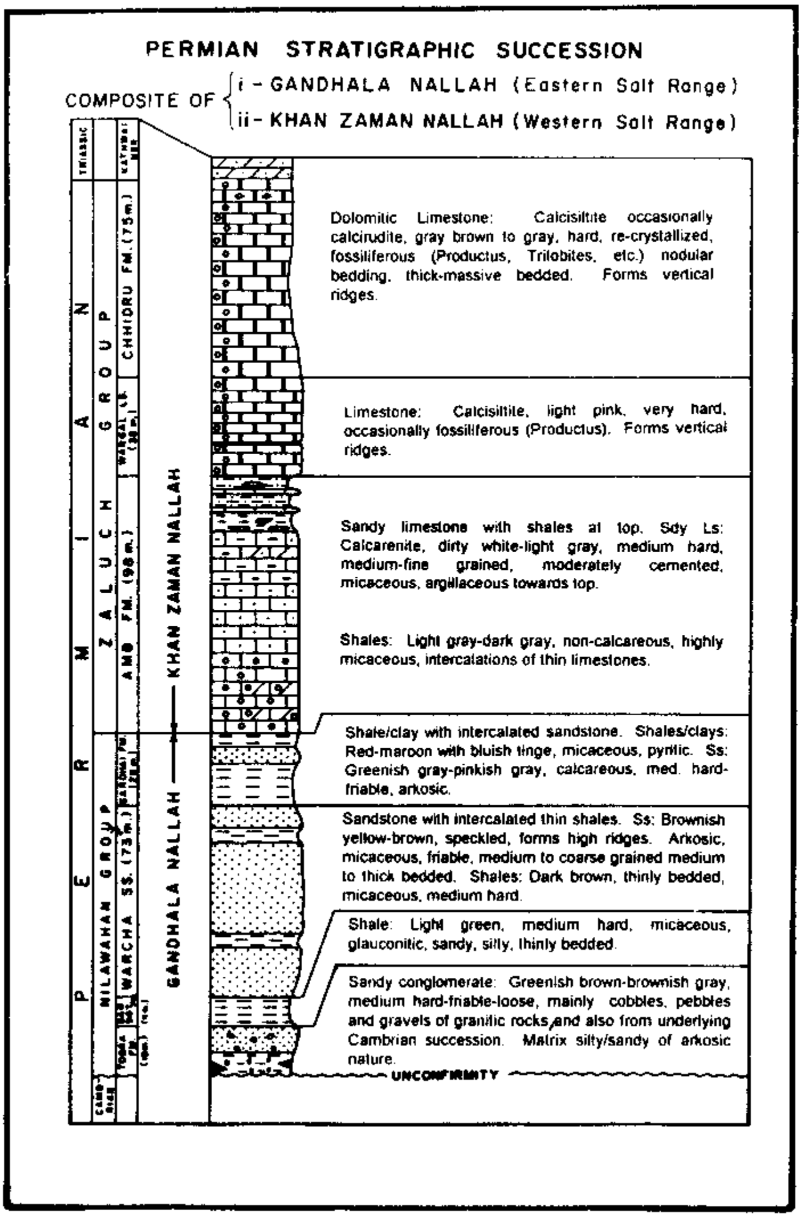

Figure - 9.3 Lithostratigraphic Column of Permian in Salt range

Dhariala wells and up to Adhi and Joya Mair. In East Potwar it is difficult to differentiate this formation from the overlying Warcha Sandstone. The formation is well developed in the Punjab Plain down to at least 29° N latitude as evidenced by Bahawalpur East and Marot wells.

Its maximum thickness has been recorded in the Eastern Salt Range where it is about 50 meters thick; towards west the thickness ranges from 10-15 meters in exposed sections. In the subsurface in eastern Potwar the thickness ranges from 25 meters to 45 meters. In Punjab Plains thickness up to 80 meters is reported from wells.

The Dandot Formation has a gradational contact with the underlying Tobra Formation. The upper contact with the Warcha Sandstone is conformable and sharp. Electric logs show a distinct shift in the SP value at the contact of the Dandot and Warcha formations.

Dandot Formation consists of siltstones, sandstones and shale/clays. The shales are greenish grey, highly micaceous, glauconitic. The sandstones have dark grey to black colour due to bituminous staining. Some coaly partings have been observed in shales. The formation is more coaly towards Western Salt Range.

Dandot Formation was deposited in shallow marine and likely near shore environments with probable paralic coaly development. It is probable that a short marine phase occurred after deposition of Tobra Formation which did not extend in all parts of the basin. Plant bearing strata at certain places indicate locally fresh water deposits.

The formation displays more shales than siltstones and sandstones. The siltstones and sandstones are well sorted and possibly develop into local reservoirs. As a source of hydrocarbon generation, the formation could be rich in organic matter at places as indicated by its dark grey colour and the presence of coaly partings.

Warcha Sandstone

The Warcha Formation is widely distributed in the Salt Range and Khisor Range. In subsurface it is found as far north as Dhulian and in the south the formation extends at least down to 29° N latitude.

The thickness of the Warcha Formation in the Salt Range exposed sections ranges from 70 meters to 165 meters.

The lower contact with Dandot Formation is conformable and sharp. The upper contact with the Sardhai Formation is transitional. Sardhai Formation is bluish and greenish grey clay while the Warcha is predominantly reddish brown sandstone. Contact on electric logs show very clear shift in the SP value from Warcha to Sardhai Formation. In certain East Potwar wells, the Warcha/Dandot Formations are unconformably overlain by the Hangu Formation of the Paleocene age which show low resistivity values compared to Dandot/Warcha.

The Warcha Formation includes mainly light brown to pinkish white arkosic sandstones. They are medium to thick bedded, fine to coarse grained and intercalate comparatively thin and dark brown shales. The sandstones often have gravel and pebbles of pink granite and are commonly trough cross-bedded. The formation is locally speckled. It contains some carbonaceous shales with irregular coal seams in the Burikhel area (Western Salt Range). It is probable that the granitic detritus in the Warcha Sandstone originated from the same source as that of the Tobra Formation. The formation was deposited probably in the near shore/fluviatile environments.

The Warcha Sandstones are medium hard to friable, highly porous and can be good reservoirs for migrated oil. The chances of source rock in the Warcha Sandstone are very poor.

Sardhai Formation

This formation consists of bluish and greenish grey clays with some minor sand and siltstone beds. It depicts prominent facies change from predominantly lavender colour clays in Salt Range to black shale and brownish argillaceous limestone in the Khisor Range. This formation is missing from the Eastern Potwar area. The formation in the Khisor Range shows good source rock characteristics.

Zaluch Group

The Zaluch Group age has wide distribution in the Western Salt Range, Trans-Indus Range and in the subsurface of Potwar up to Dhulian wells and presumably Kohat area, but is absent in the Eastern Potwar/Salt Range (Fig. 9.1).

Subsequent to the deposition of the Sardhai Formation, marine conditions appear to have been established in the area. The Zaluch Group conformably overlies Nilawahan sequence while the Permian and Triassic strata are separated by an unconformity, reflecting a regression of the sea and emergent condition in the latest Permian/earliest Triassic time indicated by white sandstone bed present at top of Chhidru Formation.

The thickness of Zaluch Group in the type area, located in central Salt Range, is about 300 meters. Maximum accumulation of sediments lies in a NE-SW trending narrow basin. Thinning is pronounced towards east and the Zaluch Group is absent in the Eastern Salt Range.

The Zaluch Group consists of sandstone, shales, sandy limestone and dolomite. The group is highly fossiliferous. The three formations included in the Zaluch Group are discussed below.

Amb Formation

The formation mainly consists of brownish grey, medium to thick bedded sandy limestone or calcareous sandstones. The sandstones are fine to medium grained with some occasional beds of greenish grey and light brown sandstone in the lower part. In the upper part dark grey carbonaceous shales are present. In the Khisor Range, the lower part of the formation is composed of dark coloured shales containing thin bands of limestone. The formation is highly fossiliferous. This formation marks the first appearance of foraminifers (fusilinids) in Pakistan.

Wargal Limestone

The formation is mainly composed of carbonate rocks; the lower part mainly consists of limestone and dolomite with a few sandstone and sandy limestone intercalations whereas the middle part is mainly dolomitic limestone of cream and grey colour. Chert nodules are commonly found while in the upper part nodular, partly crinoidal limestone is present. Fossils are abundant in the formation.

Chhidru Formation

The formation at the base is composed of soft, pale yellowish grey to medium dark grey sandy shales which are 6-13 meters thick. Phosphate nodules are observed occasionally. The unit is overlain by fossiliferous, calcareous sandstone and sandy limestone. The upper part is highly fossiliferous. The top of the formation is marked by a white, fine to medium grained, ripple marked sandstone bed of 1–5 meters thickness with subordinate dark shale partings. This white sandstone is, at places, richly fossiliferous.

The lower contact of Zaluch Group with Sardhai Formation of Nilawahan Group is conformable and clear. However, it is transitional in Khisor Range. On electric logs there is a clear shift in the resistivity and SP values. In Eastern Salt Range the grayish white dolomite/limestone is unconformably overlying the Chhidru Formation.

The Permian succession is mostly considered to be deposited in shallow marine conditions. While abundance of clastic sediments increases to the east, the carbonates facies dominate toward west and south (Fig. 9.1). The limestone facies characteristic of the fold belt area is believed to be due to the distance from source of clastic sediments. Some reef environment characteristics are also present in the Zaluch Group, peripheral to the foreland area. It is reflected by the presence of corals and crinoids, dolomitization and a mottled appearance of the Wargal Limestone surface. However, reef structures are not yet known.

CONTACTS, UNCONFORMITIES AND CORRELATIONS

The Nilawahan Group in the Upper Indus Basin represents the continental environment with glacio-lacustrine/marine conditions in Early Permian as indicated by Tobra Formation. Its contact with underlying Cambrian rocks is marked by the most significant unconformity of this region. The configuration of the Tobra basin seems to be very undulatory (Fig. 9.4) as the forma-

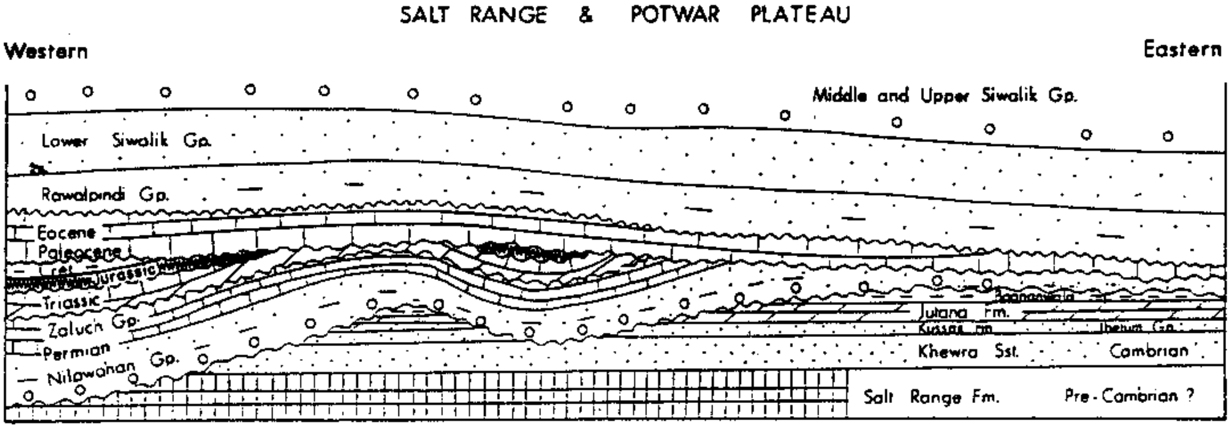

Figure - 9.4 Diagrammatic Sketch showing Major Unconformities Exposed In The Salt Range (after Gansser, 1964)

tion is thickest (140 meters) in the Western Salt Range representing glacio- marine environment with the proximity of land and varying thicknesses on either side (Fig. 9.5). Similarly overlying Dandot Formation is

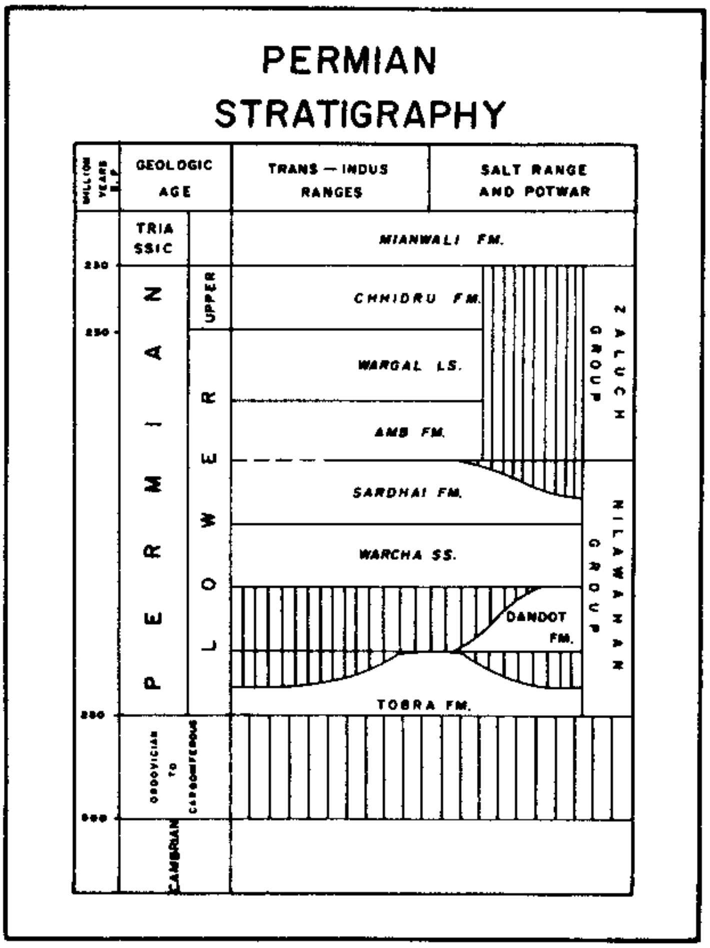

Figure - 9.5 Permian Stratigraphy

preserved in the Eastern Salt Range but is progressively thinning towards Western Salt Range and is completely missing in Trans Indus Range (Fig. 9.5) indicating an overall lacuna in the region. This is followed by a relatively continuous sedimentation till the onset of deposition of Zaluch Group. However, in Khisor Range, Sardhai Formation is represented by dark coloured shales with subordinate limestones marking the transition between the depositional environment of Warcha Sandstone and that of Amb Formation.

Base Permian makes a regional unconformity and is picked very easily both in the field and on wireline logs. In the Eastern Salt Range the upper Zaluch (top Permian) is missing because of a deeper cut of Paleocene unconformity (Fig. 9.4) indicating a paleohigh in that region. However, in the Western Salt Range, Surghar Range and Khisor Range the Permo-Triassic boundary can be easily recognized in the field as it is marked by a 2-3 meters thick dolomite bed representing a stratigraphic marker (Kathwai Member). A detailed account of the Permo/Triassic Boundary will be discussed under Triassic section.

SOURCE AND RESERVOIR ROCKS

Shales of Dandot Formation, with some coaly partings, are good source rock. Similarly, black shales of Sardhai Formation yield petroliferous smell when hammered. The high content of the organic matter in the limestone and the existence of black shaly horizons of Zaluch Group provide source rock characteristic to this group. Organic matter seems to be land derived and would generate gaseous hydrocarbons and paraffinic crude. Maturity level of these rocks also appears to be very high since they have undergone tremendous change on account of their burial through both time and temperature.

The reservoir potential of the Permian rocks is also good as Zaluch Group was deposited in shallow marine environment with clastic sediments of Amb and Chhidru Formation while Nilawahan Group represents the continental facies. In the wells of the Potwar basin the Permian sequence is very compact with very low porosity and permeability. Limestones are tight and sandstones are well cemented reflecting very low porosity. However, Tobra and Dandot/ Warcha have flowed oil in Adhi field whereas Amb and Wargal are producing in Dhurnal field. In the Dhulian well, Permian sandy limestone produced salt water associated with some oil traces. These facts certainly account for the possibilities of finding good Permian prospects in subsurface.

As far as the log analyses of Permian rocks is concerned, it would not really pose much problem as most of the limestones are clean and tight and the hole is generally in gauge. However, for clastic sediments the resistivities of connate and bound water needs to be calculated carefully.

Typical average Rw value of the Tobra Formation is 0.04 ohm-m with average salinity of 85,000 ppm NaCl.

SEISMIC CHARACTERISTICS

Top of Tobra Formation is picked as a very strong reflector showing widespread continuity particularly in East Potwar. The frequency of the reflections is low while the amplitude is very strong. In East Potwar other Permian Formations are too thin to be resolved on seismic. However, good quality data acquisition (dynamite) coupled with modern day stratigraphic processing would resolve the information present between the lines.

Dandot Formation is not a good seismic reflector because of lack of acoustic contrast above and below.

DRILLING CHARACTERISTICS

The Permian rocks are represented by limestones, sandstones and shales. No special treatment of drilling muds is, therefore, required. Low water loss and low solid muds are desirable which, on the one hand, help to overcome caving/heaving problems in shale and on the other, do not allow thick cake formation against porous formations. The thick cake causes tight pull and pipe drag problems.

No loss of circulation problems have been observed while drilling in the Permian formations. However, since potential reservoirs are present, losses, if any, should be cured with acid soluble loss circulation material (LCM). Use of conventional LCM i.e., cotton seed hull, rice husk and sand dust etc. should be avoided to minimize risk of reservoir damage.

The Permian formations are very hard and should be drilled with diamond impregnated bits to avoid undergauge hole and frequent bit trips. Optimum bit nozzle size should be selected to avoid jetting action which would cause shale washouts and induced loss of circulation. Too large a nozzle size will adversely affect hydraulic parameters.

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10
TRIASSIC

Triassic rocks are distributed throughout Pakistan; however the subsurface control is not sufficient as most of the exploratory wells have not tested the Triassic sequence. The distribution of Triassic sediments is limited in the east by the Indian Shield and in the north and west by the Axial Belt. Their pattern of distribution and the depositional extent are controlled by the Sargodha High. In the Upper Indus Basin (Kohat-Potwar-Trans Indus Ranges), Triassic is recognised by distinct lithological units in surface exposures. Presence of Triassic in Lower Indus Basin is established by isolated outcrops near Wulgai and Khuzdar in the Axial Belt area and by a questionable Triassic sequence encountered in Nabisar (Stanvac, 1958) and Jhat Pat (Amoco, 1974) wells. One unit of limited Triassic is also reported from Sarai Sidhu (Amoco, 1973) well in Punjab Plains.

A Triassic/Jurassic disconformity is recognised in Upper Indus Basin but the contact is considered transitional in Lower Indus Basin and Axial Belt.

Triassic strata are partly missing from Eastern Salt Range and are not encountered in any well drilled in Eastern Potwar area. They, however, are best represented in surface exposures in Khisor Range (Tapan Wahan section), central Surghar Range (Landa & Narmia sections, Fig. 10.1) and are thinning towards Western Salt Range (Nammal Section, Fig. 10.2).

TECTONICS AND DEPOSITIONAL SETTINGS

Early Triassic marks the rifting of Gondwanaland from Iran and Afghanistan Block. As a result rapid transgression occurred and wide spread marine conditions were established. Shallow marine sandstones, shales, continental red beds and shallow water carbonates as well as deeper pelagic limestones were deposited. Triassic carbonates were deposited in the Indus Basin and Axial Belt but thick clastics were still absent.

Middle Triassic marks the first differentiation of sediments on either side of the Paleo-Tethys suture. Up to this point shelf sediments had been in depositional continuity.

Late Triassic orogeny is one of the major events in the geological history of Pakistan. This marks the collision between various small continental fragments rifted away from north Gondwanaland and the southern margin of Laurasia. This impact resulted in the final closing of Paleo-Tethys and the continued opening up of Neo-Tethys. In the latest Triassic to earliest Jurassic a break in sedimentation occurred which represents a major unconformity.

PERMO/TRIASSIC BOUNDARY

Kummel & Teichert (1970) placed the Permo-Triassic Boundary at the contact of dolomite unit of lower Kathwai Member of Mianwali Formation and the upper white sandstone unit of Chhidru Formation. However, it was controversial as Permian brachiopods have been reported from the dolomite unit of Kathwai Member. Other authors tend to place the boundary where the Permian brachiopods become extinct and Triassic ammonoids emerge.

According to a study by the Pakistani-Japanese Research Group (PJRG) the Kathwai Member can be divided into three units. Lower unit is characterized by the presence of dolostone and sandstone with large amount of clastic grains. The middle unit corresponds to Main Dolomite unit. Upper unit includes dolomite and limestone. Echinoids casts are common throughout but they tend to decrease rapidly towards top of the member. Dolomitization seems to be related with the frequency of occurrence of echinoids casts. Hence on this basis they placed the boundary at the contact of lower and the middle unit of Kathwai Member (Nakizawa, 1983) as this also marks the change in the sediment characteristics and depositional environments which was the criterion adopted by Kummel & Teichert (1970) when they placed the boundary at Chhidru/Kathwai contact.

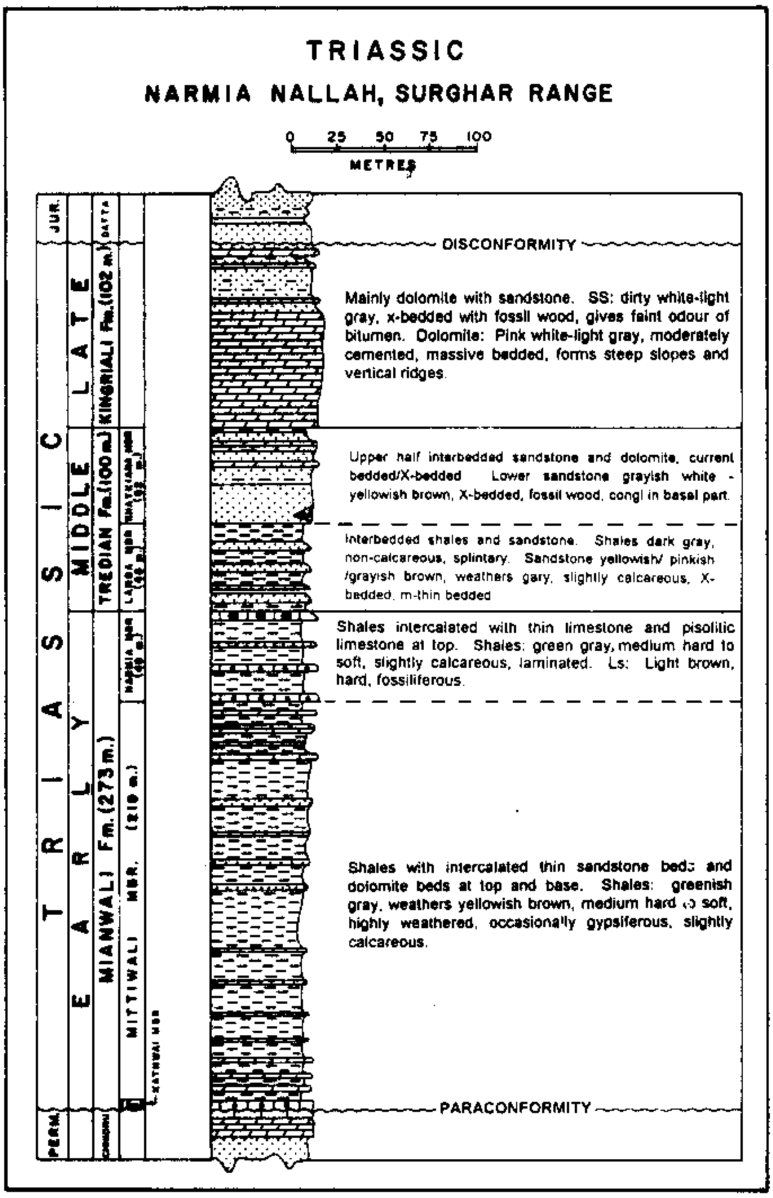

Figure - 10.1 Lithostratigraphic Column of Triassic in Surghar Range

LITHOSTRATIGRAPHIC DIVISIONS

In Central and Southern Indus Basin, the Wulgai Formation represents the Triassic. In Upper Indus Basin, the Triassic system is represented by the Kingriali, Tredian (Chak Jabbi) and Mianwali formations

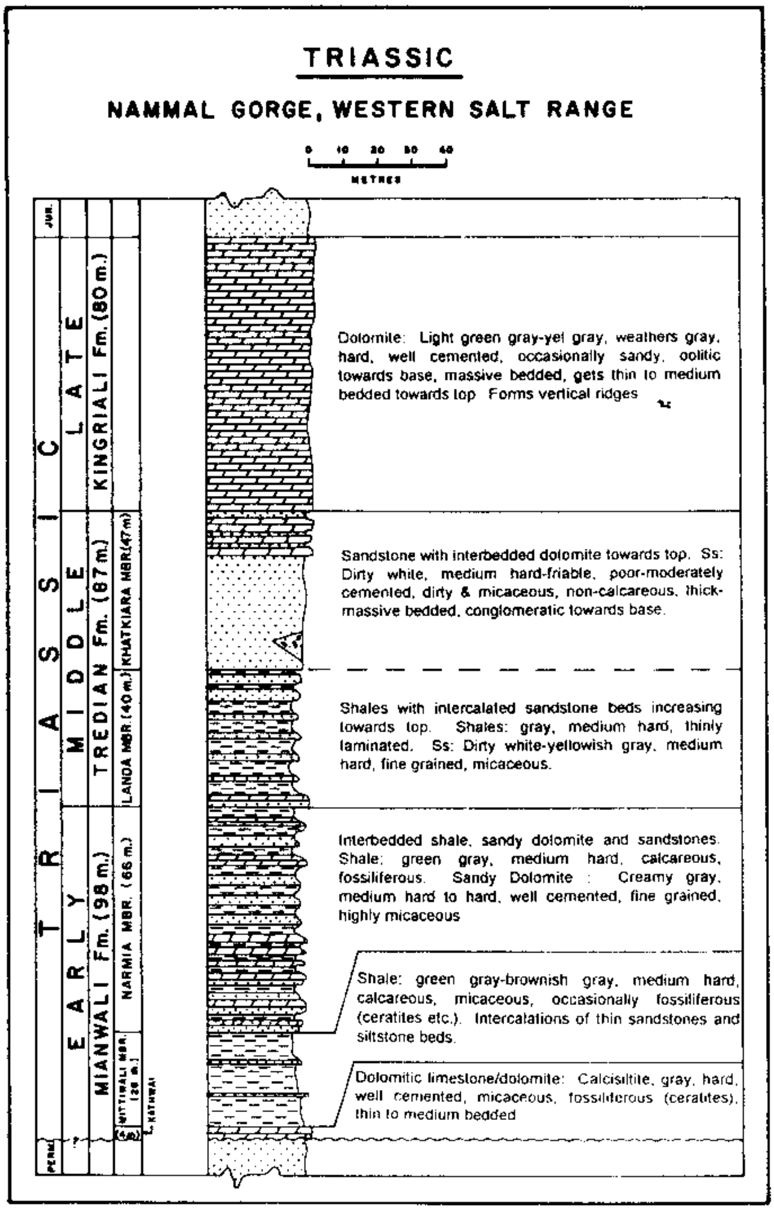

Figure - 10.2 Lithostratigraphic Column of Triassic in Western Salt Range

which overlie Chhidru Formation of Permian age (Fig. 10.3).

Central and Southern Indus Basin

Wulgai Formation

This formation is exposed in Axial Belt near the village of Wulgai and possibly extends in the subsurface as far south as Nabisar well.

The lower unit consists of dark grey to black shales and mudstones with subordinate limestones or calcareous mudstones. The unit is 300-500 meters thick.

The middle unit is interbedded shales, limestones and sandstones. Mudstones and shales are dark grey while the sandstones are both compositionally and texturally immature. The unit is about 200 meters thick.

The upper unit consists of shale, marl and thin crystalline limestones of black, dark grey or greenish-grey colour. Maximum thickness of this unit is about 300 meters Upper Indus Basin.

Total formation thickness is about 1200 meters.

Mianwali Formation

Mianwali Formation is very versatile in terms of lithological characteristics and contains limestones, shales, sandstones, siltstones, dolomites and dolomitic limestones. Mianwali Formation yields recognizable fossil assemblage which includes worm burrows (Zoophycus), ceratites, brachiopods etc. This formation is divided into three members and the total thickness is about 130 meters.

Kathwai Member

This member is very consistent and uniform in lithology. It consists of dolomite, pink brown (weathers to brownish orange), very hard, sandy, glauconitic, and ferruginous. It tends to protrude outward topographically and is a very useful stratigraphic marker in the field. Thickness of the member is about 4-5 meters.

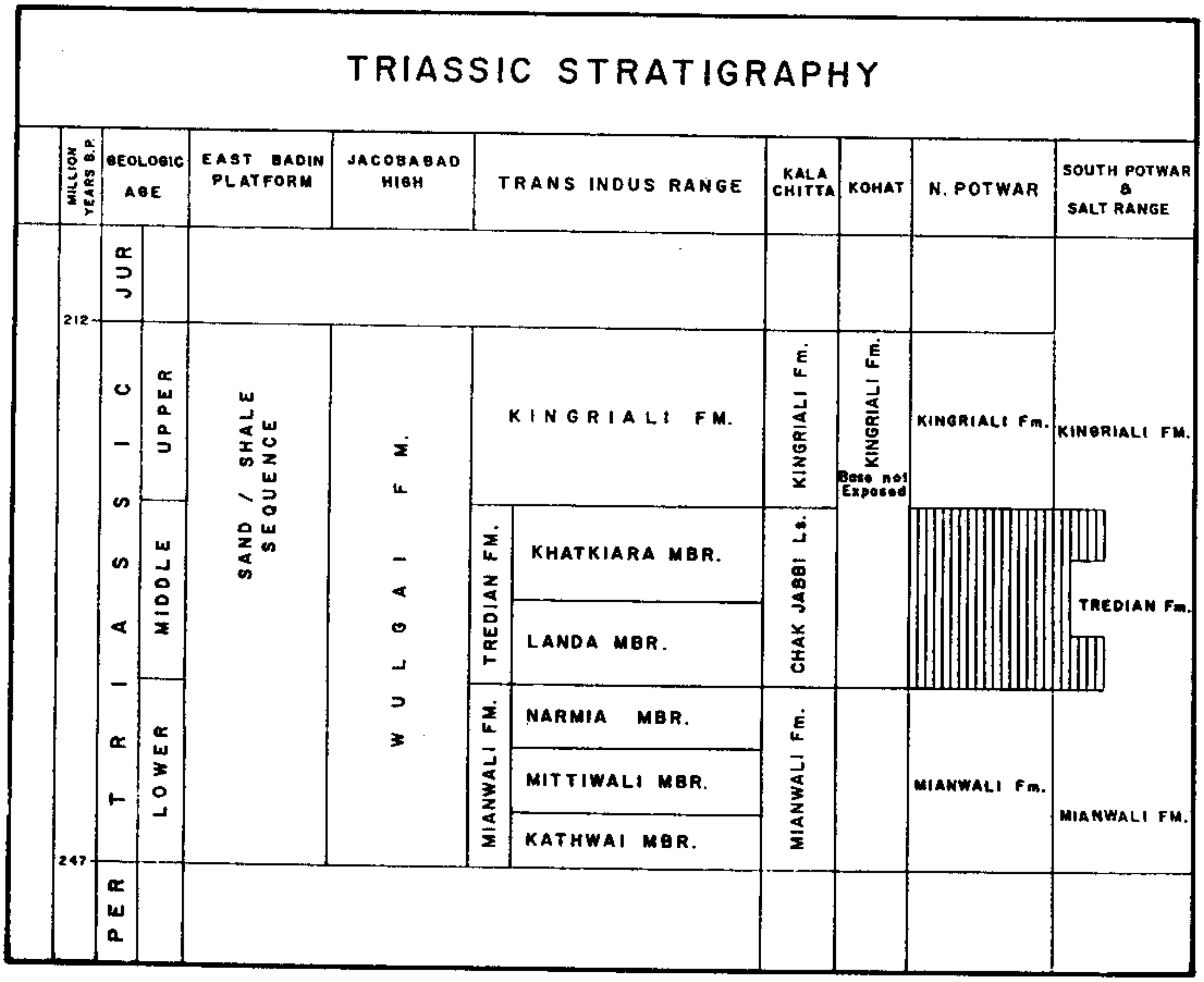

Figure - 10.3 Triassic Stratigraphy

Mittiwali Member

This member consists of limestones, shales, siltstones with subordinate sandstones. Limestone is brownish grey (weathers to yellowish grey), hard, compact, argillaceous, dolomitic. Sandstones are thin-bedded, greenish grey, fine grained, well sorted, micaceous, ferruginous, and calcareous.

Thickness of the member is about 100 meters.

Narmia Member

This member consists of silty shales with thin beds of dolomite and minor sandstones. Shales are greenish grey (weather to light grey), medium hard, occasionally micaceous, and bioturbated, thin bedded. Dolomitic limestone is calcisiltite, light grey (weathers to brown),hard, compact, recrystallised and has occasional fractures filled with calcite.

Thickness of the member is about 25 meters.

TREDIAN FORMATION

The formation defines the sandy facies of Triassic. It has been divided into Landa and Khatkiara members.

Thickness of the formation is about 80 meters.

Landa Member

This member includes interbedded shales and sandstones. Shales are grey to dark grey, laminated, blocky and carbonaceous. Sandstones are rusty brown, fine grained, sub-angular, well sorted, flaky, micaceous and limonitic.

Thickness of the member is 20 - 30 meters.

Khatkiara Member

The member consists of massive sandstone with the inclusion of some dolomite in the upper part which marks the gradation of sandstone facies into dolomitic facies of Kingriali Formation.

Sandstone is orange-greyish (weathers to grey), friable, fine-medium grained, arkosic, limonitic, cross bedded and ripple marked. Sandstone at places also depicts mamillary textures. Dolomite is rudaceous, light brown to grey (weathers to dark brown), hard, ferruginous and crinoidal.

Thickness of the member is 40 - 60 meters.

Chak Jabbi Limestone

Its stratigraphic position is similar to the above mentioned Tredian Formation (Fig. 10.3). The limestone is medium bedded, grey, sublithographic and partly dolomitized. It is exposed in cores of anticlines in eastern Kala Chitta Range.

Thickness is about 30 meters.

Kingriali Formation

This formation is predominantly composed of dolomites with minor limestone which at places is dolomitic. The formation has been divided into three units in Saiyiduwali area, Khisor Range, as under:

The lower unit (66.5 meters) consists of dolomites with subordinate limestones and minor sandstones. Dolomite is lutaceous, light grey-brown (weathers to brownish orange), hard, compact, dense, recrystallized, ferruginous and tightly fractured. Limestone is calcarenite, creamy white (weathers brown), hard, dense, chalky, dolomitic, slightly ferruginous. Upper part of this unit contains argillaceous limestone, light yellow, green (weathers orange), medium hard, dense, limonitic and bioturbated. Lower part of this unit contains two beds of sandstones. One is greenish grey to brownish orange (weathers dark brown), medium hard, friable, fine-medium grained, moderately sorted, arkosic, ferruginous, and micaceous. The other sandstone is creamy white-light grey (weathers same), friable, fine grained, well sorted, sub angular-sub rounded, with tiny nodules of chalk.

The middle unit (10 meters) is composed of dolomite, light-dark brown (weathers brownish grey), hard, brittle, highly fractured, crumpled, and massive. Its contact with the upper unit is scoured.

The upper unit (18 meters +) consists of interbedded dolomites, argillaceous limestones and marly limestones. Dolomite is greyish, brown, hard, cherty, ferruginous, cross bedded and solution pitted. Limestone is yellow-yellowish green (weathers light brown), medium hard, ferruginous, fractured, marly, nodular and fossiliferous. This upper unit has also been referred to as 'Gori Tangi Dolomitic Limestone & Shale Member'.

The lower contact of the Kingriali Formation with Tredian Formation is transitional.

Average formation thickness is about 100 meters.

SOURCE ROCKS

The Triassic units in the Upper Indus Basin mark the versatility of their environments of deposition. Some of these units, as observed in the field, were deposited in open marine and basinal settings responsible for preservation of organic matter. No hydrocarbons, so far, are reported to have been generated from these rocks.

In the Lower Indus Basin the distribution of Triassic is poorly known. However, Triassic carbonate platforms were widespread along the margin of Paleo-Tethys and associated shales are likely to have good source rock potential.

RESERVOIR ROCKS

As discussed earlier the best representation and division of Triassic is observed in the Upper Indus Basin. The Lower Mianwali Formation consists of mixed lithologies and does not have any reservoir potential. Upper Kingriali Formation consists of limestone and dolomite which are highly recrystallized and would hardly show any development of secondary porosity in subsurface. Middle Tredian Formation has one member (Khatkiara Member) which is of non-marine origin and is consistently uniform over the entire area. This member depicts some good reservoir characteristics. A tar seepage is located near Kundal in the Khisor Range where very heavy oil has been seeping through the unconformable contact of Khatkiara Member and Siwaliks. This indicates good permeability of this member through which light hydrocarbons seep to the surface and biodegrade to from large pools of heavy oil.

LOG RESPONSE / CONTACTS

Lithologic characteristics of Triassic units vary significantly from north to south. In upper Indus Basin contacts of different members and formations can be picked easily on logs as they are related to the change in lithology. However, southward in the lower Indus Basin the contact between Triassic and Jurassic is transitional and may only be picked by palynology.

DRILLING CHARACTERISTICS

Only a few exploratory wells in the Indus Basin have penetrated the Triassic sequence. However, no abnormal drilling conditions have been reported in the wells.

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11
Jurassic

Jurassic rocks are very well represented throughout Pakistan. However, they are restricted to Middle and Lower Jurassic; the Upper Jurassic is absent. These are the oldest rocks exposed in most of the Axial Belt and form the core of many anticlines in Sulaiman Range and Trans Indus Range. Isolated outcrop patches are present in Cutch, Jaisalmer (India) and in the Salt Range. In the north, the Jurassic is limited by outcrop belt of Precambrian crystalline rocks, the eastern boundary is represented by the erosional limit (Fig. 11.1). Best representation of these rocks in Indus Basin is in Samana Range, Kohat, Central Surghar Range, Sheikh Budin Hills (Marwat Range), along Sulaiman Range and further south in Kirthar Range. Fig. 11.2 and 11.3 represent generalised Jurassic stratigraphy in Khuzdar area and Sheikh Budin Hills respectively, and Fig. 11.4 shows the stratigraphic relationship across Lower Indus Basin.

The truncation of Jurassic rocks in Eastern Salt Range and Eastern Potwar Plateau (refer back to Fig. 9.4) is caused by Pre-Tertiary uplift and erosion. Fig. 11.5 is a regional stratigraphic correlation of Jurassic rocks across Indus Basin.

Because of the very uniform pattern of deposition in Central and Southern Indus basins, Jurassic rocks are inferred to attain a thickness of over 5,000 meters in Central Kirthar and Sulaiman basins.

TECTONICS AND DEPOSITIONAL SETTING

The advent of Jurassic is marked by the break in deposition. Rifting and break-up of Gondwana continued during the Jurassic. In Southern Indus Basin the submergence of platform produced deep water sedimentation of Shirinab and Chiltan formations where deposition kept pace with subsidence. Deposition varied with environments ranging from marshy to high–energy oolite or reef.

Fluvial to shoreline facies were deposited in Cutch while interbedded clastic shelf deposits and sandy coastal facies were laid down in eastern Kirthar and Sulaiman basins and carbonate facies on an outer continental shelf. Adjacent to the Axial Belt, which was a submarine ridge, a narrow zone of shelf facies was deposited.

At the end of Middle Jurassic, Axial Belt became temporarily emergent with deposition of carbonaceous clastics and coal seams. Following this, the basin subsided again and deep water, open marine limestones of

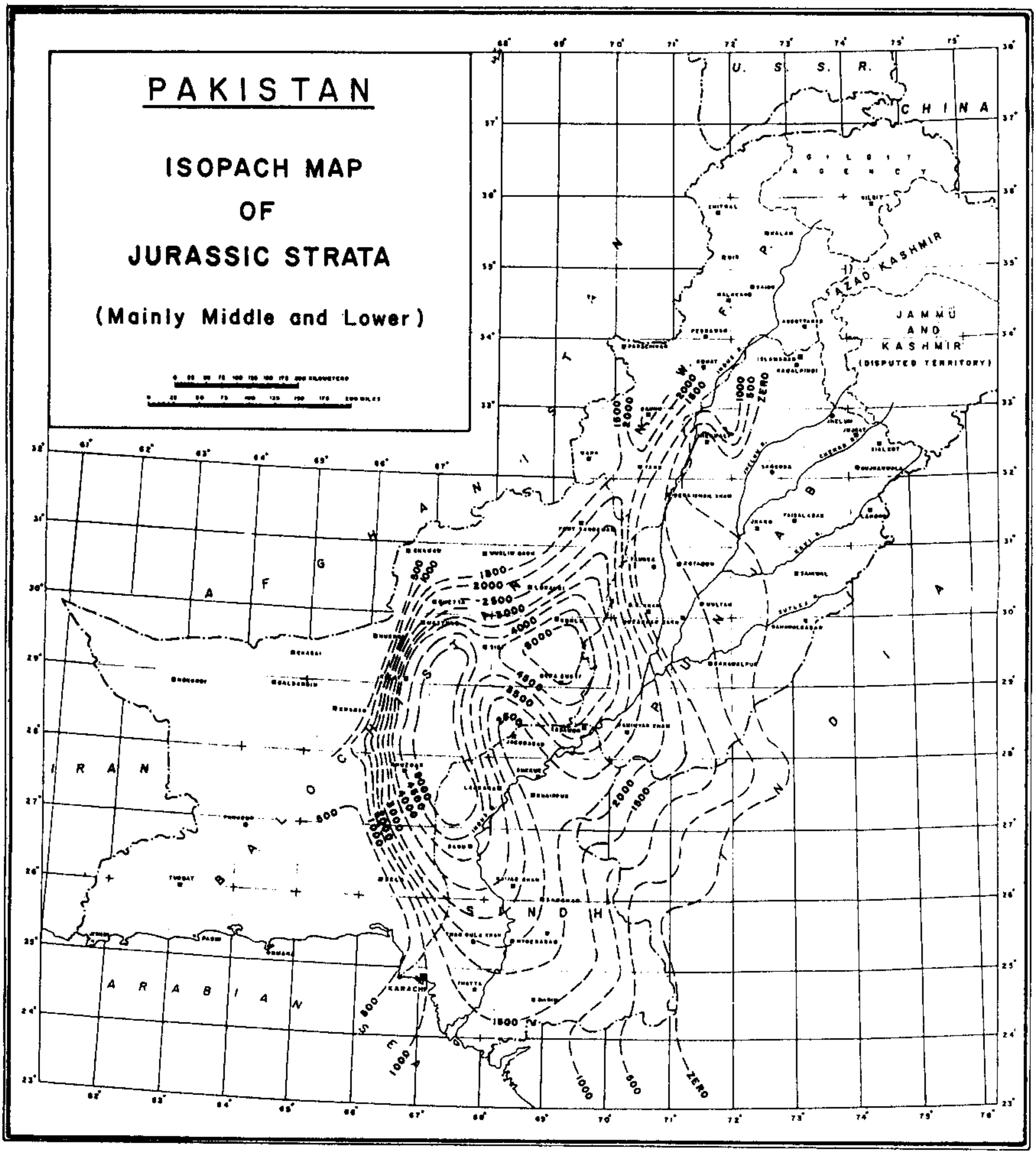

Figure - 11.1 Isopach Map of Jurassic Strata (Mainly Middle and Lower)

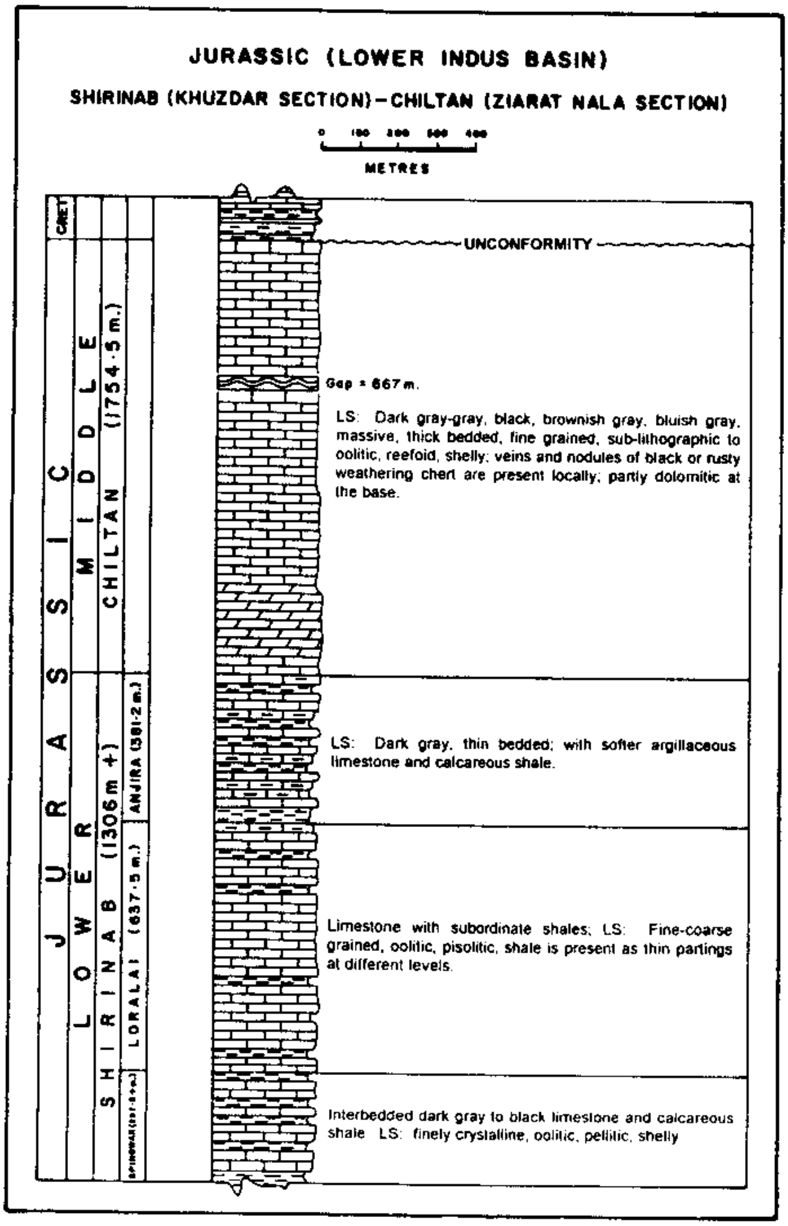

Figure - 11.2 Lithostratigraphic Column of Jurassic in Lower Indus Basin

In the Upper Indus Basin, earliest Jurassic sediments are absent due to regional uplift at the end of Triassic. The advent of Jurassic in this region is marked by a large deltaic setting, of which mainly delta front bodies are exposed. Texture and structure of the sand bodies of Datta Formation is indicative of their distributary channel deposition. These sands are usually overlain by overbank deposits. Presence of organic matter, rich black clays and coal disseminations indicate neighbouring swamp environment. Large thicknesses of Datta Formation are exposed in Marwat Range which marks the depocenter of this formation.

Deposition of Datta Formation was followed by significant sea level changes. Shinawari Formation , a thin bedded limestone and shale sequence with intercalations of sandstones is indicative of sea level changes with sea gradually getting shallower. This is recorded in the upper Samana Suk Formation which includes calcirudite and oolitic limestones at the base. The supply of terrigenous material decreased which resulted in the dominance of limestones. The deposition of Samana Suk Formation also marks occasional subaerial exposures resulting in thinly penetrating lithification followed by bores. Presence of mud cracks indicates the periodic occurrence of tidal flat environment. Some cross beddings are also observed in calcarenite and calcirudite facies indicating shoaling above the wave base in longshore

Loralai and Anjira members were deposited in the eastern trough areas and biohermal and oolitic limestones in the central part. Shallow water limestones were deposited in the extreme west on a platform created by uplift of the Axial Belt. However, it is likely that further Gondwana fragmentation in Middle Jurassic (Callovian) resulted in major regression causing the absence of younger Jurassic sediments in Southern Indus Basin.

current regime. All of these evidences suggest that Samana Suk Formation was deposited in shallow carbonate shelf conditions with periodic vertical oscillation of wave base.

Jurassic period also marks the presence of many higher features on the Indian Continental Shelf in those times. This is evidenced by Lower Eocene directly overlying Jurassic in northern part of Jacobabad High while in southern part of the High, in Khairpur area, thick Cretaceous sediments are present overlying Jurassic limestones.

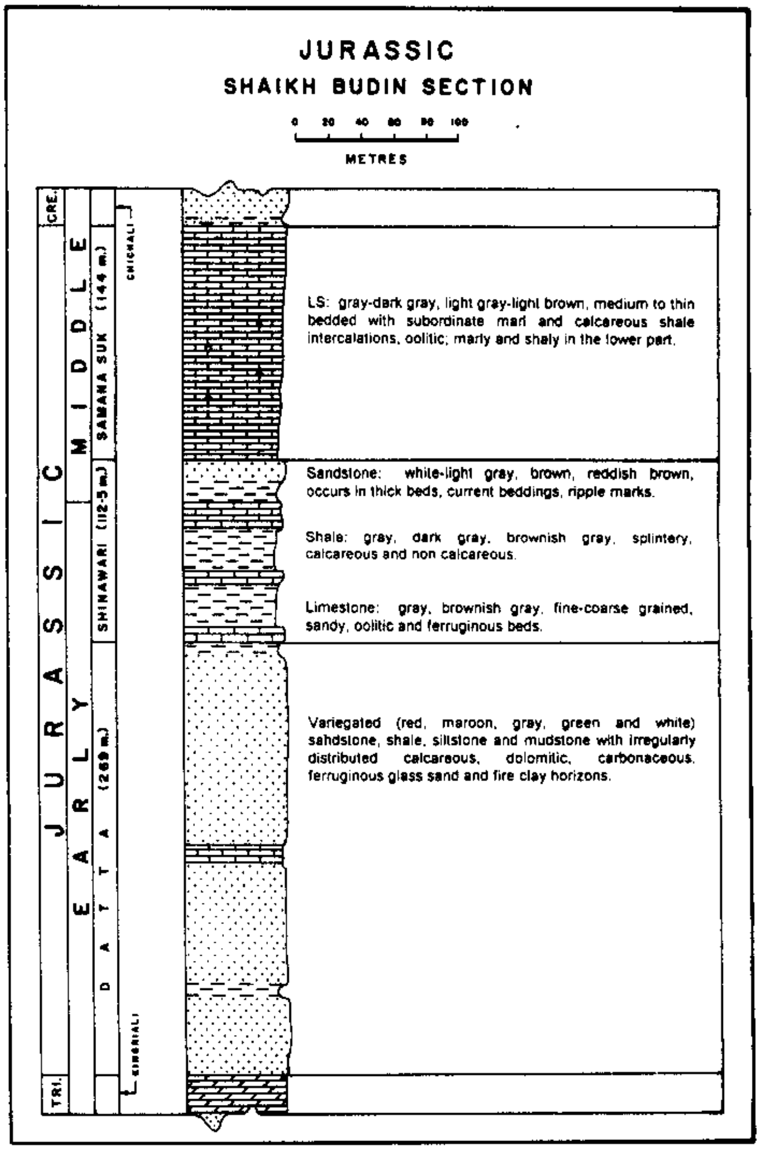

Figure - 11.3 Lithostratigraphic Column of Jurassic at Shaikh Budin Section

LITHOSTRATIGRAPHIC DIVISIONS

Southern and Central Indus Basin

Mazar Drik Formation	U.Bathonian-L.Callovian
Chiltan Limestone	M. Jurassic
Shirinab Formation	L. Jurassic

Upper Indus Basin

Samana Suk Formation	U.Bathonian-M.Callovian
Shinawari Formation	Toarcian
Datta Formation	Pre-Toarcian

LOWER INDUS BASIN

SHIRINAB FORMATION

This is widely developed in the Sulaiman and Kirthar provinces and more particularly in the adjoining Axial Belt.

It consists of interbedded limestones and shales which grade downward into a dominant shale lithology of Wulgai Formation of Triassic age. The limestone is thin to medium bedded, grey to dark grey and black. Argillaceous limestone is present at different levels and is generally associated with shale. The lower part locally includes sandstone intercalations. The associated shale is of grey to dark grey colour but occasionally orange, yellow, green and red varieties are also present.

The formation may be divided into three

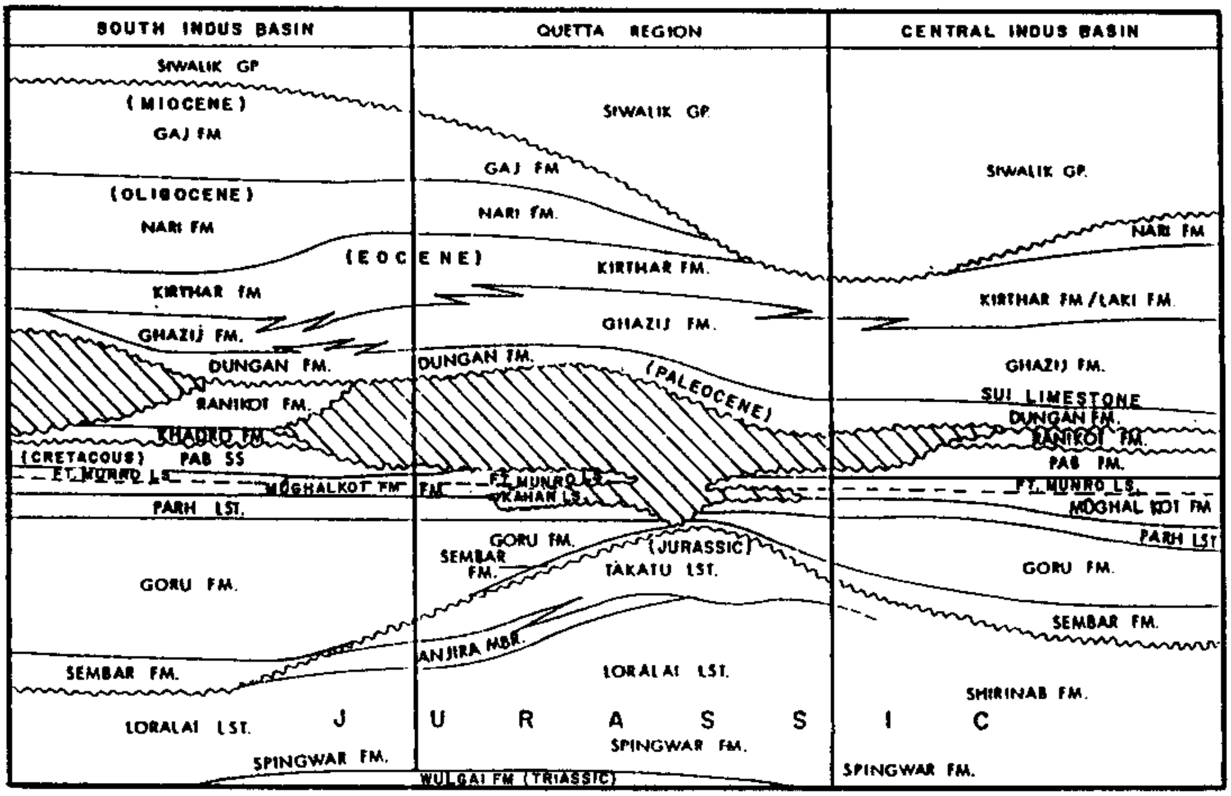

Figure - 11.4 Stratigraphic Relationship, Lower Indus Basin

members depending on the increase or decrease of shale in the generally thin to medium bedded limestone. These members are as follows:

Spingwar Member consists of interbedded dark grey to black limestones and calcareous shales. The member is 648 meters thick in the type section.

Loralai Limestone Member is distinguished from the underlying Spingwar Member by the predominance of thin to medium bedded grey, dark grey and black limestones. Shale is very subordinate and is present as thin partings at different levels. The thickness in the type section is 424 meters.

Anjira Member is recognized as a distinct unit in western Kirthar Range, south of Kalat and in the Axial Belt area around Khuzdar. The lithology is dark grey thinly bedded limestones, soft argillaceous limestones and calcareous shales. In the type area it is 90 meters thick but thickens to 367 meters in Khuzdar.

The thickness of Shirinab Formation is estimated to range between 1,500 meters and 3,000 meters

Chiltan Limestone

This is typically a massive, thick bedded, dark limestone. It contains pisolitic limestone beds locally. The texture varies from fine grained, sublithographic to oolitic, reefoid and shelly. Its upper contact with Mazar Drik Formation is gradational but in many areas this upper formation is not developed and Chiltan has direct contact with Sembar Formation of Neocomian age (Cretaceous). Its thickness is estimated to be over 1,800 meters near Quetta.

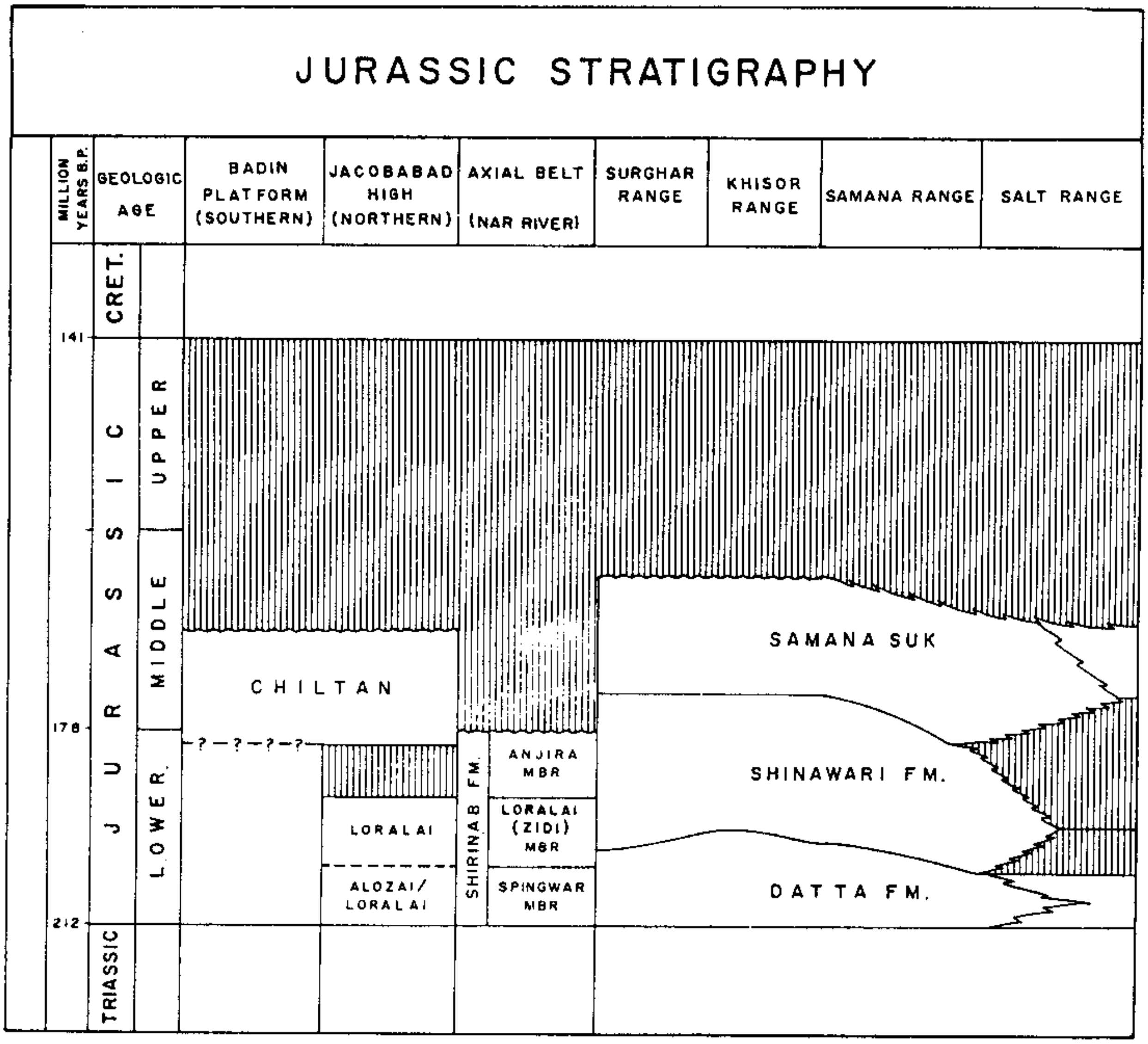

Figure - 11.5 Jurassic Stratigraphy

Mazar Drik Formation

In the type area of Mazar Drik, in the Marri hills, the formation consists of interbedded grey limestones and dark shales. It overlies transitionally the Chiltan Limestone and has an early Callovian fauna in the upper part. Its thickness in Mazar Drik is less than 30 meters The formation is not developed in Sulaiman Range.

Upper Indus Basin

Datta Formation

The Datta Formation, mainly sandstone, rests disconformably on the Kingriali Formation (Triassic). The sandstones are of continental origin, very clean and are mainly quartzose, fine to coarse grained, slightly carbonaceous and friable with very high porosity. Individual beds range in thickness up to 25 meters. Weathered surfaces show variable colours, mainly red, maroon, grey, white because of which the name 'Variegated Series' was given by earlier professionals. Each sand bed of this formation represents a fine upward cycle. The lignite and wood debris are also common. Carbonaceous, laminated and sandy shales are also found intercalated with the sandstones. Fig. 11.6 is the isopach map of Datta Formation in Trans-Indus area.

The thickness of this formation ranges from 40 meters in Dhulian oil field (Central Potwar Plateau) to over 300 meters in Sheikh Budin area (Trans-Indus Range) where the depocenter of the delta front lies (Fig. 11.6). The depositional environments of this formation are versatile and are representative of distributary channel, overbank or abandoned channel, swamp, interdistributary bay, mud flat and delta front.

Shinawari Formation

This is composed predominantly of marine shales, occasional sandstones and thin bedded limestones. These limestones range from cross bedded oolitic calcarenites to lutaceous bioclastic calcarenites. It is conformable with the underlying Datta Formation. Its thickness ranges from 150 to 180 meters in Sheikh Budin (Fig. 11.7). This formation represents the frequent fluctuations of the shelf with continued supply of terrigenous material which decreased at the top.

Samana Suk Formation

This mainly consists of thin bedded limestones and intercalated shales/marlstones. The limestones range from dense calcilutites to fine pelletal calcarenites containing occasional thin dolomites. Boring surfaces are also abundant throughout this formation. Cross-beddings are also common in calcirudites and calcarenites. Its upper contact with Chichali Formation is disconformable.

The thickness of this formation varies from 5 meters at Nammal Gorge in the

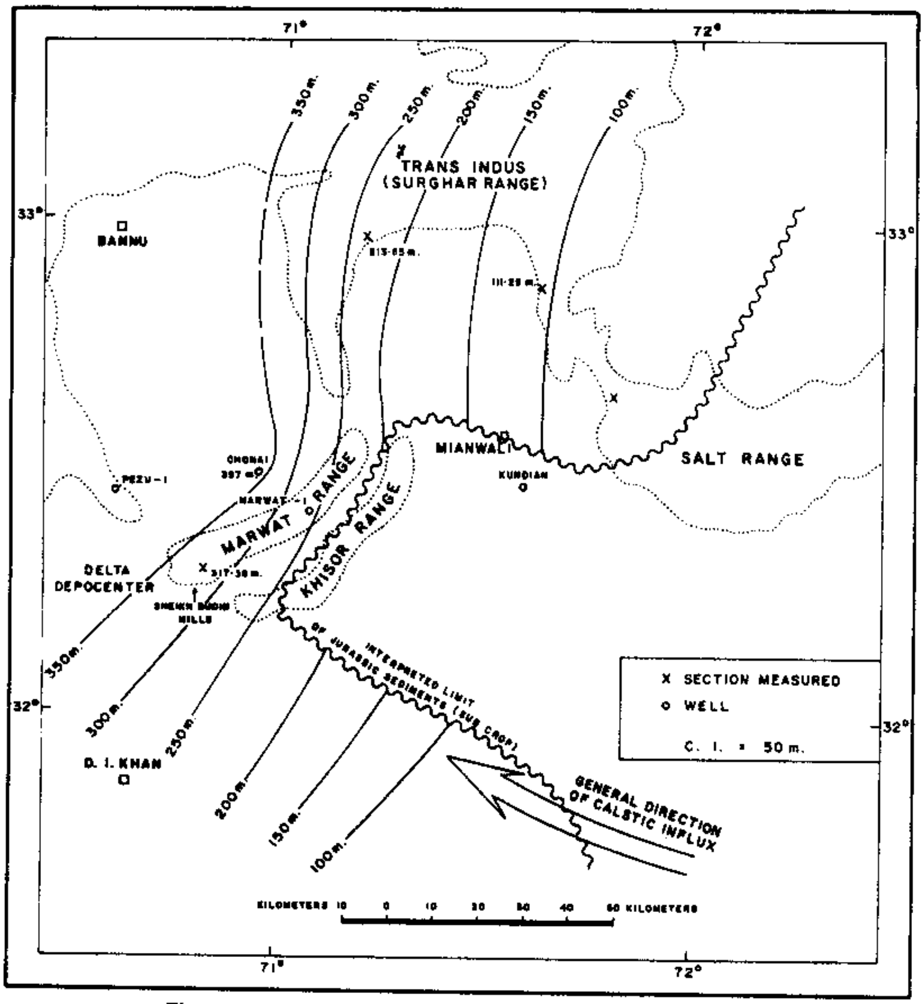

Figure - 11.6 Isopach Map, Datta Formation (Lower Jurassic) east to over 300 meters westwards in Pezu area. Fig. 11.7 and Fig. 11.8 are the Isopach maps of Shinawari and Samana Suk formations respectively.

Thinly interbedded dolomites reflect deposition under tidal conditions. The deposition of this formation also marks the occasional subaerial exposures resulting in thinly penetrating lithification followed by boring. Presence of mud cracks in calcilutites indicates the periodic prevalence of tidal flat environment.

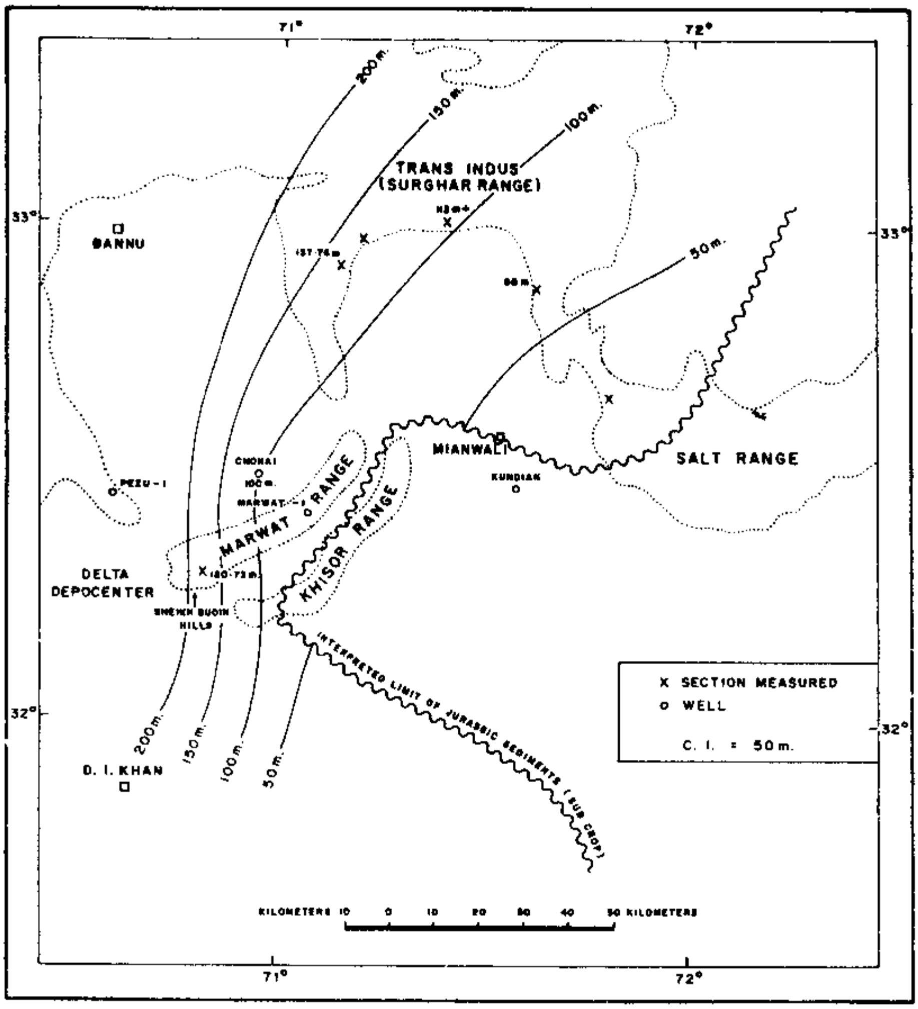

Figure - 11.7 Isopach Map, Shinawari Formation (Lower Jurassic)

CONTACTS

The contact of Jurassic and Cretaceous is very easily recognised on ditch cuttings and wireline logs as it marks an unconformity and a sudden change from clastic to nonclastic content throughout Pakistan. However, the contact between Shinawari and Samana Suk formations is transitional and is marked at the increase of the frequency of shale beds; contact between Datta and Shinawari is sharp and is recognised as the maroon silty sandstone is encountered. In the same way contact of Triassic and Jurassic is also very sharp, i.e. from clastic to a nonclastic regime. The same situation is reflected on wireline logs and use of GR (Gamma Ray), LDT (lithodensity tool) and PEF (Photoelectric coefficient) helps a great deal in differentiating these formations. Special attention should be paid to the mud properties while using PEF curve as it is greatly affected by barite in the mud system.

In the Central and Southern Indus basins, however, the formations below Chiltan Limestone have not been penetrated except in a few wells and it is difficult to establish wireline log criteria to differentiate between older units.

SOURCE ROCKS

In the Upper Indus Basin, some beds of Datta Formation represent swampy deposi-

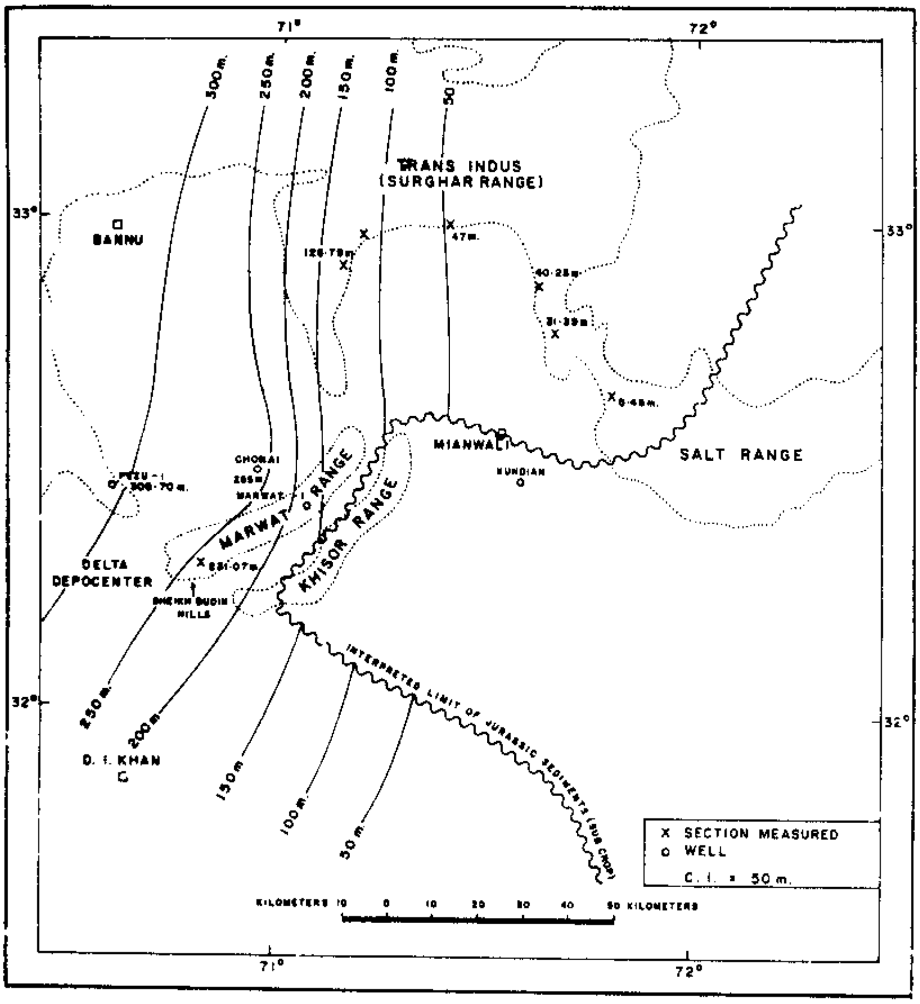

Figure - 11.8 Isopach Map, Samana Suk Formation (Middle Jurassic)

tional environment indicated by the presence of organic matter, rich black clays and coal disseminations. These beds and part of Shinawari Formation are believed to be fair source rocks of Jurassic in this region.

In the Central and Southern Indus Basin, the dark color of Loralai and Anjira members of Shirinab Formation indicates source rock richness but they need to be tested for TOC (Total organic carbon) and maturity. At places the Chiltan Limestone is also organic rich and seems to have generated hydrocarbons.

However, overall source rock potential of Jurassic in Pakistan is fair to poor.

RESERVOIR ROCKS

The Jurassic is represented by the enormous thickness of sedimentary rocks including shales, limestones and sandstones. In the Upper Indus Basin, Datta Sandstone is producing in Toot, Meyal and Dhulian fields. Very thick Jurassic exposures in Sheikh Budin Hills (Marwat Range) mark the depocenter. These delta front facies bear very good reservoir characteristics in thick sandstone beds, which are clean and quartzose. Rw values in Datta Sandstone are around 0.02 with salinity values ranging from 145,000 to 200,000 ppm NaCl.

Samana Suk Formation represents a nearshore environment which favours the development of reservoir characteristics. Some high energy facies of this formation also depict good reservoir potential, especially if fractured. The formation has matrix porosity value of 10 – 15% and contains fresh water in wells located on the Punjab Platform.

In the Central and Southern Indus Basin, Jurassic is mostly nonclastic and there are some indications of the development of porosity (10 – 12%) in Chiltan Limestone at deeper levels (more than 4,000 meters) in one of the wells. This particular facies marks the oolites shoal. Rw value range from 0.02 to 0.03 with average salinity of 140,000 ppm NaCl.

In the southern part of Southern Indus Basin (near Nabisar) clastic environment is dominating and seems to be taking over near Nagar Parkar due to the proximity of Indian Shield.

DRILLING CHARACTERISTICS

The Jurassic limestone encountered in the subsurface is extremely hard. It exhibits conchoidal fractures and is very abrasive resulting in low rate of penetration. The hole tends to be undergauge.

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12
Cretaceous

REGIONAL DISTRIBUTION

The Cretaceous system in Pakistan covers an area of approximately 280,000 sq. km; some 52% of the total prospective sedimentary basin (540,000 sq. km), and extends over a large part of the Lower Indus, Kohat and Potwar basins.

The Cretaceous outcrops extend from Waziristan (Kurram Formation) in the north to Cutch in the south, and from Jaisalmir arch in the east to as far west as Axial Belt and beyond in the Ras Koh Range of Balochistan Basin.

The Early Cretaceous marks the actual separation of Eastern Gondwanaland (India–Antarctica–Australia) from the Western Gondwanaland (Africa–South America). The greater India broke up from Eastern Gondwanaland some 120 Ma (Aptian), the time when Sembar/Goru were being deposited. The whole Cretaceous, therefore, represented shallow seas while northern floor of the southern arm of the Tethys was subducting beneath the Iran–Afghanistan microcontinent and the northern floor of main Tethys was subducting beneath the Tibetan plateau.

THICKNESS

In the Lower Indus Basin and adjoining areas of the Axial Belt, the Cretaceous sediments are several hundred meters thick (Fig. 12.1). The thickness, however, decreases considerably in the Kohat–Potwar Province. Greatest accumulation took place in Karachi sub-basin (embayment) where sediments of up to 4,500 meters thickness were deposited.

In Karachi Embayment area the Sembar and Goru are up to 3,000 meters thick but the area appears to be less active during Parh/Moghal Kot time. During Pab time this area again became locus of active sedimentation. However, about this time, Jacobabad High became more prominent and hindered any more Cretaceous sedimentation there. Cretaceous sediments thin out gradually east and west of Karachi embayment. Thick (up to 3,000 meters) Cretaceous sediments in the Sui-Sulaiman Trough are present. In Waziristan area also, large accumulations of upper Cretaceous rocks (Kurram Formation equivalent to Lumshiwal Formation of Upper Indus Basin) were deposited.

The absence of Cretaceous sediments from the sloping shelf on the Punjab platform and in the Eastern Potwar marks the limit of final regression of upper Cretaceous seas from the Indian shield area resulting in emergence and intense erosion.

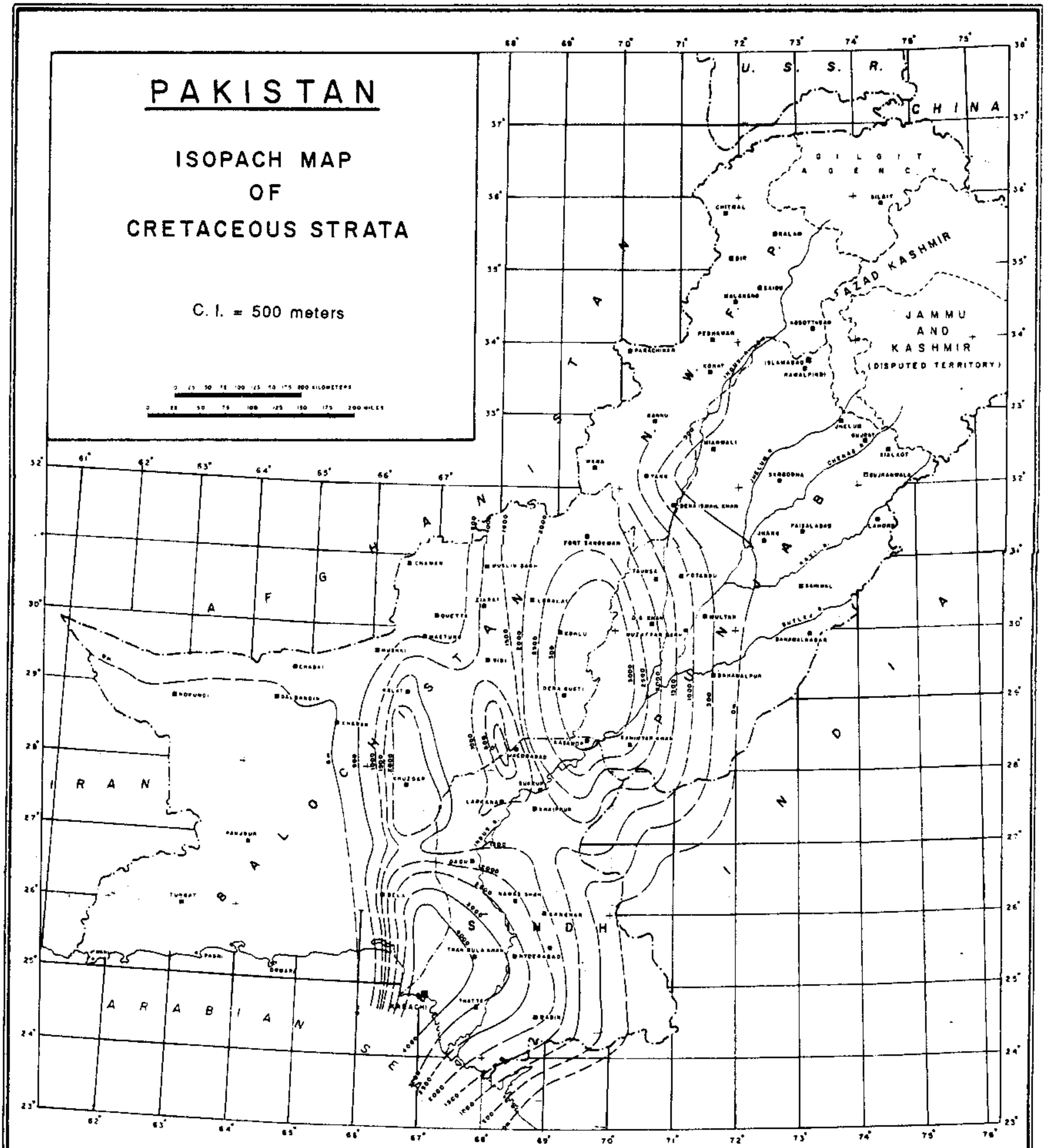

Figure - 12.1 Isopach Map of Cretaceous Strata

LITHOSTRATIGRAPHIC DIVISIONS

The heterogeneous lithological characteristics of the Cretaceous formations result from variety of provenance and different processes of sediment transport. Lithology of Cretaceous sediments vary from shale to sandstone to conglomerate to limestone.

In the Indus and Balochistan basins the following formations have been recognised in the Cretaceous:

Lower Indus Basin	
Moro Formation	Maestrichtian
Pab Sandstone	Maestrichtian
Fort Munro Formation	Late Campanian-Maestrichtian
Moghal Kot Formation	Maestrichtian
Parh Limestone	Cenomanian-Turonian
Goru Formation	Albian-Aptian
Sembar Formation	Neocomian
Upper Indus Basin	
Kawagarh Formation	Maestrichtian
Lumshiwal Formation	Albian-Aptian
Chichali Formation	Neocomian
Axial Belt	
Bela Volcanic Group	
Balochistan Basin	
Humai Formation	
Sinjrani Volcanic Group	

Fig. 12.2 is the chronostratigraphic correlation of Cretaceous units across Indus Basin.

In most areas Lower Cretaceous rocks are mainly arenaceous and argillaceous in the lower part, followed by marine carbonates and clastic sediments in the upper part.

In the Balochistan Basin, the sequence predominantly consists of carbonates with significant amount of volcanics, shales, sandstones and conglomerates.

In the Axial belt, arenaceous and argillaceous strata include both soft and hard rocks. These comprise conglomerates, shales, marls, limestones, basic lava flows, chert, serpentinite and other basic and ultrabasic intrusives. Thickness of this entity varies from 1,500 to 4,000 meters

Figs. 12.3 through 12.7 show generalized Cretaceous lithostratigraphy in Badin Platform, Southern Sulaiman Basin, Moghal Kot Gorge, Surghar Range and Samana Range respectively.

LOWER INDUS BASIN

SEMBAR FORMATION

The Sembar Formation occurs virtually throughout the Indus Basin. In isolated areas in northern Pakistan and in northwestern India, the formation is represented by beds assigned to the Spiti Shale and Guimal Sandstone. The Sembar is correlated with the Chichali Formation of the Trans-Indus and Kohat–Potwar Provinces.

The thickest sediments of typical Sembar appearance are those deposited in the apparently closed basin in Sulaiman Lobe area. The formation within this basin approaches more than 1,000 meters in thickness. In the Karachi Embayment the Sembar is over 760 meters in thickness. Eastwards, thinning appears against the Indian Shield and the Cutch positive areas, as evidenced by outcrop of Jurassic and older rocks in those areas. Possibly most of the thinning is due to erosional truncation. It is suspected that thinning due to onlap may also have occurred. Westward and northward, within the Kirthar and Sulaiman Fold Belts, Sembar sediments are also thin, primarily, it is believed, due to deposition atop positive elements in those areas and because of distance from the source of coarse clastics which in part make up the formation. Locally, unconformity appears to exist between the Sembar and the Goru and some

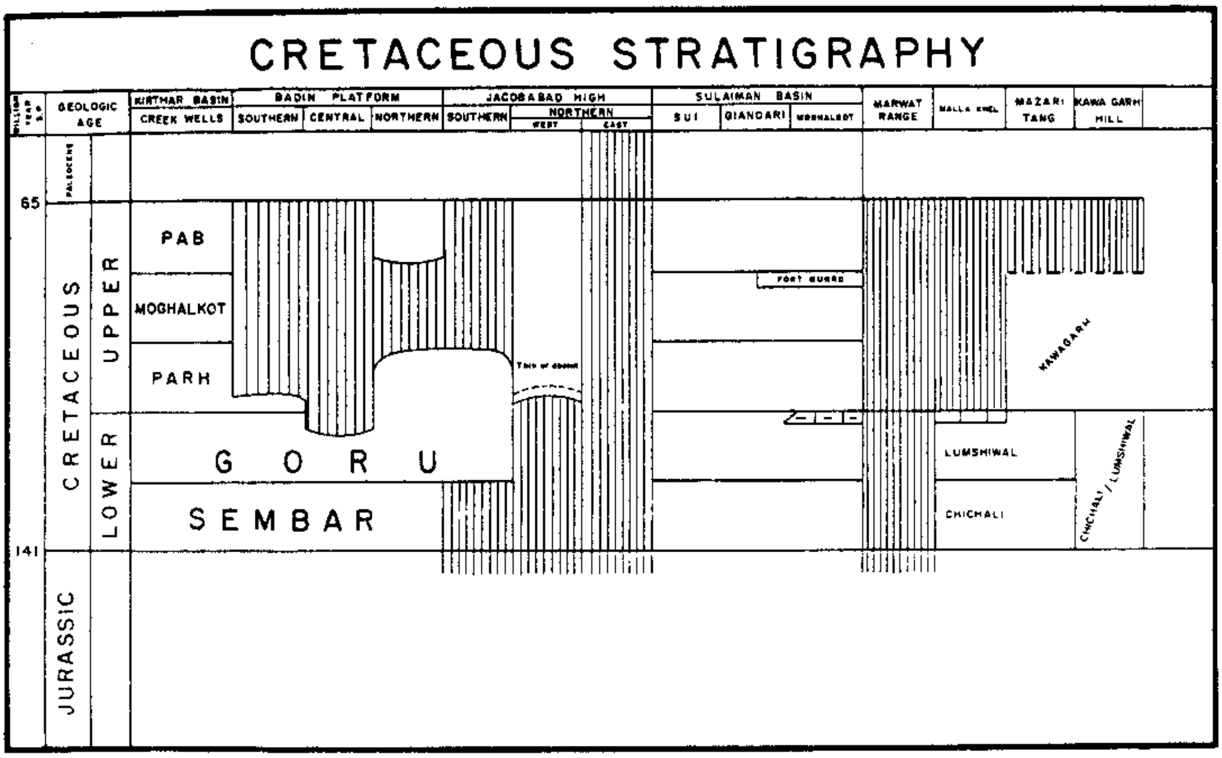

Figure - 12.2 Cretaceous Stratigraphy

thinning may be due to the pre-Goru erosion. West of the northern part of the Sulaiman Range in Waziristan area, there is an area-wise restricted basin with sediments correlated as Sembar. Being of the same age, though not lithologically similar, these red and green partially metamorphosed shales are believed to be laterally equivalent to Sembar and attain a thickness of 1,500 meters

The Sembar is composed mainly of clastic rocks, primarily shales followed by sandstones and siltstone with minor limestones. The sandstone, probably derived from the Indian Shield, is more abundant near the eastern limits of the formation, decreasing to the west; shale and siltstone units are more abundant to the west, decreasing proportionately to the east.

Characteristically the formation, in outcrop, consists of black silty shale with nodular black siltstone and limestone beds. In subsurface, considerable quantities of sandstone are also present. Glauconite is generally present in most occurrences and is characteristic of the formation.

The sand component of the formation is essentially restricted to the central and eastern portions of the distribution area reflecting proximity to the source. It appears probable that the relatively negative area of the alluvial plains may have acted as a trap for sand accumulation and that the positive areas of the Fold Belts received only the finer grades of clastics albeit in limited amounts.

The Sembar is considered to have been deposited on a broad shelf, gently sloping westward off the Indian Shield. Some silling is believed to have existed and circulation was restricted.

Numerous good source rock determinations as well as gas and oil shows have been reported from the Sembar. These sug-

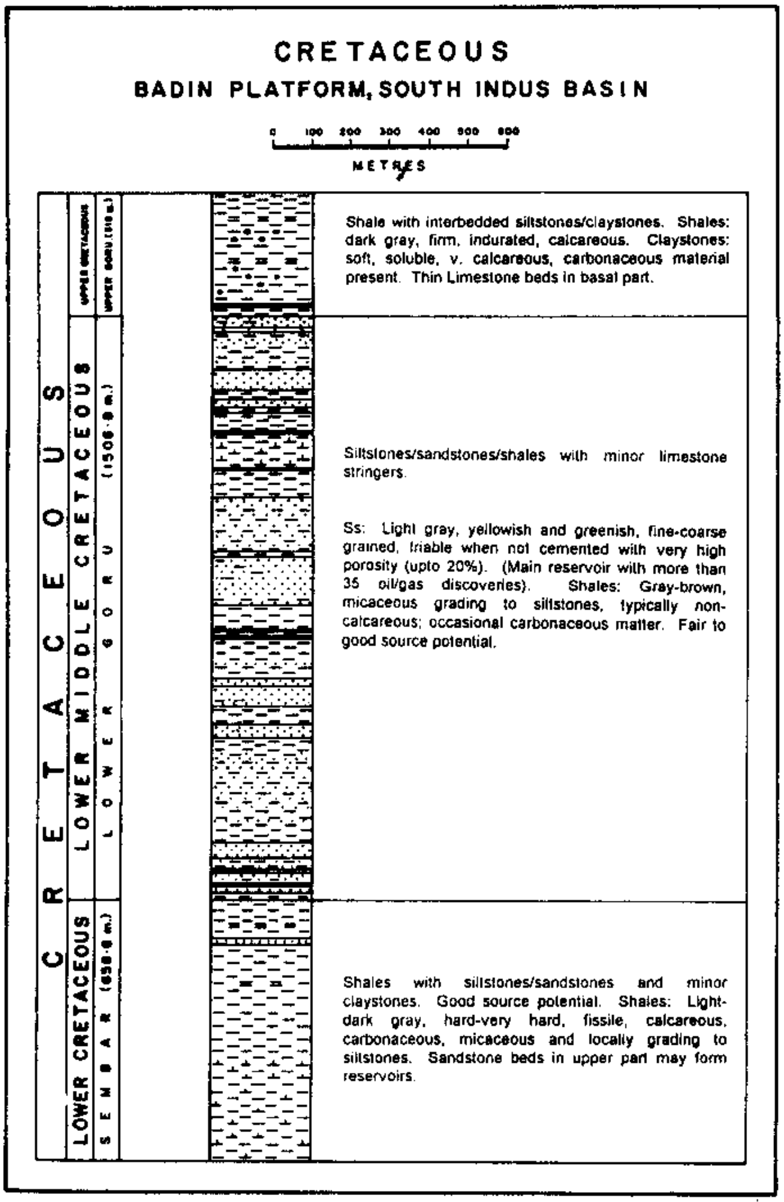

Figure - 12.3 Lithostratigraphic Column of Cretaceous in Badin Platform.

gest the presence of reducing conditions and are in agreement with other similar indications. Sembar Formation is believed to be the source of hydrocarbons in the Badin Platform fields and huge gas accumulation in Sulaiman Province. Potential reservoirs occur within the sandstones of the formation. The chances of Sembar–sourced oil migration into the underlying Jurassic formations against faults also appear to be relatively favourable.

Goru Formation

The sand in Goru is the most important entity in the Lower Indus Basin from petroleum reservoir point of view. The shales of Goru are the most widely distributed of post–Jurassic formations. It extends from Waziristan to as far south as Cutch in India.

The thickest Goru sedimentation occurs within the Karachi Embayment. Regionally the thickness increases towards the center of the Karachi Embayment. One of the wells located west of Badin Platform partially penetrated about 2,360 meters of Goru section. In the Kirthar Fold Belt, the Goru Formation thins gradually to the north while the large part of the Sulaiman Fold Belt also seems to have relatively thin Goru sediments. At least the part of the Kirthar Fold Belt north of 28° N latitude and the Sulaiman Fold Belt appear to have been relatively positive areas within Goru time and it appears probable that at this time there was already a restricted high area which divided the Balochistan and the Indus basins. Between the Duki High and the Axial Belt, east of Quetta, a subsidiary low existed in which thick deposits of Goru were laid down. These deposits differ from typical Goru, especially in colour. The formation was probably not deposited around the northern part of Khairpur–Jacobabad High; the relatively thin deposits towards south are due to Late Cretaceous or Early Paleocene erosion.

In the west, along the margin of the

Axial Belt, the formation is absent, mainly because of erosion. In the east, it is not present in Cutch and Jaisalmer area mainly due to non-deposition.

The Goru Formation is dominantly shale or mudstone, frequently calcareous. It is thin-bedded where bedding is discernible and ranges in colour from black to grey and locally maroon. Sand is rare in the upper part with increasing tendency towards base where it has developed into a producing reservoir (Lower Sindh). Only locally does limestone form a significant percentage of the formation. On the basis of its lithological content it has been divided into Lower Goru and Upper Goru. The name Lower Goru has been applied to the lower sandy member, whereas within the same area, the upper shale unit is termed as Upper Goru.

Of considerable significance is the appearance of sandstones in Lower Goru in Sulaiman Lobe to Badin Platform in the southeast. The wells drilled in Badin area exhibit a lateral facies change from east to west, from producible sand/shale sequence in Lower Goru to non-reservoir sand/shale facies, which in turn is entirely represented by shales further west. The zone of facies lateral change, from sand to shale, has been an area of major interest to oil companies as it bears all the hydrocarbon potential in Badin area and further northwards at least up to Kandhkot.

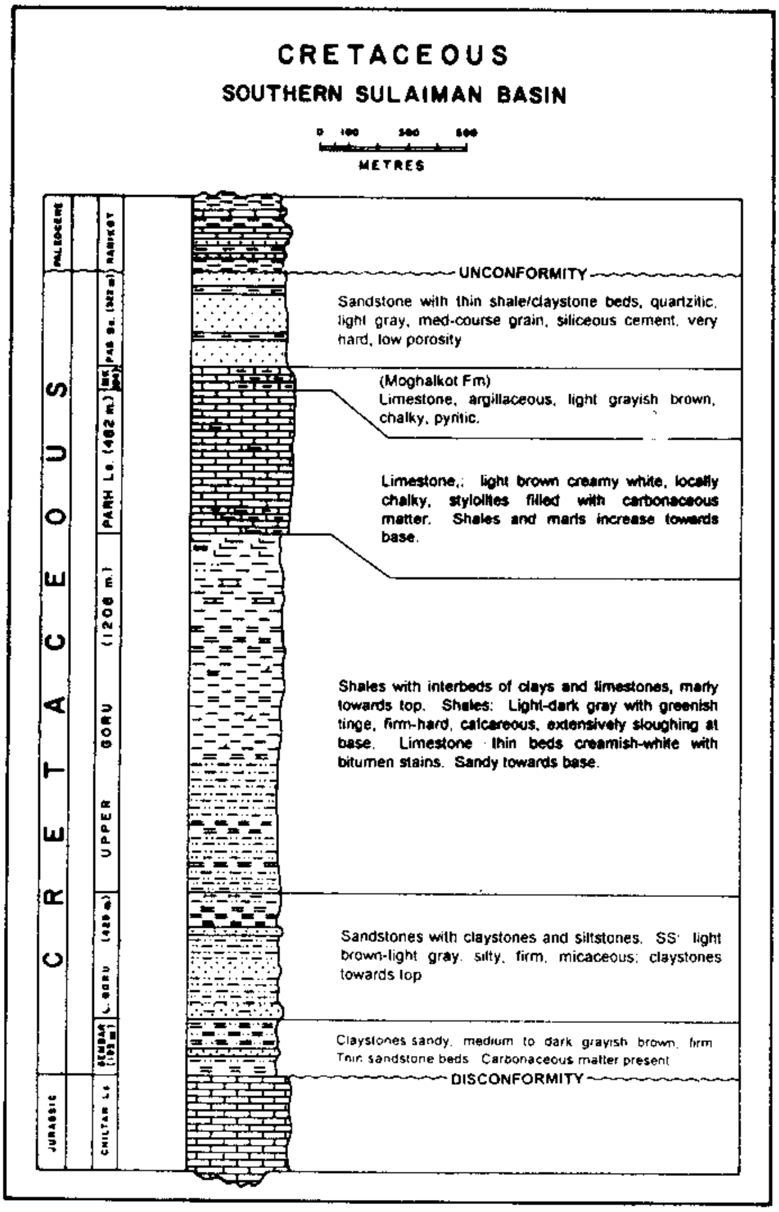

Figure - 12.4 Lithostratigraphic Column of Cretaceous in Southern Sulaiman Basin

Within the Kirthar Fold Belt, many sections show an increase in lime content and red coloration, especially near the top of the section. The cause for these facts are unknown but the former, at least, may be related simply to distance from source of clastic sediments.

Faunas within the Goru are dominantly of pelagic nature. In a reasonably complete section the sequence of pelagic faunas, which starts near the base with a dominantly radiolarian fauna, is gradually displaced above

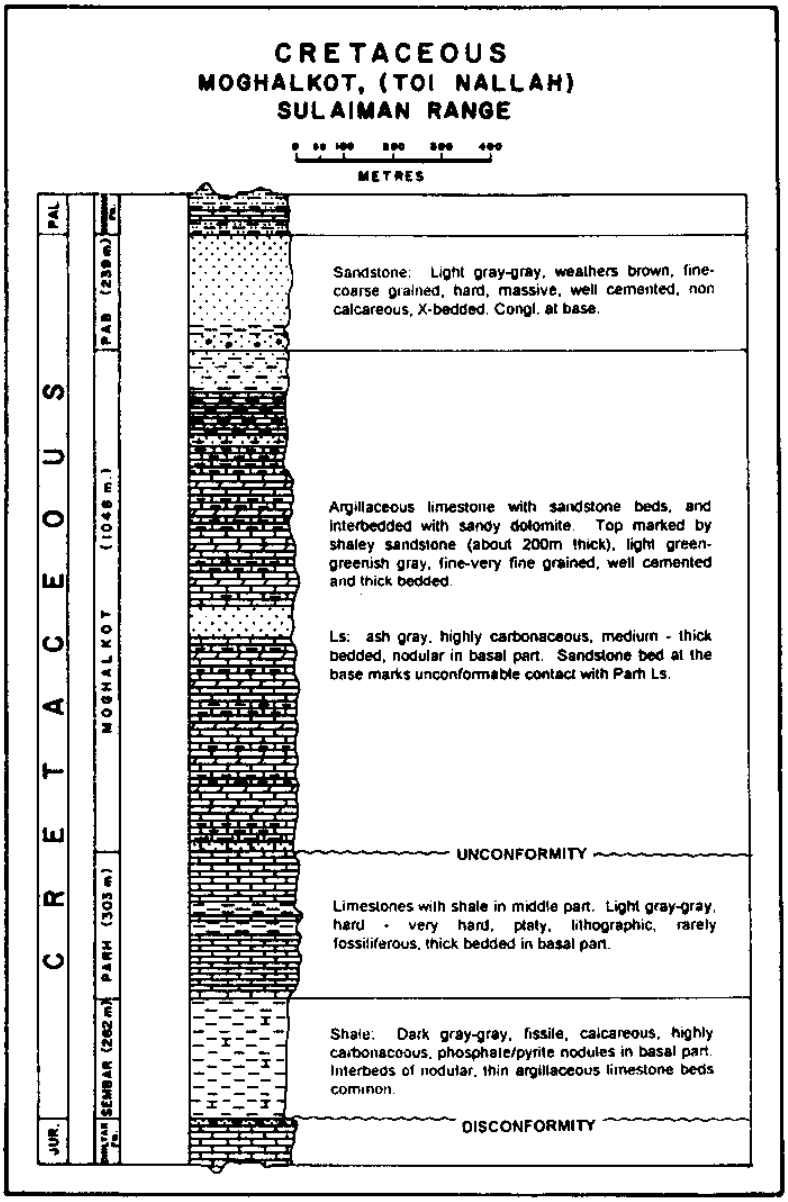

Figure - 12.5 Lithostratigraphic Column of Cretaceous at Moghalkot (Sulaiman Range)

by minute globigerinids which are in turn displaced by a Globotruncana fauna further up in the section. The increasing numbers and diversity of Globotruncana fauna culminates in Senonian times. A sharp decrease in argillaceous content marks the close of Goru time and initiation of Parh deposition. Locally, an unconformity separates the two formations but in most localities the change is transitional. Faunal control is poor in the lower portion of the Goru and, therefore, the time of initiation of Goru deposition is not exactly known. In most sections, the Albian–Aptian appears to be represented within the lower part of the formation.

Environment appears to have been generally marine with relatively deep water as indicated by the generally pelagic fauna. Minor zones with a rich benthonic fauna seem to represent local shallowing of the sea. It would appear that some restriction of circulation existed within the lower parts of the formation but, with passage of time, circulation improved to the point that open sea conditions prevailed later. Lower Goru, however, represents the environment ranging from barrier bar to lower shore facies to deltaic. Estuarine conditions are also believed to have existed, shallow enough to have permitted existence of oysters and smaller pelecypods.

The petroleum potential of Lower Goru Sand is very good as it contains all the hydrocarbons in Sindh Monocline.

Parh Limestone

The Parh Limestone occurs widely throughout the Indus Basin from the Karachi area to the southern Waziristan. Erosional truncation has generally restricted the formation to an area of distribution lesser than that of the underlying Goru and Sembar formations. Its western margin is determined by the Axial Belt.

The greatest accumulation of Parh

Limestone, approximately 600 meters, is just west of the Kirthar Range deposited in a narrow elongate north-south area. The underlying Goru Formation is generally thin in this area and possibly indicates that the locally thick Parh may be due to a facies change within the Goru as well as deposition in a depression.

Elsewhere the Parh is generally thin, though locally thick deposits in the Bugti Hills and Sulaiman Range may indicate the initial position of the Sui and Sulaiman Troughs.

The formation is thin or absent as a result of erosion over the Jacobabad High. This positive feature is considered to be primarily a post–Parh development though it may have had its initial growth in pre-Sembar times.

The absence of Parh to the east is in agreement with the concept of a truncated, westward dipping pre-Tertiary shelf, and represents the erosional and depositional limits, except towards Badin Platform where significant facies change occur in Goru lithology. The western limit of the formation represents erosion against the exposed Axial Belt in the Pab Range area and elsewhere denotes the limits of outcrops.

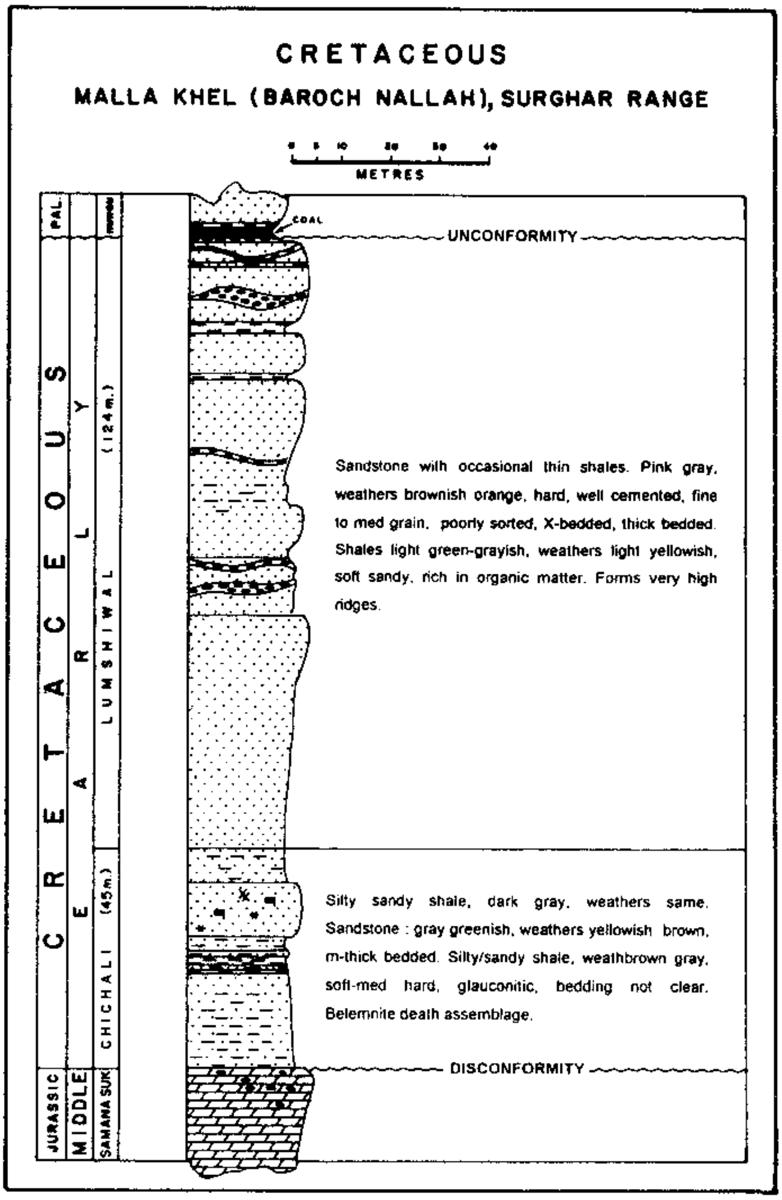

Figure - 12.6 Lithostratigraphic Column of Cretaceous in Surghar Range

The Parh is the most uniform post-Jurassic formation in the Indus Basin. It represents a light grey, white, cream to tan, thin bedded argillaceous limestone which typically exhibits lithographic to porcellaneous character and can be easily recognised in the field. In the subsurface, limestone of similar lithology but with ample shale content, is placed within the underlying Goru or overlying Moghal Kot formations. A maroon band generally occurs at or just below the base.

Abundant pelagic foraminifera characterize the Parh and indicate a Senonian age. The fauna is dominated by Globotruncana, Globigerina and Gumbelina. No macrofossils are known. The Parh consists mainly of limestone. Minor varia-

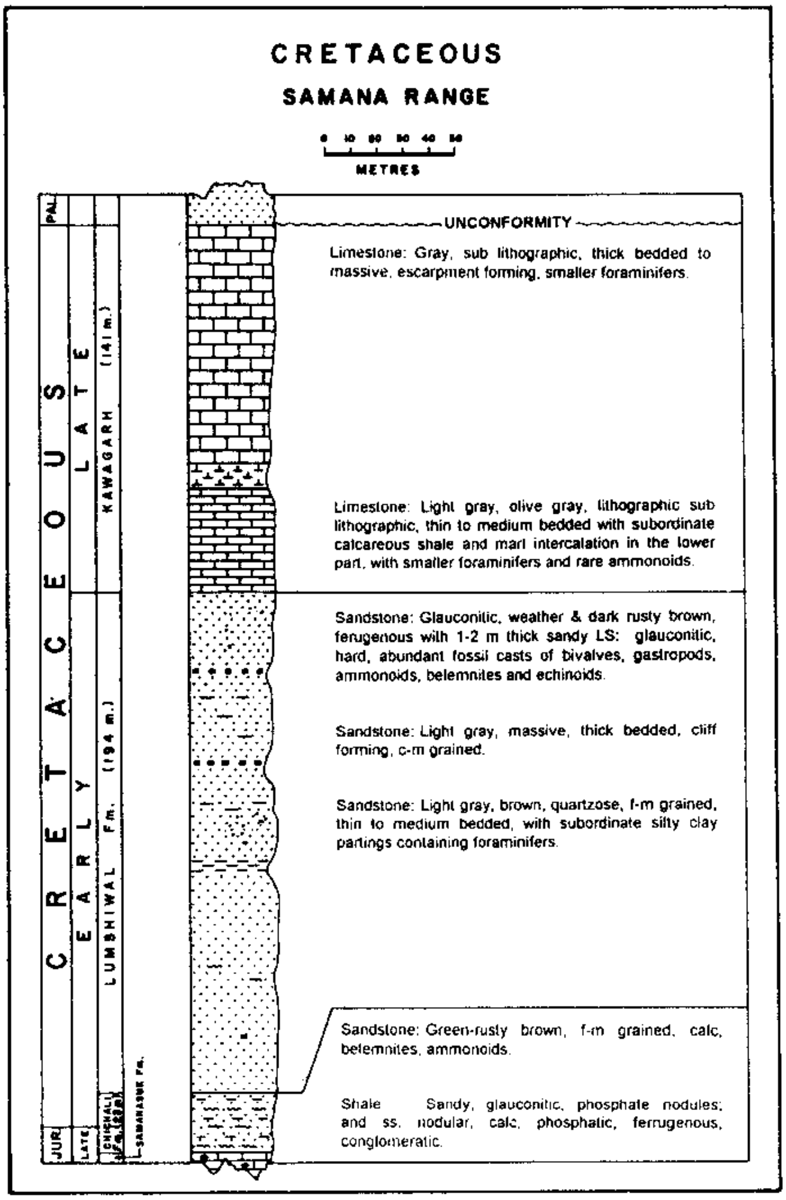

Figure - 12.7 Lithostratigraphic Column of Cretaceous in Samana Range

present limit and subsequently removed by erosion.

Both the microfauna and the micritic nature of the limestone indicate deposition far from source areas of clastic sediments, a factor which probably accounts for its overall thinness. Its widespread distribution results from a general transgression of the sea during the early Upper Cretaceous.

No oil or gas shows have been found in the Parh Limestone in the subsurface and no surface seeps are known. Abundant organic life was present during its deposition but silled basins, necessary to preserve the organic debris, are not known to have existed. The argillaceous content and compact nature of the limestone has resulted in very low primary porosity. The formation can be a reservoir through development of secondary porosity.

tions in colour and argillaceous content exist but do not appear to be of regional significance.

The Parh Limestone is considered a result of deposition in clear deep water and represents a general deepening and flooding of the lower and middle Cretaceous shallow areas. Shallow water equivalents of the limestone are possibly represented in the Southern Indus Basin and may have been deposited extensively east of the

Moghal Kot / Fort Munro Formation

The Moghal Kot Formation has a slightly more restricted distribution than the underlying Parh Formation in the Southern Indus Basin, while it extends more into the north as a narrow but deep basin. However, it is deposited in same general pattern but underlies only the small portion of the Indus plain immediately adjacent to the Fold Belt. It is limited on the west by the Axial Belt and is absent in two small areas east of Quetta.

The accumulation of only 300 meters of sediments, in the small area of Kacchi

Trough, is reminiscent of the depositional setting it established in Parh time.

Over 600 meters of strata accumulated in a large depression of the Bugti Hills oriented in a general east-west direction. This depression is a continuation of the one developed during Parh times and is the first good expression of the closed Upper Cretaceous–Paleocene basin.

Another small depression, with 600 meters of rock accumulation, lies trending east-west near Quetta. The depression is separated from the Bugti Hill region by a positive east-west oriented area.

The maximum accumulation of Moghal Kot Formation occurs in a narrow elongated 'S' shaped basin which extends from the Duki area to north of Sulaiman Fold Belt. Sediments of the order of 2,100 meters are accumulated in this narrow trough. The focus of sedimentation lies in Waziristan, the north-west extent of which falls near Khawari Kwar. Upper Cretaceous sediments do not extend beyond Khawari Kwar (33° N Latitude).

The absence of strata in the Jacobabad–Khairpur area is considered partially the result of post-Moghal Kot erosion on the Jacobabad High as well as thinning of strata over the developing uplift during Moghal Kot times.

The absence of strata in the two areas, east of Quetta, is also the result of post-Moghal Kot erosion, though the uplift responsible for the erosion developed during Moghal Kot deposition and undoubtedly caused some thinning of strata along its axis. This uplift is a branch of the Axial Belt and has been named after the village of Duki.

The eastern limit of the formation is projected on a west dipping, truncated pre-Tertiary shelf. The western edge reflects the general erosional limits south of the 28th parallel; above the parallel the general limit of outcrops control the depositional configuration.

The Moghal Kot Formation is a very heterogeneous unit. It is generally a dark grey, calcareous mudstone with scattered intercalations of quartzose sandstone and argillaceous limestone. A dark limestone, often sandy, at the top of the formation is widely distributed and has been called the Fort Munro Limestone Member. Dolomite is common in the upper part of the formation and is frequently related to unconformities in that position.

Both shallow water and deep water fauna occur in the Moghal Kot and indicate Campanian–Maestrichtian age. The shallow water fauna consist of Omphalocyclus, Siderolites, and Orbitoides. The deep water fauna consist of Globotruncana, Globigerina, Guembelina, and associated forms. Commonly, these forms are extremely impoverished and reflect very unfavourable conditions for their existence.

The lithofacies pattern of the formation is quite varied. In general, the clastics account for the thick accumulations and the carbonates, with fine clastics, were laid down in thinner sequences. Areas of predominant carbonate composition are generally those in which the Fort Munro member is best developed.

Most of the shale and sandstone were deposited in the depressions north of the Duki uplift and in the northern part of the Bugti Depression. These depressions acted as settling basins for the clastics, particularly the one immediately north of Duki Uplift.

Shale accounts for the thickest

sequences in the Sulaiman–Waziristan Trough and Kacchi Trough. Northern Bugti Hill area also had attracted considerable amount of shale.

The limestone increases in amount away from the main areas of clastic deposition. Only in the depression in the Bugti area did sequences, containing limestone, accumulate in great thicknesses.

Most of Moghal Kot deposition consisted of limestone and shale. Changes into dominantly shale deposition and dominantly limestone deposition are gradational. These are considered to have occurred in response to negative and positive areas on the sea floor.

The Moghal Kot Formation was mainly deposited in shallow water. The clastic–filled depressions (between Muslimbagh and the northern Sulaiman Range) maintained a balance between influx of detritus and subsidence. Most of the limestone (including the Fort Munro member) is of shallow water origin and its thinness indicates deposition on shelf areas or along developing positive trends. The thick limestone and shale sequence in the outer Sulaiman Lobe area was laid down on the outer shelf.

Deep sea conditions continued in the Kacchi Trough and Northern Sulaiman from Parh times. These are represented by Shelf and Slope mud and are paralleled by shallow areas developed along the Axial Belt and the Jacobabad High. The Trough probably became partially silled later during Moghal Kot deposition.

A prolific oil seepage from the Moghal Kot / Pab Sandstone contact occurs in a water course near Moghal Kot village. Gas accumulation was established in Jandran well (Amoco). Indications of silled conditions, necessary for generating hydrocarbons, are present in Sulaiman Range and Kacchi Trough. The Jacobabad High is updip from the trough and any hydrocarbons sourced in the trough could accumulate along its west flank. Similarly deep sea facies in Sulaiman Range may have generated hydrocarbons to fill the turbidite sand reservoirs within. Additionally, in the general area of the Bugti Hills, conditions of restricted circulation are believed to have existed, especially near the end of Moghal Kot times. Fauna, however, are impoverished, except in the Fort Munro member. Elsewhere the strata of the formation were deposited in dominantly shallow, aerated waters, not favourable for source conditions.

Fort Munro Limestone member is confined mainly to the Sui and Sulaiman Trough areas. Locally, the Fort Munro is faunally rich and contains potential reef–building organism. This fact, plus the existence of the overlying Pab Sandstone which could serve as a reservoir, makes this portion of the section appear favourable from the standpoint of petroleum potential.

Pab Sandstone

The Pab Sandstone occurs in two large separate areas and is areally the most restricted of the Cretaceous formations. The southern area extends from Karachi to the Kirthar Range. It underlies the Indus Plain only in a small area north of the Laki Range and extending east of Khairpur–Jacobabad High. It is bounded on the west by the Axial Belt area. The northern area extends from north of Khairpur–Jacobabad High through Sulaiman Lobe to Waziristan and Kohat. The formation is absent in the Sibi re-entrant, Trans-Indus Ranges and Potwar.

The Pab Sandstone was deposited in excess of 300 meters in an elongate, northeast-southwest oriented broad depression now represented by Sulaiman Range area. This depression, though probably genetically related to the Moghal Kot basin, may represent a lateral gradation between the two formations as indicated by thickness relations.

The thickest sequence of Pab accumulated adjacent to the Axial Belt in the area north and northwest of Karachi. Over 1,200 meters was deposited in a narrow northwest–southeast oriented depression. The eastward thinning from this depression is accompanied by an increase in thickness of the underlying Moghal Kot Formation and indicates that thinning of the Pab may be by lateral gradation into the Moghal Kot rather than against a positive feature.

Absence of Pab Sandstone on Punjab Platform supports the concept of truncated pre-Tertiary strata west of Indian Shield. The depositional limits of Pab Sandstone are along the flanks of Sibi re-entrant in Central Indus Basin. West of the Pab Range the formation is absent and marks the edge of Indian Plate.

The Pab is light grey to light tan to brown, quartzose, fine to coarse grained, hard to soft sandstone. It is occasionally conglomeratic and generally cross-bedded. Thin intercalations of dark grey shales are common and in the south it locally contains interbeds of argillaceous, micritic limestone.

Sandstone accounts for most of the lithology and comprises all of the formation in the Sulaiman Range area as well as most of the formation in the south.

The sandstone component of the Pab is not known to contain any fauna. A Globotruncana fauna characterizes the micritic limestone interbeds and indicates a Maestrichtian age. The Pab is considered to have been deposited in shallow water, not far removed from shore line and suggests a continuation of the shallow water environment characteristic of the Moghal Kot deposition. Locally in the south, deep sea strata are present within the Pab Formation.

In the Moghal Kot seepage area, most of the oil seeps from the Pab. Pab Sandstone also forms petroleum reservoir at Pirkoh, Loti, Dhodak and Rodho fields.

The formation is considered to have no source potential.

UPPER INDUS BASIN

Cretaceous period is also represented in Upper Indus Basin. These rocks are largely missing from Eastern Potwar Plateau but are more completely present in the northern and western part. The absence/small thickness of Cretaceous rocks in this basin is attributed to the erosional truncation. The period has been mainly divided into following formations:

Kawagarh Formation	Late Cretaceous
Lumshiwal Formation	Early Cretaceous
Chichali Formation	Late Jurassic to Early Cretaceous

Chichali Formation

The formation is exposed in Western Salt Range, Samana Range, Surghar Range and Sheikh Budin Hills near Pezu. Chichali Pass in Surghar Range has been designated as its type section where it is 48 meters thick.

The formation consists of sandstone which is dark green, greenish grey, glauconitic and fossiliferous with shale which is dark grey, bluish grey, greenish grey, sandy, silty and glauconitic.

Three distinct members have been recognised in Western Salt Range, Trans-Indus Ranges and Samana Range (Kohat). The lower member is sandy glauconitic shale with phosphate nodules; Middle member is dark grey glauconitic, calcareous and fossiliferous sandstone; Upper member is glauconitic sandstone which is generally unfossiliferous but locally with some bivalves and ammonities.

Owing to its deposition in reducing environments, the formation bears source rock characteristics.

Its upper contact with Lumshiwal Formation is conformable and gradational while its lower contact with Samana Suk Formation is disconformable.

The formation is correlated with Sembar Formation of Lower Indus Basin.

Lumshiwal Formation

This formation is also exposed in Western Salt Range, Samana Range, Surghar Range and Sheikh Budin Hills and has also been encountered in some wells drilled on Punjab Platform. Its thickness in type locality, Lumshiwal (Salt Range), is 120 meters.

The formation consists of sandstone which is light grey, thick bedded to massive, current bedded, feldspathic, ferruginous and contains carbonaceous material in the upper part. Subordinate shale is silty, sandy and glauconitic.

In Trans-Indus Range, it is of continental origin but elsewhere it is marine containing siltstone and shelly limestone. In Samana Range, lower part is fine to medium grained, thick to medium bedded consisting of quartzose sandstone with subordinate clay partings.

The formation bears good reservoir characteristics and has been established to contain gas in Panjpir and Nandpur gas fields.

Its upper contact with Kawagarh Formation in Hazara–Kohat is disconformable while its lower contact with Chichali Formation is conformable and gradational.

It is correlated with Goru Formation of Lower Indus Basin.

Kawagarh Formation

This formation is developed only in Kohat, Kala Chitta, Nizampur and Hazara. Kawagarh Hills, north of Kala Chitta, have been designated as its type locality where the thickness ranges from 40 meters to 70 meters.

The formation consists of dark marl, calcareous shale, and nodular / argillaceous limestone.

In the type locality two members, lower Challor Silli and upper Tsukail Tsuk have been recognised.

In Hazara, upper part is arenaceous and named as Nara Sandstone. In Eastern Kohat, lower part consists of dolomitic limestone. In West Samana Range, limestone is typically lithographic to sublithographic, grey, olive grey, light grey with marl and shale.

Its upper contact with Hangu Formation (Paleocene) is disconformable while the lower contact with Lumshiwal Formation is also disconformable in Hazara–Kohat.

The formation is correlated with Parh Limestone, Moghal Kot Formation and Pab Sandstone of Lower Indus Basin.

CONTACTS

The Cretaceous/Jurassic contact is disconformable in the Indus Basin. The end of Jurassic is marked by a regressive phase and the Early Cretaceous represents a transgressive phase, thus the contact is easily discernible in the outcrops, ditch cuttings and on wireline logs. The shaly response on the logs is very characteristic of Early Cretaceous sediments.

End of Cretaceous (Mesozoic era) marks a worldwide regression and as such continuous sedimentation from Maestrichtian (Upper Cretaceous) to Danian (Basal Tertiary) is very rare in the world. Cretaceous/ Tertiary contact in Karachi Embayment and South Lasbela area, however, indicates continued sedimentation. In South Lasbela, a stratigraphic entity, Korara Shale, marks uninterrupted sedimentation from Maestrichtian to Danian. This is recognizable only on the basis of fossil assemblage. The upper contact of Cretaceous with Paleocene is an interesting phenomenon observed in Pakistan. It has economic importance as the contact is marked by laterite, bauxite, coal and iron deposits in different parts of Pakistan.

Since Top Cretaceous is generally marked by regressive phase and Basal Tertiary by transgressive seas, their contact is very easily recognised on ditch cuttings and wireline logs.

UNCONFORMITIES

Cretaceous spans over about 65 million years which was mainly controlled by northward drift of Indian Plate and its convergence towards Eurasian Plate. It is, therefore, marked by several sea level fluctuations and climatic changes. These changes account for several unconformities of local and regional nature.

Regional unconformities exist between the Pab Sandstone and the overlying Tertiary towards south, whereas in northern part of Pakistan the Tertiary is underlain by Lumshiwal Sandstone and the Kawagarh carbonates.

The absence of Pab Sandstone west of Jacobabad High would indicate an unconformity between Moghal Kot Formation and the directly overlying Tertiary rocks. Late Cretaceous/Early Tertiary erosion was very pronounced locally along the edge of the Indian shield in area around Khairpur–Jacobabad High.

These unconformities are likely to have played important role both in the erosion of seals resulting in destruction of accumulated hydrocarbons and in providing pathways for migration of hydrocarbons generated later.

SOURCE ROCKS

Beginning of the Cretaceous marks the worldwide rising of the sea level which made the organic life flourish. Furthermore, basin wide anoxia caused preservation of organic matter. Time and temperature conditions were also favourable to turn this preserved organic matter into hydrocarbons.

Cretaceous shales of Sembar, Goru and Moghal Kot Formations are both widespread and thick. They contain abundant organic matter and generally exhibit good source rock characteristics. Moreover, most of the Cretaceous subcrops lie within oil window. Source rock analysis of some of the samples from Cretaceous shales indicate that they are fairly mature for hydrocarbon generation. These shales are thick enough to give rise to huge hydrocarbon reserves in the potential and producing reservoirs. The major component of Badin oil is believed to have sourced from Sembar shales. This oil was generated on platform and migrated updip; this has been proved by oil to source correlation and source rock typing.

Similarly all of the gas/gas condensate fields discovered in Central Indus Basin (Sui, Kandhkot, Mazarani, Dhodak, Rodho etc.) have the source of their hydrocarbons in Cretaceous. These are the only sediments below the reservoirs and close to these fields, which are organic rich and lie within oil/gas window. As such they could have generated large amount of hydrocarbons. The younger sediments are mature in trough areas like Kachhi, Sibi, Karachi, and Sulaiman Troughs.

In Upper Indus Basin, Chichali Formation which is equivalent to Sembar Formation also bears some source rock characteristics with the presence of coal beds and richness in organic matter content.

RESERVOIR ROCKS

The thick Cretaceous sediments present some very good reservoirs in Indus Basin. In the Central Indus Basin (Sulaiman sub-Basin), Pab Sandstone is the reservoir in Pirkoh Gas Field and Dhodak/Rodho gas-condensate fields. Moghal Kot Formation exhibits good reservoir characteristics in Jandran. The Lower Goru sands, with porosity in range 5–30%, constitute the reservoir in the oil and gas fields discovered in the Badin Platform/Sindh Monocline area. These include the oilfields of Khaskeli, Laghari, Dhabi, Nari, Mazari, South Mazari, Makhdumpur, Tando Alam, Bobi etc. and gas fields of Kadanwari and Miano.

The time equivalent of Goru Formation in Upper Indus Basin; the Lumshiwal Sandstone, constitutes the reservoir at the Panjpir and Nandpur gas discoveries in the Punjab Platform area. Lumshiwal Sandstone porosity ranges from 5 – 10% and contains fresh water. Lumshiwal Sandstone is also a potential reservoir rock in Bannu Depression area as it is widely exposed in Marwat and Surghar Ranges. This formation is underlain by Chichali Formation which also exhibits reservoir rock characteristics in its sandstone facies.

Moghal Kot Formation and Parh Limestone show good potential for the development of secondary porosity in limestone. Texture of Pab sandstones indicate good signs of primary (intergranular) porosity and potential for the development of secondary porosity. The porosity in Pab Sandstone, in discovered fields (Pirkoh, Dhodak and Rodho), ranges from 5 – 15%.

The famous Moghal Kot oil seepage occurs in the basal outcrops of Pab Sandstone which is another indication of hydrocarbon generation and its migration through permeable Pab Sandstone.

Other Cretaceous rocks with reservoir potential are possible reef and forereef facies of Parh Limestone and delta and submarine fan facies of Moghal Kot Formation.

LOG RESPONSE

As discussed earlier, the two main contacts, Cretaceous / Tertiary and Jurassic / Cretaceous, are relatively easier to recognise on logs due to sharp lithological differences. However, formation boundaries within the Cretaceous are mostly transitional and are not so easy to discern on wireline logs.

Since most of Cretaceous sedimentation in Indus Basin is marked by dominant terrigenous influx, other logging parameters like those of matrix, clay, and formation fluid are difficult to derive because of multi-mineralic nature of these sediments. It has been found that modern logging suite works very well across these sediments. This suite may include density, neutron, and other electric logs.

Rw (Resistivity of Water) values of Lower Goru in Badin area range from 0.01 to 0.06 ohm-m. Salinity ranges from 25,000 to 150,000 ppm from west to east. This variation is attributed to a dewatering of Sembar Shales in the western part where they are buried deeper and substantially thick at the expense of coarse clastics of Lower Goru sands.

Rw value of Pab Sandstone is around 0.1 ohm-m with salinity ranges of 22,000 to 40,000 ppm NaCl.

SEISMIC CHARACTERISTICS

Most of the Indus Basin is covered by single fold seismic surveys and some of the more prolific areas are covered by multifold seismic surveys. The single fold seismic survey, conducted in fifties, however, could not reliably map the events corresponding to the Cretaceous and deeper horizons in the Lower Indus Basin as the Basalt, present at the base of the Tertiary, acts as an energy barrier. Also, multiples are generated by Tertiary limestone beds. Furthermore, Mesozoic subsurface picture in the Badin Platform, with extensional fault blocks as the main hydrocarbon traps, is entirely different from the Tertiary subsurface structural style.

Modern digital recording and processing techniques have led to considerable improvement in data acquisition and interpretation which has greatly enhanced the understanding of the Cretaceous stratigraphy, particularly in the Lower Indus Basin.

In Kirthar Basin, reflections show fair to good continuity and moderate to strong amplitude indicative of high to moderate energy environment prevailing on Shelf to Platform. In Sulaiman Basin, reflectors are less continuous and show fair to weak amplitude indicative of outer shelf to slope condition. In Punjab Plain, reflectors are like those in Sulaiman Basin. In Potwar, Cretaceous sediments are too thin to show any significant seismic characteristics. The nature of seismic reflectors become complex in all of the northern areas.

DRILLING CHARACTERISTICS

Drilling rate in Cretaceous sediments is generally low because of their compactness corresponding to their age and the extent of overburden they have been subjected to. Average rate of penetration ranges from 0.5 m/hour in Sembar Formation to 7 m/hour in Pab Sandstone indicating a decrease in older sediments. Very hard and abrasive sections of Pab Sandstone result in undergauged hole.

Regardless of their consolidation/compactness, the shales (Sembar and Goru) of Cretaceous section have a tendency to slough and cave-in thus making the hole rugose. Hole rugosity affects the logging characteristics and tends to mask the information present in the peaks and wiggles of the wireline logs.

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13

Paleocene

REGIONAL DISTRIBUTION

Rocks of Paleocene age are distributed throughout the Indus Basin (Fig. 13.1) in three depositional provinces; Potwar–Kohat, Sulaiman and Kirthar. The rocks are exposed at the eastern margin of the Fold Belt and at the northern margin of Bannu and Soan Depressions in Kohat and Kala Chitta Ranges respectively. In the Lower Indus Basin, the Paleocene rocks are limited on the east by a subsurface erosional edge roughly parallel to the Indian Shield. The western limit is parallel to the Axial Belt, a belt of folded rocks that separates the Indus Basin from the Balochistan Basin. Facies changes and erosional truncations are common all across the Indus Basin.

DEPOSITIONAL ENVIRONMENTS

The end of Cretaceous and the advent of Tertiary is marked by northward journey of Indian Plate which accelerated (16 cm/yr., Powell 1979) during Paleocene. The early Paleocene (Danian) strata are present in Central Sulaiman Basin and part of Kirthar Basin; the rest of Paleocene is represented throughout Pakistan with some local unconformities.

The collision of the Indian and Eurasian Plates resulted in emergence of numerous local areas throughout the Tertiary in the Lower Indus Basin. This basin is marked by various phases of transgression and regression. Early Paleocene (Danian) transgression deposited Khadro Formation in the negative areas of Central Sulaiman (Tangi Sar/Drug Lahar, Rakhi Nallah sections) and Kirthar (Bara Nallah section) basins while other areas did not receive Danian sediments. Jacobabad High played an important role in distributing the Paleocene sediments. The Kirthar sub-Basin was the main depocenter during the Danian with predominant clastic facies. In Karachi Embayment there seems to be uninterrupted Cretaceous–Paleocene sedimentation whereby Korara Shale was deposited.

This transgression was followed by a rapid short-lived regression before the main Paleocene (Ranikot) sea transgressed and covered the whole Indus Basin. In Central and Southern Indus Basin the rocks of the Paleocene age are almost entirely of marine origin. Dominant lithology is limestone with subordinate marls and varying proportions of shale, sandstone and conglomerate. However, in part of Sulaiman Basin these are marked by predominant shale lithology suggesting an overwhelming rise of sea level at places.

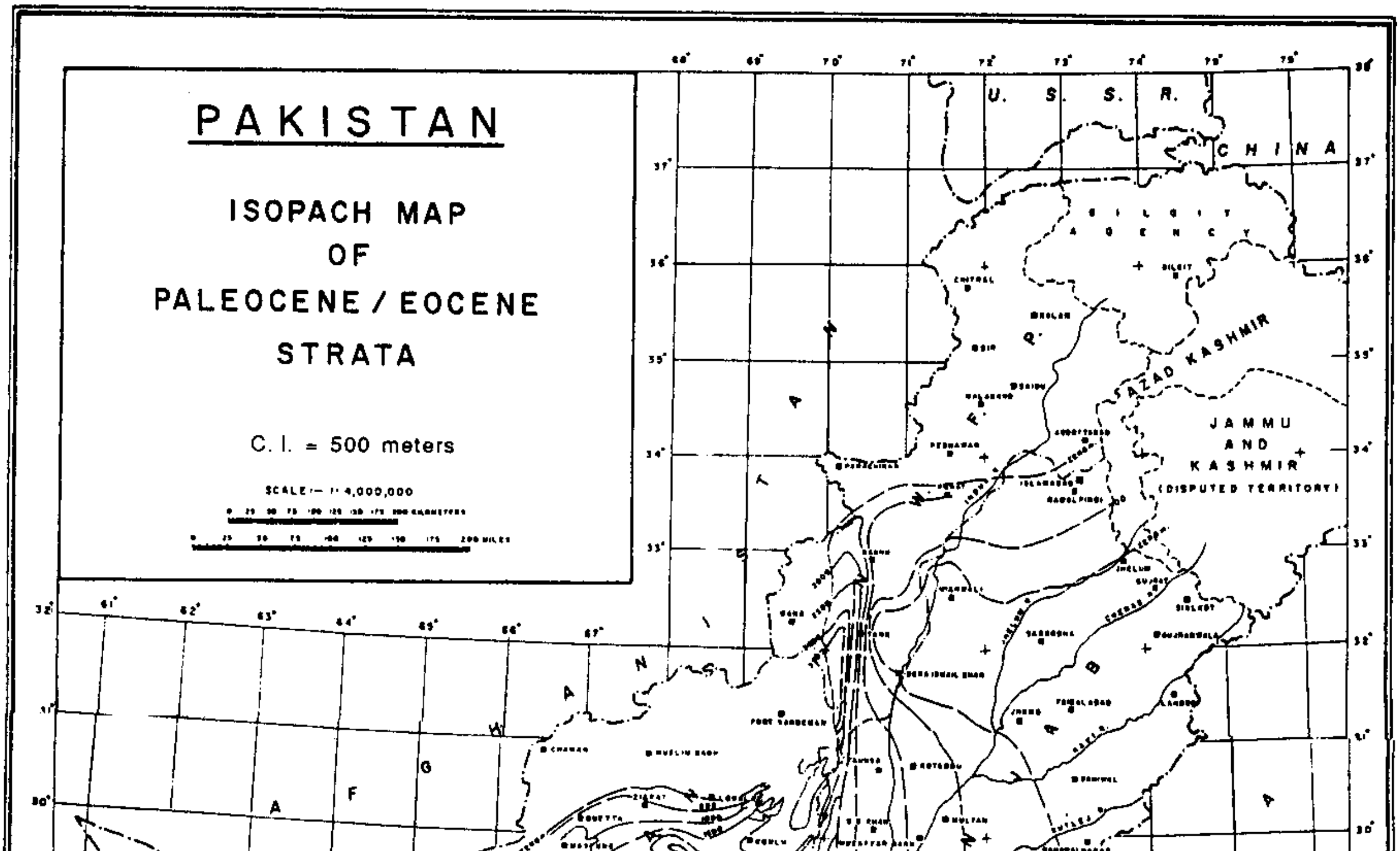

Figure - 13.1 Isopach Map of Paleocene/Eocene Strata

The Kirthar sub-Basin contains a higher proportion of clastics than Sulaiman, perhaps due to the westward extension of the Indian Shield. The sandstone/shale ratio decreases away from the Indian Shield and as discussed earlier the amount of shale increases abundantly in Rakhi Nallah, Tangi Sar section and also in Sui area.

In early Paleocene, as a result of east-west compression and north-south tension and counter clockwise rotation of Indian Plate, thoelitic basalts extruded and covered the older weathered formation of Late Cretaceous and Danian ages. This phenomenon was restricted to southern Kirthar region and Badin Platform. Early Paleocene was also the time when ophiolite melange was formed as a result of island arc-continent collision.

In Upper Indus Basin, the end of Cretaceous is marked by the northward regression of the sea. This regional emergence was probably caused by the isostatic readjustment related to the separation of the Indo–Pakistan subcontinent from Madagascar. This uplift was responsible for the removal of the sediments even down to the Cambrian at places (in the south). However, toward north in the Kohat area (Samana Range) where the uplift was not pronounced, the Upper Cretaceous strata (Kawagarh Formation) survived erosion. Following this uplift, as the continental block drifted northward, normal marine sedimentation gradually resumed in the Early Paleocene, beginning with the sedimentation of Hangu Sandstone in a coastal setting with greater marine influence in the northern area followed by Lockhart Limestone deposition in shallow water environment and that of Patala Formation in shallow marine to deltaic environment. During the last episode the Paleo–shoreline was probably overlapped by the margin of Salt Range as indicated by thin coal deposits in that area.

CONTACTS, UNCONFORMITIES AND CORRELATIONS

Cretaceous – Tertiary Unconformity

The end of Mesozoic is marked by regression of sea in most of Pakistan. This phenomenon was more pronounced in Upper Indus Basin and already positive areas (Khairpur–Jacobabad High) of Sulaiman and Kirthar basins.

In Salt Range and Potwar Plateau, this has resulted in non-deposition or erosion of not only Cretaceous but Jurassic, Triassic and Permian strata also. As seen from west to east, the intensity of erosion increases. (Refer back to Fig. 9.4).

In Kohat area, the unconformity seems to have affected the least as the upper most Cretaceous (Kawagarh Formation) underlies Paleocene.

In Central and Southern Indus basins, there are numerous indications which suggest very little gap, if any, between Cretaceous and Paleocene sedimentation. However, on Khairpur–Jacobabad High and its related structures the Paleocene strata are missing.

Stratigraphy

- Rocks of Upper Indus Basin are classified as Hangu, Lockhart and Patala formations. In the Central Indus Basin these are termed as Dunghan Formation. In the Southern Indus Basin these are grouped together as Ranikot Group which is subdivided into Khadro, Bara and Lakhra formations in outcrop sections (Bara Nai).

- Rocks of Paleocene (Post Danian) in the Eastern Sulaiman Range are mainly represented by nodular limestone and sandstone with subordinate shales in the lower part where the environment was shallower. However, Central Sulaiman Basin (Rakhi Nallah and Tangi Sar/Drug Lahar) received fair amount of terrigenous material, at the expense of continental collision, in the form of Lower Rakhi Gaj Shales which are equivalent to Dunghan limestone present in the eastern (Zindapir) and northern (Shpalai, Gat Tangi and Moghal Kot) parts of the area. Fig. 13.2 shows the above correlation.

LITHOSTRATIGRAPHIC DIVISIONS

The major Paleocene lithostratigraphic units of Indus Basin are shown in Fig. 13.3. For detailed lithologic description of individual formations, voluminous published literature is available (e.g. Stratigraphy of Pakistan by Shah, S.M.I., 1977) for reference.

SOURCE ROCKS

Except for some sandstones and high energy limestones, Paleocene presents an overall low energy and anoxic environment favouring the abundance and preservation of organic matter.

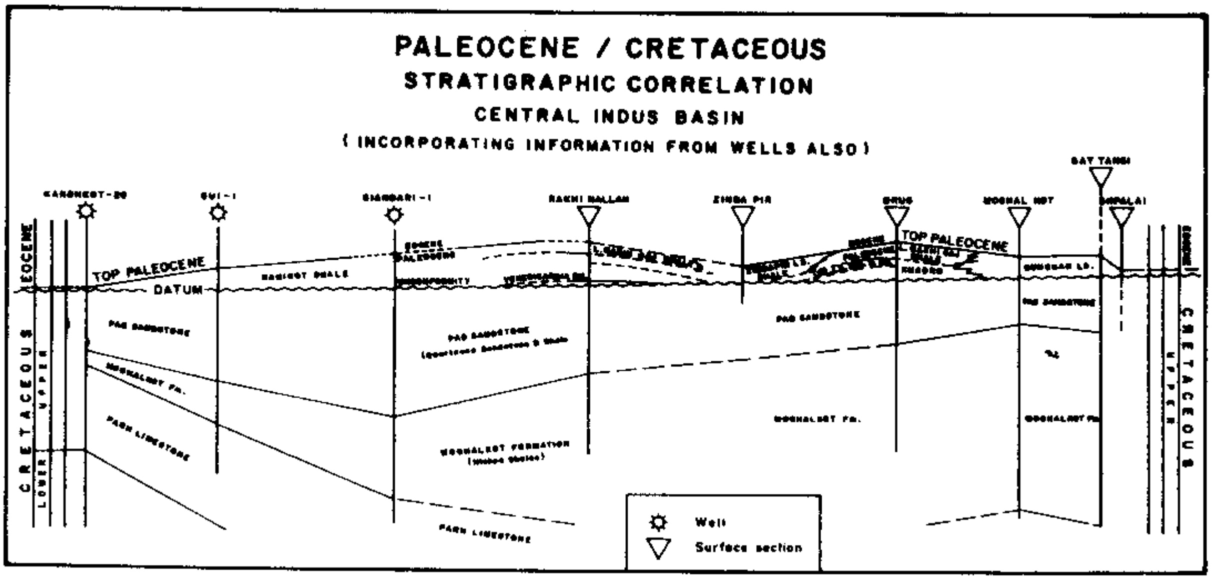

Figure - 13.2 Paleocene/Cretaceous stratigraphic Correlation in Central Indus Basin.
Note: For location see Figure 14.3

- In Northern Kohat and Northern Potwar, the Paleocene is represented predominantly by carbonate facies rather than fine clastics.
- Southern part of Kirthar sub-Basin is also characterised by the inter-multiple (up to 7) pulses of tholeiitic basalt eruption in Danian/post-Danian times.

In Upper Indus Basin, the Upper Paleocene Patala Shale is considered to be the major source rock of this region. The total organic carbon content of this formation is in the range of 0.5–3.5%. The formation was deposited in shallow marine to deltaic environment accounting for the incorporation of both terrestrial and marine organic matter. The latter gives rise to the generation of

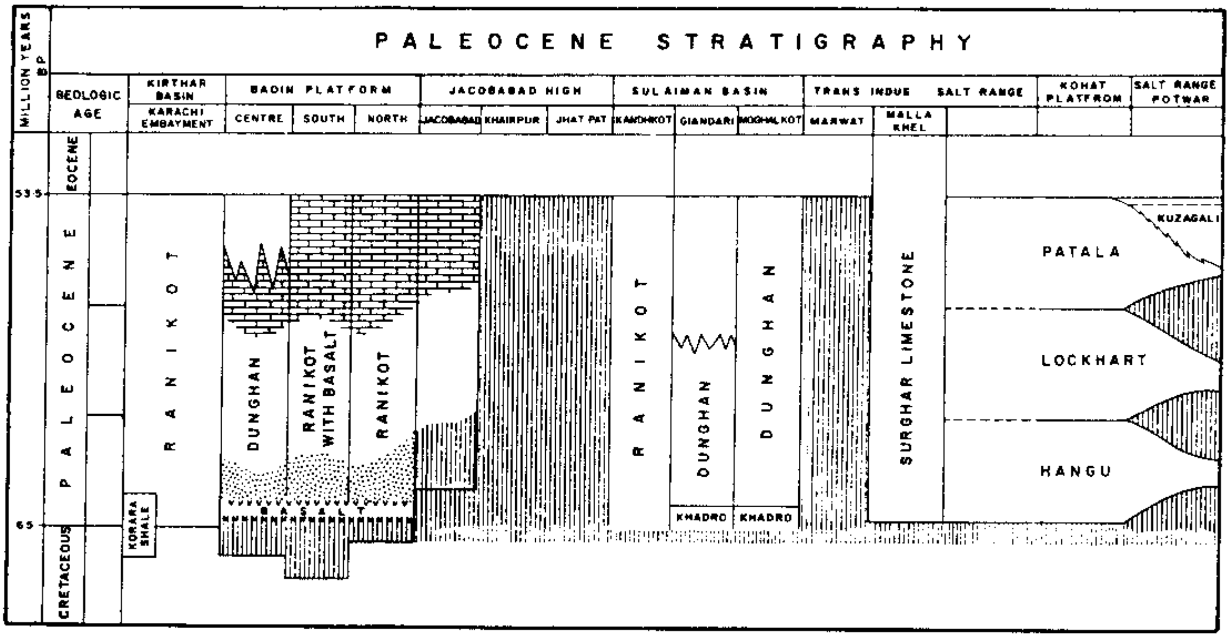

Figure - 13.3 Paleocene Stratigraphy

normal crude while the former generates gas and paraffinic crude. Hangu Formation also contains some coal seams at its base in Surghar Range and Lockhart Limestone also has fair amount of organic matter which gives fetid odour when broken or reacted with hydrochloric acid.

In Lower Indus Basin, Ranikot Shale was used to be considered as the main source for all the gas present in this region. However, this theory does not seem to hold any more since nowhere Ranikot is mature enough as to generate the thermal gas of the quality of Sui, Kandhkot, Pirkoh etc. Nevertheless, Ranikot Shales have been thrown into the oil window in trough areas (e.g. Sibi Trough, Karachi Embayment) and might have generated liquid hydrocarbons.

RESERVOIR ROCKS

Before the discovery of oil in Lower Goru sands, Paleocene rocks were considered to be the second most prolific reservoirs after Eocene. Paleocene reservoirs are productive in all parts of Indus Basin i.e. Upper Indus Basin (Chak Naurang, Dhulian, Dhurnal, Toot & Meyal), Sulaiman Basin (Dhodak & Rodho), Central Indus Basin (Pirkoh), and Kirthar Basin (Sari Singh, Hundi and Kothar).

Oil bearing Paleocene rocks in the Potwar–Kohat Province are 90 to more than 150 meters thick, with a clastic ratio of 1 or less and a sandstone–shale ratio of less than 1/4. Generally the oil zones are associated with an interbedded sequence of mostly limestone and shale with thickness of 90 meters or more. Oil has not been found in Paleocene rocks which were predominantly clastic.

Similarly, in Lower Indus Basin, hydrocarbons have been found in interbedded sequence of sandstone, shale and limestone, that has a thickness of 300 meters or more with predominance of shale.

In the north (Upper Indus Basin), limestones have both matrix and fracture porosity; fractures provide the higher fluid flow potential. In Lower Indus Basin, reservoir voidage is provided mainly by primary and secondary porosities in both sandstone and limestone.

So far the Central Indus Basin is characterised to be a gas prone province. However, the famous Khattan oil seepage (at the Dunghan/Ghazij contact) and condensate flow from Dunghan Formation in one of the Loti wells contradict this hypothesis.

Log Response

Because of typical characteristics of the lithologies of individual formations of Paleocene in Upper Indus Basin, the contacts are easy to pick on wireline logs. These characteristics are: unconformity at Paleocene/pre-Paleocene contact, sandstone/shale sequence of Hangu/Dhak Pass Formation, limestone/shale sequence of Lockhart Formation and shale/limestone sequence of Patala Formation.

In Lower Indus Basin, however, the criteria to distinguish between individual units has not been established so far on the basis of wireline logs. Their lower boundary, at most places, is marked by an unconformity and is discerned easily. The upper boundary with Eocene strata is marked on logs in the light of the knowledge from nearby outcrop sections and well to well correlations.

Log interpretation of these rocks should not be complex since there is a better control on matrix parameters because abundant data is available from surface outcrop sections. Fluid parameters may pose some constraints which can be overcome by various sensitivity runs.

Rw values for Ranikot sand (in Lower Indus Basin) are variable and go up to 0.1 ohm-m with salinity about 30,000 PPM. Rw values for Patala Limestone (in Upper Indus Basin) are also around 0.1 ohm-m and salinity range of 22,000 – 37,000 ppm Nacl.

SEISMIC CHARACTERISTICS

In the Potwar Basin and Lower Indus Basin, the top and base of Paleocene is easily recognizable on seismic data. However, the Paleocene sequence being heterogeneous and fairly thick, it is difficult to recognise each formation seismically. In those parts of the basin where the Paleocene is not well represented, it loses its seismic character.

DRILLING CHARACTERISTICS

No abnormal formation pressures or serious drilling problems have been encountered in the wells; loss of circulation is encountered in the porous reservoirs of the gas fields.

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14
Eocene

Eocene is the most important epoch in the geological history of Pakistan as it presents the highest hydrocarbon yield; especially Eocene carbonate reservoirs are commercially the most significant. This is partly because carbonate sedimentation was fairly widespread, particularly in Central Pakistan, despite the tectonic instability of the Northern Indo–Pakistani megacontinent due to convergence followed by collision.

Facies changes across the Indus Basin represent widespread carbonate platforms and shale basins with selective barred and silled basins. Due to this effect the chronostratigraphic correlation becomes a tedious yet very interesting task.

Central Pakistan was unaffected by collisional events. However, subsidence within Mesozoic rift basins continued during the Paleogene. The Indo–Pakistani continental margin in the Lower Indus Basin was not very active, during the Paleogene, being affected only by subsidence and minor localised uplifts. Paleo–highs such as Khairpur–Jacobabad and Mari–Kandhkot, (refer back Fig. 3.3) which had formed during the Mesozoic when adjoining areas rifted apart, were essentially subaqueous islands in an otherwise stable carbonate platform environments.

Carbonate sedimentation was essentially affected by sea level changes. Terrigenous input in Central Pakistan was limited to marine transgressive events when the carbonates were essentially drowned. Fine grained predominantly shale lithologies, punctuated by carbonate tempestites, were deposited as the Ghazij, Drazinda and Dozkushtak shale sequences.

REGIONAL DISTRIBUTION

Eocene strata are the most extensively developed and widespread. These rocks occur from offshore Karachi in the south to the Attock–Cherat Range in the north. Its eastern limits roughly follow the Pakistan–India geographical boundary through the Jaisalmer and Cutch areas. The western boundary is the Axial Belt which is mostly erosional/structural. The thickness of rocks ranges from few hundred meters to about 4,200m (northern Sulaiman Range). Throughout the Indus Basin the Eocene is represented by carbonates and their deeper equivalent shales with evaporites and some turbidity sand pulses. Its distribution area is almost same as that of the total Indus Basin. Fig. 14.1 shows the distribution of the Eocene outcrops in Lower Indus Basin.

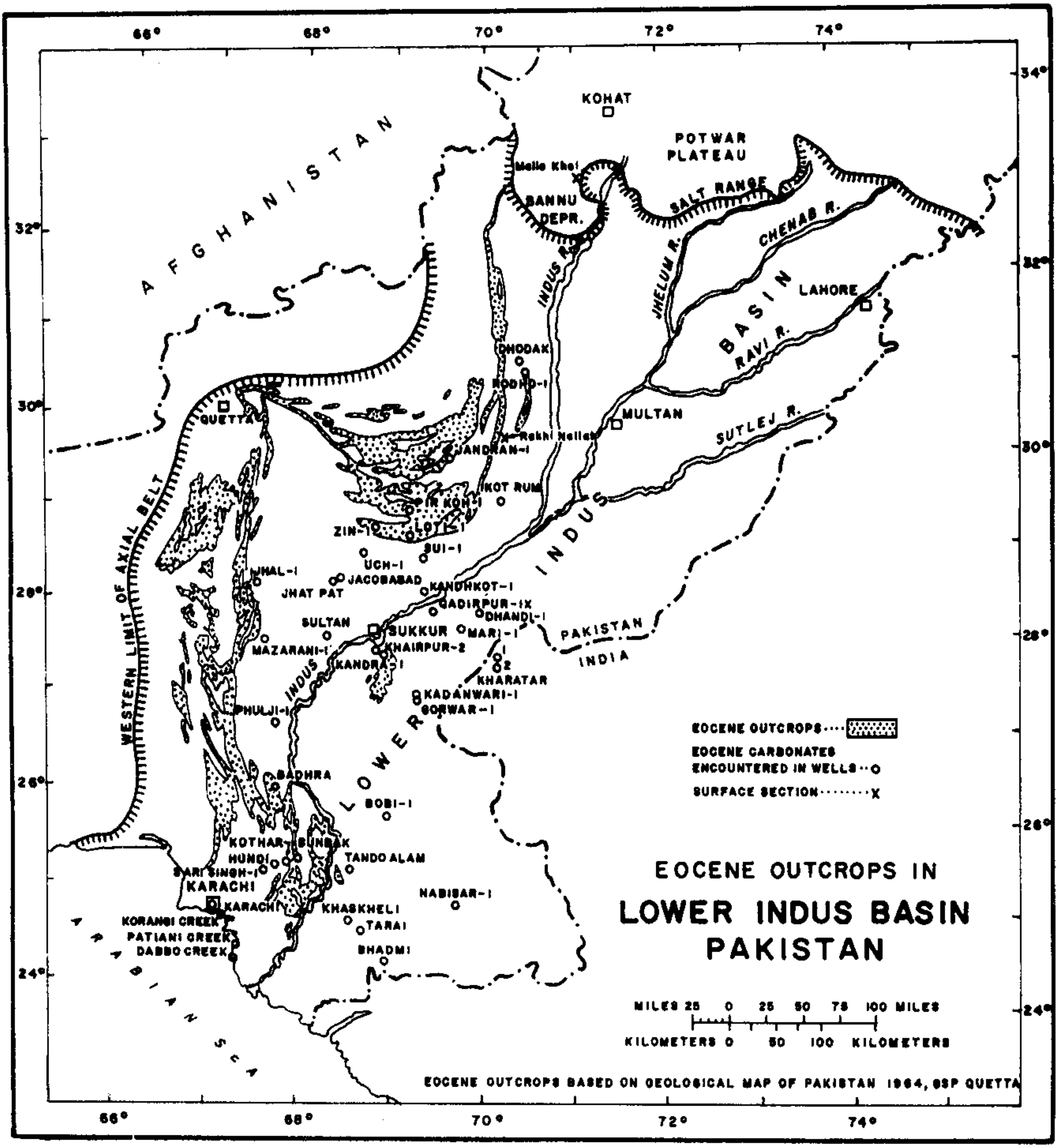

Figure - 14.1 Extent of Eocene outcrops alongwith the key well locations and surface sections, Lower Indus Basin (after Siddiqui and Khan, 1992)

TECTONICS AND SEA LEVEL CHANGES AND THEIR IMPLICATION ON DEPOSITIONAL SYSTEMS

The Eocene marks the initial contact of the Indo–Pakistani subcontinent with the Chitral/Ladakh island arc system or the southern continental margin of Eurasia. As the northward movement of India slowed down, it began to rotate counter clockwise. This caused the development of widespread and stable shallow water carbonate platforms with a few depressions in Sulaiman Basin and restrictions in Kohat Basin. This was also the time of ophiolite emplacement in the subduction zone complex in northern Balochistan.

Towards the end of the Paleocene, a second Tertiary regression is evident in most parts of the region. In Sindh and Balochistan, coal deposits were formed at this time; Hyderabad Arch became emergent and tectonically active during Paleocene period with erosion over its surface and formation of so called Basal Laki Laterites.

In the Sulaiman sub-Basin, continental collision and emergence in Early Eocene is indicated by the thickness of the Ghazij Formation (3,000 meters) in the northern Sulaiman Range which contains mudstones, siltstones and sandstones in the upper part. The mudstones and sandstones are gypsiferous and ferruginous, marking nearshore oxidizing conditions.

The detailed discussion on sea level changes and carbonate deposition in the following paragraphs is based on subsurface data from the Central Indus Basin area.

The shelf progradation of the Ranikot Sands was abruptly terminated by the Late Danian to Thanetian rise in sea level. The Ranikot strandline deposits located in a belt running through the Jaisalmer area were drowned and the transgression of Upper Ranikot Shales commenced. During this portion of the Epoch, terrigenous influx waned allowing the initiation of carbonate sedimentation to proceed as the sea level rose during the transgression. Planktonic foraminiferal lime mudstones were deposited over the Upper Ranikot Shales. The carbonate sedimentation was episodic in nature allowing alternating lime mudstones and poorly sorted foraminiferal wackestones to be deposited as interbedded sequences. This was followed by a sudden lowering of the sea level when Sui area was possibly subaereally exposed.

Study of cores suggests that algal mat development was prolific. Stromatolite facies can be recognized in cored wells at Sui. At the same time gastropods appeared as browsers to feed on the mats. Although the stratigraphic record is usually fragmentary in nature, it appears well preserved at Sui and the classic supratidal to subtidal carbonate facies can be recognized in the Sui cores.

This association of supratidal carbonates in turn was drowned by tempestites consisting of death assemblages of high spired gastropods. A 20 meters thick foraminiferal shoal facies onlapped the tempestites giving way to carbonate sedimentation that took place within the fair weather wave base being marked by several shoaling upward cycles of parasequences ranging texturally from wackestones to foraminiferal grainstones. In Sui region this megasequence consists of numerous shoaling upward cycles which attain a thickness of 400 meters.

The carbonate unit (a prolific gas producer) overlying the Upper Ranikot Shales in Sui and Kandhkot gas fields is appropriately named as 'Sui Main Limestone' by Pakistan Petroleum Limited–the discoverer of these fields. This succession of carbonates at Sui, where it is well developed, represents the subsurface 'Type Section' for the carbonate facies described herein; these are not represented anywhere in the Axial Belt outcrops. The Dunghan Formation is not equivalent to or a facies variant of Sui Main Limestone.

Onlapping the Sui Main Limestone in Sui and Kandhkot areas is a glauconitic deposit, locally termed as the Ghazij Shale. It represents a sequence that is part of the larger entity termed as the Ghazij Formation which developed, in part, at the expense of Sui Main Limestone (or vice versa), north of Zin and overlies the Sui Main Limestone. The overlying unit, already defined as the Ghazij Shale, has fewer lime interbeds in the Sui area but becomes lime dominated in the nearby area south eastwards. According to Singh (1984) this transgressive facies extends well into the Jaisalmer area in India where it is known as Khinsar Shales.

The sea level lowered briefly in mid Ghazij times. This permitted carbonate sedimentation known as the Sui Upper Limestone (SUL) to proceed once more. However, unlike the Sui Main Limestone which was exclusively a carbonate, the SUL environment allowed interbedded foraminiferal packstone/grainstone and shale/lime mudstone intervals to act as inter-reservoir seals. Thus far commercial gas in Sui Upper Limestone has been discovered only at Sui and the Kandhkot / Qadirpur complex. The Sui Upper Limestone can be recognized at Zin, Loti and Pirkoh, but does not have reservoir potential.

The end Eocene (Laki) is marked by a short period of regression followed by transgression which is represented by Baska Shales. This particular facies is widespread throughout the Sulaiman Range. It is probably equivalent to the Lower Alabaster Shales recognized in wells at Sui and Kandhkot Gas Fields where only two thin gypsum markers are encountered. (Fig. 14.2).

Tangi Sar/Drug Lahar section (see Fig. 14.3 for location) also marks the regressive depocenter during Early Eocene as limestone/shale ratio in the Rubbly Limestone Member (Fig. 14.2) abruptly increases and likewise gypsum/shale ratio in Baska Shale Member also increases appreciably. The limestone content of Rubbly Limestone Member is typical of restricted platform depositional settings which further shallowed to form an evaporite platform in Baska time.

Early Eocene in Kirthar sub-Basin is characterised by predominant limestone with subordinate shales (Laki, Tiyon Formation, Chat Beds, Meting Limestone and Meting Shale (refer back Table 5.1).

Marine sedimentation continued in Upper Indus Basin with deposition of a mainly calcareous–argillaceous sequence. The Early Eocene tends to be more evaporitic at Kohat relative to Potwar indicating the restriction of basin locally. In Kohat area, green Panoba Shales with dispersed glauconite may suggest marine stillstands. Hemipelagic deep sea clays including glauconite are deposited at very low sedimentation rates.

Towards the end of Early Eocene, there was again a wide spread but short-lived regression. In parts of Sindh, this is marked by unconformity between Laki and Kirthar; in Kohat and Potwar, it is shown by the presence of an evaporite series with gypsum or gypsiferous shales. Sulaiman Basin also has gypsum and associated gypsiferous shales (Baska Shales). In Kohat, salt is associated with such evaporites. Middle Eocene witnessed perhaps the most important and widespread of all the transgressions in the history of Lower Tertiary of the region.

In Lower Indus Basin, following the short lived regression, depocenter expanded and the Kirthar Sea transgressed into the area giving rise to the deposition of areally distinct lithological entities i.e. Habib Rahi Limestone, Sirki (Domanda) Shale, Pirkoh Limestone and Drazinda Shale (equivalent to Dozkushtak, in Sui and Kandhkot region) members of Kirthar Formation (Fig. 14.2). The lowest bed of Kirthar Formation marks the vast death assemblage of Assilines and is traceable all along the Sulaiman Range. This indicates highly prosperous conditions and then a catastrophic decline in sea level. Subsequently, environment became shallower but getting medium to deeper intermittently to deposit Domanda, Pirkoh and Drazinda Members.

The carbonate facies in the type section of Habib Rahi Limestone Member in Sulaiman Range are quite different from Central Pakistan, Kohat and Mari gas field areas. This member is also represented in Jaiselmer in India (Singh, 1984).

Habib Rahi, while also gas bearing in Sui, Kandhkot and Qadirpur gas fields, is the only gas reservoir in the Mari gas field. However, Middle Eocene is much better represented in Kohat Basin and may form a reservoir in Kohat Plateau and Bannu Depression.

Pirkoh Limestone Member is water wet in all the gasfields in Central Pakistan. Similar to the other older carbonates described above, Pirkoh limestones also consist of various parasequences of foraminiferal wackestones ranging to grainstones.

Relative to Potwar, the frontal Salt and Trans-Indus ranges facies at Kohat are more basinward and affected by uplift in Late Early–Middle Eocene times during the early stages of the Himalayan orogeny when remnants of the Tethys shrunk to the size of small brackish water bodies.

In comparison to Potwar, the Middle Eocene is far better represented at Kohat.

STRATIGRAPHIC EQUIVALENCE AND LITHOSTRATIGRAPPHIC DIVISIONS

As mentioned earlier the stratigraphic equivalence across different sub-basins is the most interesting aspect of this period. For this purpose the Indus Basin is divided into Kohat, Potwar, sub-Sulaiman, Middle Indus, and sub-Kirthar basins.

The stratigraphic variations from south to north are depicted in Fig. 14.2.

In Kohat Basin, the Eocene is represented by Panoba, Shekhan, Kuldana and Kohat formations in stratigraphic order (Fig. 14.2). The Panoba Shale shows considerable facies change from north to south. Along the northern part of the Eocene belt of rocks, the Panoba is shale; to the south its position is occupied by Bahadurkhel Salt. In Surghar Range, about 45 miles to the south, the Panoba Shale is equivalent to part of the Sakesar Limestone. Similarly the Shekhan Limestone in the northern part of the Eocene belt of rocks changes southward into Jatta Gypsum and Salt. At Surghar Range the Shekhan Limestone correlates with the upper part of Sakesar Limestone.

In Potwar Basin, only Early Eocene is present and is represented by Nammal, Sakesar and Chorgali/Bhadrar Formations (Fig. 14.2).

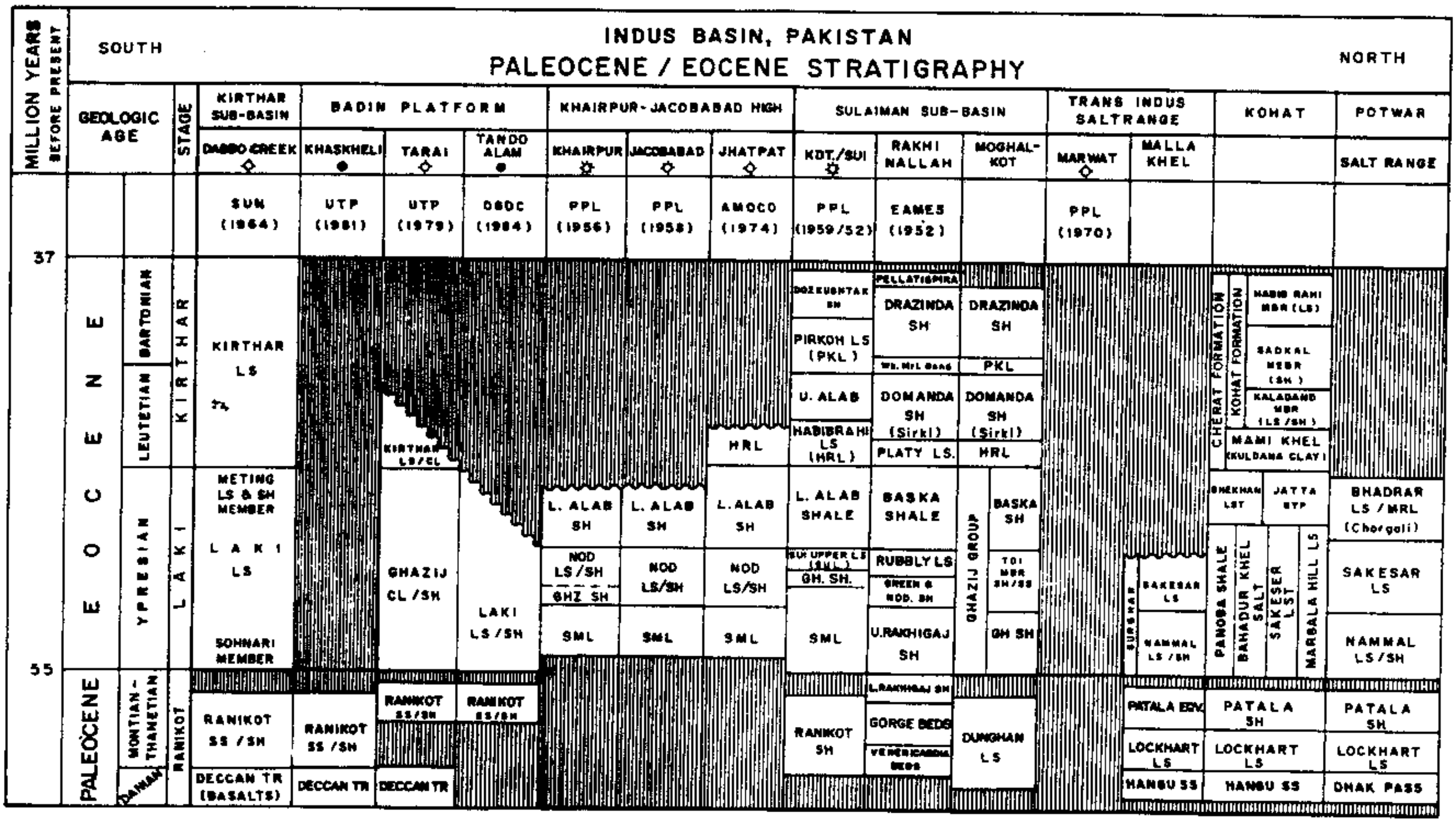

Figure - 14.2 Subsurface and surface Paleocene / Eocene stratigrapy based on surface sections and exploratory wells evidence. For location see Figure 14.1 (after Siddiqui and Khan, 1992)

In Lower Indus Basin, Eocene is broadly classified into two stages, Lower Eocene Laki Stage and Middle-Upper Eocene Kirthar Stage, separated by a short-lived regression. In Kirthar sub-Basin, the terminology of Laki and Kirthar Formations is more widely used with further local classifications. In Laki Range of this basin the Laki Formation is divided into Meting Limestone, Meting Shale and Laki Limestone Members. The term Kirthar Formation is more widely used even up to Kohat Basin. In the Middle Indus Basin (Sui-Kandhkot), Ghazij Formation contains predominant limestone and limestone/shale sequences. It shows a significant facies change towards north; the frequency and content of limestone decreases and the formation is divided into several distinct units (Ghazij Shale/Green & Nodular Shale, Rubbly Limestone and Baska Shale Members). These members are correlatable with the units encountered in Sui-Kandhkot region (Sui Main Limestone/Ghazij Shale, Sui Upper Limestone and Lower Alabaster Shale Members). Finally as one moves to the north of Sulaiman Range (Moghal Kot area), the Ghazij Shale becomes 3,000 meters thick at the expense of all other members of Ghazij Formation present in the south. Carbonate facies in this area is represented by deposition of thin beds of Pirkoh and Habib Rahi limestones during Kirthar times. This phenomenon is clearly depicted in Fig. 14.3.

Kirthar Formation is well developed in Kirthar sub-Basin and mid-Central Indus Basin. It is also regionally correlatable all across the Lower Indus Basin with its equivalence found in Kohat Basin.

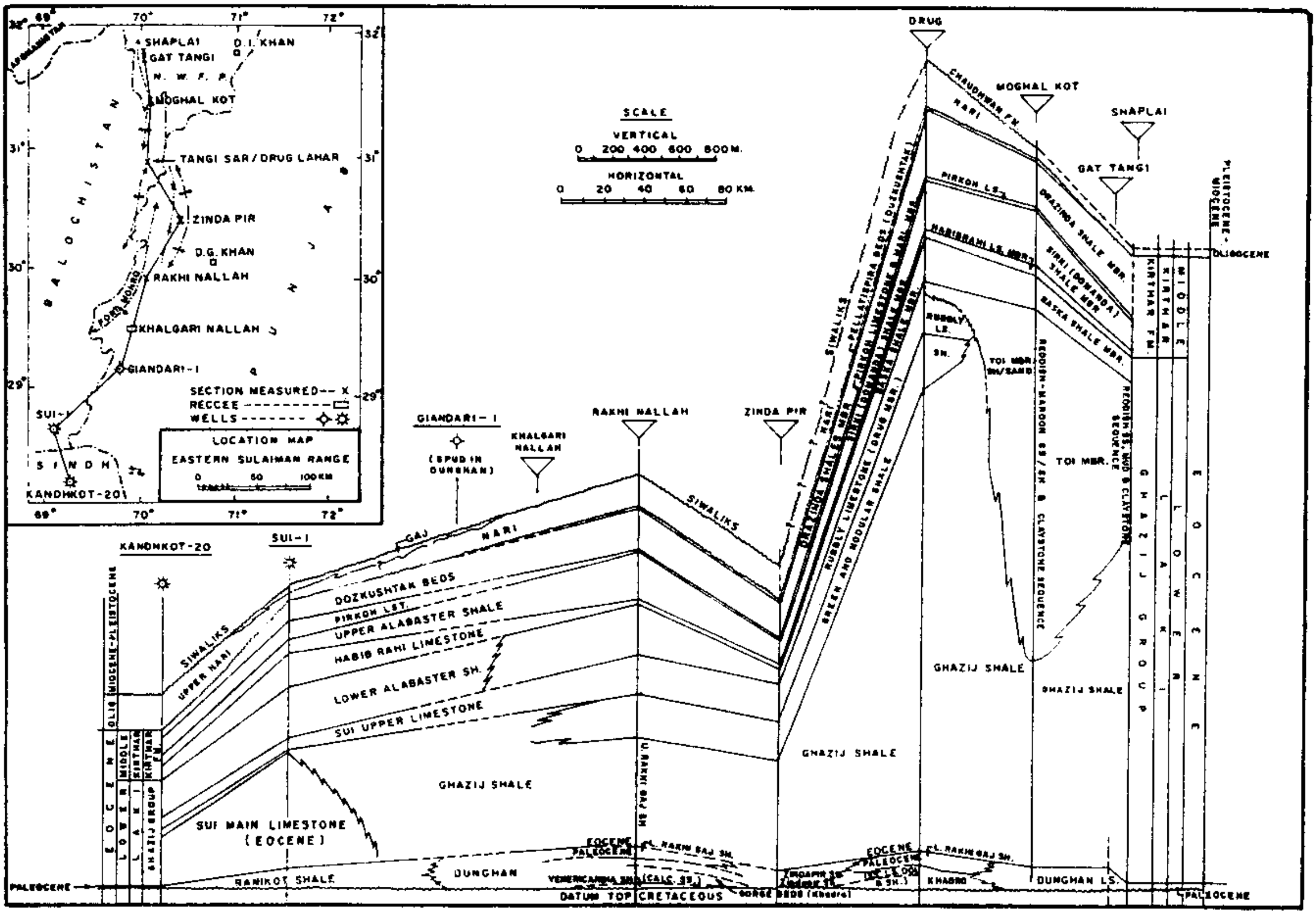

Figure - 14.3 Paleocene/Eocene stratigraphic correlation, Lower Indus Basin (after Siddiqui and Khan, 1992)

MIDDLE INDUS CARBONATE PLATFORM (Sui–Mazarani region)

Middle Indus Basin is the largest, the oldest and traditional gas producing region of Pakistan. Gas accumulation is in the shallow water carbonates deposited on a broad and stable carbonate platform which extends far into the south in Kirthar sub-Basin. However, the porosity development and its survival through diagenetic processes is restricted to Middle Indus Basin where several gas fields (Sui, Kandhkot, Loti, Zin, Uch, Khairpur, Badar, Sara and Mazarani) are located (Fig. 14.1).

LIMESTONE LITHOLOGY TYPES

The major limestone units, Sui Main, Sui Upper and Habib Rahi are each overlain by the terrigenous mudstone representing widespread transgressions. In addition the upper most Eocene carbonate facies, Pirkoh Limestone, is also underlain/overlain by thick shaly facies.

Each of these limestone entities is represented by characteristic lithology types which together signify certain depositional environment and facies association.

Sui Main Limestone (SML)

The lithology types identified within Sui Main Limestone are as follows:

1. Dasycladacean algal lime packstone / wackestone to grainstone.
2. Large benthonic foraminiferal lime packstone to grainstone.
3. Large benthonic foraminiferal lime wackestone / packstone.
4. Planktonic foraminiferal lime wackestone to packstone / mudstone.
5. Small benthonic foraminiferal lime packstone / wackestone.
6. Echinoderm lime wackestone.
7. Dolomitic limestone/calcareous dolomite.
8. Terrigenous mudstone.

These are the types recognised in Sui, Kandhkot and Khairpur areas with relative abundance.

Similar lithotypes are recognised in chronostratigraphically equivalent limestones in Mazarani Field and Laki Range further south.

Sui area is characterised by abundant algal packstone/wackestone, benthonic foraminiferal packstone/wackestone, benthonic foraminferal grainstone with other less common lithotypes. Kandhkot area is dominated by large benthonic foraminiferal wackestone to packstone and planktonic foraminiferal wackestone to packstone, Dascycladacean algal wackestone to grainstone / packstone with relatively rare 'small' benthonic foraminiferal wackestone/ packstone etc. and locally common 'large' benthonic foraminiferal packstone / grainstone.

In Khairpur/Kandra area, the most dominant lithology type is planktonic/benthonic foraminiferal lime mudstone with some argillaceous content. The other common lithology is foraminiferal wackestone. Ellipsoidal calcite nodules embedded in lime mud matrix are also observed. Faunal assemblage is foraminifers, pelecypods, echinoids, fish debris, ostracods, and bryozoans. No Dascycladacean algae is found.

In the Mazarani area, the lithology type varies from bottom to top as variably shaly foraminiferal wackestone/packstone, variably clayey foraminiferal packstone and wackestone, skeletal clayey packstone and grainstone and variably clayey foraminiferal packstone. The lime secreting lithothamian red algae are more common at Mazarani. The common faunal assemblage is foraminifers, echinoids, bivalves, bryozoans, gastropods etc.

In the Laki Range near Thano Bola Khan, thick succession of Laki limestone is exposed. This is mainly characterised by large and small benthonic foraminiferal packstone and wackestone with less common lime mudstones.

Sui Upper Limestone (SUL)

As the name suggests, this unit was first recognised in Sui Gas Field and is correlated with Rubbly Limestone Member exposed at the outer periphery of Sulaiman Range up to Drug area (Fig. 14.3).

This unit is a calcareous shale (argillaceous limestone)/limestone sequence and is separated from underlying Sui Main Limestone by Ghazij Shale which is the cap rock for SML with variable thicknesses in different gas fields.

The main lithology types of this unit, as recognised in Sui and Kandhkot areas, are as follows:

1. Benthonic foraminiferal packstone/ wackestone.

2. Dasycladacean algal lime packstone/wackestone.
3. Echinoderm wackestone.
4. Benthonic foraminiferal grainstone.
5. Calcareous dolomite.
6. Planktonic foraminiferal packstone/mudstone.
7. Terrigenous mudstone.

The dominant lithology types in Sui area are Algal packstone / wackestone and Benthonic foraminiferal packstone / wackestone, while in Kandhkot area Benthonic foraminifera – echinoderm lime wackestone forms the more common lithology type with common algal lime packstone.

In Algal lime wackestone/packstone litholgies the dominant biotic component is Dascycladacean algae, together with benthonic foraminifers (alveolinids, nummutulids, rotalids, and milliolids), planktonic foraminifers, bivalves, etc. The lime mud matrix only locally contains minor amount of terrigenous mud mainly concentrated with pressure solutions.

In Sui area, the large benthonic foraminferal packstone / wackestone are absent in the middle part while smaller benthonics are common.

The planktonic foraminiferal packstone/mudstone are present, though scattered, in Sui area only. Benthonic foraminiferal grainstone is also present in Sui but rarely. The non-reservoir lithologies of Sui Upper Limestone are dominated by argillaceous content. The Terrigenous mudstones are also present in the form of intercalations. Their contact with adjacent lithologies are masked by bioturbation and pressure solution activities.

Habib Rahi Limestone (HRL)

This lower most member of the Kirthar Formation is the most widespread entity in its occurrence and has been recognized in the whole Lower Indus Basin, in both subsurface and the surface exposures. The unit provides a useful marker along the Sulaiman Range while interpreting satellite imagery.

The lithology types identified in this entity are as follows:

1. Benthonic foraminiferal packstone/wackestone.
2. Planktonic foraminiferal packstone/mudstone/wackestone.
3. Benthonic foraminiferal grainstone.
4. Algal packstone/wackestone.
5. Echinoderm wackestone.
6. Calcareous dolomite.
7. Terrigenous mudstone.

In Sui area, the most dominant lithology type is Benthonic foraminiferal packstone/wackestone with grainstone deposited at the base. The foraminifers are both larger and smaller. The most common skeletal components are milliolid, rotalid,, and larger foraminifera which are uncommon in the lower (half) part of HRL.

In Kandhkot area, the most dominant lithotype is Planktonic foraminiferal lime mudstone to wackestone. The major biotic components are planktonic foraminifers together with large benthonic, rotalid and foraminifera, ostracods, echinoderms, bivalves, bryozoans etc. Terrigenous mudstones increase towards Kandhkot area.

While tracing this formation in the outcrops, it was observed that its lower portion is composed of large benthonic foraminiferal (mainly Assilina) grainstone and marl bands with decrease in grain size vertically grading into lime wackestone/mudstone.

PIRKOH LIMESTONE (PKL)

This limestone consists of foraminiferal wackestone/ grainstone with minor lime mudstones. The abundant faunal contents are foraminifera (Discocyclina). This also contains few marl and terrigenous bands. The cementing material is sparite along with micrite matrix.

FACIES ASSOCIATION IN LOWER INDUS BASIN

The Early Eocene reservoir (Sui Main Limestone) reaches its maximum thickness at Sui (667m) and is of the order of 300 m at Kandhkot. It thins in the direction of Jacobabad High and the Mari Gas Field to approximately 200 m. North of Sui Gas Field the Sui Main Limestone passes laterally into Ghazij Shale. This abrupt change occurs between Zin and Pirkoh structures. Isopach map of SML, shown in Fig. 14.4, indicates that the platform was going through differential subsidence and Sui/Mazarani were the depocenters where thickest carbonate development took place on either side of Khairpur–Jacobabad High. Similarly Middle Eocene Habib Rahi Limestone is gas bearing in Mari, Qadirpur, Kandhkot and Sui fields.

This Early and Middle Eocene carbonate platform is characterized by both vertical and lateral facies changes. Nine facies associations have been recognized in Early and Middle Eocene carbonates in Sui-Kandhkot area. These facies, with relative abundance, are believed to be present in Early to Middle Eocene carbonates throughout the Lower Indus Basin and Upper Indus Basin as well. Fig. 14.5 is the interpreted depositional model for the development of these facies. Table 14.1 summarises the lithology types and facies association observed in Eocene carbonates; Table 14.2 is the summary of the following facies association and their characteristic faunal contents.

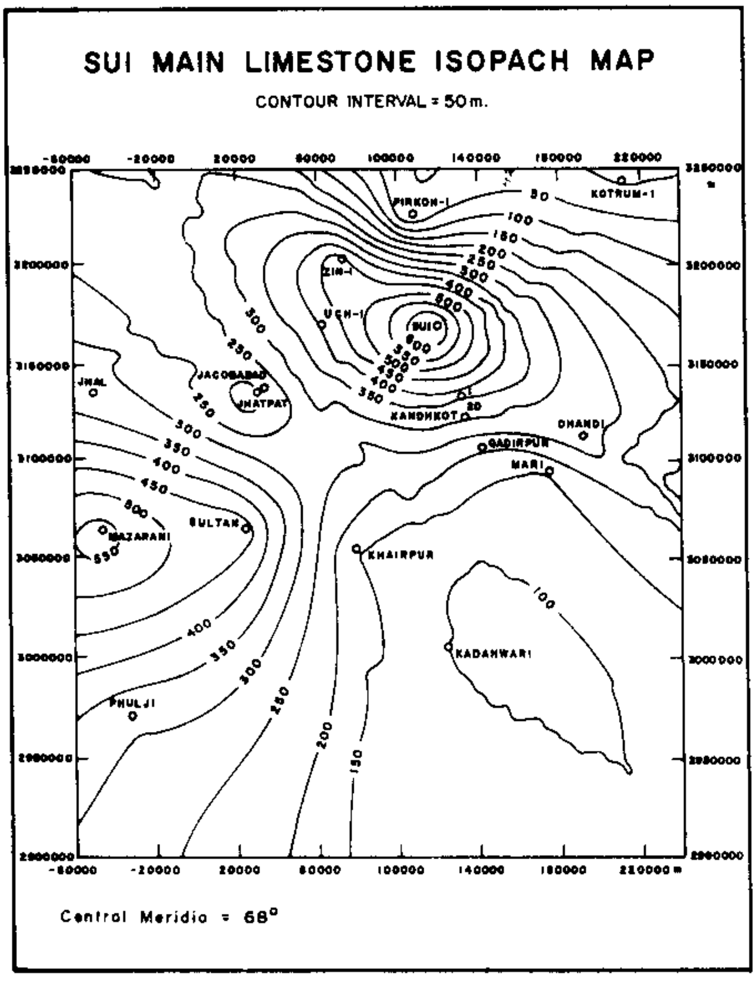

Figure - 14.4 Isopach Map of Sui Main Limestone showing two distinct areas of maximum carbonate development - one around Sui and the other around Mazarani. (after Siddiqui and Khan, 1992)

Shallow Subtidal Facies (SSF): These facies represent the inner margin of inner shelf indicated by an association of

LOWER INDUS BASIN, PAKISTAN
EOCENE CARBONATE FACIES ASSOCIATION AND LITHOLOGY TYPES

FACIES	DOMINANT LITHOLOGY TYPE	DEPOSITIONAL SETTING (WATER DEPTH)	LOCALITY * IN ORDER OF ABUNDANCE
SSF	DAP/LBW/SBW	Shallow Subtidal (<5M)	Kandhkot/Mazarani /Sui
RBF-ISF	SBW/LBW	Inner shelf (5-20m)	Kandra/Kandhkot/Sui
NSF	LBG	Inner shelf (<50m)	Kandhkot
FIS	LBW/PFW/SBW/BFM	Middle to outer shelf (20-130m)	Kandhkot/Kandra
MSSF	LBG/SBG	Middle shelf (< 25-130m)	Sui
MSF	LBW/SBW/DLS	Middle shelf (<25-130m)	Sui/Kandhkot
OSSF	PFW/LBG	Outer shelf (< 130m)	Sui
OS-SF	PFP/PFM	Outer shelf-slope (70-130m)	Mazarani/Sui
DTM	TM	Slope (>130m)	Kandhkot

* Data from other fields not available

FACIES
- SSF Shallow Subtidal Facies Association (SSF)
- RBF-ISF Restricted Back shoal to Inner shelf facies Association (RBF-ISF)
- NSF Nummulite Shoal Facies Association (NSF)
- FIS Fore Shoal - Intershoal Facies Association (FIS)
- MSSF Middle Shelf Sand Facies Association (MSSF)
- MSF Middle Shelf Facies Association (MSF)
- OSSF Outer Shelf Sand Facies Association (OSSF)
- OS-SF Outer Shelf-Slope Facies Association (OS-SF)
- DTM Deep Terrigenous Mudstone Facies Association (DTM)

LITHOLOGY TYPES
- DAP Dasycladacean Algal lime packstone to grainstone
- SBG Small Benthonic foraminiferal grainstone
- SBW Small Benthonic foraminiferal lime wackestone/packstone
- BFM Benthonic foraminiferal lime mudstone
- LBG Large Benthonic foraminiferal lime packstone/grainstone
- LBW Large Benthonic foraminiferal lime wackestone to packstone.
- PFW Planktonic foraminiferal lime wackestone to packstone.
- PFP/PFM Planktonic foraminiferal lime ;ackstone/mudstone.
- DLS Dolomitic limestone.
- TM Terrigenous mudstone

Table-14.1 (after Siddiqui and Khan, 1992)

FACIES ASSOCIATION	MAIN FAUNAL CONTENT
Shallow Subtidal (SSF)	Dascycladacean Algae, large benthonics
Restricted Backshoal (RBF)	Small benthonics (milliolid)
Nummulite Shoal (NSF)	Large benthonics (Nummulite, Assilina & Discocyclina), Algae.
Fore Shoal & Intershoal (FIS)	Large benthonics, planktonics, occasionally smaller benthonics.
Middle Shelf Sand (MSSF)	Larger and smaller benthonics
Middle Shelf (MSF)	Larger and smaller benthonics, Algae, Echinoderms.
Outer Shelf Sand (OSSF)	Robust larger benthonics, planktonics with terrigenous mud, Echinoderms.
Outer Shelf Slope (OS-SF)	Planktonics, rare benthonics & Echinoderms.
Deep Water Terrigenous Mudstone (DTM)	Pelagic & Nectonic

Table-14.2 (after Siddiqui and Khan, 1992)

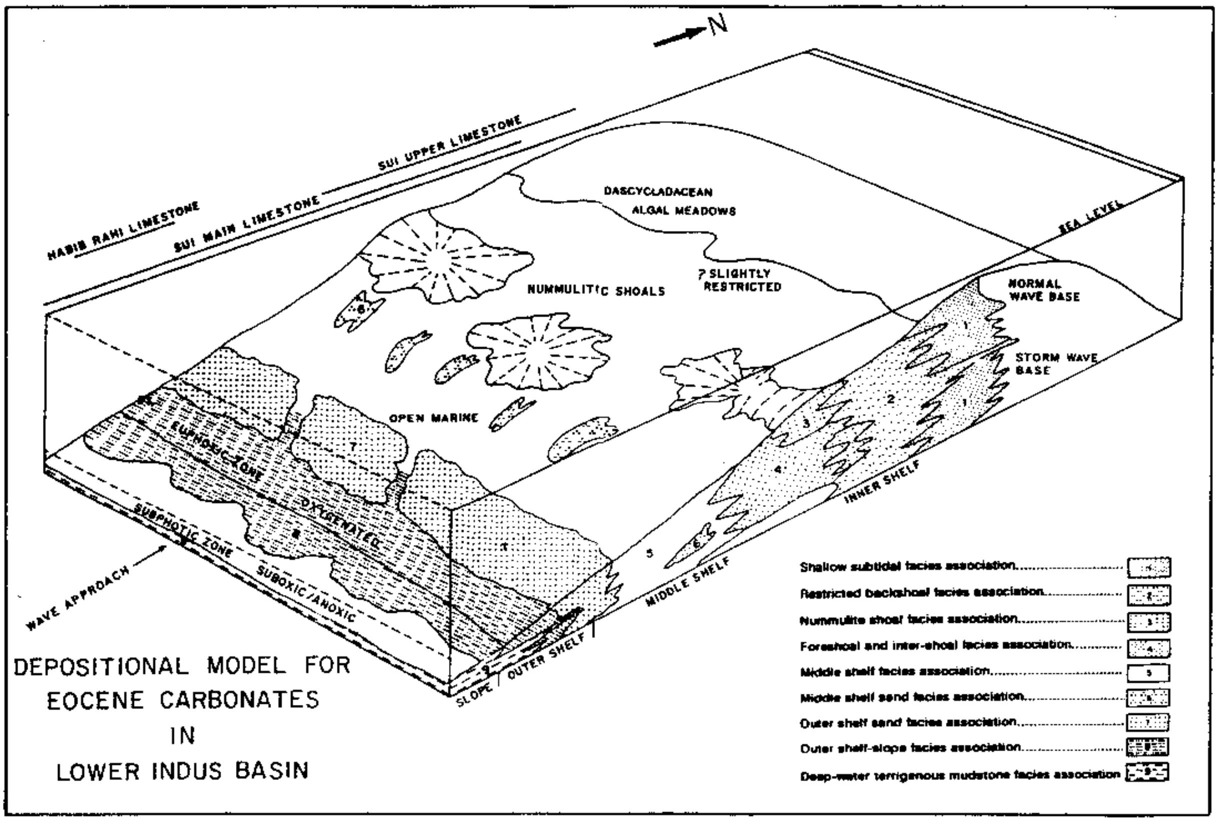

Figure - 14.5 Depositional model for Eocene carbonates in Lower Indus Basin showing the distribution of different facies in inner shelf to outer shelf and slope settings. (after Siddiqui and Khan, 1992)

Dascycladacean algae/skeletal wackestone to grainstone/ packstone.

The presence of Dascycladacean algae in Sui and Kandhkot area suggests low energy and warm marine environment. The extensive bioturbation is seen in Sui, Kandhkot and Mazarani areas.

Restricted Backshoal Facies (RBF): This marks the back lagoonal association, shoreward of Nummulites shoals and seaward of SSF, indicated by 'small' benthonic foraminiferal (miliolid) lime wackestone/ packstone in which milliolid foraminifers predominate.

The predominance of small milliolid formainifers within this facies association suggests that deposition took place within water of normal marine or slightly restricted water circulation. Deposition of this facies is thought to have occurred in a warm inner shelf (15–20 meters), low energy environment. This facies has very limited occurrence.

Nummulite Shoal Facies (NSF): This is marked by moderate to high energy Nummulite shoals at the margin of inner shelf. It consists of 'large' benthonic foraminifera (Nummulites, Assilina and Discocyclina sp.) lime packstone to grainstone lithology. Since the buildup of Nummulite shoal is associated with algae and diatoms, light requirement of these organisms restricts the depth to less than 50 meters. The reworking of these Nummulites is indicated by sedimentary structures like imbrication which in turn indicates lack of any binding material. This facies is limited in its extent.

Foreshoal and Intershoal Facies (FIF): The FIF as recognized in Sui and Kandhkot, is represented by carbonates deposited between outer inner shelf and inner middle shelf. This facies consists of 'large' benthonic foraminifera lime wackestone to packstone, the planktonic foraminifera lime wackestone to packstone and occasionally the 'small' benthonic foraminifera lime wackestone/ packstone lithologies.

This facies shows the variation in the predominance of the various foraminifera types, from large benthonic to planktonic, reflecting variation in water depth. The imbrication of larger benthonic foraminifera with individual fining upward sequence, indicates the reworking of these allochems from nearby shoals to water depth below storm wave base. Bioturbation is also common indicating well oxygenated bottom sediments.

Middle Shelf Sand Facies (MSSF): This facies association is dominated by bioclastic pelloidal lime grainstone. The larger and smaller benthonic foraminifera are the main allochems which are well sorted. However, they are abraded, associated with loss of lime mud, indicating high energy depositional system. The facies is very much related to Nummulite shoal facies and may have formed a barrier responsible for low energy conditions prevalent in the inner and part of the middle shelf.

Middle Shelf Facies (MSF): This is the most dominant facies of SML in Sui field. The main lithology type is bioclastic packstone and wackestone with both smaller and larger benthonic foraminifera. The association of algal material with larger benthonic foraminifera, extensive bioturbation, little or no winnowing of lime mud matrix are indicative of water depth between 25 to 130 meters, above or below normal wave base. However, alternate occurrence of echinoderm wackestone with almost no algae indicates the intermittent rise of sea level.

Outer Shelf Sand Facies (OSSF): This facies is characterized by occasionally argillaceous lime packstone. The biota is dominated by robust larger foraminifera with less common echinoderms and planktonic foraminifera. This is a common facies in Mazarani.

The presence of larger benthonic foraminifera suggests deposition within photic zone, while the planktonic foraminifera and settling out of terrigenous mud indicate a relatively deeper water position on the shelf, below normal wave base. The larger benthonic foraminifera, therefore, represents residual or lag deposits while smaller forms were not preserved. The infiltration of terrigenous mud took place after the passage of storm when the flow regime of storm ebb events was lowered.

Outer Shelf – Slope Facies (OS-SF): This facies is characterized by bioclastic, frequently pelletal, lime wackestone and mudstone. The allochems are dominated by planktonic foraminifera, relatively rare echinoderm, smaller and larger benthonic foraminifera. The abundance of planktonic foraminifera, non-sorting of allochems and lack of algae suggest deposition in open marine water below storm wave base but above Carbonate Compensation Depth (CCD). The presence of shallow water benthonic organisms also suggests intermittent shallowing. This facies is more common in Mazarani area.

Deep Water Terrigenous Mudstone (DTM): It is an outer shelf/slope association gradational with FIF and consists of terrigenous mudstone. This facies provides the important reservoir barriers in Kandhkot area and is present intermittently in the upper 50–60 meters of SML. It is restricted to only top 20 meters in Sui area where it provides the transitional contact between SML and Ghazij Shales (cap rock). However, its distribution and thickness is controlled by the extension and prevalence of outer shelf environment.

This facies is gradational with Outer Shelf – Slope Facies and represent the surface below CCD. It also consists of limited bioclastic debris and very rare bioturbation. This facies marks the marine transgression and represent deposition in a quiet outer shelf – slope environment below photic zone, where only pelagic or nectonic organisms prevailed.

The association of these facies characterises the relative sea level changes depicting shoaling upward sequences.

VERTICAL FACIES CHANGES

SUI MAIN LIMESTONE: The deposition of Sui Main Limestone represents generally a shallowing upward trend with several cycles recognized in different areas:

Sui Area: Three shallowing upward cycles can be recognised in Sui Field.

The oldest unit (about 150–180 meters) is benthonic foraminiferal packstone with subordinate wackestones deposited in normal salinity marine water in middle shelf to outer shelf – slope environment. Outer shelf sand bodies are occasionally developed.

Middle unit (about 150 meters) consists of bioclastic lime packstones with subordinate wackestones and grainstones, deposited in a variety of inner to middle shelf environment with variable salinities and circulation.

Upper Unit (about 350 meters) consists of bioclastic, frequently pelletal or pelloidal lime packstones with subordinate grainstones and wackestones, deposited in middle to inner shelf environment (where marine circulation was restricted ?)

Kandhkot Area: Three shallowing upward cycles have been recognized in Kandhkot Field also. The base of each cycle is marked by a rapid transgressive event, normally represented by terrigenous mudstone deposition. Sequence grades from the deep water terrigenous mudstone facies association through the foreshoal into the nummulitic facies association and further into backshoal facies association.

Fig. 14.6 is the Electric log correlation of Kandhkot, Sui and Pirkoh wells showing log characteristics of the vertical and lateral facies changes in SML.

Mazarani Area: In Mazarani Field, about 600 meters of Laki Limestone was deposited in low energy shelf environment with several shallowing upward cycles, representing deep marine shelf to subtidal facies.

The general sequence from bottom to top in Mazarani Field is deposition of argillaceous foraminiferal wackestone/packstone and grainstone on a shallowing shelf, followed by development of very argillaceous skeletal packstone on a deepening shelf, which in turn was followed by shallowing of shelf and deposition of packstone and grainstone. This was followed by regional deepening and deposition of deep terrigenous mudstones (Chat Beds).

Vicinity of Khairpur–Jacobabad High: Similar observations were made in Sultan (Petro–Canada Pakistan Incorporated, 1990) and Kandra (Premier Exploration Pakistan Limited, 1990) wells with more argillaceous content in the middle part of the unit on wire-line logs. In Sultan well more than

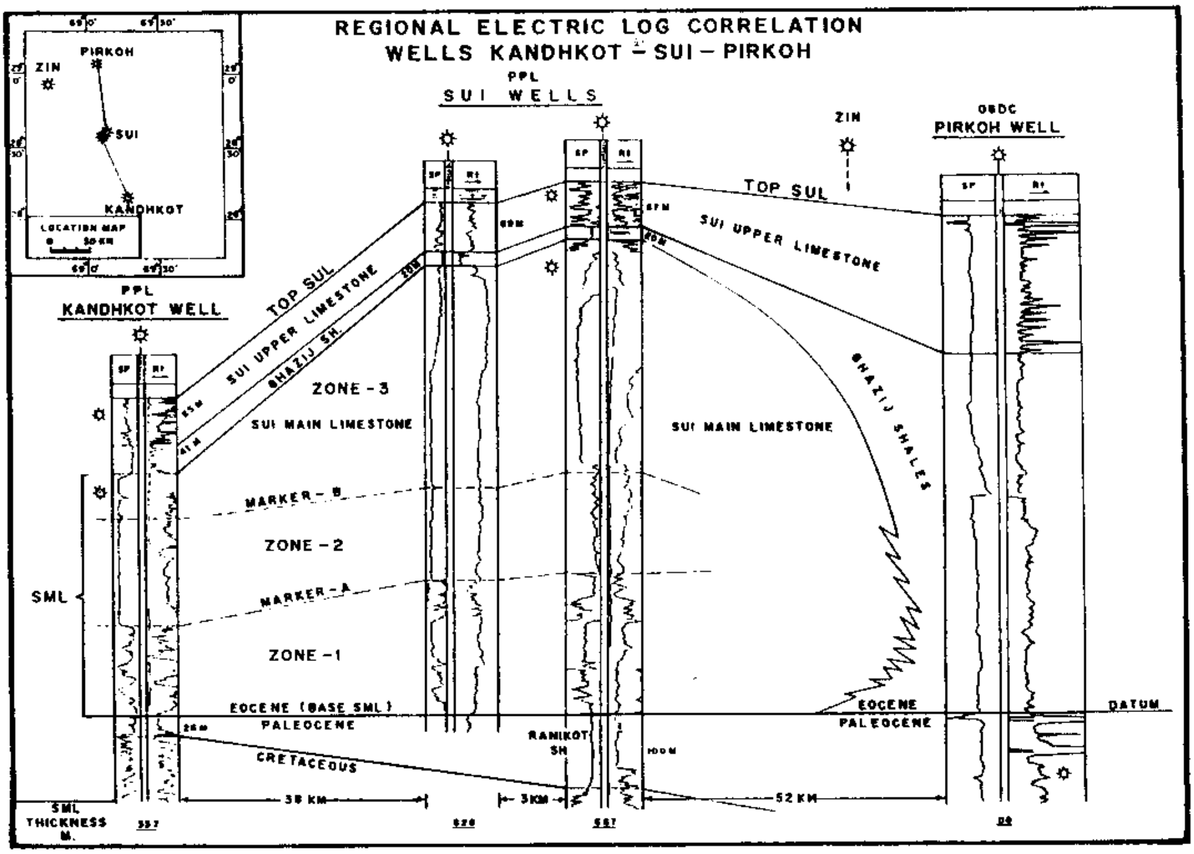

Figure - 14.6 Regional electric log correlation of Sui Main Limestone. (after Siddiqui and Khan, 1992)

550m of early Eocene carbonate development took place; while in Khairpur/Kandra area about 150m of SML was deposited. There are at least two shallowing upward cycles observed on wire-line logs. The cores of Kandra SML indicate dominant lithology type being lime mudstone to packstone with predominant micrite indicating lack of hydraulic energies, although the depositional surface was a plaeo–high.

Fig. 14.7 is the Gamma Ray – Porosity log correlation of Mazarani, Sultan and Kandra wells showing the vertical and lateral facies changes in SML.

The deposition of SML was followed by widespread transgression which could prevail even up to the topographically highest areas of Sui and deposited 20 meters of terrigenous mudstones (Ghazij Shales) over Sui structure.

SUI UPPER LIMESTONE: Unlike the Sui Main Limestone, this formation represents a transgressive upward sequence with gradual deepening of waters indicated by the increasing percentage of planktonic foraminifera. The vertical sequence grades from inner to middle shelf facies association into argillaceous limestone / terrigenous mudstone facies. This kept going back to the same cycle as much as nine times until the major marine transgression occurred to deposit Lower Alabaster Shales (Fig. 14.2). This gave rise to 9-10 gas bearing zones in Sui, Kandhkot area.

HABIB RAHI LIMESTONE: The deposition of this unit represents a deepening upward trend indicated by predominant planktonic biota. There is apparently no cyclic trend.

LATERAL FACIES CHANGES

Eocene carbonate facies association and lithology types suggest that the carbonate development occurred on an extensive and relatively stable marine shelf environment.

SUI MAIN LIMESTONE: The comparison of Sui Main Limestone facies present in Sui Field with those in other areas, indicates that the Sui area was quite shallow with extensive proliferation of foraminifera and other organisms and it had sufficient hydraulic energy available to winnow away the lime mud matrix to lead to better reservoir development.

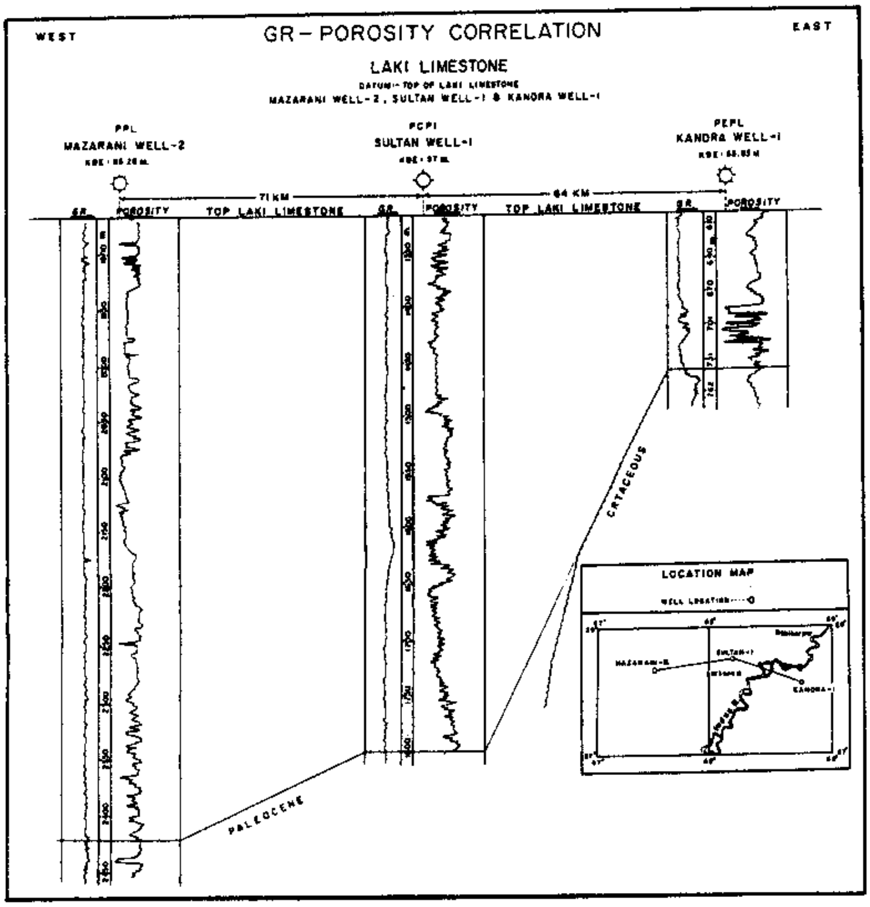

Figure - 14.7 GR-Porosity log Correlation of Mazarani, Sultan and Kandra well (after Siddiqui and Khan, 1992)

Northward of Sui, the environment gradually became deeper with sudden deepening occurring between Zin and Pirkoh structures suggesting a regional paleo–slope (Fig. 14.6).

However, the shelf gradually dipped towards west and south also with several swells and hollows, as suggested by the presence of terrigenous mudstone in wells south and west of Sui. The Khairpur–Jacobabad High represents a paleo feature in the middle of the Eocene sea, thus marking the absence of high energy and preserving the lime mud content in limestones encountered in wells drilled on that High. Fig. 14.8, a 3-Dimensional view of Fig. 14.4, shows the hollow between Sui-Kandhkot and Mazarani areas which represents Khairpur–Jacobabad High.

The absence of SML/SUL reservoir facies over Mari structure indicates that his was a local high in early Eocene time and it was only affected by the transgressive events. However, good reservoir facies start developing again east of Mari as confirmed by the recent gas discovery at Sara and gas discoveries of Tanot, Manhera Tibba, Ghotaru etc., in India.

Similarly the development of Hyderabad Arc, which is manifested by present day Laki Range, during Eocene time, influenced the facies association in that area.

Fig. 14.9 is a structure contour map on

present day base Laki Formation, drawn to depict the trend of Eocene depositional surface. Although the structures north of Sui have uplifted the base Laki, the trend as indicated by facies variation is confirmed by this map.

SUI UPPER LIMESTONE: This entity is not clearly recognized in wells located on Khairpur–Jacobabad High and to its west.

However, it is present in Kandhkot and Sui fields and is exposed at the outer periphery of Sulaiman Range. From Kandhkot to Sui area, it shows a relatively deepening trend.

Its lateral extent indicates that an extensive shoreline had developed in this period from a little south of Kandhkot following the trend of the Sulaiman Lobe and north-south running Sulaiman Range. This entity developed parallel to the shoreline.

HABIB RAHI LIMESTONE: While moving from Sui/Kandhkot area, where mainly middle to outer shelf carbonate facies are recognized, to the north into the Sulaiman Range a progressive deepening upward trend is observed. Prevalence of anoxia in the upper part resulted in the preservation of organic matter. Several oil shales have been confirmed (Raza, 1991) in the outcrops in north-south running Sulaiman Range.

SOURCE ROCKS

Eocene rocks are also likely to have generated hydrocarbons. In Middle Indus

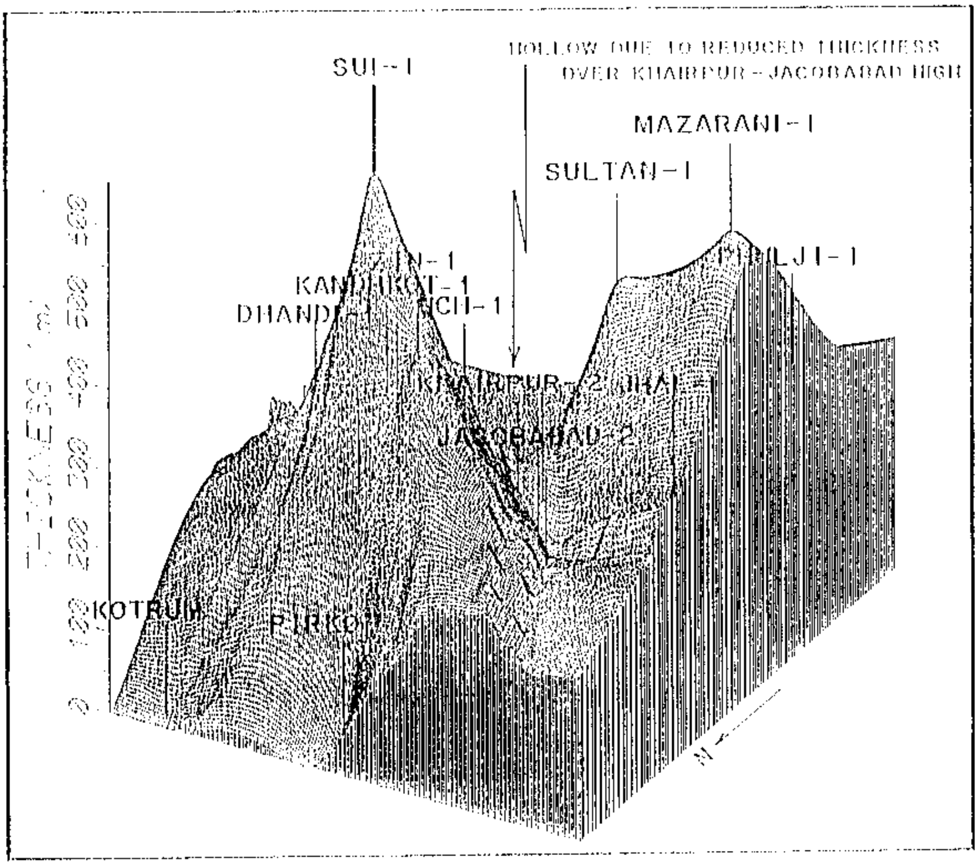

Figure - 14.8 Three dimensional view of Fig-14.4 showing a sedimentary hollow which marks the Khairpur - Jacobabad High. (after Siddiqui and Khan, 1992)

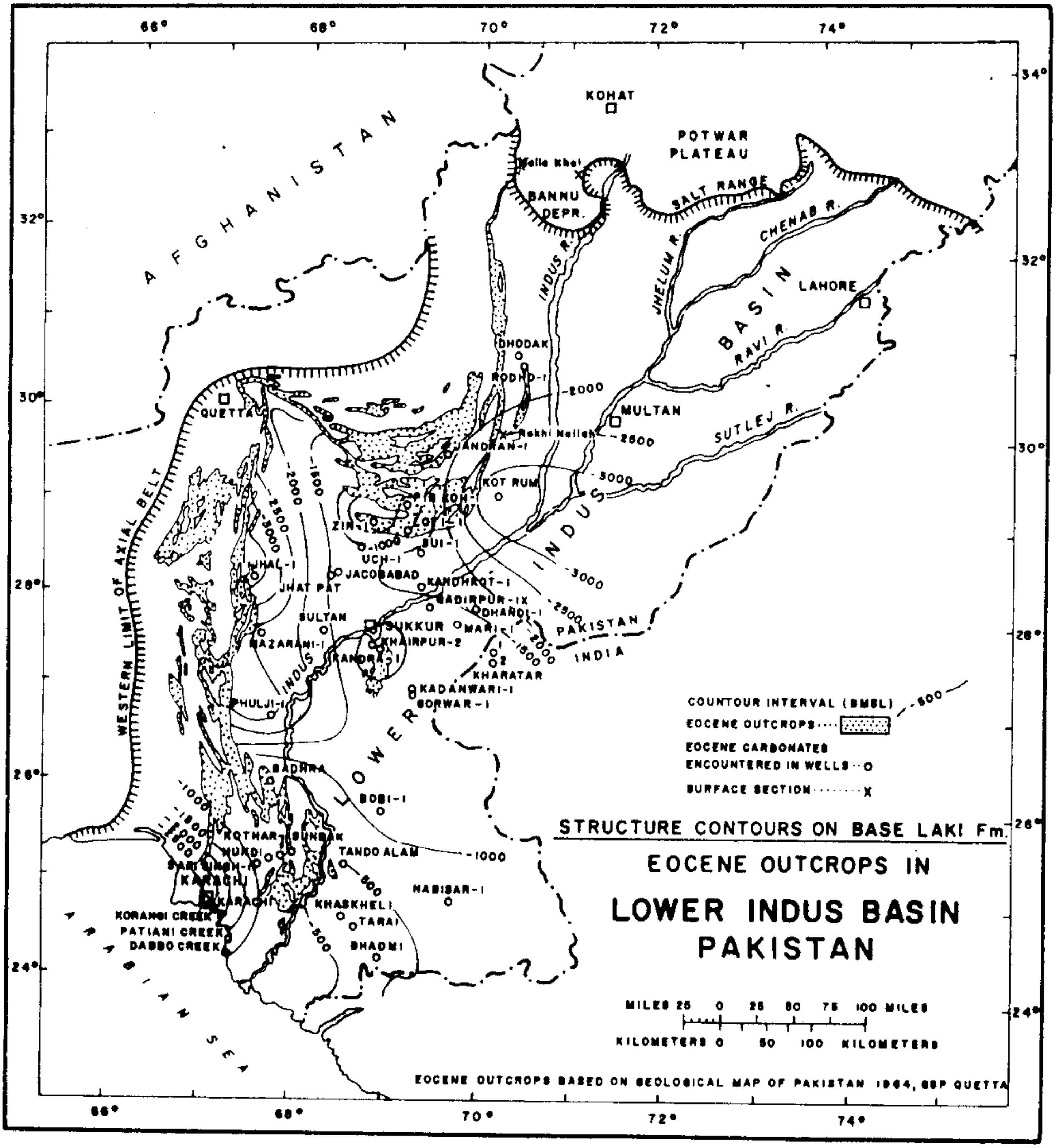

Figure - 14.9 Structural Contour Map on base Laki Formation showing generally a deepening trend towards Mazarani and Karachi, Lower Indus Basin. (after Siddiqui and Khan, 1992)

Basin, source rock analysis of Early Eocene rocks (SML etc.) indicates the presence of organic matter of algal and sapropel type with Total Organic Carbon (TOC) ranging from 0.2 to 2.5 percent. Potential yield of some of the samples is over 15,000 ppm indicative of good quality source rock. Similarly, Middle Eocene Habib Rahi Limestone Member of Kirthar Formation contains the maximum reported TOC of 5.25 % and potential yield of as much as 32,560 ppm. In outcrop sections, Habib Rahi Limestone appears to be organic rich and burns when lit. But the areas so far explored by drilling or surface geological measurements do not show the maturity of these source rocks. However, these rocks may have attained maturity in trough areas like Sibi Trough and the area west of Jacobabad–Khairpur High. (refer back Fig. 3.3)

In Kohat Basin, possible source rocks include marine shales of Sakesar, Nammal and Kohat formations as well as shales within the evaporitic sequences of Bahadurkhel Salt and Jatta Gypsum of Kohat area. Some stream beds along these evaporites contain significant amount of lipids leached from organic rich shales contained in evaporitic sequence. Various seepages associated with these sequences are reported in Kohat area.

RESERVOIR CHARACTERISTICS

As stated earlier the rocks of this period have accumulated the maximum quantity of hydrocarbons discovered so far in Indus Basin. In Middle Indus Basin, the Eocene limestones have excellent reservoir qualities. The Early Eocene Sui Main Limestone is gas bearing in many fields. Good porosity development in these limestones is because of their buildup on a stable platform, while timely gas entrapment is responsible for the preservation of porosity. The limestone reservoirs in this region depict following type of porosities: Matrix microporosity, Mouldic porosity, Vugular porosity, Intragranular porosity and Intercrystalline porosity. It has been observed that dominant pore types are Matrix microporosity system developed by the framework of clay sized carbonate matrix. However, the interconnection and bigger voidage is provided by vugs and mouldic porosity.

Facies association seems to have some control over the reservoir development. The lithologies that deposited in the setting where more hydraulic energy was prevailing lead to better reservoir characteristics. Hence shallow platform carbonates deposited within the photic zones and the fairweather wave base influenced only by wave dominated current activity resulted in 'clean' well sorted carbonates of faunal content. If these deposits are preserved without bioturbation they usually form very good reservoirs.

Storm reworking and bioturbation of carbonates degrades reservoir potential because both of these processes disrupt textural fabric. Bioturbation of episodic carbonate deposits adds terrigenous clays into the disrupted carbonate fabrics. The presence of clays also sometimes baffled by blue green algal mats serves as a catalyst for chemical compaction. During compaction, solution seams are formed in isolation or as swarms that anastomose around elliptical burrows. This fabric can cause nodularity of rock which can be accentuated during solution leaching and outcrop weathering. Such rock types have no preserved primary porosity and can have effective secondary porosity only as a result of fracturing. Once the rock is fractured secondary porosities such as mouldic, vuggy and intercrystalline porosities result. This is only true of extensively bioturbated limestones.

Fractures, although present at Sui and Kandhkot, are not the most important factors contributing to the development of effective reservoir porosity and permeability at Sui and Kandhkot.

Southern limit of Early Eocene limestones as reservoirs fall south of Mazarani and Khairpur Fields. In rest of the Kirthar sub-Basin, although considerable outcrops/ subcrops are present, Laki limestones do not form reservoirs.

In Upper Indus, Potwar Basin, traditional oil bearing reservoirs belong to Early Eocene limestones. These limestones have very low matrix porosity and fractures provide most of the voidage. The intensity and orientation of fractures are controlled by the tectonic/structural style of the area which is governed by Himalayan orogeny. In this basin, Sakesar and Chorgali formations form the fractured reservoirs for various oil fields. Adhi (PPL), Fim Kassar, Chak Naurang, Dakhni (OGDC), Balkassar (POL), Dhurnal (OXY).

Log Interpretation in Early Eocene Carbonate Reservoirs

Although log interpretation seems to be simple because of its more or less monomineralic (calcite/dolomite) character, it becomes complex owing to the heterogeneity of limestone facies and variation in clay content.

Porosity measurements from logs do not often match with core porosities as the two are entirely different modes of measurements. Core porosities are measured on core plugs representing one point whereas the porosity logs average the formation over their resolution thus giving three dimensional average. These differences are enhanced by the heterogeneity of reservoir.

Furthermore, water saturations are worked out on the basis of resistivity values where the path of current is controlled by tortuosity. In the case of larger heterogeneity and thus higher tortuosity, path of the current is also tortuous and will read higher resistivities leading to erroneously higher hydrocarbon saturations. These calculations are controlled by using appropriate cementation factor (m) measured on core samples in the laboratory.

As mentioned earlier, these limestones in the Upper Indus Basin are highly fractured and most of the reservoir voidage is provided by these fractures. Since logging measurements are restricted to the wellbore, these fractures are not resolved with confidence in terms of percentage porosity. Hence, water saturations thus calculated have low reliability. This problem may, however, be handled to some extent by using Formation Micro Scanner (FMS). Because of its very high resolution, this tool can indicate the orientation, type, and frequency of fractures.

SEISMIC CHARACTERISTICS

In the Potwar–Kohat basins, the top Eocene is characterised by high amplitude and continuous reflectors throughout and a very prominent marker for subsurface structural and stratigraphic control.

Similarly in the Central Indus Basin, the top of the Sui Main Limestone (Early Eocene) is a characteristic intra–Eocene reflector because of its acoustic contact with the overlying Ghazij shale which is seismically transparent and devoid of any significant character.

DRILLING CHARACTERISTICS

The Eocene rocks are represented by very heterogeneous lithological assemblage (shales, limestone, evaporite, coal and minor sandstone) in the various basins of Pakistan. In the carbonates, the main drilling problems are severe loss of drilling fluids in porous/fractured gas bearing reservoirs (Sui Main Limestone and Habib Rahi Limestone). Special care is required in handling conditions of potential blow out and permanent formation damage to the reservoir.

The Eocene shales have sloughing tendency. Therefore, the hole should not be left uncased for long periods.

Sticky hole conditions are also experienced where considerable thick Eocene shales are drilled.

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Post-Eocene

This system is mainly controlled by the tectonic activities related to the Himalayan orogeny in the north and the emergence of Axial Belt in the west as a result of collision between Indian and Eurasian Plates. The sedimentation was dominated by continental conditions.

The whole area of Upper Indus Basin was uplifted. The rising Himalayan chains to the north provided sediments which were deposited in a deepening molasse trough. These fresh water molasse deposits of the Rawalpindi and Siwalik groups are up to 7,500 meters thick in the deeply subsided parts of Potwar

The western part of Central and Southern Indus Basin was uplifted, though locally marine conditions persisted in parts of the Karachi Trough and the present Indus Offshore area. The Oligocene Nari Formation developed in these localized basins and consists of high-energy limestones, ferruginous sandy siltstones and some local shales. In the Offshore area, reefs have been recognized near the shelf–slope break. Miocene/Pliocene sediments were deposited in the depression areas of the Siwalik Basin which was formed as a result of the development of the proto–Indus drainage system. This is characterized by fluvial sedimentation.

REGIONAL DISTRIBUTION

Except for Nari/Gaj Formations which are restricted to Lower Indus Basin, Post-Eocene is the most widely distributed system of Pakistan as also indicated in Fig. 15.1.

The Oligocene is represented by the Nari Formation (Fig. 15.2). This formation is present in the limited area within and along the southern folded belt between Karachi and Quetta. It does not extend beyond Laki Range towards east, while towards west it is confined to both sides of Axial Belt. In the Northern Sulaiman Range, limited exposures of Oligocene are reported in the form of Chitarwata Formation. This formation has been mapped very recently to extend in the subsurface in the Sulaiman Foredeep.

The Miocene is represented by the Gaj Formation and occurs in two separate areas in a narrow zone between Karachi and Quetta, generally coinciding with the eastern portion of Nari distribution (Fig. 15.3). Towards east it is limited by 68° longitude and towards west by the folded belt and by the Pab Range in isolated occurrence in the south.

The Murree and Kamlial Formations of Miocene age are restricted to Upper Indus

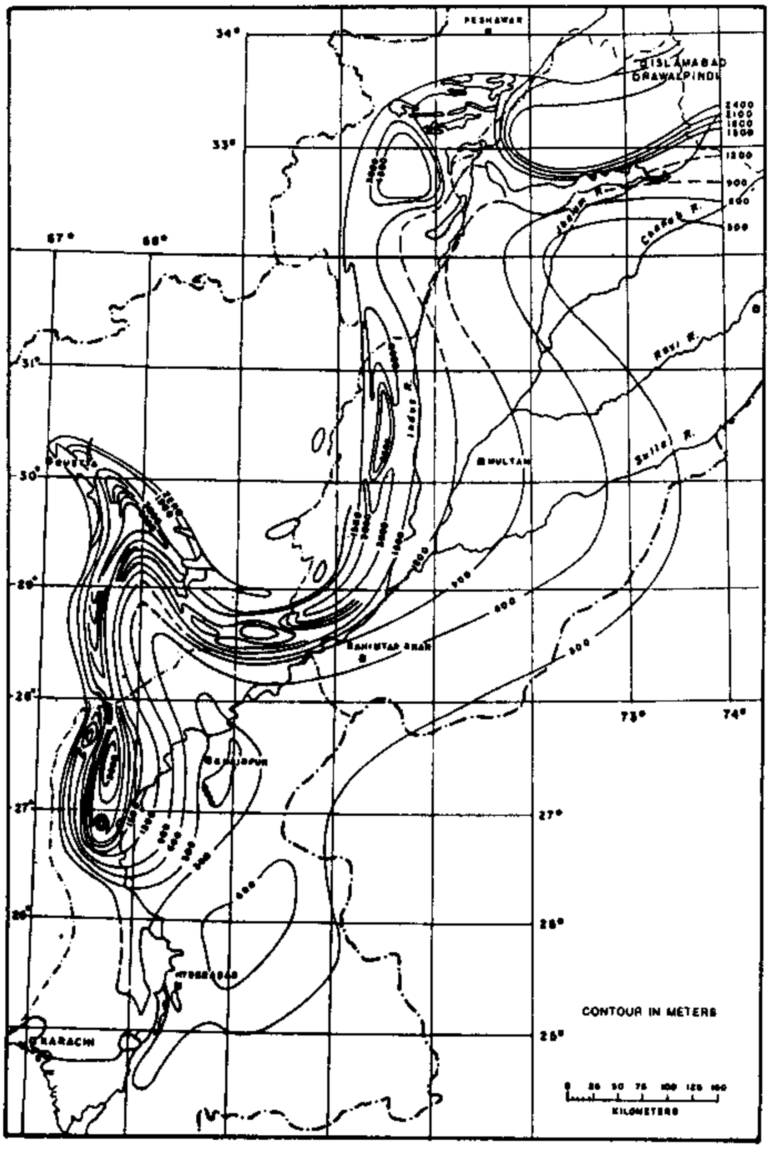

Figure - 15.1 Thickness map of Siwalik/Rawalpindi Group and Recent Sediments

Basin. However, their presence is reported from Karampur well, south of Sargodha High. In the north, they occur as far as Balakot in Hazara–Kashmir Syntaxis.

Rocks of Siwalik Group and sediments of sub-Recent to Recent occur from Murree in the north to Cutch area in the south. They underlie the whole of the Indus Flood Plain except for isolated outcrops of older strata and occur in the outer folds of northern and southern folded belt.

TECTONIC/GEOLOGICAL HISTORY

In Late Eocene, collision and rotation between Eurasian and Indian Plates intensified and major transform faults, namely Chaman and Ornach–Nal Faults, began to develop and Neo-Tethys was virtually all consumed.

Eocene/Oligocene boundary is characterized by general climatic cooling in all ocean basins. This event is indicated by the presence of widespread erosional hiatuses in the sedimentary record.

Tectonic activity related to the Himalayan orogeny commenced during the Late Eocene and continued through the Oligocene, Miocene, Pliocene and Quaternary. Oligocene is marked by the most dramatic change in the climate which gave rise to the lowering of Carbonate Compensation Depth (CCD) suitable for development of massive carbonates. During this period shallow water carbonates and clastics were deposited in the southern part of the Indus Basin and Axial Belt. Northern part of Pakistan did not receive any sedimentation as it was uplifted as a result of Himalayan orogeny.

Miocene saw the onset of underthrusting at the site of former convergence zone, intense metamorphism, formation of new intracontinental subduction zone at the Main Central Thrust (MCT) followed by extensive crustal shortening. The rate of northern movement of Indian Plate slowed to 3-4 cm/year. The rising Himalayas and Axial Belt supplied the sediments for Gaj Formation in south and Rawalpindi Group in north indicating general southward regression. Underthrusting of the northern edge of Indian Plate continued through middle Miocene to Recent, accounting for severe crustal shortening. The Himalayan uplift reached its climax during the Plio–Pleistocene. As a result of these uplifting activities great thicknesses (up to 6,000 meters) of continental clastics were deposited in the basinal areas in the form of Siwaliks.

Since Indian Plate has continued to converge through recent times, Siwaliks sediments are also affected by folding and faulting. Later, erosion of these sediments contributed towards the buildup of Indus and Ganges fans offshore.

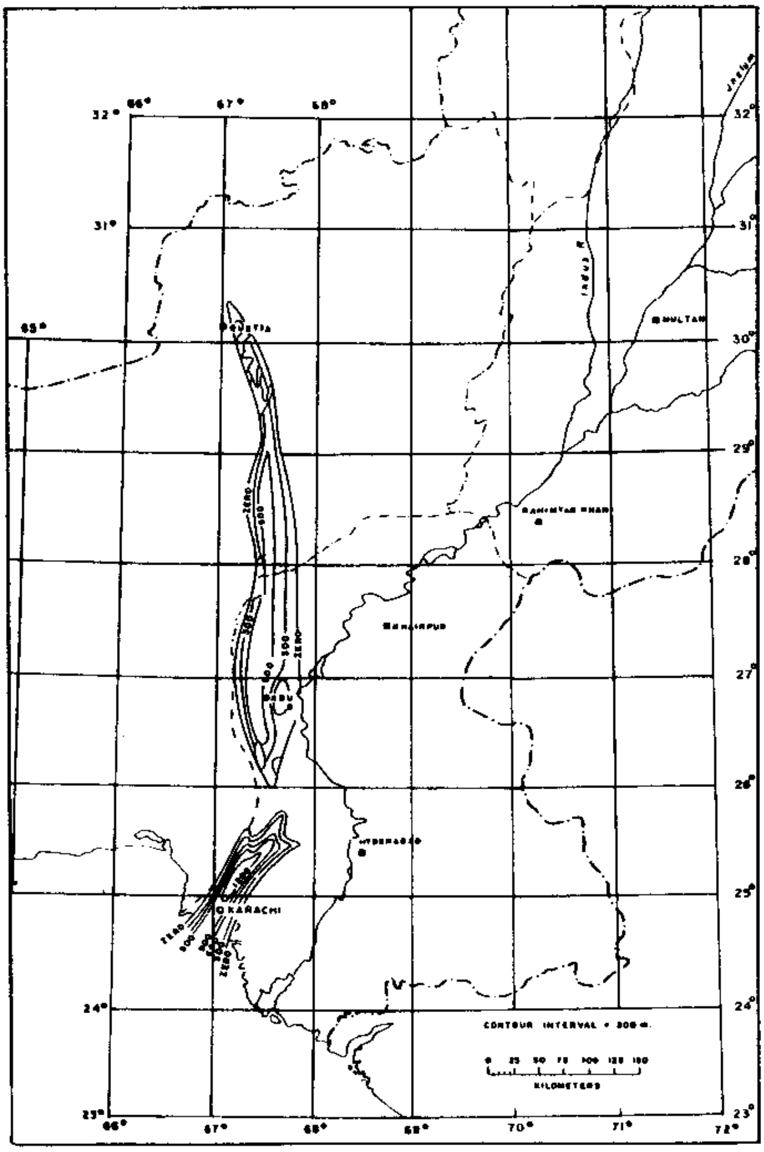

Figure - 15.2 Thickness map of Nari Formation

STRATIGRAPHY

As discussed in the preceding paragraphs, Lower and Upper Indus basins have different lithostratigraphic divisions which are as follows.

Upper Indus Basin

	Lei Conglomerate	Pleistocene
	Soan Fm	Lt.Plio-Pleistocene
Siwalik Group	Dhok Pathan Fm	Lt.Pliocene
	Nagri Fm	E. Miocene
	Chinji Fm	Lt.Miocene-E. Pliocene
Rawalpindi Group	Kamlial Fm	M.-Lt.Miocene
	Murree Fm	E.-M. Miocene

Lower Indus Basin

	Lei Conglomerate	Pleistocene
	Soan Fm	Lt.Plio-Pleistocene
	Siwalik Group	Lt.Miocene-Pliocene
	Gaj Fm	E.-M. Miocene
	Nari Fm	Oligocene

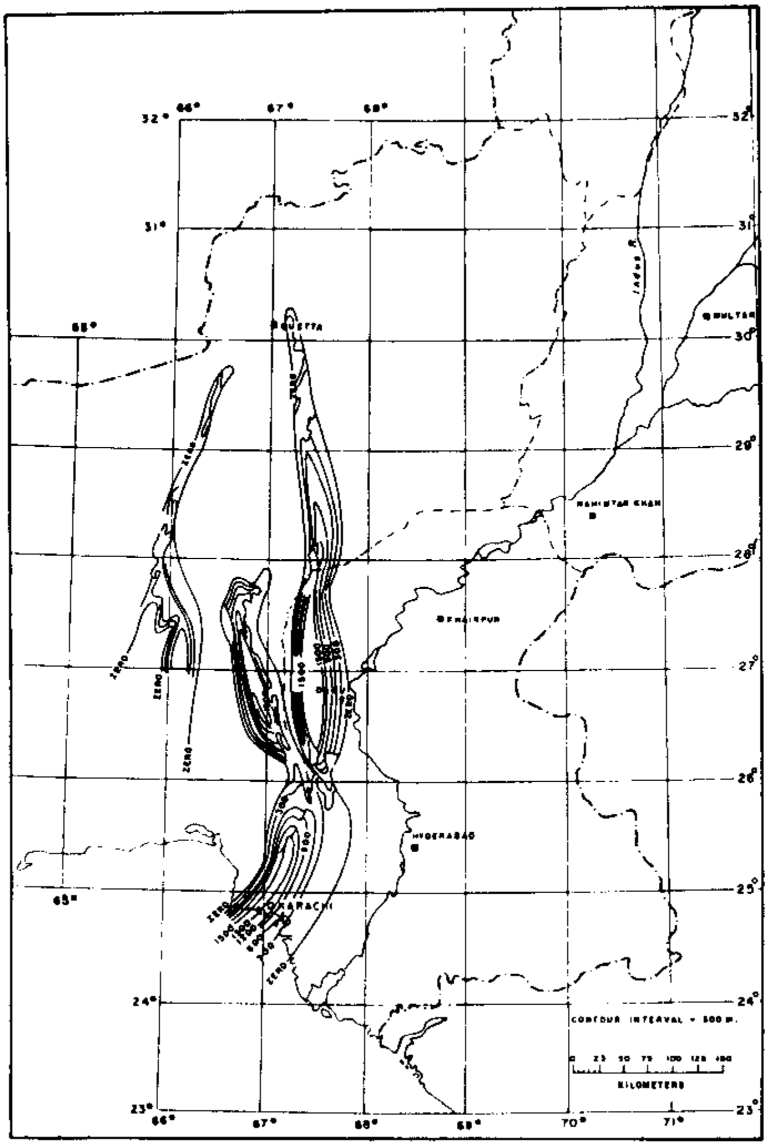

Figure - 15.3 Thickness map of Gaj Formation

THICKNESS, LITHOLOGY AND CONTACTS

Lower Indus Basin

Nari Formation consists of sandstones and shales with subordinate limestone and minor conglomerate. Nal Member comprising crystalline limestone forms the lower part and is exposed only near Nal in Axial Belt. Thickness of Nari Formation is 1,400 meters at type locality in Gaj River, Kirthar Range. In Kirthar sub-Basin, it varies from 1,820 to 1,050 meters (at Mazarani). It is 150–300 meters in Sulaiman sub-Basin and 200 meters in Quetta. Upper contact of Nari Formation is conformable with Gaj Formation; however, it is unconformable with Siwaliks in Sulaiman sub-Basin (e.g. Sui). Lower contact is conformable and gradational with Kirthar and Nisai Formation but unconformable with Laki and Ghazij Formations in Hyderabad area.

Gaj Formation is composed of shales with subordinate sandstone and limestone. Shales are mostly gypsiferous. At type locality (Gaj River) it is 650 meters thick; 600–750 meters in other areas. In subsurface, offshore Karachi it is 50–65 meters thick and 90 meters in Quetta. Its upper contact with Siwalik Group and lower contact with Nari Formation is transitional and conformable. Gaj/Nari contact is exposed north of Karachi.

Siwalik Group consists of sandstones with alternating bands of argillaceous material. This is the outwash deposit laid down by the fluvial system developed between Himalayan front and Arabian Sea. Thickness of this group varies largely and goes up to 4,500 meters in foredeep areas (e.g. Sulaiman Foredeep, Sibi and Karachi Troughs and Karachi Embayment). Its lower contact is mostly conformable except for few localities in western Kirthar and eastern Sulaiman sub-basins where it unconformably overlies Laki and Kirthar formations. Upper contact with

Lei Conglomerate is unconformable.

Lei Conglomerate is regarded as a valley fill deposit consisting of boulder and pebble conglomerates with minor coarse bedded sandstones.

Upper Indus Basin

Rawalpindi Group

Post-Eocene stratigraphy starts with Miocene. The Rawalpindi Group is subdivided into Murree and Kamlial formations. Murree Formation consists of dark red, purple and grey sandstones alternating with purple/red shales and conglomerates. Its thickness in the Northern Potwar is more than 3,000 meters; it thins out to 9 meters at Banda Daud Shah in western Kohat and is 180–600 meters thick in northern Salt Range. Its upper contact is conformable/transitional with Kamlial Formation and lower contact is erosional with various Eocene formations.

Kamlial Formation is composed of purple, grey and dark brick red sandstones with subordinate interbeds of hard, purple shale and purple, yellow interformational conglomerate. It is distinguished from underlying Murree Formation on the basis of spheroidal weathering and predominant tourmaline content over epidote. Its thickness is 90 meters at type locality (SW of Kamlial, Attock), 580 meters at Khaur, 650 meters at Soan Gorge, 60 meters at Ling River, 100–150 meters in subsurface at Balkasar and Pamal Domeli and 120–300 meters in western Potwar. Its upper and lower contacts are conformable. However, lower contact with Murree Formation is also transitional and unconformable with Sakesar Limestone at places.

Siwalik Group

Siwalik Group consists of Chinji, Nagri and Dhok Pathan formations. The Lower Siwaliks are derived from the crystalline and metamorphic terrains of the higher Himalayas and the Upper Siwalik deposits consist of recycled Lower and Middle Siwalik debris.

Chinji Formation consists of red clay with subordinate brown grey sandstone and scattered pebbles of quartz and thin lenses of interformational conglomerate. Its thickness is 750 meters south of Chinji, Attock. In subsurface, it varies from 1,320 meters at Toot, 1,300 meters at Dhulian to 1,050 meters at Khaur. Upper contact with Nagri Formation and lower contact with Kamlial Formation are conformable.

Nagri Formation consists of greenish grey sandstone with subordinate clay which is brown, reddish grey and pale orange, sandy and silty. It is 1,000 meters thick at Khaur, 1,070 meters at Dhulian and 915 meters at Joya Mair. Its lower and upper contacts are conformable.

Dhok Pathan Formation is composed of cyclic alternations of grey, light grey, white, reddish brown, occasionally brownish grey, greenish grey, brown or buff sandstones and clays which are orange brown, dull red or reddish brown, calcareous and sandy. Minor intercalations of yellowish brown siltstone, lenses and layers of conglomerates are typical of the upper part. It reaches its maximum thickness of 1,820 meters southeast of Khair-i-Murat; it is 885 meters thick at Khaur and 90 meters at Toot. It is conformably overlain by Nagri Formation while the upper contact with Soan Formation is erosional.

Lei / Soan Formation

Soan Formation consists of compact and massive conglomerate interbedded with orange, brown, pink, red and soft claystone and grey, greenish and coarse grained, soft sandstone. The thickness varies from 120–450 meters. Its lower and upper contacts are unconformable.

Soan Formation is overlain by Lei Conglomerate which is a valley fill deposit and dates back to 1.5 Ma. It consists of conglomerates with minor sandstone and siltstone. Its thickness varies from 150–900 meters This is overlain by sub-recent deposits.

PETROLEUM POTENTIAL

Post-Eocene sediments have played a very important role in the maturity of younger source rocks in depression areas. This period accounts for the rapid clastic sedimentation at the expense of Himalayan uplift and subsequent erosion of uplifted rocks. Petroleum generation is directly related to the scale of time and the thermal regime the strata is subjected to. Rapid burial of Eocene and older rocks have placed them in petroleum generation window in the basinal areas. In some cases even Post-Eocene rocks have become mature.

Lower Indus Basin

Source rock characteristics of exposed Post-Eocene rocks are poor. However, oil/gas prone organic matter has been identified in offshore wells. Nari and Gaj Formations depict good reservoir characteristics but have not been tested for hydrocarbons in the wells drilled to date.

Upper Indus Basin

Bannu and Soan Depressions are considered to be the major kitchen areas of this basin which are filled with Post-Eocene sediments.

First commercial oil in the Potwar area was produced from the Miocene (Murree Formation) at Khaur in 1915. Otherwise only minor indications of hydrocarbons have been encountered in this formation in some Potwar wells. The presence of oil in Murree Formation depends upon the breaching of underlying Eocene reservoir and the availability of reservoir and seal in the basal Murree Formation.

LOG RESPONSE

The boundary between Eocene and Post-Eocene formations is characterised by sudden change from non-clastic to clastic facies which is clearly discernible on any log. However, log response within Post-Eocene formations is generally poor to fair for determination of lithological boundaries and formation fluid content due to poor deflection of SP, high formation resistivities due to relatively fresh formation water, (deposition in continental environment) and large hole size. The Gamma Ray and resistivity logs can, however, be used for gross correlation of formation boundaries across individual structures particularly in the Upper (Potwar) Indus Basin where the Post-Eocene formations are fairly thick and have been separately identified lithologically i.e. the Murree, Kamlial, Chinji etc.

SEISMIC CHARACTERISTICS

The Post-Eocene rocks can be seismically identified as a package in the on-shore areas, being generally loose, under-compacted and continental deposits, compared to the underlying more competent lithologies. The top Eocene/base Oligocene–

Miocene event shows good continuity because of sharp velocity contrast; however, intraformational seismic continuity within the Post-Eocene sediments is not easily discernible.

DRILLING CHARACTERISTICS

Drilling through Post-Eocene rocks in Lower Indus Basin, except for offshore, is usually problem free. As the sediments are undercompacted and unconsolidated; weight on bit and mud hydraulics have to be monitored carefully. As the hole in the first stage drilling is large and accounts for heavy volume of drill cuttings which have to be cleared, optimum mud hydraulics is very necessary. Loss of circulation is not unusual and is cured by use of LCM in mud or placing cement plugs depending on severity of circulation loss.

However, in the Upper Indus Basin, the thick molasse sequence of sandstone, shale and conglomerate contains over–pressured water sands and constitute a drilling hazard over most of the area. Such severe drilling conditions call for optimum casing design, setting depths, mud system, drilling hydraulics and techniques to control inflow and loss of circulation problems associated with reversal of pressure regimes. Section 20 (Drilling Conditions), deals in greater detail with the drilling problems associated with Post-Eocene formations in the Potwar–Kohat Basin.

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Offshore Indus

Unlike Makran region, Offshore Indus forms a part of the passive continental margin. The Offshore Indus Basin includes part of the Cutch Basin and constitutes the sedimentary region between Murray Ridge and Cutch Fault (Fig. 16.1). The basin appears to have gone through two distinct phases of geological history (Cretaceous – Eocene and Oligocene – Recent).

The Offshore Indus Basin is the southern offshore extension of the Southern Indus Basin and consists of approximately 2,000 square km area between 23^{o} and 25^{o}N latitudes and 66^{o} and 68^{o}E longitudes. This includes the southern portion of the Karachi Trough and extends 100–200 km from shore. Seven wells have so far been drilled offshore and two in the coastal region (Fig. 16.2). Some of the wells had gas shows. Non-commercial gas (2-3 MMcfd) was reportedly tested in OGDC's Pak Can-1 well (1985).

Sedimentation in the basin started in pre-Cretaceous. However, deltaic and submarine sedimentation occurred from middle Oligocene. One active and some passive submarine canyons have been distributing clastic sediments over shelf slope since plate collision.

The Indus River is about 2,900 km. long and travels a distance of 1,000–1,200 km in the plains before it joins the Arabian Sea (Kolla & Coumes, 1987). It built a delta advancing southward along the Indus Trough. Sediments discharged by the Indus River are transported further offshore, accumulate on the inner continental shelf offshore of the delta and are carried directly to the Indus fan by way of the Indus submarine canyon.

TECTONIC SETTING AND HISTORY

Offshore Indus basin is divided into platform areas and depression areas by 67^{o}E longitude hinge line which parallels Karachi Trough shore line. Fig. 16.2 shows the divisions of the platform areas.

West of 67^{o}E longitude hinge line, the post-Oligocene sedimentation seems to have been continuous, except for a short break during the Late Miocene, while post-Early Cretaceous sediments are either lacking or thinning out in the Thar Slope. Geological history of different tectonic units onshore/offshore is shown in Fig. 16.3 adopted from Kolla and Coumes (1987).

Offshore Indus Basin is unique in its post-Oligocene stratigraphy which is tectonically controlled. Before the onset of Indus River system, stratigraphy of this basin was compatible with that of Southern

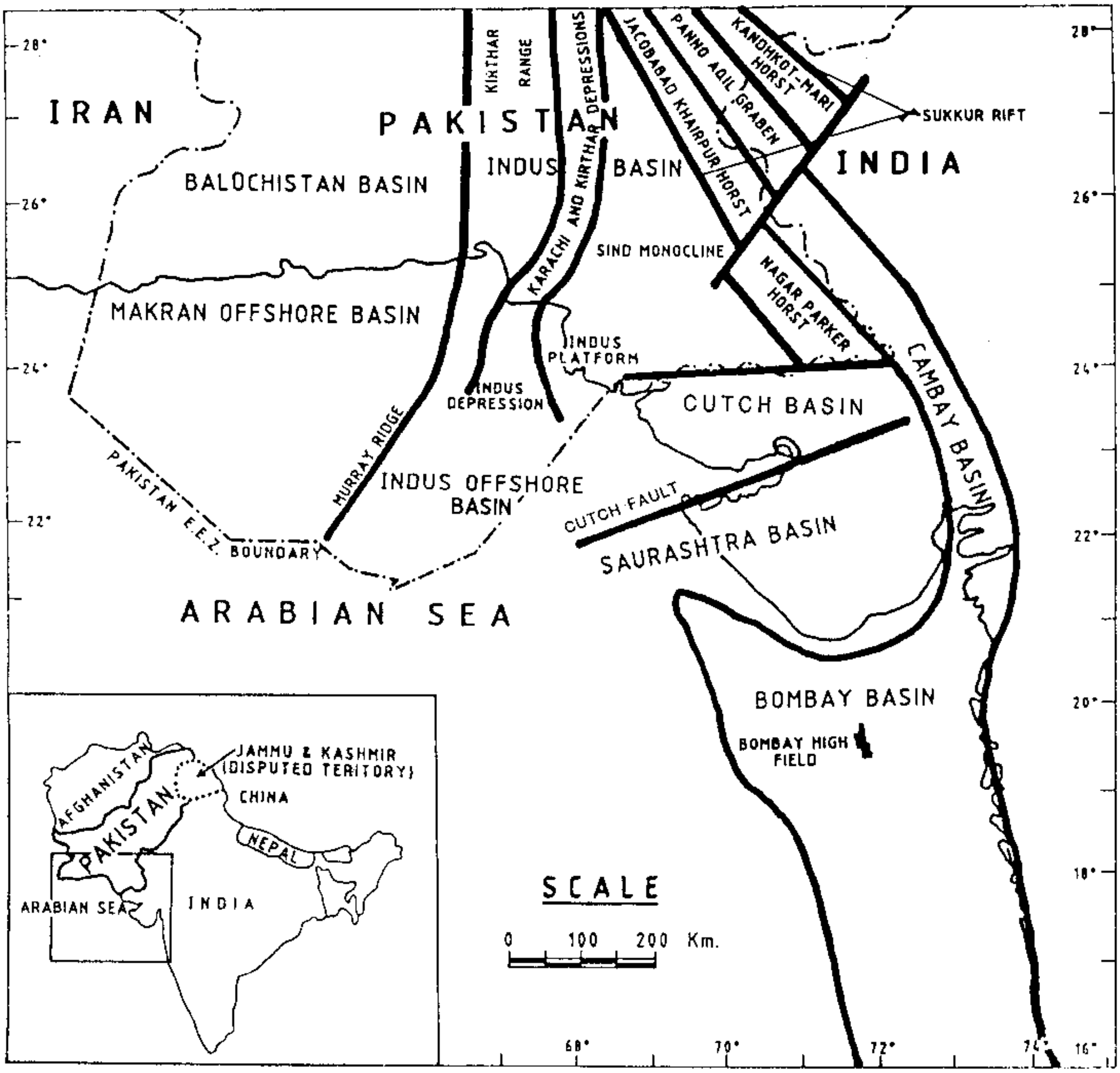


Figure - 16.1 Offshore Indus Basin and other tectonic zones (after Raza et al, 1990)

Indus Basin. The closure of Tethys sea by the end of Eocene caused significant uplift of the Himalayas. This uplifting continues to the present day with some major pulses during the middle to Late Miocene and Late Pliocene to Middle Pleistocene. Thus it can be inferred that the Indus River probably came into existence after the Early Eocene but before the Miocene. The Deep Sea Drilling Project (DSDP) sites 220–223, Leg 23 Weiser (1974), dates the onset of Indus sedimentation as late Oligocene.

LITHOSTRATIGRAPHIC DIVISION

The wells so far drilled in this basin show extreme lateral variation both from north to south and west to east. However, this variation forms a pattern as regards the rate and direction of sedimentation. (Fig. 16.4, 16.5, & 16.6 show this variation).

Stratigraphic succession penetrated in Dabbo Creek well (Sun Oil – 1964), being deepest, is most representative of the offshore platform area.

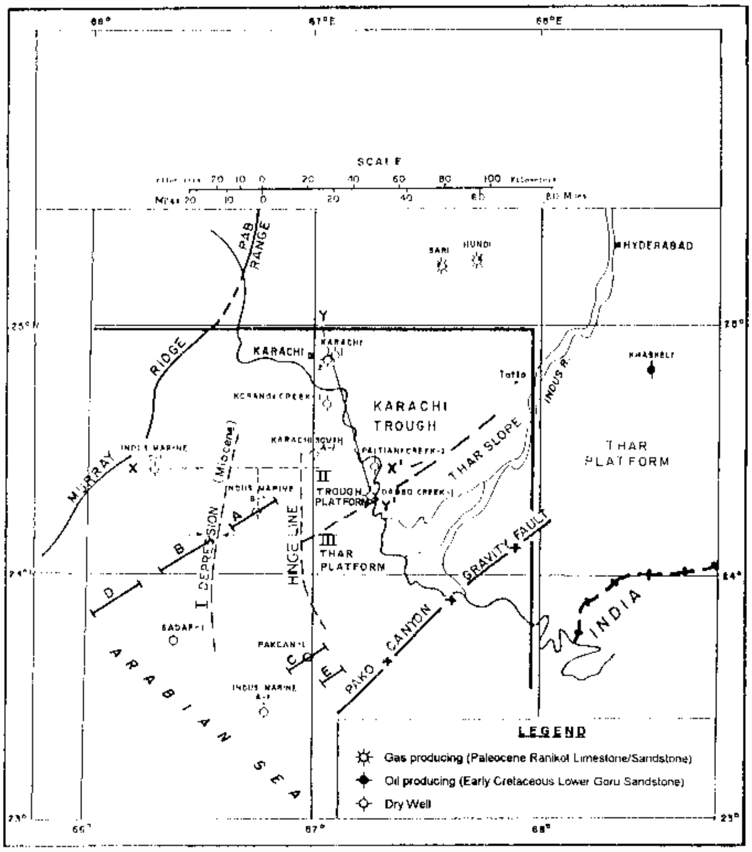


Figure - 16.2 Offshore Indus Basin, tectonic divisions and location of wells; I. Offshore depressions; II. Trough platform; III. Thar platform (delta area). A,B,C,D & E refer to seismic profiles shown in Fig 16.9A, B; 16.10 A,B: and 16.11 (after Shuaib, 1982)

Cretaceous

The Early Cretaceous Sembar/Goru formations are the oldest rock units penetrated by wells drilled so far. The formation is over 1,900 meters thick and consists of interbedded shale, siltstone, and sandstone. The Upper Goru is almost entirely a shaly facies. Overlying the Goru is the Parh Limestone which is about 136 meters thick. The Moghal Kot Formation consists mainly of limestone interbedded with shale. Upper most Cretaceous Pab Formation is poorly developed in Offshore Indus. It is either absent or where present, it is not more than 50 meters thick as observed in some of the wells.

Paleocene

The Ranikot Formation of Paleocene age is present in the Karachi Offshore Platform. However, the Upper Ranikot has only been encountered in one of the platform wells and consists mainly of interbedded shale and limestone. The Lower Ranikot consists of sandstone interbedded with shale and layers of 'basalt' and reach a maximum thickness of about 1,300 meters in the subsurface.

Eocene

Ghazij/Laki Formation of Lower Eocene age was encountered in all four wells drilled on Karachi Offshore Platform, as well as in one of the wells in the Offshore Depression close to Murray Ridge axis. This formation contains shaly facies with bands of carbonate rocks. It has a maximum thickness of 445 meters in the Offshore Platform areas. Onshore it is represented by Korara Shale encountered in Karachi wells. Kirthar Formation consists mainly of limestone interbedded with marlstone and calcareous shale and has a maximum thickness of about 1,300 meters in the subsurface.

Oligocene

Nari Formation consists mainly of limestone interbedded with marlstone and calcareous shale, commonly with bands of calcareous sandstone, especially in the upper part. Its maximum thickness is about 1,700 meters in onshore Karachi wells.

MIOCENE

Lower Miocene Gaj Formation is about 60–70 meters thick in the Offshore Platform area and is present in all the wells drilled in the region. In the Depression area maximum thickness of over 2,750 meters was encountered in the southern most offshore well. This formation comprises carbonate facies with inercalations of calcareous clastics.

Post-Lower Miocene sediments are not present in wells drilled on Offshore Platform but are well represented in Depression.

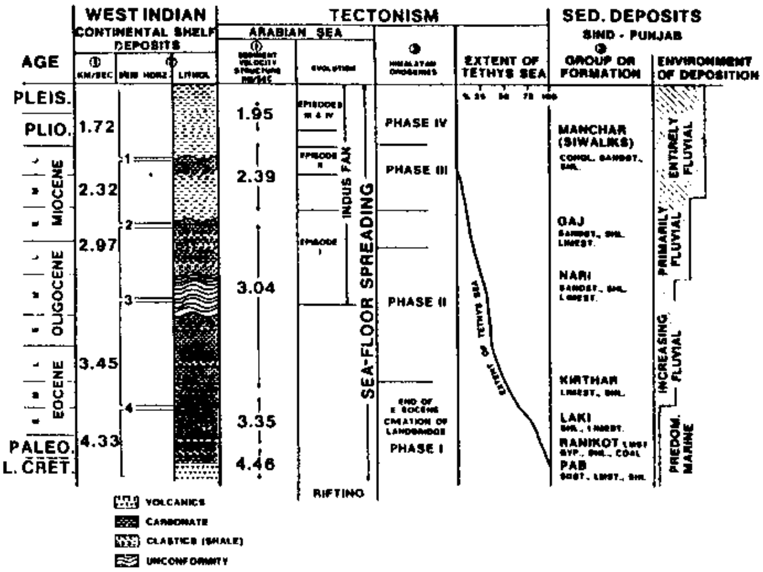


Figure - 16.3 Geologic history of land region (Sindh-Punjab, Pakistan), and Western Indian shelf, Himalayan orogenies, and evolution of Arabian Sea and Indus Fan. (after Kolla and Coumes, 1987)

It is apparent that rapid Miocene sedimentation is controlled by uplifting of Himalayas and denudation processes of the Indus River system. The dispersal of these sediments was brought about by various submarine channels and the canyon.

SOURCE ROCKS

The presence of gas shows in most of the wells and testing of non-commercial gas (from offshore standard) from one well proves the occurrence of source rocks and its maturity subject to sufficient overburden and suitable geothermal gradient.

The conventional source rock of Badin area, Sembar Shales, is present in the Indus Offshore and has been encountered in one of the Creek wells. The shales do not show any significant organic matter in this well; however, source richness is expected to improve westwards in the Depression and Platform areas and are expected to be within oil window.

Ranikot Formation (Paleocene) consists of about 2-3 meters of net interval of coal in near-shore wells. In these wells the TOC ranges from 3 – 8%.

Laki Formation also contains some organic matter in Creek wells which is mostly land derived and forms a poor source for gas.

Kirthar Formation with 20 meters of net interval of organic rich shales has some potential for generation of light oil/gas in one of the Creek wells. However, in the Depression area Kirthar Formation contains lean source rocks with largely woody kerogen.

Nari Formation has thin silt beds with very good potential for gas generation in the coastal area.

Very thick Miocene sediments are present in Offshore Depression where the targets are Miocene reservoirs. These rocks are mostly lean with TOC improving towards west, which ranges between 0.6 – 0.75%. However, this organic matter is abundantly land derived and accounts for poor source for gas.

WELL	ONSHORE: KARACHI-1 (PPL)	ONSHORE: KARACHI-2 (PPL)	OFFSHORE PLATFORM: KORANGI CREEK-1 (SUN)	OFFSHORE PLATFORM: PAITIANI CREEK-1 (SUN)	OFFSHORE PLATFORM: DABBO CREEK-1 (SUN)	OFFSHORE PLATFORM: KARACHI SOUTH-A (HUSKY)	OFFSHORE DEPRESSION: INDUS MARINE C-1 (WINTERSHALL)	OFFSHORE DEPRESSION: INDUS MARINE B-1 (WINTERSHALL)	OFFSHORE DEPRESSION: INDUS MARINE A-1 (WINTERSHALL)
LATITUDE	24°-52'-50"	24°-50'-48"	24°-42'-42"	24°-27'-00"	24°-20'-02"	24°-29'-08.3"	24°-35'-56"	24°-15'-02"	23°-27'-27.9"
LONGITUDE	67°-04'-40"	67°-04'-37"	67°-04'-14"	67°-17'-30"	67°-16'-42"	67°-00'-29.7"	66°-18'-24"	66°-45'-20"	66°-48'-25.5"
SPUD IN DATE	07-08-1956	26-04-1959	25-10-1964	20-06-1964	08-12-1963	26-02-1978	04-03-1975	15-12-1972	12-09-1972
RIG RELEASE DATE	31-07-1957	29-12-1959	21-02-1965	22-10-1964	07-08-1964	10-05-1978	13-05-1975	14-03-1973	14-12-1972
G. E. (m)	56	54	-5	-4	-6	-21	-76	-73	-105
K. B. (m)	59	59	16	17	19	16	11	11	11
T. D. from M. S. L. (m)	-2976	-3888	-4124	-2643	-4335	-3337	-1931	-3793	-2830
T. D. below K. B. (m)	3035	3947	4140	2660	4354	3353	1942	3804	2841
WELL STATUS	Gas shows in Kirthar and U. Nari (D&A)	Gas shows in Karara Shale and U Nari (D&A)	Gas shows in Paleocene - Eocene sections (D&A)	Gas shows in U. Cretaceous section (D&A)	Gas shows in L. to U. Cretaceous section (D&A)	High Gas reading in Paleocene section (D&A)	Gas traces in Lower to Middle Miocene section (D&A)	Gas traces in Lower Miocene section (D&A)	Gas traces in Middle Miocene section (D&A)

ERA	PERIOD		FORMATION	Karachi-1 LITHOLOGY	THICK (m)	Karachi-2 LITHOLOGY	THICK (m)	Korangi Creek-1 LITHOLOGY	THICK (m)	Paitiani Creek-1 LITHOLOGY	THICK (m)	Dabbo Creek-1 LITHOLOGY	THICK (m)	Karachi South-A LITHOLOGY	THICK (m)	Indus Marine C-1 LITHOLOGY	THICK (m)	Indus Marine B-1 LITHOLOGY	THICK (m)	Indus Marine A-1 LITHOLOGY	THICK (m)
CENOZOIC	QUATERNARY	HOLOCENE						Alluvium	241	Alluvium	332	Alluvium	378	Intercl Clay - Silt fine Sst. with Congl bands - fossils.	423						
CENOZOIC	QUATERNARY	PLEISTOCENE														Intercl Clay, Silt - Sst with Congl. bands - fossils	59	Same as Indus Marine C-1 well	193	Same as Indus Marine B-1 well	291
CENOZOIC	TERTIARY, NEOGENE	PLIOCENE	MANCHAR														56		276		395
CENOZOIC	TERTIARY, NEOGENE	MIOCENE	GAJ U																		1028
CENOZOIC	TERTIARY, NEOGENE	MIOCENE	GAJ M													Intercl Calc - Clay - Sh - Slt. with Lst. - Sst. beds	646	Intercl Calc. Sh. - Silt - Sst. with Lst. bands.	500		+1011
CENOZOIC	TERTIARY, NEOGENE	MIOCENE	GAJ L	Mainly Lst. with Sh. bands	724	Same as Karachi-1 well.	688	Mainly Lst. with Sh. bands	55	Same as Korangi Creek-1 well	66	Same as Paitiani Creek-1 well	67	Same as Dabbo Creek-1 well	375		736		+2749		
CENOZOIC	TERTIARY, PALEOGENE	OLIGOCENE	NARI U	Intercl Sh - Sst - Lst.	1673		1696	Mainly Lst. with Marl - Sh.	597		586		461		1215		28				
CENOZOIC	TERTIARY, PALEOGENE	OLIGOCENE	NARI L	Mainly Lst. - Marl.	56		80														
CENOZOIC	TERTIARY, PALEOGENE	EOCENE, LATE	KIRTHAR	Mainly Lst. with Calc. Sh.	96		246	Lst. interbed with Sh.	1283		171		121		544		70 / 25				
CENOZOIC	TERTIARY, PALEOGENE	EOCENE, EARLY	GHAJIZ / LAKI	Karara Shales	+283	Karara Shales	+1232	Mainly Sh. with Lst. bands	445		235		50		186	Mainly Sh. with Sst. - Lst. bands	+33				
CENOZOIC	TERTIARY, PALEOGENE	PALEOCENE	RANIKOT U							Lst. - Sh interbed	180										
CENOZOIC	TERTIARY, PALEOGENE	PALEOCENE	RANIKOT L					Sst. - Sh. beds with Basalt layers	1329	Same as Korangi well	752		703		503						
MESOZOIC	CRETACEOUS	LATE	PAB							Sst. mainly	51		36		27						
MESOZOIC	CRETACEOUS	LATE	MUGHAL KOT					Lst. interbed Sh.	+169	Same as Korangi well.	+266		468		+43						
MESOZOIC	CRETACEOUS	LATE	PARH									Mainly Lst.	136								
MESOZOIC	CRETACEOUS	EARLY	GORU U									Mainly Sh.	242								
MESOZOIC	CRETACEOUS	EARLY	GORU L									Interbed Sst. & Sh.	970								
MESOZOIC	CRETACEOUS	EARLY	SEMBAR									Sst. with Sh. beds.	+697								

ABBREVIATIONS

M. S. L.	Mean Seawater Level
G. E.	Ground Elevation / Sea floor from M. S. L.
K. B.	Kelly Bushing Elevation above M. S. L.
T. D.	Total Depth
D. A.	Dry and Abandoned
Congl.	Conglomerate
Sst	Sandstone
Slt.	Siltstone
Sh.	Shale
Lst.	Limestone
Intercl	Intercalation
Interbed	Interbeded
Calc.	Calcareous

Figure - 16.4 Data of wells drilled in Indus offshore basin area. Locations given on Fig-16.2 (after Shuaib, 1982)

At present, a thick oxygen minimum zone (< 0.5ml/liter) extends from depths of 100–1,500 meters along the northern margin of Arabian Sea, which is very prolific for the preservation of organic matter. Analogs of this basin in the world are known for large accumulation of hydrocarbons. Therefore, it is likely that good source rocks in Miocene/Pliocene sequence are present since the environment for the deposition and preservation has not changed drastically during Miocene/Pliocene. (McHargue & Webb, 1986). In Indus Offshore, the geothermal gradient (Fig. 16.7) is the highest (3 °C/100 meters) nearshore close to the hinge line (Long 67°E) and decreases towards Offshore Depression in the west. The geothermal gradient is controlled by Paleoslope rather than depth in the Offshore Platform and Depression area as the post Late Oligocene sedimentation has been very rapid (Indus fan contains about 7,000 meters of sediments). To attain the maturity level for oil generation, greater burial depth is a crucial factor for younger source rocks (Oligocene/Miocene). The low geothermal gradient in the younger sediments in the Depression area may be the reason for lack of success of the Sadaf-1 well drilled in this region.

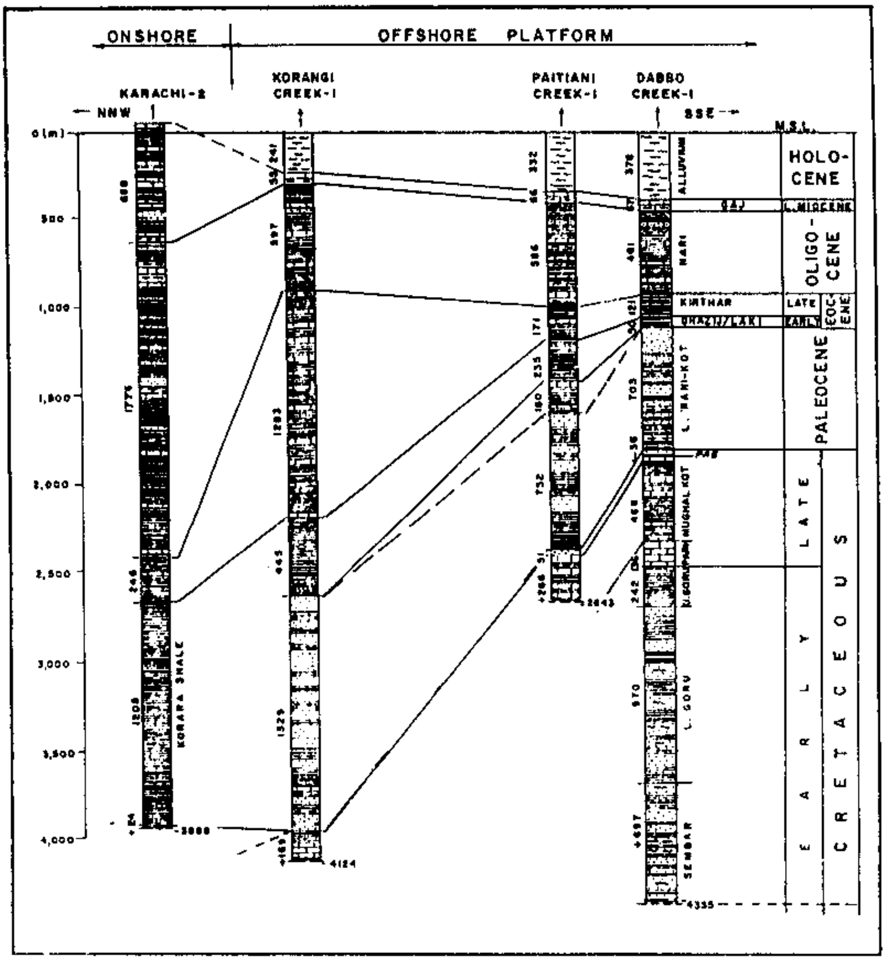


Figure - 16.5 Cross Section of YY' showing stratigraphic relations. Locations of wells and section are shown on Figure–16.2. See Figure 16.6 for legend (after Shuaib, 1982)

However, the older source rocks (Cretaceous) would be mature in relatively shallower nearshore (platform) area while they would be overcooked in Depression areas.

RESERVOIR ROCKS

From the foregoing it is evident that the Cretaceous and Paleocene reservoirs would be quite deep in the offshore depression areas and the objectives would, therefore, be restricted to Miocene / Pliocene sand – silt sequence. In the Platform areas the potential reservoirs are compatible with their counterparts in Karachi Trough and Thar Slope onshore. Sembar and Goru Sands

(Cretaceous), Ranikot Sand (Paleocene) and Laki and Kirthar limestones of Eocene age are likely to bear the reservoir potential. These formations have gas shows in some wells drilled on Offshore Platform.

Three offshore wells drilled by Wintershall failed to encounter any reservoir (Table 16.1) as they were abandoned before reaching the target depth due to technical reasons after encountering high formation pressure.

COASTAL REGION/OFFSHORE DEPRESSION WELLS					
Company	Well Name	Year	Whether objective was reached	TD (below MSL) in metres)	Remarks
Sun Oil	Dabbo Creek-1	1964	Yes	4354.1(-4335)	Minor gas shows, Plugged and abandoned.
	Korangi Creek-1	1964-65	Yes	4139.8(-4124)	Gas shows in Paleocene-Eocene Section. Plugged and abandoned.
	Patiani Creek-1	1964	Yes	2659.2(-2643)	Gas shows in upper part of Mughalkot. Plugged and abandoned.
Wintershall	Indus Marine-A1	1972-73	Partially	2841.2(-2831)	Abandoned for technical reasons after kicking.
	Indus Marine-B1	1972-74	Partially	3804.2(-3793)	Abandoned for technical reasons after kicking.
	Indus Marine-C1	1975	No	1942(-1932)	Formation pressure required mud weight greater than the fracture gradient at the bottom. Plugged and abandoned.
Husky	Karachi-South-A1	1978	No	3353(-3343)	Tops of formations were found lower than expected. Abandoned.
OGDC	PakCan-1	1985-86	Yes	3701	Non commercial gas discovery in Miocene. Plugged and abandoned.
Occidental	Sadaf-1	1990	Yes	3981	Dry, plugged and abandoned.

Table - 16.1 Coastal Region/Offshore Depression Wells (after Raza et al, 1990)

OGDC's well Pak Can-1 encountered certain Miocene reservoir intervals which were tested for 2-3 MMcfd of gas. Although Oxy's well Sadaf-1 failed to prove the presence of any hydrocarbons, it encountered some sand intervals with very good porosity.

Since the stratigraphy of the Miocene/ Pliocene sequence of Depression area is not known, it is believed that the reservoir characteristics are to be picked by seismic stratigraphy and their extent mapped for prospect evaluation.

One of the seismic line south of Pak Can-1 indicates the presence of a reef at Eocene level (Fig. 16.11).

SEISMIC CHARACTERISTICS

Since the lithology and the source/reservoir characteristics of different rock units in subsurface offshore is not known, the only tool to decipher the lithological, reservoir and sedimentological patterns is 'seismic stratigraphy'.

On the basis of seismic stratigraphy, Indus fan is characterized by four facies based on their amplitude, continuity and geometry (McHargue & Webb, 1986). These facies are low-amplitude, continuous (L-C); high-amplitude, continuous (H-C); low- amplitude, discontinuous (L-D); and high-amplitude, discontinuous (H-D). In this context H-D facies is considered to have the best economic value. This represents mixed coarse and fine clastics, including reservoir quality sand. The other facies are interpreted to represent fine clastics of reservoir quality. Table 16.2 summarizes the Indus fan seismic facies and their characteristics. Fig. 16.8 shows typical seismic sections of Indus fan with seismic facies distribution.

Other important feature observed on the seismic sections of Offshore Indus is the presence of sinuous and gravity growth faults (Figs. 16.9A and 9B; Figs. 16.10A and

10B). Reef development at Eocene level can also be seen on one of the seismic lines (Fig. 16.11). Location of these lines is shown in Fig. 16.2.

DRILLING CHARACTERISTICS

The drilling of offshore wells require special attention from safety point of view as it involves exposure of drilling outfit and personnel to potentially hazardous conditions of rough and agitated sea during the monsoon season. The Indus Offshore offers a relatively stable environment and tolerable climate. As far as the drilling conditions are concerned, most of the Indus Offshore is located within the normal hydrostatic gradient limits except for the areas close to Murray Ridge where the required mud weight exceeded the fracture gradient of the formation (Fig. 16.12). Exploration in deeper waters (in excess of 300 meters) requires greater attention to drilling muds. Some of the common problems in the deeper areas are expected to be associated with shales, because of their rapid

Indus Fan Seismic Facies and Their Characteristics

	Low-Amplitude Continuous (L-C)	High Amplitude Continuous (H-C)	Low-Amplitude Discontinuous (L-D)	High Amplitude Discontinuous (H-D)
Amplitude	low	high	low to moderately low	high
Continuity	high	high	low	low
Internal geometry	convergent	convergent to parallel	complex; truncated, inclined, or obscure	highly discontinuous, subarcuate to subparallel
External geometry	wedge	wedge to draped sheet on fan; tabular on shelf	lenticular on a large scale	irregular to lenticular
Distribution	flanks channels of aggradational zone	flanks channels transitional zone; dominant on outer shelf and interchannel areas	dominant within canyon complexes and transitional channels; common in aggradational channels	within channels, especially adjacent to levee face and toe, and along channel base
Interpreted lithofacies	siltstone	alternating fine-grained sandstone, siltstone, and shale	mudstone	coarse clastics including sandstone
Interpreted origin	fine-grained over-bank turbidites of aggrading levees	interbedded turbidites and hemipelagites on fan; prodelta mudstone on shelf	lateral accretion of canyon walls; overbank fines from thalweg within channels	channel axis deposits

Table - 16.2 Indus Fan Seismic Facies and their Characteristics (after Mc Hargue and Webb, 1986)

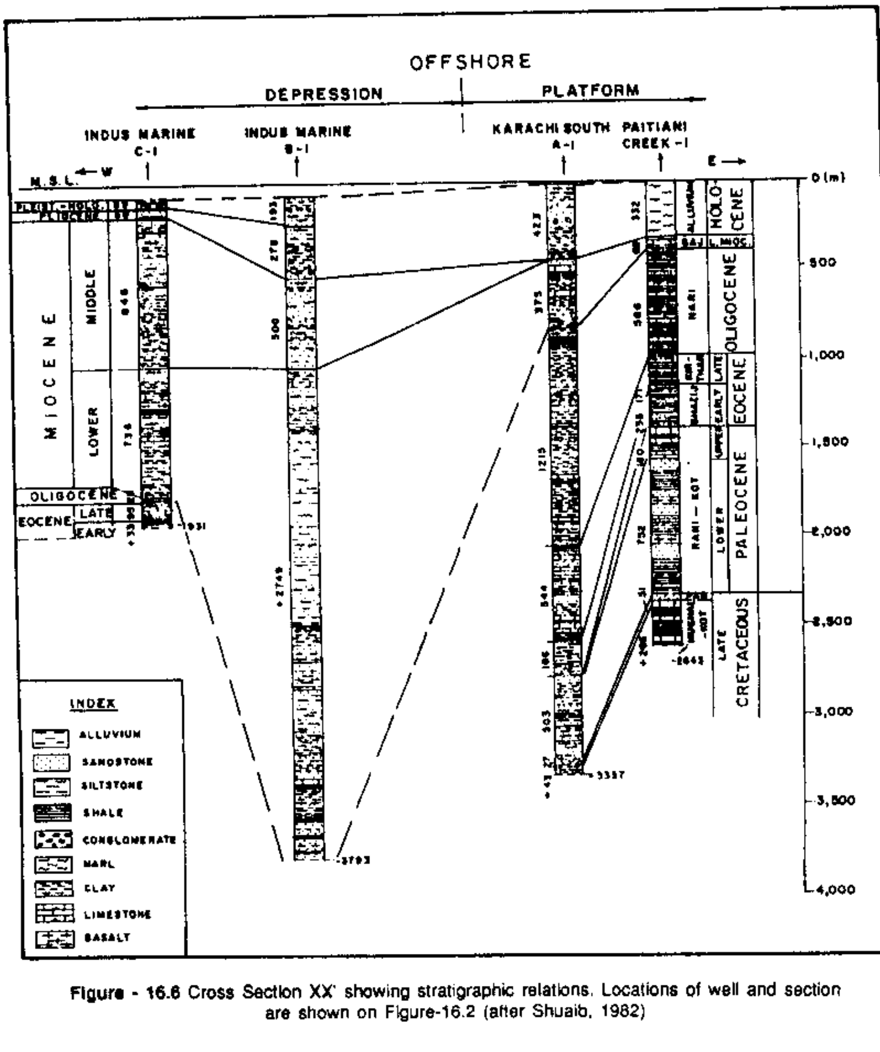


Figure - 16.6 Cross Section XX' showing stratigraphic relations. Locations of well and section are shown on Figure-16.2 (after Shuaib, 1982)

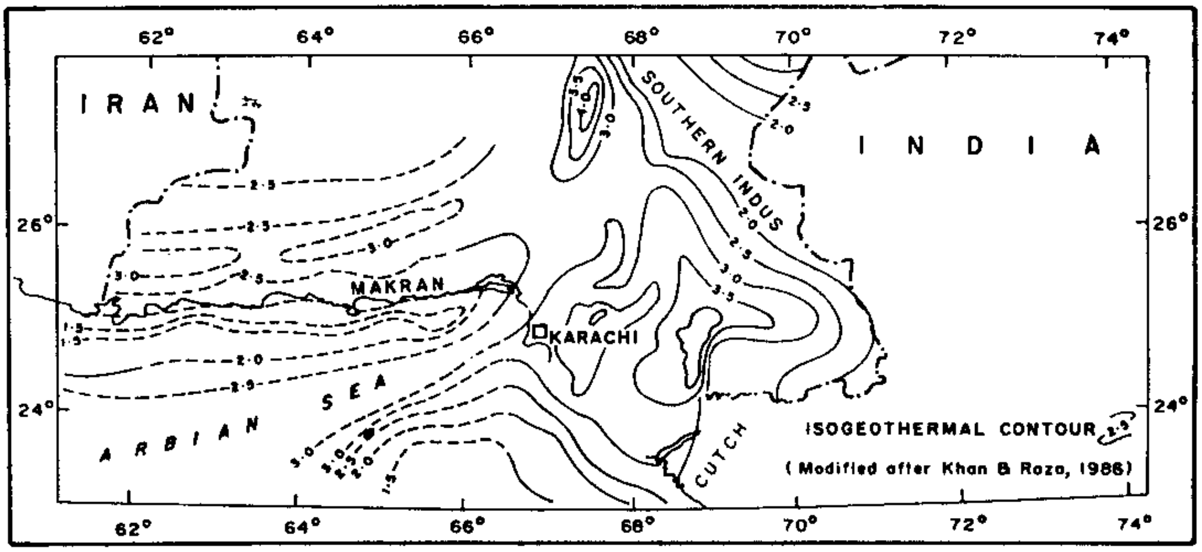


Figure - 16.7 Geothermal Contours in Southern Indus, Cutch and Makran Basins

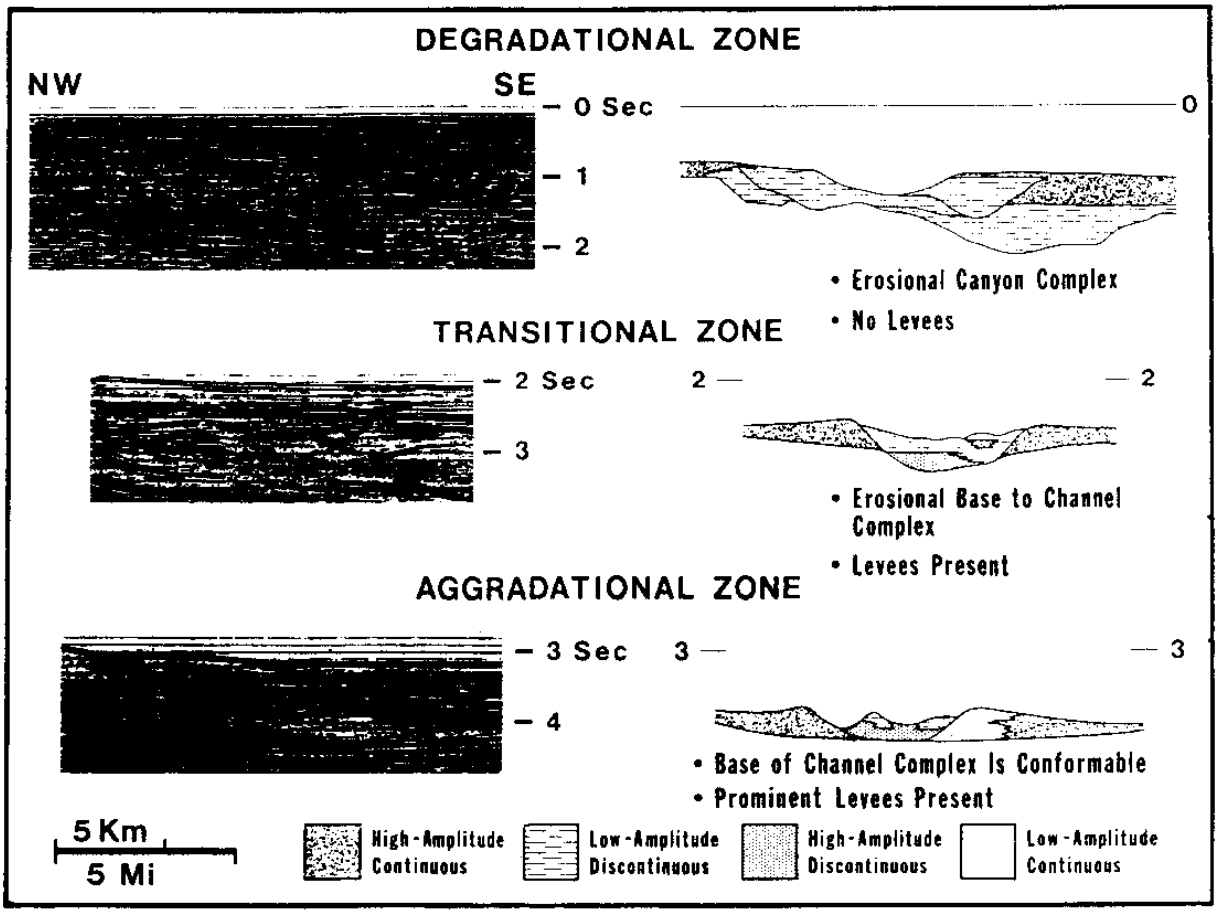


Figure - 16.8 Distribution of seismic facies in typical seismic sections of Indus Fan system (after Mc Hargue and Webb, 1986)

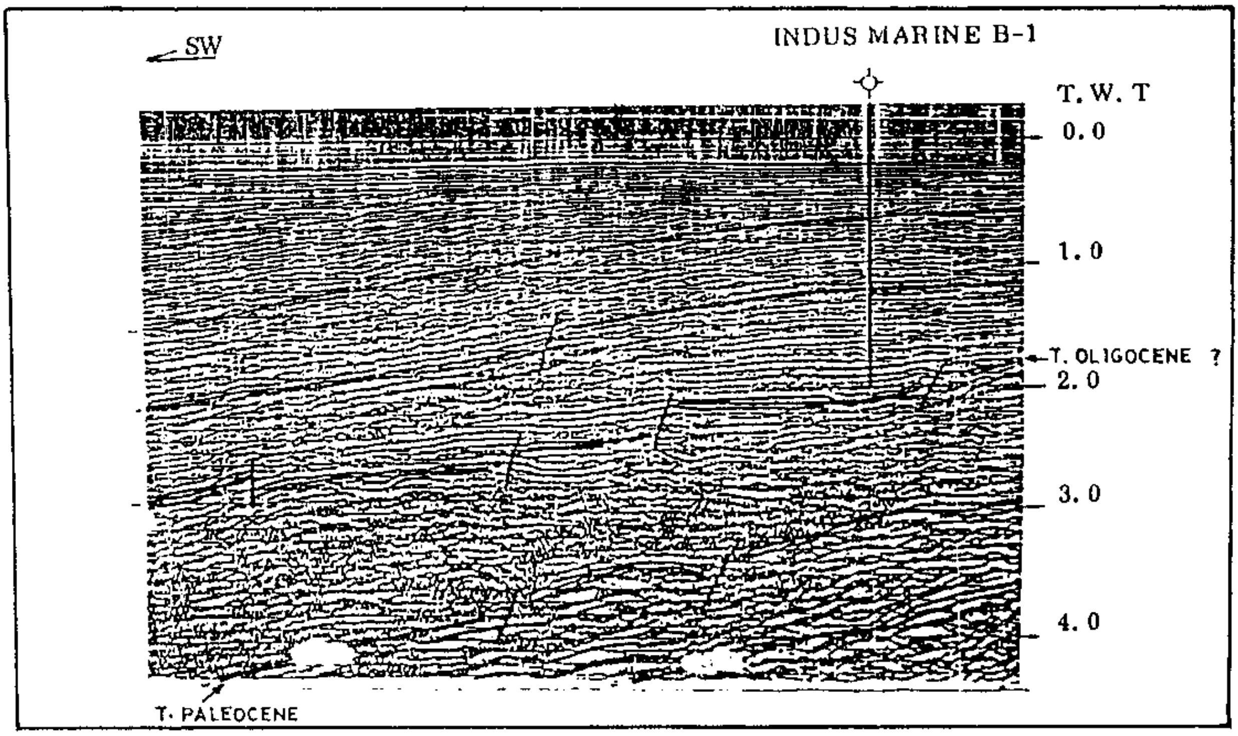


Figure - 16.9A Profile along line A showing normal faults at different stratigraphic levels. For location see Figure-16.2 (after Raza et al 1990)

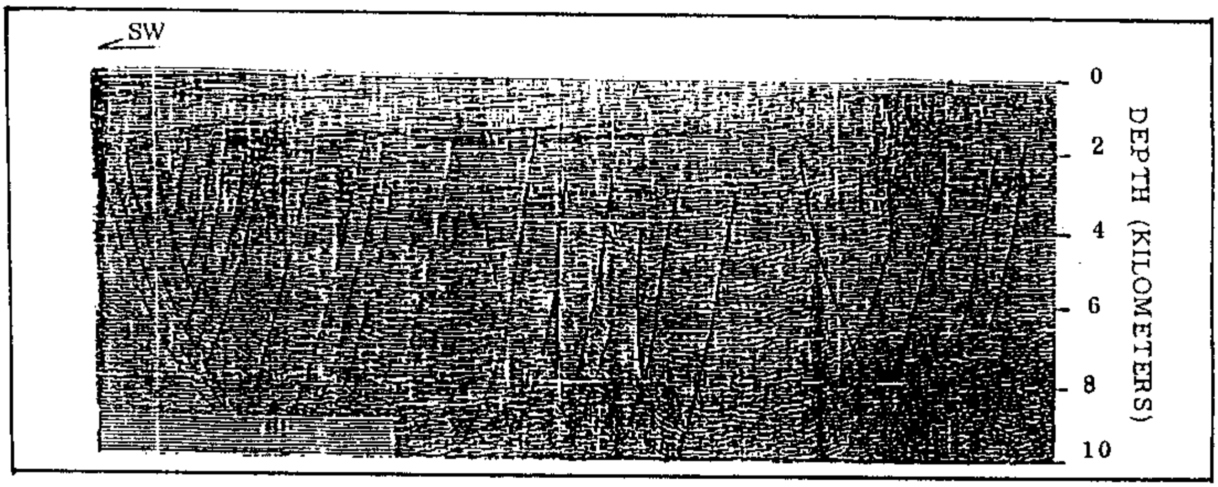


Figure - 16.9B Profile along line B showing highly faulted section. The faults are normal, down-to-the basin type. For location see Figure-16.2 (after Raza et al 1990)

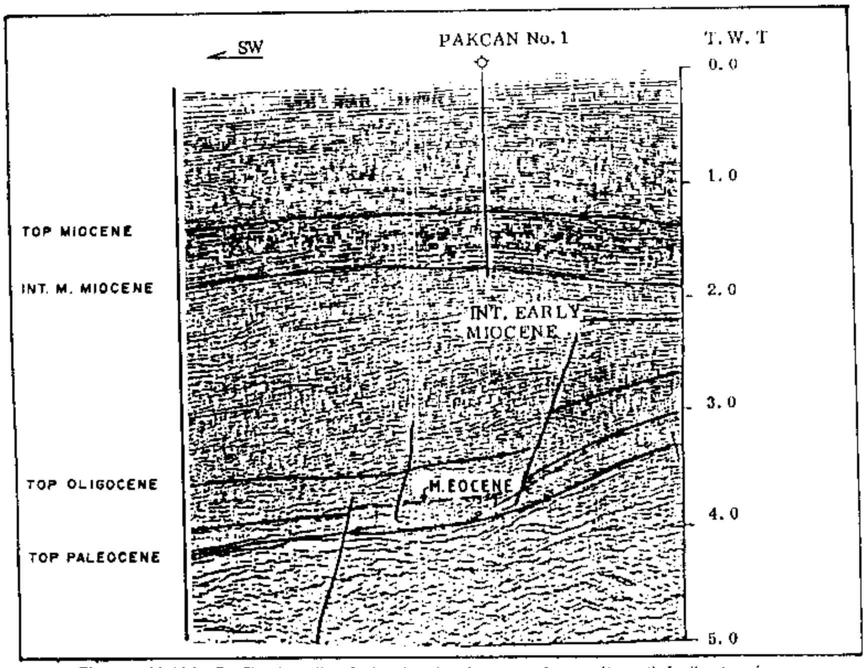


Figure - 16.10A Profile along line C showing development of normal/growth faults at various stratigraphic levels. For location see Figure-16.2 (after Raza et al 1990)

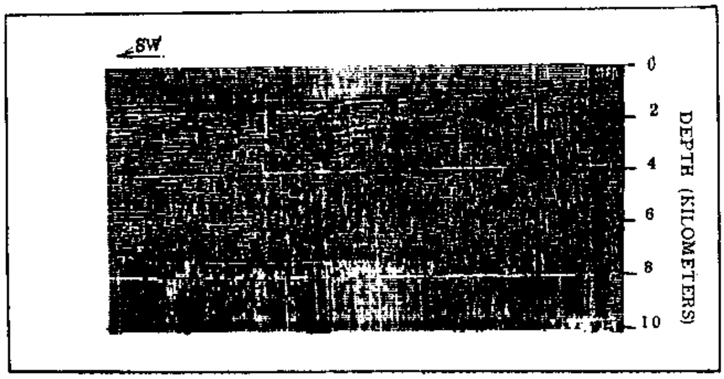


Figure - 16.10B Profile along line D showing assymmetric folds developed due to shale diaprism. For location see Figure-16.2 (after Raza et al 1990)

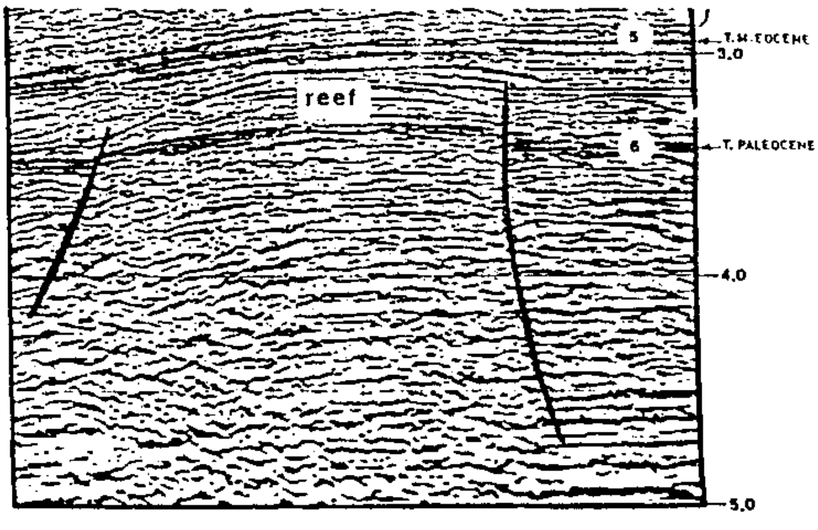
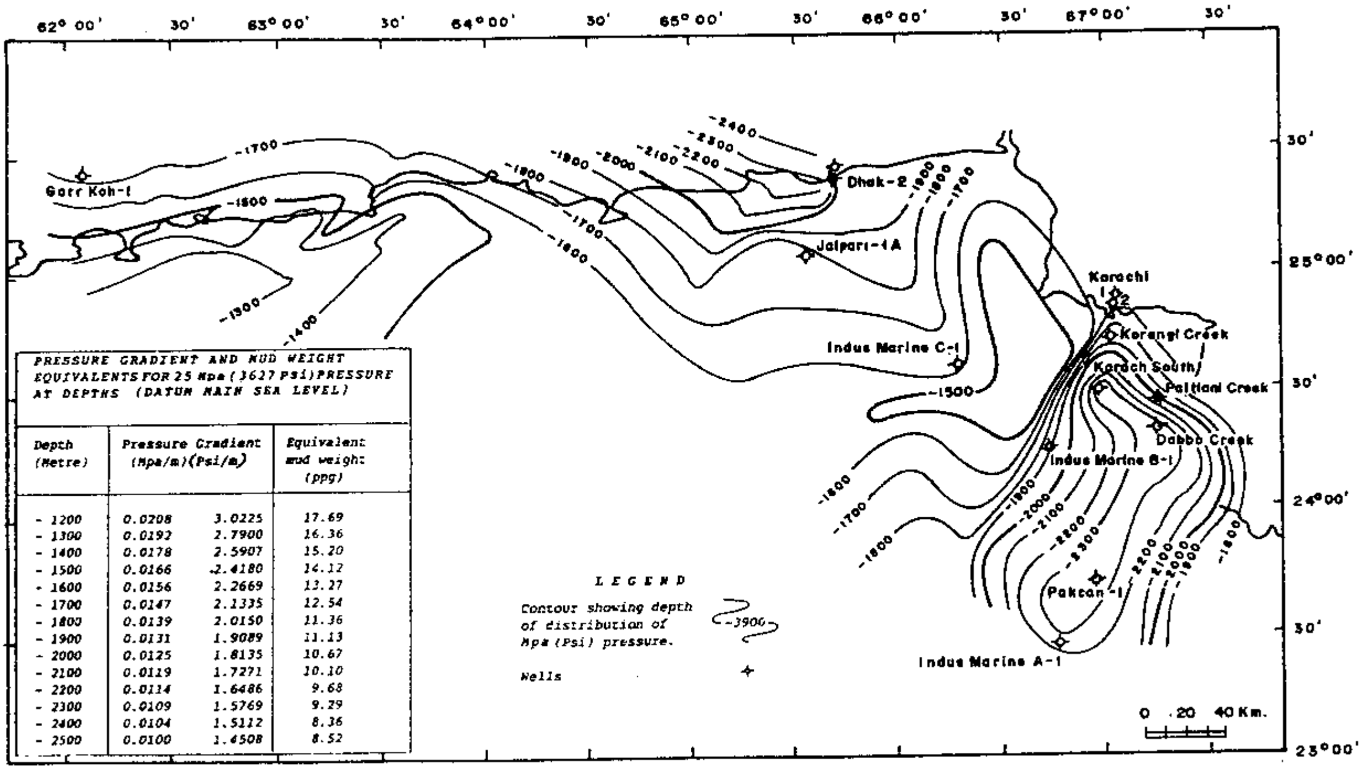


Figure - 16.11 Profile along line E showing probable reef build up at Eocene level. For location see Figure-16.2 (after Raza et al 1990)



PRESSURE GRADIENT AND MUD WEIGHT EQUIVALENTS FOR 25 Mpa (3627 Psi) PRESSURE AT DEPTHS (DATUM MAIN SEA LEVEL)

Depth (Metre)	Pressure Gradient (Mpa/m)	(Psi/m)	Equivalent mud weight (ppg)
- 1200	0.0208	3.0225	17.69
- 1300	0.0192	2.7900	16.36
- 1400	0.0178	2.5907	15.20
- 1500	0.0166	2.4180	14.12
- 1600	0.0156	2.2669	13.27
- 1700	0.0147	2.1335	12.54
- 1800	0.0139	2.0150	11.36
- 1900	0.0131	1.9089	11.13
- 2000	0.0125	1.8135	10.67
- 2100	0.0119	1.7271	10.10
- 2200	0.0114	1.6486	9.68
- 2300	0.0109	1.5769	9.29
- 2400	0.0104	1.5112	8.36
- 2500	0.0100	1.4508	8.52

Figure - 16.12 Drilling/seismically predicted formation pressure distribution of 25 MPa (3627 Psi) at various depths (after Raza et al, 1980, modified)

rate of deposition, compaction, water content and poor fracture integrity. Control of high solids and large volume of muds require special handling.

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17
Balochistan Basin

The understanding of Balochistan Basin has been greatly enhanced by the excellent publication 'Geodynamics of Pakistan' by the Geological Survey of Pakistan, 1979.

This onshore–offshore basin, covers an area of about 300,000 sq. km, is the least explored in Pakistan. Only six wells have been drilled in the region to date. What is more, these were abandoned either due to operational difficulties or geological complexities. No commercial hydrocarbons have so far been proven in the basin. In the east, it is separated from Indus Basin (Fig. 17.1) by Chaman Transform Zone whereas the western part extends into Iran. This basin presents a different geological history compared to the Indus Basin; that of an arc-trench system from north to south where Arabian Oceanic Plate is subducting beneath the continental margin of Eurasian Plate (Lut and Afghan blocks).

From south to north this arc-trench system is divided into Makran Trench, Coastal Makran Depression, Makran (Panjgur) Accretionary Prism, Hamun-i-Mashkel (Kharan) Fore-Arc Basin, Ras Koh Arc, Mirjawa–Dalbandin Trough (Inter Arc region) and Chagai Arc (Fig. 17.2).

Makran Coast is a great festoon of folded and faulted Tertiary sediments extending 800 km from Las Bela axial fold belt on the east to the Oman line on the west.

The subduction of oceanic crust under the Makran region of eastern Iran and western Pakistan started in Late Cretaceous and is continuing through modern times.

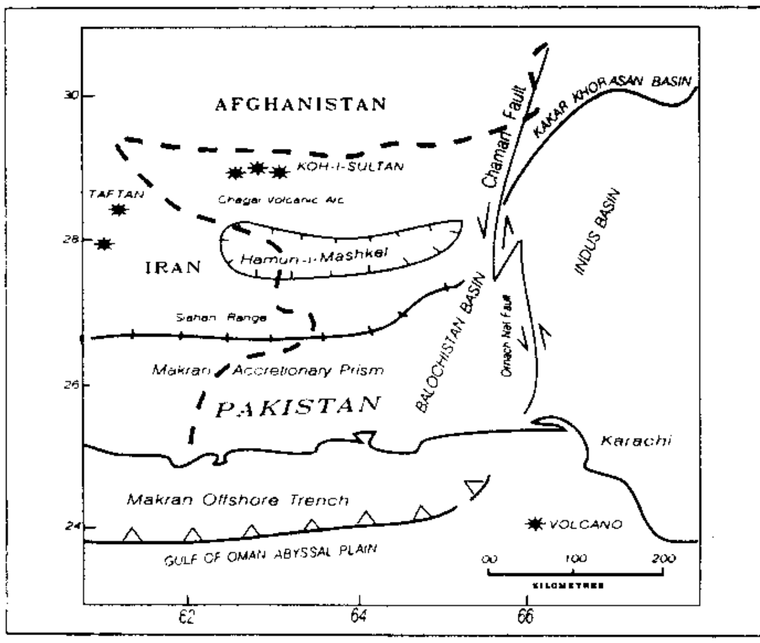


Figure - 17.1 Balochistan Basin (after Farah et al, 1984)

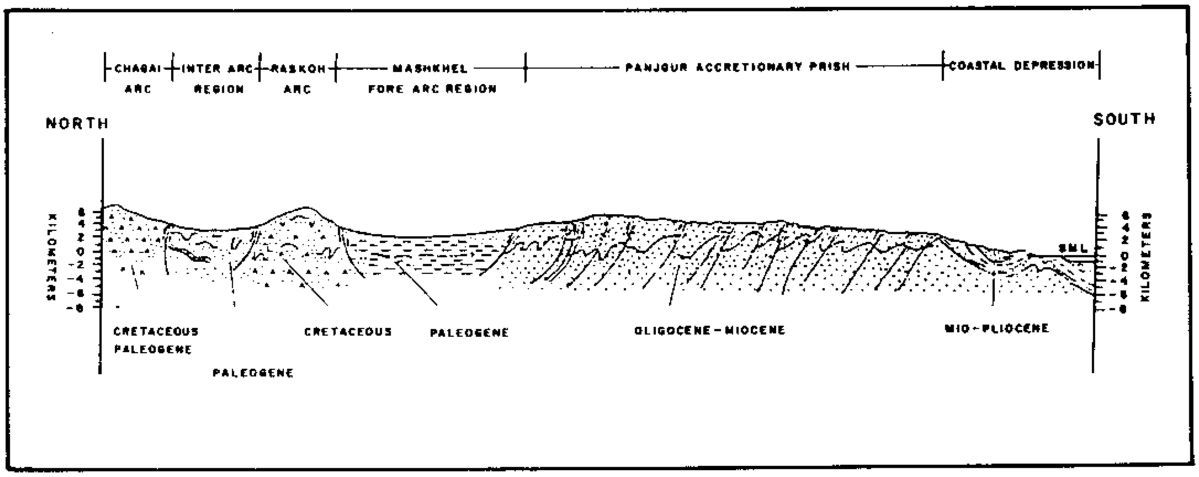


Figure - 17.2 Geological section across Balochistan basin (after Raza et al, 1989)

This led to the generation of Arc-Trench system which is known to be widest in the world. The Arc-Trench gap is of the order of 500 km, far wider than most systems. The examples with unusually large arc-trench gaps are found in northern New Zealand and the Gulf of Alaska.

One school of thought suggests that shoreline has migrated 250 km southward since Oligocene and the present day trench represents an incipient subduction. The Chagai Arc may be the remnant of the volcanic activity related with the initial subduction of the oceanic lithosphere which might have been interrupted by the huge influx of terrigenous sediments from the Axial Belt formed by collision of Indian Plate with Eurasian Plate, both being continental land masses.

This Arc-Trench system is unique in a number of ways: (i) Fore-Arc Basin and most of the Accretionary Prism are emergent, thus making surface geological investigation possible, (ii) Even intense deformation has not created structural incoherence in the exposed strata.

STRATIGRAPHY

The sedimentary rocks exposed in Balochistan Basin range in age from Cretaceous to Recent (Fig. 17.3) with older rocks exposed in the north and younger to the south. The deposition of younger sedimentary rocks is controlled by the subduction of Arabian Oceanic Plate under the Makran Continental Plate.

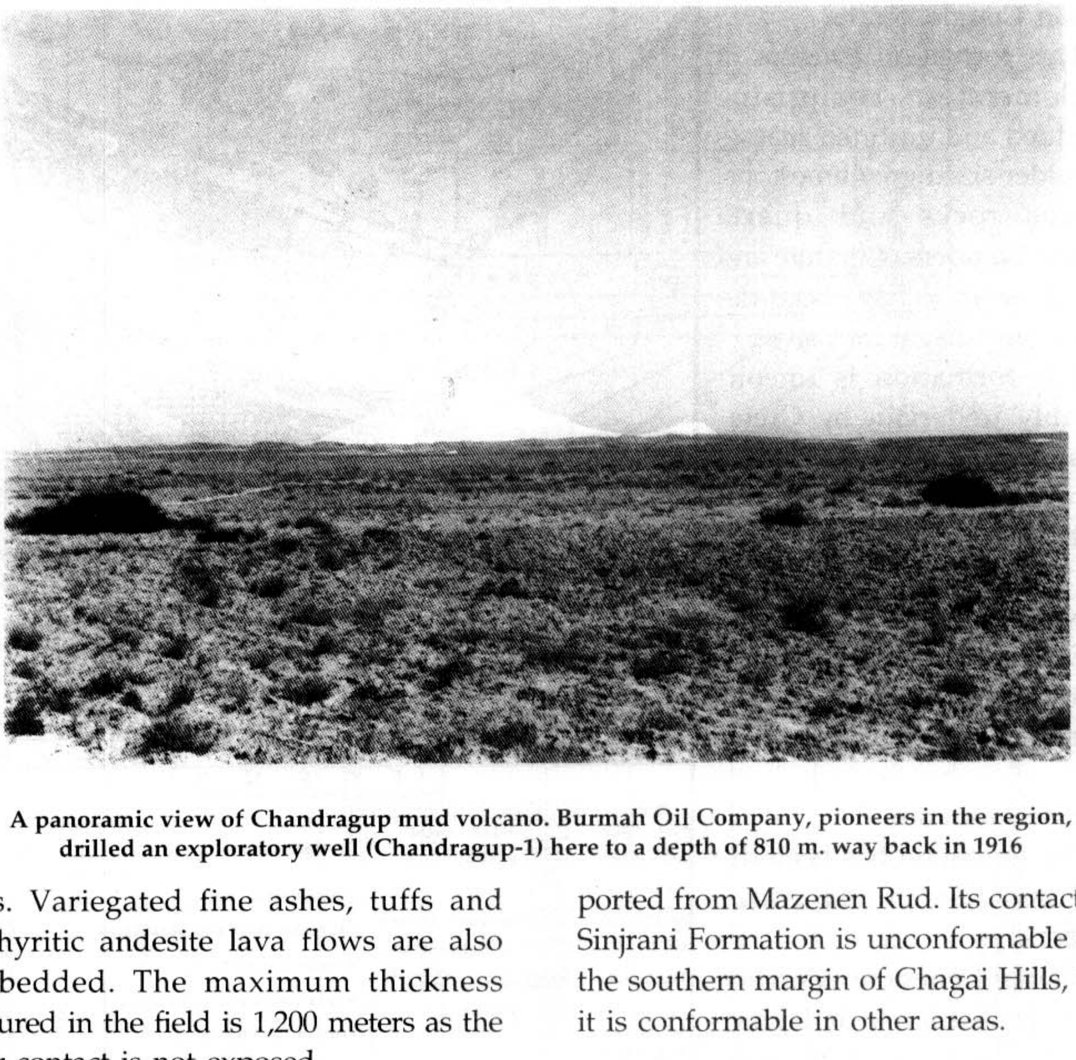
Representative stratigraphic section is summarized in Fig. 17.4. The stratigraphy of this basin is complex and shows a great deal of variation from one end to the other.

Fig. 17.5 represents isopachs of total sedimentary thickness in Balochistan Basin.

CRETACEOUS

Sinjrani Formation

This formation is exposed in Chagai and Ras Koh area, the northern most part of the Balochistan Basin. The formation consists of volcanic rocks and thin beds of shale, sandstone and limestone. Grey, green and black agglomerates and volcanic conglomerates are the dominant rock



A panoramic view of Chandragup mud volcano. Burmah Oil Company, pioneers in the region, drilled an exploratory well (Chandragup-1) here to a depth of 810 m. way back in 1916

types. Variegated fine ashes, tuffs and porphyritic andesite lava flows are also interbedded. The maximum thickness measured in the field is 1,200 meters as the lower contact is not exposed.

Humai Formation

The formation consists of fossiliferous limestone, shale, siltstone and some volcanics. Near its type locality, at Koh-I-Humai in northwest Balochistan, it is composed of greenish grey and purplish shales, calcareous sandstones, siltstones, thin-bedded limestones and volcanic conglomerates in the lower part and massive, dense, reefoid limestones with abundant Hippurites in the upper part. This formation is also restricted to the northern part (Eruptive Zone) of Balochistan Basin.

Thickness of up to 300 meters is reported from Mazenen Rud. Its contact with Sinjrani Formation is unconformable along the southern margin of Chagai Hills, while it is conformable in other areas.

PALEOCENE

Rakhshani Formation

This formation is also restricted to northern part and comprises sandstone and limestone with volcanic agglomerates. Beds of conglomerates, basaltic and andesitic lava flows, tuff are also common. Thickness varies considerably from 150 meters to a maximum of 2,400 meters south of Robat. It represents the shallow marine environment near the volcanic centre of the Chagai area.

The formation is conformably underlain by the Humai Formation in the Chagai and Dalbandin areas and by the Sinjrani Formation in the Ras Koh Range.

Ispikan Conglomerate

This formation consists of conglomerates comprising unbedded and unsorted masses of boulder-sized grey limestone, igneous rocks and quartz pebbles. Boulders of granite and andesite seem to have been derived from Chagai intrusives.

The formation is unconformably underlain by Cretaceous marls and is restricted to only one locality i.e. Ispikan in North Makran.

EOCENE

Eocene rocks are exposed in Eruptive Zone and western part of Makran.

Saindak Formation

The formation has been divided into Kharan and Wakai Members.

Kharan Limestone Member consists of medium to dark grey, thin to thick bedded, fine grained, argillaceous limestones. The limestones are locally highly fossiliferous, reefoid and have a petroliferous odour when broken. Grey to brown calcareous shale is also intercalated with alternations of grey to greenish brown, fine to medium grained calcareous sandstones.

This member attains a maximum thickness of 600 meters in the north-western corner of Eruptive Zone. It is conformably underlain by Rakhshani Formation. It was deposited on a structural high of Ras Koh anticlinorium.

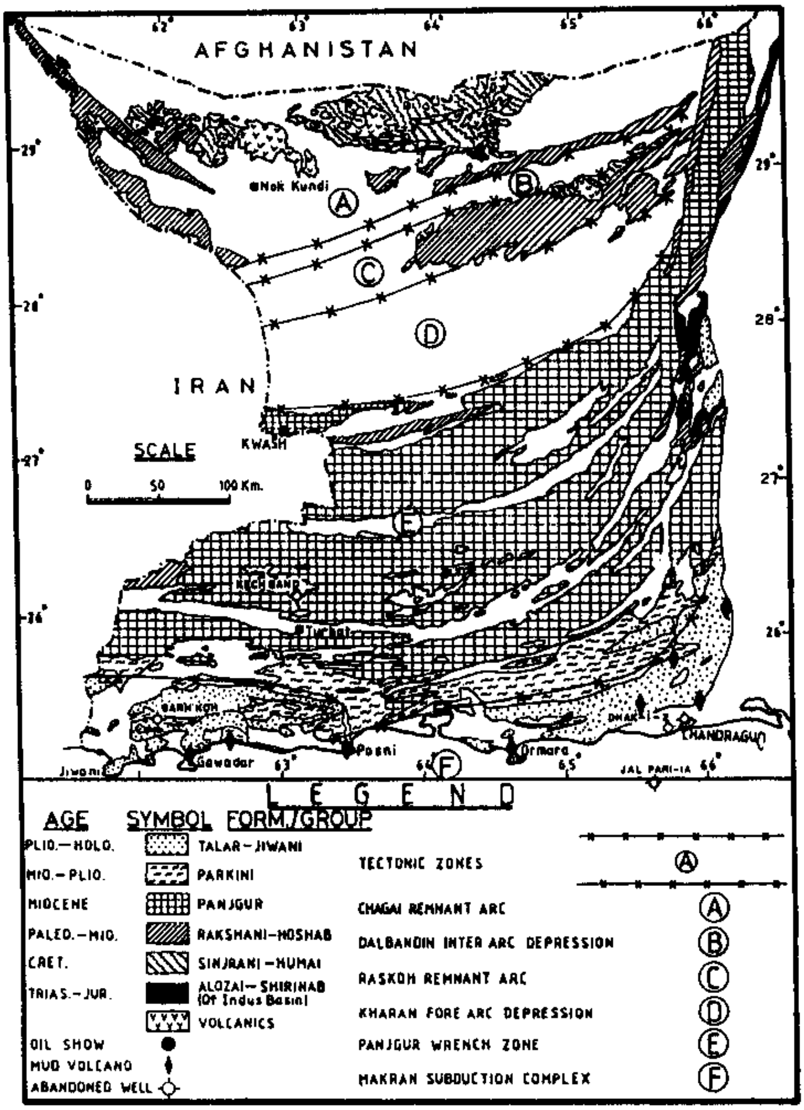


Figure - 17.3 Geological map of Balochistan basin with tectonic zones, (after Raza et al, 1991)

Wakai Member consists of reefoid limestone, marls and shales with subordinate sandstones and conglomerates. Limestones have petroliferous smell.

Wakai Member is restricted to the central part of the basin (Kech Bund area). It was deposited along the flanks of regional highs. Its lower contact is unconformable.

Limestones of this formation have reservoir characteristics.

BALOCHISTAN BASIN STRATIGRAPHY

Era	Period	Epoch	CHAGAI-RASKOH ARC AND HAMUN-I-MASHKHEL FORE ARC BASIN: NORTH CHAGAI & RAS KOH BELT	CHAGAI-RASKOH ARC AND HAMUN-I-MASHKHEL FORE ARC BASIN: NAUSHERWAN & MIRJAWA-DALBANDIN BELTS	MAKRAN ACCRETIONARY BASIN: NORTH MAKRAN & ZHOB	MAKRAN ACCRETIONARY BASIN: SOUTH MAKRAN	AXIAL BELT
CENOZOIC	QUATERNARY	PLEISTOCENE & RECENT	Recent Deposits Subrecent Deposits		Recent Deposits Subrecent Deposits	Extrusive Mud	
CENOZOIC	QUATERNARY	PLEISTOCENE & RECENT	KOH-I-SULTAN KAMEROD	KAMEROD FM	KAMEROD FM KECH Cg	JIWANI FM ORMARA FM	BOSTAN FM KECH Cg HARO Cg
CENOZOIC	TERTIARY	PLIOCENE		DALBANDIN FM		CHATTI MS	HINGLAJ MS
CENOZOIC	TERTIARY	MIOCENE			SHAIGALU SS DIZ SS	TALAR SS PARKINI MS	SHAIGALU SS MULTANA Cg GRESHAK NAL LS
CENOZOIC	TERTIARY	OLIGOCENE	AMALAF FM	NAUROZ FM	PANJGUR SS TURBAT GR BINGA Cg HOSHAB Sh MURGHA FAQIRZAI Sh	PANJGUR SS	MURGHA FAQIRZAI WAKABI LS
CENOZOIC	TERTIARY	EOCENE	PISHI GR SAINDAK FM	KHARAN LS ROBAT LS WASHAP LS	SIAHAN Sh WAKAI LS		NIMARGH LS NASAI Gr MARAP CG
CENOZOIC	TERTIARY	PALEOCENE	JUZZAK FM RAKHSHANI FM	JUZZAK FM RAKHSHANI FM	ISPIKAN Cg		GIDAR DHOR GR WAD LS THAR
MESOZOIC		CRETACEOUS	HUMAI FM KUCHAKKI VC SINJRANI VC	MAZENEN LS	PARH Sr (Iran border)		PAB SS PARH Sr PARH Gr
MESOZOIC		JURASSIC					CHILTAN LS LORALAI LS SHIRINAB FM ALOZAI Gr ZIDI FM WINDAR Gr
MESOZOIC & PALEOZOIC	TRIASSIC & PERMO-CARB						

INTRUSIVE ROCKS

RAS KOH intrusions: post-Paleocene, pre-Middle Eocene
SHOR KOH intrusions: post-Middle Eocene probably pre-Oligocene
BUNAP intrusions: post-Paleocene, pre-Middle Eocene, but probably pre RAS KOH
CHAGAI intrusions: late Cretaceous to Eocene

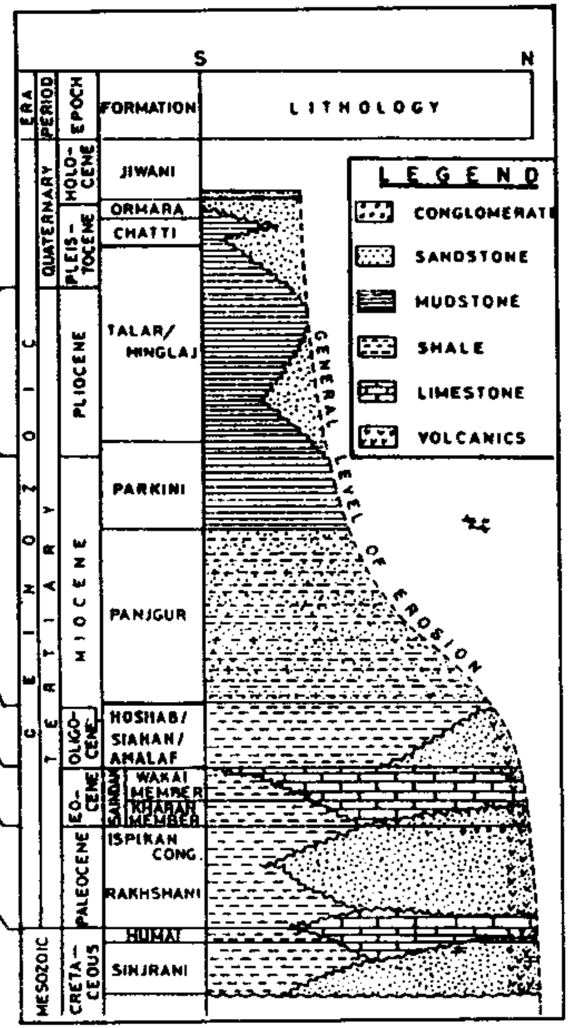


Figure - 17.4 Regional Balochistan Basin Stratigraphy and the Stratigraphic Column (after Raza et al, 1991)

Oligocene

The sedimentation during and post Oligocene was controlled by the volcanic activity in the north and the coalescence of Indian and Eurasian Plates which gave rise to the formation of Axial Belt and much of the tectonic shed was depositing in the depression areas of Balochistan Basin. Following formations are recognized.

Amalaf Formation

This formation is exposed in the northern areas of the basin and consists of volcanic rocks and occasional beds of red shales and sandstone. The volcanics comprise beds of fine to coarse ash and conglomerate with subordinate andesitic lava flows. The formation is restricted to the western part of Mirjawa–Dalbandin Trough of the Eruptive Zone where it attains the thickness of 300 meters. Sandstones of this formation have fair to good reservoir potential.

This formation is unconformably overlain by the Saindak Formation.

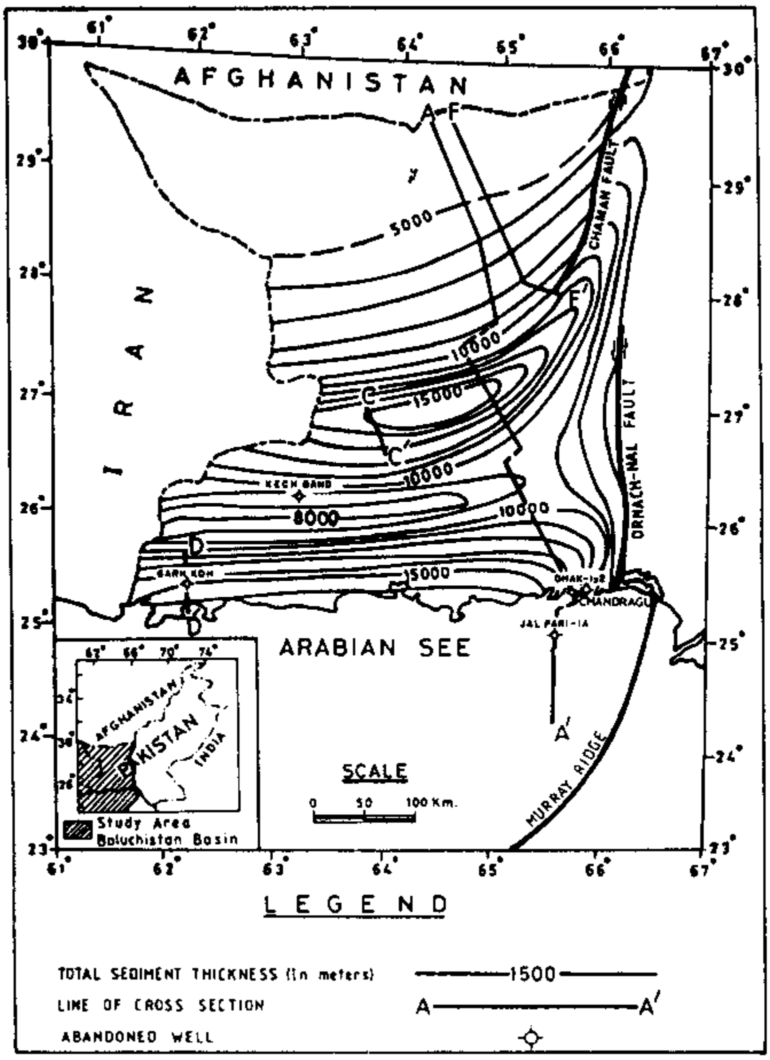


Figure - 17.5 Sedimentary fill of Balochistan Basin (after Raza et al, 1992)

Siahan / Hoshab Formation

This formation is exposed in the central part of the basin. It is a basin or slope facies consisting of deep water shales with subordinate sandstone. The formation extends into Miocene in the south. The sandstones of Siahan have reservoir potential.

Miocene

This period is predominantly represented in the central and the southern part of the basin with younger rock units in the south.

Panjgur Formation

The type locality of the formation is near Panjgur in the North Makran area. The formation consists of interbedded marine shale and sandstone. Thick bedded sandstones with small proportion of shale beds were deposited by turbidity currents. This formation is as much as 400 meters thick. Sandstones are micaceous, quartzose, fine-medium grained and occasionally coarse grained with thin shale interbeds. Sandstone beds form prominent ridges along anticlinal cores.

This formation depicts fair to good reservoir characteristics. Middle Miocene age is given to this formation.

Parkini Formation

The type locality of this formation is Parkini Kaur, a tributary of Hingol River. The formation consists of mainly grey, slightly clacareous mudstone. It is commonly massive or thick-bedded, with discernible lamination and bedding. Thin siltstone or very fine grained sandstone beds are present in some zones. The formation was deposited on slopes in upper to lower bathyal depths (more than 200 meters).

The formation is exposed in two major belts: i) across the central section on the south flank of Gokh Prush Band, ii) in the vicinity of Kappar and along the coast to Ras Shamal Bandar, where thickness is about 1,600 meters

The formation bears source rock characteristics.

Pliocene

This period is represented by Talar Formation restricted to the southern part of the basin.

Talar Formation

The formation was named after good exposures in Talar Gorge in Western Makran. It is composed mainly of regularly interbedded marine sandstone, shale and mudstone. The sandstone is medium to coarse grained, soft and crumbly, generally 1-2 meters thick beds with maximum of 3 meters thickness. However, the middle part of the formation is predominantly massive sandstone. Some layers are cross–bedded and some are ripple marked. Thickness of the formation is estimated at 5,000 meters The formation represents the depositional environment ranging from mainly slope to outer shelf, inner shelf and nearshore.

Sandstone beds of this formation may be prospective reservoirs.

Pleistocene

This period was largely influenced by the main phase of the Himalayan orogeny which began in early Pleistocene.

Chatti Formation

This formation was named after Chatti, about 30km northwest of Gwadar.

The formation is similar to Parkini Formation and contains interbedded mudstone/siltstone and thin impure limestone beds. The siltstone beds, a few centimeters to 0.5 meters thick and widely interspersed in the thick units of mudstone, are greenish brown. The resistant layers of siltstone and fine sandstone form low ridges.

The thickness of this formation is reported to be more than 1,300 meters.

The formation represents mainly shelf deposit with less dominant slope facies.

Ormara Formation

This formation was named after Ormara headlands on the coast of Arabian Sea. It consists of shale, sandstone, and conglomerate with shell-bearing beds in the upper part. The lower part of the formation is mainly soft, poorly consolidated, sandy clay. The sandstone is light brown, medium to coarse grained and poorly consolidated.

Maximum thickness of more than 1,000 meters is reported for this formation at Astola Island, (the island came into existence after 1945 earthquake). This formation has angular unconformable relationship with underlying formation.

In terms of depositional environment, it represents a regressive cycle from inner shelf to nearshore marine.

Jiwani Formation

This formation was named after the coastal village of Jiwani. It consists of limestone, conglomerate and sandstone, weathering ferruginous brown. The limestone is coquina of small shell fragments in a sandy, hard, calcareous matrix forming porous beds 0.3-2 meters thick. Conglomerate contains the pebbles of Wakai Limestone.

Jiwani Formation is restricted to coastal area and its thickness is about 30 meters at Jiwani headland. It represents the shoreline facies.

MAJOR TECTONIC ELEMENTS AND THEIR HYDROCARBON POTENTIAL

In view of the hydrocarbon potential of this arc-trench setting, following main features from north to south are discussed in details:

1. Volcanic Arc with associated depression
2. Hamun-i-Mashkel Fore-Arc Basin & Kharan Desert
3. Makran Accretionary Prism.

VOLCANIC ARC

This is the characteristic feature of the convergent plate boundaries associated with subduction of oceanic lithosphere. Balochistan volcanic arc is associated with continental plate over-riding oceanic lithosphere. A zone of Quaternary volcanism stretches from north of Chagai Hills at the Pakistan/Afghanistan border region, across the Pakistan/Iran boarder, and into SE Iran (Fig. 17.1) marking Koh-I-Sultan, Taftan, and Bazman volcanic centres respectively.

The general geologic setting appears to involve an Andean-type andesitic arc in the Chagai Hills, Ras Koh and Saindak areas which was most active from the Middle Cretaceous to the Early Paleocene. Chagai Arc was subjected to recurrent uplift through the Paleogene, accompanied by the corresponding formation of the Mirjawa-Dalbandin Trough between the Chagai igneous belt and the Ras Koh Range.

It is postulated that this region accumulated about 10,000 meters of Cretaceous (Cenomanian) Sinjrani volcanic groups, in Mashki Chah area. This is conformably overlain by Humai Formation of Cretaceous (Mastrichtian) age. The upper part of this formation is thick-bedded to massive, biohermal limestone up to 300 meters thick in the outlier of Sorkoh. The lower part, up to 1,700 meters thick at Amir Chah, is composed mainly of thin-bedded, fine-grained limestone and mudstone. At places, it also contains tuff and agglomerates and conglomerates composed of limestone and volcanic debris. Humai Formation is overlain by Rakhshani and Juzzak formations which in turn underlie Saindak Formation. These two formations are about 2,500 meters thick and are of Paleocene–Oligocene age. Juzzak Formation consists of flysch like facies with layers of limestone and volcanic conglomerates. Saindak Formation is composed mainly of mudstones with beds of nummulitic limestone apparently formed in shallow water conditions. Overlying gypsiferous silts and conglomerates of the Kamerod Formation of Miocene age have an angular unconformable relationship with Juzzak and Saindak formations. Final phase was dominated by erosion and peneplanation, followed by accumulation of the Quaternary and older Alluvium. This was accompanied by a resumption of Volcanism–the eruption of andesitic pyroclastics and lavas. Another important feature of this area is stock–like bodies of igneous rocks, i.e. diorite, granodiorite, granite and quartz diorite intruding Sinjrani, Humai and Juzzak rocks.

From structural geological point of view Chagai Hills are generally horizontal to gently dipping. Small scale structures are dominated by two sets of faults at approximately right angle to one another. Reverse faults are less common.

Mirjawa – Dalbandin synclinorium, south of Chagai uplift, represents trough into which large amounts of sediments were shed down during Paleogene. More common structures in Mirjawa synclinorium are folds and reverse faults which are aligned mainly east-west. In the Dalbandin area, broad and doubly plunging synclines are common fold type. Anticlines are commonly faulted. This area is characterised by greater thickness of sediments and greater depth of the original synclinal depression as compared to Mirjawa synclinorium.

Chagai Hills, Ras Koh Range and the intervening Mirjawa–Dalbandin depression, being part of the Paleogene volcanic arc and subduction complex, are considered to have low petroleum potential. However, arc-trench phenomenon have given rise to a geologically complex scenario that has excellent mineral potential.

HAMUN-I-MASHKEL FORE-ARC BASIN

Two large depressions, Jaz Murian in Iran and Hamun-i-Mashkel in Pakistan immediately south of Volcanic arc, are termed as Fore-Arc Basins. Hamun-i-Mashkel Basin (Fig. 17.1) constitutes a flat area of Hamun-i-Mashkel and Kharan Desert which are covered by Quaternary sands. The basin is believed to contain huge thickness of sedimentary rocks of possible Paleocene age. Structures in fore-arc basins are typically complex with both normal and reverse block faulting and thrust faulted blocks.

In a trench-arc system as that of Balochistan Basin, fore-arc basins are considered to bear the best petroleum prospects, such as Cook Inlet basin of Alaska, with total oil and gas recoverable reserves of more than 1 billion bbls of oil equivalent.

Stratigraphy

Since this area is covered by Quaternary sediments, its stratigraphy is vaguely known from the outcrops at the periphery. Stratigraphic sequences would probably be same as found in Volcanic Arc region.

Source Rocks

Fore-arc basin is usually characterised by young and less mature source rocks. However, it appears from the surrounding exposures that deposition has probably occurred more or less continuously since Paleocene and may have begun in Cretaceous. If a thick sedimentary succession is present as confirmed by Aeromagnetic surveys also (Raza et al, 1989) then conditions are ideal for hydrocarbon generation.

Back reef facies associated with Kharan Formation of Eocene age consists of limestones that have petroliferous odour. It is also likely that hydrocarbon might have generated in adjacent shales.

Kwash oil seep (Fig. 17.3) of Siahan Range is reported to be in rocks of Eocene age. This indicates that oil has been generated in the area.

Reservoir Rocks

In terms of reservoir characteristics, petroleum potential of fore-arc basin area is regarded as moderate. Provenance is usually located in the back-area where the rocks are predominantly volcanic which shed a lot of dirty sand into the basin with various types of clays. Deposition foci are also frequently shifted due to tectonic instability. In this case the only reservoir rock type is limestone deposited as carbonate build-ups along the basin margin.

In Hamun-i-Mashkel Fore-Arc Basin, there are indications that Kharan Limestone was deposited. This limestone bears reservoir qualities. In addition, this basin is bounded in the north by crystalline rocks of Afghan block and intrusives of Chagai area which provide the sediments that are likely to be clean, quartzose and feldspathic, free from clay and lithic fragments. Such sandstones have all the potential for good quality reservoir at depth. Entrapment mechanism in such basin is both structural and stratigraphic. Traps are associated with deltaic, nearshore and submarine fan and carbonate built-up settings.

In order to assess the potential of this fore-arc basin and unveil the buried structural/stratigraphic configuration, good quality seismic survey and its stratigraphic processing is necessarily required.

MAKRAN ACCRETIONARY PRISM

This is the only area of Balochistan Basin where all past drilling activity has been undertaken (Fig. 17.5).

In a trench-arc system the accretionary prism forms the most proximal part to the trench. Accretionary prisms are formed by scraping of the sedimentary cover off the subducting plate and its stacking and deformation into ridges at the frontal fold. These are explained in terms of simple imbricate thrust model.

Makran Accretionary Prism, one of the widest (170 km.) in the world, starts at the Northern Makran (Siahan Range) and extends south through Central Makran coastal ranges.

These ranges predominantly comprise deformed flysch (Panjgur Sandstone) of Miocene age in the south and probable Paleogene age in the north. The strata becomes younger southward where accretion is still going on near the trench.

Stratigraphy

The peripheral outcrops of the region are highly imbricated and severely deformed turbidites of the Middle to Late Oligocene Panjgur Formation, underlain by the abyssal Hoshab and Siahan Shales of Late Eocene to Early Oligocene age.

In the north, the older stratigraphy is represented by Ispikan Conglomerate (Paleocene), Nisai Formation (Eocene) and Khojak Formation (Late Eocene–Oligocene) which in turn is overlain by Talar and Chatti formations west of Pasni and Hinglaj Formation east of it.

Fig. 17.6 shows the stratigraphy of Makran Cost Ranges.

In the Makran Coast Range, Panjgur Formation (Flysch) appears to be overlain by Parkini Formation.

The sediments of Hoshab Shale and Panjgur/Parkini Formations were deposited on the ocean floor of the Gulf of Oman and were incorporated into the accretionary complex during Neogene, thus shortening and thickening them from an initial 4-5 km. to 15–20 km.

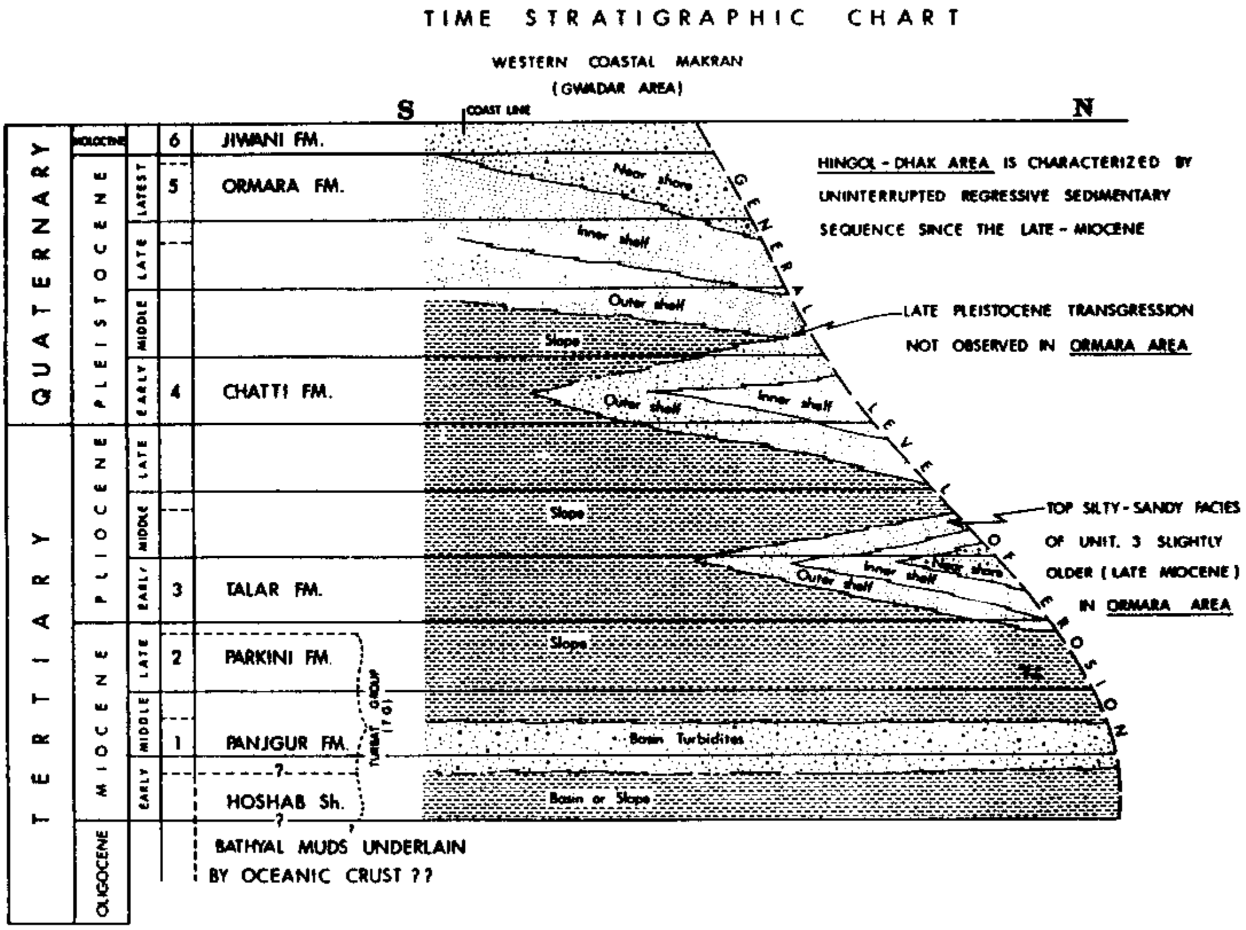


Figure - 17.6 Time-stratigraphic-facies chart for Pakistan coastal Makran. Boundaries between units 1 to 6 are mapped in Fig.-17.7. The time sequence is based on calcareous nannofossils. Formation names in the central column are those employed by the Hunting Survey (1960) for major lithofacies. Ages suggested in 1960 were generally based on foraminifers or stratigraphic position and were generally older than those indicated by calcareous nannofossils. (after Harms et al, 1984)

Sedimentology and Geological History

The oldest rocks reported are Cretaceous Marls (Parh LS?) which were deposited on deep ocean floor. These are overlain by Ispikan Conglomerates (Paleocene) reported from only one locality in northern Makran, and were derived from erosion of basement and Cretaceous volcanic rocks.

During Eocene massive, reefoid limestones of Nisai Formation, associated with shales, were deposited along regional highs. This was followed by the deposition of flysch (Khojak Formation) during Late Eocene to Oligocene. This continental setting, which was established in Oligocene, has continued through to the present day and, has been regressing southward.

Sandstones and shales of Khojak Formation were deposited in a shallow marine environment and were pushed down by the turbidity currents to the base of the continental slope where they became part of the Accretionary Prism. The Oligocene shore line was consistent with the present day Siahan Range. This was followed by a major episode of uplift during Late Oligocene probably because of the collision of Lut and Afghan Block and emergence of Axial Belt as a result of collision between Indian and Eurasian Continental Plates in the east. Uplifting of these surrounding land masses became the major provinces for the deposition of huge thicknesses of terrigenous sediments from Miocene onward.

Miocene – Paleocene sedimentation was mostly restricted to the South Makran and Makran Coast Ranges.

Deposition of Hoshab Shale in Early Miocene occurred in basin or slope environments.

During Middle Miocene, thick-bedded sandstone and conglomerate with small proportions of thin shale beds of Panjgur Formation were deposited by turbidity currents in South Makran. This formation depicts all of the features, both sedimentary and paleontological in a turbidity current deposit. Depositional region was probably a Middle Miocene deep-sea fan (Harmes et al, 1984).

Since Late Miocene, the Makran Coast area has received deposits of shale-slope-shoreline representing progradational or regressive episodes/cycles. This has given rise to the deposition of almost 7,000 meters thick sediments. Each phase ranges in thickness from 1,000 to 3,000 meters and has bathyal massive mudstone deposited on slopes overlain by coarsening upward sequence of sandstone of outer to inner shelf deposit. These cycles are clearly shown in Fig. 17.6. Near-shore deposits are mostly represented in Late Pleistocene or Holocene sequences.

Source Rocks

The most encouraging features, which substantiate the evidence of hydrocarbons generation in the Makran region, are presence of numerous gas seeps occurring as spectacular mud volcanoes or subdued pools onshore and as bubbling gas and turbid water offshore. The Kawash oil seepage described earlier, has an important bearing on source rock maturity in Makran Accretionary Prism.

The source rock evaluation of any area is carried out on the basis of organic richness of the source beds and there thermal maturity. Unfortunately the Pre-Miocene stratigraphy of the Makran region is not exposed, although they are expected to be finer grained since they provided the detachment zone for folding.

The total organic carbon content of the rocks vary from lean to moderate. There is a very large volume of mudstone deposited in slope and outer shelf environments incorporating significant amount of organic matter. As a principle, sediments are first deposited in a shelf environment and later incorporated in accretionary prism complex by the action of turbidity currents. In terms of thermal maturity the region appears to be cool with an average geothermal gradient of 1.82 $^{o}C/100$ meters. For hydrocarbon generation in relatively younger rocks, this gradient has to be compensated with rapid burial which has been the case. However thermal modeling and prediction of hydrocarbon evolution is difficult due to complex structural history of the region.

However, the isotopic composition of the gas from mud volcanoes is heavier which suggests that the gas is generated from a thermally mature source. It can be summarized that present maturity level has been attained because Makran Zone is mostly underlain by oceanic crust and would be subject to higher heat flow than basins underlain by continental crust.

Reservoir Rocks

The sedimentological evidences suggest that this region has received huge amount of sand which is of poor to good reservoir quality. The Middle Eocene Panjgur Formation is an ideal candidate for reservoir. This was deposited by turbidity currents. It is fine to medium grained, free of clays and bioturbation. The porosity in outcrops ranges from 10% to 25%.

Late Miocene to Pleistocene deposits represent outer to inner shelf and shoreline sandstone sequence, of which inner shelf and shoreline sandstone is coarser and better sorted. However, these facies are not expected to be represented at depth.

SEISMIC CHARACTERISTICS

Seismic data was mainly shot in the offshore with some onshore coverage for both academic and exploratory purposes during 1961 and 1982. The data has resulted in the delineation of many fascinating features which would have otherwise been impossible to be deciphered. Fig. 17.7 shows geological map of coastal Makran; Fig. 17.8 shows three structural cross-sections along AA', BB', and CC' (Fig. 17.7). Fig. 17.9 shows seismic profiles along section AA' and CC' respectively.

Some profiles shot to delineate the subsea accretionary prism and subducting oceanic plate have also led to the resolution of the arc-trench system (Fig. 17.10).

Quality of data spreads from patches of good to patches of poor in shelf/slope facies whereas data of abyssal plain shows relatively better reflection continuity in the first 5 seconds of depth. The deep water data at places is plagued with water bottom multiples.

The interpretation of data requires thorough knowledge of seismic stratigraphy, marine tectonics and the geology of continental margins.

To say the least it is the offshore seismic which has unveiled yet another fascinating discipline of Earth Sciences i.e. Arc-Trench System and Marine Tectonics.

DRILLING CHARACTERISTICS

Following wells have been drilled in Balochistan Basin.

Well	Company	Year	TD(m)
Chandragup	BOC	1916	810
Dhak-1	Hunt	1956	2,562
Dhak-2	Hunt	1956	4,455
Kech Band-1	Tide Water	1962	3,349
Garr Koh-1	Marathon	1975	3,624
Jalpari-1 (offshore)	Marathon	1977	2,008

All of these wells had to be abandoned prematurely due to geological or operational problems. The main operational problem in coastal region has been abnormally high pressures in younger sand/shale sequences. These pressures are the result of rapid sedimentation and non-expulsion of formation water. This has also resulted in the intrusion of shale diapirs.

Similarly, geological problem encountered in well Kech Band-1 (Tide Water) was the imbricated section (repeated thrust sheets) of Miocene sequence, typical of the accretionary prism complex.

Modern high resolution seismic may now be able to correctly distinguish the repeated stratigraphic succession from the normal. Also, the operational problems could be handled with the state-of-the-art drilling technology available today.

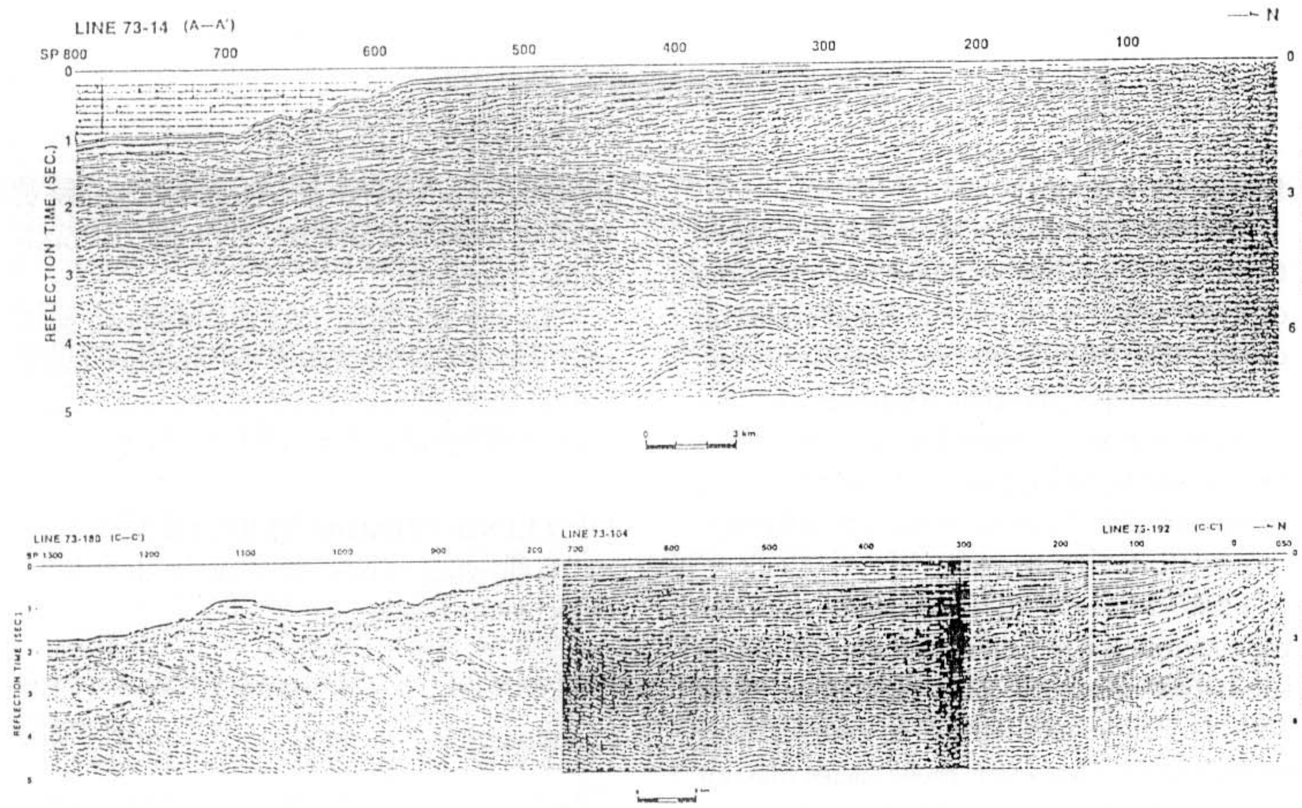


Figure - 17.9 Seismic Sections across coastal Makran. The sections located on Figure-17.7 as AA' (above) and CC' (below)

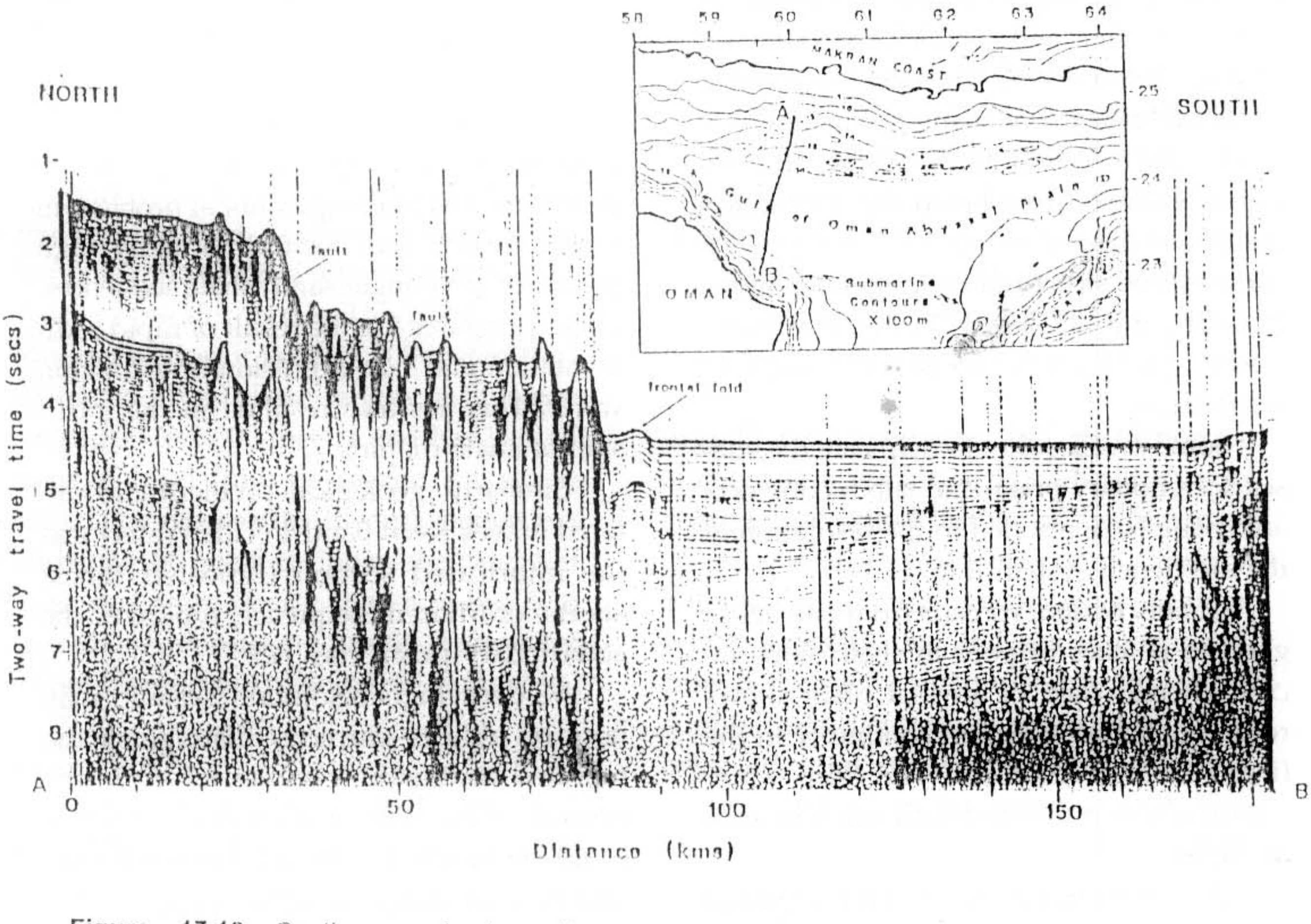


Figure - 17.10 Continuous seismic profile across the Makran continental margin. Notice the frontal fold and the prominent scarps which mark the position of recently active faults which penetrate the accretionary sediment wedge. Vertical exaggeration at sea floor approx. 10x, See inset for line location AB (after White, 1979)

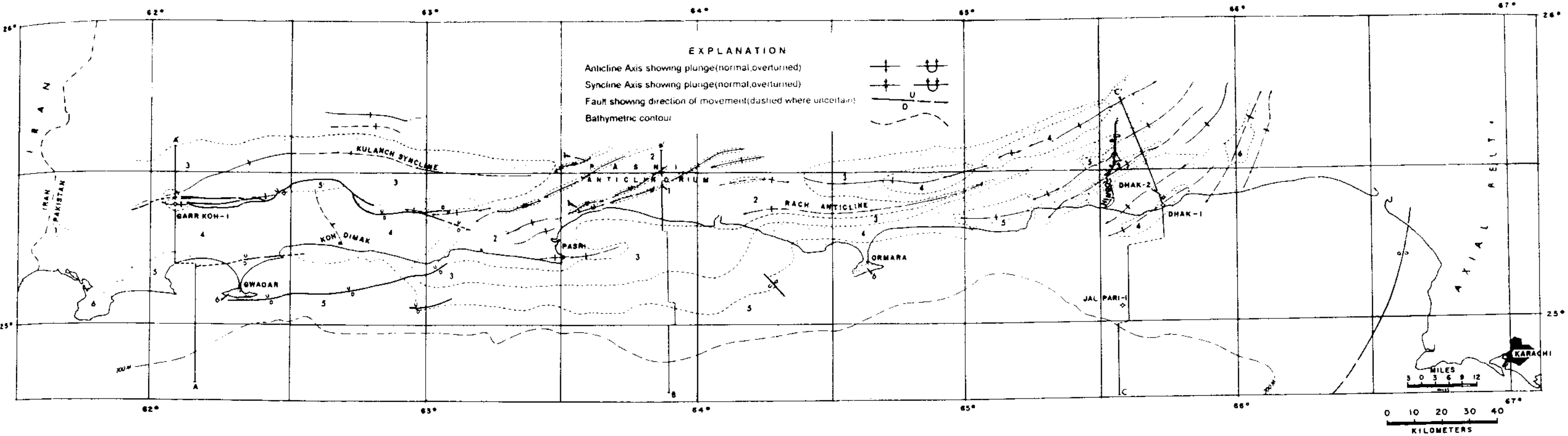


Figure - 17.7 Geological map of coastal Makran. North-south structural sections shown in Figure-17.8 are located in the west, central, and eastern parts of the map area. Map units numbering 1 through 6 from oldest to youngest are defined on the time-stratigraphic chart of Figure-17.6 (after Harms et al, 1984)

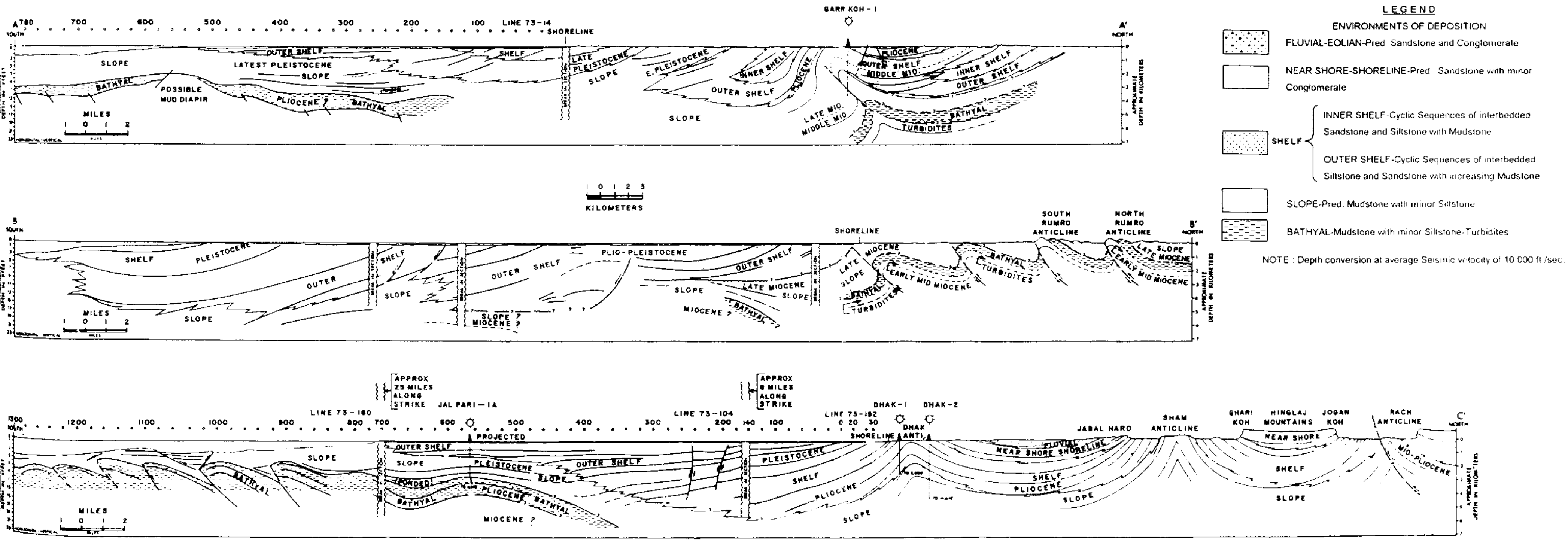


Figure - 17.8 Structural cross sections of coastal Makran. Sections are located on Figure-17.7. Typical seismic sections, illustrated in Figure-17.9, are indicated by line and shotpoint numbers. Note that there is no vertical exaggeration on the sections of this figure, seismic sections have been converted to depth using suitable velocity functions. (after Harms et al, 1984)

EXPLORATION POTENTIAL

Generally Balochistan Basin is regarded as high risk high cost exploration area mainly because of lack of full geological understanding, sparse drilling, and non-availability of infra structure.

However, this basin is considered to bear all the necessary characteristics that qualify it as a possible hydrocarbon province.

Hamun-i-Mashkel Fore-Arc Basin has the best petroleum potential as petroleum has been found in its analogues in the world. The sedimentological evidences suggest that both source and reservoir rocks have been deposited in the basin with source thrown in the oil window.

Because of the pattern of deposition the basin has the possibility for the development of both stratigraphic and structural traps.

However, the Makran Accretionary Prism is characterised by severely reverse faulted structures. Traces of these faults are consistent with the axes of folds. This severity must have transmitted its effects to the north to give rise to the formation of buried structures in the Fore-Arc Basin.

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18

Source Rocks And Geothermal Gradients

SOURCE ROCK DISTRIBUTION

Potential source rocks, ranging in age from the Cambrian to Eocene, are fairly well distributed in the sedimentary basins of Pakistan. These source rocks differ in the type of organic matter, abundance and maturity in the different basins and have generated oil, gas and condensate. Pakistan has been divided into three basins for discussing the source rock distribution and geothermal gradients as under:

1. Upper Indus Basin
2. Central Indus Basin, and
3. Southern Indus Basin

Fig. 18.1 shows the effective source rock distribution in the Central and Southern Indus Basin.

UPPER INDUS BASIN

Precambrian

The locally developed oil shales of the Salt Range Formation are excellent potential source rocks particularly in the top part of the formation in the Eastern Salt Range, with a total organic carbon content (TOC) of 30%. The maximum thickness of the shale is 1-2 meters. In Western Salt Range, the middle part of the formation has a TOC of about 6%. The oil shales in the Salt Range Formation are relatively immature. However, in areas where it is buried deep enough, the oil shales would have considerable potential for oil generation.

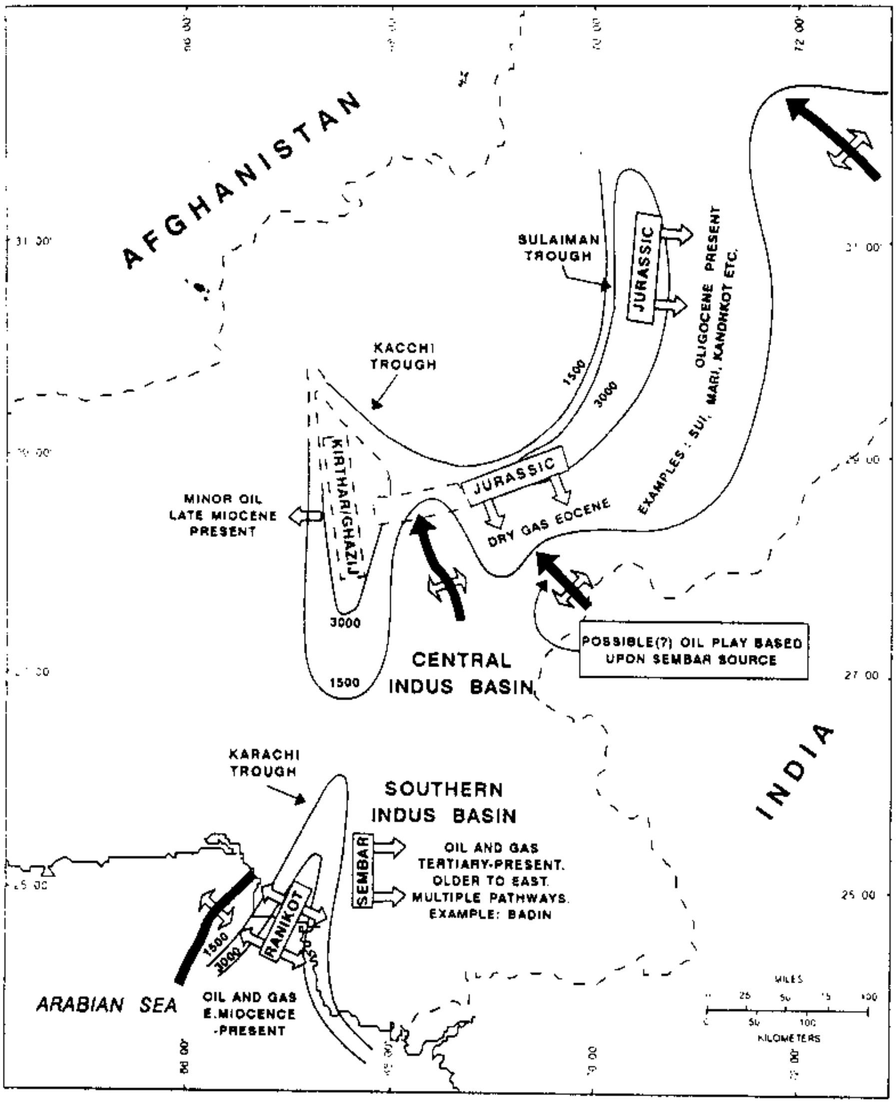
Paleozoic

In the eastern Potwar Basin, source rocks of Permian age have potential for both oil and condensate generation. The source rocks are relatively rich in organic matter and show good maturity. Further south, the shale intervals of Sardhai Formation vary from poor, fair to good source rocks, with potential for both oil and gas generation.

Mesozoic

The shales of Datta Formation (Jurassic) in Salt Range area, Chichali Formation (Cretaceous) in Kohat area and Sembar equivalent (Cretaceous) organic rich rocks in the Kala Chitta Range are potential source rocks. These rocks show fair to good maturity and can serve as potential oil source.

EFFECTIVE SOURCE ROCKS



STRUCTURE BASE TERTIARY, CONTOURS IN METERS

Figure - 18.1 Effective Source Rocks

TERTIARY

Paleocene - In the southern part of the Upper Indus Basin, the Patala and Hangu formations show fair to good TOC content and are relatively mature. These formations have good potential as oil source rocks. In the Kohat area these formations have higher TOC content, are more mature (VR = 1.0) and have excellent potential as oil source rocks. Patala Formation is quite thick (150 meters) in northeastern Kohat; the shales in this formation are dark grey to black. In the Hazara region, Lokchart Limestone is slightly bituminous and has potential for oil generation. The organic matter is, however, overcooked.

Patala Formation is well developed in northeastern Salt Range. However, best source rock properties are present east of Khairabad. Coal beds within Patala Formation, in Central and Eastern Salt Range, are also important having very high bitumen extract and a high genetic potential.

In Eastern Potwar, the Patala Formation and to some extent the Lockhart Formation, are proven source rocks for high quality oil. The source rocks are rich in organic matter and are mature. Further south the whole Paleocene succession has associated organic matter. However, these source rocks, for the most part, are relatively lean and marginally mature to immature. They have a mixed potential for oil and gas at places but on the whole are insignificant as source rocks.

Eocene – In eastern Potwar, the Chorgali and Sakesar carbonates contain fair to good amount of mature organic matter. These carbonates are proven source rocks in at least two oil fields. The oils show low sulphur and high API hydrocarbon contents which point to a mature source. In Kohat area, oil shales are present in Jatta Gypsum of Eocene age with TOC of more than 25%. These oil shales are about 6 meters thick and would have great source rock potential but for their immaturity which is reflected by their low vitrinite reflectance (VR) values.

Further south the carbonates also have associated organic matter, however, these are low in TOC and generally immature to marginally mature and insignificant as source rocks. Interbedded shales in Chorgali and Sakesar formations are also low in organic matter and generally immature.

Summary

The Paleocene and Eocene shales are proven source rocks in the Upper Indus Basin. In terms of TOC, areal distribution and thickness, the formations have potential for generation of substantial quantities of hydrocarbons.

CENTRAL INDUS BASIN

Paleozoic

In the Punjab platform area, the Paleozoic formations, wherever encountered, are generally lean and immature with poor gas potential. Fig. 18.2 shows one possible location where effective Permian source rock may be present.

Mesozoic

Triassic – The source rocks in the Triassic Formations are immature and lean in organic matter having poor potential. Exceptions are the thin coal beds at places which have good potential for gas generation. Fig. 18.2 shows one possible location where effective Triassic source rock may be present.

Jurassic – The Datta and Shinawari Formations show good to very good potential as oil and gas source rocks in the Platform area. Coal beds in these formations, though of limited aerial extent, have very good potential for gas generation. Chiltan Limestone, present in the trough part of the basin, falls in the oil and gas window but it is lean in organic matter and ineffective as source rock. Effective source rock distribution and oil window maturity at its base is shown in Fig. 18.3.

Cretaceous – This basin was an area of extensional tectonics during the Lower to Middle Cretaceous associated with slightly restricted circulation of the sea waters at the north-western margin of Indian Plate. Lower Cretaceous source rocks (Sembar Formation) were deposited while the basin was opening up and anoxia was prevailing. Similarly Middle to Upper Cretaceous clastics were deposited in setting favourable for preservation of organic matters.

The source rocks exist in Sembar and Goru Formations of Lower Middle Cretaceous as observed in the outcrops in the Sulaiman Range and in the wells drilled in Sulaiman province. In addition the source potential of Upper Cretaceous Moghal Kot Formation at the margin of Central Indus Basin is also very good as it was deposited in the slope environment providing anoxic conditions for the preservation of organic matter.

Fig. 18.4 and 18.5 show the distribution of source rocks in Sembar and Goru Formations and maturity at the base, respectively. Fig. 18.6 is the regional source-rock evaluation of Sembar and Goru formations. Fig. 18.7 shows the maturity at base Tertiary level. Similarly the Chichali Formation at places in the platform area has good source rock potential for oil and gas but is immature.

PERMIAN & TRIASSIC SOURCE ROCKS

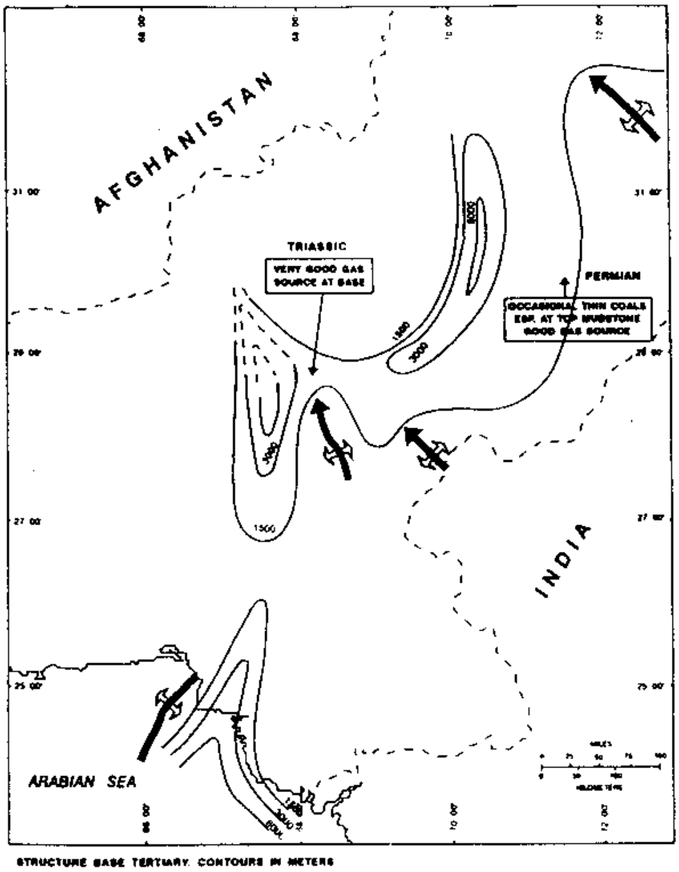


Figure - 18.2 Permian & Triassic Source Rocks

JURASSIC SOURCE ROCKS

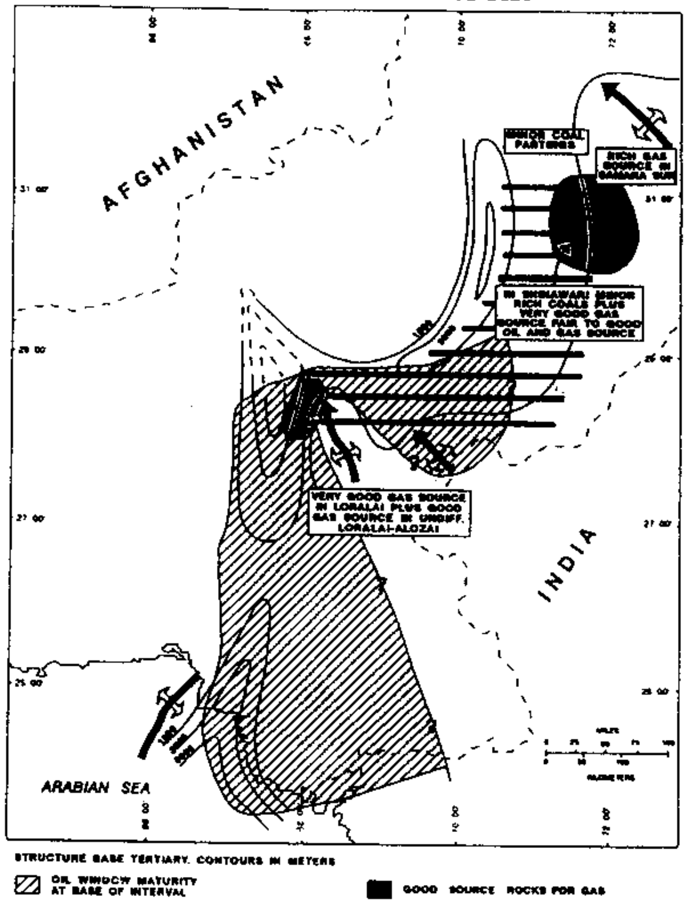


Figure - 18.3 Jurassic Source Rocks

SEMBAR FORMATION SOURCE ROCKS

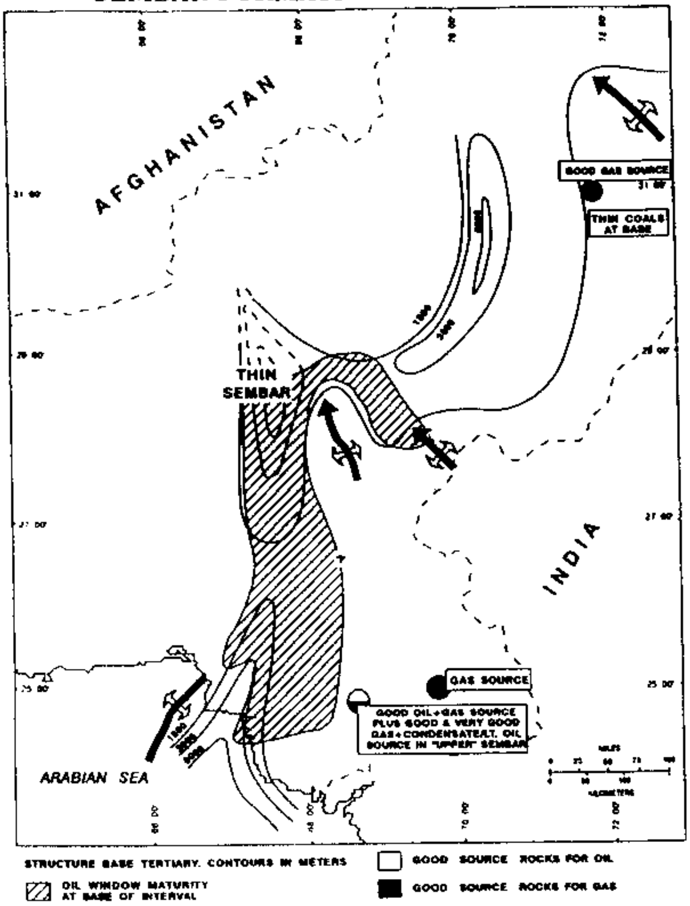


Figure - 18.4 Sembar Formation Source Rocks

GORU FORMATION SOURCE ROCKS

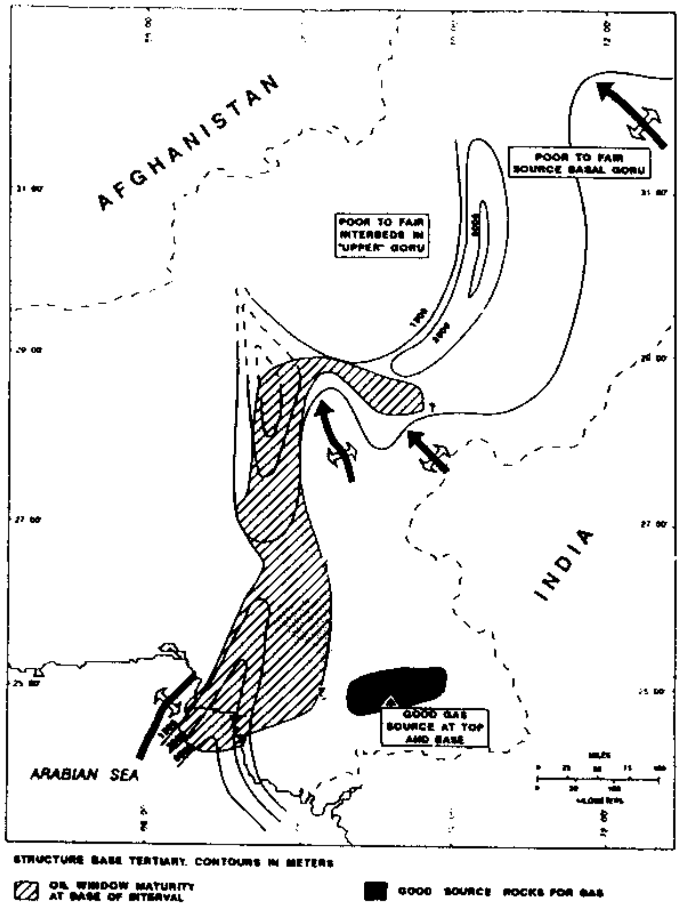


Figure - 18.5 Goru Formation Source Rocks

Tertiary

Paleocene – The Paleocene rocks, for the most part, consist of poor source rocks with significant exceptions. In two wells drilled on the Punjab Platform area, the Paleocene contains carbonaceous mudstones 1.5 to 3 meters thick, which are potentially good to very good source rocks for generating gas and light oil. However, these beds were not encountered in the other wells and do not extend laterally into the Trough area. The source rocks have not attained maturity and are especially immature in the Platform area. Fig. 18.8 shows the Paleocene source rock distribution and maturity at its base.

Eocene – The Eocene Limestones are fairly thick but are lean in organic matter. Their potential as source rock is poor. Shales of Eocene are also low in organic carbon but are gas prone. In the Platform area, coaly mudstone bed (about 7.5 meters) with high organic carbon content was encountered in one of the wells. The organic matter has potential for both oil and gas generation; however, it is totally immature in this region. Fig. 18.9 shows the Eocene source rock distribution and maturity at its base. Fig. 18.10 depicts regional source rock evaluation of Paleocene and Eocene rocks.

A very important organic facies is present in Middle Eocene of Sulaiman Range in Kirthar Formation. It contains low grade oil shales with TOC up to 11% and extends over more than 300 kilometers North-South (from South Waziristan to SW of Jampur) and more than 70 kilometers East-West (from Rakhni/Kingri to Zindapir). It reaches a maximum thickness of 100 meters at northern Zindapir anticline. Although thermally immature, it is likely to attain sufficient maturity in the adjoining depression areas.

Similarly good quality source rocks were also observed in similar facies (Middle Eocene Habib Rahi Limestone) in Kandhkot area and they are expected to be present in Kirthar Depression.

Miocene – Miocene source rocks with minor exceptions are generally lean and immature and can be discounted as potential hydrocarbon source rocks. Basal Oligocene contains organic rich shales; however, the beds are thin and discontinuous with little potential as source rocks. Fig. 18.11 shows Miocene–Oligocene source rock distribution and maturity at base Oligocene.

Summary

The Cretaceous (Sembar) and Jurassic Formations are the potential source rocks in the Central Indus Basin. The Sembar contains rich source rocks for gas generation both in the Platform and Trough areas where these source rocks could have attained the desired maturity. However, these source rocks occur as thin and laterally discontinuous beds.

The Jurassic Formations contain rich source rocks in the Punjab Platform and also in the Trough area. These source rocks are present as thin beds with a cumulative thickness of 3–9 meters Deposition of source beds was not a regional event; these beds represent different times and places during the Jurassic where the environment was conducive for the deposition of rich source rocks. These source rocks have not attained sufficient maturity in the Punjab Platform but in the Trough area should have acquired maturity to generate large volumes of gas.

Another important potential source rock is present in Middle Eocene Kirthar Formation which by its organic matter richness can be termed as oil shale and must attain maturity in Depression areas.

REGIONAL SOURCE ROCK EVALUATION - GORU & SEMBAR

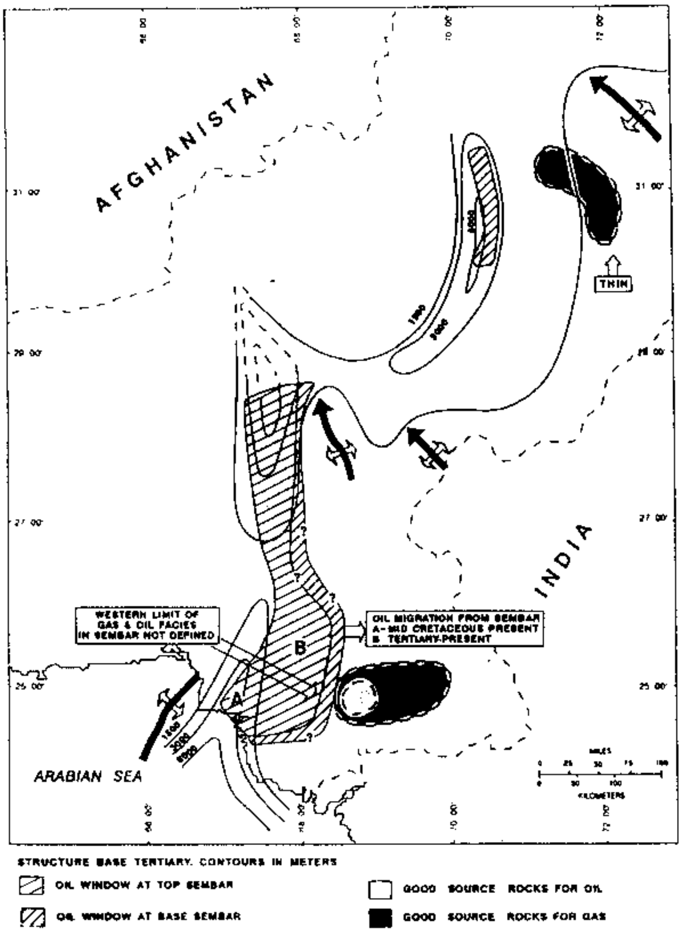


Figure - 18.6 Regional Source Rock Evaluation - Goru & Sembar

MATURITIES AT BASE TERTIARY

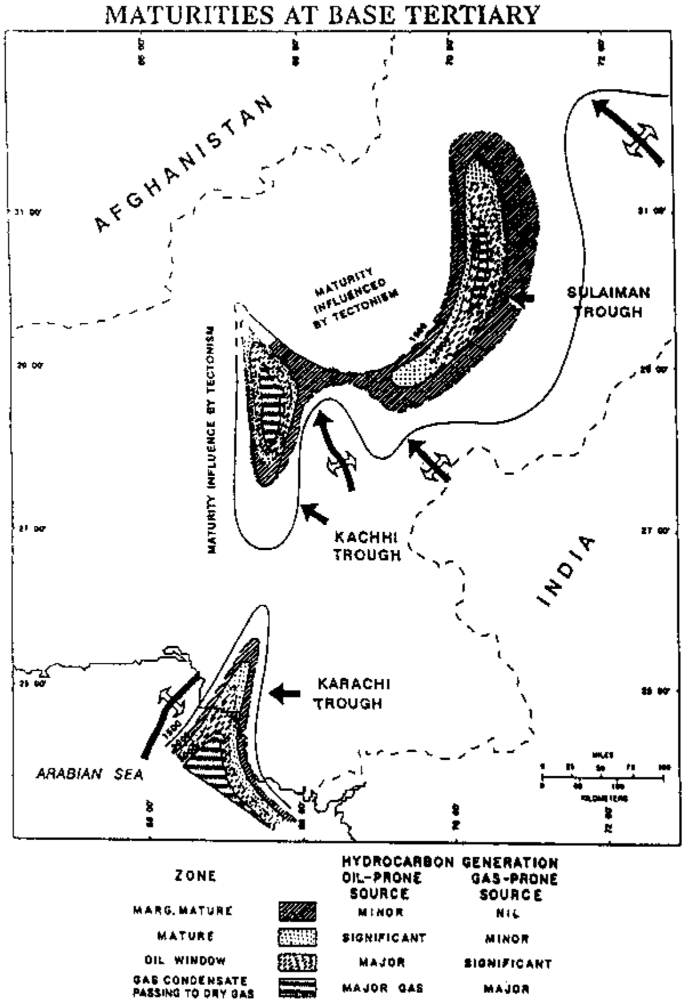


Figure - 18.7 Maturities at Base Tertiary

SOUTHERN INDUS BASIN

Paleozoic

No data is available on Permian and older strata for the Lower Indus Basin as these have not been drilled.

Mesozoic

Triassic – Good to very good source rocks rich in organic matter are present on the Jacobabad High but are too thin to be of significance. On the Thar Slope, these sediments are lean and unimportant.

Jurassic – Source rocks of good quality are present on the Jacobabad High which probably extend out into the Trough area in the northern part of the basin. Here the source rocks would have attained the desired maturity for hydrocarbon generation. Effective Jurassic source rock distribution and oil window maturity at its base is shown in Fig. 18.3.

Cretaceous – Source rock data in the southern part of the Trough area in the South Indus Basin is limited and the interval appears to be lean. In the north, the Goru and Sembar formations are poor source rocks. Better source rocks in the Cretaceous are restricted to the Thar Platform where Goru contains approximately 15 meters of good gas bearing and the Sembar 75 meters of good gas and condensate bearing source rocks. In the east of the Thar Platform, the Goru source facies are immature as they do not fall within the oil window. Sembar, however, is mature and these thick sediments are capable of generating both gas and condensate. Fig. 18.4 and Fig. 18.5 show the distribution of source rocks in Sembar and Goru formations and maturity at the base respectively. Fig. 18.6 is the regional source rock evaluation of Sembar and Goru formations. Fig. 18.7 shows the maturity at base Tertiary level.

The maturity data suggests that most of the Badin oil has been generated on Platform rather than in Karachi Trough and migrated updip via different pathways.

Tertiary

Paleocene – Northern part of Southern Indus Basin contains oil prone source rocks. However, Paleocene is leaner in organic matter and thinner than in Eocene. Though the oil window is more extensive any major oil generation is ruled out.

In the south, facies with a mixed potential for oil and gas are present. These are thicker and more wide spread compared to Eocene and extend from the onshore Thar Slope to the coast. The Paleocene source sediments thicken towards the coast and in all probability lie within the oil window maturity. Thus the Ranikot Formation in the offshore of the basin includes substantial amount of mature source rocks for the generation of both oil and gas. Fig. 18.8 shows the Paleocene source rock distribution and maturity at its base.

Eocene – The Eocene contains source rocks for both oil and gas. In the northern part of the basin Kirthar Formation is oil prone and the source rock has a thickness of 12 meters. An additional 9 meters of source rock is likely to be present within the Ghazij Formation. The shales are widespread and would have attained enough maturity to extend into the oil window in the center of the Trough area.

Oil and gas prone source rocks in basal Ghazij are present in the Khairpur–Jacobabad High region. These source rocks are about 7-8 meters thick and may correlate with the shales encountered in Karachi

Embayment suggesting that oil prone facies extend into the southern part of the basin. Good source facies is present within the Kirthar Formation in the southern part of the basin as seen in Creek wells. This source has potential for gas and light oil. However, it has a maximum thickness of 1.5 meters and the shale is thought to have been deposited locally.

Potentially good to rich source rocks for gas of Laki–Ghazij age are present in the Thar Slope and extend out into the Trough area. The sediments are about 30 meters thick in the slope area but decrease towards the coast and are very thin in Creek wells. These shales are immature in the slope area but would acquire maturity a short distance offshore and could source both condensate and gas.

Fig. 18.9 shows the Eocene source rock distribution and maturity at its base. Fig. 18.10 depicts regional source rock evaluation of Paleocene and Eocene rocks.

Summary

Thus within the Eocene of Southern Indus Basin the Kirthar and Ghazij formations are oil prone. As discussed earlier, Habib Rahi Limestone Member of Kirthar Formation is organic rich in the Central Indus Basin including Sui and Kandhkot gas fields region. Similarly this formation, exposed in the Kirthar Range, comprises reasonable organic matter. Hence it is likely to be present in the Kirthar Depression including Kacchi and Sibi Troughs.

Ghazij and Laki formations in the south (Karachi Trough) are characterized by gas and condensate source rocks; the oil prone facies are very limited.

In the northern part (Kacchi Trough) no oil generated from Eocene source has yet been discovered probably due to lack of exploration.

In Offshore, however, Eocene sediments may have attained enough maturation in the deeper parts of the Trough to generate both gas and condensate.

Oligocene – Potentially good and rich source rocks are present. However, these source rocks are thin, limited in volume and unimportant. Fig. 18.11 shows Miocene–Oligocene source rock distribution and maturity at base Oligocene.

The source rock characteristics of Offshore Indus are dealt with in a separate section.

GEOTHERMAL GRADIENTS AND SOURCE ROCK MATURITY

It is now established that temperature plays the most important role in the transformation of organic matter into hydrocarbons. It forms the top apex of organic matter-time-temperature triangle which is used as one of the most significant exploration tools to determine the hydrocarbon potential of any area. According to Lopatin (in Wapples, 1980) the rate of hydrocarbon generation is linearly related to time but exponentially to temperature i.e. if a rock unit generates hydrocarbons at 130 ^{o}C in 70 million years, at 140 ^{o}C it will generate hydrocarbons in 35 million years and at 150 ^{o}C in 17.5 million years. This method is known as Lopatin's time and temperature analysis which has been very effectively used to predict the presence of hydrocarbons in a given area with known geothermal gradients and burial history. However, for the areas which have not gone through major tectonic phases in the past geological history the following temperature ranges are given for generation of different types of

PALEOCENE SOURCE ROCKS

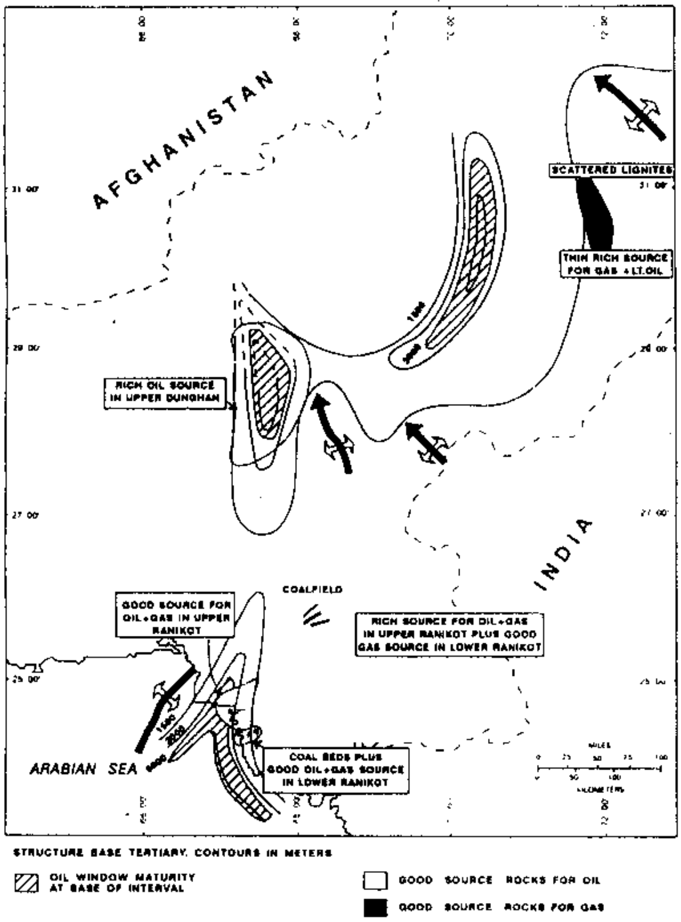


Figure - 18.8 Paleocene Source Rocks

EOCENE SOURCE ROCKS

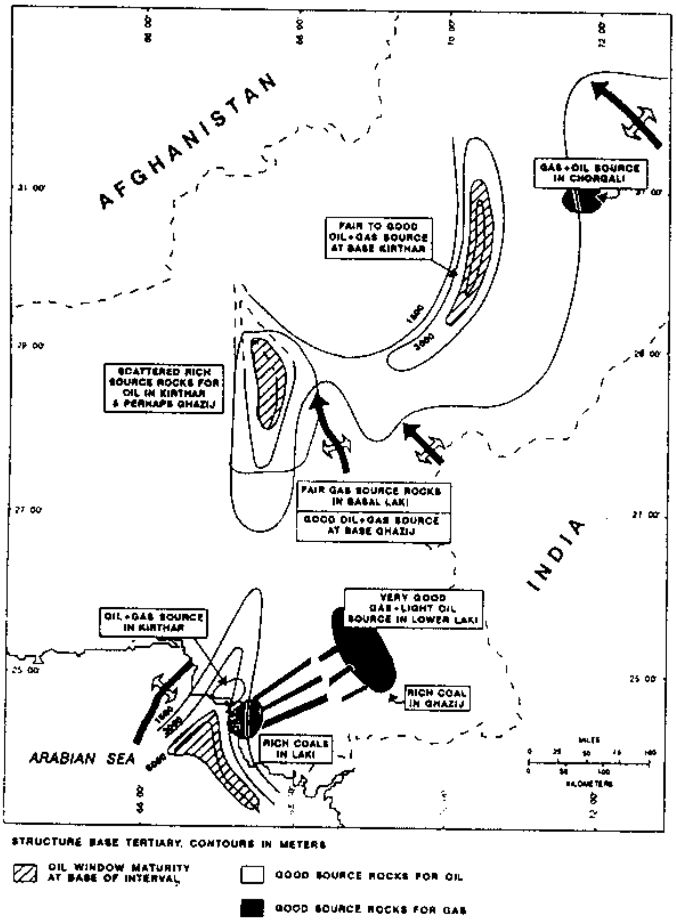


Figure - 18.9 Eocene Source Rocks

REGIONAL SOURCE ROCK EVALUATION-EOCENE & PALEOCENE

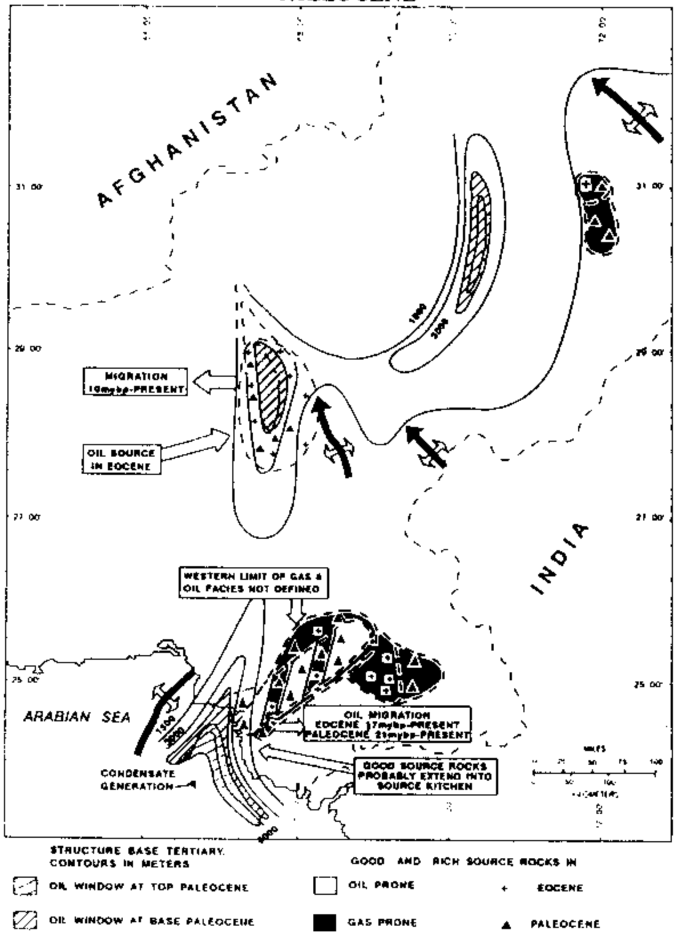


Figure - 18.10 Regional Source Rock Evaluation-Eocene & Paleocene

MIOCENE-OLIGOCENE SOURCE ROCKS

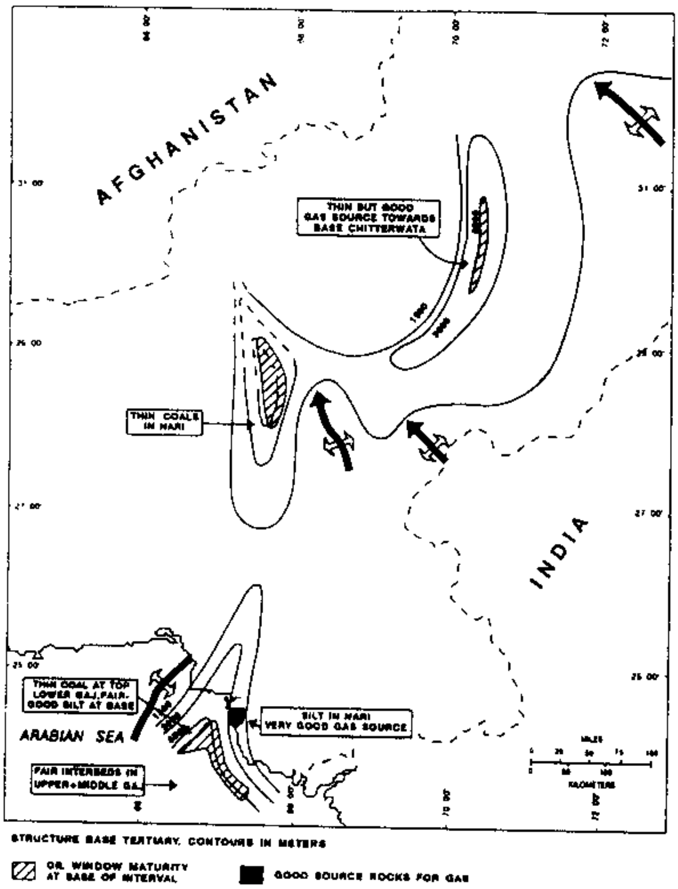


Figure - 18.11 Miocene-Oligocene Source Rocks hydrocarbons by various authors:

Biogenic gas only	=	69 – 82 °C
Oil and Gas (the oil window)	=	82 – 132 °C
Gas Condensate	=	132 – 163 °C
Dry Gas	=	163 – 260 °C
Barren	=	More than 260 °C

The rise in temperature with depth indicates that there is a vast amount of heat energy flowing toward the surface. The source of heat in the earth's crust may be in the outward flow of heat from the central core of the earth (in the presence of igneous magmas that are cooling), in the disintegration of radio-active elements or in the heat of subcrustal thermal convection currents.

The correct prediction of geothermal gradient requires thorough and conceptual understanding of the tectonic framework, depositional settings and basin evaluation. Geothermal gradients in petroleum industry are calculated from temperatures recorded during wireline logging; for this purpose the last suite of log is used as it accounts for the maximum elapsed time between the cessation of mud circulation and temperature measurements. In most accurate computations, different time elapsed measurements are recorded and are corrected by certain projection functions for the most stable value. Gradients are calculated as follows:

$$G = \frac{T2 - T1}{D2 - D1} \times 100$$

where,

G = Geothermal gradient in °C/100m

T_2 = Formation Temperature, °C

T_1 = Mean Surface Temperature, °C

D_2 = Depth of Formation, m

D_1 = 0 (if T_1 is surface temperature) m

The isogeothermal gradient map of Pakistan (Fig. 18.12) is related to the depositional setting, the epieorogenic movements within the basement, the thermal conductivities of different formations, volcanic episodes etc.

Geothermal gradients in relation to oil window for different regions of Pakistan are shown in Fig. 18.13.

The maximum geothermal gradients are observed in Sulaiman region around Giandari Well (4.1°C/100m) extending to Sui, Kandhkot and Mari gas fields region. It is interesting to note that the Giandari area marks the Cretaceous depocenter. In Sulaiman region isogeothermal gradient map conforms with Cretaceous isopach map. This indicates that Cretaceous rocks, being 143–65 million years old, have had sufficient time to dissipate the heat energy of the growing basement during this period; as Cretaceous marks the period of substantial epeiorogenic activities within basement of this region. Mari-Jaisalmer and Khairpur-Jacobabad Highs are the manifestations of these activities. Such a high geothermal gradient may have eased the Cretaceous source rocks (e.g. Sembar Shales) out of oil window and is probably responsible for the generation and accumulation of a huge volume of gas (about 30 Tcf, recoverable) in this region. This is substantiated by the Carbon isotopic analysis of these gases (~-35°/oo) which characterises their thermal origin rather than biogenic, as reported by earlier authors. Burial history curve of Central Indus Basin (Sui region) also indicates that the oil window lies between 2,117 and 3,380 meters in Pab-Parh (U. Cretaceous) section, whereas Lower Goru-Sembar (L. Cretaceous) are already out of oil window. (Fig. 18.14).

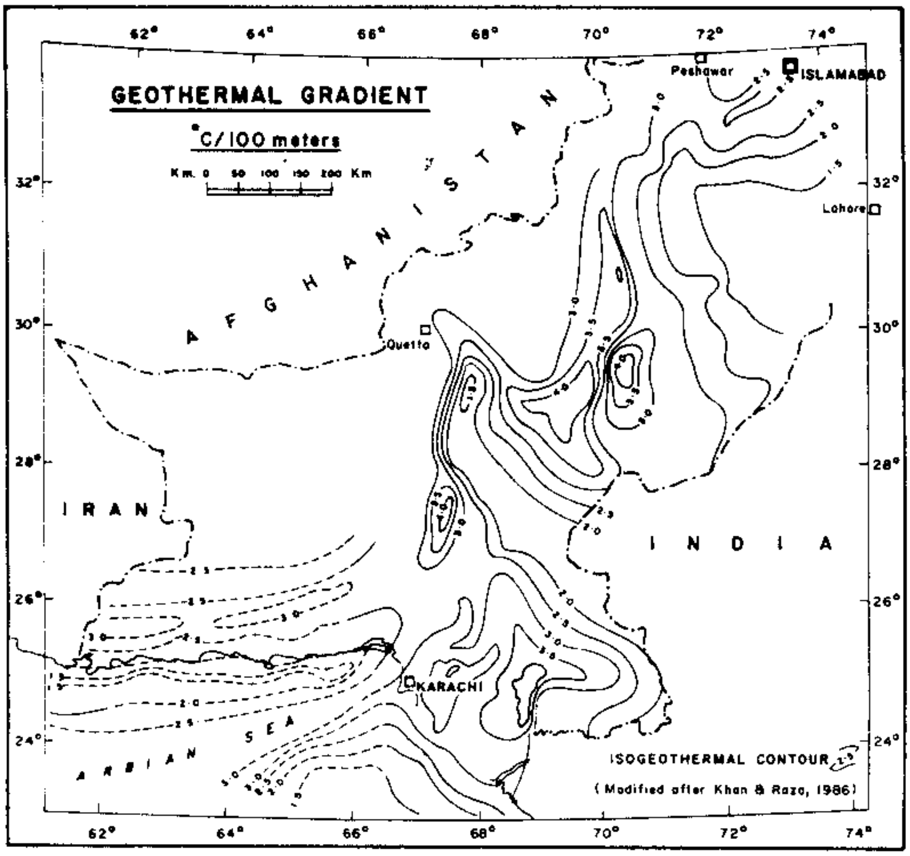


Figure - 18.12 Isogeothermal Gradient Map of Pakistan

Burial history curves have been constructed for the Platform, Depression, the Fold Belt areas of the Central Indus Basin and are shown in Figs. 18.15 a, b, & c. The analyses indicate that only Cretaceous is mature over Platform areas while strata up to Middle Eocene are mature in Depression areas.

Fig. 18.16, 18.17 and 18.18 show the timing of hydrocarbon generation in Jurassic, Goru/ Sembar and Paleocene/ Eocene rocks respectively.

Potwar region, which has been the traditional oil producing area of Pakistan since the early part of this century, has the average geothermal gradient of the order of 2°C/100 meters. Hence the general range of oil window is between 2,750–5,200 meters.

The reason for its being such a prolific basin is the ideal coexistence of source, reservoir and trap within a favourable geothermal regime. In all of the oil producing structures, both source and reservoir lie within oil window (Fig. 18.19a). The Adhi gas/condensate is produced from Khewra(Cambrian) and Tobra (Permian) reservoirs. This gas/condensate is considered to have been sourced from the Patala Formation (Paleocene) which is taken below the oil window in the depression areas towards west.

The geothermal gradient decreases as one proceeds towards the platform areas away from the ranges (e.g. Lilla, Warnali, Pabbi Hill, Kundian wells) on account of the fact that thick Mesozoic and Tertiary sequences are missing in this region and older rocks are predominantly overlain by mollase sediments. Fig. 18.19b shows that top of oil window lies below the total depth of these wells. The lower thermal conductivity of underlying salt and the overlying molasses is probably one of the factors responsible for low geothermal gradients. The other factor could be the stable character of Indian Shield throughout the geological history which has not resulted in heat flow due to convection. The other wells drilled on Punjab Platform (Kamiab, Budhuana, Sarai Sidhu, Tola, Karampur and Marot wells)

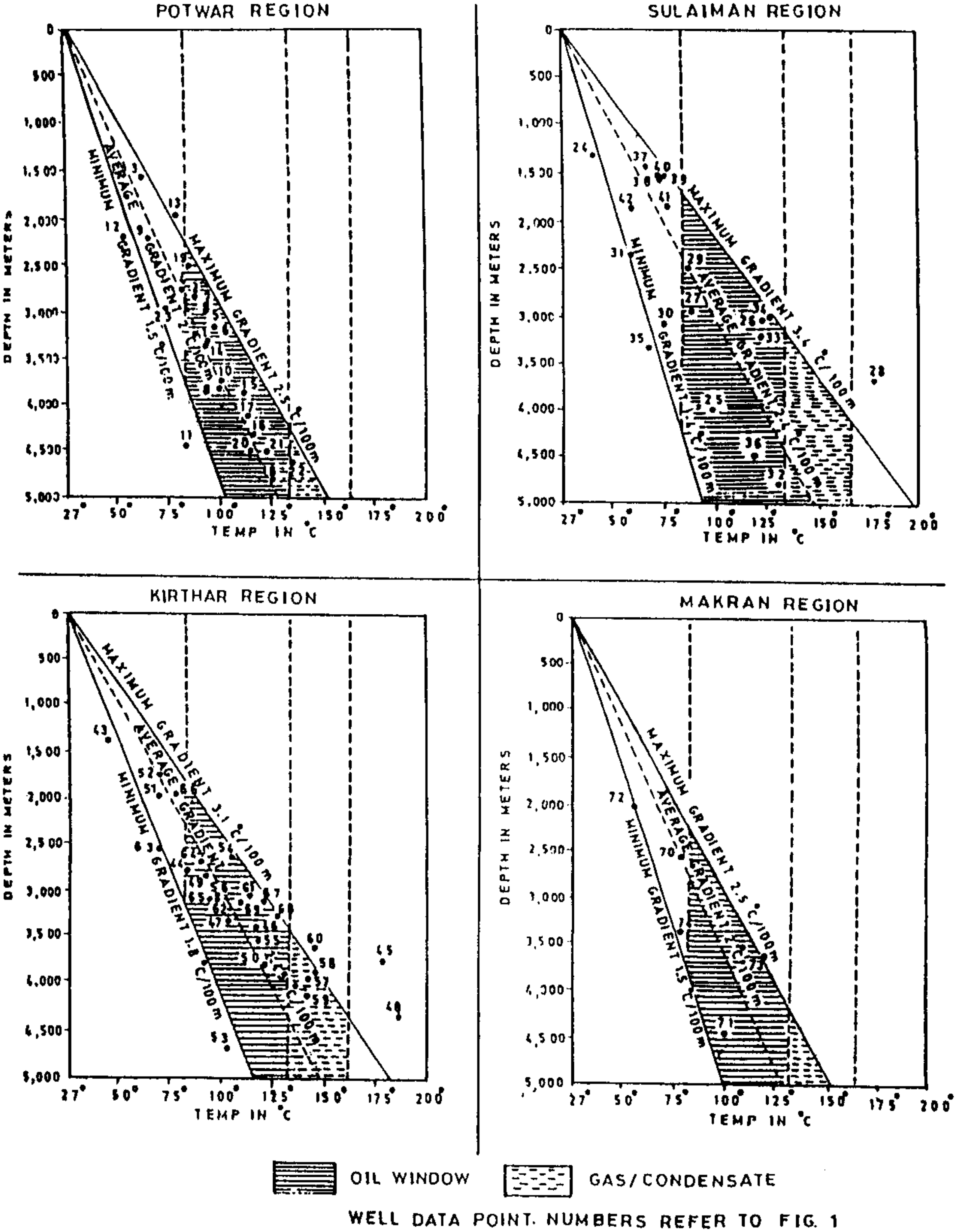


Figure - 18.13 Regional pattern of the geothermal gradients showing "oil windows" (after Khan & Raza, 1986)

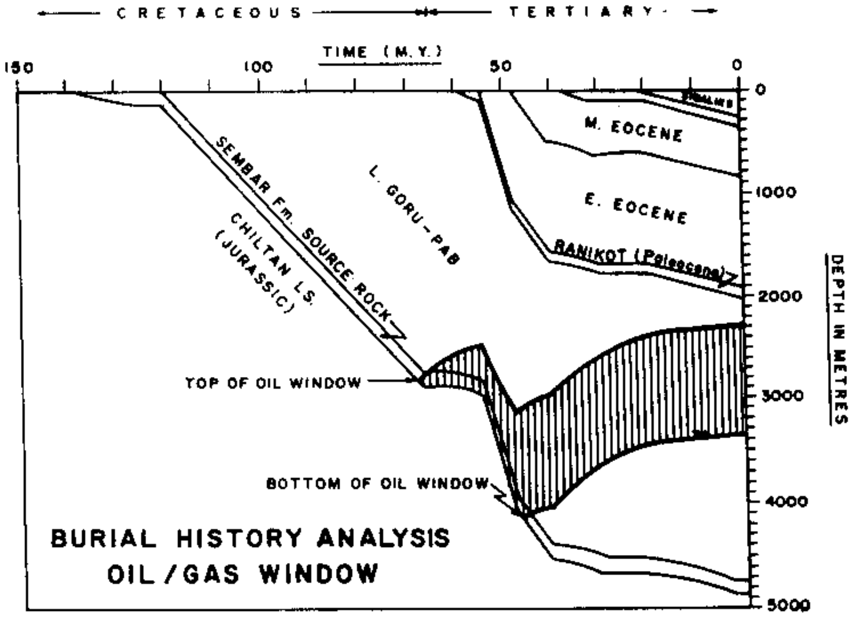


Figure - 18.14 Central Indus Basin with minimum thickness of Siwaliks. Organic matter mainly oil prone in E.Cret.-M.Eocene; Rocks are mature upto Pab

south of Sargodha High also encountered low geothermal gradients probably for the reason cited above. The oil window in these wells lie far below the prospective horizons (Fig. 18.19c).

The behaviour of the oil window in the central part of Sulaiman region is shown in Fig. 18.19d.

The geothermal gradients in the northern Kirthar region are slightly lower than those in southern Sulaiman region (2–2.5 °C/100m) with anomalously low value in Jhatpat well. This may be due to much greater depth to the basements as Jurassic sediments are indicated to be very thick on gravity map. However, in southern Kirthar region the values of geothermal gradient are between 2.5-3.0 °C/100 meters The oil window limits for a north-south distribution of wells in Kirthar region is shown in Fig. 18.19e. Fig. 18.20 shows the burial history curve for the Kirthar Depression area modeled for 5,000 meters of Siwaliks overburden. This depicts that the rocks of Eocene age are in oil window.

The Badin area (Sindh Monocline or Thar Platform) is the most prolific oil producing region of Lower Indus Basin. In this region also the geothermal gradients increase away from the stable Indian Shield (Nagar Parkar High). The wells drilled on the eastern part of the Platform (Nabisar, Digh, Badin, Patar) encountered geothermal gradient of 2.1-2.3 °C/100 meters. Here the oil window exists below the potential source rock (Sembar Formation). However, the geothermal gradients in-

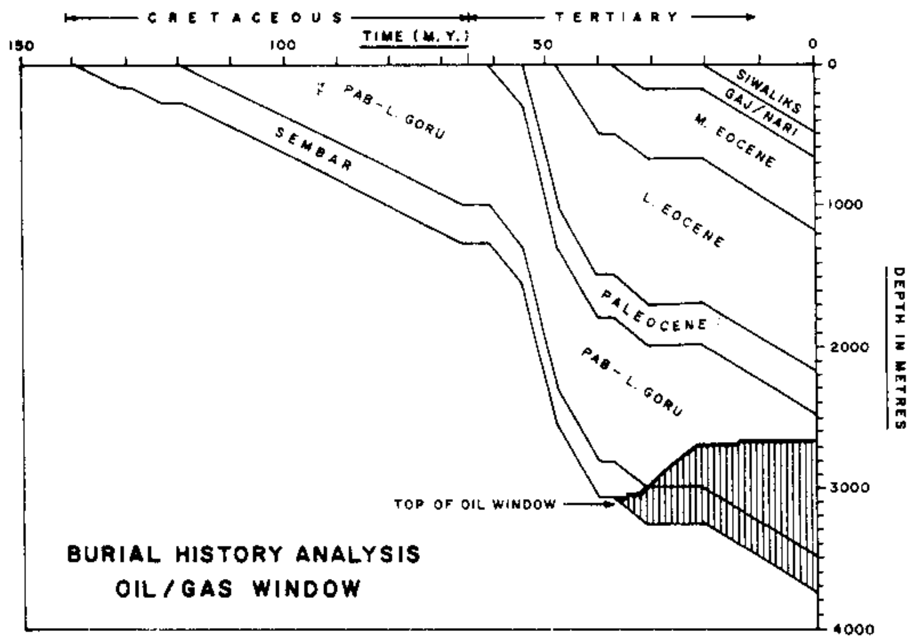


Figure-18.15(a) Punjab Platform Area with 500m of Siwaliks overburden. Only Cretaceous is mature

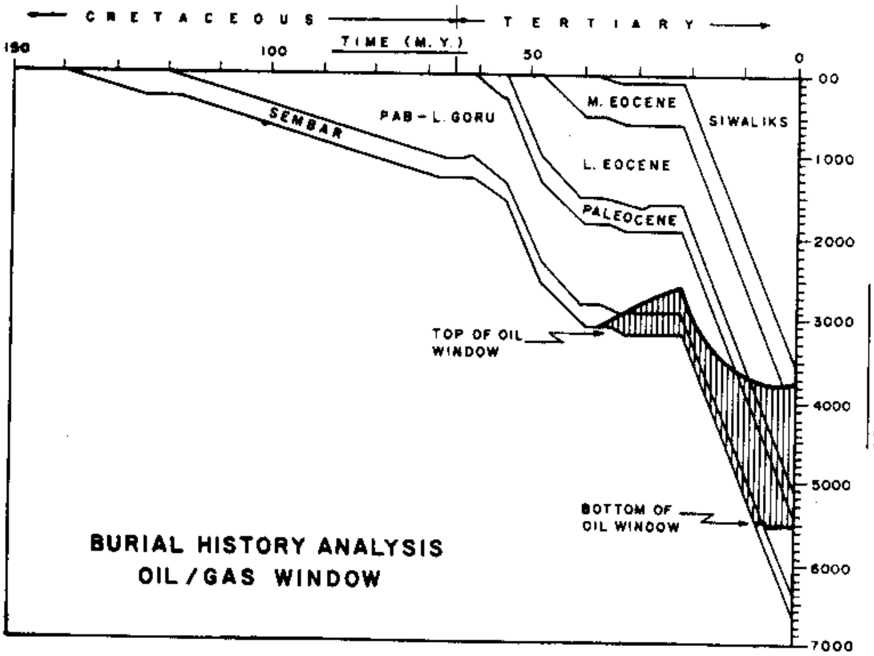


Figure - 18.15(b) Sulaiman Depression with 3500m of Siwaliks overburden. Strata upto M.Eocene (HRL) are mature

crease towards west (Talhar, Mirpur Batoro, Damiri wells) probably related to Cretaceous - Paleocene basaltic flows giving rise to the significant heat flow in the region. Fig. 18.19(f) shows the character of oil window in Badin area. Hence the eastern margin of the western Thar Platform depicts the excellent coexistence of presence of oil window within organic rich Sembar shales (overlying Lower Goru sand reservoirs) and the availability of proper intraformational seals. The western margin of Thar Platform bears the potential for mature gases.

In Offshore Indus, the geothermal gradients decrease away from the shore towards the Offshore Depression. In the nearshore wells, relatively higher values are because of Cretaceous/Paleocene lava flows and lesser thicknesses of Neogene sediments.

The lower geothermal gradients in Offshore Depression are attributed to the rapid deposition of Post-Oligocene sediments which have pushed the oil window (Fig. 18.21) much deeper as the basement temperatures have not stabilized/dissipated as yet. Pak Can-1, the only well which produced hydrocarbons, is located near the hinge line that separates Offshore Platform from Offshore Depression. The geothermal gradients near this hinge line are of the order of 2.5-3.0°C/100 meters. Although more prolific source/reservoir conditions exist in Offshore

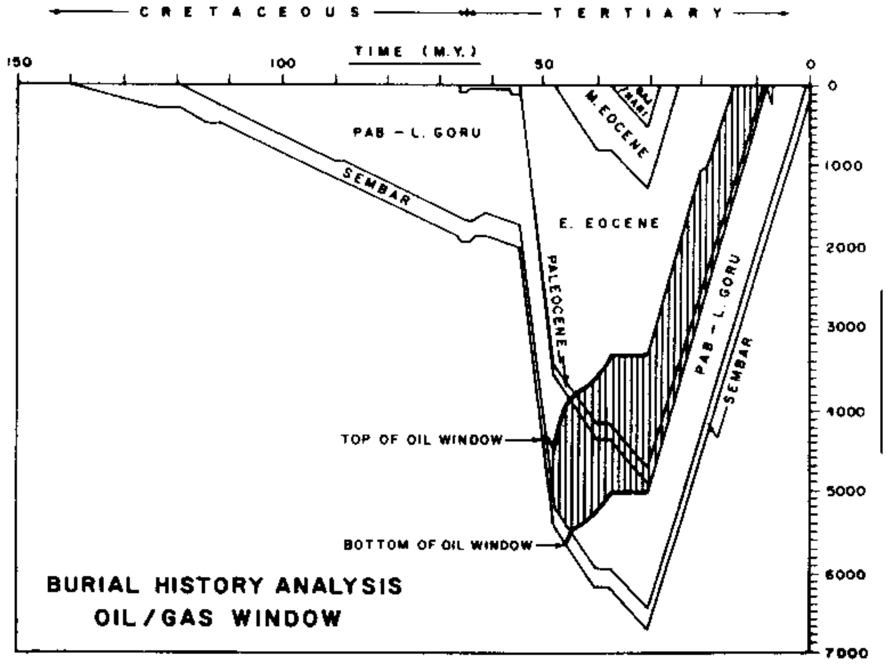
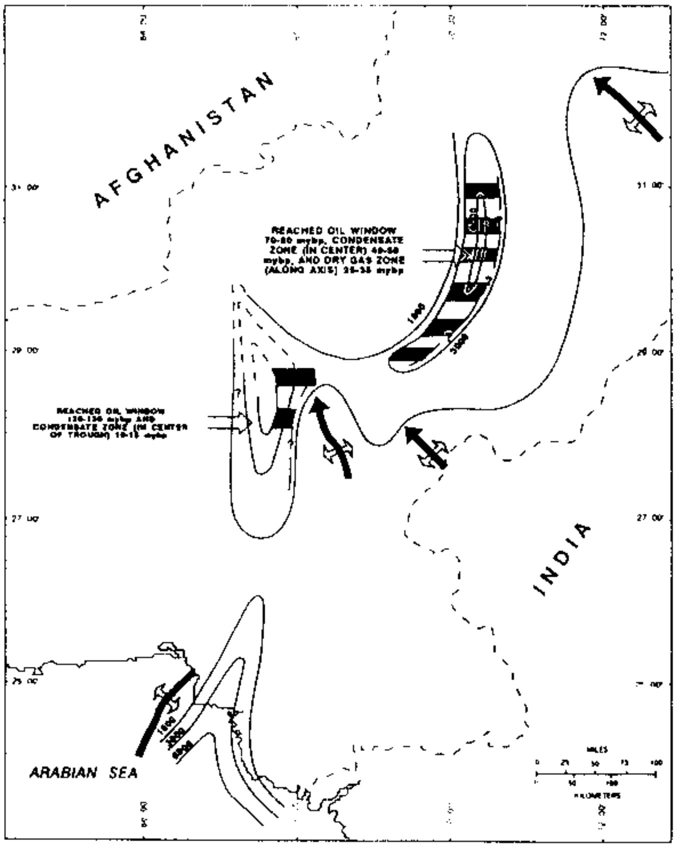


Figure - 18.15(c) Sulaiman Fold Belt (with Sembar Fm. Exposed)

TIMING OF HYDROCARBON GENERATION IN JURASSIC

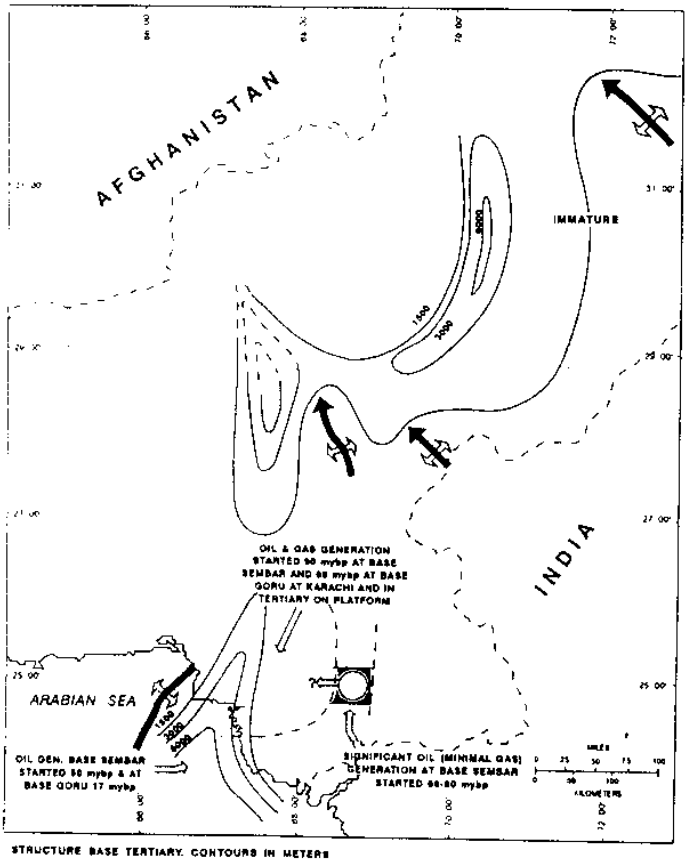


STRUCTURE BASE TERTIARY. CONTOURS IN METERS

GAS PRONE

Figure - 18.16 Timing of Hydrocarbon Generation in Jurassic

TIMING OF OIL GENERATION IN GORU & SEMBAR



STRUCTURE BASE TERTIARY. CONTOURS IN METERS

GAS PRONE

OIL PRONE (IN SEMBAR)

Figure - 18.17 Timing of Oil Generation in Goru & Sembar

TIMING OF OIL GENERATION IN EOCENE & PALEOCENE

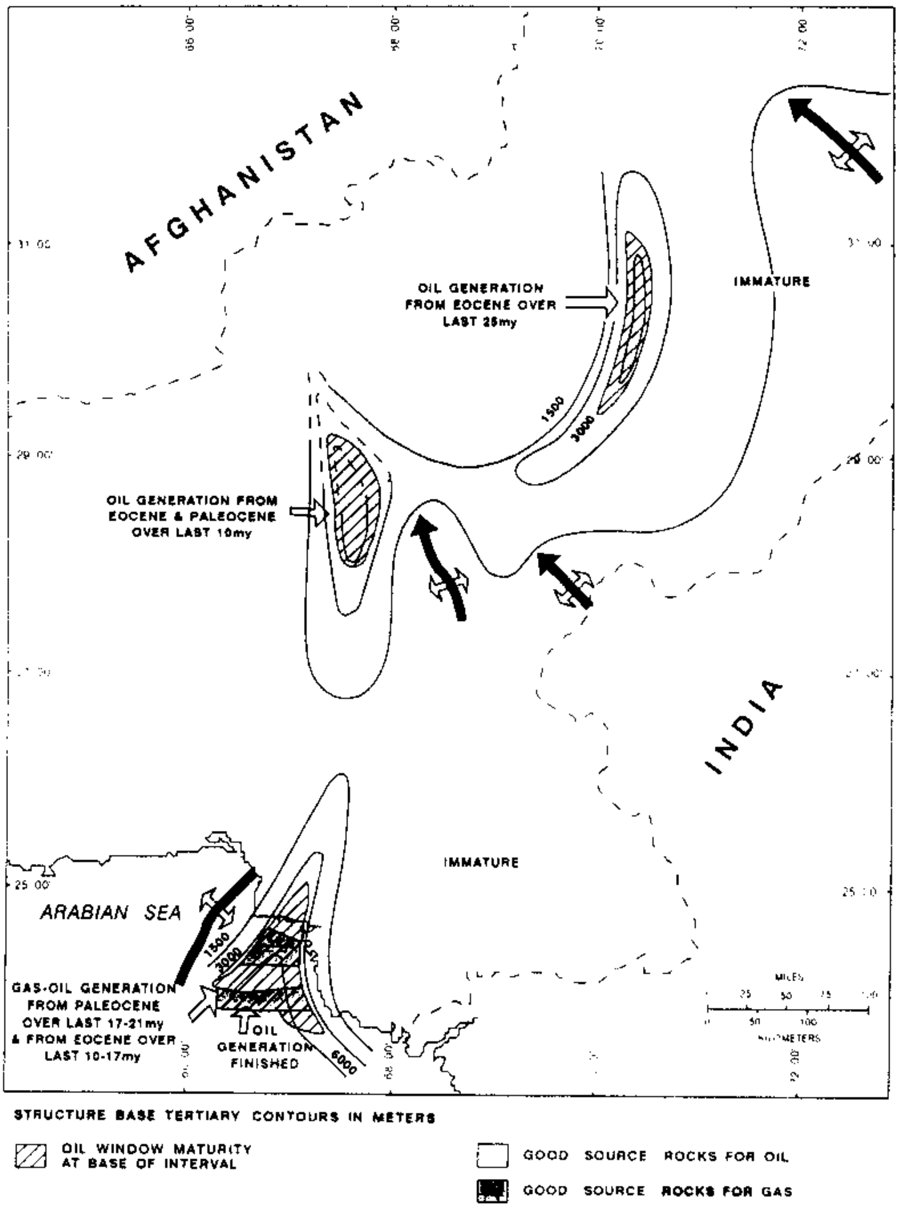


Figure - 18.18 Timing of Oil Generation in Eocene & Paleocene

Depression, the oil window lies quite deep (4,200 meters), giving it a characteristic of a cool basin.

On the basis of six wells drilled in Makran region, this part of Balochistan Basin is considered to be a cooler region. Geothermal gradients range from 1.5-1.9^{o}C/100m with a maximum value of about 2.7^{o}C/100m at Garkoh-1 near the western border of Balochistan. The low gradients are believed to be the result of thick Neogene sedimentation. These sediments have been imbricated to form the Makran Accretionary Prism at the expense of subduction of Arabian Oceanic Plate under Makran Continental margin. This imbricate thrusting has given rise to the pseudo increase in the thickness of these sediments. All of these factors have resulted in the lack of dissipation of heat energy from the basement and under-thrusted oceanic plate to the overlying sediments.

The detailed account of the geothermal gradient scenario of Pakistan indicates that there exists a very delicate balance between the temperature regime prevailing in a region and the petroleum prospectivity thereof and type of hydrocarbons present therein. All of the parameters are very much related to the tectonic/basinal framework and depositional settings. Figs. 18.19(a) to 18.19(f) summarise the source rock evaluation of different periods in the Central and Southern Indus basins.

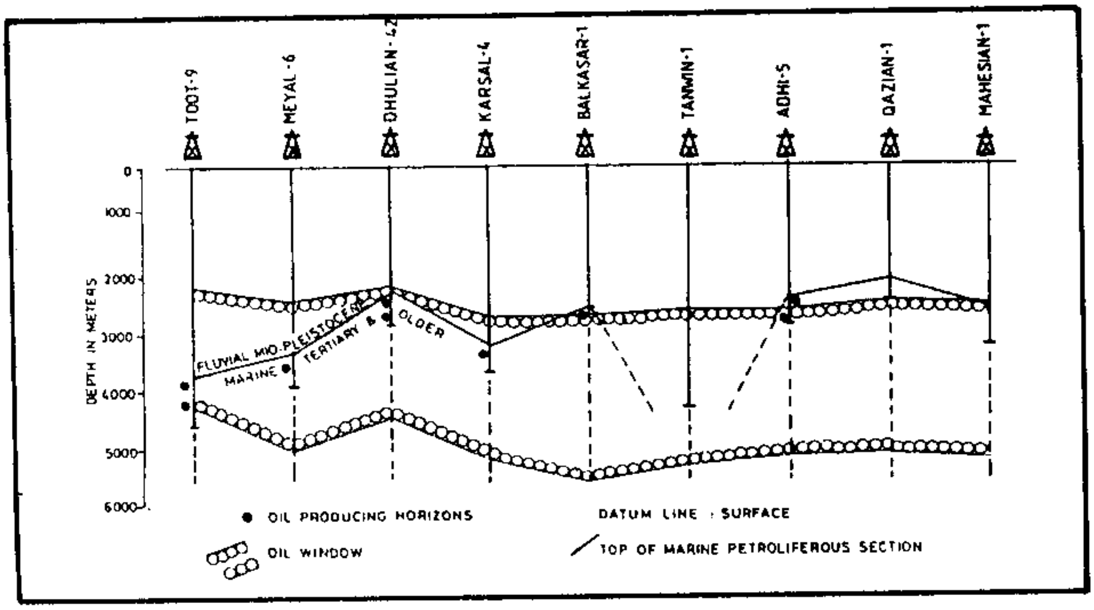


Figure - 18.19(a) Correlation of the "oil window" in the Potwar oilfield region

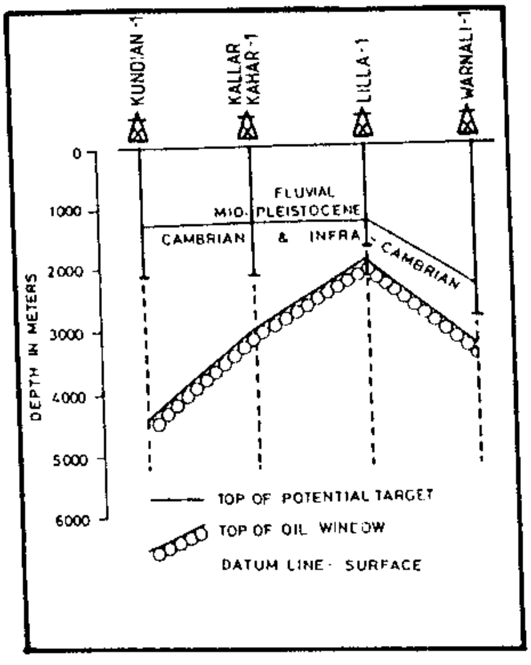


Figure - 18.19(b) Correlation of the "oil window" in the Southern Marginal areas of the Potwar region

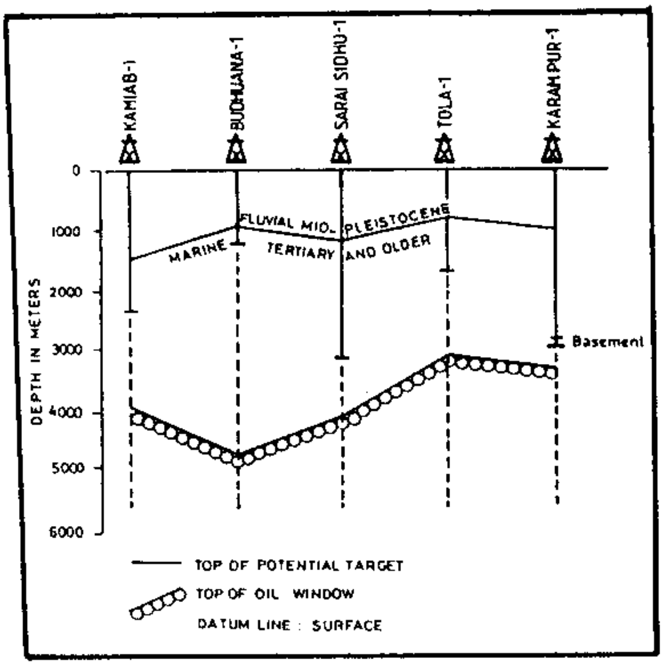


Figure - 18.19(c) Correlation of the "oil window" in the Northern Marginal areas of the Sulaiman region

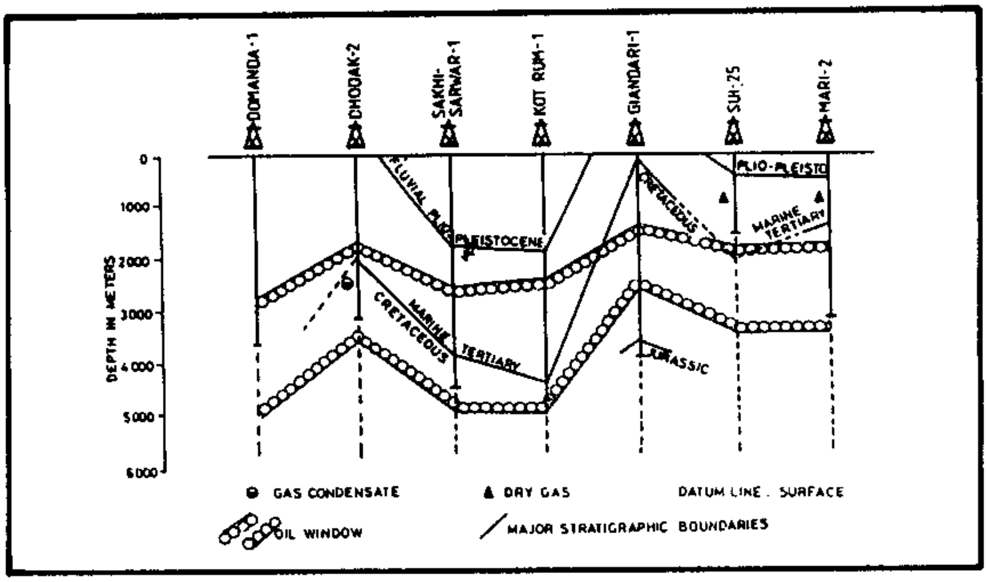


Figure - 18.19(d) Correlation of the "oil window" in the central part of the Sulaiman region

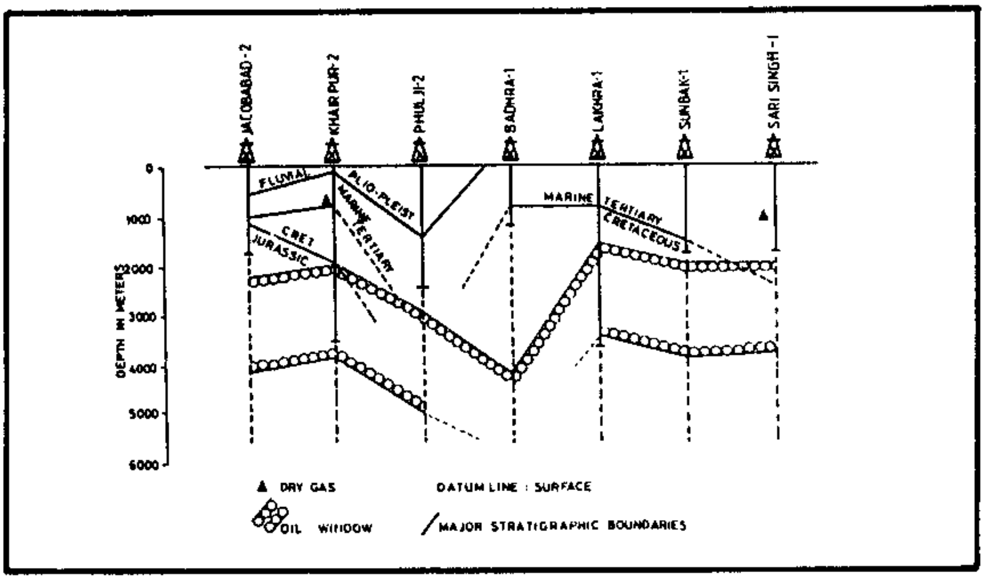


Figure - 18.19(e) Correlation of the "oil window" in the Northern Kirthar region

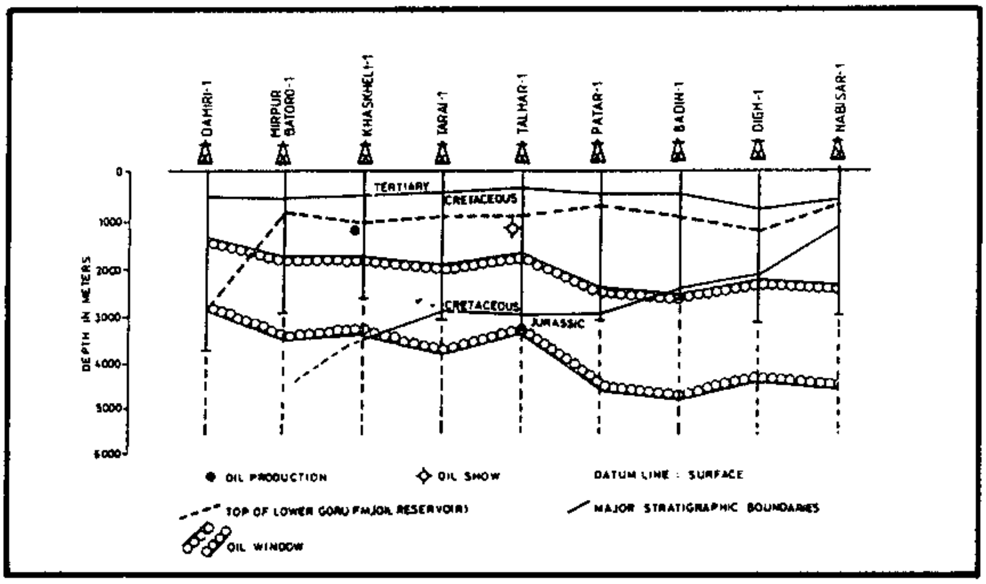


Figure - 18.19(f) Correlation of the "oil window" in the Badin Area, Southern Kirthar region

(after Khan & Raza, 1986)

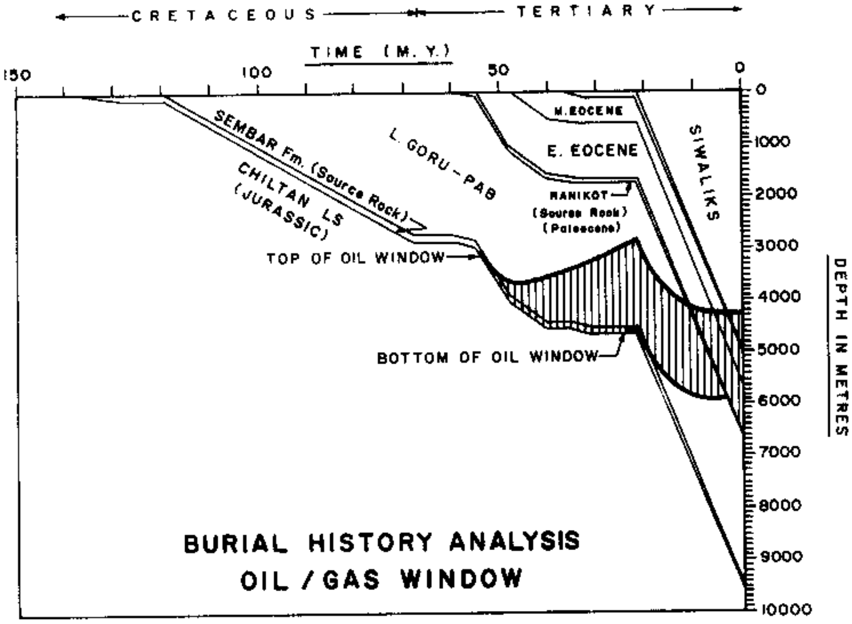


Figure - 18.20 Middle Indus Basin, Kirthar Depression Area with 5000m of Siwaliks. Organic matter mainly oil prone in E.Cret-M.Eocene, rocks are mature upto M.Eocene

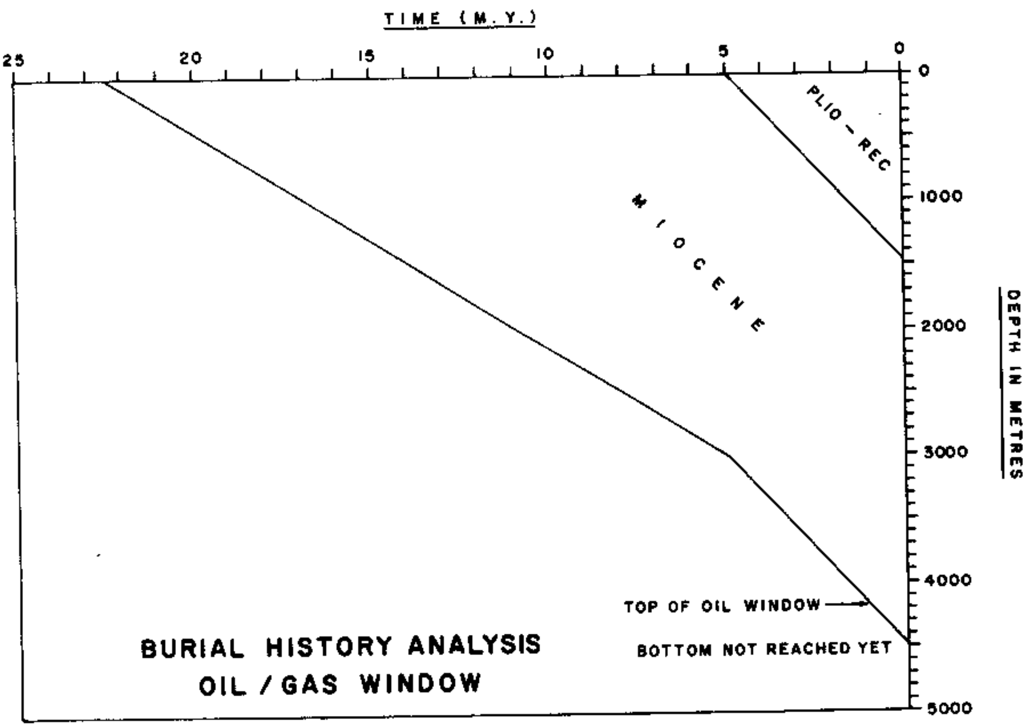


Figure - 18.21 Indus Offshore Depression

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19

Gas Composition And Genesis

The major (non-associated) gas fields of Pakistan are concentrated in the Central Indus Basin, which is flanked on the west and south by the Khairpur–Jacobabad High and on the north-east by Sargodha High. It is the most prolific gas producing basin in this part of the sub-continent and is unique in the sense that it has produced only gas and very little condensate. Gas wetness increases to the north and south.

Study of several gas analyses from Southern Indus Basin has provided useful information in terms of the source rock type, its maturity, and time of generation of gaseous hydrocarbons.

Tectonic features such as structural highs seem to play an important role in the distribution of associated non-hydrocarbon gases like carbon dioxide and nitrogen.

Natural gases occur in a variety of environments and may show marked variations both in their composition and mode of origin. In this section the gases (with emphasis on non-associated gases) of Lower Indus Basin (Fig. 19.1) are characterized by: i)variations in concentration of their components, ii) their mode of origin, iii) calculated vitrinite reflectance (Ro) values and iv) burial history analysis.

Concentration contour maps for methane, ethane plus (C2+), carbon dioxide and nitrogen over Lower Indus Basin have been generated to show their relative distribution.

Carbon and hydrogen isotopic ratios in methane are useful for recognition of origin of gases. Schoell's classification (1983) is used for genetic classification. It must be emphasised that this is an empirical approach with certain limitations. Carbon isotopic concentration of methane has been correlated with C2+ concentration, deuterium concentration of methane and carbon isotopic concentration of ethane, to determine the origin of gases.

Vitrinite reflectance (Ro) values have been calculated for methane and higher hydrocarbons from the available isotopic data for different gas fields to determine the maturity and potential of source rocks.

Burial history curves for Central Indus Basin have been generated to see if they relate to the calculated Ro values. Both the burial history and calculated Ro values have been used to substantiate the results deduced from Schoell's plots (1983).

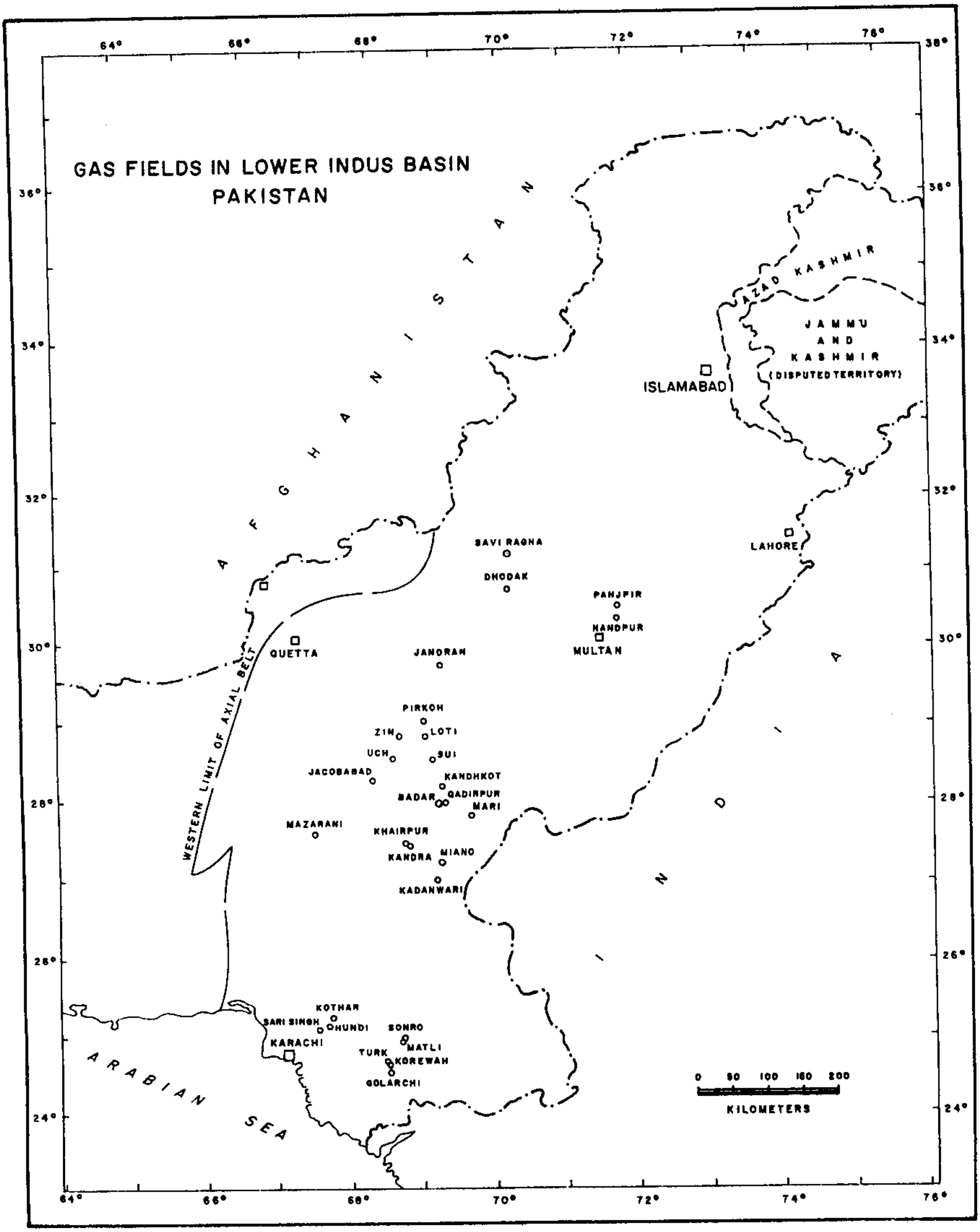

Figure - 19.1 Gas Fields in Lower Indus Basin (after Khan and Ahmad, 1992)

GENETIC CHARACTERISATION OF GASEOUS HYDROCARBONS

COMPOSITIONAL VARIATION IN GASEOUS HYDROCARBONS

Distribution of Carbon Dioxide Concentration (%)

Trend of carbon dioxide concentration contours (Fig. 19.2) follow the trend of the Khairpur–Jacobabad High with highest values at Khairpur-2 and Kandra-1.

Concentration decreases away from the High indicating a relationship between carbon dioxide concentration and the High. Sub-crops of Jurassic limestone would be nearer to the Eocene Limestone reservoirs near the High.

Possible reasons for high carbon dioxide concentrations are:

1. By oxidation of hydrocarbons through contact with mineralised water.
2. By heating of Jurassic carbonates (impure carbonates at $150^{o}C$ and pure limestone around 400^{o} C).
3. By action of certain anaerobic bacteria in attacking hydrocarbons.

Citing a specific reason for the high concentration is difficult due to lack of data on carbon isotope of the carbon dioxide.

Distribution of Nitrogen Concentration (%)

Trend of nitrogen concentration contours (Fig. 19.3), like carbon dioxide, follow the Khairpur – Jacobabad High with highest values at Jacobabad-2. In addition nitrogen concentration increases towards Punjab Platform (Nandpur and Panjpir Gas fields) and in the south at Sonro Gas Field in Badin area.

It has been reported (Williams, 1990) that nitrogen (ammonia) is released within the oil window during the maturation of the organic matter. Some of the nitrogen released is incorporated into clay (illite) while the rest is available for migration. As the source rock attains greater maturity and enters the thermogenic gas generation stage, heating of illite releases nitrogen. The nitrogen released in this process migrates updip with the gaseous hydrocarbons.

The concept may be applied to the Khairpur–Jacobabad High and the Punjab Platform area. It would mean that the Nandpur and Panjpir gases originated in the deeper Sulaiman Foredeep areas and then migrated, an observation supported by the fact that the source rock in the platform area would not be buried to sufficient depths to generate gaseous hydrocarbons. In Badin area, the concept may be applied with certain limitations.

Distribution of Methane Concentration (%)

Methane concentration values (Fig. 19.4) decrease towards the apex of the Khairpur–Jacobabad High where there is a corresponding increase in concentration of carbon dioxide and nitrogen. Away from the High, methane concentration increases at Pirkoh, Loti and Sui in the east, Mazarani in the west and Kadanwari in the south.

Relatively low methane concentration (71%) at Mari may similarly be attributed to the Mari–Jaisalmer High.

Distribution of Ethane Plus (C2+) Concentration (%)

C2+ concentration values (Fig. 19.5) are minimum in the Central Indus Basin, marked by Kadanwari in the south and Sui, Pirkoh and Loti in the north. The area may be regarded as 'dry gas region'. Ethane plus

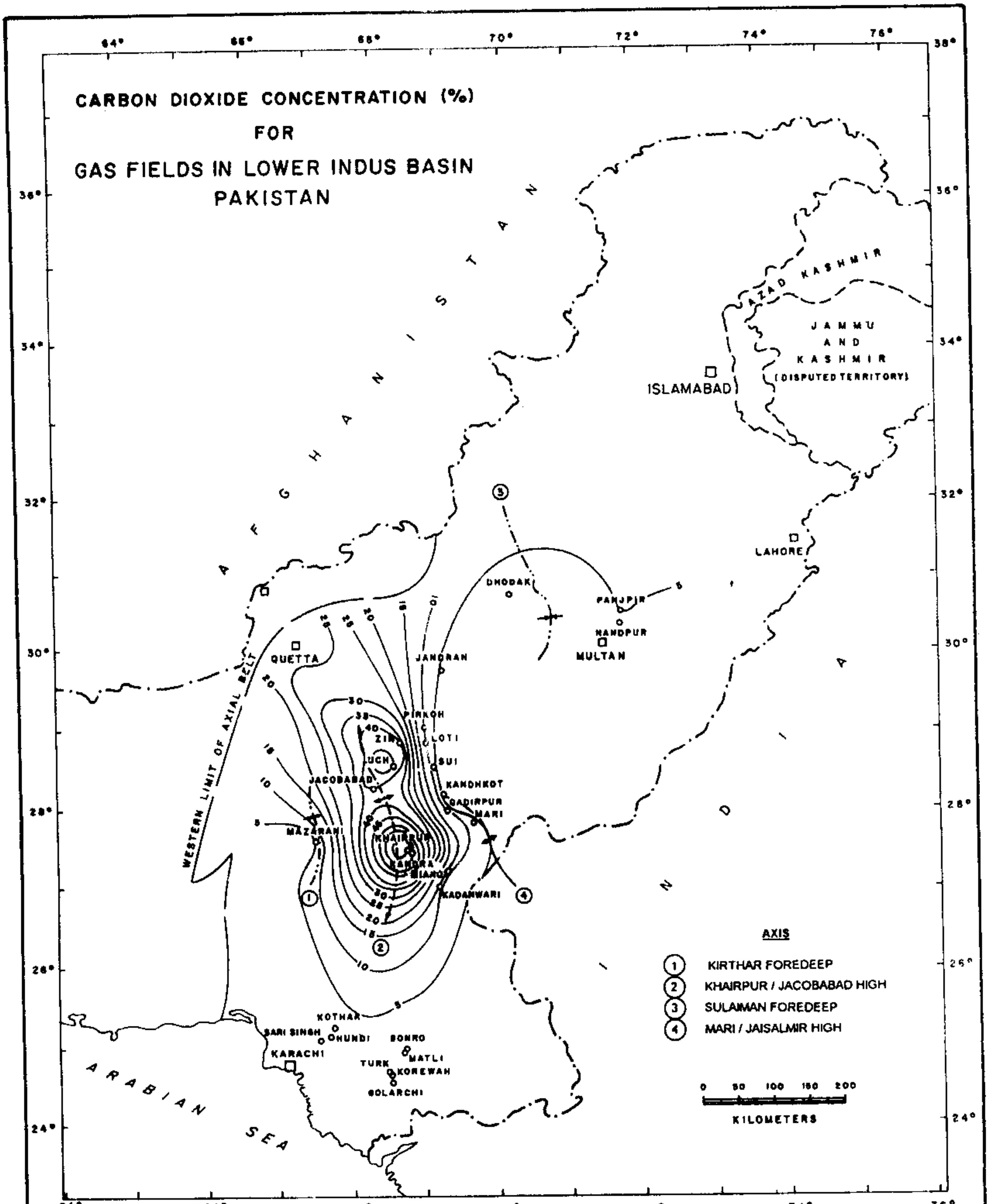

Figure - 19.2 Carbon Dioxide Concentration(%) (after Khan and Ahmad, 1992)

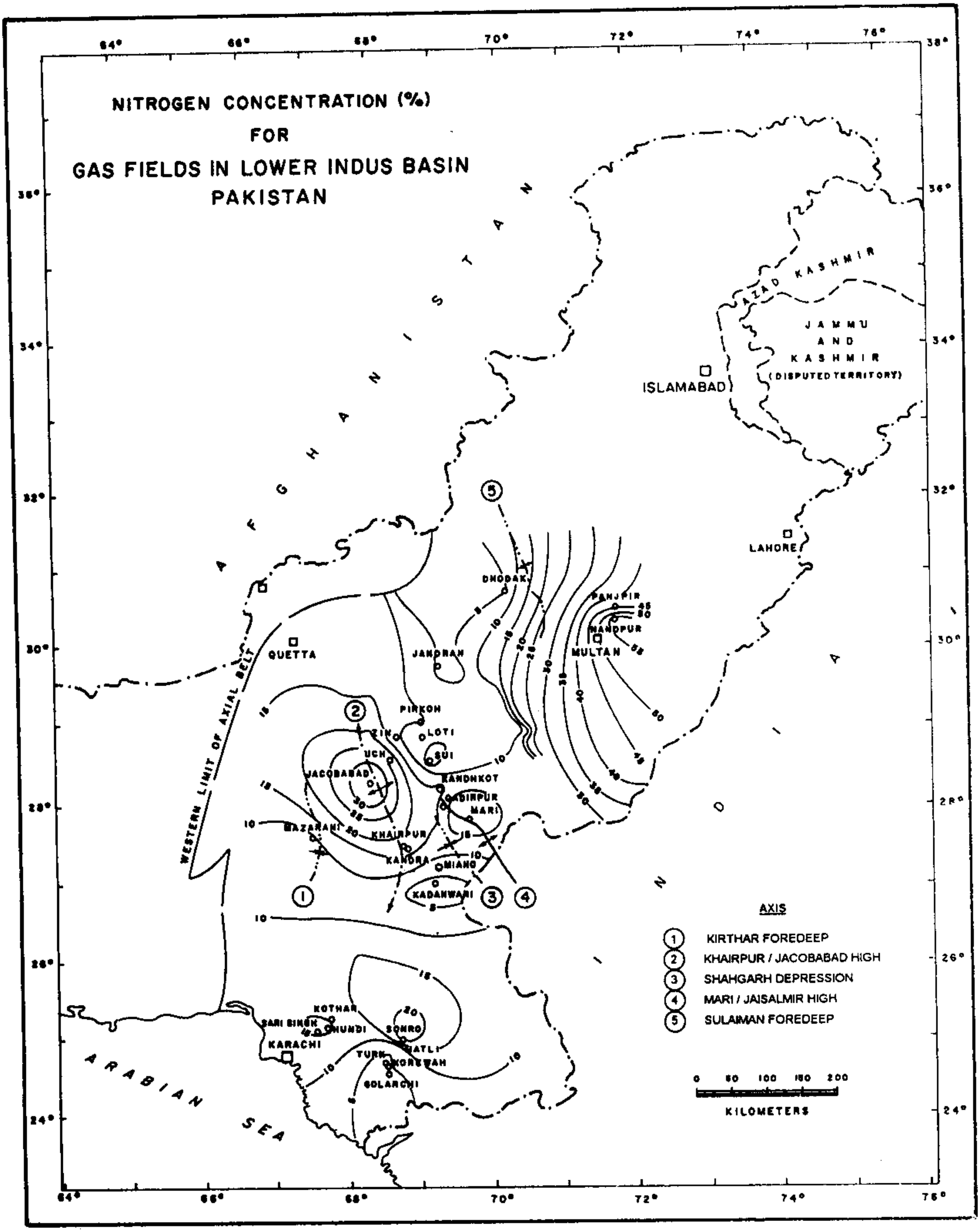

Figure - 19.3 Nitrogen Concentration(%) (after Khan and Ahmad, 1992)

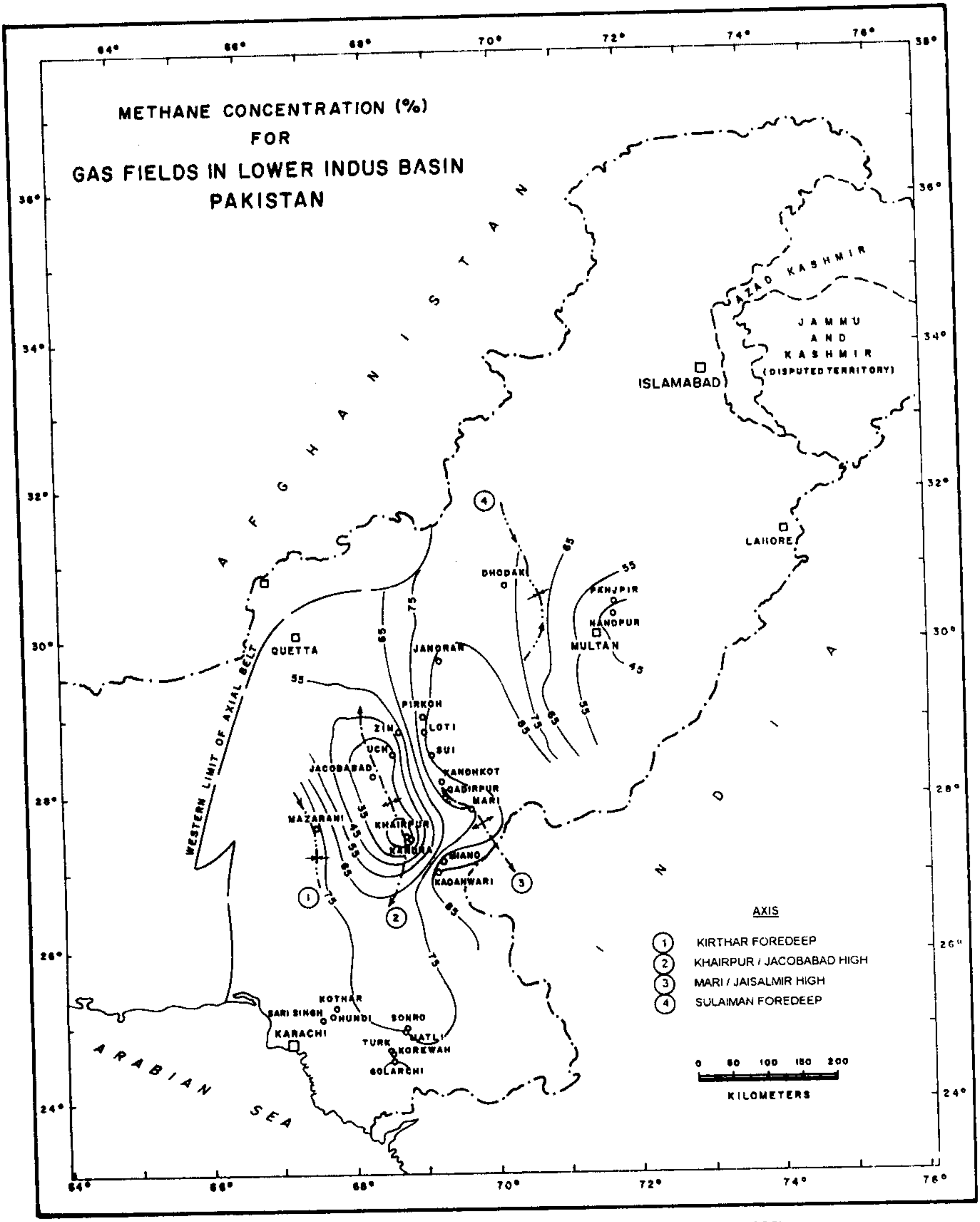

Figure - 19.4 Methane Concentration(%) (after Khan and Ahmad, 1992)

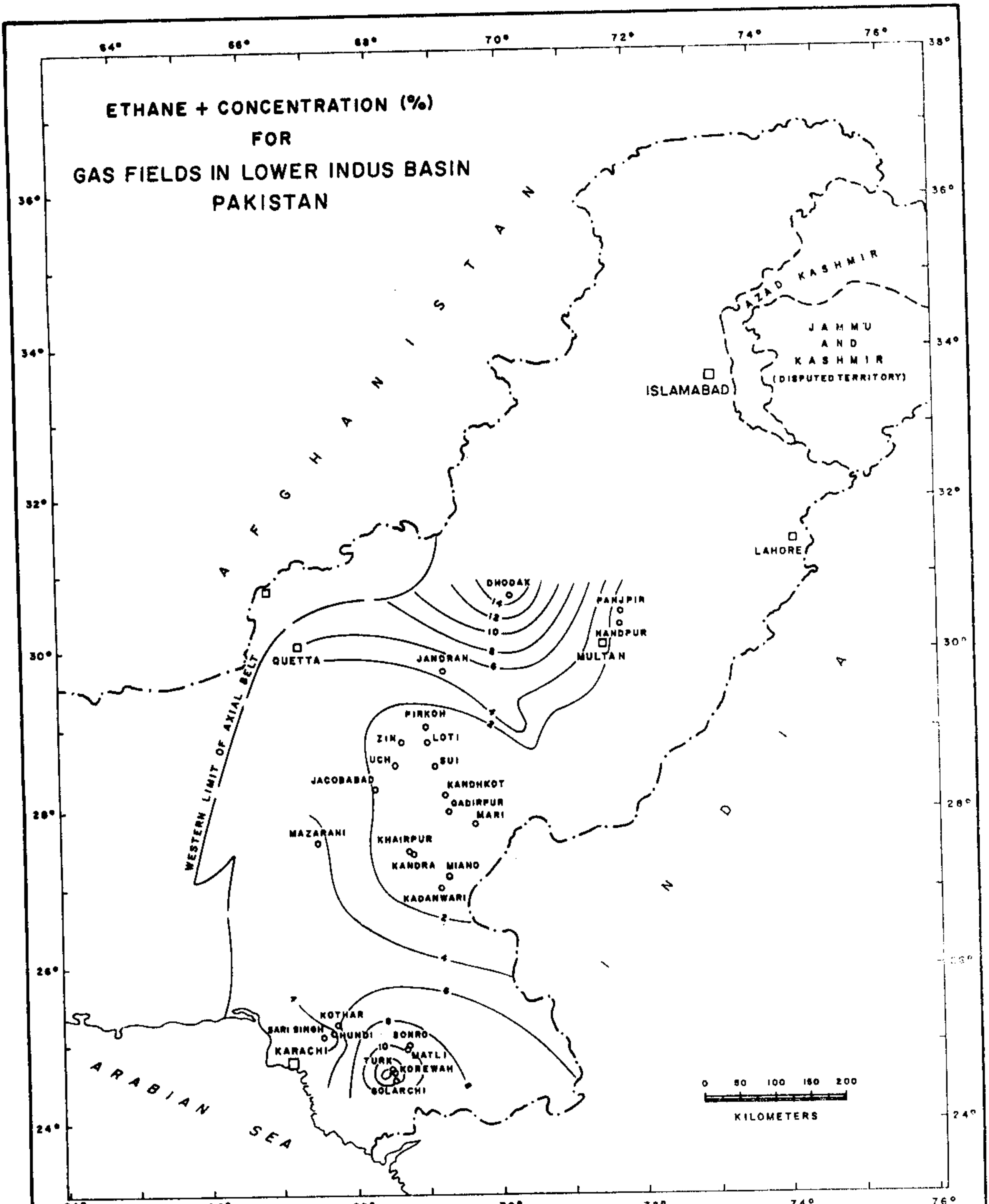

Figure - 19.5 Ethane + Concentration(%) (after Khan and Ahmad, 1992) concentration increases to the north (Dhodak 15.7%), west (Mazarani 4.7%) and south (Badin area up to 16%), which may be regarded as gas/condensate areas.

Analysis of Carbon and Hydrogen Isotopic Data

Usefulness of carbon isotopic data to determine the origin of gases has long been established. Origin of different gases have been determined with the help of Schoell's classification (1983). The isotopic and compositional variations in gases have been described in terms of i) processes during formation of gases such as bacterial degradation or thermal maturation and ii) processes during secondary migration.

Migration of gases does not significantly alter their isotopic composition as isotopic and compositional variations reflect processes during the formation of gases. Mixing of gases of different origin, however, may significantly alter the isotopic composition.

13C concentration of methane has been correlated with C2+ concentration, deuterium concentration of methane and 13C concentration of ethane, for different gas samples. Carbon and hydrogen isotope data indicate the gases to be of thermogenic nature.

Ethane plus (C2+) Concentration in Relation to 13C Concentration of Methane (13C1)

Fig. 19.6 is a plot of C2+ concentration against 13C1 concentration, where different fields symbolise various genetic types of natural gases. Three processes which affect the 13C1 and C2+ concentration – i) Maturation (both parameters), ii) Mixing (both parameters) and iii) Migration (C2+ concentration) – are considered.

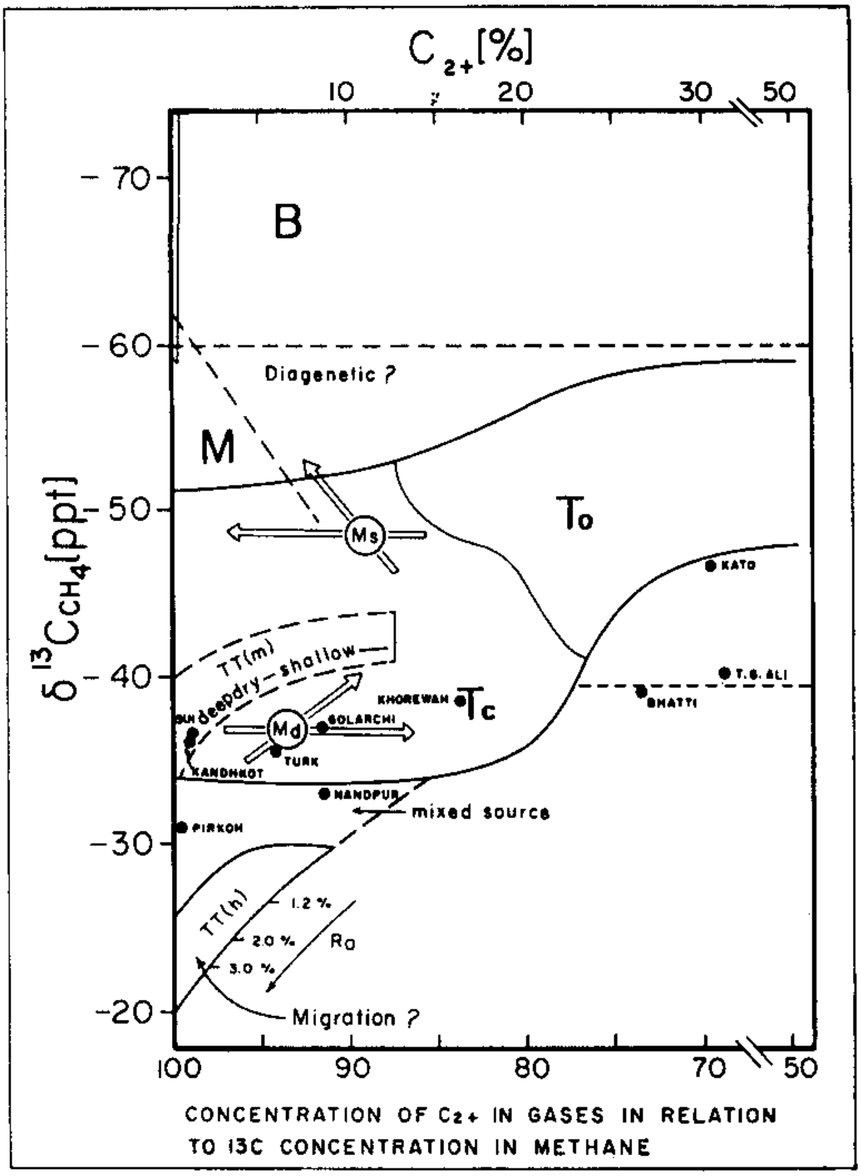

Figure - 19.6 Concentration of C_2+ in gases in relation to 13C Concentration in Methane

Associated gases (high C2+ concentration) may become depleted in their C2+ concentration during migration as these are stripped preferentially, while their concentration may remain the same.

Deep dry methane formed in the overmature zone may act as carrier for C2+ hydrocarbons. Such gases would be enriched in their wet content (horizontal arrow, Fig. 19.6). Shallow migration of gases result in depletion of C2+ concentration as these are removed preferentially during migration through less permeable and unconsolidated sediments, (horizontal arrow Ms, Fig. 19.6).

Plotting of different gas samples in Fig. 19.6 show that Sui and Kandhkot gases are of deep dry nature, derived from marine sapropelic source. Similarly Pirkoh and Nandpur are deep dry gases derived from a mixed source. Badin fields vary from non-associated gases with some condensate (Turk, Golarchi and Khorewah fields) to gases associated with oil (Bhatti, Tando Ghulam Ali and Kato fields).

Deuterium Concentration in Relation to 13C Concentration of Methane (13C1)

Fig. 19.7 is a plot of Deuterium concentration in relation to 13C1 concentration. Three primary genetic types of gases; biogenic, associated and non-associated, are recognised. Biogenic gases range in their Deuterium and 13C1 values from –150 to –250 parts per thousand (ppt) and –60 to –75 ppt respectively and have different values for marine and terrestrial source. Deuterium value of approximately –150 ppt is taken as the end of oil generation zone. In methane of dry non-associated gases, deuterium concentration increases with increasing maturity.

Plotting of different gas samples in Fig. 19.7, show Sui, Kandhkot, Nandpur, Golarchi, Turk and Khorewah gases to be of non-associated nature derived mainly from marine organic matter, with some humic input for Pirkoh and Nandpur gases. The hydrocarbon gases of Bhatti, Jamali and Tando Ghulam Ali fields are associated with condensate/oil.

Relation Between 13C Concentration of Methane and Ethane

Fields in Fig. 19.8 define the different genetic origin by the 13C concentration of methane and ethane. For cogenetic (compounds formed from same process and at same level of maturity of organic matter) methane–ethane pairs, ethane is 5–10 ppt enriched in 13C than methane. Mixing of gases of different origin affects the 13C of methane. If bacterial gas is added to thermogenic gas, the result would be depletion of 13C1 (arrow Ms, Fig. 19.8). Mixing of deep dry gas with associated gas would lead to enrichment of 13C1 (arrow Md, Fig. 19.8).

Plotting of different gas samples in Fig. 19.8 shows that all gases except Tando Ghulam Ali and Jamali are non-associated in nature, derived from marine source. Tando Ghulam Ali and Jamali gases fall in the mixed gas field.

Determination of Source Rock Maturity From Calculated Vitrinite Reflectance (Ro) Values

Experts have attempted to empirically relate the carbon isotopic values with the vitrinite reflectance (Ro) values, to determine the maturity of source rocks. The function derived by Faber (1987) appears to have better control for gases derived predomi-

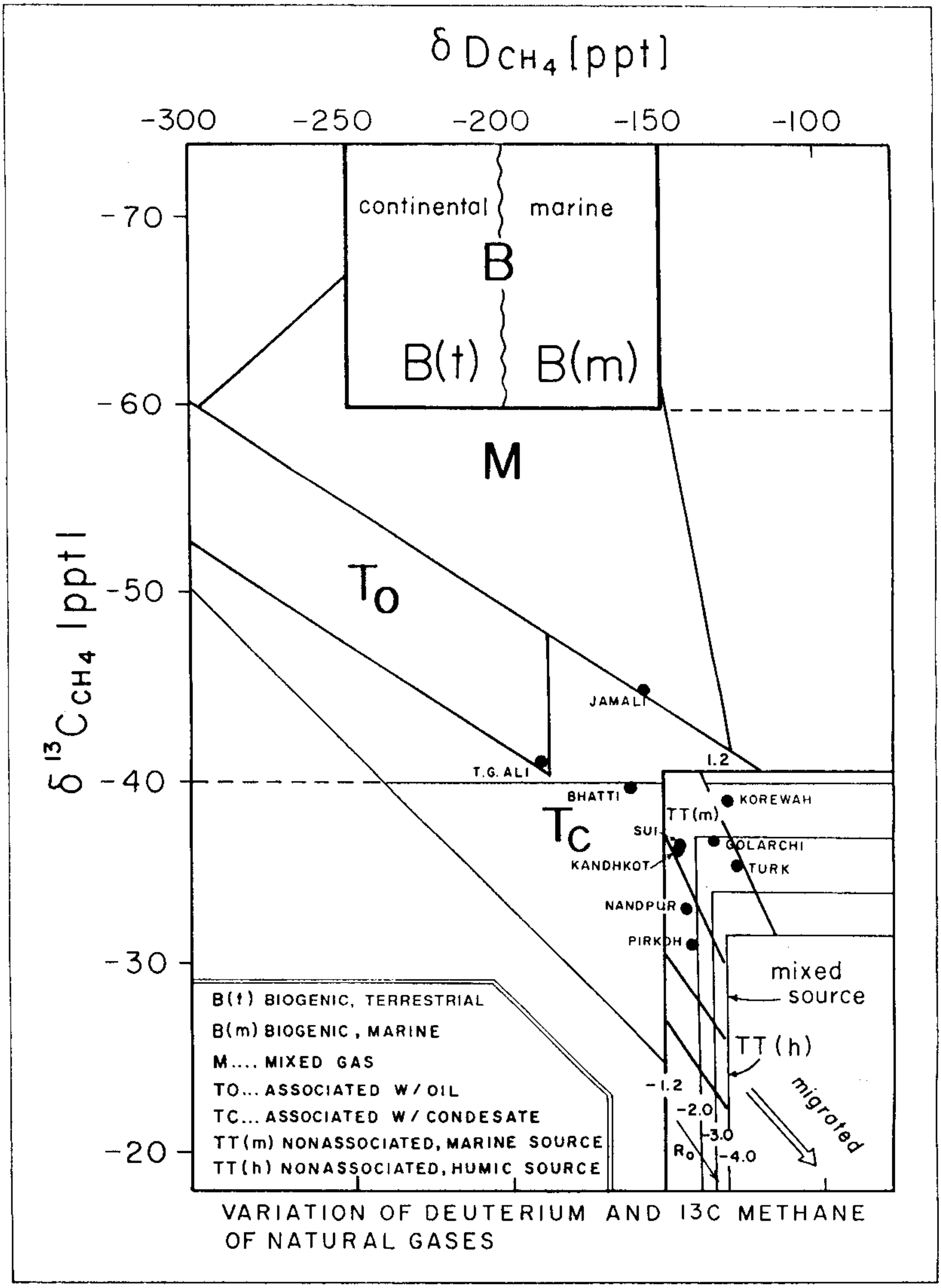

Figure - 19.7 Variation of Deuterium and 13C Methane of natural gases (Schoell, 1983) (after Khan and Ahmad, 1992)

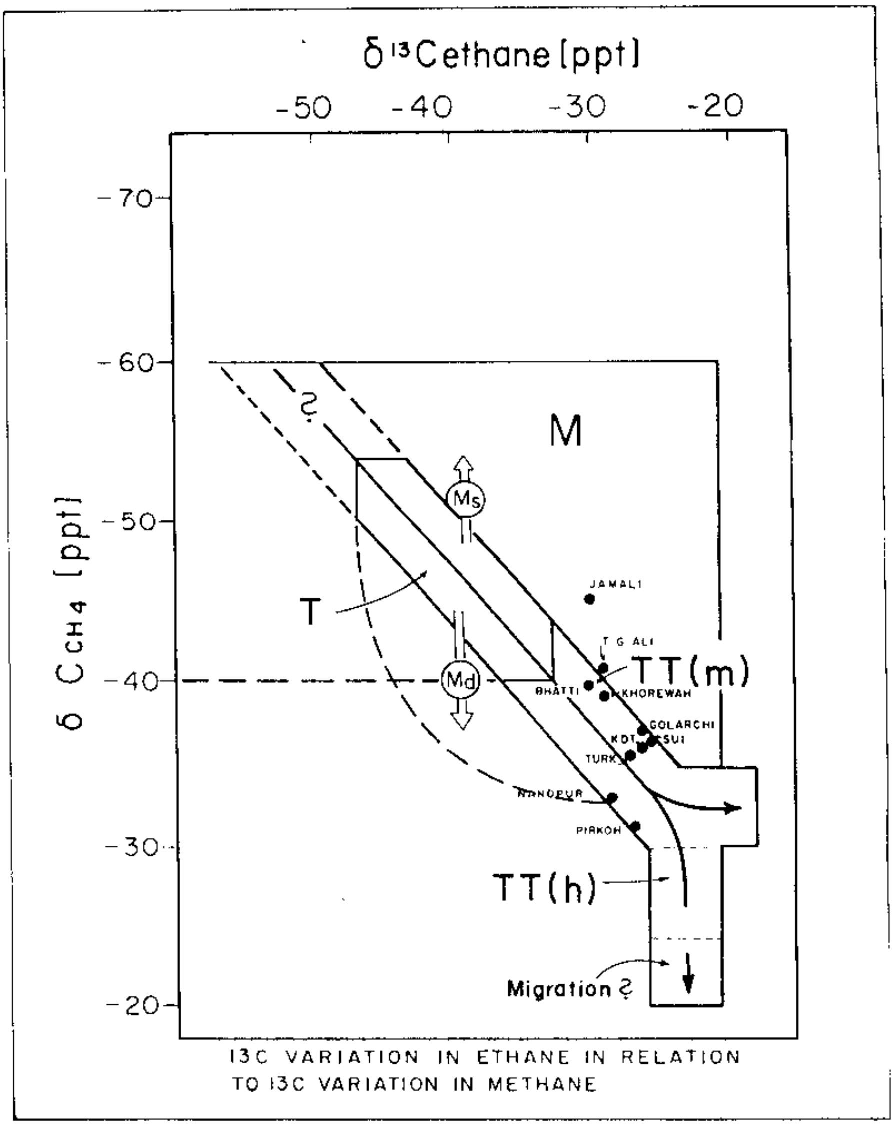

Figure - 19.8 13C variation in Ethane in relation to 13C variation in Methane (Schoell, 1983) (after Khan and Ahmad, 1992)

nantly from marine source. Calculated vitrinite reflectance values for methane, ethane and propane for some of the fields are listed as Table 19.1.

Calculated Ro values of Sui and Kandhkot gases indicate that methane and ethane were generated at more or less similar levels of maturity of the organic matter. Higher hydrocarbons were generated earlier at lower levels of maturity and migrated.

Ro values for Pirkoh and Nandpur gases indicate that ethane and higher hydrocarbons were generated at a lower level of maturity of the source rock, whereas the maturity at the time of generation of methane was much higher (Ro = 4.4 – 4.7% for Pirkoh and Ro = 3.4% for Nandpur).This could only mean that the source rock was buried deeper at the time of generation of methane.

Badin area gases (fields to the south) were generated at a lower maturity level than Sui and Kandhkot. Calculated Ro values for methane, ethane and propane show small variations, indicating a gently dipping kitchen area. The Ro values fall in the wet gas range.

Burial History Analyses

It has been established (Lopatin, 1971 in Waples, 1980) that there exists an exponential relationship between time and temperature in terms of hydrocarbon generation — increasing temperature by 10°C reduces the time required for hydrocarbon generation by 50%.

Burial history models for Sui (Fig. 19.9) and adjoining Trough areas, where the thickness of Mio-Plio-Pleistocene sequence could be up to 5,000 meters, are shown in Fig. 19.9 & Fig. 19.10 respectively. Sembar in the Sui area is over mature for oil generation and is at present in the gas generating

CALCULATED VITRINITE REFLECTANCE VALUES (Ro)

FIELD	RC 1	RC 2	RC 3
SUI	2 - 2.2	2.1 - 2.5	1.3 - 1.6
KANDHKOT	2.17 - 2.5	2.05	1.46
PIRKOH	4.4 - 4.7	1.7 - 2.0	1.4 - 2.1
NANDPUR	3.40	1.55	1.16
GOLARCHI	1.9	2.08	1.93
TURK	2.3	1.88	2.13

RC 1, RC 2, RC 3 { Calculated vitrinite reflectance value for the source rock that generated methane, ethane, and propane respectively.

Table - 19.1 (after Khan and Ahmad, 1992)

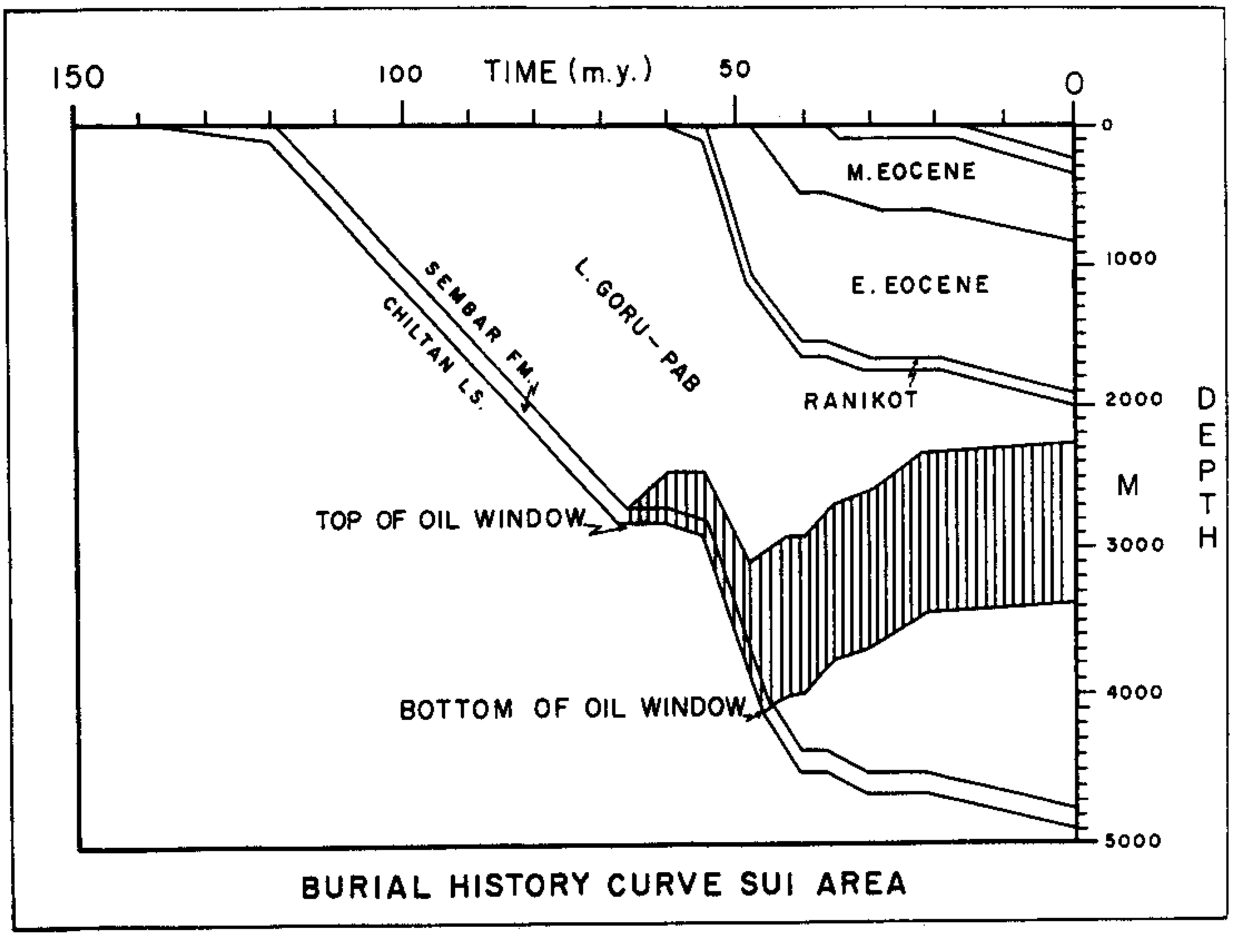

Figure - 19.9 Burial History Curve, Sui Area (after Khan and Ahmad, 1992)

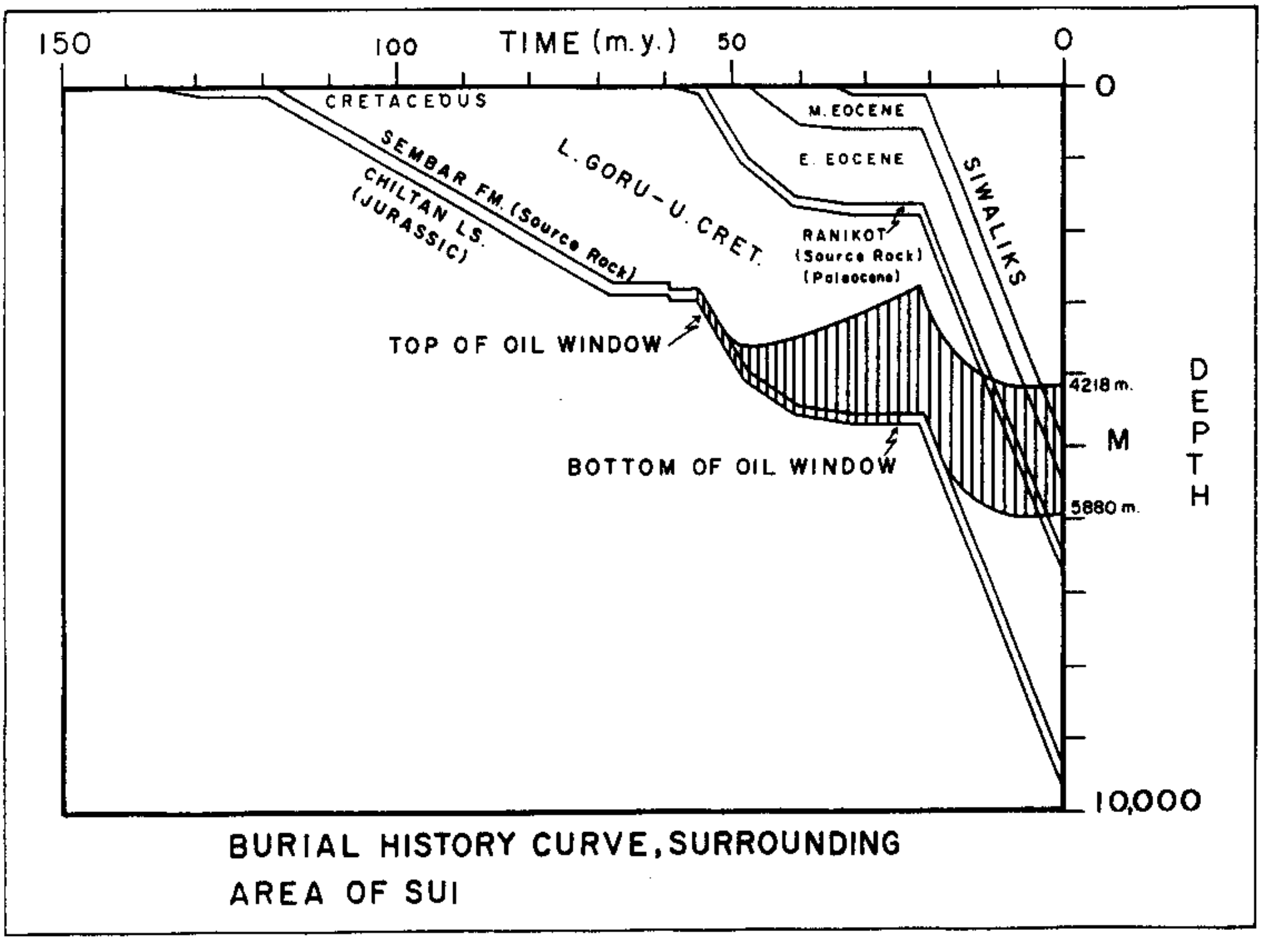

Figure - 19.10 Burial History Curve, Surrounding Area of Sui (after Khan and Ahmad, 1992)

stage. In the adjoining Trough areas, with a thick Siwaliks overburden of about 5,000 meters but a lower geothermal gradient than the Sui area, Sembar shales would still fall in the thermogenic gas generating stage.

Time Temperature Indices (TTI), worked out from the curves, match with the calculated Ro values from carbon isotope data. Thus, Sembar in the Sui and adjoining areas is in the dry gas generating stage.

SUMMARY

In conclusion plotting of carbon and hydrogen isotopic ratios for Sui, Kandhkot and Pirkoh and calculated vitrinite reflectance values suggest that these gases are deep dry or non-associated in origin. Low C2+ concentration and high methane concentration in these and other fields of the area also suggest that middle part of Lower Indus Basin is a dry gas region. Gases from Punjab Platform are similarly of deep dry origin, while Badin gases are generally associated in nature.

The organic matter is predominantly marine sapropelic with higher terrestrial input for Pirkoh and Nandpur (Punjab Platform) gases. Also at the time of generation of methane, the organic matter was buried much deeper at Pirkoh and Nandpur. To the south and north of the middle part of Lower Indus Basin, C2+ concentration increases, indicating that these are gas/condensate or associated gas regions.

Khairpur – Jacobabad High has played a dominant role in the distribution of associated non-hydrocarbon gases (carbon dioxide and nitrogen) with highest concentration near the apex.

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20
Drilling Conditions

The subsurface conditions in different basins of Pakistan vary considerably; this has necessitated evolving and adopting appropriate drilling policies to meet the operating conditions for drilling of exploratory and development wells to objective depths.

Planning of wells, monitoring of drilling operations, selection of 'kick' control procedures and wellbore integrity are critical factors for successful operations.

Broad guidelines, based on experience, have been developed with respect to size, type, grade and setting depths of casings, cementation techniques, type of drilling fluids and other drilling parameters to successfully meet specific operating requirements.

These guidelines have seen the test of times and can be followed for planning of wells in various basins.

The drilling practices in Pakistan have kept pace with the improvements in international technology over the years. Some of the earlier oil discoveries in the Potwar Basin, from the turn of the century to the fifties, were made with steam powered drilling outfits with such techniques as 'washing' of mud for removal of drilled solids and recovery of barytes by settling. Chinji (Miocene) clay/shale from nearby outcrops in the Potwar hills was commonly used for preparation of drilling mud. Blending of cement and additives was conducted manually in open ramps with shovels.

With timely acquisition of improved equipment, consumable materials, innovations in technology etc., deeper and difficult prospects have been drilled and tested and indeed further discoveries made. Most of the equipment and materials for exploration activities need to be imported as also specialised contract services. Costs and drilling time are of course functions of such variables as logistics, drilling conditions, depths etc.

Fig. 20.1 illustrates basin-wise relative density of exploratory / development wells. Basin-wise drilling record (1947–1993) is shown in Fig. 20.2 and 20.3.

POTWAR / KOHAT BASINS

To-date about 40 exploratory wells have been drilled in the Potwar/Kohat Basin since 1947. In most of the prospective areas, the depths to objective reservoirs in Eocene/Paleocene and Permian/Cambrian Formations range from 3,500 to 4,500 meters

The level of exploratory drilling has remained low due to difficult drilling conditions and relatively high cost.

The abnormally high formation pressures and reversal of pressure regimes in the Post-Eocene Siwalik Formations in Potwar provide a challenge of extremely difficult drilling conditions. Pressures close to geostatic have been encountered at shallow depths.

High pressure formation water inflows and heavy losses of circulation have led to premature abandonment of wells on account of collapsed casing, bridging, caving, cratering around the wells and internal/surface blowouts.

In the Eastern Potwar basin, rapid rate of deposition and quick burial, followed by uplifting and pressuring due to tectonic activity appear to be the major causes of abnormally high subsurface pressures. This is particularly true in the tightly folded and faulted structures. The abnormally high subsurface pressures encountered in some of the wells probably represent the residual hydrostatic 'fossil' pressures trapped in lenticular sand bodies dating from the time of deposition of the Siwaliks. This phenomenon may also partly be the expression of large tectonic stresses and forces of compression during the folding of the anticlines in this sub-Himalayan region. The sands perhaps were at slightly higher pressure than hydrostatic due to rapid rate of deposition and quick burial prior to uplifting. The undercompacted nature of shales in Chinji, Kamlial and Murree formations, as suggested by Sonic Transit Time well logs,

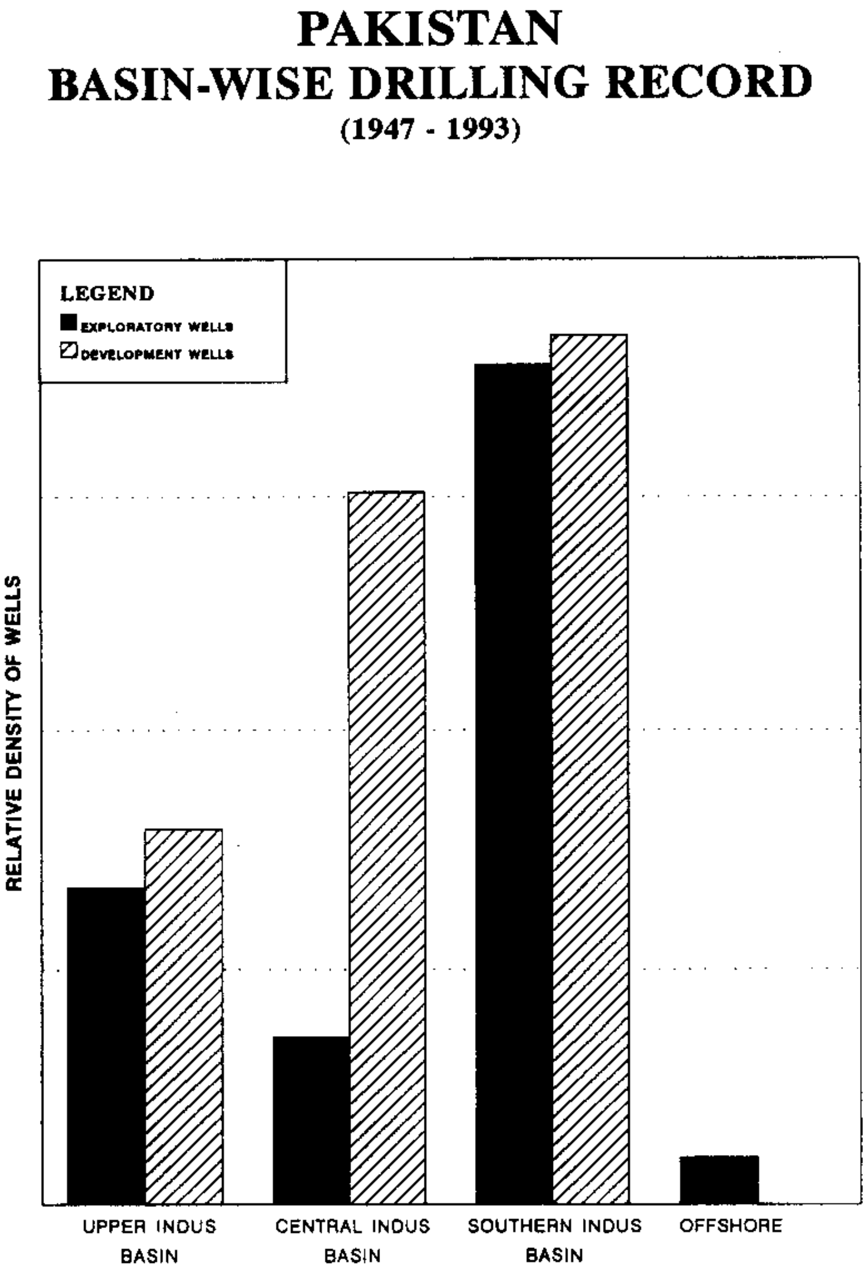

Figure - 20.1 Basin-wise relative density of exploratory and development wells

PAKISTAN
BASIN-WISE DRILLING RECORD
(1947 - 1993)

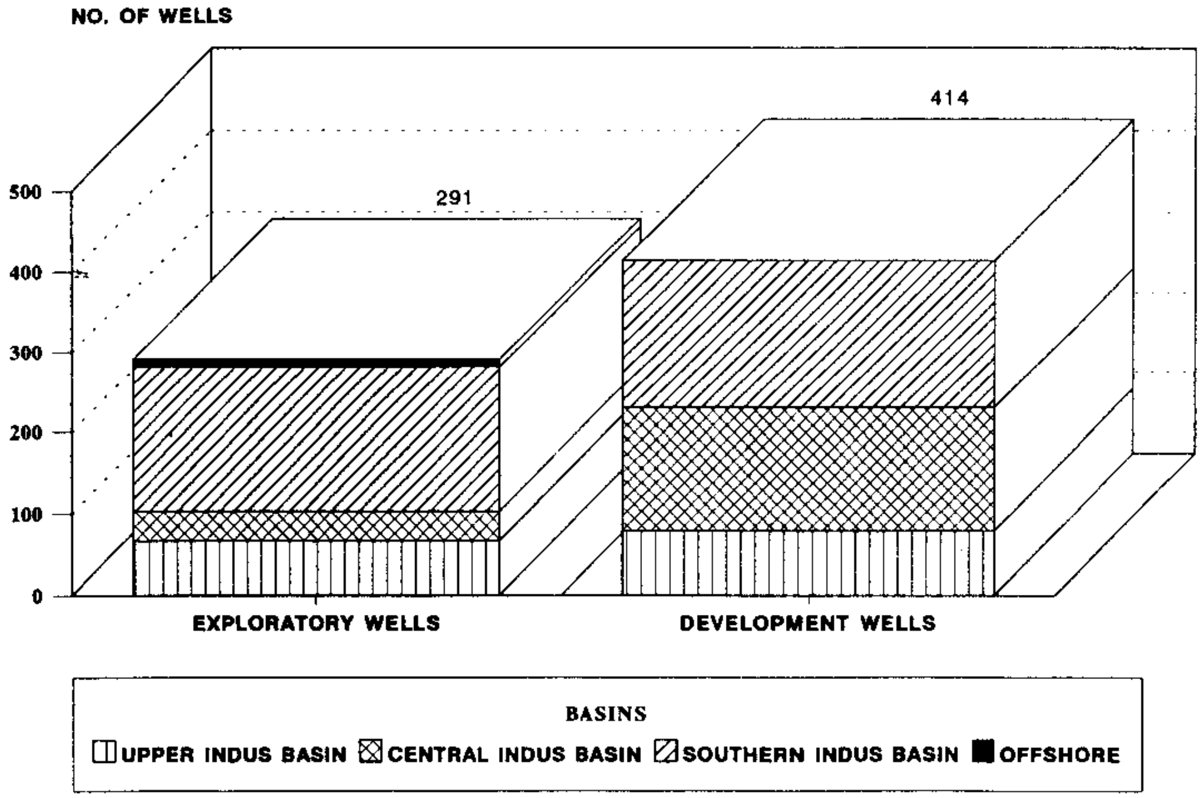

Figure - 20.2 Basin-wise exploratory and development drilling record

is also reflective of rapid rate of deposition and quick burial.

The phenomenon of reversal of pressure regimes and presence of sand bodies at relatively lower pressures, cause severe losses of circulation, and could be attributed to upward movement of fluid through faults or to depletion of these sand bodies through earlier abandoned wells left to flow formation water to waste at surface for several years.

It is extremely difficult to predict the depths of over-pressured zones in Potwar from the experience of already drilled wells, reason being the lenticularity or absence of correlation of sands between wells, combined with unknown displacement of sands along faults and varying behaviour of same sands in different wells. Study of regional variation of mud weights used to control the high formation pressures, however, does show a trend of severity of pressures increasing towards the eastern part of the basin.

The highest formation pressures have been encountered while drilling at the crest of the anticlines located in the eastern part of the basin.

Conventional pore pressure detection techniques, including measurement of shale density, drilling exponent, drilling rate and flow line temperatures are extensively used

PAKISTAN
INDUS BASIN
BASINWISE DRILLING RECORD
(1947 - 1993)

YEAR	EXPLORATORY WELLS				DEVELOPMENT WELLS				YEAR
	UPPER INDUS BASIN	CENTRAL INDUS BASIN	SOUTHERN INDUS BASIN	OFFSHORE	UPPER INDUS BASIN	CENTRAL INDUS BASIN	SOUTHERN INDUS BASIN	OFFSHORE	
1947	0	0	0	0	2	0	0	0	1947
48	0	0	1	0	3	0	0	0	48
49	0	0	0	0	2	0	0	0	49
50	0	0	0	0	3	0	0	0	50
51	1	1	0	0	3	0	0	0	51
52	3	0	0	0	2	1	0	0	52
53	0	1	0	0	5	0	0	0	53
54	0	0	0	0	2	4	0	0	54
55	1	1	0	0	1	0	0	0	55
56	3	0	4	0	1	0	0	0	56
57	4	0	5	0	2	0	1	0	57
58	0	2	9	0	1	0	0	0	58
59	3	1	3	0	1	0	1	0	59
60	0	0	1	0	2	1	0	0	60
61	1	0	1	0	2	0	0	0	61
62	0	0	0	0	2	0	0	0	62
63	3	0	0	1	0	0	0	0	63
64	2	0	0	2	2	2	0	0	64
65	1	1	1	0	1	2	1	0	65
66	1	0	0	0	0	2	7	0	66
67	0	0	0	0	0	0	0	0	67
68	2	0	0	0	1	2	0	0	68
69	2	0	1	0	1	0	0	0	69
70	0	0	0	0	2	1	0	0	70
71	1	0	1	0	0	1	1	0	71
72	0	0	1	2	2	0	1	0	72
73	0	3	0	0	0	1	1	0	73
74	0	3	1	0	2	1	2	0	74
75	0	4	1	1	1	1	0	0	75
76	0	1	0	0	1	2	0	0	76
77	2	1	0	0	0	1	5	0	77
78	1	0	0	1	0	1	3	0	78
79	2	0	3	0	2	1	0	0	79
80	1	1	1	0	3	3	0	0	80
81	3	1	3	0	3	4	9	0	81
82	2	0	2	0	5	5	4	0	82
83	3	0	6	0	2	8	1	0	83
84	1	4	15	0	2	15	7	0	84
85	3	0	13	1	1	22	37	0	85
86	0	3	8	0	2	20	31	0	86
87	2	1	9	0	1	13	9	0	87
88	4	1	17	0	0	2	7	0	88
89	3	1	17	0	3	11	21	0	89
90	4	0	11	1	0	12	11	0	90
1991	2	0	10	0	2	12	7	0	1991
1992	3	1	13	1	2	0	2	0	1992
1993	3	4	20	0	4	0	15	0	1993
TOTAL	67	36	178	10	79	161	104	0	

Figure - 20.3 Tabulation of year-wise exploratory and development drilling in different basins

for early detection of high pressures. Several papers have been published on the subject which provide a good account of the severity of the drilling problems encountered in Potwar Basin and possible solutions to handle the abnormal conditions (Kadri, 1991).

Fig. 20.4, illustrates the casing policies adopted in the East Potwar area to overcome the problems discussed above. More than normal number of casing strings starting with large diameter casing at surface and availability of 'trouble strings' provide the desired flexibility in handling these extremely difficult drilling conditions.

CENTRAL INDUS BASIN

The Central Indus Basin has been relatively more explored due to discoveries of natural gas in this area in the early stage (1952–60) of exploration in Pakistan. The depth to the main gas producing Tertiary carbonate reservoirs range from 2,000 to 3,000 meters. The depth to Cretaceous sandstone reservoir in the recently discovered natural gas fields range from 3,500 to 4,500 meters.

Severe loss of circulation of the drilling fluid in the fractured and porous gas bearing Tertiary carbonates (Sui, Kandhkot and Qadirpur gas fields for example) requires careful handling to avoid loss of rig time, damage to gas bearing reservoirs and even potential blow-outs. Loss of circulation has also been observed in the Cretaceous sandstone reservoirs.

DRILLING CONDITIONS

EAST POTWAR BASIN

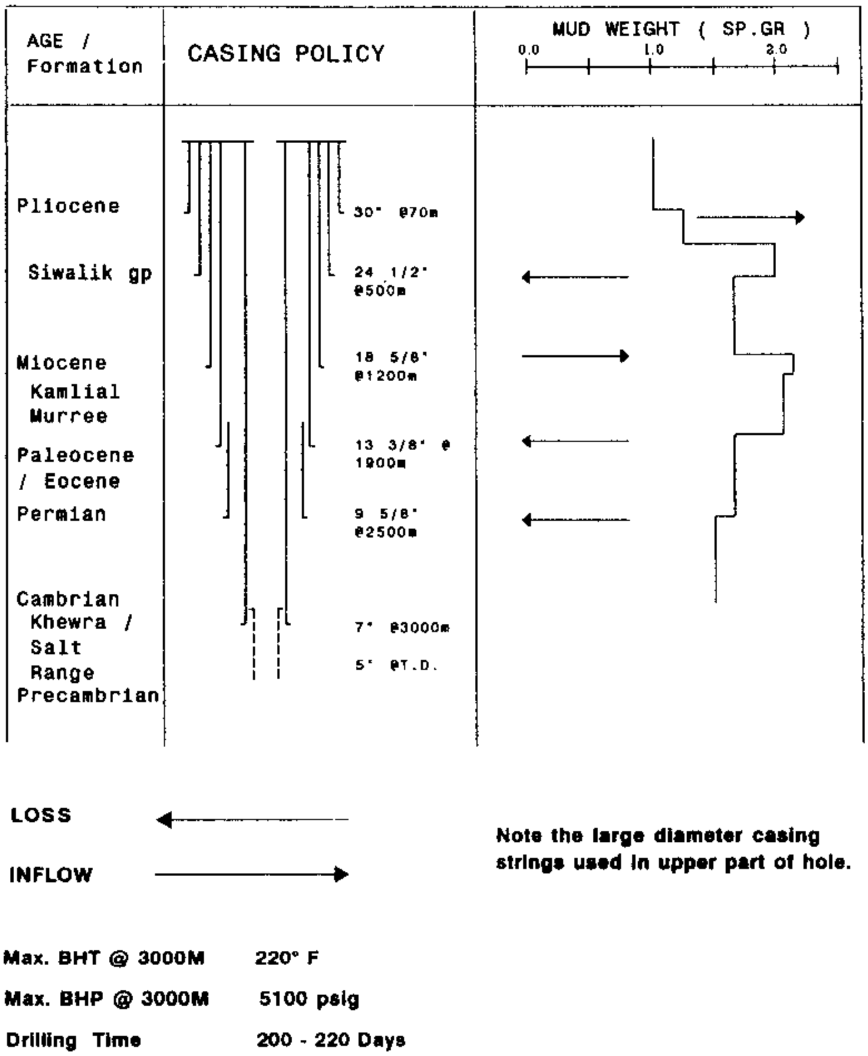

Figure - 20.4 Casing policy for a typical well in East Potwar basin

In the Southern part of the Central Indus Basin (Sui, Kandhkot, Pirkot region) abnormally high formation pressures have been encountered in the sand/shale sequence of the Goru formation in some of the exploratory wells. Heavy mud (1.8 sp. gr.) has been used to control the formation pressure. High pressure/temperature logging, testing tools and Blow out Preventors (BOP), are also required to handle the operations. Special mud and cement additives are necessary in view of the high formation temperatures associated with abnormally high formation pressure.

The high formation pressures in this region can be attributed to 'Aquathermal Pressuring'.

When a subsiding rock body gets isolated by the material of low permeability, the isolated system becomes one of constant density because fixed material is trapped in an essentially constant volume. The pressure and temperature of the sealed volume then will be related by one of the isodensity lines rather than by geothermal gradient at the expense of thermal expansion of water (Barker, 1972 and Khan, 1994, Fig. 20.5). If this phenomenon is coupled with hydrocarbon generation then the volume increases as a result of kerogen to bitumen (hydrocarbon) conversion and exerts extra pressure (this phenomenon is also accounted for the primary migration of hydrocarbon from source rock to reservoir rock).

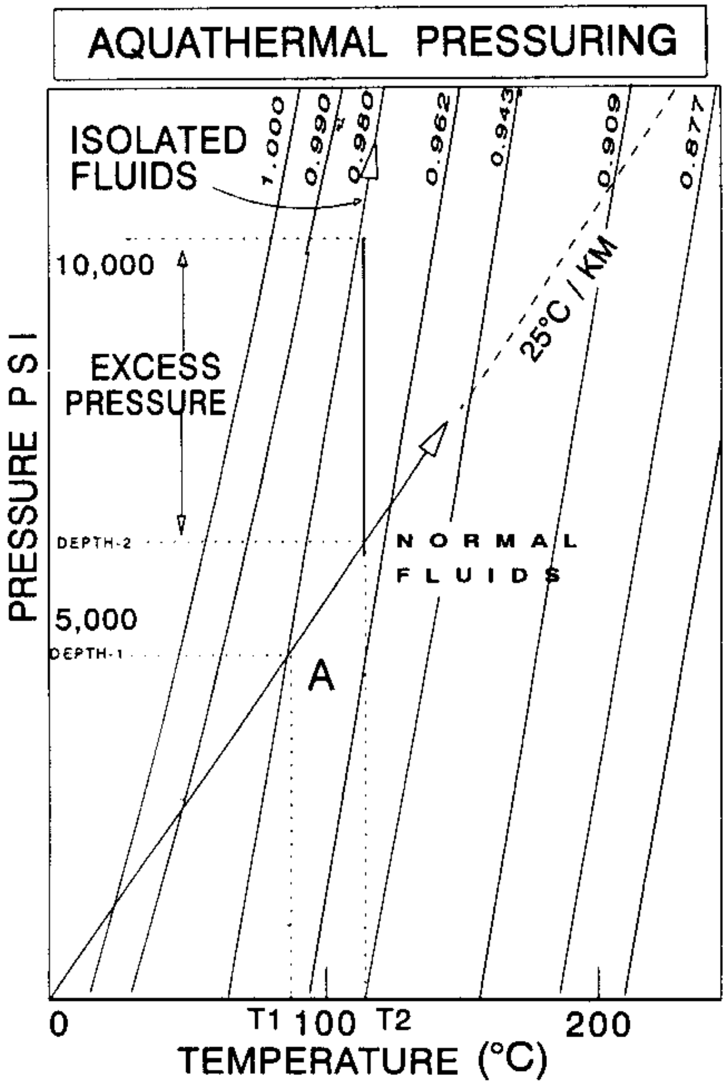

Figure - 20.5 Pressure - temperature - density diagram for water with super imposed geothermal gradients of 2.5°C/100m, showing P-T relation for normal and isolated fluids as temperature rises

In the southern part of Central Indus Basin, ideal conditions exist, for Aquathermal Pressuring i.e., there has been no indications of significant uplifting and outer shelf and slope sand/shale sequence seems to have been isolated at greater depth. Isolation is suggested by rise in geothermal gradient, lack of very good porosities/permeabilities, and presence of relatively fresher water at this great depth. Rise in geothermal gradient is accounted for by decay of radioactive elements present in clays and lack of effective dissipation of thermal energy as undercompacted and organic rich shales are usually not good conductors of heat. After isolation, pressure gradient follow the isodensity line and pressure increases abruptly by up to 5000 psi (Fig. 20.6).

Smectite to Illite conversion has also been contributing factor in this area as indicated by the presence of fresher water and huge thickness of 'clayey sediments' (Smectite to Illite conversion releases fresh water as much as 10% of the volume of the isolated sediment). This process needs temperature in excess of 100° C which have been recorded in the region.

Fig. 20.7 illustrates the typical casing policy for exploratory wells in Central Indus Basin.

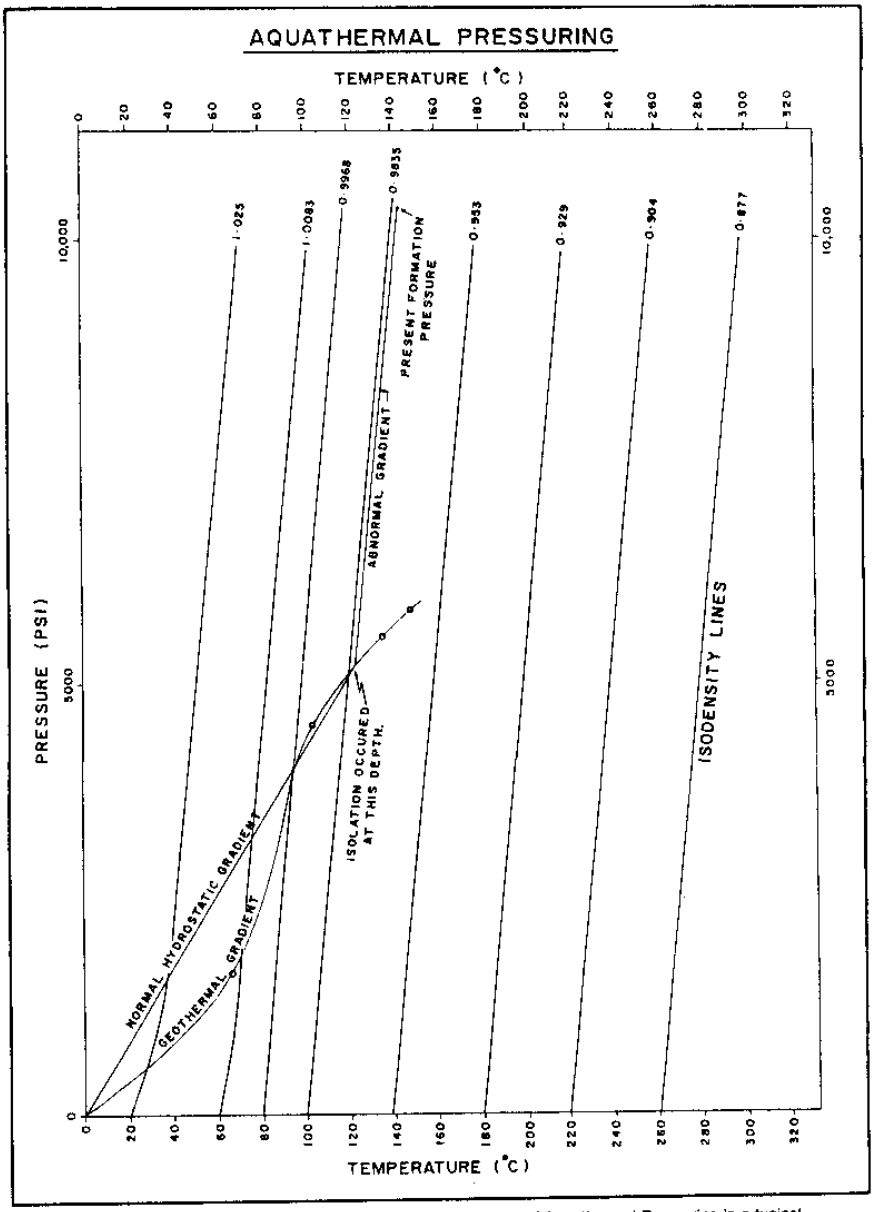

Figure - 20.6 Abrupt rise of pressure due to Phenomenon of Aquathermal Pressuring in a typical well in Central Indus Basin

ing conditions have been encountered in most wells. Drilling through the thick Cretaceous (Goru and Sembar) shales requires extra care. The shales tend to slough and cave-in. Frequent short trips in the shale section help to maintain good hole conditions. The exposed shales should not be allowed to remain uncased for long periods. Some of the Cretaceous sandstones (Pab) are quite abrasive and hard requiring proper bit selection to improve rate of penetration.

Fig. 20.8 Illustrates typical casing policy for exploratory wells.

OFFSHORE INDUS AND MAKRAN BASIN

Exploratory drilling in the Off-shore commenced in 1963 when Sun Oil drilled the first off-shore well. (Dabbo Creek-1, 4,354 meters) in the Indus delta with a jackup rig.

SOUTHERN INDUS BASIN

During the 1980s the Southern Indus Basin witnessed fairly accelerated exploratory drilling activity (Fig. 20.1 and 20.3) following the discovery of oil in Badin area. Until 1991, more than hundred exploratory wells had been drilled.

The depth to the Cretaceous sandstone reservoirs range from about 2,200 to 3,500 meters in most of the fields. No severe drill-

Only ten exploratory wells had been drilled, until early 1990s, in the off-shore area constituting about 240,000 sq. kms.

The depth to objective reservoirs up to the Cretaceous Formation in the Indus Offshore Platform range from 3,500 to 4,200 meters. However, wells drilled to similar depths in the deep Indus Depression and Makran Basin have penetrated sediments of Miocene/Oligocene age.

Drilling problems are mainly associated with high formation pressures and temperatures. The high pressures are associated with young Tertiary sediments of Miocene/Oligocene age. Mud weights higher than fracture gradient pressures have been used in some wells to control inflow of formation fluids. However, these problems can be overcome by adopting suitable casing design and setting depths. Conventional pore pressure prediction and detection techniques have been found to be fairly reliable in the off-shore region.

Special additives are essential to maintain desired mud properties in view of high mud weights and bottom hole temperatures.

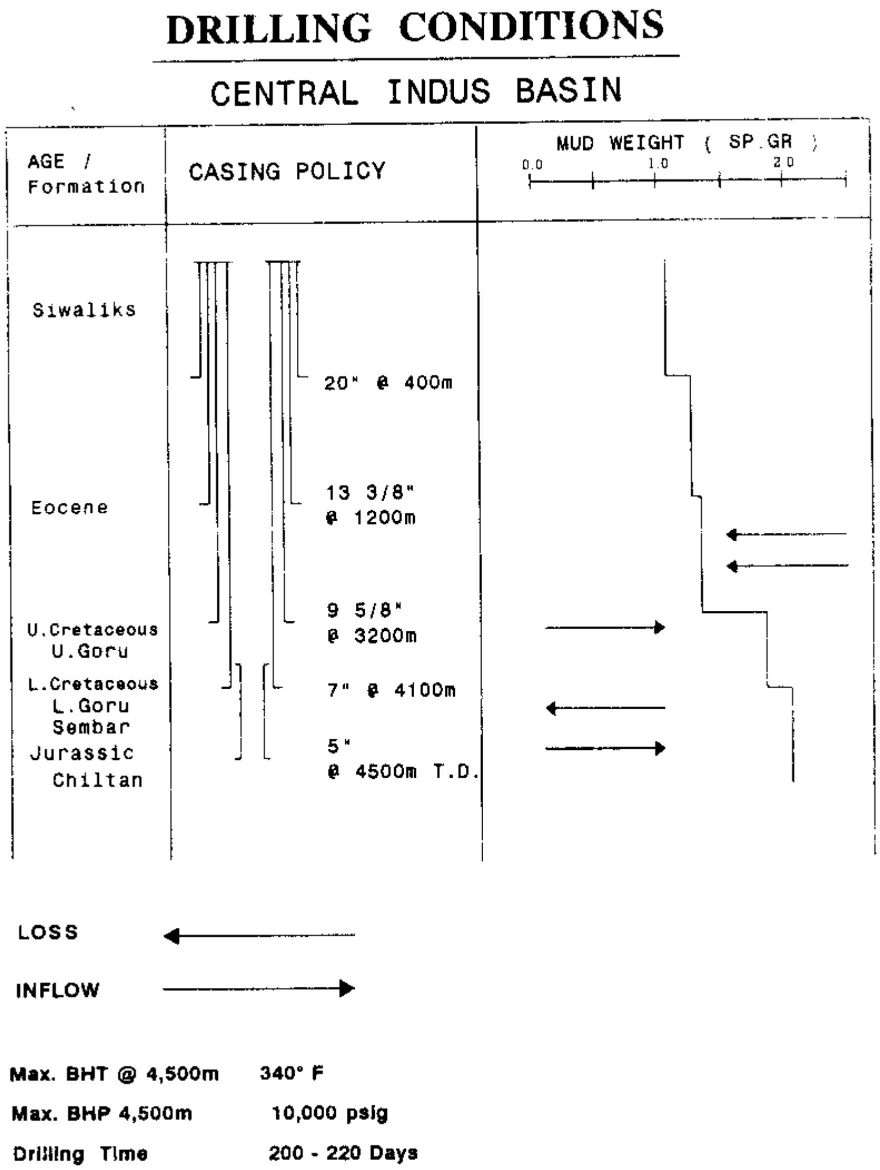

Figure - 20.7 Casing policy for a typical well in Central Indus Basin

In the Indus coastal/mangrove region, exploratory drilling has been conducted using jackup rigs. While drilling in this part of the Offshore special consideration is required to maintain safety of surface facilities and drilling rig in view of piling up of loose sand discharged by the Indus drainage system. During monsoon season deep scouring in the creeks and delta has been observed due to moving sands.

This can be a potential hazard for jack ups as it can cause the rig to tilt.

In the deeper wells of Offshore Indus and Makran Basin, conventional drilling equipment and facilities have been utilized successfully (Raza et al., 1990).

Fig. 20.9 Illustrates typical casing policy for offshore exploratory wells.

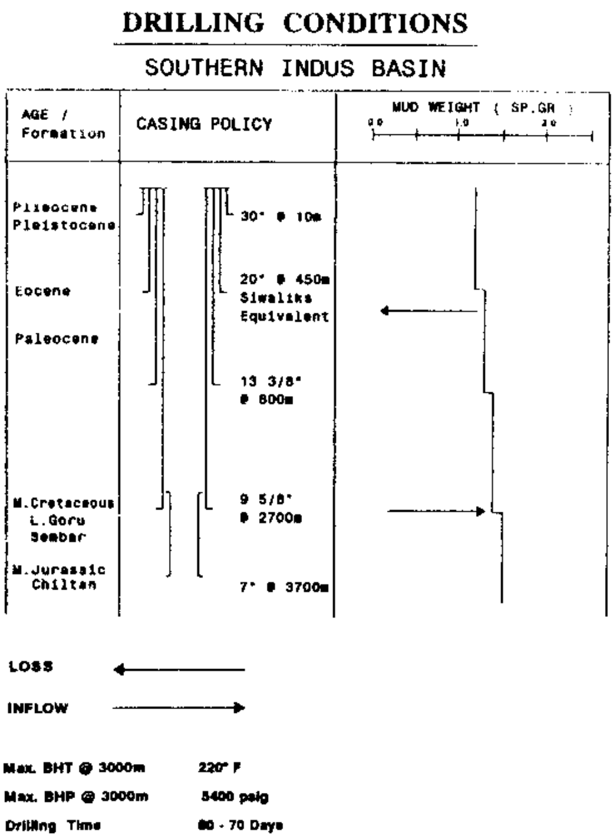

Figure - 20.8 Casing policy for a typical well in Southern Indus Basin

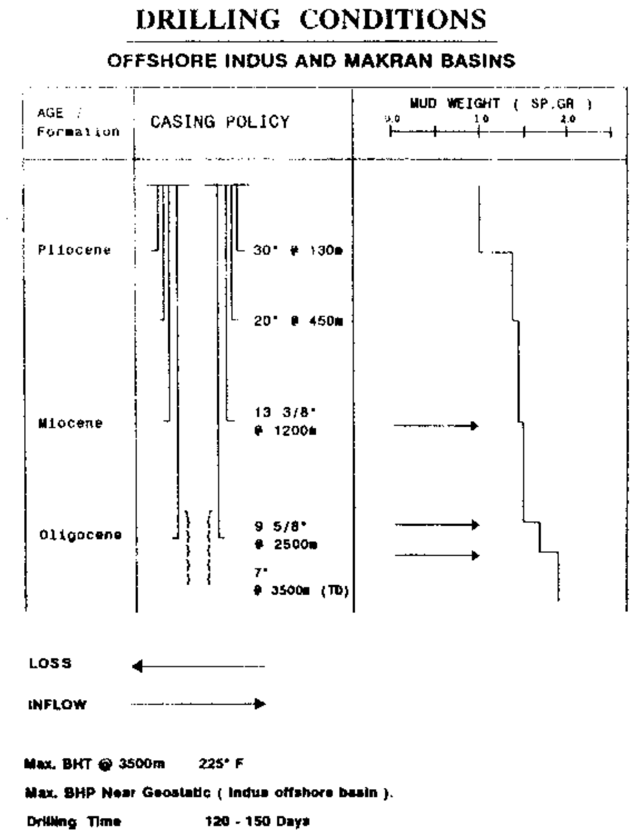

Figure - 20.9 Casing policy for a typical well in Offshore Indus and Makran Basins

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21

Structural Styles and Petroleum Plays

Pakistan is located at the junction of three main plate margins; the Indian, Eurasian and Arabian plates. The myriad style of structures reflect the evolution of Pakistan Sedimentary Basin.

These structures offer multiple petroleum prospects. The earlier exploration approach overlooked the dynamics of plate movement, hydrocarbon generation, migration and formation of traps in time and space for accumulation of hydrocarbons.

Structures in the Indus Basin exhibit fascinating array of styles resulting from compressional tectonics at the foreland margin, basement uplifts in platform areas and extensional tectonics in the Thar Platform extending up to Khairpur– Jacobabad High. The magnitude of structural deformation and crustal shortening is directly related to the intensity of compressive / tensile stresses, types of sediment and the proximity to the main areas of orogenic activity.

The development of new petroleum play concepts and their successful application in world's oil producing basins, led some of the major oil companies to explore for analogues in Pakistan which provide excellent opportunities of exploring for traps developed as a result of the interaction between the three main plates.

New petroleum plays, which are productive in various basins around the world, have emerged in several comparable areas of Pakistan in the last two decades (Fig. 21.1). These new play concepts have developed in the light of plate tectonics, better understanding of the tectonic framework of Pakistan, regional geological and geophysical studies, structural analyses and satellite imagery.

SOUTHERN INDUS BASIN

On the basis of structural styles, this basin can be divided into three segments i.e. i) Kirthar Fold Belt/Foredeep, ii) Thar Platform and iii) Offshore Indus.

Kirthar Fold Belt/Foredeep

Structures located in Kirthar Fold Belt/ Foredeep are related to compression and strike-slip movements of the western margin of the Indian Plate where significant amount of crustal shortening occurred against Eurasian Plate. Thrusted anticlines like Mazarani, Jhal, and Sanni are such examples. Intense structural deformation in Kirthar Range has resulted in deep seated thrusts. The sedimentary package from Cretaceous to Siwaliks is reportedly thrusted

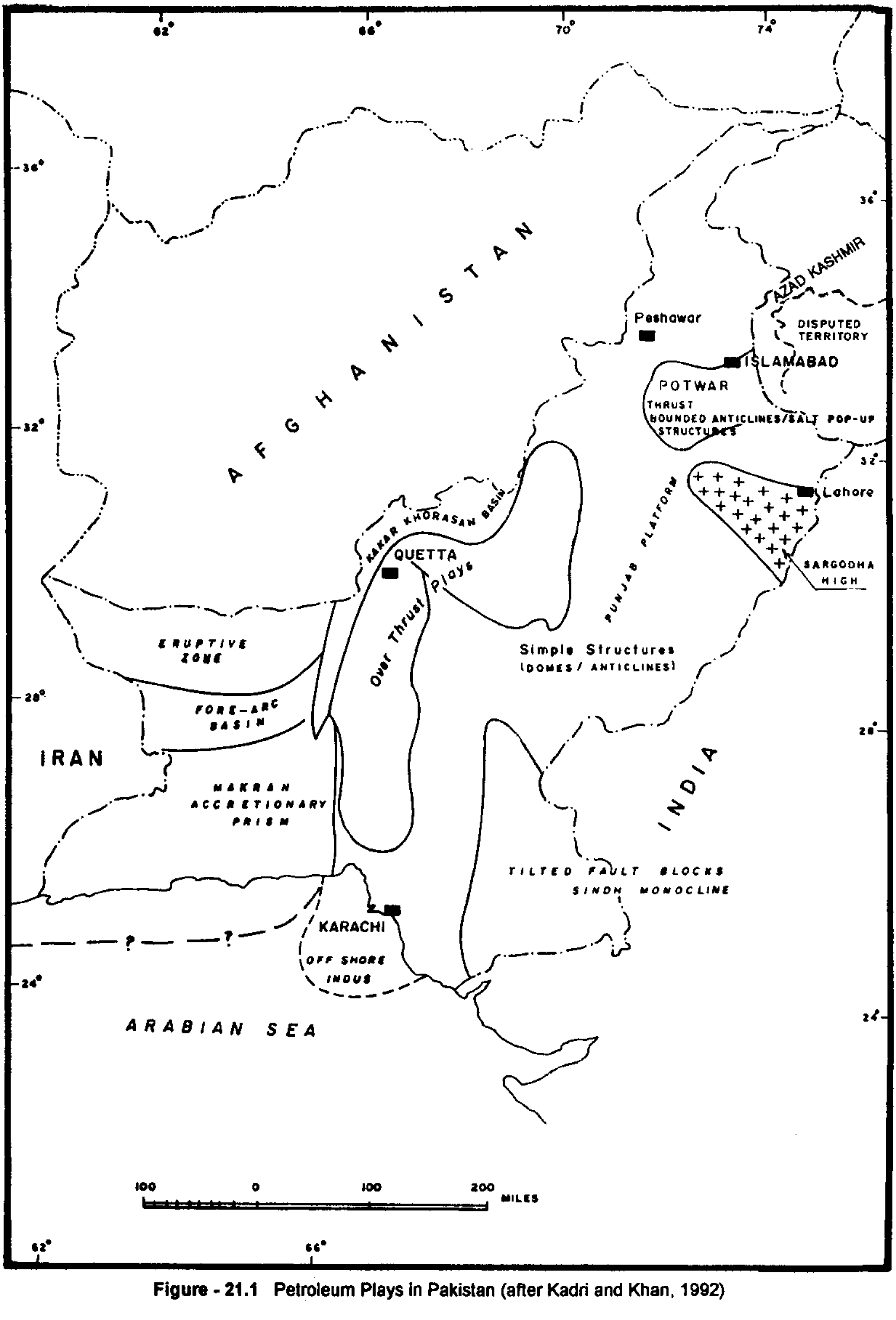

Figure - 21.1 Petroleum Plays in Pakistan (after Kadri and Khan, 1992)

over the Nari Formation of Oligocene age on the western flank of the Kirthar Foredeep.

Initially the tectonic regime in this region was believed to be related to the movement of Precambrian basement since Jurassic time. However, according to recent theories, crustal shortening is associated with overthrusting, giving rise to the formation of duplex structures similar to those in Wyoming over–thrust belt in the United States where world class petroleum reserves have been proven. There are hydrocarbon occurrences in overthrust belts of Wyoming (USA), Alberta (Canada) and Vienna Basin (Austria).

Delineation of structures in such tectonic setting require conceptual understanding, application of state-of-the-art seismic technology and basin modeling.

Thar/Badin Platform

After the discovery of Sui Gas Field in 1952 with recoverable reserves of more than 8 TCF, equivalent to about one billion barrels of oil, Pakistan's sedimentary basins attracted worldwide attention. The Lower Indus Basin was considered by some to be the mirror image of the prolific Arabian Basin (Fig. 21.2).

The search was, therefore, directed towards locating large structures in the Lower Indus Basin, considered to be a region of compressional tectonics. However, the exploration efforts were not successful as most of the seismic data was acquired on single fold analogue in an area where size of structures proved to be much smaller than anticipated. Today one would consider this seismic data acquisition technique to be a

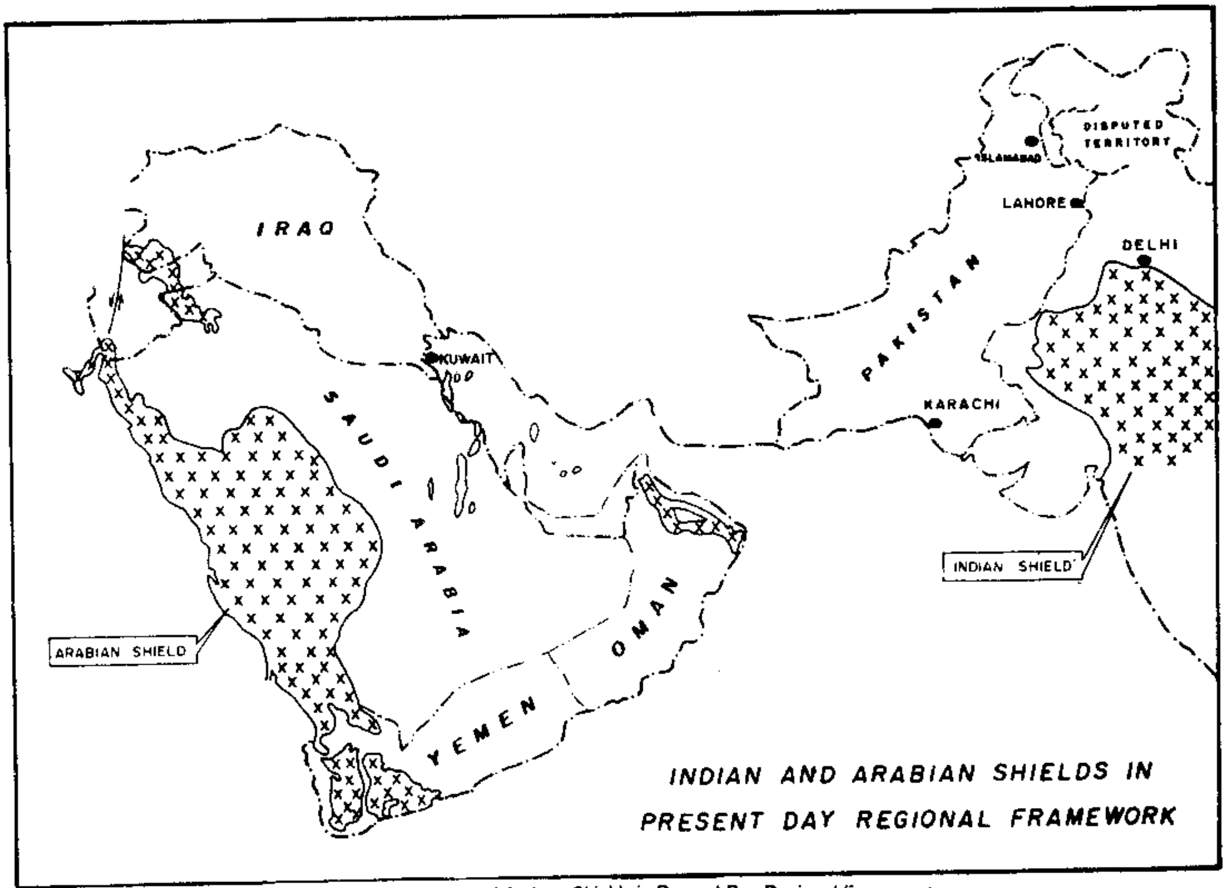

Figure - 21.2 Indian and Arabian Shields in Present Day Regional Framework

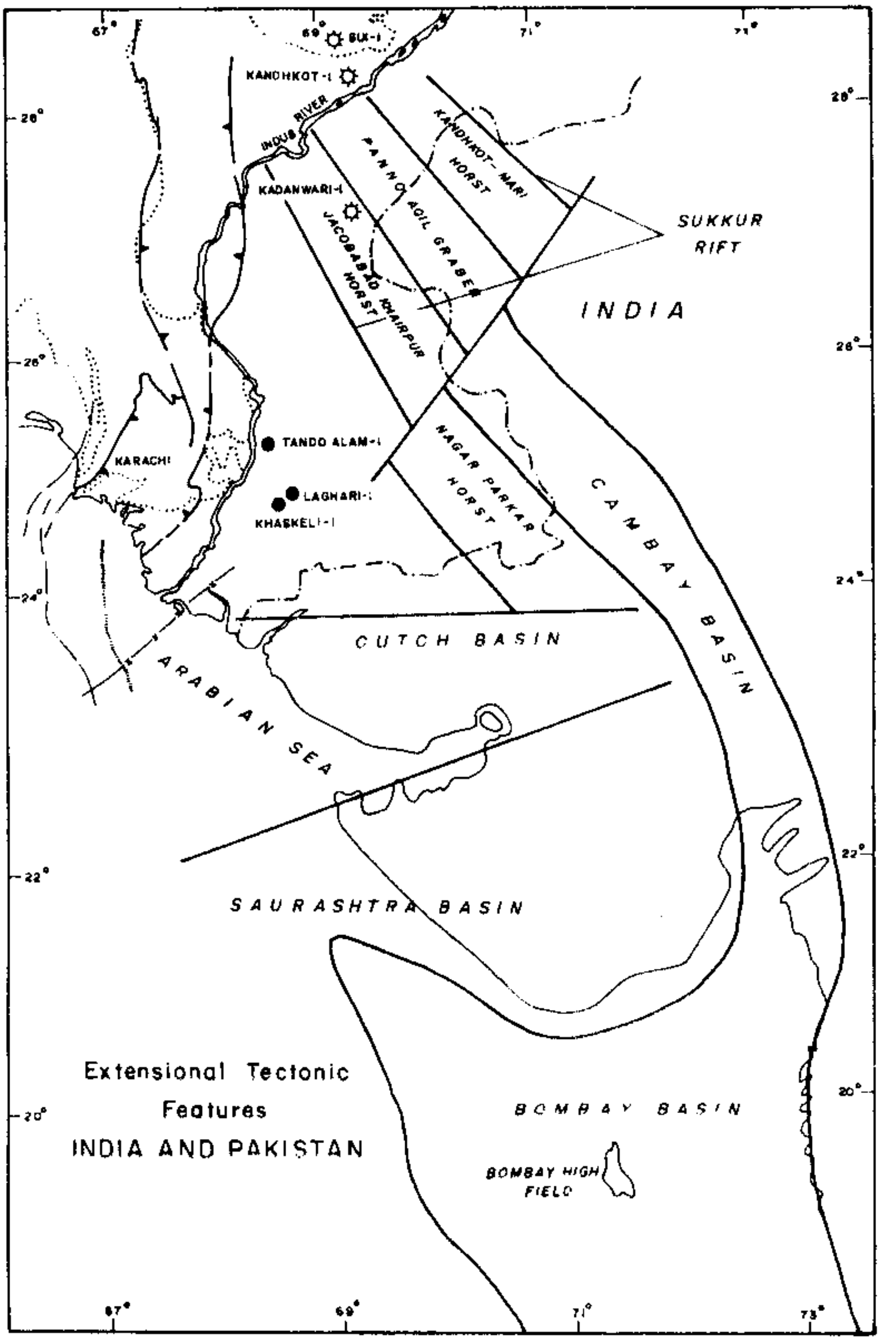

Figure - 21.3 Extensional Tectonic Features of India and Pakistan (after Kadri and Khan, 1992)

primitive tool. Presence of Paleocene basalts in the sub-surface in the southern part of Lower Indus Basin also added to the problem of seismic data acquisition and interpretation.

The Thar Platform, commonly known as Badin Platform, is now believed to be the continuation of the oil producing Cambay and Cutch Rift Basins (Fig. 21.3) of India which came into existence in early Cretaceous as a result of divergence of south western margin of Indian Plate. The extensional tectonics resulted in the formation of tilted fault blocks trapping hydrocarbons generated during Cretaceous.

The deposition of organic rich Sembar source rocks (Lower Cretaceous) took place while the basin was opening up and anoxia was prevailing. Subsequently rocks of Goru Formation were deposited, followed by extensional faulting and flow of basaltic lavas ('Deccan traps' equivalent) at the expense of continued marginal rifting. The continued rifting was responsible for the formation of structural traps. The generation and maturation of hydrocarbons was possibly assisted by heat flow from basaltic lavas.

Today (1992) this area is producing over 30,000 barrels of oil per day and 150 MMcfd gas, from Cretaceous sandstone reservoirs where the hydrocarbons are trapped in small faulted blocks. This basin was formed as a result of rifting, similar in style to Cambay and Cutch Basins.

Offshore Indus

Offshore Indus is a part of the passive Indian continental margin and represents two distinct tectonic (structure forming) episodes and three types of traps i.e. the Thar Platform tilted fault blocks formed during Lower Cretaceous, the Eocene carbonate build-ups over the shelf edge, Post-Eocene growth faults, roll-over anticlines and subtle traps in the fan and deltaic sediments. These features have been identified on the basis of seismic data. (Fig. 21.4).

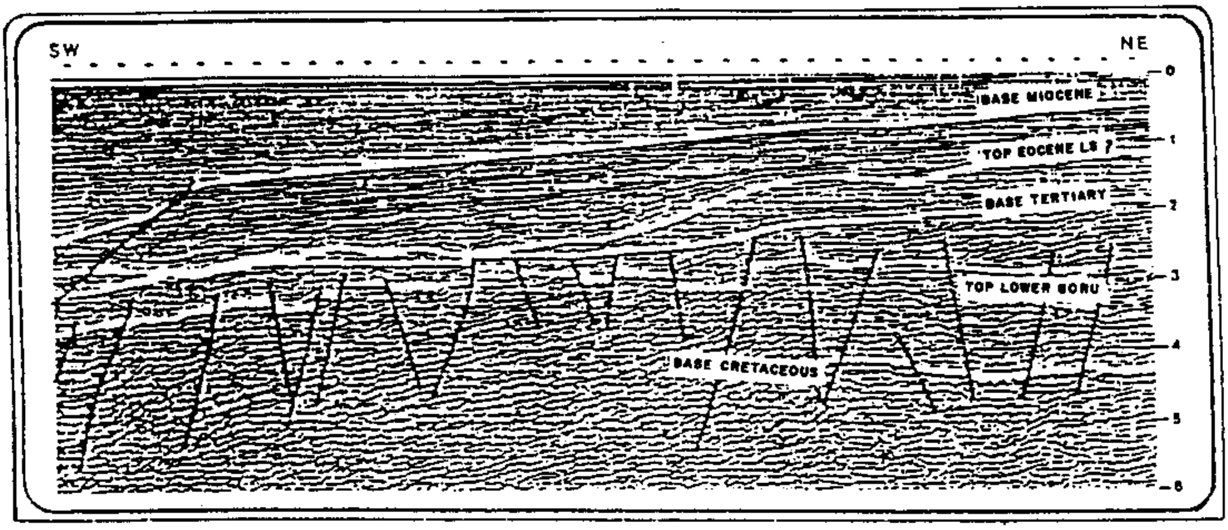

Figure - 21.4 Offshore Indus Structural Style (after Soulsby and Kemal, 1988)

The Offshore Indus Delta region is believed to be analogous in its structural style and stratigraphy to many of the Tertiary oil producing deltas, e.g. Mahakam Delta (Indonesia) and Niger Delta (Nigeria) etc.

Indus Delta/Fan is one of the largest in the world. The Fan has a length of about 1,500 km and a maximum width of 960 km (Kolla & Coumes, 1987). It has a sedimentary thickness of more than 7,000 meters (McHargue & Webb, 1986). This sedimentary package contains various source/reservoir facies with sufficient overburden for source rock maturation.

CENTRAL INDUS BASIN

This basin is very important in terms of its natural gas yield. To-date (1993) about 25 Tcf original recoverable gas reserves have been discovered in 13 fields. The structures present in this basin were formed as a result of basement uplift (e.g. gentle domal structures like Khairpur, Kandhkot, Mari etc.) and compressional tectonics (e.g. Inner and Outer Sulaiman folded zone). These range from simple dome (Sui) to very complex duplex types (outer folded zone).

Sulaiman Fold Belt

Similar to Kirthar Fold Belt, Sulaiman Fold Belt represents the thin skinned tectonics where the rigid basement is not playing any major role. The sedimentary cover becomes imbricated due to severe compression and its intensity increases northwards of Sui. (Fig. 21.5).

West of Sulaiman Depression the wrench component also becomes significant in the north-south oriented Sulaiman Range. Similar to Kirthar Fold Belt, duplex structures are expected in the northern part of

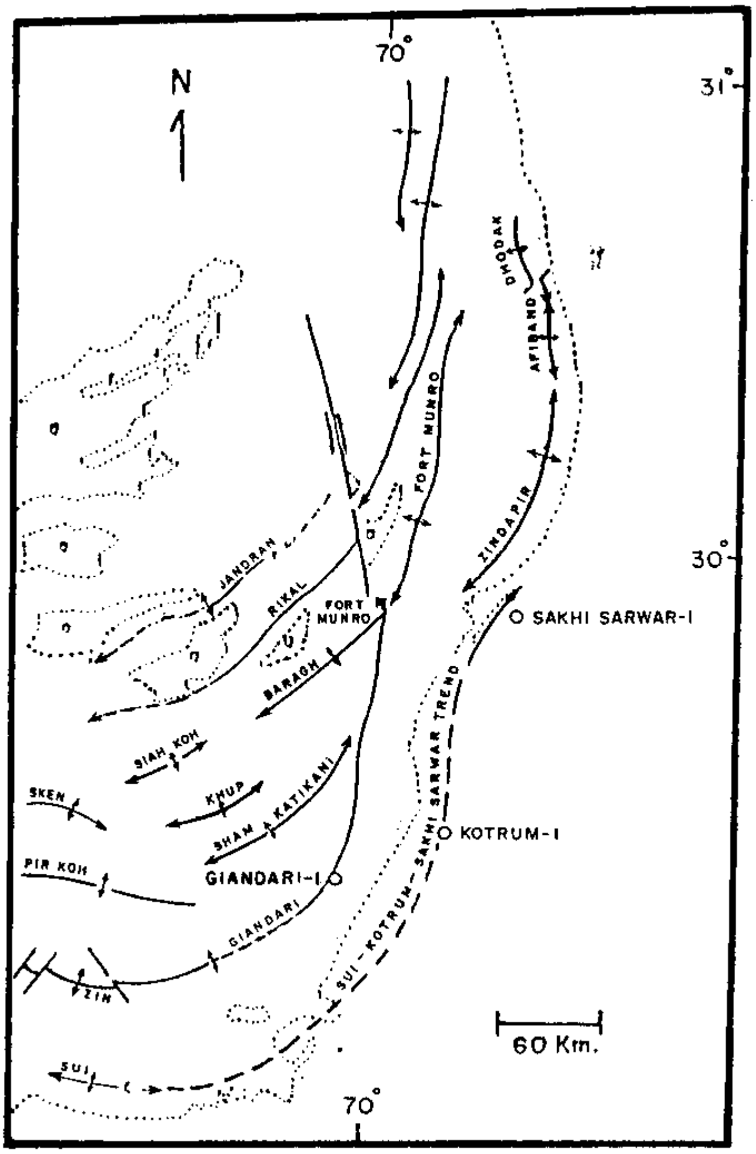

Figure - 21.5 Sulaiman Fold Belt

Sulaiman Range also (Fig. 21.6)

The arcuate nature of Sulaiman Range and the large fold wave length in the south (i.e. Sui, Uch, Zin etc.) indicate that this range slid over a decollement in a similar way as its analogue in the north; the Salt Range. Structures in Sulaiman Fold Belt become simpler and younger towards the periphery of the arcuate belt.

It can be summarized that the Sulaiman Fold Belt represents compressional and strike-slip tectonics.

Punjab Platform

In the seventies, the Punjab Platform area was explored on the basis of the so-called 'Oman Model' which envisaged salt related dynamics, affecting Paleozoic strata, for structural closure.

This argument was based on the fact that in Precambrian time, the Indian shield along with African/Arabian shields was part of the super-continent, Pangea, located much to the south. Reconstruction of Pangea during the Precambrian indicates that the northern and north-western margins of these shields were characterized by evaporitic (salt/anhydrite) basins. This is confirmed by the presence of Precambrian evaporitic sequence (Salt Range Formation) in Potwar and Punjab Platform and a similar evaporitic sequence (Huqf Group) of the same age with suitable combination of source and reservoir rocks in the oil producing basin of Oman. Fig. 21.7 shows the stratigraphic onlaps of Cambrian and Permian against Infra-Cambrian Shield; Fig. 21.8 shows the erosional truncation of Permian against Siwaliks in Punjab Platform.

UPPER INDUS BASIN

For the purpose of classification of structures, this basin can be divided into Kohat Plateau/Eocene Salt Zone, Bannu Depression, Main Boundary Thrust and the Potwar Plateau.

The Main Boundary Thrust (MBT) is taken as a safe definable northern boundary of structural style manifested in the

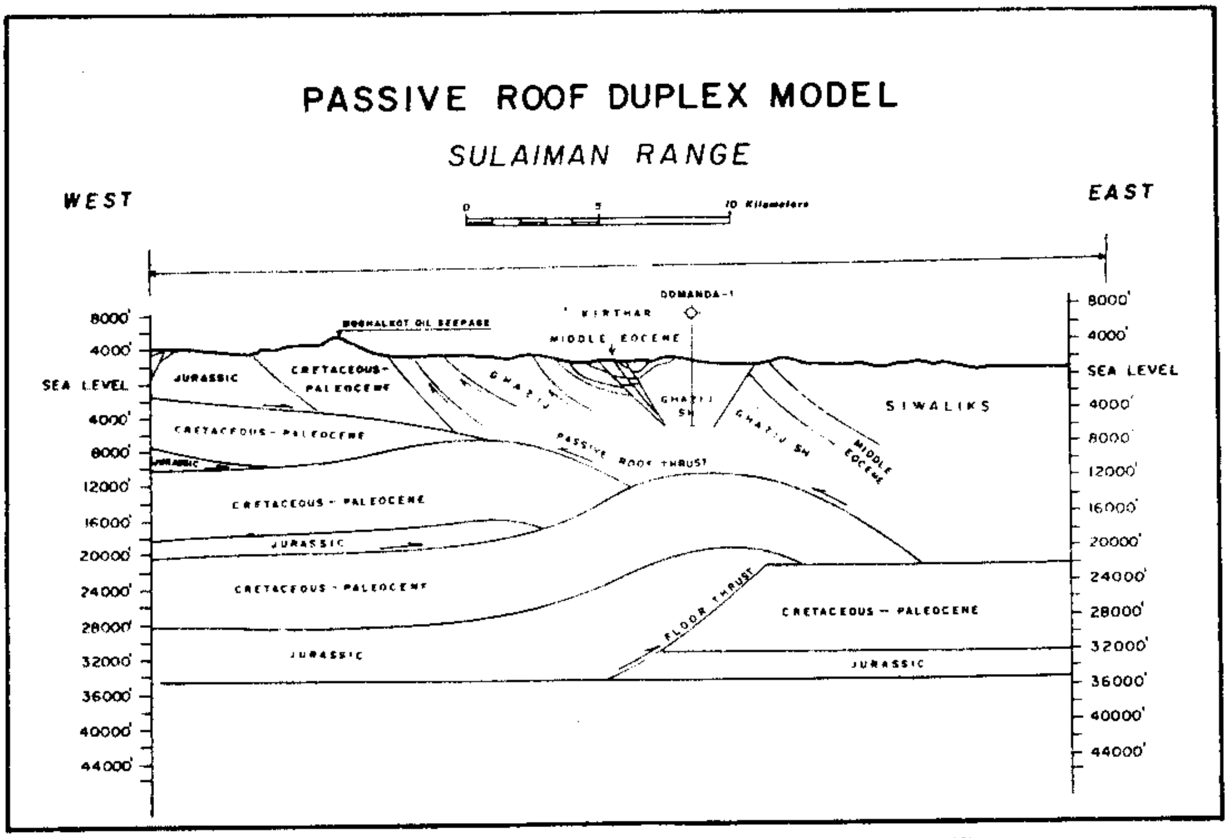

Figure - 21.6 Passive Roof Duplex Model, Sulaiman Range (after Kadri and Khan, 1992)

Upper Indus Basin. The deformation near MBT started in early Miocene and propagated southward to give rise to Kohat/ Potwar plateaus and Trans-Indus/Salt

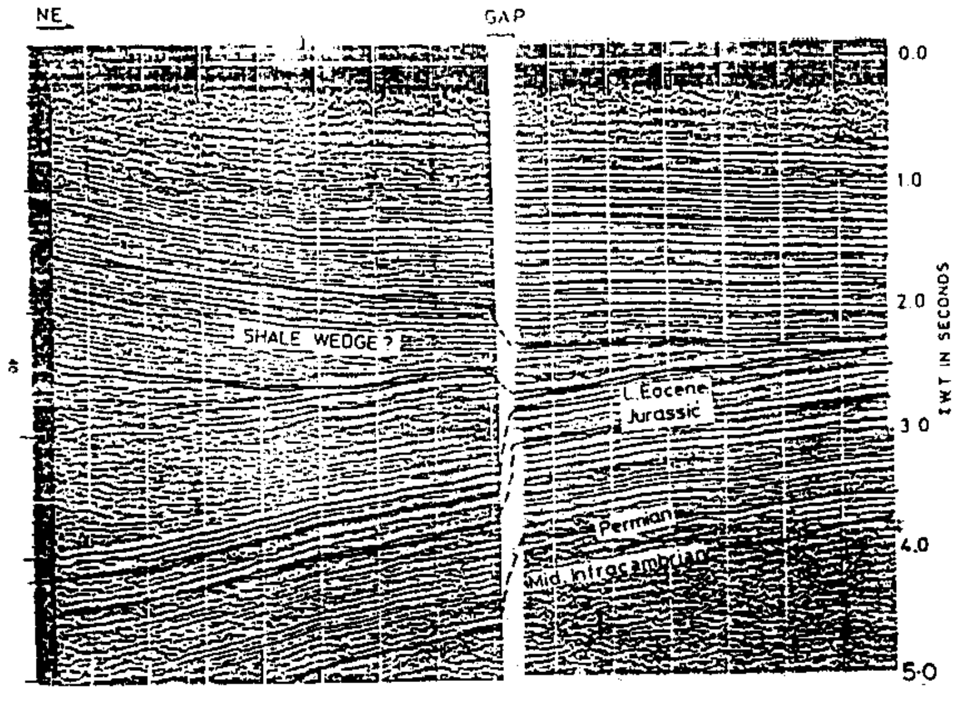

Figure - 21.7 Seismic Profile showing westerly dip of rock units and their thinning out towards east in central Punjab Platform (after Raza et al, 1989)

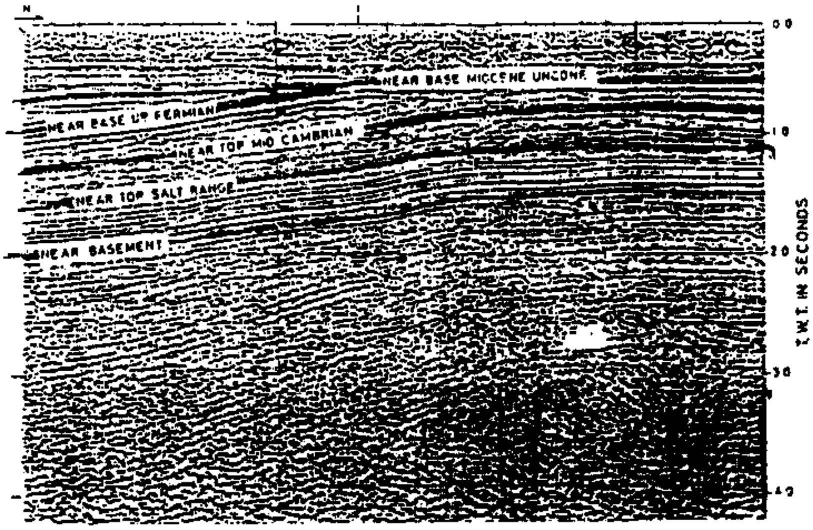

Figure - 21.8 Seismic Profile showing truncation of Permian Strata against Molasse unconformity in Punjab Platform (after Raza, 1989)

ranges. The deformation as young as 0.4 Ma has been documented in the Salt Range.

The present day course of river Indus appears to divide open marine environment observed in the Eocene formations of Potwar to the east from the restricted depositional environment of Eocene Kohat basin in the west.

Kohat Plateau/Eocene Salt Zone

Kohat Plateau exhibits the structural style related to thin skinned tectonics typical of the plastic strata. Since the Eocene in this region is represented mainly by evaporite sequence (Jatta Gypsum, Bahadurkhel Salt) and shale/claystone sequence (Panoba Shale, Mamikhel Clay), they tend to flow like toothpaste under severe compression. This phenomenon is evident on surface structures where the fold strikes are seen to be curving irregularly (e.g. Nandrakki, Shakardarra, Latambar, Bahadurkhel etc.).

Seismic lines extending from Kohat city across the Kohat Plateau into the northern Kalabagh Fault zone, were interpreted by McDougall & Hussain, 1991. These lines indicate that there are at least two detachment surfaces; one within Eocambrian Salt Range Formation and the other in the Tertiary plastic sequence to give rise to the southward verging duplexes. (Fig. 21.9)

Bannu Depression

Bannu Depression is surrounded by Kohat Plateau/Eocene Salt zone in the north, Surghar and Khisor/Marwat ranges in the east and southeast, Pezu/Bhittani Range in southwest and by Kurram Fault in the west. This depression was formed due to the southward thrusting of Trans-Indus ranges thus giving rise to extensional movements and formation of fault related traps in Mesozoic sediments (seismic evidence). Severe thrusting and wrenching is also observed in Pezu-Bhittani Range, Marwat Range and Sheikh Budin Hills (Pezu uplift).

Potwar Plateau

Potwar Plateau is bounded by the Kala-Chitta and Margalla Hills to the north, the Indus River and Kohat Plateau to the west

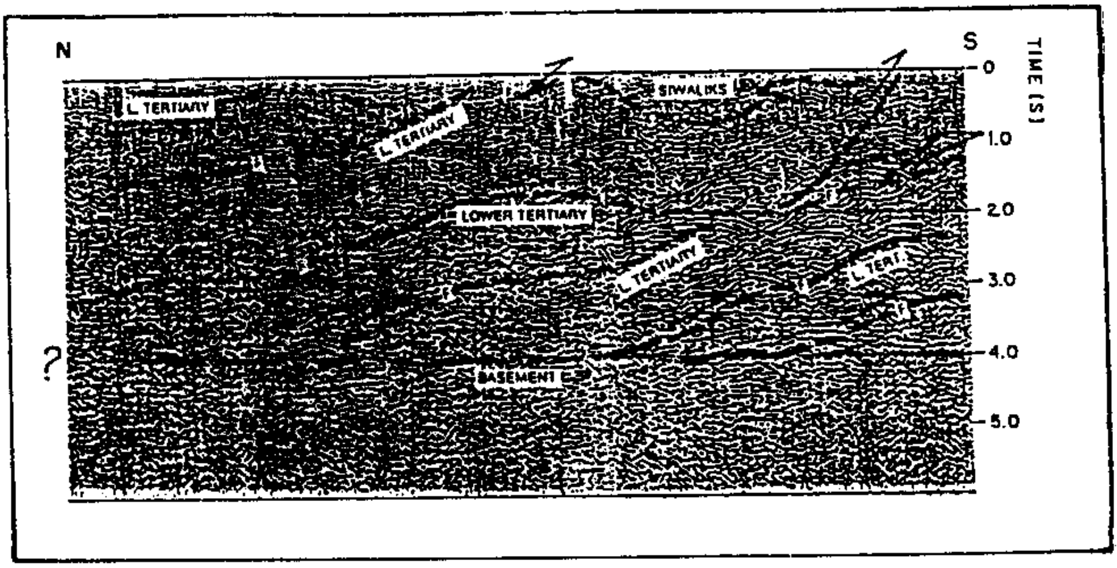

Figure - 21.9 NS seismic line across Kohat Plateau and Salt Zone showing thin skinned tectonics

and the Jhelum River and Hazara–Kashmir Syntaxis to the east. Structural trends in the East Potwar Plateau are long (northeast-southwest oriented) and continuous, consisting of salt-cored anticlines separated by broad synclines. Tanwin-Bains-Buttar and Joya Mair-Chak Naurang-Adhi-Gungrilla-Kallar are such main trends. These structures are mostly bounded by hinterland and foreland verging faults. The doubly verging thrusts, fault propagation folds, and triangle and pop-up zones are thought to have been formed due to strike– slip movement along the decollment surface.

Fig. 21.10 represents interpreted seismic sections, by different authors, to highlight multiple structural leads in Pakistan. In contrast to the East Potwar Plateau, the Central and West Potwar Plateau have been known for lack of significant evaporite sequence. In Central and Western Potwar Plateau, the structures become complicated across the Soan Syncline and the region is called Northern Potwar Deformed Zone (NPDZ).

In terms of petroleum geology the 'Potwar Model', postulated at the turn of century, is now better understood by the use of sophisticated seismic technology. In most cases, surface geological features do not truly reflect the subsurface structural style. Prospectivity of the basin has been significantly enhanced by discovery of hydrocarbons in the deeper Paleozoic reservoirs. Previous exploratory drilling was restricted to the fractured Tertiary carbonates. Recent discoveries in the Potwar are the result of correct delineation of the subsurface crest.

It is hence concluded that Upper Indus Basin and part of Central Indus Basin, with their plateau and high ranges, show that the structures in the area have developed at the expense of relatively thin skinned tectonics without any significant contribution from the basement. Based on seismic evidence the basement dips gently (2° – 4°) north-westward.

BALOCHISTAN BASIN

This basin, was formed as a result of subduction of Arabian Oceanic Plate under the Makran Continental Margin and is structurally very complex (Fig. 21.11). The

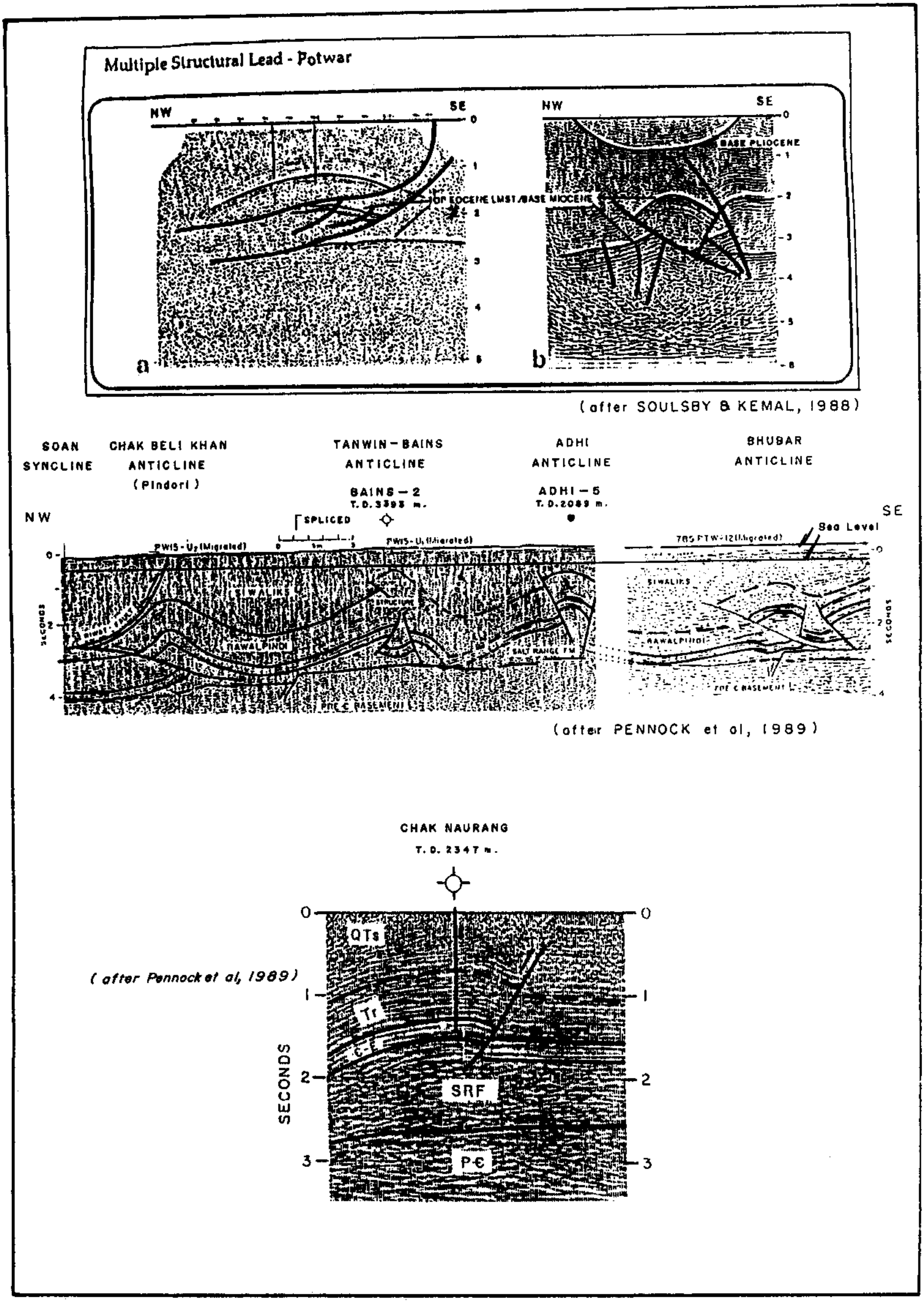

Figure - 21.10 Seismic Profile showing Different Structural Styles in Potwar Area

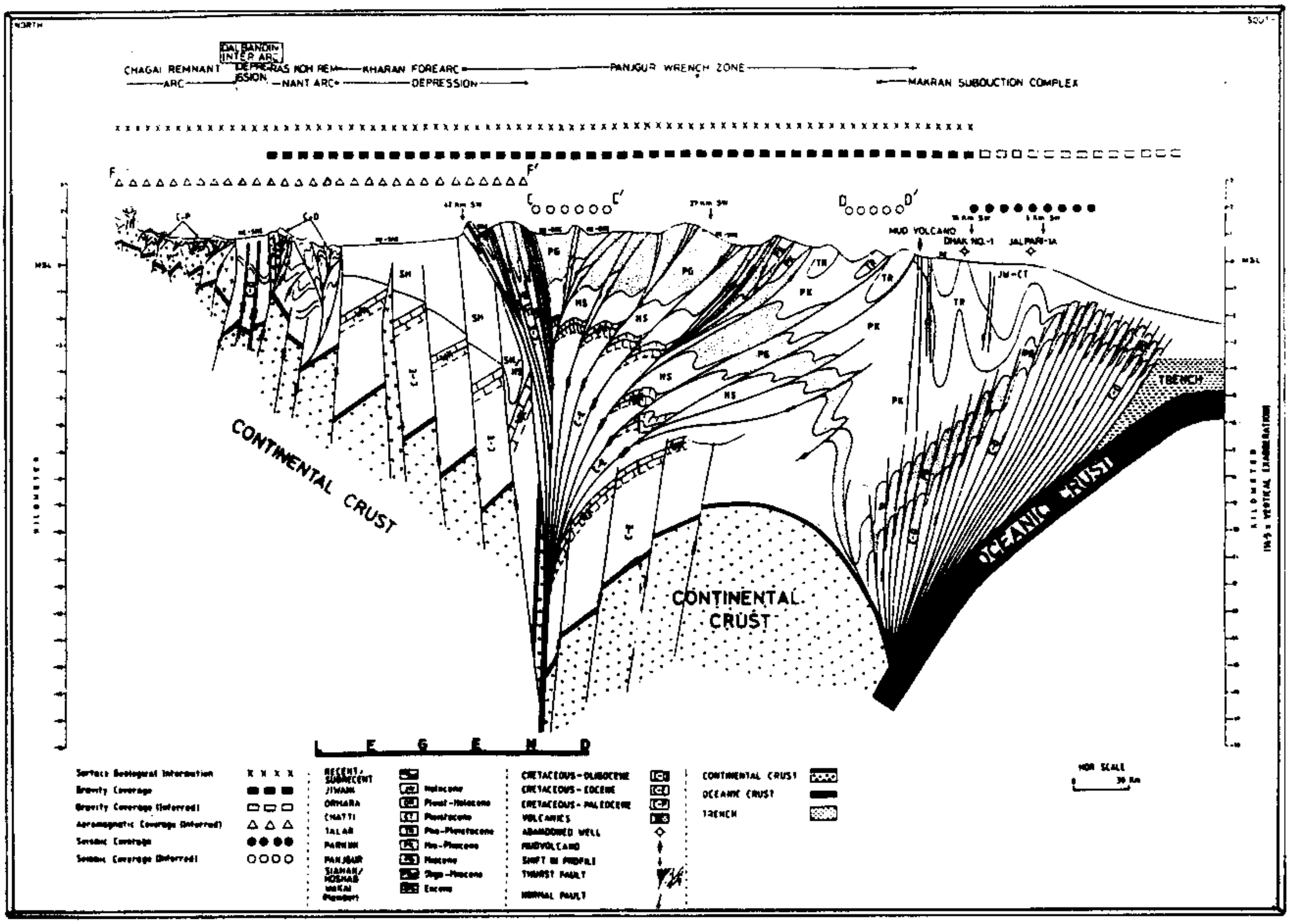

Figure - 21.11 Structural and Tectonic Model of Balochistan Basin (after Raza et al, 1991)

structural style is developed through the evolution of the Trench– Arc System.

Tectonic elements of this basin are discussed in a separate section. However, the structural style of three prospective segments is being dealt with here.

Makran Accretionary Prism

The east-west trending coastal ranges in the Makran Basin in Pakistan were believed to be the eastern extension of the Iranian oil producing basins (Fig. 21.12). However, later studies have indicated the coastal Makran, extending across Iran– Pakistan, to be an accretionary prism formed due to the subduction of the oceanic crust and is different from the Iranian oil producing Zagros basin (Fig. 21.12).

Makran Accretionary Prism is believed to extend into Iranian Makran and the Strait of Hormuz and is marked by imbricate thrust wedges and steep asymmetrical tight folds. Folds generally strike east-west. Broad, open, synclinal outliers occur along the coastal ranges north of Kappar and Ormara. Some major anticlines were delineated by seismic in the Coastal and Offshore Makran region. Fig. 21.13 represents a simplified structural model of plays in Balochistan Basin.

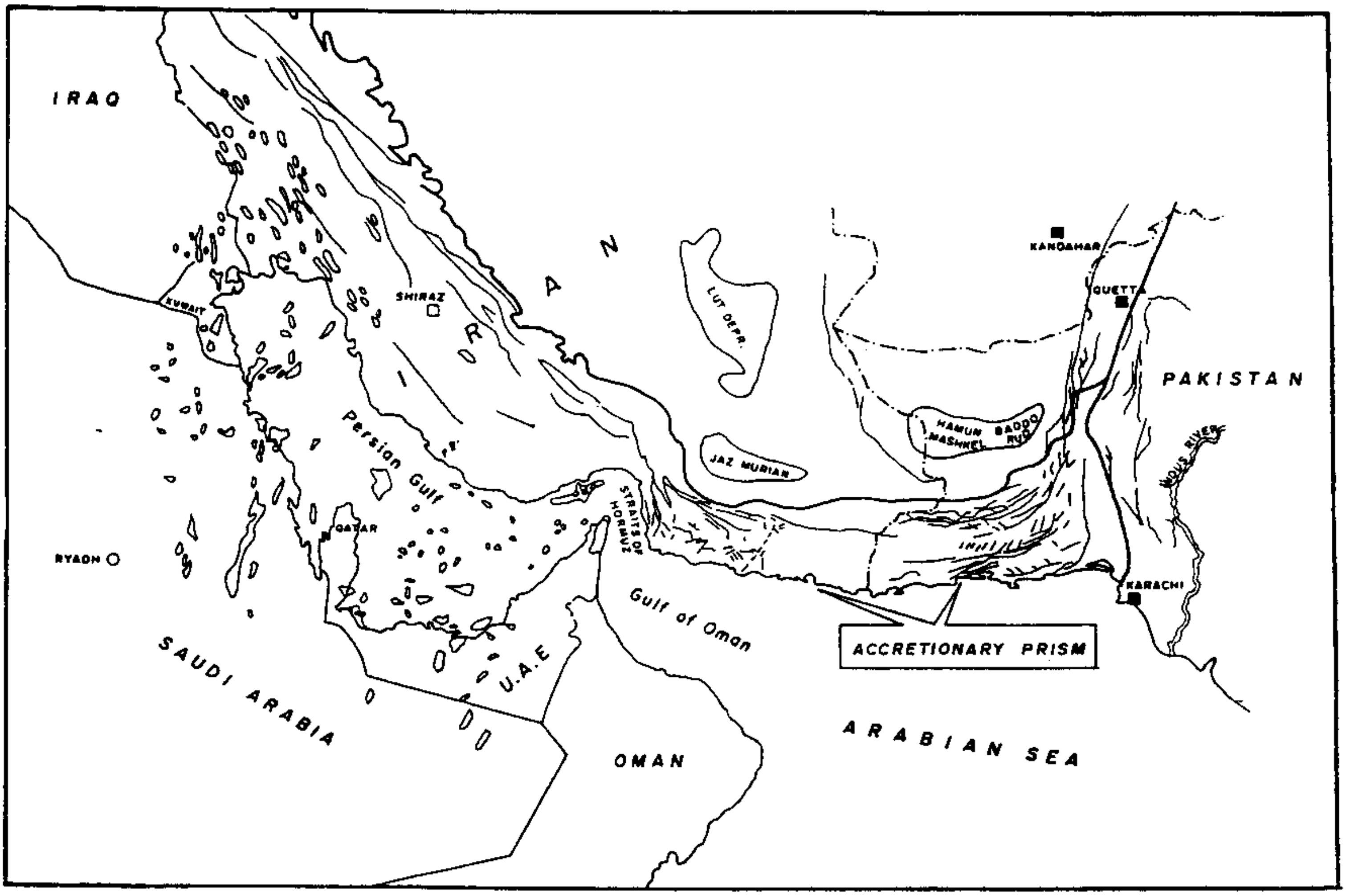

Figure - 21.12 Accretionary Prism of Pakistan/Iranian Makran and Middle East Oil Producing Basin (after Kadri and Khan, 1992)

Raza et. al. (1991) postulate that imbricated thrusts and tight folds could only be surface features and the structures at depth might be simpler. They support this theory on the basis of the decreasing dip against depth in Dhak Well-2 drilled by Hunts on the Makran coast. This is further substantiated by the presence of tight and overturned anticlines in Panjgur and broad, open synclines in Talar.

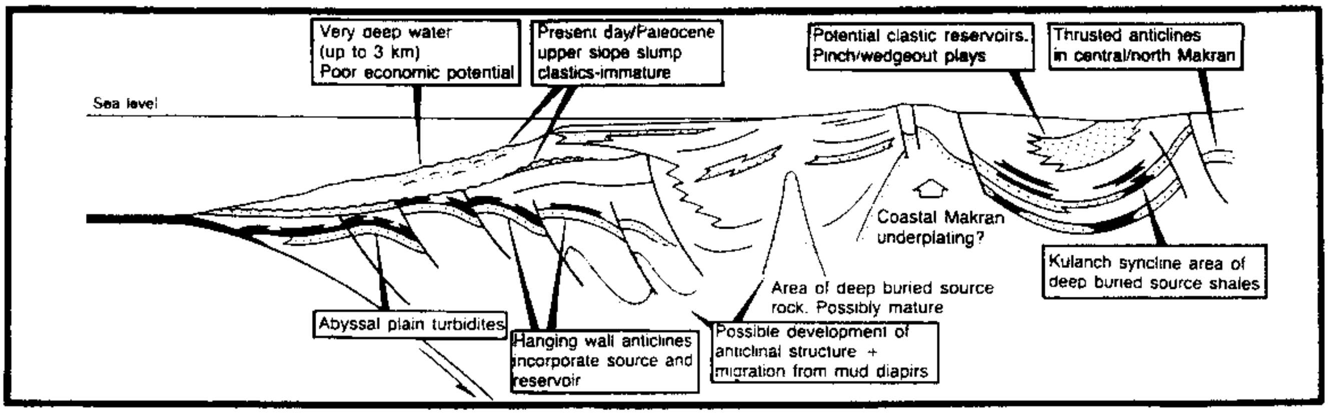

Figure - 21.13 Balochistan Basin Plays (after Soulsby and Kemal, 1988)

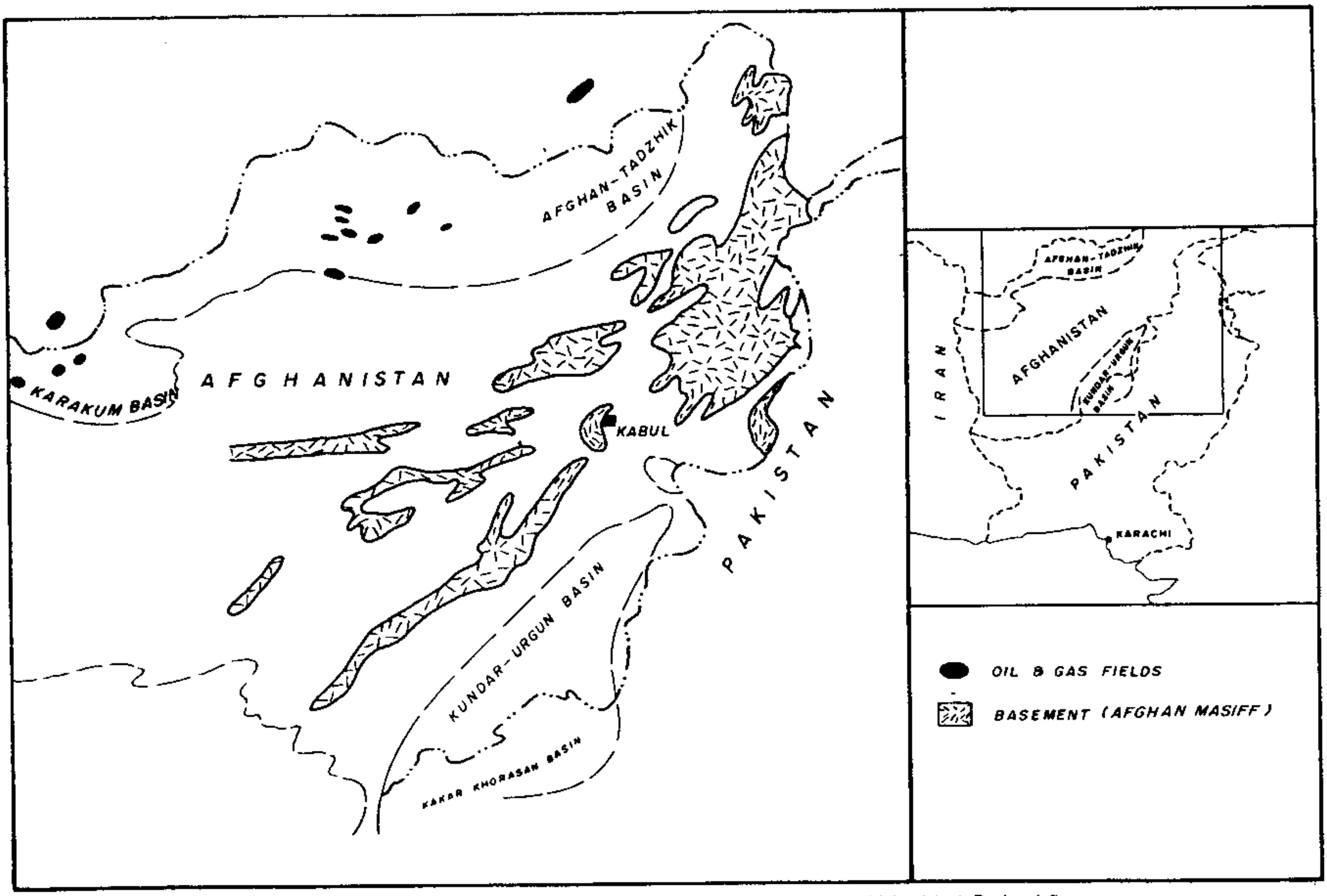

Figure 21.14 Location of Kakar-Khorasan (Pakistan) and Kundar-Urgun (Afghanistan) Basins (after Kadri and Khan, 1992)

The Coastal Makran area is characterized by Mud Volcanoes emanating methane which appears to have a deep origin. This suggests the presence of mature organic matter. The stratigraphy presents a combination of cap and reservoir rocks. Hence, this area is characterized by all the prerequisites for commercial accumulation of hydrocarbons. Basin modeling and modern seismic will greatly help in a better understanding of the plays and in delineation of simple structures.

Hamun-i-Mashkel Fore-Arc Basin

The other prospective segment in this Trench-Arc-System is the Hamun-i-Mashkel Fore-Arc Basin, located further north of the Accretionary Prism and is covered by alluvium. Hamun-i-Mashkel area was considered to be a closed intra-cratonic basin. However, the regional tectonic setting of the basin and gravity/magnetic data indicate that the Hamun-i-Mashkel is a fore-arc basin (Fig. 21.12)in the trench-arc system with possibilities of traps in normal and reverse fault blocks and thrust faulted folds. There are numerous extensional features present in the subsurface.

Entrapment mechanism in such basins is both structural and stratigraphic. Traps are associated with deltaic, nearshore and submarine fans and carbonate build-ups.

In a trench-arc system the fore-arc basins are considered to be most prospective. The Cook Inlet, Alaska and Sacramento Valley, California, are such examples. Total recoverable reserves in Cook Inlet are estimated at more than 1 billion bbls of oil equivalent.

KAKAR KHORASAN BASIN (PISHIN BASIN)

There is yet another segment of Balochistan Basin located north of Quetta and Pishin, known as Kakar Khorasan Basin. Satellite imagery shows that this is the southward extension of the prospective but unexplored Kundar-Urgun Basin of Afghanistan.

This basin is located south of Afghan Massif (Fig. 21.14) and is relatively unexplored. Published information is very scanty.

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22

Producing and Potential Oil and Gas Reservoirs

Reservoir rocks in the various basins of Pakistan are present in the formations ranging in age from Cambrian to Mio-Pliocene. These reservoir rocks are represented by both clastic and non-clastic facies. It is worth mentioning that prior to 1980s the Eocene / Paleocene carbonates constituted more than 90% of the producing oil and gas reservoirs. Subsequently, sandstone and coarser clastic reservoirs were established in Cambrian, Permian and Cretaceous. However, in the off-shore basin the Miocene sandstone reservoirs were also considered as the primary objectives. In some off-shore structures, reef development is also recognised on seismic. In Makran (Balochistan Basin), the Miocene/ Oligocene sandstone reservoirs are considered to be suitable for accumulation of hydrocarbons. Table 22.1 shows the occurrence of hydrocarbons in various formations and their dominant lithology.

The reservoir characteristics of various producing and potential reservoir formations of the Lower and Upper Indus basins are given in Tables 22.2 and 22.3. These characteristics are based on reservoir type, depth and their response to various standard logging tools (Gamma ray, density, neutron, SP and resistivities). Based on experience and keeping in view the rock type, formation fluids encountered in exploratory wells drilled in different basins of Pakistan, the suggested optimum logging suite is also indicated in the last column of the tables.

PRODUCING RESERVOIR ROCKS

UPPER INDUS BASIN (including Bannu-Kohat & Punjab Plains)

AGE / FORMATION / LITHOLOGY	OIL / GAS FIELDS	
Eocene/Paleocene: Lockhart/Sakesar/ Chorgali: Limestone	Dhurnal, Chak Naurang, Balkassar, Dakhni	OIL
Jurassic: Datta: Sandstone Samana Suk: Limestone	Dhulian, Toot, Meyal	OIL
Permian: Tobra: Conglomerate Nilawahan/Zaluch Group: Sandstone/ Limestone	Adhi, Dhurnal	OIL
Cambrian: Khewra: Sandstone:	Adhi, Missa Keswal	GAS/ CONDENSATE

Cumulative thickness of reservoirs: 800 - 1,000 meters

CENTRAL INDUS BASIN

AGE / FORMATION / LITHOLOGY	OIL / GAS FIELDS	
Eocene: Sui Main/Sui Upper/Habib Rahi: Limestone	Sui, Kandhkot, Loti, Zin, Uch, Khairpur, Mazarani	GAS
Paleocene: Ranikot: Limestone/Sandstone	Pirkoh, Rodho, Dhodak	GAS/ CONDENSATE
Cretaceous: Pab/Lower Goru: Sandstone	Pirkoh, Rodho, Dhodak	GAS/ CONDENSATE

Cumulative thickness of reservoirs: 1,500 meters

SOUTH INDUS BASIN

AGE / FORMATION / LITHOLOGY	OIL / GAS FIELDS	
Paleocene: Ranikot: Limestone/Sandstone	Sari, Hundi, Kothar	GAS
Cretaceous: Lower Goru: Sandstone	Khaskeli, Laghari, Mazari, Turk, Golarchi, etc.	OIL/GAS

Cumulative thickness of reservoirs: 400 meters

Table - 22.1 Producing Reservoir Rocks

RESERVOIR CHARACTERISTICS

LOWER INDUS BASIN

AGE		FORMATION	OIL & GAS REGIONS	RESERVOIR TYPE / DEPTH (M)	POROSITY TYPE / RANGE	GR CHARACTERISTICS & CLAY TYPE	RW RANGE	NaCl PPM	FORMATION TEMP Deg.F	SP CHARACTERISTICS	DENSITY/NEUTRON CHARACTERISTICS	SUGGESTED LOGGING SUITE
JURASSIC	MIDDLE	CHILTAN	PUNJAB PLATFORM	3900 Carbonate	MATRIX 10 - 12 %	FAIRLY CLEAN LIMESTONE LITTLE BIT SHALY DISPERSED CLAYS	0.02 - 0.03 AV: 0.025	140000	175	SOME DEFLECTION	DOLOMITIC SOME TIME MATRIX VERY TIGHT	LDL-CNL-NGS DLL-MSFL-GR AS-GR FMS-GR
CRETACEOUS	EARLY	LOWER GORU	SIND MONOCLINE	800 - 1800 Sandstone	MATRIX 5 - 30 %	SANDS ARE FAIRLY CLEAN TO SHALY SOME TIME HIGH GR ACTIVITY DUE TO RADIO ACTIVE SANDS	0.01 - 0.06 AV: 0.03	80000 TO 160000	190 - 220	VERY WELL DEVELOPED DEFLECTION DEPENDENT ON MUD RESISTIVITY	DENSITY NEUTRON READINGS SOME TIMES AFFECTED BY BAD HOLE CONDITIONS	LDL-CNL-NGS DLL-MSFL-GR BHC-GR SHDT-GR
	LATE	PARH	PUNJAB PLATFORM CENTRAL INDUS BASIN	2000 Carbonate	MATRIX 4 %	CLEAN LIMESTONE	0.1	18500	290	SOME DEVELOPMENT	DENSITY-NEUTRON SUGGESTED LITTLE BIT DOLOMITIC	LDL-CNL-NGS DLL-MSFL-GR BHC-GR SHDT-GR
		MOGHAL KOT	OUTER SULAIMAN FOLDED ZONE	800 Carbonate / Sandstone					130			
		PAB SANDSTONE	INNER SULAIMAN FOLDED ZONE	1500 - 2000 Sandstone	MATRIX 5 - 15 % FRACTURED AS WELL	GR-READS LOW RELATIVELY CLEAN SANDSTONE	0.1 VARIABLE	30000 TO 40000	130 - 200	WELL DEVELOPED	NORMAL GAS EFFECT	LDL-CNL-NGS DLL-MSFL-GR BHC-GR FMS-GR EPT
TERTIARY	PALEOCENE	RANIKOT	KARACHI TROUGH SULAIMAN LOBE	1000 - 1700 Sandstone / Carbonate	MATRIX 5 - 10 % FRACTURED AS WELL	SHALE SAND SEQUENCES MIXED CLAYS	VARIABLE	26000 TO 27000	160 - 200	LITTLE BIT DEVELOPED	TIGHT TO LITTLE BIT POROSITY DEVELOPMENT CALCITIC CEMENTED GAS EFFECT	LDL-CNL-NGS DLL-MSFL-GR BHC-GR FMS-GR
	EOCENE	SUI MAIN LS. (LAKI) & SUI UPPER LS. AND GHAZIJ SH	CENTRAL INDUS BASIN	600 - 1900 Carbonate	MATRIX 10 - 15 %	VERY CLEAN LIMESTONE (SML) RADIO ACTIVITY IN SML DUE TO RADIO ACTIVE MINERALS NOT DUE TO CLAYS	0.1 - 0.15 AV: 0.1	30000 TO 50000	110 - 160	WEL DEVELOPED	GAS EFFECT SOME TIMES DENSITY READS TO LOW AFFECTED BY THE PRESENCE OF FRACTURES	LDL-CNL-NGS DLL-MSFL-GR BHC-GR FMS-GR EPT
		HABIB RAHI LIMESTONE	CENTRAL INDUS BASIN	650 - 900 Carbonate	MATRIX 10 - 12 %	LITTLE BIT SHALY	0.2 - 0.3 AV: 0.25	15000	120	WELL DEVELOPED	GAS EFFECT ON DENSITY- NEUTRON	LDL-CNL-NGS DLL-MSFL-GR BHC-GR FMS-GR EPT

S.R.H.G : U-I-CHA.XLS

Table - 22.2 Reservoir and Logging Characteristics of various producing and potential reservoirs in Lower Indus Basin low wells were sunk in this vicinity. Only small quantity of oil was obtained. Recently (1992),an oil discovery was announced by OGDC in the vicinity (Sadkal-1).

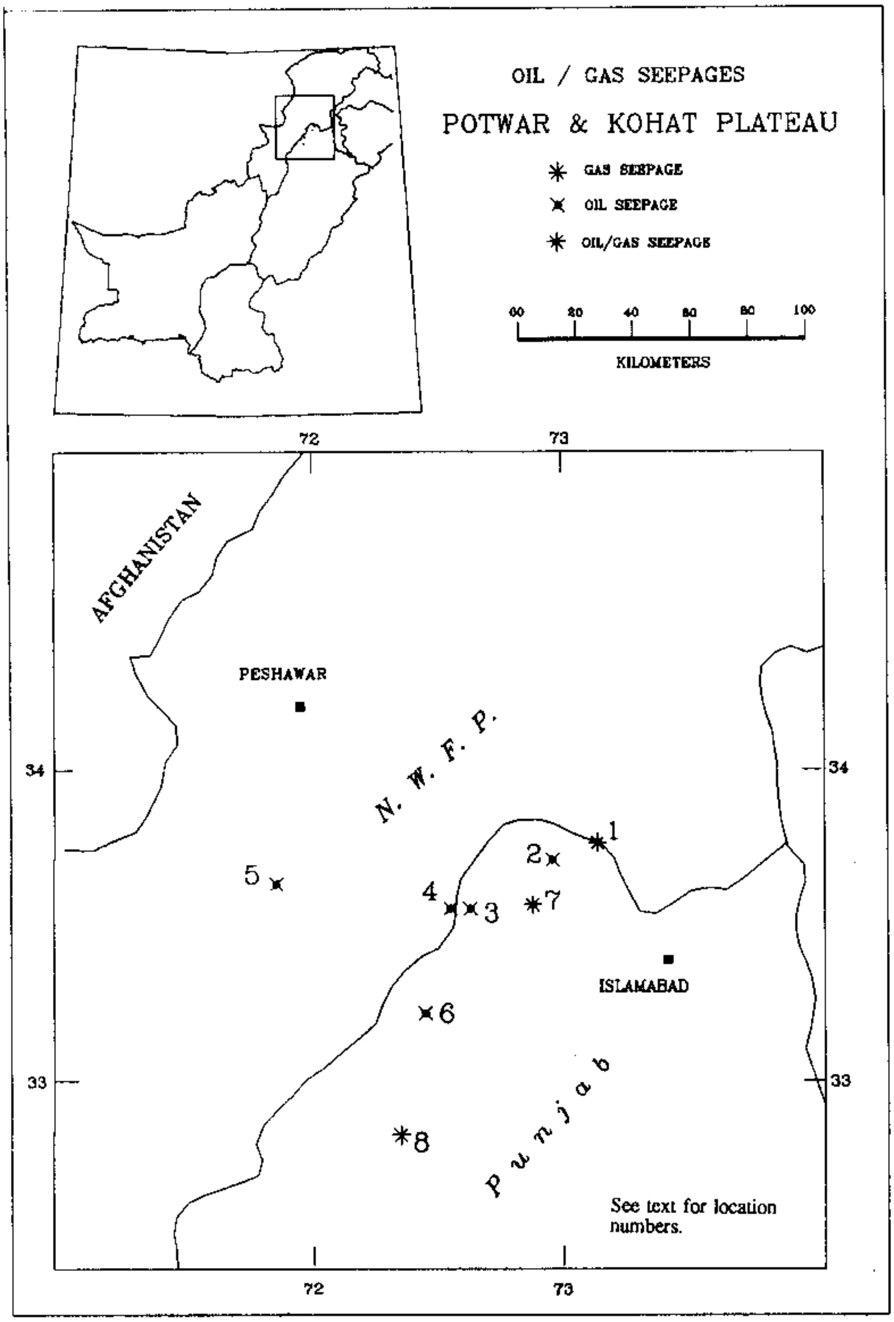


Figure - 23.1 Oil / Gas Seepages - Potwar & Kohat Plateau

4. Chharat

Coordinates: 33° 35' N
72° 33' E

A number of seepages of oil accompanied by some gas occur. In 1869, pits were dug to a depth of 21 meters near these seepages and later a well was drilled to 100 meters by 'Original Oil Syndicate'. This well was abandoned in 1890 having obtained a 'very good' show of oil at about 55 meters. Recently (1991), an oil discovery was announced by OGDC in this vicinity (Bhal Syedan-1).

5. Panoba

Coordinates: 33° 37' N
71° 54' E

A seepage of oil occurs in Shekhan Limestone (Eocene) on the southern flank of the Panoba–Tarkhobi anticline.

The oil occurs as films on the outcrops and in the form of small pools.

6. Khaur

Coordinates: 33° 16' N
72° 28' E

Near the crest of the Khaur dome and not far from the summit, two fairly large seepages are reported.

The Khaur oilfield was discovered in 1915 and has now depleted.

7. Khairi–Murat

Seepages occur at four localities near the eastern end of the Khairi–Murat Range.

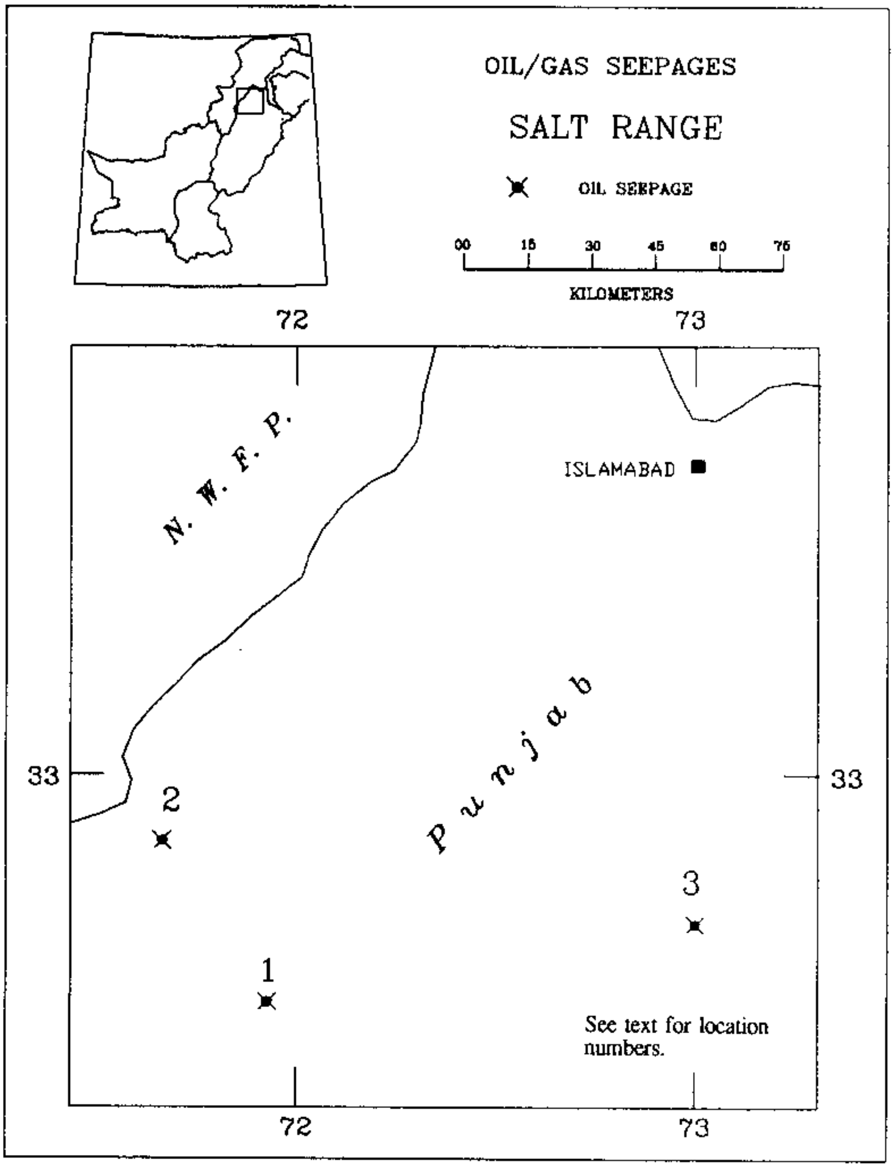


Figure - 23.2 Oil / Gas Seepages - Salt Range

8. Jhatla
Coordinates: 32° 49' N
72° 20.5' E

Three small seepages of gas (one of which is accompanied by warm sulphurous water) are reported in Gandial Nallah (stream) on the Jhatla dome.

SALT RANGE
(Fig. 23.2)

In numerous localities along the northern flank of the Salt Range, seepages of oil and tar-stained rock have been reported.

These live seepages and exposures of heavy oil stained sands appear to be grouped between 72° 05'E and 72° 22' E.

These are confined to the basal part of the Kamlials (Miocene) just above the unconformable contact between the Kamlials and the Eocene Limestone.

One of the seepages is briefly described as follows:

Sil River – Basala Kas Junction
Coordinates: 33° 30.5' N
72° 54' E

A faint seepage of oil and gas occurs in a band of almost vertical Eocene Limestone beds which probably represents the core of an overthrust anticlinal pucker.

It is generally believed that these seeps represent migrated hydrocarbons along the unconformity at the base of the Upper Tertiaries.

1. Salgi (Sulgi)
Coordinates: 32° 31' N
71° 56' E

Oil seepages occur in the Sulgi or Amb Glen, near Amb village in the Salt Range. The seepages are confined to Siwalik strata above the junction of the basal Siwalik conglomerate with the underlying massive

Eocene Limestone. The seepages consist of heavy black oil oozing from a strongly saturated zone about 2 meters thick; sandstone bands up to 3 meters above this zone are stained with migrated oil.

2. Jaba

Coordinates: 32° 52' N
71° 41' E

Two prolific groups of seepages occur about 1 km south of Jaba village in Western Salt Range. The oil oozes from fractures, joint planes and fault planes. It is accompanied by hydrogen sulphide and milky white sulphur.

3. Khewra

Coordinates: 32° 39' N
73° 1' E

Black bituminous shale occurs near the top of the Saline Series (Precambrian) in Khewra Gorge.

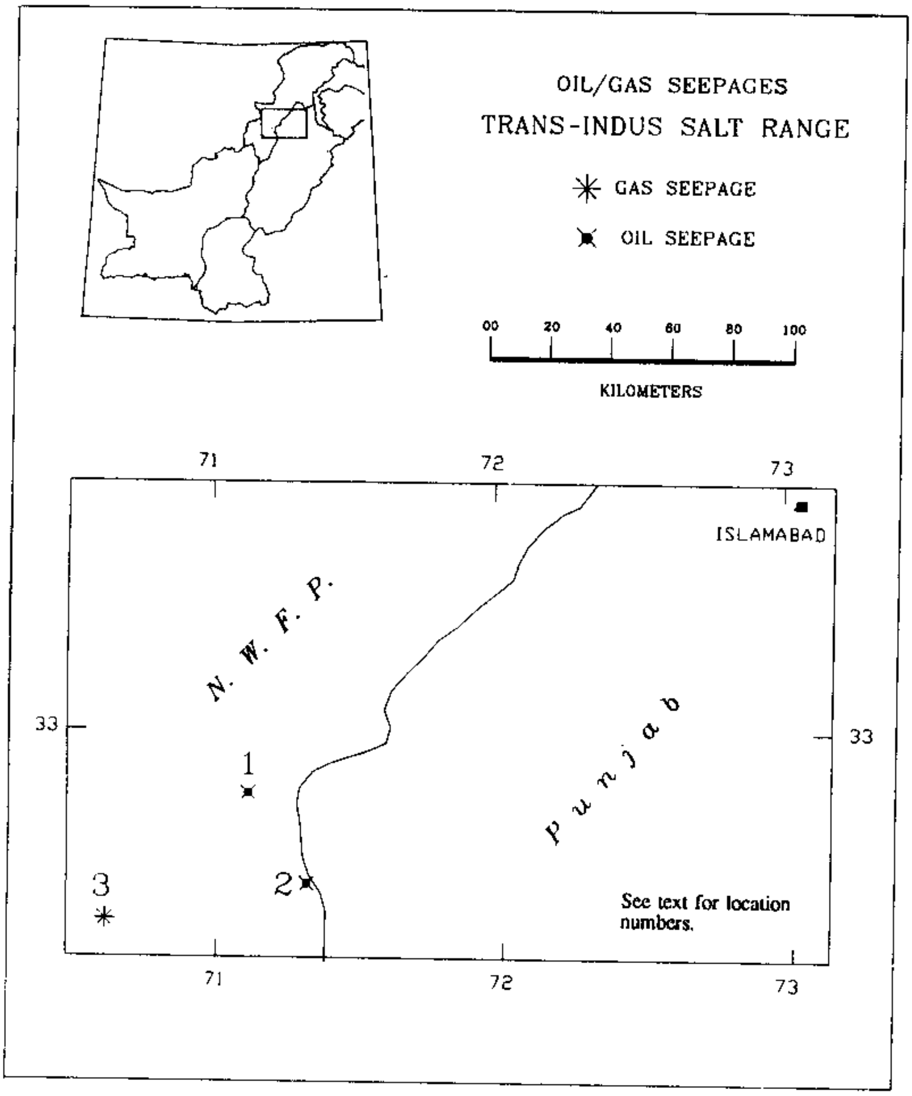


Figure - 23.3 Oil / Gas Seepages - Trans Indus Salt Range

TRANS-INDUS SALT RANGE
(Fig. 23.3)

1. Mitha Khattak

Coordinates: 32° 48.5' N
71° 7.25'E

Globules of thick dark oil are reported in pools in Poya Tangi – a small stream near the crest, on the western flank of Surghar Anticline. The show occurs at the top of a group of greenish – brown sandstones, associated with Siwalik – Eocene unconformity.

2. Kundal

Coordinates: 32° 32.25' N
71° 18.25' E

Oil seepages (thick tar) occur at the Siwalik–Triassic contact south of Kundal village in Algad Nallah. The seepages in the form of several pools consist of thick tar with smaller quantities of heavy oil.

3. Pezu – Bain Pass

Coordinates: 32° 26' N
70° 37' E

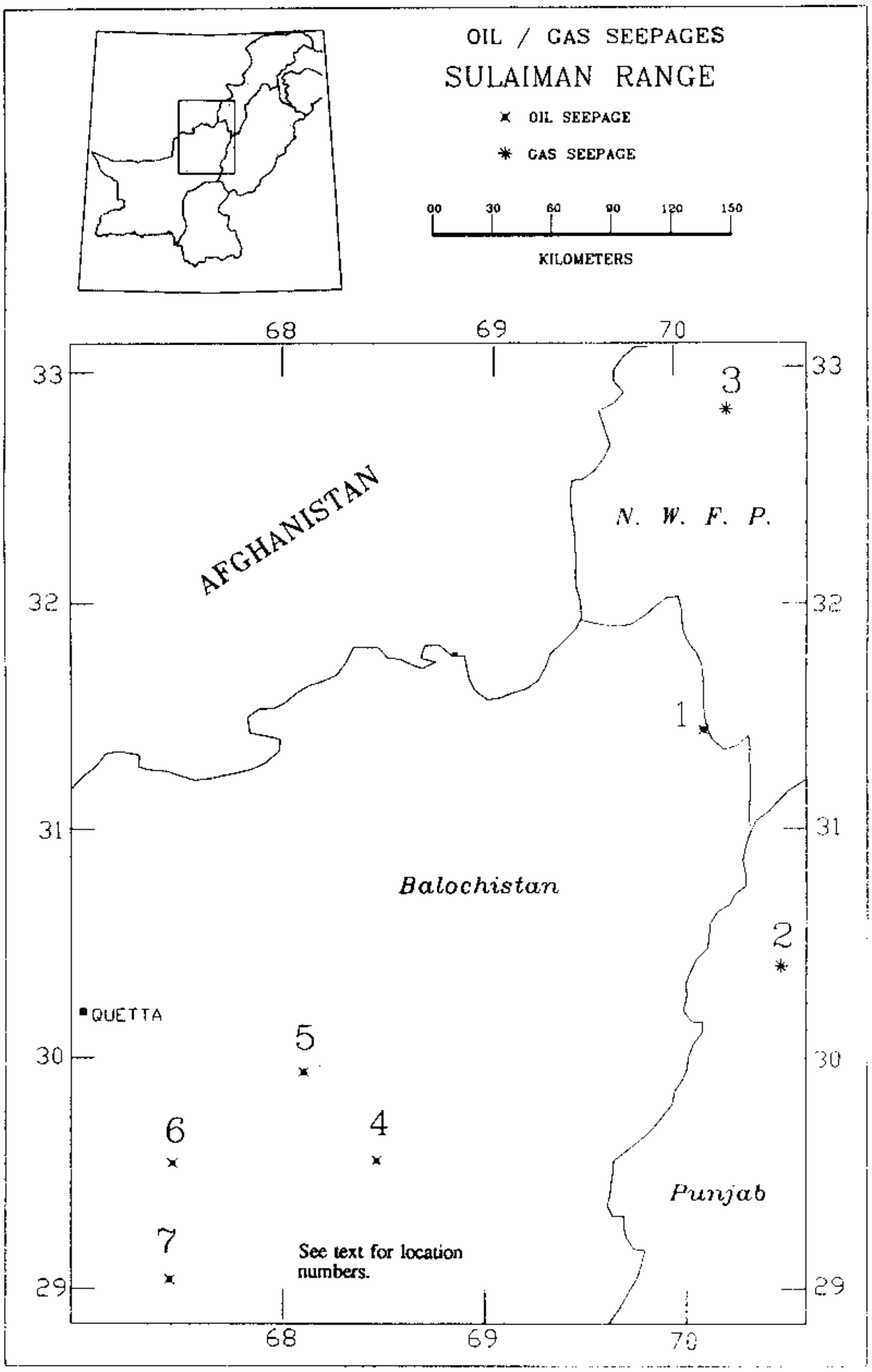


Figure - 23.4 Oil / Gas Seepages - Sulaiman Range

This is a gas seepage which occurs within Siwalik directly on an east-west trending thrust fault which divides the Pezu structure. Very low pressure of gas at surface and its analysis (CH4 80%) suggests that this gas has a very deep source and is traveling through a deep seated fault. The seepages can be put to fire and are used by local pawindas (migratory tribes) for cooking etc.

SULAIMAN RANGE
(Fig. 23.4)

Shows of oil or gas associated with Upper Cretaceous rocks occur in many places along the Sulaiman Lobe and further north-east in the Sulaiman range. These shows are described in detail below:

1. Moghal Kot
Coordinates: 31° 27' N
70° 06' E

Seepages of oil occur in the Moghal Kot (Cretaceous) Formation along the contact with overlaying Pab Sandstone in Toi Nallah, just west of Moghal Kot fort.

This is the main seepage in the Sulaiman Range and probably the most prolific light oil seepage in Pakistan.

2. Zinda Pir
Coordinates: 30° 24.5' N
70° 29' E

Strong gas seepages, through vents, are reported in the beds of Sori River just west of where it crosses the crest of the Zinda Pir dome. The shows and bituminous matter occur at the top of the massive Pab Sandstone (Upper Cretaceous). During recent visits the seepages could not be located except a hot spring in the vicinity.

3. Kiwa River

Coordinates: 32° 51.5' N
70° 14.5' E

Small gas vents are present. In some cases the gas is accompanied by strong springs of somewhat saline water; in others only sticky, bluish mud issues and the vents have all the characteristics of small mud volcanoes. The gas is inflammable.

4. Khattan

Coordinates: 29° 34' N
68° 28' E

Seepages of heavy oil accompanied by springs of hot sulphurous water occur in the valley of the Khattan or Sart stream along the Dunghan (Paleocene) – Ghazij (Eocene) boundary across the westerly pitching end of a large anticline. Oil is also found filling cracks in the Dunghan Limestone and Ghazij Shales.

Between 1884 and 1892, thirteen wells (maximum depth 350 meters) were drilled in this area. Ten of these appear to have been in the neighbourhood of the seepages.

The total production from the area from 1886–1892 (Balochistan District Gazetteer Vol. III, p.143) was 777,225 gallons, and in 12 months from 1893 Messrs. Mac Bean & Co. produced 60,000 gallons, making a total of 837,225 gallons.

Though a fair amount of oil was obtained from the shallow wells, the quality of the oil was not good and the yield was not sufficiently large to be economic.

5. Spintangi

Coordinates: 29° 57' N
68° 6' E

In 1890, R. D. Oldham recorded the occurrence of traces of oil in the Dunghan Limestone in this neighbourhood. These traces consist of bitumen either included in the calcite of veins or lining cracks in the limestone and are most plentiful near the crest at the pitching ends of the various anticlines (e.g. Gulucha Anticline).

Towards the end of 1890, a well was drilled near Spintangi presumably on Oldham's selected location. It reached a depth of 170 meters where it struck a strong flow of hot sulphurous water (30,000 gallons/hour) and was abandoned (1891). The well found no evidence of oil.

6. Gokurth (Kirta)

Coordinates: 29° 32.75' N
67° 27.5' E

These oil seepages are located 1.2 km WSW of Gokurth and 2.4 km west of Kirta fold and are associated with a faulted and fractured zone. The oil has probably migrated upwards from a horizon lower than any exposed at the surface.

The seepages, as patches of oil stains in gravels, are reported for about a length of 800 meters along the foot of Push Thal Range.

7. Sanni

Coordinates: 29° 2' N
67° 27' E

Thin films of tar are recorded in the workings of some old sulphur mines.

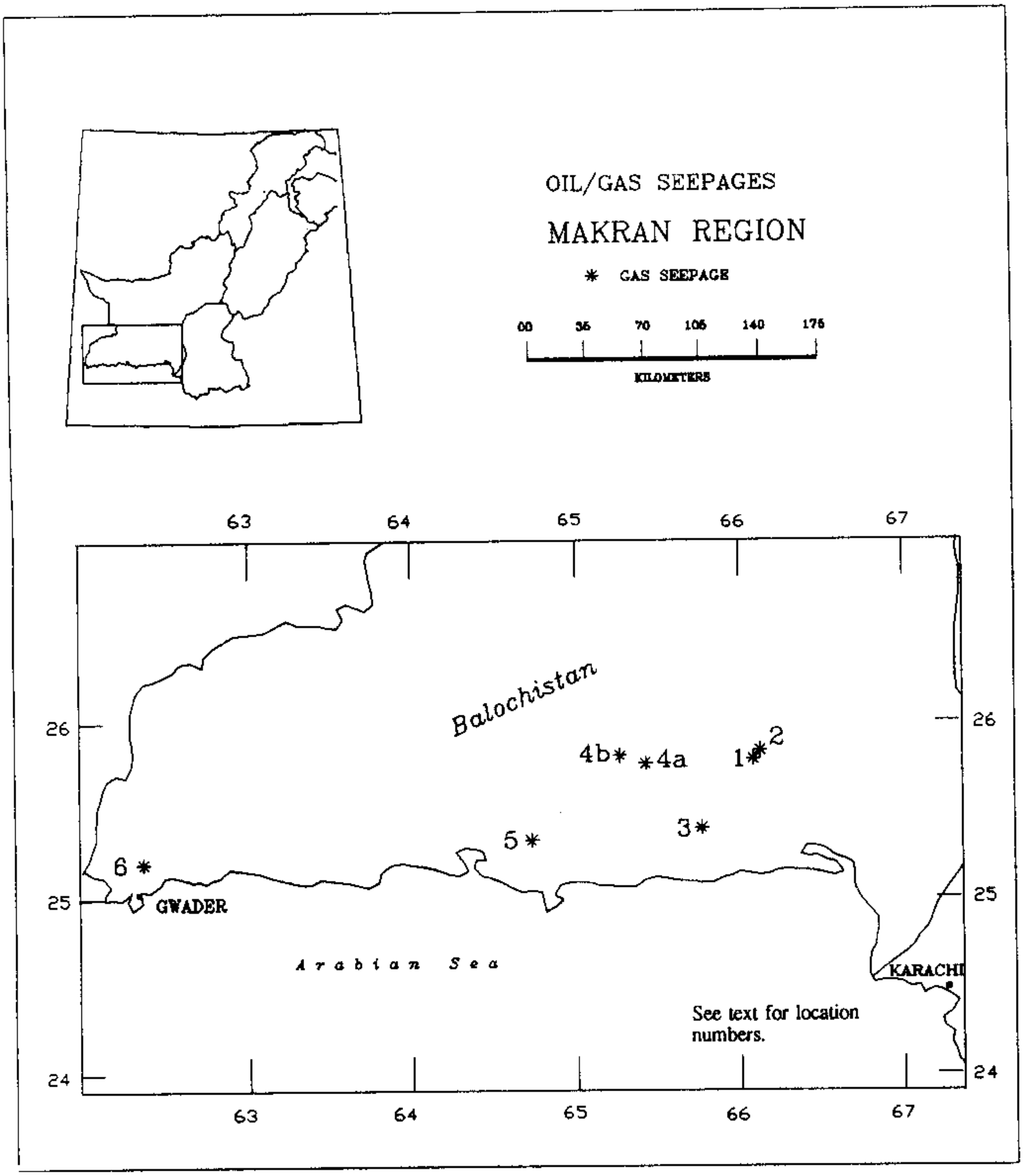


Figure - 23.5 Oil / Gas Seepages - Makran Region

MAKRAN
(Fig. 23.5)

General and Historical

During investigation in the early part of the 20th century, mud volcanoes were observed east of the Hingol River but no oil or direct manifestation of petroleum was observed.

As a result of this work, the Burmah Oil Company drilled a test well at Chandragup in 1916. This well found no oil and was abandoned in 1919.

Along the coastal region of Lasbela and

introduced in a few countries, initially unsuccessfully, as early as the 1920s. In 1948, the Government of Venezuela introduced a tax on Company profits at the rate of 50 per cent. In 1950 Saudi Arabia passed a similar law.

Between early 1950s and early 1970s, there was an enormous expansion of world wide petroleum exploration and many new companies entered the field. One important result of this increase in exploration activity was the rapid development of new contract forms to replace the traditional 'Concession' arrangements.

STATE INVOLVEMENT IN PETROLEUM EXPLORATION

Fairly early on, the State had begun to directly participate in petroleum exploration. The USSR had nationalised its oil industry in the years following the revolution of 1917 and Mexico, in 1938, had expropriated the assets of foreign oil companies in favour of PEMEX (the national oil company). The concept of the joint venture between a State oil company and a foreign oil company was introduced in 1957 by the National Iranian Oil Company (NIOC) which entered into an agreement with AGIP, the Italian State Oil Company.

From the point of view of evolution of contract types, Indonesia's role is important. In 1963, it introduced the concept of the 'Production Sharing' contract which is also, for this reason, known after its national oil company, Pertamina. This is an arrangement under which the contracting company finances exploration, development and production with a right to recoup its investments in these activities out of a stated percentage of production. The remaining production is shared between the oil company and the State in an agreed ratio.

The 1960s and 70s saw the formation and growth of the Organization of Petroleum Exporting Countries (OPEC) and more nationalization of the petroleum sector: Algeria, Iraq, Iran, Kuwait, Venezuela and Saudi Arabia. This could be seen as a reaction to the trend which prevailed in the 1930s and 1940s when the major oil companies known as the 'seven sisters', were dominant.

In Pakistan, subsequent to the promulgation of Pakistan Petroleum Production Rules (discussed later) in 1949, the Government participated directly in oil/gas exploration/production activities through equity participation in Pakistani companies. These were, (a) Pakistan Oilfields Limited established in 1949 (a subsidiary of Attock Oil Company of U.K.) in which Government held 30% equity shareholding, and (b) Pakistan Petroleum Limited (PPL) incorporated in 1950 with similar Government equity participation. PPL inherited the operations of Burmah Oil Company (Pakistan Concessions) Limited – a wholly owned subsidiary of Burmah Oil Company of U.K., which held 70% equity in Pakistan Petroleum Limited. The petroleum concessions under which local companies (and subsequently foreign companies) operated until about the early 1970s were the 'Profit Sharing' type.

The national oil company, Oil and Gas Development Corporation (OGDC) was established by an Ordinance in 1961 and undertook exploration activities in competition with other operating companies. From 1970s Government started participating in Joint Venture Agreements (either directly or through OGDC) with companies operating in Pakistan and newcomers. The Government participation/joint venture terms varied with time. Government's share in exploration stage was nominal – 5 to 15% with an option to 'buy back' (increase its working interest) up to 40 to 50% upon commercial discovery with or without payment of proportionate differential pre-commercial discovery expenditure.

However, according to the 1991 Petroleum Policy (revised September 1992) the standing practice of the Government (or OGDC on its behalf) sharing, described in previous para, was replaced by negotiations or competitive bidding, (if there be more than one applicant), to determine these shares or to adopt any other suitable formula like Production Sharing.

In 1993 and 1994, the Government of Pakistan (GOP) announced a package of incentives to achieve the required pace of exploration.

LEGISLATION

The broad framework of the terms governing exploration and production in Pakistan is laid down in the Government's Model Concession Agreement (with Joint Operating Agreement and Accounting Procedure). At the time of independence in 1947, Pakistan inherited the Petroleum Act 1934 and the Mines Act 1923. Income Tax for petroleum operations was governed by Schedule II of the Income Tax Act 1922. In 1948, the Regulation of Mines and Oilfields and Mineral Development (Government) Control Act was enacted, under which Petroleum Production Rules were formulated, first in 1949 and then in 1986. The 1949 Rules continue to apply to all Concessions granted before enactment of the 1986 Rules. In 1979, a new Income Tax Ordinance was passed which substituted the Income Tax Act, 1922. Schedule V (Part I) of this Ordinance contains the Rules for taxation of profits from the business of petroleum operations and has replaced Schedule II of the Income Tax Act 1922.

Under Pakistani law, subsurface rights to Petroleum (oil and gas) and a few minerals vest in the Federal Government. Such rights are leased by the State to the exploration companies for fixed periods of time. The Regulation of Mines and Oilfields and Mineral Development (Government) Control Act 1948 allows the Government ('The President'), to enter into a Production Sharing Agreement at the time of grant of the petroleum right. However, the petroleum concession agreements which the Government presently enters into are not of the Production Sharing type; these are the Concession (also called the Tax/Royalty) type.

TAX/ROYALTY TYPE CONTRACT

In common with other countries where the Tax/Royalty type contract is used, the typical Pakistani form has the following characteristics:

1. The concession area is limited.
2. The duration of the concession is limited with the provision for renewal for a longer period in the event of commercial discovery.
3. The Government receives a percentage (currently 12.5%) of production, in cash or kind, as royalty, income tax and production bonuses.
4. Direct or indirect Government participation, usually with a minority interest.
5. In accordance with the provisions of the 1986 Rules, Government has authority to exercise control over and monitor operations of Petro-

leum exploration companies.

Fig. 24.1 shows comparison of contractual profitability of foreign companies operating in Pakistan with companies operating in some other countries, prior to the announcement of Petroleum Policy in 1991 (revised in September 1992), subsequently in 1993 and 1994. The petroleum policy issues are reviewed and modified from time to time to keep pace with the national and international developments and trends in petroleum exploration and production sectors and are subject to revision.

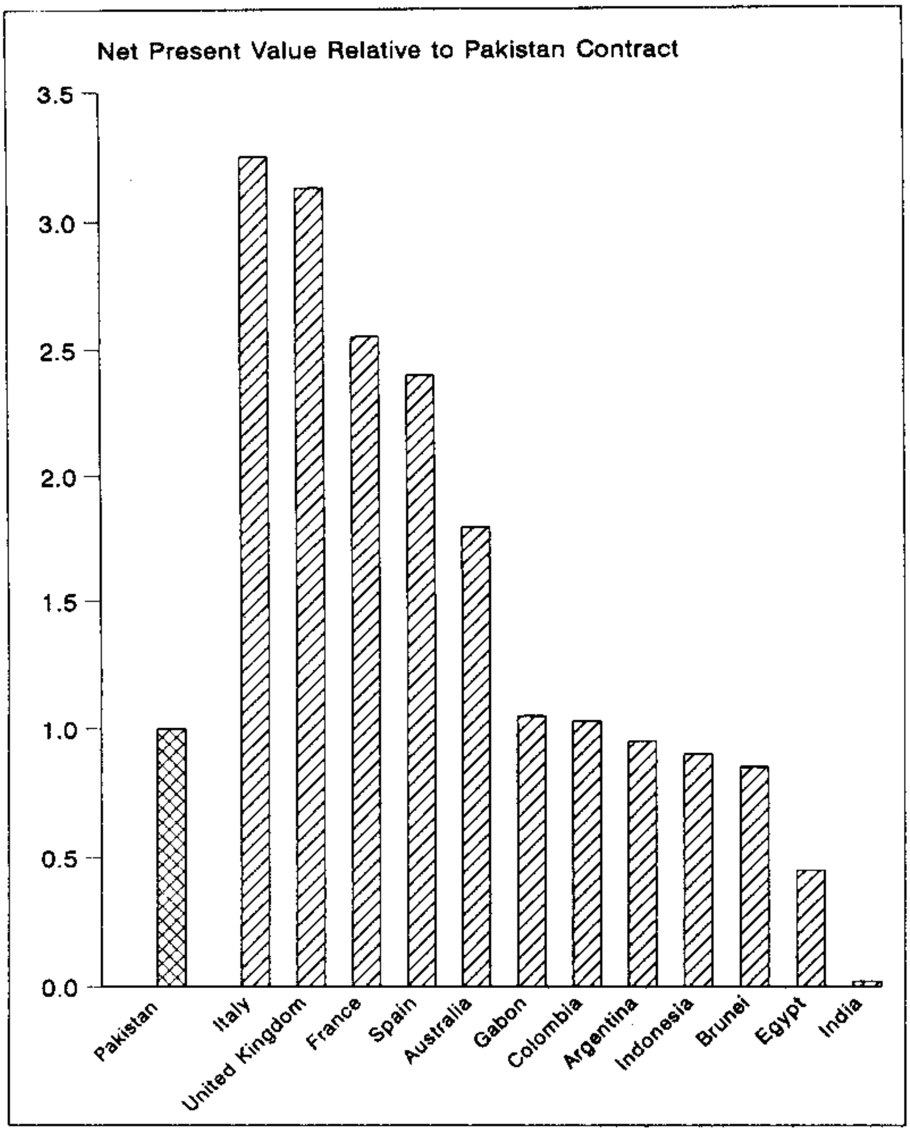


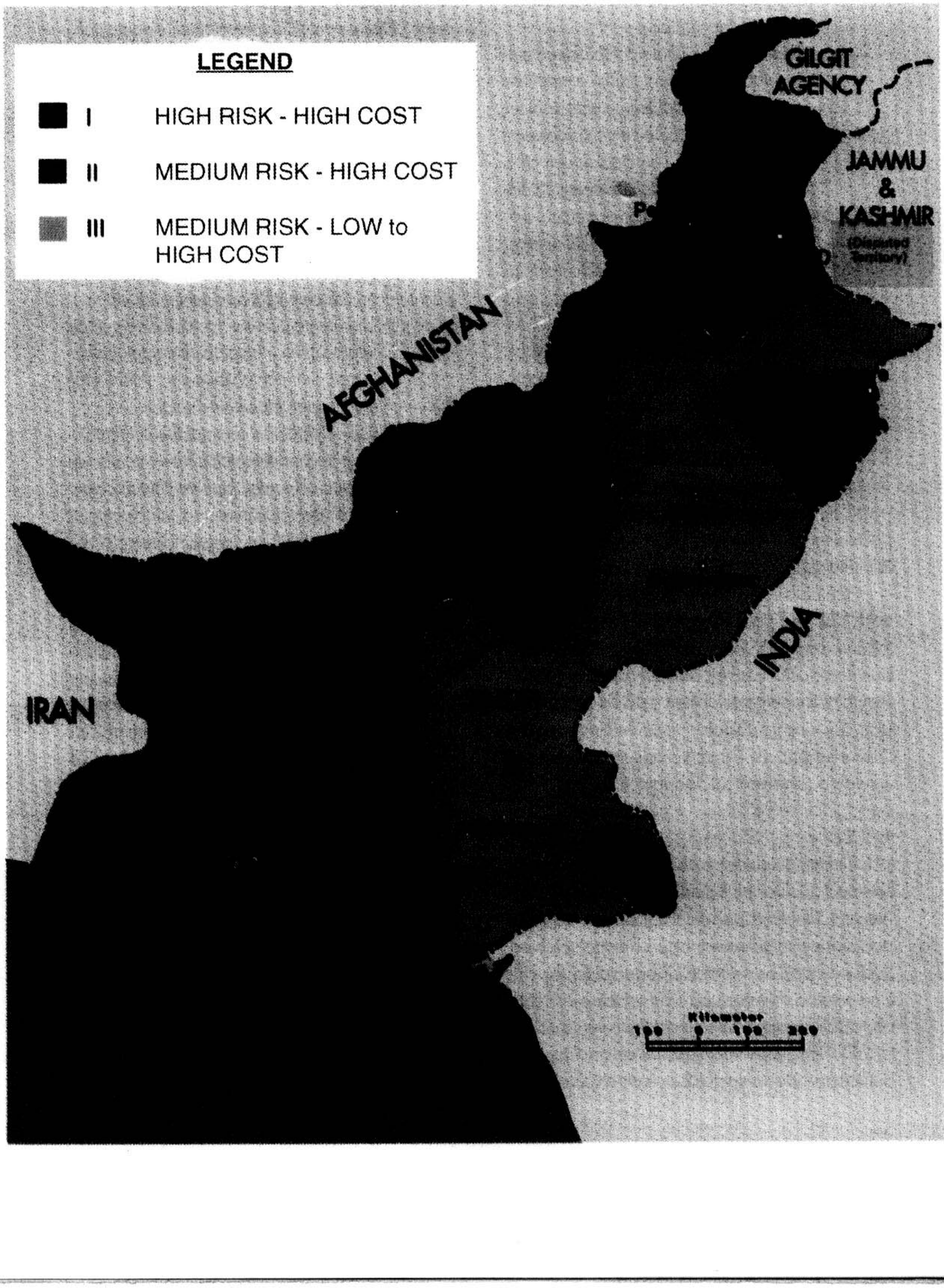
Figure- 24.1 Comparison of Contractual Profitability value to Foreign Contractor,40 MMB Oil, 40 MMBOE Gas Discoveries

TERMS PREVAILING

Under the new petroleum policy (1994), the country has been divided into three zones (1, 2 and 3) which are shown in Fig. 24.2 and are elaborated in Section 25. Fiscal terms have been defined and fixed for the three zones.

The new petroleum policy offers major incentives for investment in the upstream and downstream petroleum sectors. The main terms prevailing in Pakistan at present are as follows:

1. **Type of Petroleum Rights**
   a) 'Reconnaissance Permit': which is non-exclusive and allows geological, geochemical and geophysical work as well as shallow drilling to a maximum depth of 200 meters. The permit is valid for one year with a possible one year renewal.
   b) 'Exploration Licence': which is granted for an initial period of three years for a maximum area of 7,500 sq. kms. The licence is renewable for up to three one-year periods for areas onshore and five one-year periods for offshore areas. It may also be renewed for appraisal of a discovery. Prior to first renewal at


LEGEND
I HIGH RISK - HIGH COST
II MEDIUM RISK - HIGH COST
III MEDIUM RISK - LOW to HIGH COST
GILGIT AGENCY
JAMMU & KASHMIR
AFGHANISTAN
IRAN
INDIA

least 50% of the area has to be relinquished, unless otherwise stipulated in the licence.

c) 'Development and Production Lease': which can only cover the delineated discovery area. Under the Model Petroleum Concession Agreement and the Petroleum (Exploration and Production) Rules 1986, after completion of the appraisal programme the Working Interest Owners are required to submit a Development Plan and application for a Lease to the Government for a discovery deemed by them to be a Commercial Discovery. The Lease is initially granted for up to 20 years onshore and 25 years offshore, both periods being renewable for an additional five year term.

2. Royalty

This is 12.5% of the Wellhead Value for both Oil and Gas as per 1948 Regulation of Mines and Oilfields and Mineral Development (Government Control) Act 1948. Royalty forms part of the sum of payments (for tax computation – see below) to the Government. In other words, it constitutes advance payment of income tax.

3. Tax

Taxation provisions and mechanisms are laid down in Schedule V of the 1979 Income Tax Ordinance. Inter alia these offer two options, of which one is to be selected by the company at the time of signing the Concession Agreement, for writing-off (being allowed as a Tax deduction against income) 'lost expenditure'. Exploration expenditure is recognised as lost expenditure for Tax computation only on (a) surrender of an area, or (b) on abandonment of a dry hole. The two options referred above are:

a) Rule 2(3)(a) of Schedule V (Part I). Lost expenditure in any year can be set off against the income of that year from (i) the business of exploration and production of petroleum and (ii) any business other than exploration and production of petroleum. Such lost expenditure as is not wholly set off in that year can be carried forward to be set off in a similar manner in the following years up to a maximum of six years. If not set off within six years this lost expenditure will lapse.

b) Rule 2(3)(b) of Schedule V (Part I): Lost expenditure in any year can be set off only against the income from the business of exploration and production of petroleum in the year in which commercial production has commenced. Such lost expenditure as is not wholly set off in that year can be carried forward to be set off in a similar manner in the following years up to a maximum of ten years. If not set off within ten years the lost expenditure will lapse.

Income Tax rates (1994 Policy) for the three zones are as follows:

Zone 1	50%
Zone 2	52½%
Zone 3	55%

Payments to Government include Royalty, annual rental of the Development and Production Lease and such other levies as are peculiarly applicable to oil production or to extractive industries and are not generally imposed upon all industrial and commercial activities.

The business of exploration and production of petroleum of a company is now considered as a whole and as such any/each concession of the same company is not isolated for this purpose. Consequently, now there is no ring fence; meaning that the lost expenditure of one concession can be set off against the income of the same company from the same or any other concession.

4. Depreciation

Depreciation is allowed in accordance with Schedule III of the Income Tax Ordinance.

5. Depletion Allowance

In determining the income from the production of petroleum for any year ending after the date on which commercial production has commenced, an allowance for depletion equal to fifteen percent (15%) of the gross receipt representing the well-head value of the production is allowed provided that such allowance does not exceed fifty percent (50%) of the profits or gains of such undertaking before deduction of such allowance.

6. GOP Working Interest (Pre and Post Commercial Discovery)

All concession agreements will provide for a 5% carry for the GOP during the exploration phase. The expenditure incurred will be reimbursed by the GOP after Commercial Discovery in installments through production over a 5 year period. The level of GOP Working Interest in each Commercial Discovery based on three geological zones determined on the basis of prospectivity and corresponding financial and economic parameters will be as under:

Zone-1	15%	(High risk/ High cost)
Zone-2	20%	(Medium risk/ High cost)
Zone-3	25%	(Medium risk/ Low to High cost)

7. Producer Pricing

According to the new petroleum policy (1994) the producer prices are as follows:

a) Oil: The price for Crude Oil delivered at the refinery gate shall be based on a basket of Arabian/Persian Gulf Crude Oils plus or minus a quality differential between the basket and the local crude. No other adjustment or discount will apply.

b) Condensate: The price for Condensate will be the FOB price of internationally quoted comparable Condensate. No other adjustment will apply.

c) Non-Associated Gas: The price for Non-Associated Gas will be indexed to the price of a basket of Arabian/Persian Gulf Crude Oils as follows:

Zone-1	$77\frac{1}{2}$%
Zone-2	$72\frac{1}{2}$%
Zone-3	$67\frac{1}{2}$%

d) Associated Gas: The price for Associated Gas shall be equal to the price of Non-Associated Gas as applicable to each Zone for acceptable gas specifications.

e) Liquefied Petroleum Gas: The LPG producers are given incentive through a higher price (FOB) subject to a maximum of US$ 175 per metric ton for incremental production. For new projects, C&F parity prices, based on proper port off-loading facilities, will be allowed.

f) Incentive for Deeper Drilling: For existing Lease areas, if a company discovers hydrocarbons below the deepest known producing horizon, it shall be entitled to the same price formula for oil and gas discovered from such deeper horizon as is applicable to the respective Zone under the new policy (1994).

g) Import Duties: No custom duty shall be payable for import of equipment and material for exploration, development, production and enhanced petroleum recovery. However after commercial discovery annual, deffered consolidated fee equal to 3% of the total invoice value of the material, equipment etc. will be paid.

8. Domestic Supply

The Government has a first right over the Petroleum produced in the country and can require the leaseholder to supply the entire quantity for the domestic market.

9. Production Bonuses

Initial production bonus is payable at the time of commencement of Commercial Production. Subsequent amounts of production bonuses are related with the attainment of different levels of cumulative production. These are not stipulated by law nor are they deductible as 'payments to Government':

10. Local Employment, Training, Social Welfare.

Local employment, training and social welfare schemes, with defined investment levels, will apply to all existing and new concessions.

11. Control of Environmental Pollution

The Petroleum Concession Agreement imposes obligations on the Operator to observe all laws, rules and regulations in respect of safety in operations and the control of environmental pollution. The relevant laws in this area are the Oil and Gas (Safety in Drilling and Production) Regulations 1974, the Territorial Waters and Maritime Zone Act 1976 and the Pakistan Environmental Protection Ordinance 1983. The Oil and Gas Regulations 1974 apply to drilling operations, both off-shore and on-shore, and stipulate applicable safety standards and procedures. The growing concern about protection of the environment is addressed by the Environmental Protection Ordinance 1983 and the Territorial Waters and Maritime Zone Act 1976 which lay down environmental standards to be regulated through Environmental Protection Agencies. Under the new petroleum policy (1994), incentives have been provided for energy conservation, environment and safety control.

ADVANTAGES/DISADVANTAGES OF TAX / ROYALTY TYPE CONTRACT

In the Tax/Royalty type contract being followed at present in Pakistan, the Government's role is to a great extent passive, though the Government does exercise regulatory powers. The Director General Petroleum Concessions (DGPC) is the Chairman of each joint venture Operating Committee normally with no voting right. Under the Pakistan Petroleum (Exploration and Production) Rules 1986, all data is the property of the Government. The Director

General Petroleum Concessions has the power to inspect the well/plants, logs, other records and accounts. He also has the right to receive various reports in relation to Petroleum operations as specified in the Rules. The declaration of commerciality, the development plan, training programme etc are subject to Government approval.

In cases where OGDC is the Operator of the concession, the Government does participate in the management of operations. OGDC also applies for areas independently which it operates. In Joint Venture companies in which the Government has equity participation, it has representation on the Board of Directors and participates in the management policies of the company.

The advantage of this type of system is that the State's financial involvement during the risk phase is small. In situations where there is competitive bidding, the State's recovery and returns can also be substantial in terms of bonuses, royalty etc. The disadvantage is that a regime which has returns based on productivity would not take into account factors such as geological prospectivity, well productivity, costs and price projections. This may discourage the development of marginal fields especially since the State takes a large portion of the post discovery working interest and pays discounted oil and gas prices.

As a matter of policy change, the Government, for the first time, offered exploration blocks for competitive bidding by companies in the first round held in 1989. Forty three blocks were offered (36 onshore and 7 offshore). A second round was announced in early 1993 when further 17 blocks were offered.

In deciding which type of legal and fiscal regime will apply, the Government has to keep in mind its overall national objective, the country's petroleum potential, extent of exploration activity and success ratio. A proven oil producing country will obviously be able to demand better terms in comparison to a country where the exploration risk is perceived to be high. Thus the evolution of contract types in Pakistan will be directly linked to exploration activity and the discovery of petroleum resources.

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25

Economics of Petroleum Exploration/ Production

Petroleum plays a very important role in controlling the geopolitical equilibrium of the world. Despite the availability of alternate forms of energy, oil/gas are still the cheapest source. In spite of the decline in oil price after mid 1980s, exploration activities have continued with greater emphasis in non-traditional areas and less explored basins such as Pakistan.

Oil and gas are non-renewable resources and have to be replenished by producers, with new reserves. This is important for survival and growth of an oil/gas exploration/production organization and fulfillment of energy requirements of a nation. Discovering additional petroleum reserves is vital for a country like Pakistan which currently (1992-93) imports about 70% of its petroleum requirements: a very heavy burden (30% of export earnings) on its foreign exchange resources.

Pakistan, at the time of independence in 1947, produced 1,500 bpd of oil. Subsequently the oil production gradually rose to 10,000 bpd in 1960s. It was, however, in mid seventies that exploration for oil gained momentum followed by discoveries/development and rapid increase in production from early 1980s (Fig. 25.1). After the first spectacular, and still the biggest, gas discovery (Sui, 1952) followed by Mari (1957), new natural gas discoveries were also made during this period and steady increase in gas demand (Fig. 25.1) was met by development of producing fields and fresh discoveries. In mid 1992, natural gas recoverable reserves of Pakistan stood at about 23 Tcf (Fig. 25.2).

Pakistan, however, continues to remain a net energy importer (Fig. 25.3) relying heavily on fossil fuels (Fig. 25.4) for its requirements. Pakistan's total energy requirement for 1992 stood at 32 million tons of oil equivalent, of which over 80% was met by fossil fuels. An overview of Pakistan's petroleum industry is presented in Fig. 25.5.

Exploration for petroleum requires large high risk investment and from an investor's standpoint, it has to be related with adequate return or profit on this expenditure. In this section, economics of petroleum exploration and production will be dealt from an independent oil company's point of view, operating under the present petroleum policy and fiscal regime in Pakistan.

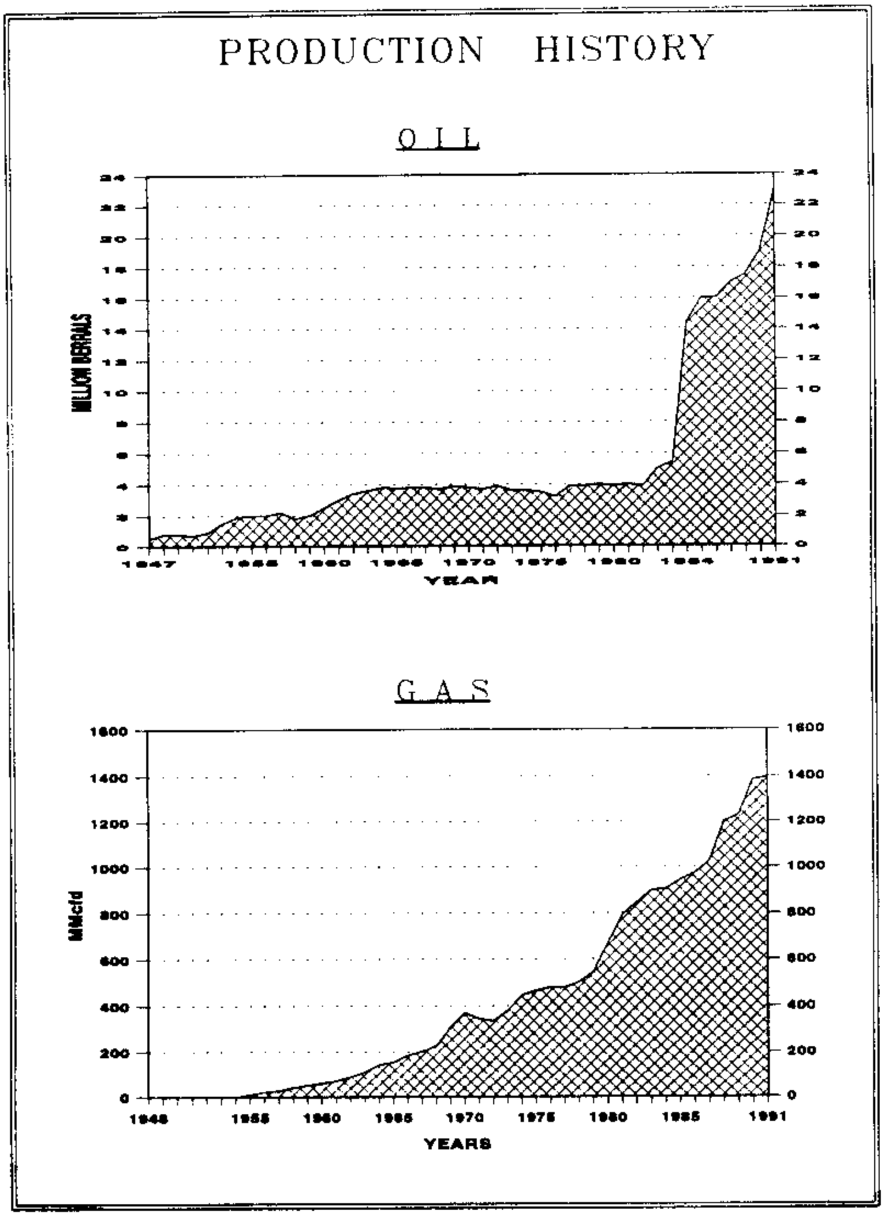


Figure - 26.1 Production History

RISK ANALYSIS

Petroleum exploration is characterized as a 'risk intensive' business. This is mainly due to the geological risk of drilling a dry or non-productive well. Other risks such as political, economic, prices, environmental etc. also need consideration. Another aspect which needs consideration is 'Uncertainty'. Although the two, 'Risk' and 'Uncertainty', are used interchangeably, however, there is a subtle difference which is explained below.

The 'Risk' is an 'opportunity for loss'. It involves size of investment, potential gain or loss and probability of the most likely outcome. 'Uncertainty' refers to the range of probabilities that some conditions may exist or occur. Hence, every exploration decision involves considerations of both Risk and Uncertainty.

Evaluation of 'Risk' and 'Uncertainty' involves knowledge of probability analysis. Probability is the mathematical evaluation of uncertainty of events. The range of probability is from zero to one with the highest value of probability being assigned to the case which is most likely to occur. A probability of 0.8 for a particular event relative to a probability of 0.4 means that the occurrence of a 0.8 probability event is twice more likely than the 0.4 probability event.

In evaluation of 'Risk' and 'Uncertainty', it is necessary that one is able to recognize a situation where the confidence in its occurrence is not 100%. It is then necessary to subdivide this situation into major components and quantify the 'Risk' and 'Uncertainty' of each sub-event.

One of the methods used to quantify

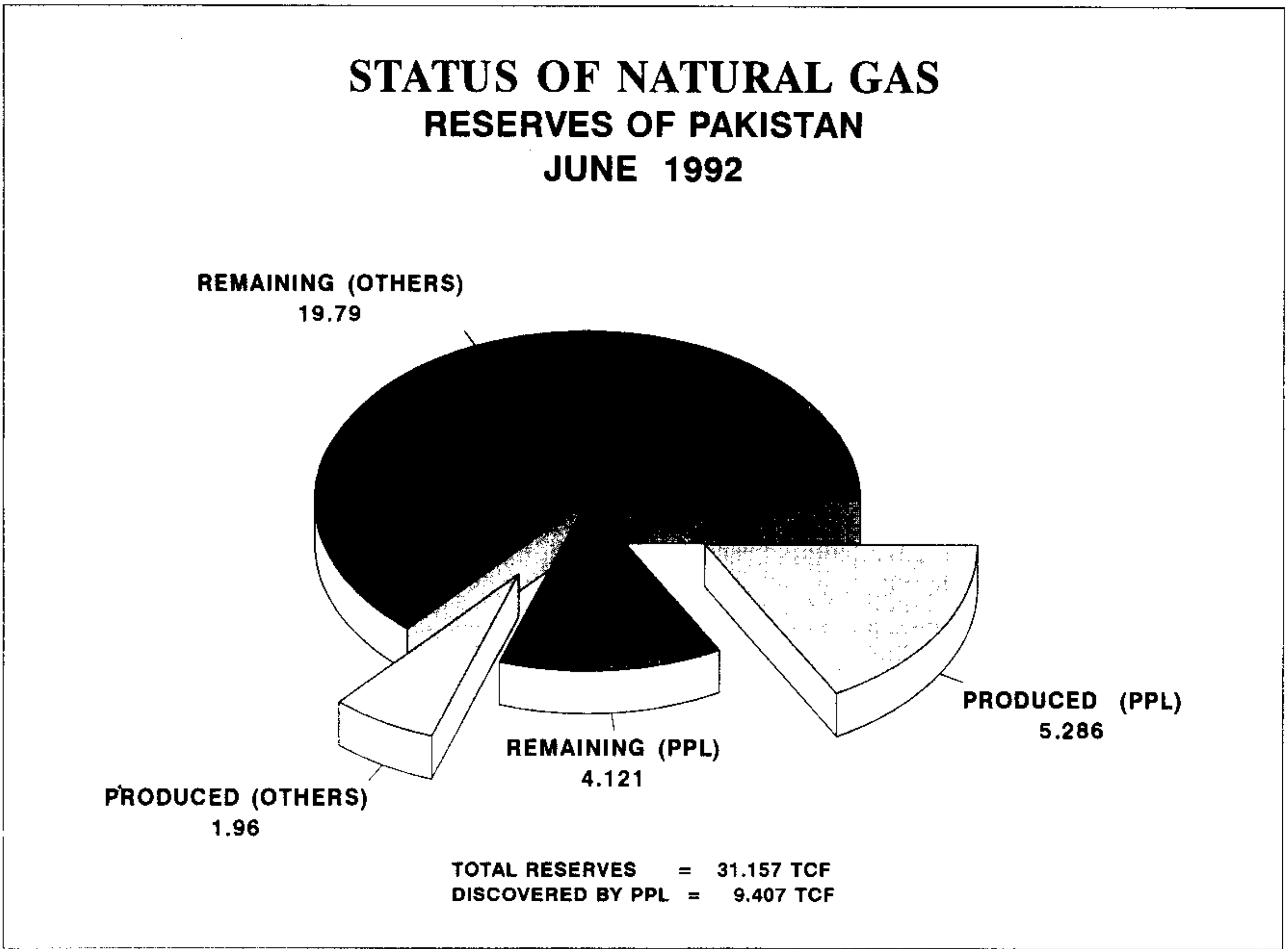
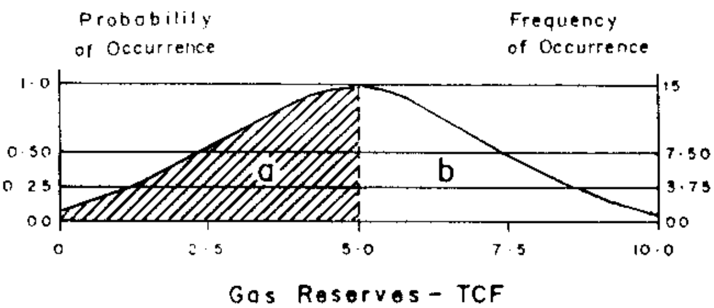


Figure - 25.2 Status of Natural Gas Reserves of Pakistan, June 1992

the probability of occurrence of an event is to develop a frequency distribution of this occurrence. This frequency distribution is evolved over time and incorporates the historical events. As an example let us look at the probability of occurrence of hydrocarbon reserves.



This is a normal frequency distribution curve which shows the most likely probability of occurrence to be 5 Tcf (best estimate), with 2.5 Tcf and 7.5 Tcf having the same probability of occurrence. Frequency distributions may be skewed to one side or the other depending on the data. The probability of the most likely case, which is also called 'Risk', is the ratio of area 'a' to the area 'a' plus 'b'. Whereas 'Uncertainty' is the range of minimum to maximum values.

This type of frequency distribution

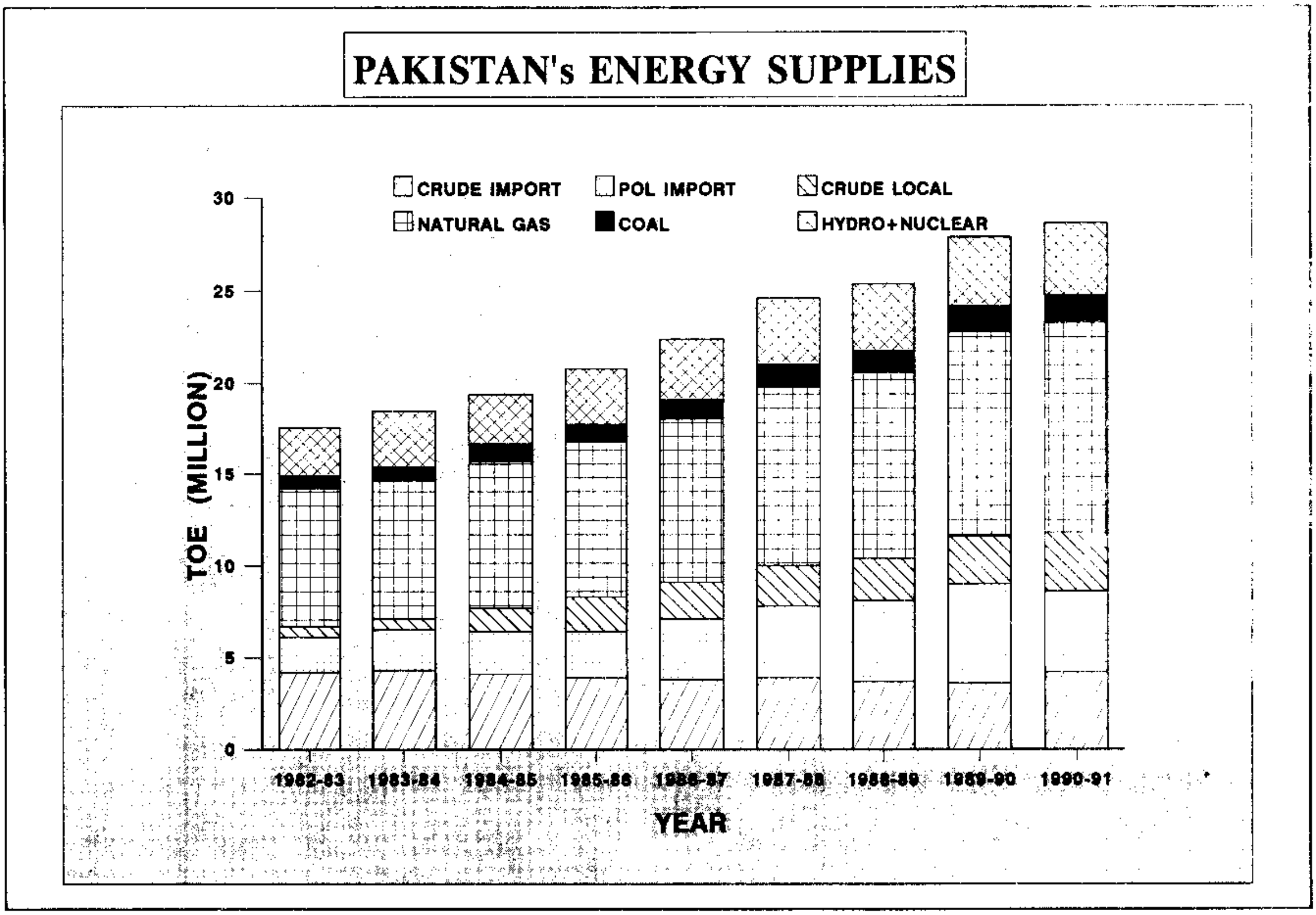


Figure - 25.3 Pakistan's Energy Supplies

should be made for each sub-event in order to arrive at probability estimates for each sub-event. For improving the 'Risk' the probability range ought to be minimised by selecting appropriate areas where frequency of data is high. As an example let us look at the probability of discovering hydrocarbons. This event can be sub-divided into the following six major sub-events:

Basin Type and Geologic Age

Cratonic, Rift, extensional, compressional, etc.

Sedimentary Sequence

Marine, non-marine, depositional conditions, aerial distribution, thickness of potential sources and reservoirs, cap rock etc.

Presence and Maturity of Source Rock

Amount Of Organic Matter

- Drainage Area
- Source Rock Thickness
- Total Organic Carbon
- Type of Organic matter

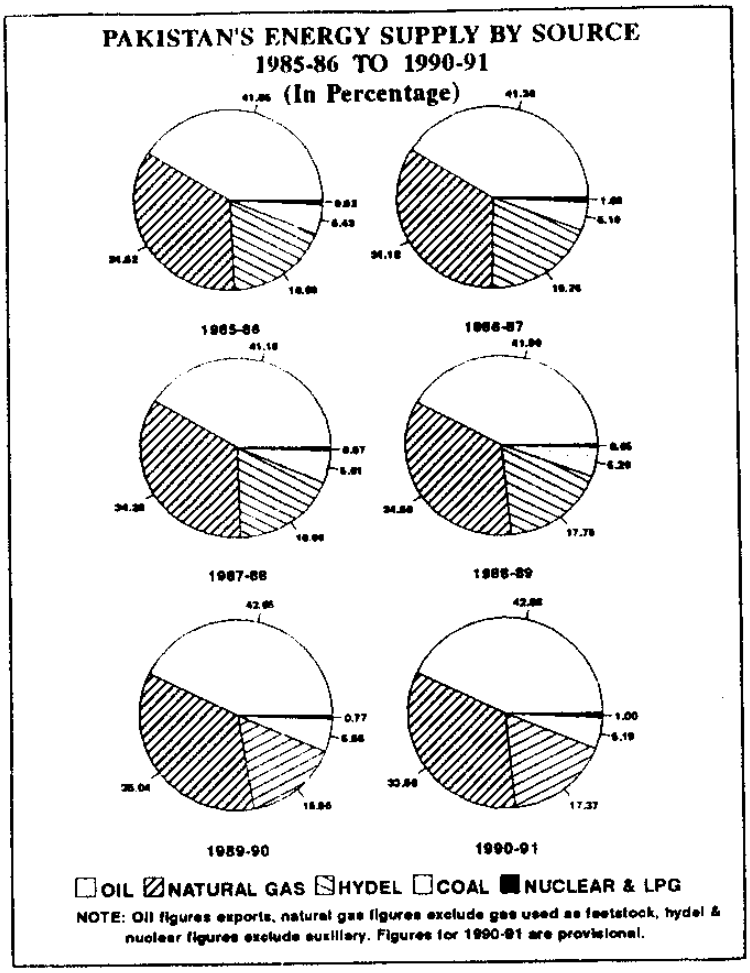


Figure - 25.4 Pakistan's Energy Supply by Source, 1985-86 to 1990-91

PAKISTAN
1992 PETROLEUM INDUSTRY OVERVIEW

Pakistan's Energy Requirements (MTOE/Year)	32
Requirements Met By (%):	
Oil	41
Natural Gas	36
Hydel Power	17
Coal	5
LPG & Nuclear	1
Energy Consumption Sectorwise (%):	
Domestic	18
Commercial	3
Industrial	27
Agriculture	6
Transport	18
Power Generation	22
Fertiliser*	3
Others	3
* Excluding feedstock of 60% total gas supply to fertiliser industry.	
Oil Production (BPD)	60,450
OGDC	25,570
Union Texas Pak	17,740
Occidental	11,250
POL	3,425
PPL	2,465
Gas Production (MMcfd)	1,517
PPL	802
MGCL	261
OGDC	249
Union Texas Pak	142
Occidental	26
POL	17
Oil Refining (Design Capacity MT/Year)	
National Refinery Ltd	2.92
Pakistan Refinery Ltd	2.13
Attock Refinery Ltd	1.41

Figure - 25.5 Pakistan 1992 Petroleum Industry Overview

Quality and Maturation of Hydrocarbons
- Time, Temperature
- Biodegradation
- Overcooking (related to maturation)

Presence and Quality of Reservoir
- Thickness
- Depth
- Porosity
- Permeability
- Continuity
- Hydrocarbon type & quality
- Pressure (Drive)

Presence of Migration Path
- Primary - Expulsion
- Secondary
- Timing
- Flushing
- Diffusion

Presence of Trap/Seal
- Closure Size
- Seals
- Top, Bottom, Lateral
- Timing

In an unexplored basin, the probability of occurrence of these sub-events is low as data is limited to surface geological work with no well control. Assigning probability estimates to each sub-event and computing the combined probability would result in a value of 0.0156; for an exploratory well this factor is also termed the 'Chance of Success'.

In an extensively explored basin the probability of occurrence of third and fourth sub-events would be very high with probability decreasing for the fifth and sixth.

	Unexplored Basin	Explored Basin
Presence & Maturity of Source Rock	0.5	0.95
Presence of reservoir quality Rock	0.5	0.95
Presence of Migration Path	0.25	0.75
Presence of Trap/Seal	0.25	0.75
Combined probability	0.0156	0.508

The above example shows that in this case the 'Risk' of discovering hydrocarbons in an unexplored basin is over 30 times greater than in an explored basin. These estimates of probability can be improved as additional data becomes available.

Such an evaluation of 'Risk' and 'Uncertainty' is carried out at each stage commencing from prospect evaluation to field development. Risk analysis has been considerably aided with the progress made in microcomputers. Software is now available for analysis of the frequency of occurrence data and subsequent 'Risk' analysis.

All of these factors, outlined above, lead to the estimation of 'Risk' in discovering commercially productive reserves. The total 'Risk' of the venture would be calculated as discussed in the previous paragraphs. The professional explorationist is required to minimise the 'Risk' exposure by collecting data where insufficiency exists and selecting areas where probability range is narrow.

Fig. 25.6 & 25.7 are examples for potential gas prospects in Central Indus Basin.

The areas around oil and gas discoveries with proven commercial potential are regarded low risk areas (e.g. Sui, Kandhkot, Khaskheli, Potwar etc.), while those areas where no significant exploration work has been undertaken and are considered geologically complex, are high risk areas (e.g. Kakar Khorasan Basin, Balochistan Basin, offshore Indus and Makran).

The sedimentary basins of Pakistan, based on present understanding, can be divided into three categories on the basis of prospectivity, regional geology, exploration history, success ratio, oil / gas discoveries, available geological / geophysical data, cost of additional data acquisition, exploratory drilling and field development cost, access to refineries, gas transmission system, consumption centres etc. These categories are:

i) High risk–High cost: Offshore Indus / Makran, Waziristan, Peshawar Basin, and subthrust plays in Potwar.
ii) Medium risk–High cost: Potwar/ Kohat, Bannu Basin, Kirthar, Sulaiman Fold Belt and deep plays in Central Indus Basin.
iii) Medium risk–Low to High cost: Punjab Platform, Kirthar / Sulaiman Foredeep. Central Indus Basin Tertiary objectives. Badin Platform (Paleozoic and Mesozoic objectives).

The economic package in the Petroleum Policy (1994) has been defined and fixed for the three zones.

PROFITABILITY INDICATORS

While making an investment in any enterprise an entrepreneur requires a realistic

PROSPECT RESERVES ESTIMATES

COUNTRY : PAKISTAN	BASIN : CENTRAL INDUS	PROSPECT : GAS	HORIZON : SUI MAIN

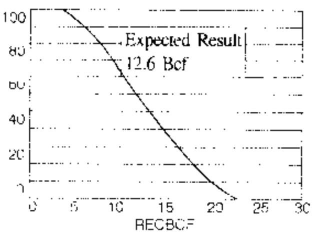
Input Data: Optimistic Case

Variable	Unit	Shape	Minimum	Mode	Maximum
Area	km2	Single		8	
Vertical Closure	m	Single	-	20	-
Rock Volume	m km2	Single		109.5	
Net pay to Total	%	Triangle	17	38	58
Porosity	%	Triangle	15	19	23
Water Saturation	%	Triangle	25	30	40
Formation Volume Factor	vol/vol	Triangle	113	119	125
Recovery Factor	%	Triangle	60	70	80
Hydrocarbon Fraction	%	Triangle	70	80	90

Results Summary

	Recoverable unrisked Reserves (BCF)
Expected/Mean	12.6
Maximum	17.0
Minimum	8.5

SUI MAIN
MONTE CARLO RESERVE ESTIMATE



Comments
Reservoir parameters and gas composition from nearby fields in similar geologic setting

Figure 25.6 Reserve Estimates and Risk analysis of a very small gas prospect in Lower Indus Basin

PROSPECT RESERVES ESTIMATES

COUNTRY : PAKISTAN	BASIN : CENTRAL INDUS	PROSPECT : GAS	HORIZON : SUI MAIN

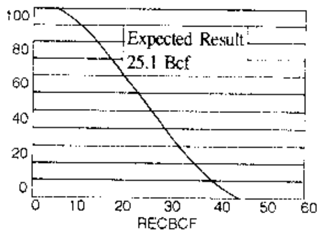
Input Data: Optimistic Case

Variable	Unit	Shape	Minimum	Mode	Maximum
Area	km2	Single		10	
Vertical Closuure	m	Single	-	45	
Rock Volume	m km2	Single		218.5	
Net pay to Total	%	Triangle	17	38	[illegible]
Porosity	%	Triangle	15	19	[illegible]
Water Saturation	%	Triangle	25	30	[illegible]
Formation Volume Factor	vol/vol	Triangle	113	119	[illegible]
Recovery Factor	%	Triangle	60	70	80
Hydrocarbon Fraction	%	Triangle	70	80	90

Results Summary

	Recoverable unrisked Reserves (BCF)
Expected/Mean	25.1
Maximum	33.7
Minimum	16.8

SUI MAIN
MONTE CARLO RESERVE ESTIMATE



Comments
Reservoir parameters and gas composition from nearby fields in similar geologic setting

Figure - 25.7 Reserve Estiamtes and Risk analysis for a marginal gas prospect in Central Indus Basin.

basis for evaluating the economic worth or profitability of a venture. This section discusses some of the commonly used measures of profitability for a decision on economic acceptability of a project. These measures are also referred to as profitability indicators, economic yardsticks or economic decision criteria. The profitability indicators discussed in this chapter are:

Payout Time
Profit to Investment Ratio
Rate of Return
Net Present Value Profit

Other indicators such as Appreciation of Equity, Percentage Gain on Investment etc are also prevalent but their use is not very common. In general, the indicators should have the following characteristics:

i) Comparison and ranking of profitability of an investment venture should be possible.
ii) It should be referable to a minimum value such as cost of capital etc.
iii) The time value of money should be reflected and it should cater for the organization's fiscal policies.

Payout Time

The payout time of an investment is the length of time it takes for the cumulative net revenues to equal the investment. This measure provides an approximate indication of the rate of cash flow generation. Since it measures the time of payback of an investment only, the overall profitability of the venture remains unknown. However, it gives an indication of the time a venture would take to start making a profit after recovery of initial investment.

On its own, this indicator is not sufficient to base an investment decision on.

Profit To Investment Ratio

The profit to investment ratio reflects the total profitability of a venture. This is defined as the ratio of total net profit to investment over the life of the venture. A variant used is the Return on Investment (ROI). ROI is the ratio of the total revenue to investment. The difference between the two is that while total net profit i.e. income minus expenditure, is considered in the first case, the second case (ROI) considers the total income.

Net Present Value Profit

The Net Present Value Profit or NPV employs the concept of time value of money. This concept means that the value of a monetary unit today is more than its value in the future. The factor by which value of money decreases with time is termed as the 'discount factor' and is compounded on an annual basis. The NPV of a venture is determined by calculating the net profit for each year. These values are then adjusted to a base year by multiplying with each year's discount factor. The total net profit thus calculated is the NPV at the annual discount factor.

<u>**Example**</u>

The net annual profit calculated for a five year period of a project is –500, –200, 400, 400, 400. The NPV of the project at a 10% annual discount factor calculated on a first year basis is as follows:

Year	Annual Profit (Loss)	Discount Factor	NPV
0	(500)	1	–500.0
1	(200)	$1.000 - \frac{10}{100} = 0.900$	–180.0
2	400	$0.900 - \frac{0.900}{100} = 0.810$	324.0
3	400	$0.810 - \frac{0.810}{100} = 0.729$	291.6
4	400	$0.729 - \frac{0.729}{100} = 0.656$	262.4
		Total NPV	198.0

The choice of the discount factor varies with the fiscal regime and conditions of a specific situation. A venture is considered profitable if the NPV is a positive number.

Internal Rate of Return (IRR)

This is the most commonly used indicator for evaluation of investment opportunities. The Internal Rate of Return (IRR) is the annual discount rate which makes the NPV of a project zero over the life of the project. A project is economically viable if the IRR is greater than a minimum reference value; such as the cost of capital plus a certain profit margin.

The earlier described 'payout time' and 'profit to investment ratios' are sometimes calculated on a present value basis i.e. taking the time-value of money concept into consideration. The four indicators discussed above generally provide a good indication on a venture's profitability.

MINIMUM EXPLORATORY WORK OBLIGATIONS

The motivation for any entrepreneur in undertaking an investment venture is the profit. In a free market situation, profits are linked with risk. Higher the risk the greater would be the expected profit. It is, therefore, necessary to carry out risk and economic evaluation in order to ascertain the profitability of an exploration venture.

After technical evaluation of a prospect has been completed, estimates for the following should be available: (Fig. 25.8)

Chances of success

Volume and type of reserves

Areal extent of reservoir

Depth of reservoir

Pressure and temperature of reservoir

Productivity of reservoir

At this stage of prospect evaluation both the technical / geological and financial factors are taken into account to work out the economic scenario. Based on the economic scenario the companies decide their strategies for commitments to be made with respect to the work programme in Exploration Licence application. This becomes even more important for expected marginal fields.

A minimum exploratory work programme, a requirement of the licencing authority of the Government of Pakistan, is to be offered by the bidder when making an Exploration Licence application. This obligation is determined on the basis of the factors mentioned in the previous paragraphs.

Example

Typical work obligations offered by a bidder for an area of 4,500 sq. km located in Lower Indus Basin, would be about 1,200 line km seismic survey, drilling of one firm and possibly two conditional appraisal wells to test the objective reservoir. In addition, the companies also commit to undertake special studies (source rock/basin studies, reprocessing of seismic data etc.).

Cost estimates for these activities are prepared for subsequent use in the economic evaluation of the prospect. This represents risk investment and even if no commercial discovery is made, it does not entirely go in vain as it provides a wealth of geological information. Fig. 25.9 & 25.10 show typical annual distribution of costs for exploratory drilling phase. Fig. 25.11 & 25.12 show the exploratory well cost distribution in various basins of Pakistan.

A field development programme would include drilling of wells to obtain optimum production, installation of pipelines for collection of produced hydrocarbons, wellhead

AREA (4,500 Sq Km)

	No of Structures	Size of Structures (Sq Km)	Prospective Reservoirs	Reservoir Depth (m) (Pressure psig)	Well Depth (m)	Gross Pay (m)	Porosity (%)	Water Saturation (%)	Hydrocarbon Type	Remarks
Confidence Level	70%	50%	80%	80%	90%	80%	70%	70%	80%	
	Two (Based on commitment) 1	100	SML	800 (1300)	1500	50	15	30	Gas	Size of Fields Sui 150 Sq Km Mari 100 Sq Km Kadanwari 100 Sq Km Mazarani 22 Sq Km
	2	100	SML	1000 (1600)	1500	50	15	30	Gas	

Figure - 25.8 Basic assumptions for reserves and economic evaluation for a typical area in Central Indus Basin, covering an areal extent of about 4500 Sq. Km.

ANNUAL COST DISTRIBUTION
POTWAR EXPLORATORY DRILLING

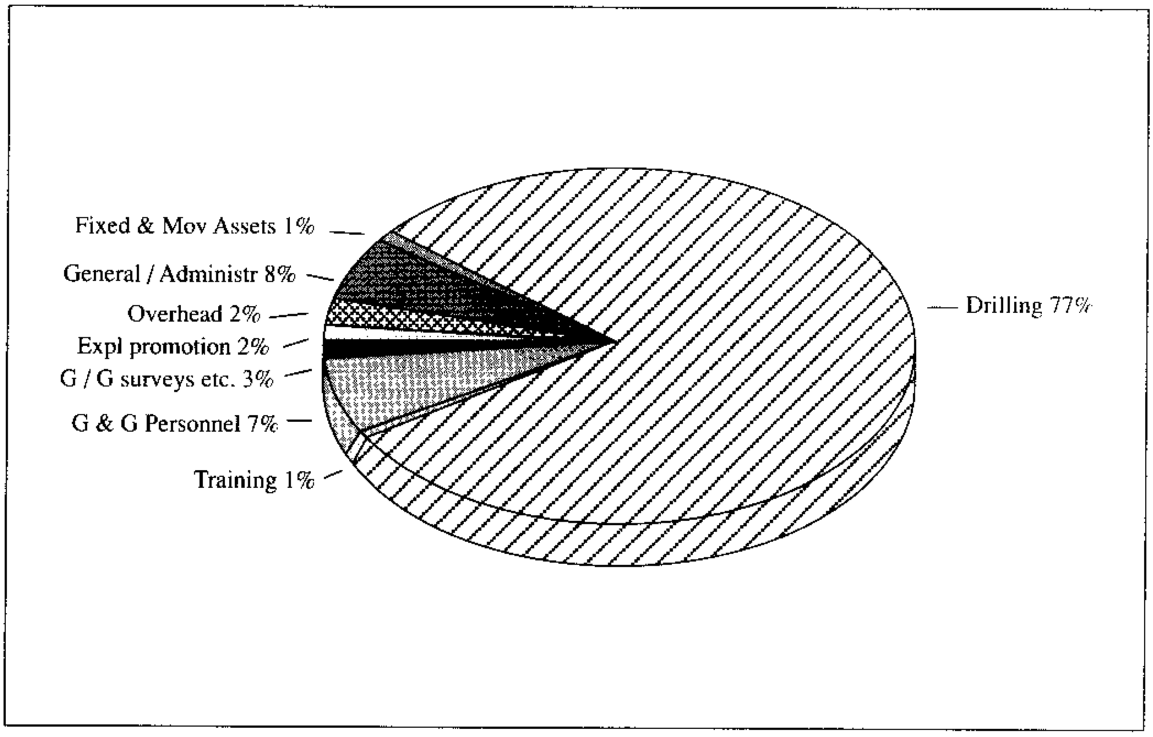


Figure - 25.9 Annual Cost Distribution - Potwar Exploratory Drilling

ANNUAL COST DISTRIBUTION
EXPLORATORY DRILLING

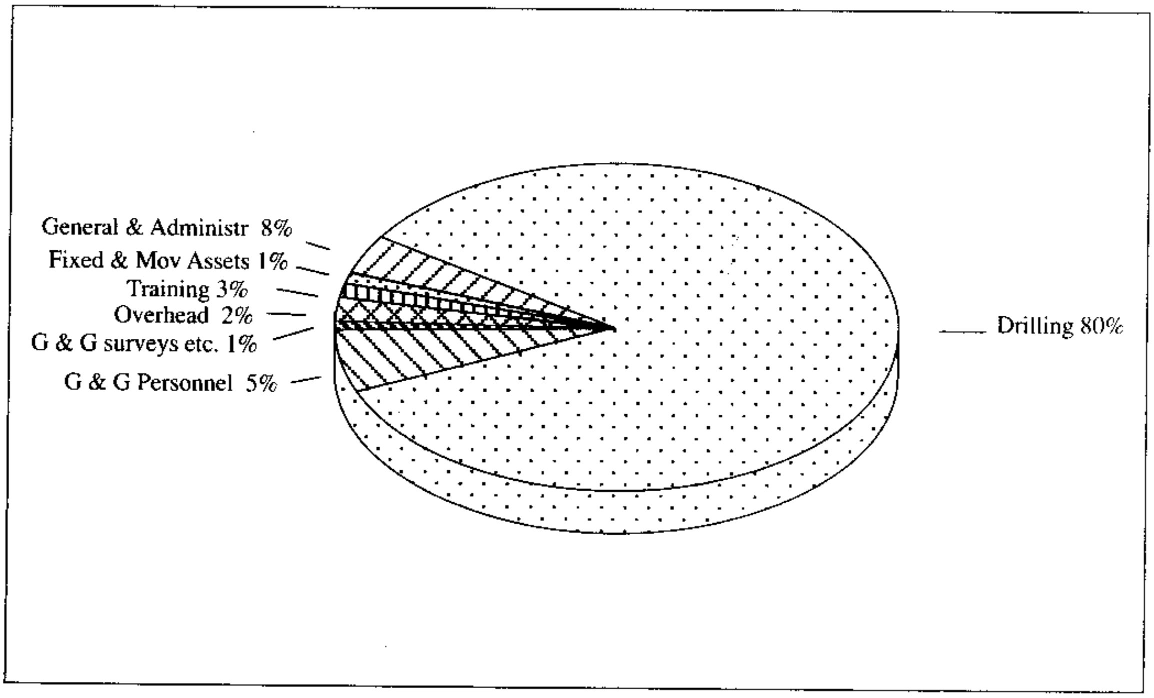


Figure - 25.10 Annual Cost Distribution - Exploratory Drilling in Central Indus Basin.

POTWAR BASIN
WELL COST DISTRIBUTION

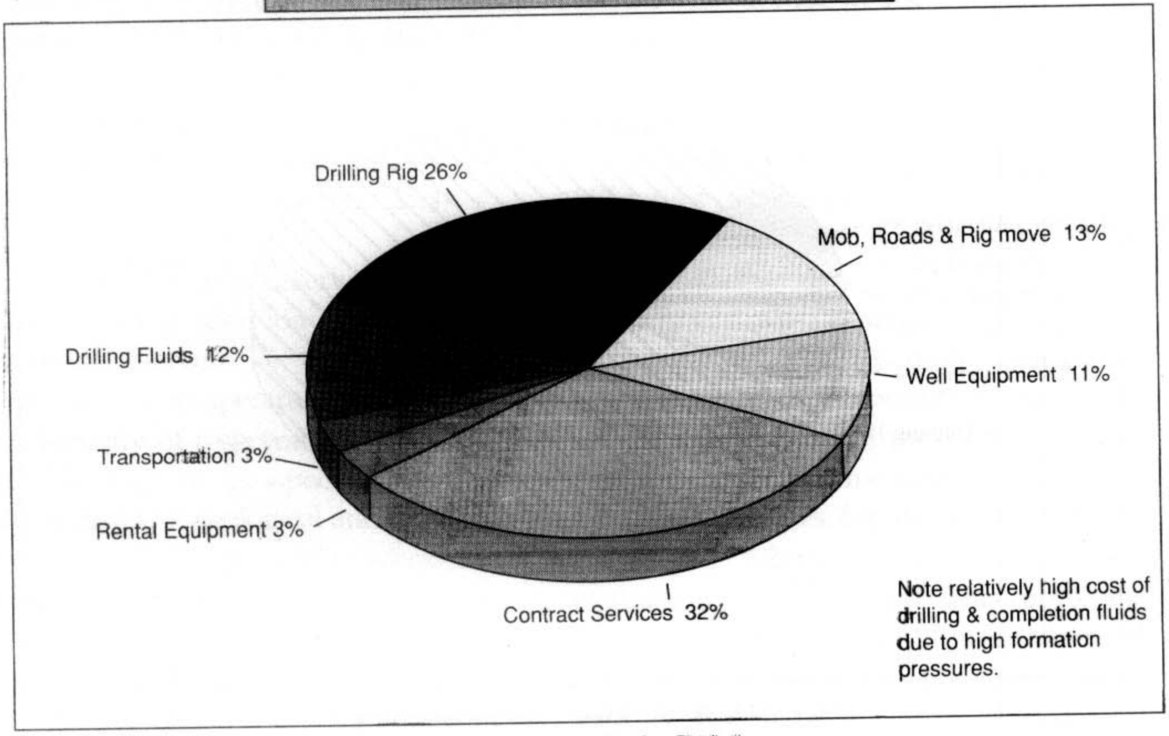


Figure - 25.11 Potwar Basin - Well Cost Distribution

CENTRAL & SOUTHERN INDUS BASIN
WELL COST DISTRIBUTION

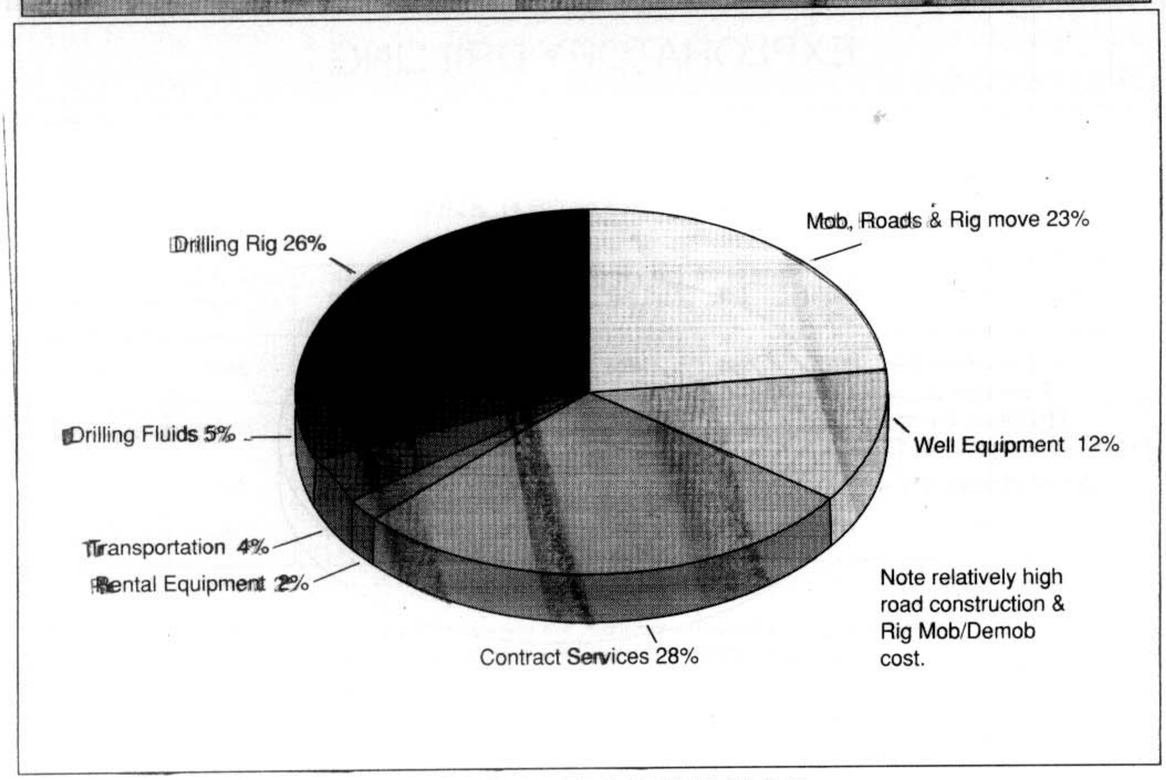


Figure - 25.12 Central & Southern Indus Basin - Well Cost Distribution

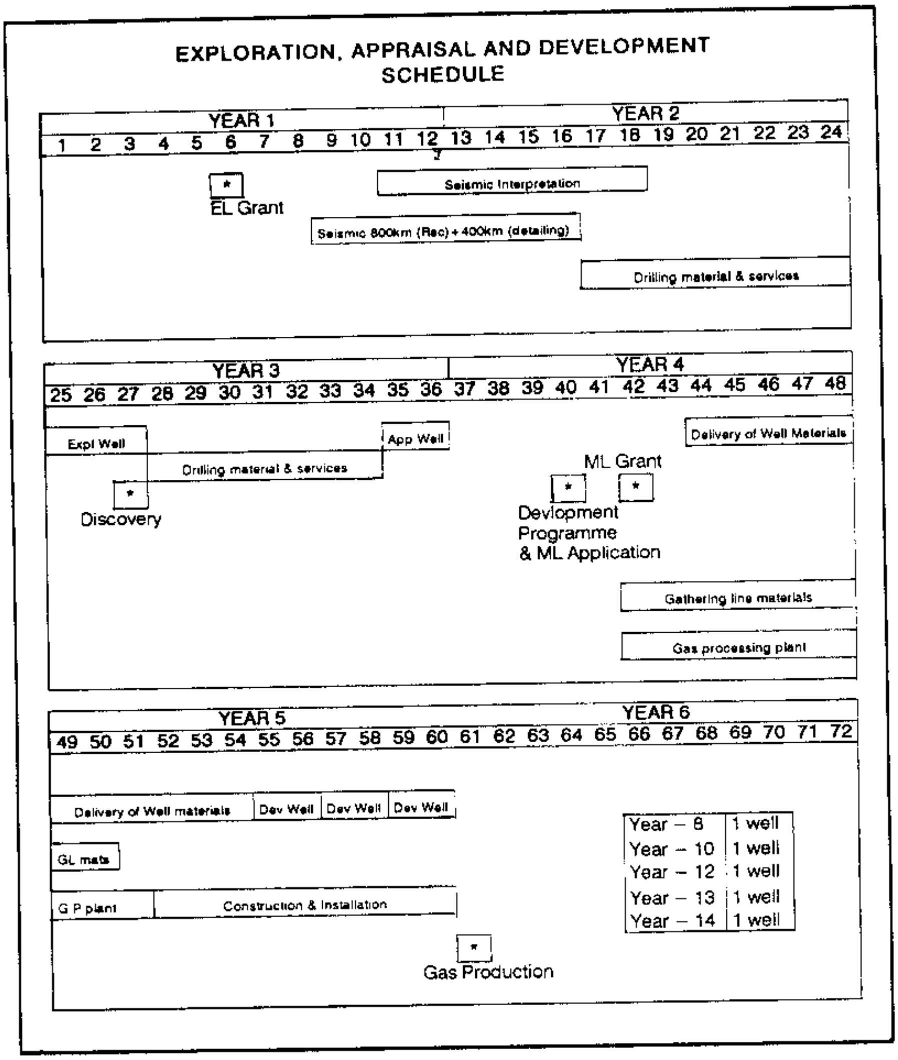


Figure - 25.13 Exploration, Appraisal and Development Schedule

hydrocarbon processing equipment and infrastructure facilities. Infill drilling and/or injection wells may also be required to maintain production and maximise ultimate recovery of hydrocarbons.

Bar chart shown in Fig. 25.13 indicates the typical work programme for Exploration, Appraisal and Development phases of a potential gas field. This bar chart is drawn on the basis of minimum exploratory work obligations and production potential of the undiscovered field. The daily production for a gas field, as a rule of thumb, is taken as 1/10,000th of the total recoverable reserves of the field. Fig. 25.14 represents the production profile for a typical medium size gas field in Central Indus Basin.

This bar chart forms the basis for costing of the expenditures envisaged during exploration, appraisal and development phases.

The major cost factors that need to be considered are as follows:

Cost of Exploration Work Programme

a) Geological and Geophysical surveys
b) Drilling and completion of Exploratory and Appraisal wells

Cost of Development Work programme

a) Development Seismic Survey
b) Drilling and completion of Development wells
c) Hydrocarbons collection pipelines
d) Hydrocarbons processing plant
e) Infrastructure facilities i.e. roads, accommodation, utilities etc.

Cost of Field Operation Work Programme

a) Drilling of infill/injection wells
b) Field operating expenses

PRODUCTION PROFILE

Initial Gas In Place	871,829 MMcf
Initial Reservoir Pressure	1,600 Psia
Field Production Rate	65 MMcfd

Prod Year	Gas-in-Place MMcf	Cumulative Production MMcf	Reservoir Pressure Psia	Field Rate MMcfd	Rate per Well MMcfd	No of Wells	Max Rate per Well MMcfd	AOFP MMcfd
1	871,829	0	1,600	0	0.0	0	0.0	26.0
2	848,104	23,725	1,556	65	13.8	5	17.2	26.0
3	824,379	47,450	1,513	65	12.9	5	16.1	24.8
4	800,654	71,175	1,469	65	12.1	5	15.1	23.7
5	776,929	94,900	1,426	65	11.2	6	14.0	22.7
6	753,204	118,625	1,382	65	10.4	6	12.9	21.6
7	729,479	142,350	1,339	65	9.5	7	11.9	20.5
8	705,754	166,075	1,295	65	8.7	7	10.9	19.5
9	682,029	189,800	1,252	65	7.9	8	9.8	18.5
10	658,304	213,525	1,208	65	7.1	9	8.8	17.5
11	635,524	236,304	1,166	62	6.2	10	7.8	16.6
12	615,575	256,253	1,130	55	5.5	10	6.8	15.7
13	598,104	273,725	1,098	48	4.8	10	6.0	14.9
14	582,808	289,020	1,070	42	4.2	10	5.2	14.2
15	569,429	302,400	1,045	37	3.7	10	4.6	13.6
16	557,741	314,087	1,024	32	3.2	10	4.0	13.1
17	547,549	324,280	1,005	28	2.8	10	3.5	12.7
18	538,680	333,148	989	24	2.4	10	3.0	12.3
19	530,984	340,845	974	21	2.1	10	2.6	12.0
20	524,326	347,502	962	18	1.8	10	2.3	11.7
21	517,153	354,676	949	20	1.6	10	2.0	11.5
22	511,255	360,574	938	16	1.3	10	1.6	11.3
23	506,445	365,383	929	13	1.1	10	1.3	11.1
24	502,561	369,268	922	11	0.9	10	1.1	10.9
25	499,459	372,370	917	8	0.7	10	0.8	10.8

Recovery @ 15 yrs	36 %
Ultimate Recovery	43 %
Delivery Pressure	600 Psig
System Press Drop	300 Psig
Maximum Wells	10

ASSUMPTIONS

1. Maximum wells drillable on the structure limited on the basis of incremental recovery per well.
2. Field rate based on 10 year production plateau allowing for drilling of maximum number of wells during first 3 years of ML.
3. Field abandonment based on delivery pressure of 600psig and system pressure drop of 350psig.
4. Condensate production assumed at 10 barrels/MMcf gas.

RESERVES IN PLACE CALCULATION

INPUT		RESULTS	
Reservoir Pressure	1,600 Psia	Formation Volume Factor	107
Reservoir Temperature	160 Deg F		
Compressibility Factor	0.85		
Area	100 Sq Km		
Gross Pay	50 m	Gas Column (meters)	50
Net/Gross	0.60	Rock Volume (cft)	1.3E+11
Porosity	0.15	Initial Gas In Place (scf)	8.7E+11
1-water saturation	0.70		

Figure - 25.14 Production Profile for a typical medium size gas field in Central Indus Basin

EXAMPLE GAS PRICE CALCULATION

The price of Non–Associated Gas (Natural Gas) was earlier linked on an import parity basis with High Sulpher Fuel Oil (HSFO). In the Petroleum Policy anounced in 1994 the price has been linked to a basket of Arabian/Persian Gulf crude oils with a parity factor based on the prospectivity zones defined in the policy. The price determination for the basket of crudes is based on the weighted average C&F price of crude imported into Pakistan during the preceding six month period. For HSFO based pricing, the arithmetic average for the past six months under Waterborne Spot Market Arab Gulf FOB with freight from Rastanura to Karachi is used.

An example calculation for HSFO and crude oil based pricing is given below. Actual pricing calculations may vary from field to field.

Marker Price US$ per M.Ton	Assumed Average Price US$ per M.Ton	Step Discount %	Resultant Price US$ per MMBTU
0 – 80	70	0	1.7160
81 – 100	90	15	1.8754
101 – 120	110	20	2.1573
121 – 140	130	28	2.2946
141 – 160	150	34	2.4269
161 – 180	170	40	2.5005
181 – 200	190	45	2.5618

The above discount table is effective for HSFO based pricing only.

	100% HSFO Parity Formula US$	Crude Oil Parity Formula US$
HSFO Spot Price (FOB) Freight Rastanura – Karachi	90.000 / Ton 3.890	
C & F Price	93.890 / M.Ton	15.000 / BBL
Assigned average price	90.000 / M.Ton	
Step Discount HSFO price band, Zone–1 (22.5% of crude oil)	13.500 / M.Ton	3.3750 / BBL
Discounted Price	76.500 / M.Ton	11.6250 / BBL
Gas price per MMBTU (Discounted HSFO price/40.792):(Crude Oil price/5.90*)	1.8754	1.9670
Calorific Value of Gas (BTU/SCF)	900	
Gas Price per Mcf	1.6879	1.7700

* Factor for conversion of crude oil Barrels to MMBTU will vary depending on the basket of crude applicable at the time of price determination

Figure – 25.15 Example Gas Price Calculation

FINANCIAL PARAMETERS

In addition to the cost of field exploration and development, the following financial parameters are taken into consideration while conducting the economic study:

1. Joint Venture (Working Interest Owners) shares during Exploration and Field Development phases
2. Royalty
3. Tax
4. Production Bonus
5. Oil/Gas Price
6. Oil Transportation Charges to the nearest refinery
7. Social Welfare Projects
8. Field Life (Determined by the production profile and contractual obligations)

OIL & GAS PRICE CALCULATIONS

The price of Non-Associated gas (Natural Gas) was earlier linked on an import parity basis with High Sulpher Fuel Oil (HSFO). However, under the 1994 Petroleum Policy, gas price has been indexed to C and F price of a basket of imported Arabian/Persian Gulf Crude Oils, with different discounts for different prospectivity zones of Pakistan.

An example price calculation formula for non-associated gas is given in Fig. 25.15. This example is based on earlier and current Petroleum Policy

Formula for crude oil price calculation is given in Fig. 25.16. However, under the 1994 Petroleum Policy, the price of crude oil delivered at the refinery gate shall be based on the C & F price of a comparable crude oil or a basket of Arabian/Persian Gulf crude oils plus or minus a quality differential between the basket of the local crude. No other adjustment or discount will apply.

The historical trend of consumer and producer gas prices in Pakistan and USA are presented in Fig. 25.17 and 25.18 respectively. The linking of gas price to HSFO price is not reflected in these figures as they are averaged on a volume basis. Historical trend of the Crude oil and HSFO prices is shown in Fig. 25.19 and 25.20.

ECONOMIC STUDY DURING EXPLORATION PHASE

Economic study of any undiscovered field is usually carried out assuming a field life of 15 to 25 years taking into account the Exploration Work Programme, Potential Reserve Estimates, Production Profile, Development Plan and financial parameters as described above. Reserves Estimates of a potential gas field are shown in Fig. 25.14 and based on these estimates Production Profile and Work Programme Bar Chart are developed and shown in Fig. 25.14 and 25.13, as discussed under the previous heading.

The revenue generated by the field is estimated on the basis of production profile and oil/gas prices prevailing at the time of evaluation and is projected for future years.

EXAMPLE CRUDE OIL PRICE CALCULATION

The Wellhead price for crude oil in Pakistan under the current policy is calculated on the following basis: –

			US $ / Bbl
a)	The arithmetic average of the FOB Spot Prices during the month of delivery of all Arabian Gulf Crude oils comparable in quality to crude oil produced from the area		18.000
b)	Plus or minus yield defferential between crude oil produced under the agreement and crude oil referred under (a) above.	(–)	(1.000)
c)	Plus freight for marine transportation from Ras Tanura to Karachi as applicable from time to time for chartered vessels. ($2.62 x ws 2.03 / 7.4917)		0.710
			17.710
d)	Minus cost of inland transportation from the well head to the nearest refinery. ($0.01 per barrel per Km x 70Km)		0.700
e)	Minus discount on the sum of (a), (b), (c) and (d) (at 10%)		1.700
	Applicable Price for Crude Oil		15.309

Discounts

Crude Oil Price US$ per Barrel	Discount Level %
0 – 11.99	0
12 – 14.99	7
15 – 20.99	10
21 – 26.99	12
27 – 34.00	15

Figure - 25.16 Example Crude Oil Price Calculation

This whole exercise is conducted to determine the profitability indicators.

An example of the economic study of a potential gas field is tabulated as Table 25.1 to show the steps required to work out the profitability indicators.

Only the very basic principles of economics as applied to petroleum exploration/ production in the backdrop of Pakistan situation, have been discussed here. There

ECONOMIC EVALUATION

	1	2	3	4	5	6	7	8	9	10
INCOME & EXPENDITURE										
SALES VOLUME										
Gas MMcf						4662.800	9125.000	9125.000	9125.000	9125.000
NGL Barrels						46626.000	91250.000	91250.000	91250.000	91250.000
PRICE										
Gas Rs/Mcf	25.410	25.918	26.437	26.966	27.505	28.055	28.616	29.188	29.772	30.367
NGL Rs/Barrel	339.241	346.026	352.946	360.005	367.206	374.549	382.040	389.681	397.475	405.424
INCOME										
Gas						128.008	261.119	266.341	271.668	277.102
NGL						17.080	34.861	35.559	36.270	36.995
Total Income						145.088	295.980	301.900	307.938	314.097
EXPENDITURE										
Royalty on Gas						16.000	32.640	33.293	33.959	34.638
Royalty on Oil						2.135	4.358	4.446	4.534	4.624
Production Bonus						12.145				
Exploration/Appraisal Cost	80.465	87.088	74.302	62.864						
Development Drilling					82.698	18.923	0.000	0.000	76.869	0.000
Field Operating Cost						8.402	14.084	15.482	17.042	18.746
Operator Overhead	1.271	1.458	1.303	1.100	2.779	1.100	1.100	1.100	2.569	1.100
Book Depreciation						14.937	5.136	5.136	13.806	6.583
Condensate Transport Charges						4.409	8.982	9.172	9.356	9.542
Expenditure before WPPF WWF	81.736	88.545	75.605	63.964	85.477	76.051	66.309	68.637	156.912	75.243
PROFIT & LOSS										
Profit (Income-Exp)	0.000	0.000	0.000	0.000	0.000	69.038	229.671	233.263	151.026	238.853
Workers' Profit Participation Fund (WPPF)	0.000	0.000	0.000	0.000	0.000	3.462	11.484	11.663	7.561	11.943
Workers' Welfare Fund (WWF)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.380	2.346	4.295
Total Expenditure	81.736	88.546	75.605	63.964	85.477	79.503	77.793	81.680	166.810	91.480
Profit Before Tax	-81.736	-88.546	-75.605	-63.964	-85.477	65.586	218.187	220.210	141.128	222.616
Less - Tax	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.484	26.035	78.839
Profit After Tax	-81.736	-88.546	-75.605	-63.964	-85.477	65.586	218.187	219.726	115.093	143.777
Unappropriated Profit of Current Year	-81.736	-88.546	-75.605	-63.964	-85.477	65.586	218.187	219.726	115.093	143.777
Unappropriated Profit of Last Year b/d		-81.736	-170.281	-245.886	-299.840	-385.317	-319.731	-101.544	118.182	233.275
Unappropriated Profit carried over	-81.736	-170.281	-245.886	-299.840	-385.317	-319.731	-101.544	118.182	233.275	377.052
TAX COMPUTATIONS										
Income Before Tax	-81.736	-88.546	-75.605	-63.964	-85.477	65.586	218.187	220.210	141.128	222.616
Add Book Depreciation	0.000	0.000	0.000	0.000	0.000	14.937	5.136	5.136	13.806	6.583
Add Royalty	0.000	0.000	0.000	0.000	0.000	0.000	0.000	37.737	38.492	39.262
Less Tax Depreciation						54.302	6.619	5.913	29.912	8.628
Less Depletion Allowance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	45.286	46.191	47.114
Taxable Income/Loss of year	-81.736	-88.545	-75.605	-63.954	-85.477	26.221	216.704	211.885	117.322	214.729
Taxable Loss of last year brought over		-81.736	-170.281	-245.886	-299.840	-385.317	-359.096	-142.392	0.000	0.000
Total	-81.736	-170.281	-245.886	-299.840	-385.317	-359.096	-142.392	69.494	117.322	214.729
Cumulative Taxable Loss carried over	81.736	170.281	245.886	299.840	385.317	359.096	142.392	0.000	0.000	0.000
Net Taxable Income	0.000	0.000	0.000	0.000	0.000	0.000	0.000	69.494	117.322	214.729
Tax on above @ 55%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	38.221	64.527	118.101
Less Royalty	0.000	0.000	0.000	0.000	0.000	0.000	0.000	37.737	38.492	39.262
Net Tax Payable	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.484	26.035	78.839
ASSETS & LIABILITIES										
CURRENT ASSETS										
Material & Spares		19.000	19.000		10.000	2.500	2.500	2.500	2.500	2.500
Trade Debtors for Gas						23.173	47.200	48.071	48.968	49.864
Trade Debtors for NGL	0.000	0.000	0.000	0.000	0.000	2.991	6.101	6.223	6.347	6.474
Advance Deposits Prepayment and other Receivables						2.000	2.000	2.000	2.000	2.000
Total	0.000	19.000	19.000	0.000	10.000	30.664	57.801	58.793	59.806	60.838
CURRENT LIABILITIES										
Royalty Payable						1.511	3.083	3.146	3.208	3.272
Excise Duty Payable						0.991	1.985	1.988	1.991	1.994
Other Credit Balances						1.500	1.500	1.500	1.500	1.500
Tax Payable/Tax Payable						0.000	0.000	0.242	13.018	38.419
WPPF	0.000	0.000	0.000	0.000	0.000	3.462	11.484	11.663	7.561	11.943
WWF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.380	2.346	4.295
Total	0.000	0.000	0.000	0.000	0.000	7.456	18.062	19.928	29.614	62.423
Net Current Assets	0.000	19.000	19.000	0.000	10.000	23.209	39.749	38.866	30.191	-1.586
Net Current Assets of Last Year		0.000	19.000	19.000	0.000	10.000	23.209	39.749	38.866	30.191
Increase/(Decrease) in Net Current Assets	0.000	19.000	0.000	-19.000	10.000	13.209	16.539	-0.884	-8.674	-31.776
CASH FLOW										
INFLOW										
Profit/(Loss) before Tax	-81.736	-88.546	-75.605	-63.964	-85.477	65.586	218.187	220.210	141.128	222.616
Add - Depreciation	0.000	0.000	0.000	0.000	0.000	14.937	5.136	5.136	13.806	6.583
Total	-81.736	-88.546	-75.605	-63.964	-85.477	80.523	223.323	225.346	154.933	229.200
OUTFLOW										
Tax Payment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.484	26.035	78.839
Capital Expenditure		[illegible]	0.862	0.000	95.176	16.607	0.000	0.000	45.600	0.000
Increase/(Decrease) in Net Current Assets	0.000	19.000	0.000	-19.000	10.000	13.209	16.539	-0.884	-8.674	-31.776
Total	0.000	28.[illegible]	0.862	-19.000	105.176	29.816	16.539	-0.400	63.161	47.063
Surplus/(deficit) in Cash	-81.736	-117.434	-84.267	-34.964	-190.653	51.706	206.784	225.745	91.772	182.146
Previous Year Cash Balance b/f		-81.736	-199.170	-283.437	-318.391	-509.044	-457.338	-250.564	-24.808	66.964
Cumulative Cash Balance at Year end	-81.736	-199.170	-283.437	-318.391	-509.044	-457.338	-250.564	-24.808	66.964	249.110
Net Cash Flow for the Year before Discount	-81.736	-117.434	-84.267	-34.964	-190.653	51.706	206.784	225.745	91.772	182.146
Cum. Cash Flow before Discount	-81.736	-199.170	-283.437	-318.391	-509.044	-457.338	-250.564	-24.808	66.964	249.110
Cash Flow Discount Factor (DCF) @ 20	1.000	0.833	0.694	0.579	0.482	0.402	0.335	0.279	0.233	0.194
Net Cash Flow for the Year after Discount	-81.736	-97.862	-58.519	-20.228	-91.943	20.780	69.252	63.001	21.343	35.301
Cum. Cash Flow After Discount	-81.736	-179.598	-238.116	-258.344	-350.287	-329.508	-260.256	-197.255	-175.912	-140.610

	11	12	13	14	15	16	17	18	19	20
INCOME & EXPENDITURE										
SALES VOLUME										
Gas MMcf	9125.000	9125.000	9125.000	9125.000	9125.000	8677.000	7847.500	7117.500	6387.500	5840.000
NGL Barrels	91250.000	91250.000	91250.000	91250.000	91250.000	85770.000	78475.000	71175.000	63875.000	58400.000
PRICE										
Gas Rs/Mcf	30.975	31.594	32.226	32.871	33.528	34.199	34.882	35.580	36.292	37.018
NGL Rs/Barrel	413.533	421.804	430.240	438.844	447.621	456.574	465.705	475.019	484.520	494.210
INCOME										
Gas	282.644	288.297	294.062	299.944	305.943	293.321	273.740	253.242	231.813	216.183
NGL	37.735	38.490	39.259	40.046	40.846	39.160	36.546	33.809	30.948	28.862
Total Income	320.379	326.786	333.322	339.990	346.789	332.481	310.287	287.051	262.762	245.044
EXPENDITURE										
Royalty on Gas	35.330	36.037	36.758	37.493	38.243	36.665	34.218	31.656	28.977	27.023
Royalty on Oil	4.717	4.811	4.907	5.006	5.106	4.895	4.568	4.226	3.869	3.608
Production Bonus										
Exploration/Appraisal Cost										
Development Drilling	0.000	0.000	110.772	0.000	134.034	0.000	0.000	0.000	0.000	0.000
Field Operating Cost	20.620	22.682	24.951	27.446	30.190	33.209	36.530	40.183	44.201	48.621
Operator Overhead	1.100	1.100	3.084	1.100	3.317	1.100	1.100	1.206	1.324	1.412
Book Depreciation	6.128	6.128	18.820	8.261	23.619	6.260	6.260	6.260	4.803	4.803
Condensate Transport Charges	9.733	9.928	10.126	10.329	10.536	10.101	9.426	8.720	7.983	7.444
Expenditure before WPPF WWF	77.628	80.686	209.418	89.634	245.044	92.230	92.102	92.250	91.156	97.911
PROFIT & LOSS										
Profit (Income-Exp)	242.750	246.100	123.903	250.354	101.744	240.251	218.184	194.801	171.606	152.134
Workers' Profit Participation Fund (WPPF)	12.138	12.305	6.195	12.518	5.087	12.013	10.908	9.740	8.580	7.607
Workers' Welfare Fund (WWF)	4.368	4.440	1.713	4.520	1.208	4.257	3.875	3.467	3.032	2.691
Total Expenditure	94.134	97.430	217.326	106.672	251.339	108.500	106.886	106.465	102.768	103.209
Profit Before Tax	226.244	229.366	115.996	233.316	95.449	223.982	203.400	181.596	159.994	141.836
Less - Tax	80.083	81.240	5.436	81.802	-10.122	75.507	67.768	59.448	50.541	43.376
Profit After Tax	146.162	148.116	110.569	151.515	105.571	148.475	135.633	122.147	109.453	98.460
Unappropriated Profit of Current Year	146.162	148.116	110.569	151.515	105.571	148.475	135.633	122.147	109.453	98.460
Unappropriated Profit of Last Year b/d	377.052	523.214	671.330	781.899	933.404	1038.975	1187.450	1323.083	1445.229	1554.682
Unappropriated Profit carried over	523.214	671.330	781.899	933.404	1038.975	1187.450	1323.083	1445.229	1554.682	1653.142
TAX COMPUTATIONS										
Income Before Tax	226.244	229.366	115.996	233.316	95.449	223.982	203.400	181.596	159.994	141.836
Add Book Depreciation	6.128	6.128	18.820	8.261	23.619	6.260	6.260	6.260	4.803	4.803
Add Royalty	40.047	40.848	41.665	42.499	43.349	41.560	38.786	35.881	32.846	30.631
Less Tax Depreciation	5.945	5.336	40.843	7.077	49.987	9.080	8.170	7.362	6.617	5.956
Less Depletion Allowance	48.057	49.018	49.998	50.998	52.018	49.872	46.543	43.058	39.414	36.757
Taxable Income/Loss of year	218.418	221.978	85.639	226.001	60.411	212.850	193.733	173.326	151.611	134.558
Taxable Loss of last year brought over	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	218.418	221.978	85.639	226.001	60.411	212.850	193.733	173.326	151.611	134.558
Cumulative Taxable Loss carried over	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Net Taxable Income	218.418	221.978	85.639	226.001	60.411	212.850	193.733	173.326	151.611	134.558
Tax on above @ 55%	120.130	122.088	47.102	124.300	33.226	117.067	106.563	95.330	83.386	74.007
Less Royalty	40.047	40.848	41.665	42.499	43.349	41.560	38.786	35.881	32.846	30.631
Net Tax Payable	80.083	81.240	5.436	81.802	-10.122	75.507	67.768	59.448	50.541	43.376
ASSETS & LIABILITIES										
CURRENT ASSETS										
Material & Spares	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500
Trade Debtors for Gas	50.788	51.730	52.691	53.671	54.671	52.346	48.799	45.078	41.212	38.386
Trade Debtors for NGL	6.604	6.736	6.870	7.008	7.148	6.863	6.386	5.917	5.416	5.051
Advance Deposits Prepayment and other Receivables	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Total	61.891	62.966	64.061	65.179	66.319	63.699	59.684	55.494	51.128	47.937
CURRENT LIABILITIES										
Royalty Payable	3.337	3.404	3.472	3.542	3.612	3.463	3.232	2.990	2.737	2.563
Excise Duty Payable	1.997	2.001	2.004	2.007	2.010	1.893	1.736	1.576	1.417	1.298
Other Credit Balances	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500
Tax Payable/Tax Payable	40.041	40.620	2.718	40.901	0.000	37.754	33.884	29.724	25.270	21.688
WPPF	12.138	12.306	6.195	12.518	5.087	12.013	10.908	9.740	8.580	7.607
WWF	4.368	4.440	1.713	4.520	1.208	4.257	3.875	3.467	3.032	2.691
Total	63.382	64.269	17.602	64.987	13.418	60.879	55.135	48.997	42.537	37.336
Net Current Assets	-1.491	-1.304	46.459	0.192	52.901	2.820	4.549	6.497	8.591	10.600
Net Current Assets of Last Year	-1.586	-1.491	-1.304	46.459	0.192	52.901	2.820	4.549	6.497	8.591
Increase/(Decrease) in Net Current Assets	0.094	0.187	47.763	-46.268	52.709	-50.081	1.730	1.948	2.094	2.009
CASH FLOW										
INFLOW										
Profit/(Loss) before Tax	226.244	229.366	115.996	233.316	95.449	223.982	203.400	181.596	159.994	141.836
Add - Depreciation	6.128	6.128	18.820	8.261	23.619	6.260	6.260	6.260	4.803	4.803
Total	232.372	235.494	134.816	241.577	119.068	230.242	209.660	187.856	164.797	146.639
OUTFLOW										
Tax Payment	80.083	81.240	5.436	61.802	0.000	75.507	67.768	59.448	50.541	43.376
Capital Expenditure	0.000	0.000	67.066	0.000	81.137	0.000	0.000	0.000	0.000	0.000
Increase/(Decrease) in Net Current Assets	0.094	0.187	47.763	-46.268	52.709	-50.081	1.730	1.948	2.094	2.009
Total	80.177	81.427	120.256	35.534	133.846	25.426	69.497	61.396	52.634	45.386
Surplus/(deficit) in Cash	152.196	154.067	14.560	206.043	-14.778	204.815	140.163	126.459	112.163	101.253
Previous Year Cash Balance b/f	249.110	401.306	566.363	569.923	775.966	761.188	966.003	1106.167	1232.625	1344.788
Cumulative Cash Balance at Year end	401.306	566.363	569.923	775.966	761.188	966.003	1106.167	1232.625	1344.788	1446.041
Net Cash Flow for the Year before Discount	152.196	154.067	14.560	206.043	-14.778	204.815	140.163	126.459	112.163	101.253
Cum. Cash Flow before Discount	401.306	566.363	569.923	775.966	761.188	966.003	1106.167	1232.625	1344.788	1446.041
Cash Flow Discount Factor (DCF) @ 20	0.162	0.135	0.112	0.093	0.078	0.065	0.054	0.045	0.038	0.031
Net Cash Flow for the Year after Discount	24.580	20.734	1.631	19.268	-1.151	13.294	7.561	5.700	4.213	3.169
Cum. Cash Flow After Discount	-116.030	-95.296	-93.663	-74.405	-75.556	-62.263	-54.681	-48.981	-44.769	-41.599

Internal Rate of Return (IRR)	0.179
Net Present Value @ 20% DCF	-34.686

Table - 25.1 Economic Evaluation

AVERAGE CONSUMER GAS PRICE PAKISTAN & USA

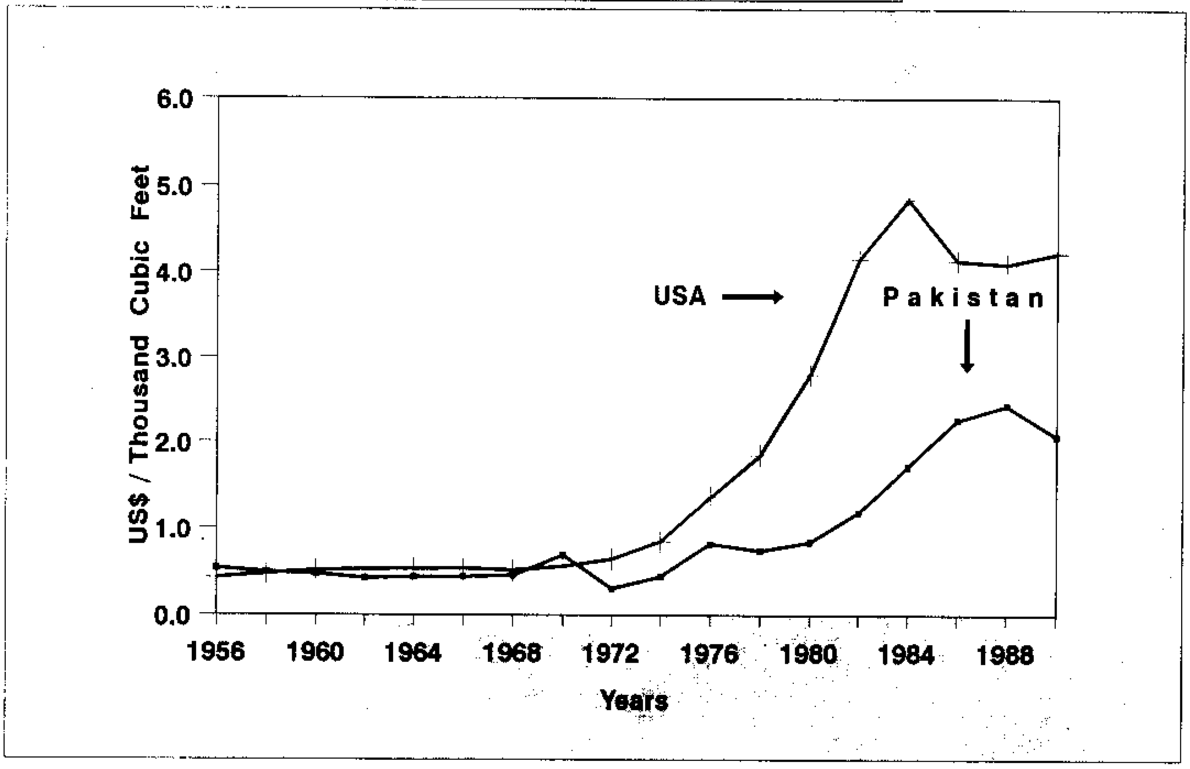


Figure - 25.17 Average Consumer Gas Price - Pakistan & USA

PRODUCERS GAS PRICE PAKISTAN & USA

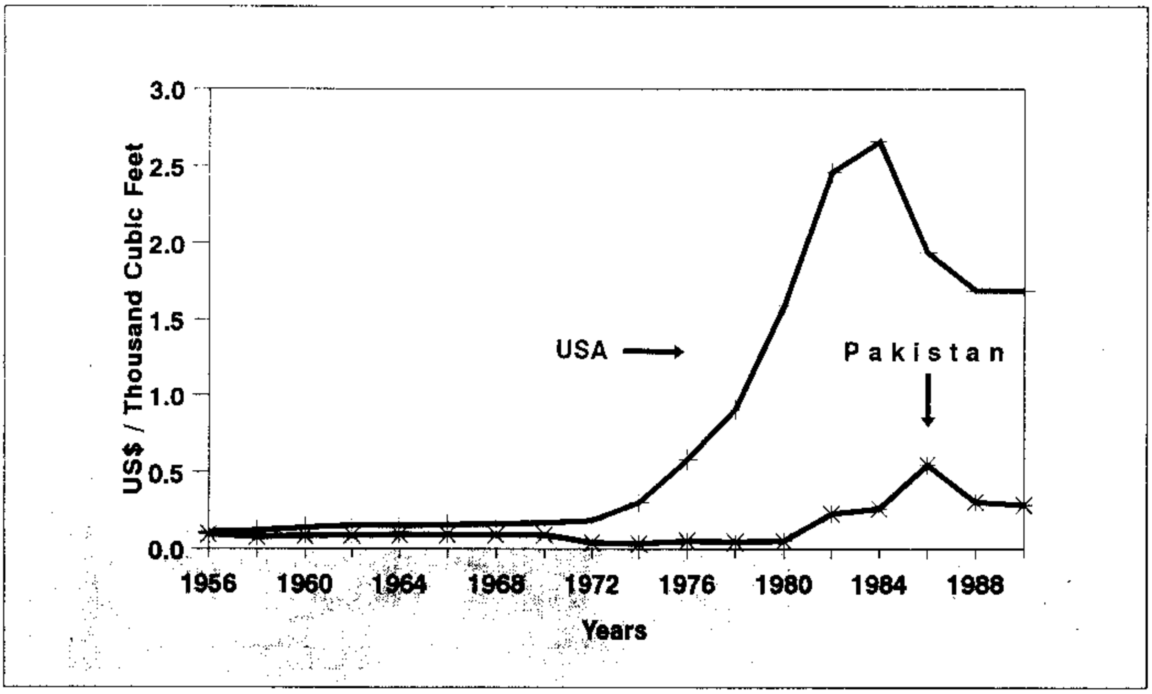


Figure - 25.18 Producers Gas Price - Pakistan & USA

CRUDE OIL PRICES
FOB Ras Tanura (US $ /Barrel)

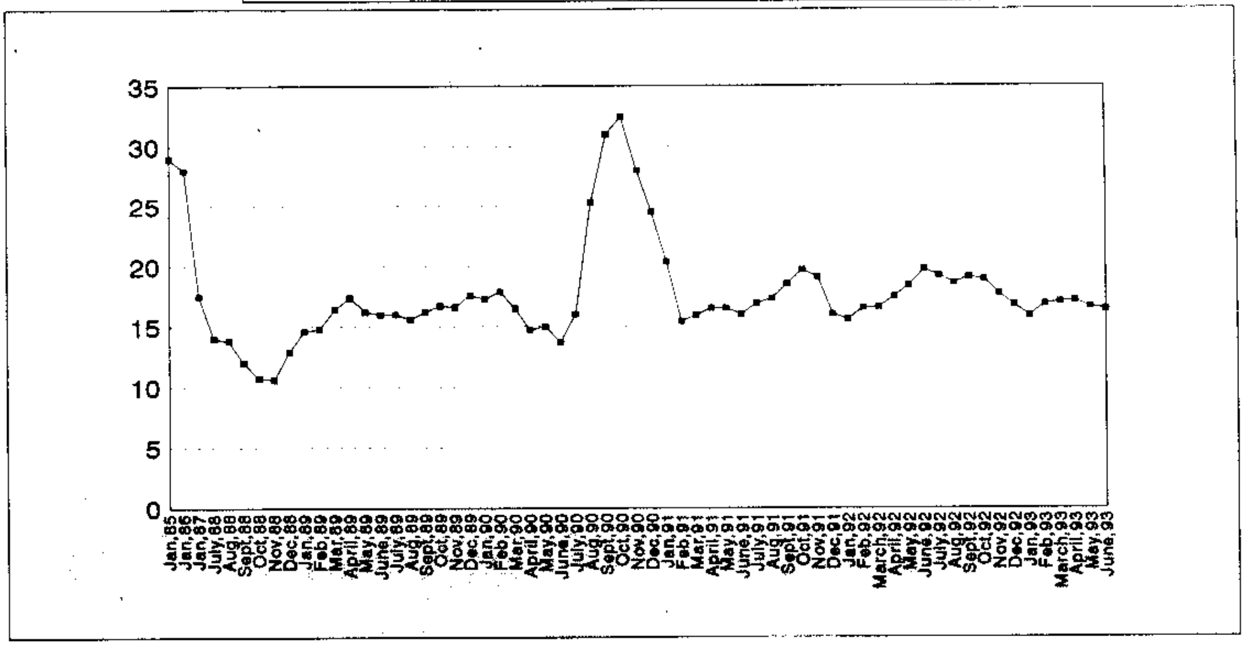


Figure - 25.19 Crude Oil Prices - FOB Ras Tanura (US $/Barrel)

HIGH SULFUR FUEL OIL PRICES
FOB Gulf Port (US $ /Ton)

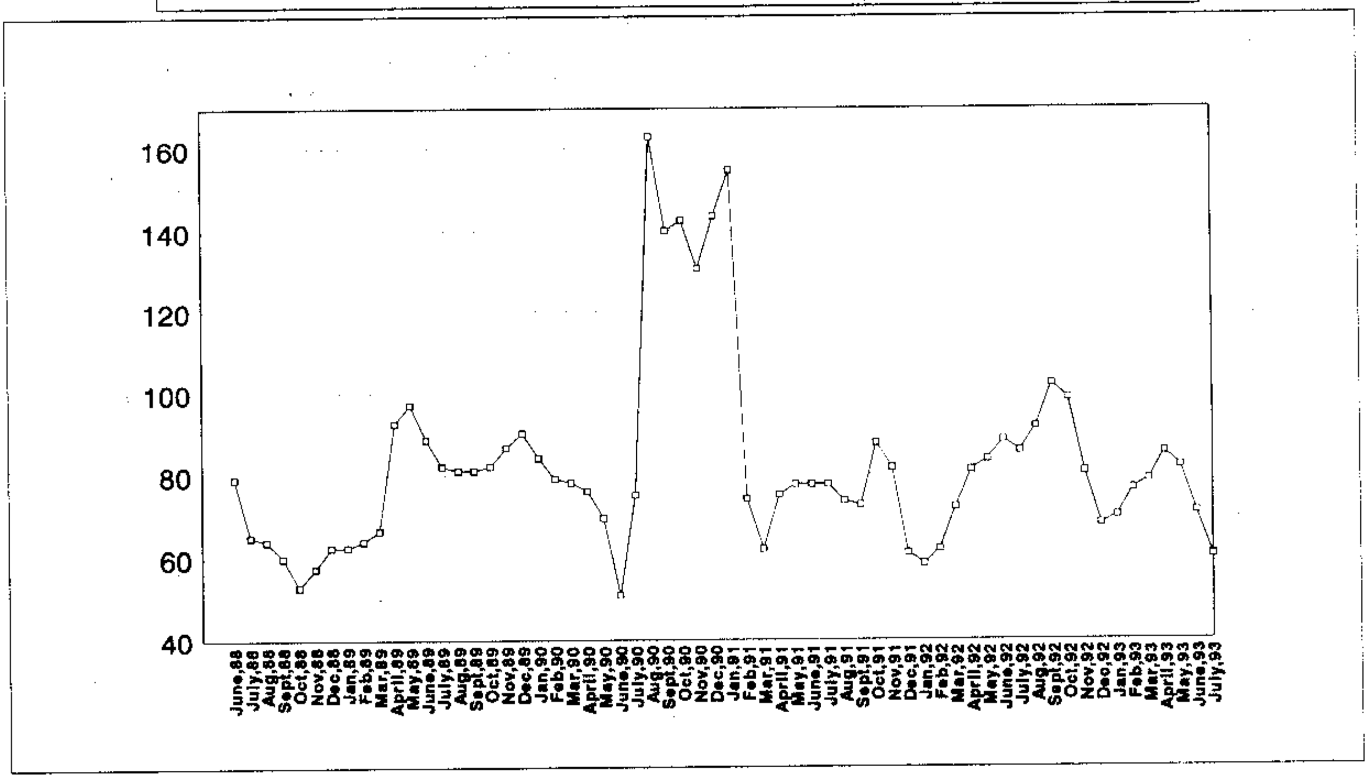


Figure - 25.20 High Sulfur fuel oil prices are many variables involved both in the technical and financial exercises requiring due care when making projections.

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