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An Overview of the Hydrocarbon Potential of the less explored Kharan Forearc Sub-Basin, Balochistan Province, Pakistan

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ABSTRACT

The Kharan forearc sub-basin remained one of the least studied parts of the Balochistan basin, and therefore neither the overall structural geometries of the region, nor their prospectivity and hydrocarbon potential were clearly understood. The sub-basin is analogous to several oil and gas producing regions elsewhere in the world.

Kharan forearc sub-basin is at about 500m above mean sea level and is constituted by flat area draped by superficial Quaternary sand deposits. It is more than 100 km wide from the foothills of Raskoh arc to the northern border of Siahan range. The aeromagnetic and gravity data over this area show considerable thickness of a sedimentary pile over the basement rocks, which could have analogous sedimentary sequence as in the Chagai and Raskoh arcs. The arc to trench distance ranges from 250 to 300 km from north to south, one of the widest in the world, similar to what is observed in the producing Cook-Inlet basin of Alaska.

Based on the field data gathered by Pakistan Petroleum Limited (PPL) and previous studies, the depositional setting of the Palaeogene succession in the Kharan forearc sub-basin indicates that there are favorable conditions for occurrence of potential source, reservoir and cap rock assemblages and a viable petroleum system. Tectonic development in Raskoh range also shows progressive decrease in the structural complexity southward resulting in likely occurrence of less complex structural traps of considerable pool size in the sub-basin.

The objective of this paper is to study and summarize the relevant data on stratigraphy, structure, and source-reservoir characteristics of the exposed sequences in the southern part of Raskoh range and extrapolate the mentioned information in Kharan sub-basin. This will lead to the understanding of basin evolution and help us propose a petroleum geological model for the area to carry out detailed exploration work.

RATIONALE

Taking cognizance of lack of interest in oil and gas exploration in Balochistan basin by national and multinational oil companies, the management of PPL envisaged an exploration program to open up Balochistan basin for hydrocarbon exploration. In this context, on the basis of analogies elsewhere in the world, prospective Kharan forearc sub-basin in the northern part of Balochistan basin was short listed for detailed evaluation.

A fieldwork program for evaluation of hydrocarbon potential of Kharan forearc region covering Kharan platform was designed with the aim to generate basic geological data for developing a geological model for the area in order to carry out further detailed exploration work. The fieldwork program for a duration of five weeks comprised measurement of twelve stratigraphic sections of Paleogene succession for identifying the source-, reservoir- and cap-rock assemblages by studying facies distribution and carrying out three structural traverses for reconstruction of structural configuration of the area.

The field work program in the southern part of Raskoh commenced from 20 March, 2003 and was completed on 23 April, 2003.

OBJECTIVES

The objective of the geological fieldwork was to collect critical data on stratigraphy, structure, and source-reservoir characteristics of the exposed sequences in the southern part of Raskoh range for understanding the evolution of Kharan sub- basin. This data set is prerequisite to document and assess the hydrocarbon potential of the stratigraphic sequences likely to extend into the Kharan sub-basin. As such the fieldwork was planned to:

i) Conduct traverses and measurement of stratigraphic sections to subdivide major depositional packages to identify depositional environments favorable for the development of source and reservoir rocks and to track lateral facies variations.

ii) Select and draw samples for biostratigraphy, source rock geochemistry and reservoir study.

iii) Analyse the structural style by field study, and integrate the data with aerial photo and LANDSAT imagery interpretation.

iv) Carry out detailed lab studies for age determination, petrography of selected samples to study diagenetic fabrics and reservoir properties, poroperm study and special core analysis of selected samples, and source-rock geochemistry of shale and limestone samples for TOC, pyrolysis and maturity analysis.

V) Integrate field data with available geological and geophysical literature to develop play concepts and to assess the hydrocarbon potential.

vi) Recommend areas for further exploration or otherwise. Select areas for further gravity and magnetic traverses and seismic acquisition.

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WORK UNDERTAKEN

The field party measured lithologic sections of the exposed stratigraphic succession and conducted stratigraphic/ structural traverses along the southern rim of the Raskoh range. The field party measured twelve stratigraphic sections with a cumulative thickness of 13,545 meters extending for more than 100 km. The party also made three structural traverses covering more than 26 Km. A total of 244 samples were collected for source rock evaluation, reservoir / petrographic analysis, and biostratigraphy.

INTRODUCTION

The Kharan sub-basin covers approximately 30,000 square kilometers and is entirely covered by superficial deposits of the Kharan desert, a regional depression approximately 500 meters above mean sea level located 450 km northwest of Karachi and 400 km southwest of Quetta (Figure 1).

The desert is characterized by shifting sand dunes and ephemeral playa lakes and forms part of the Kharan Depression (Figure 2). Elevation rise to the north towards the Ras Koh range where the highest peak is 3,000m above mean sea level and to the south towards the east-west trending Siahan range where elevation exceeds 2,000m. The climate is extreme with average summer temperature of 45° C, falling to as low as -4° C in winter. Rainfall is generally less than 150mm per year and most falls in brief storms with flash flooding down the few watercourses.

EXPLORATION HISTORY

a. Geological Studies

After independence, with the growing needs of mineral commodities by the country and the advancement of state of knowledge, the Geological Survey of Pakistan (GSP) increased its activities for systematic search of mineral deposits particularly in the northern part of the Balochistan basin.

Hunting Survey Corporation (HSC) carried out an aerial survey of the entire Balochistan basin and some parts of the Lower and Middle Indus basin on 1:40,000 scale and prepared a geological report and a series of geological maps on 1:235,440 scale. Based on available data, the GSP published a geological map of Pakistan on scale 1:2,000,000 (Bakr and Jackson, 1964). Subsequently a systematic program was initiated for mapping the Chagai and Raskoh area and so far 19 maps have been prepared on scale 1:50,000. More than 100,000 square kilometers aeromagnetic survey and gravity survey covering mineral potential areas of Chagai and Raskoh were undertaken (Spector and Associates, 1981; Rahim, 1981).

b. Hydrocarbon Exploration

History of hydrocarbon exploration in Kharan forearc sub-basin and surrounding areas is limited to the work undertaken by three exploration companies, i. e. Oil and Gas Development Company Limited (OGDCL), Union Texas Pakistan (UTP), and Murphy Pakistan Oil Company (Murphy) (Figure 3).

Murphy held an exploration license covering Kharan depression, which was kept under force majeure since 1979, as they could not undertake any work in the region till 1999 when the company was allowed to carry out aeromagnetic and geological surveys of some parts of the license areas. UTP also acquired license in the eastern extension of Mashkhel forearc regions and carried out geological studies to evaluate hydrocarbon potential of the area. The salient features of these exploration efforts are presented below:

I) OGDCL

OGDCL was granted an exploration license covering north eastern part of the Kharan forearc region. It carried out geological field work in the southern part of the Raskoh range and acquired 508 km 2D seismic (Figure 3). After initial review of the data OGDCL relinquished the Kharan area in1995.

ii) UTP

UTP (now BP Pakistan) also operated an area covering eastern part of the forearc sub-basin during 1998-99 but after conducting geological fieldwork relinquished the area.

iii) Murphy

Murphy of USA as operator of Kharan Exploration Licence (EL) covered almost the entire forearc sub-basin, located in the northern part of Balochistan basin. They conducted geological field work in 1999 (Geosurveys, 1999) and acquired 7,359 km air borne gravity and 8,772 km magnetic survey (Carson, 1999). The company was allowed to carry out gravity and magnetic surveys only in the southern part of their concession, as the northern part, which was considered more prospective by Murphy, could not be covered due to security reasons. The surveys, however, confirmed the presence of thick sedimentary cover in the southern part of Kharan EL. Although no seismic was conducted or a well drilled, the work done by Murphy is the only available recent information on the northern part of Balochistan basin (NPA Group, 1999). The company relinquished the block in 2000 (Murphy,1999).

GEOLOGICAL SETTING

It is constituted by flat area covered by Quaternary sands (Figure 2). It is more than 100 km wide from the foothills of Raskoh arc to the northern border of Siahan range. The aeromagnetic survey indicates several depressions filled with kilometers thick sediment filled depressions, which could have an analogous sedimentary sequence as in the

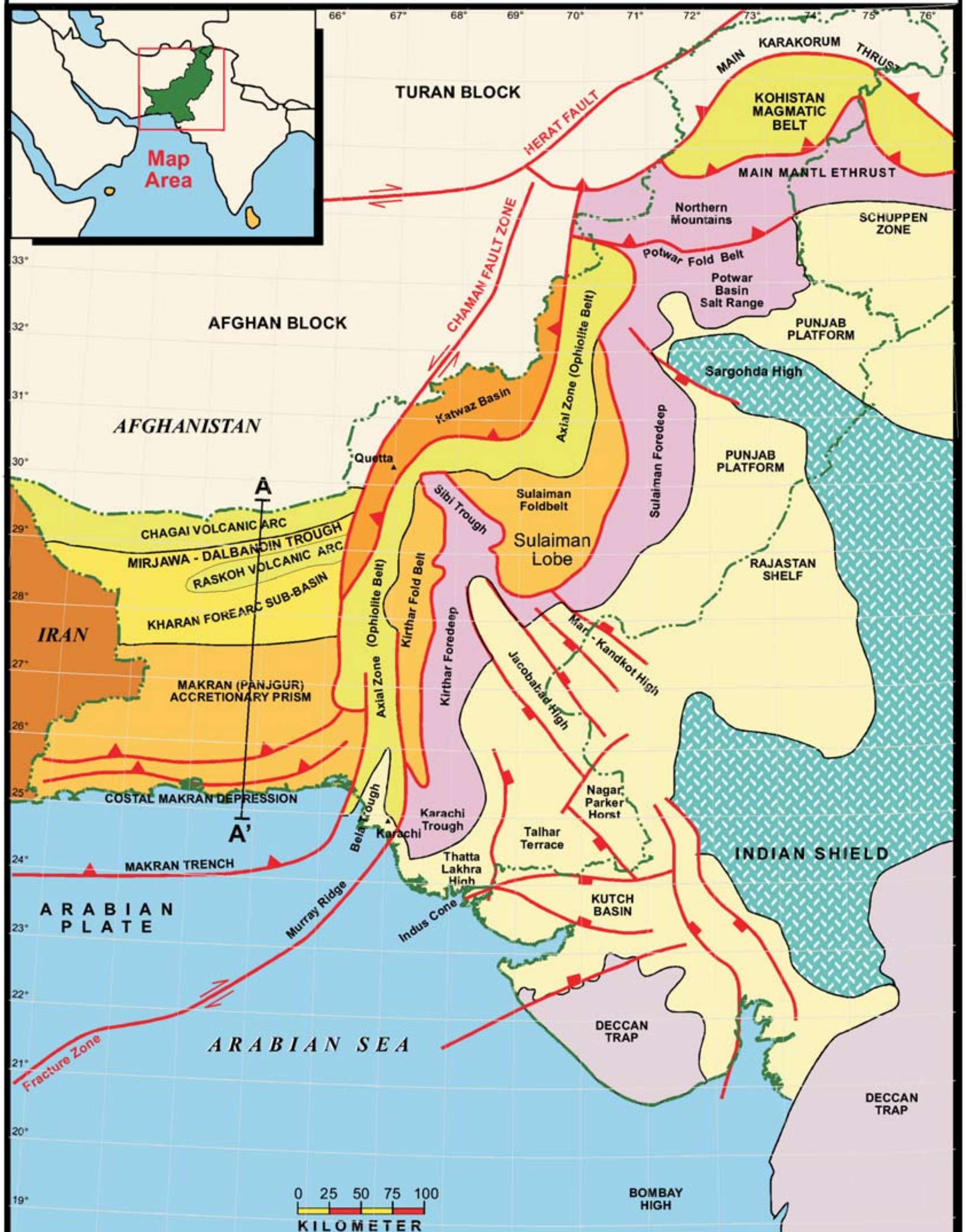

Figure 1- Sedimentary Basins of Pakistan Map Showing the Location of Kharan Forearc Sub-basin (Modified after Murphy, 1999).

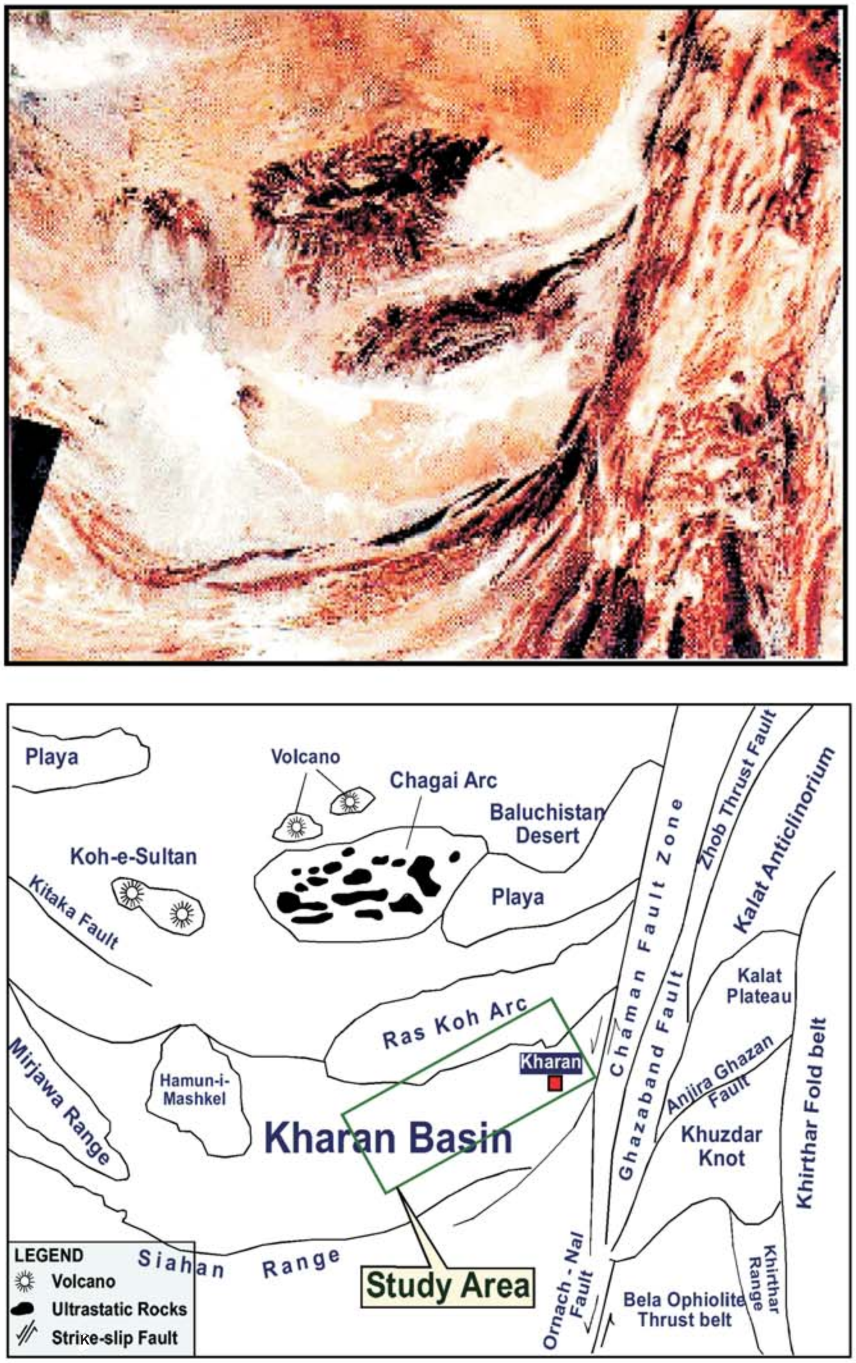

Figure 2- Physiographic and Geological Features of Kharan Forearc Sub- basin, Balochistan, Pakistan.

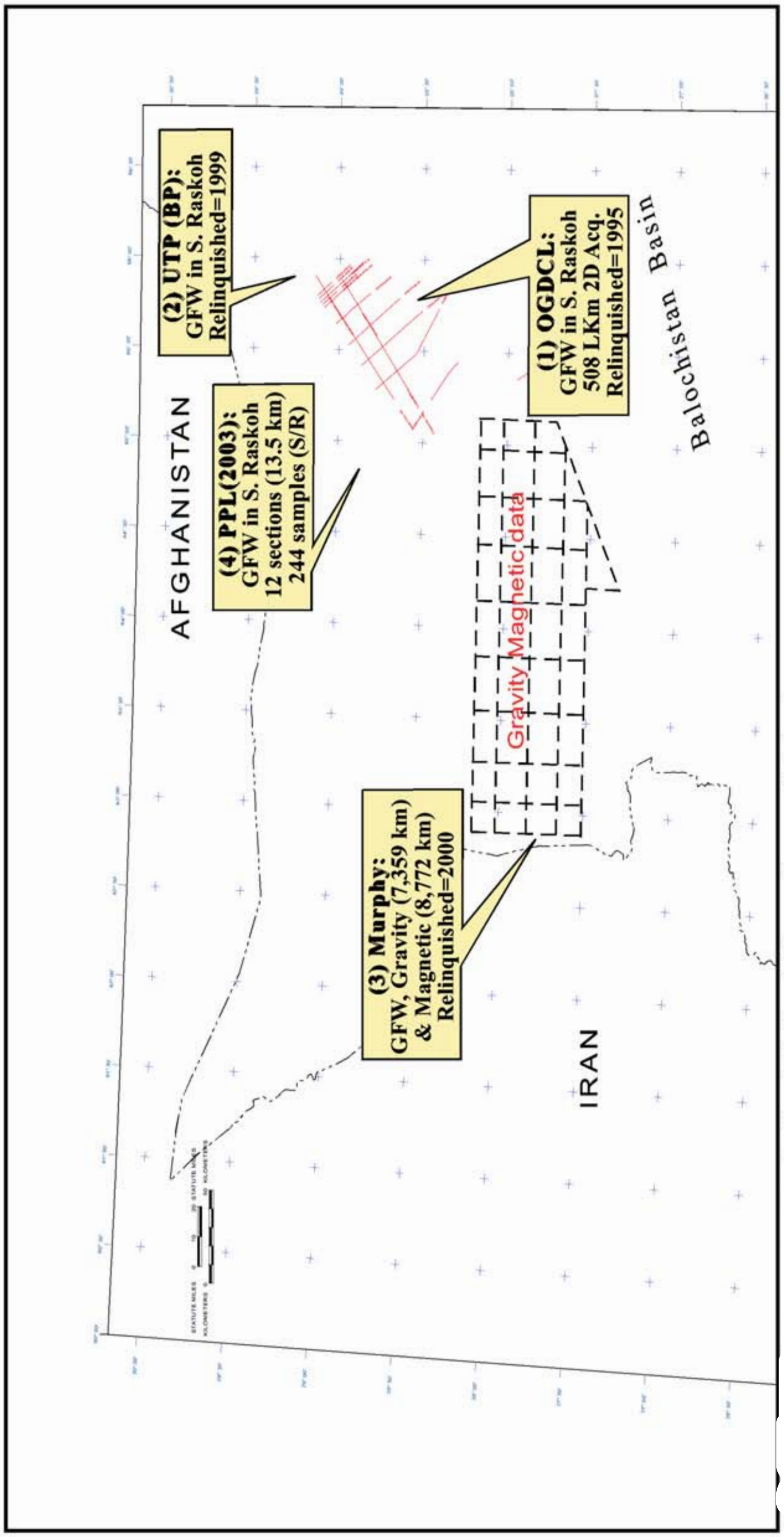

Figure 3 - History of Hydrocarbon Exploration Activities in Kharan Sub-basin.

Chagai and Raskoh arcs. This sequence provides prospects for hydrocarbon generation and accumulation.

TECTONICS AND BASIN EVALUATION

The regional setting suggests that the rifting of Gondwanaland in Permo-Triassic time also resulted in the development of Iran, Lut and Afghan microplates (Figure 4). An intra-oceanic subduction complex developed some time in mid Cretaceous along the southern margin of these microcontinents forming the northern border of Neotethys . At the same time, an island arc was formed resulting in volcanism (Sanjrani Volcanics) in Chagai and Raskoh magmatic belts. The igneous activity and uplift associated with erosion in the area seems to be concluded in the pre-Maastrichtian time and a forearc sub-basin (Dalbandin Interarc Sub-basin) was developed with the deposition of the Maastrichtian Humai limestone. Several thousand meters thick turbidities (Rakhshani Formation) were deposited and accreted with penecontemporaneous deformation during Paleocene. A period of relatively quiescence is indicated by on-lapping and shoaling limestone (Kharan Limestone and Saindak Formation) developed around structural heights during Eocene. However, much of the sediments in the forearc basin were being deposited by gravity and turbidity flows.

The Arabian Plate has been a stable craton throughout the Phanerozoic. Its north-eastward drift against the Lut block created the Zagros ranges above the Neo-Thetys subduction zone. Similarly, the nominal boundary between oceanic crust of the Arabian plate and the Eurasian plate has constituted the thrust front of the Makran accretionary continental slope (Figure 1). The subducting oceanic crust of Arabian plate dips north at an angle of less than 10^0 (Farhoodi and Karig, 1977). It is interpreted that with this trend, only under the Kharan forearc region the subducting oceanic crust steepens to sub-crustal depth of more than 40 km. The entire Makran forearc is most likely built by clastic sediments accreted to Eurasia during Cenozoic times (Jacob and Quittmeyer, 1979). Hence in Balochistan, the Arabian and Eurasian continental boundary (in terms of basement geology) probably lies under the southern part of the Raskoh Range. The subduction of Arabian plate during the Middle Miocene uplifted large area in the north and provided sediments for the prograding slope-shelf in the coastal and offshore areas.

REGIONAL STRATIGRAPHY

The Paleogeographic and stratigraphic framework of the area suggests that sequences exposed in Chagai and Raskoh arcs, Dalbandin Interarc sub- basin are likely to be present subsurface in the Kharan forearc sub-basin. Detailed stratigraphic and lithologic data of the exposed successions in the southern rim of Raskoh arc is illustrated in stratigraphic sections KN-1 to KN-10B (Table-1, Figure 5).

I) Pre-Tertiary

The Chagai and Raskoh volcanic arcs were formed during the late Cretaceous subduction of Arabian plate under the Eurasian plate. The Cretaceous strata are exposed in the Chagai arc, whereas Dalbandin interarc sub-basin may have Sanjrani Volcanics in the lower part and Upper Cretaceous Humai Formation in the upper part. The grayish green and black agglomerate and volcanic conglomerate with variegated fine grained tuff and porphyritic andesite lava flows and variable proportions of shale, sandstone and limestone mainly constitute the Sanjrani Volcanic. Poorly preserved fossils including algae, foraminifers and corals are found in the sediments of Sinjrani Volcanics. The maximum thickness seen in the field is 1,200 meters, but the entire section may be several km thick within the Chagai arc. A similar sequence is estimated to be accumulated in the Raskoh arc. It has been assigned Cretaceous age in consideration of conformable contact with overlying Humai Formation, which is mainly composed of massive to thin bedded reefoid limestone with variable portion of shales, turbiditic sandstones, siltstones and occasional volcanic conglomerates in lower part. However, presence of conglomerate at the base of the formation at several localities suggests a disconformity.

ii) Paleocene

The Rakhshani Formation of Paleocene age comprises a heterogeneous assemblage of interbedded coarse grained turbiditic sandstone and shale, with rare fine grained argillaceous limestone and lenses of conglomerate and volcanic agglomerate with local flows of basaltic and andesitic composition. These sediments appear to be the oldest exposed accretionary sediments of the Makran arc-trench system. The formation has a widespread distribution covering Chagai arc, Dalbandin inter arc sub-basin, Raskoh frontal arc and Kharan forearc sub-basin. It has variable thickness from 150-2,400 m.

The stratigraphic sections KN-4, KN-5B, KN-6 and KN-7 exhibit the lithology of the upper part of Rakhshani Formation near its contact with overlying Kharan Limestone (Table 1). The formation in the upper part at its contact with overlying Kharan Limestone is composed of an interbedded sequence of shale, fine to coarse grained volcanoclastic sandstone, conglomerate and red marl (Plate-1a and b). The shale horizons generally contain interformational and exotic clasts of marly limestone resembling with Humai Formation (Plate 2a). The sandstone show load casts and mega-ripples indicating that depositional environment became relatively paralic to shallow marine in the upper part of Rakhshani Formation (Plate-2b and 3a). Lower part is mainly composed of dark gray to brownish gray cleaved shale with thin intercalations of sandstone and rare igneous intrusions (Plate-3b and 4a). Quartz veins and sandstone lenses displaying boudinage are frequently present in the shale. They seem to be associated with stress within the shale evident from development of

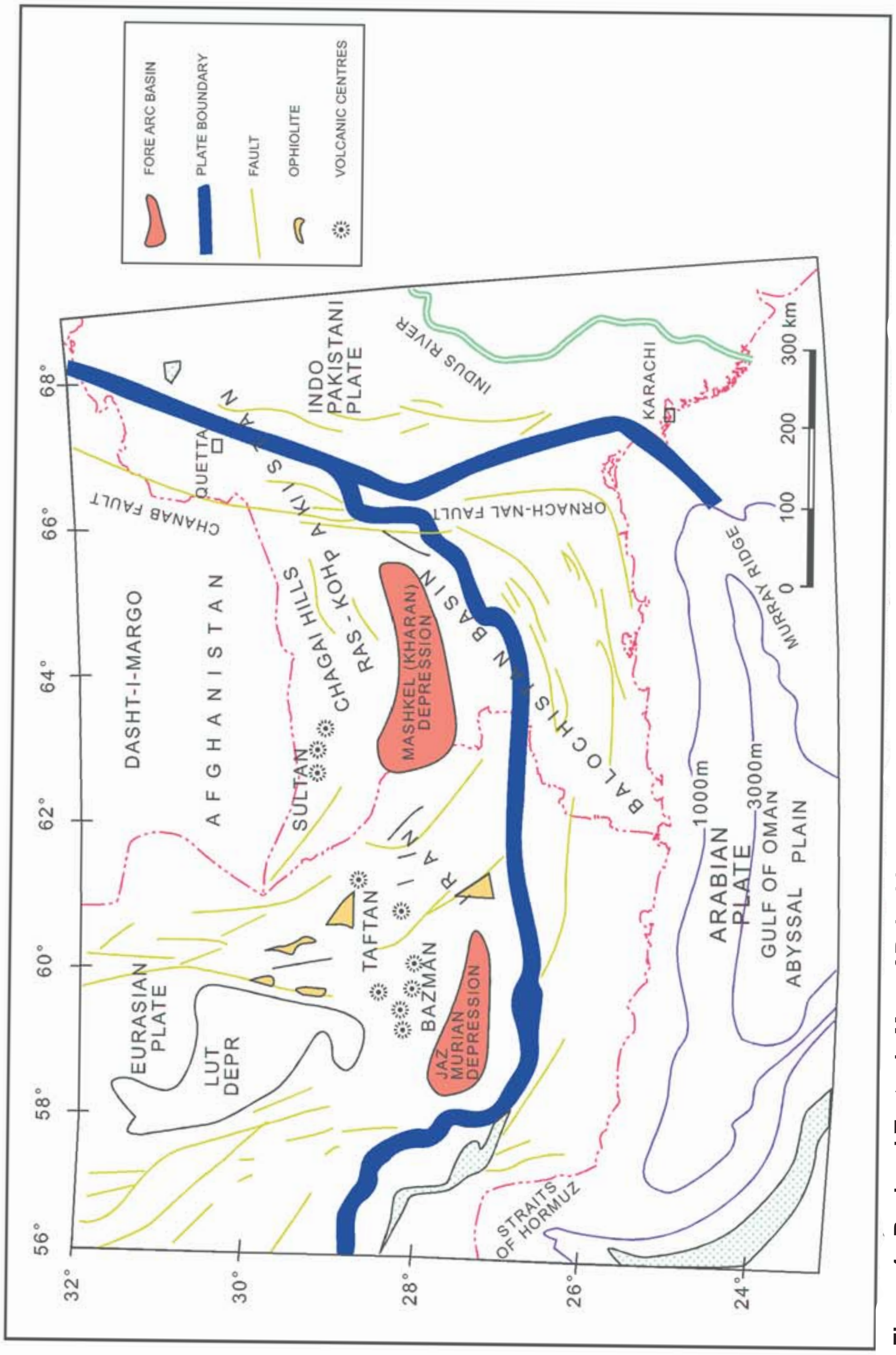

Figure 4 - Regional Tectonic Map of Balochistan and Surrounding Areas (Modified after Jacob and Quittneyer, 1979.

Table 1- Stratigraphic Sections Measured in Southern Raskoh Arc

Section No.	Section Name	Coordinates	Formation	Thickness	Samples
KN-1	Nauroz Kalat East	28° 47' 00.15"N	Nauroz Formation	2,578	10
		65° 35' 00.58"E	Kharan Limestone	50	1
KN-3	Kharan Kalat	28° 46' 39.02"N	Nauroz Formation	100	7
		65° 19' 30.00"E	Kharan Limestone	45	3
KN-4	Eri-Kalag	28° 39' 03.07"N	Kharan Limestone	428.5	5
		64° 10' 25.00"E			19
KN-5A	Buzani / Sehnach	28° 39' 00.15"N	Rakhshani Formation	931.5	32
		65° 03' 52.58"E			
KN-5B	Tatgar	28° 35' 06.22"N	Nauroz Formation	248	7
		65° 01' 20.57"E	Kharan Limestone	203.5	31
			Rakhshani Formation	129	13
KN-6	Jalw ar Kaur	28° 30' 39.00"N	Nauroz Formation	100	1
		64° 48' 49.00"E	Kharan Limestone	315.4	8
			Rakhshani Formation	453.7	13
KN-7	Macinar	28° 28' 57.70"N	Nauroz Formation	50	4
	(Hurmagai River)	64° 40' 55.30"E	Kharan Limestone	169.94	11
			Rakhshani Formation	311.7	8
KN-8	Jaodhar River	28° 25' 45.54"N	Kharan Limestone	30	9
		64° 23' 22.57"E	Rakhshani Formation	2,185.8	32
KN-9A	Mukak	28° 23' 36.40"N	Nauroz Formation	504	3
		64° 22' 25.30"E	Kharan Limestone	5	4
KN-9B	Mukak East	28° 23' 33.00"N	Kharan Limestone	12	6
		64° 24' 52.00"E	Rakhshani Formation	428	4
KN-10A	Allu Chah (A)	28° 25' 10.31"N	Nauroz Formation	1,781	7
		64° 07' 20.33"E	Volcanic	1,350	
KN-10B	Allu Chah (B)	28° 25' 45.54'N	Rakhshani Formation	1,135	6
		64° 05 22.70"E			
			Total Thickness(m)	13,545	244

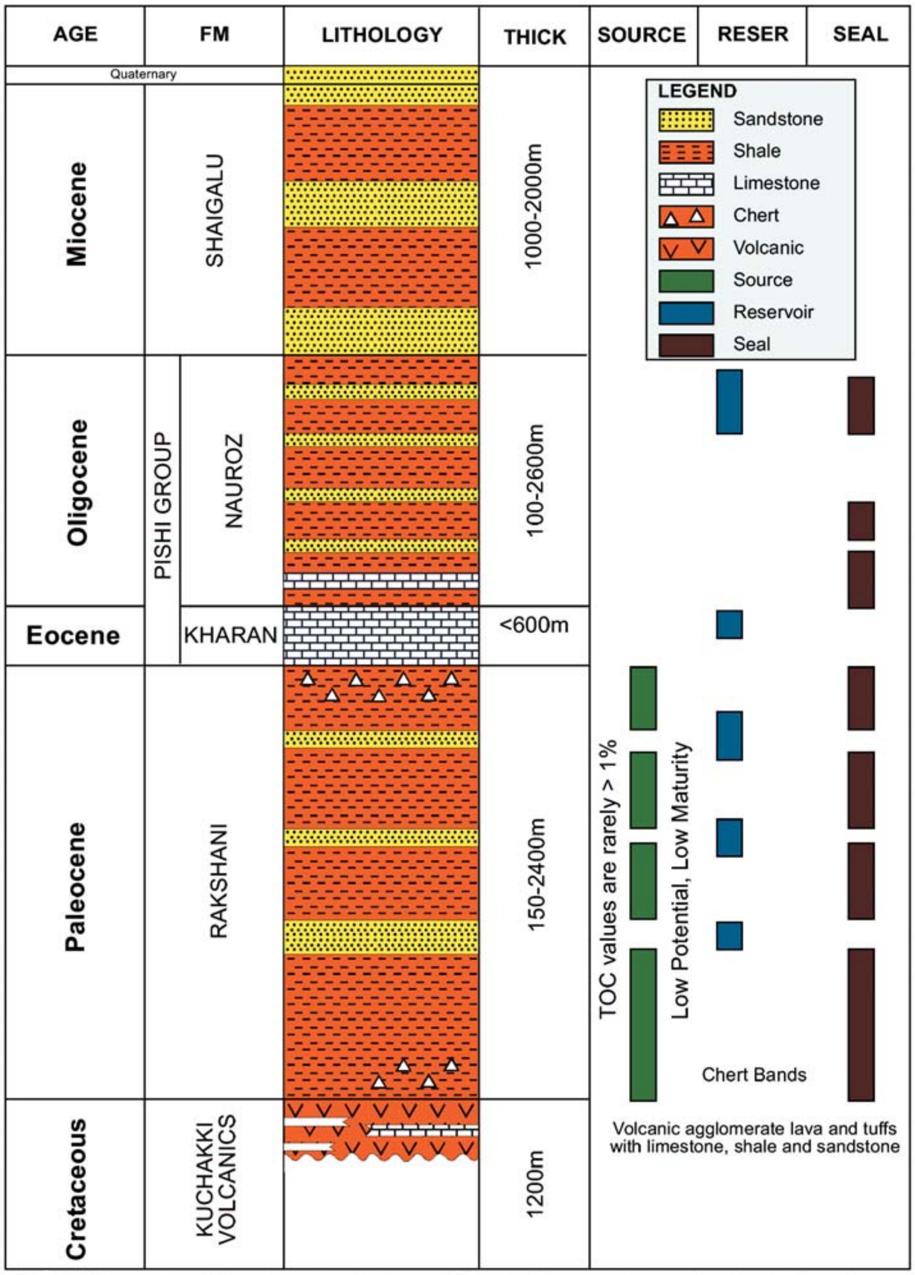

Figure 5-Generalized Stratigraphic Column of Rocks Exposed in the Southern Rim of Raskoh Range with Probable Source, Reservoir and Seal (Modified after Murphy, 1999).

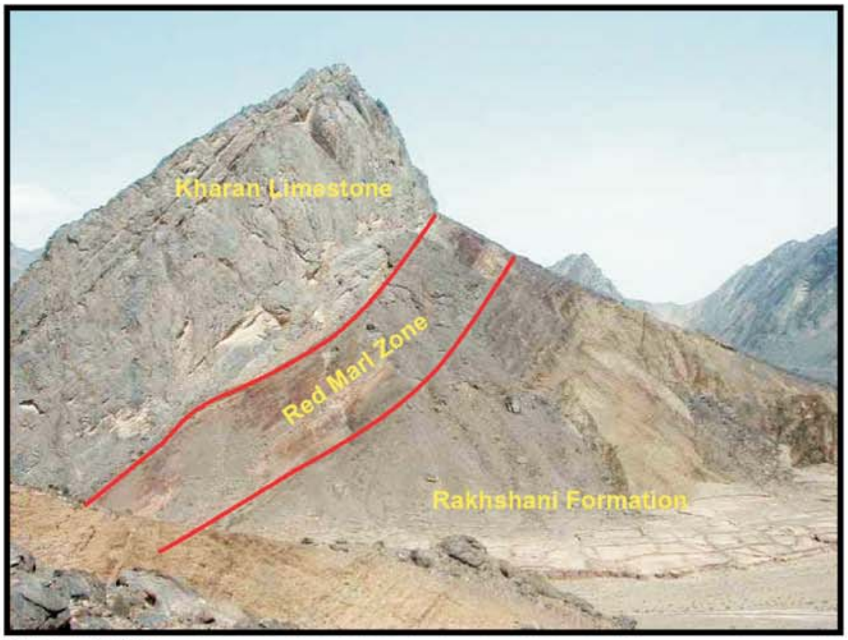

Plate - 1 (a)
Contact between Rakhshani and Kharan Limestone at Jalwar Khaur section. Reddish brown bed at the base of Kharan Limestone is related to Paleocene / Eocene unconformity. Camera facing NE. Location : 28° 30' 43'' N / 64° 48' 41'' E, Altitude=810m.

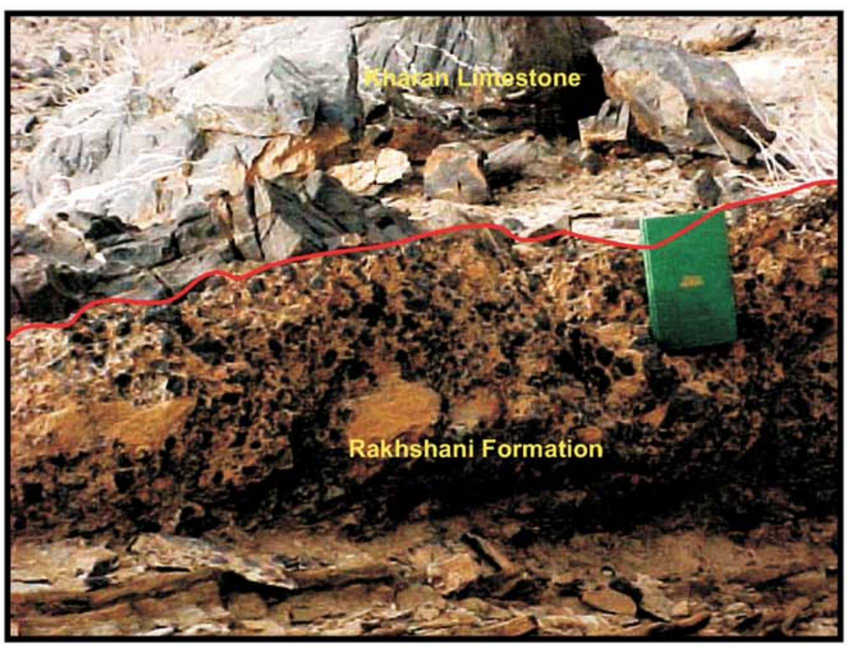

Plate - 1 (b)
Conglomerate at the base of the Kharan Fm and Rakhshani contact.

Plate - 2 (a)
Rakhshani Formation; marl with limestone and grid.

Plate - 2 (b)
Load cast at the base of sandstone bed of Rakhshani Formation. Scale is Jacob staff (4m).Location : 28^{O} 29' 02'' N / 64 40 ' 55'' E.

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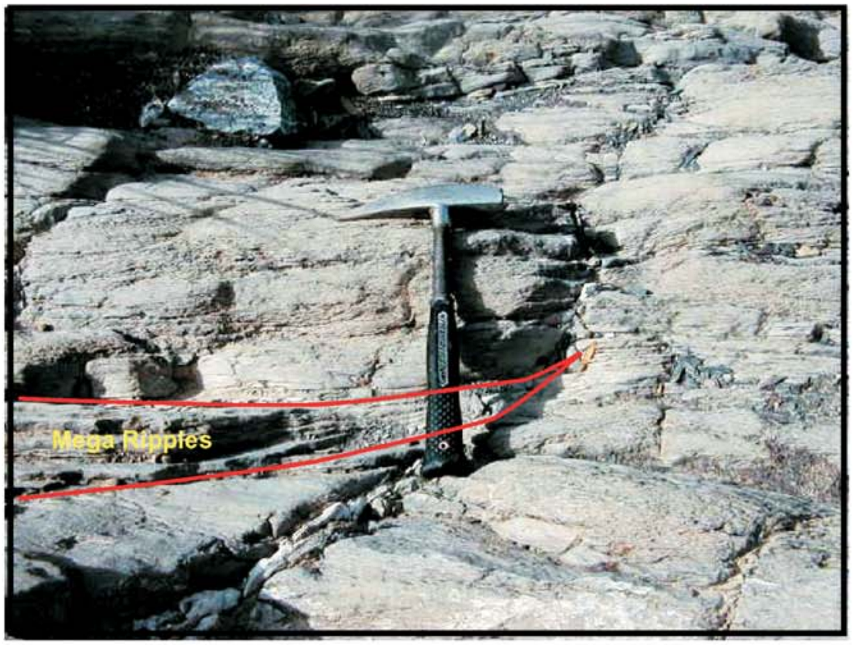

Plate - 3 (a)
Mega ripples in sandstone of Rakhshani Formation. Scale is the hammer and pencil. Location : 28° 29' 08'' N / 64 40 ' 53'' E.

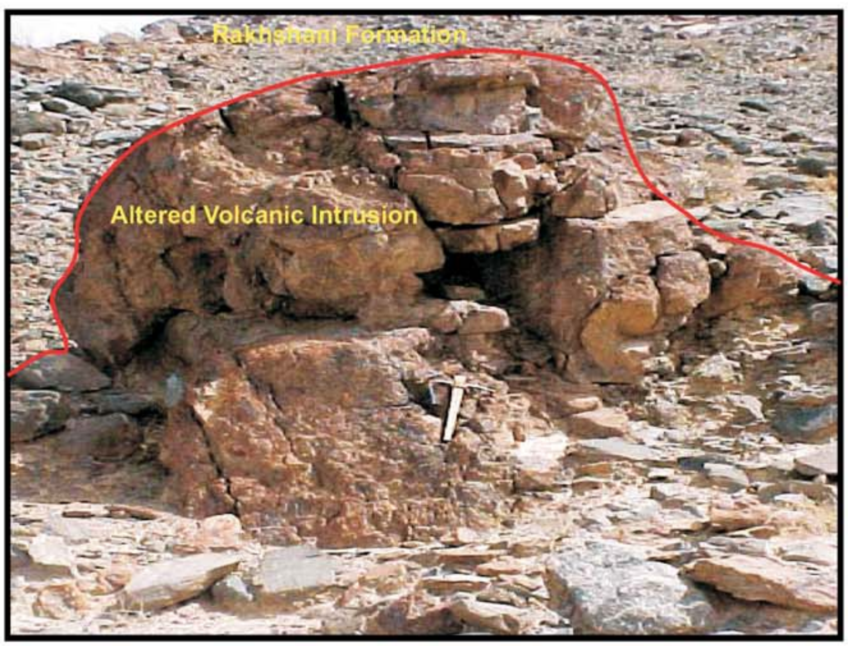

Plate - 3 (b)
Altered volcanic intrusion (sill). Shovel is for scale.

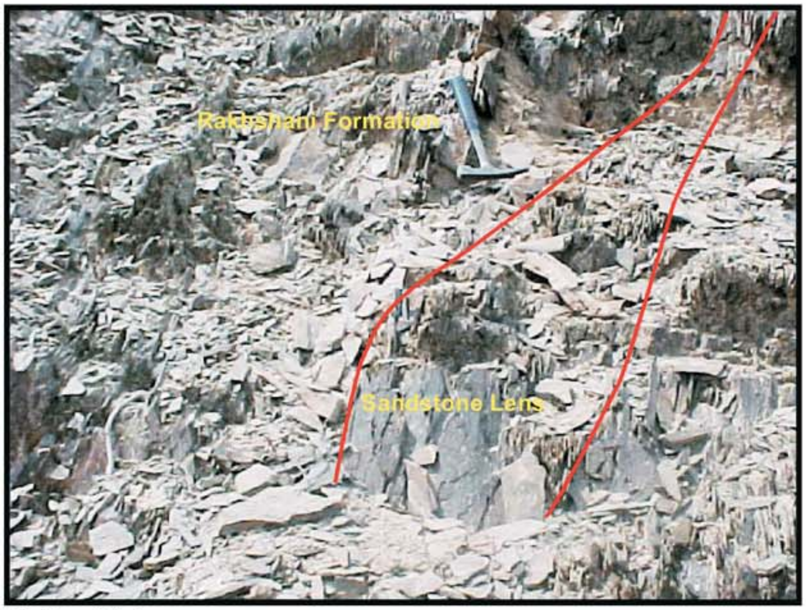

Plate - 4 (a)
Brown lens of sandstone within cleaved shales in the lower part of Rakhshani Formation.

Plate - 4 (b)
Closer view of basal Kharan Limestone with nodular cherty beds.
Location : 28° 39' 04'' N / 65° 10' 27'' E.

lineations and fractures in the nearby sandstones.

iii) Eocene

Relatively less deformed shallow water limestone (Kharan Limestone up to 600m thick) disconformably overlies the turbiditic Rakhshani Formation in the Raskoh area (Stratigraphic sections KN-4, KN-5B, KN-6 and KN-7). The formation consists of limestone, which is thin to massive bedded, nodular and at some places argillaceous containing nodular cherty beds and nodules (Plate-4b&5a). Its basal part is mainly wackstone while the upper part is dominantly grainstone and shows dolomitic bands (Plate 5b). Large vugs developed due to diagenesis of dolomitic bands in upper part of the limestone (Plate 6a) and its nodular horizons exhibit thin bedded limestone some time showing flaser bedding. Intraformational clasts and sub rounded to lenticular shaped olistoliths of the same lithology occur in the upper part of the Kharan Limestone indicating undulating basin conditions (Plate 6b and 7a). The unstable carbonate basin is evident by gravity slump features within Kharan Limestone and subsequent development of slump and gravity slides (Plate 7b) and limestone channels (Plate 8a) at Tatgar section. At places the limestone is highly fossiliferous and reefoid and gives a fetid odor. Foraminifers with some algae are dominant along with some gastropods and bivalves. The age of the formation is Early to Middle Eocene.

In the western part of Raskoh region Kharan Limestone thins out (Stratigraphic sections KN-8, KN-9A), and Eocene carbonate strata grades into the interbedded sequence of shale, sandstone and limestone of Pishi Group (Stratigraphic sections KN-9B and KN-10).

iv) Neogene

Oligocene Nauroz Formation at its type section a Kharan Kalat (Stratigraphic section KN-4) is found 2,578m thick although its stratigraphic contacts with overlying and underlying formations are obscure either due to faulting or not being exposed. However in other sections (Stratigraphic sections KN-4, KN-5B, KN-6 and KN-7), it is seen conformably deposited over the Kharan Limestone with sharp contact in most part of the Raskoh area (Plate 8b).Stratigraphic contact of Nauroz Formation and Kharan Limestone exposed in the northern limb of the Eri Kalag kink fold exhibit abrupt facies variations from limestone to greenish gray shale (Stratigraphic section KN-4). Undulating surfaces at the top most part of Kharan Limestone at its contact with Nauroz Formation indicate a possible short period of erosion or non-deposition (Plate 9a). However, west of Mukak section both the formations loose their identity and the undifferentiated Eocene and Oligocene sediments are termed as Pishi Group.

The Nauroz Formation is characterized by a shale dominated facies in the lower part while its upper part is constituted by a coarse grained sandstone sequence (Stratigraphic section KN-1). Poorly preserved sedimentary structures (mainly sole marks) and cross lamination (Plate 9b) in thicker sandstones, and straight wave ripples (Plate 10a) towards the tops of thinner sandstones, define a diverse but dominantly southward paleocurrent pattern in the Nauroz Formation. It is therefore concluded that the sandstones were derived mainly from erosion of arc related rocks. Nauroz Formation in its lower part is dominantly composed of cleaved grey green shale (Plate 10b). Shale is compact and calcareous and in basal part contains olistoliths of underlying Kharan Limestone (Plate 11a and 11b), limestone filled channels (Plate 12a and 12b) and coquina (Plate 13a).

The upper part of the formation contains progressively thicker beds of shallow water sandstone (Plate 12b). Sandstones are generally coarse to medium grained with rounded to well rounded grains in a calcareous cement. The slump features within sandstone, presence of olistostromes, coquina beds and carbonate channels indicate rapid sedimentation in unstable basin conditions prevailing during early Oligocene(Plate-13 a and b).

STRUCTURAL TRAVERSES

The Structural traverses in the periphery of Kharan forearc area indicate that the dominant structural style is the northeast to southwest trending, long and tight anticlines (Plate 14a and b) which are separated by very broad asymmetrical synclines. Plate 14a shows two closed spaced synclines in Rakshani Formation separating an anticline. The narrow anticlines are south verging and mostly asymmetrical to overturned. As such these asymmetric structures are typically very long (10-15 kms) with a continuous traces of the axial plane with steep, overturned or thrusted southern limbs having dips of 60° to 80°. Generally, the major structures are east-west Oriented due to a north-south oriented compression related to the subduction of oceanic crust in a northerly direction. The reverse faults steeply dipping to the north or northwest are roughly parallel with the fold axis. The folds generally strike east-west parallel to the regional trend. Structures are narrow, tightly folded, asymmetric anticlines, many of them are overturned and display high angle reverse faults. Fold closures are commonly observed throughout in the study area. Folds close in both directions but predominantly with shallow plunge to the east. In Kharan area, the intensity of deformation noticeably decreases southward and anticlinal structures are seen less affected by reverse faults. These structures appear to have experienced lesser shortening than the structures in northern part.

A few back thrusts particularly in the northern part of Kharan area are also visible. The young folding effects the Neogene Nauroz and Rakhshani formations as well as the underlying Kharan Limestone.

PETROLEUM PLAY ASSESSMENT

In a subduction complex, the forearc regions or basins possess the best chances of finding hydrocarbons in

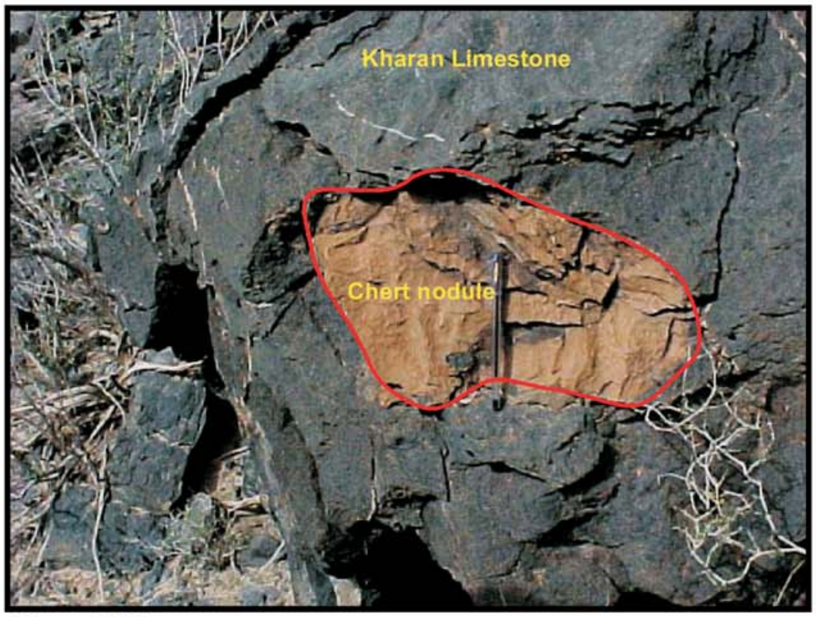

Plate - 5 (a)
Chert nodule in Kharan Limestone

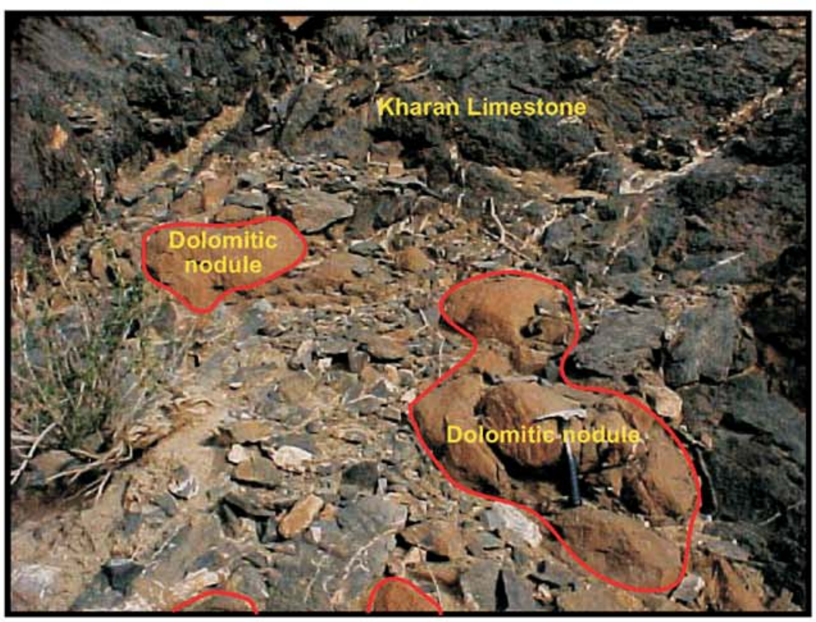

Plate - 5 (b)
Dolomitic nodule in Kharan Limestone.

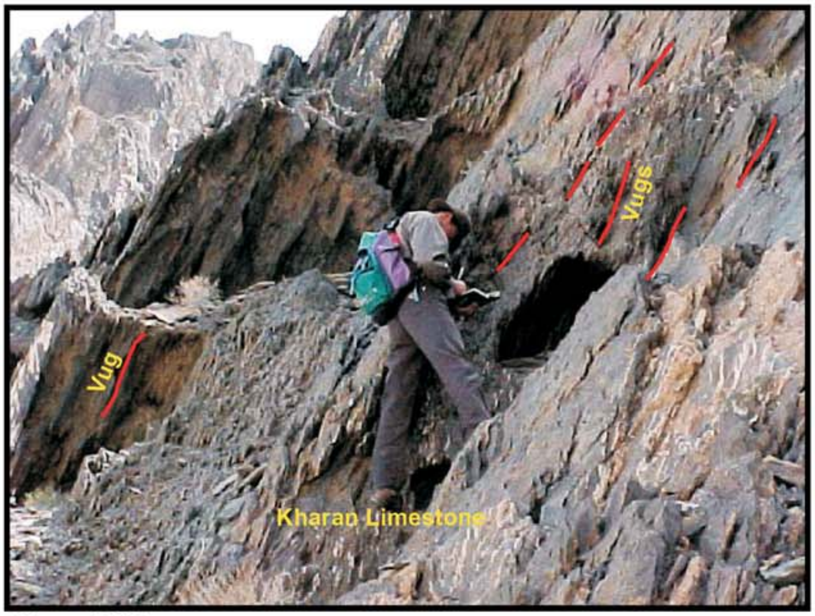

Plate - 6 (a)
Vugs and caverns in Kharan limestone porosity.

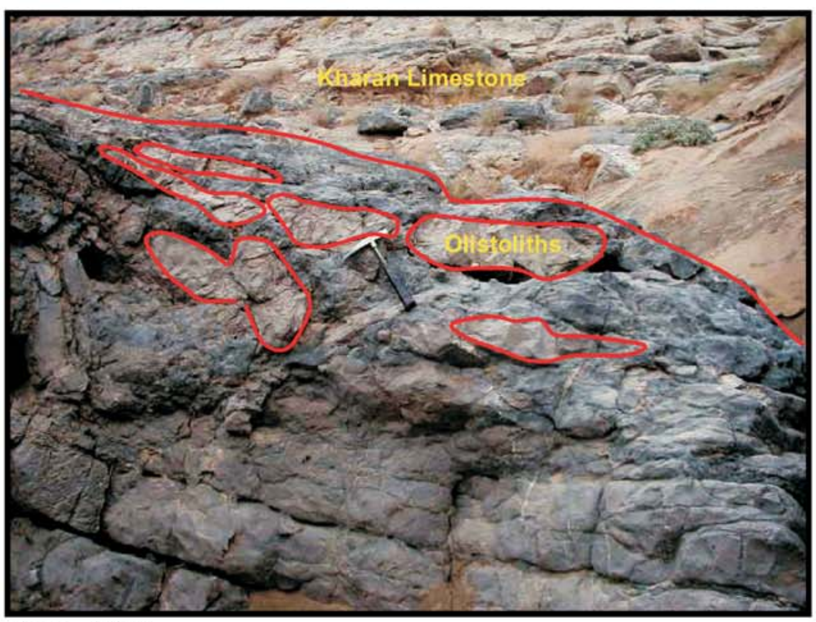

Plate - 6 (b)
Olistoliths in Kharan Limestone. Rounded / lenticular limestone of the same lithology formed due to slumping and indicating the undulating basin. Camera facing north. Location : 28° 39' 07'' N / 65° 10' 24'' E.

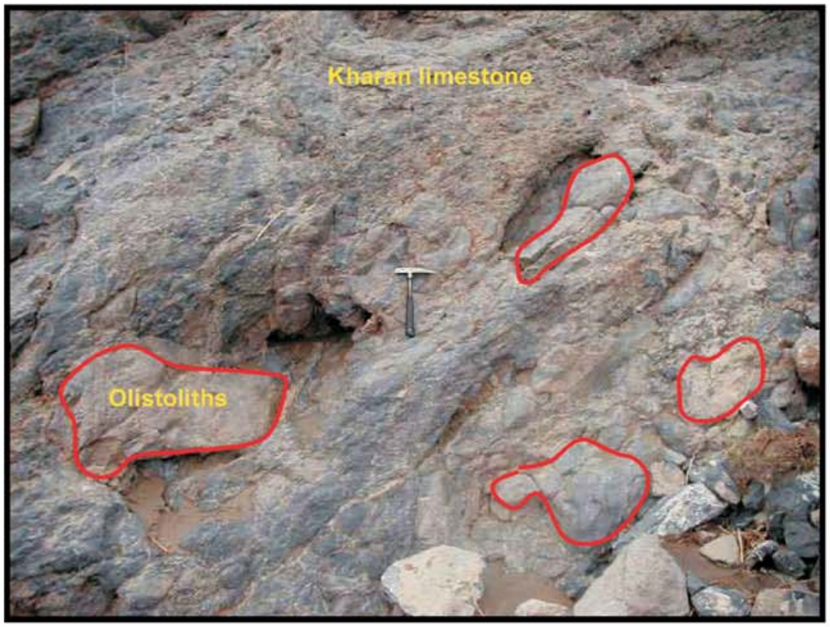

Plate - 7 (a)
Olistoliths in Kharan Limestone. Rounded / lenticular limestone of the same lithology formed due to slumping and indicating the undulating basin. Camera facing north. Location : 28° 39' 07'' N / 65° 10' 24'' E.

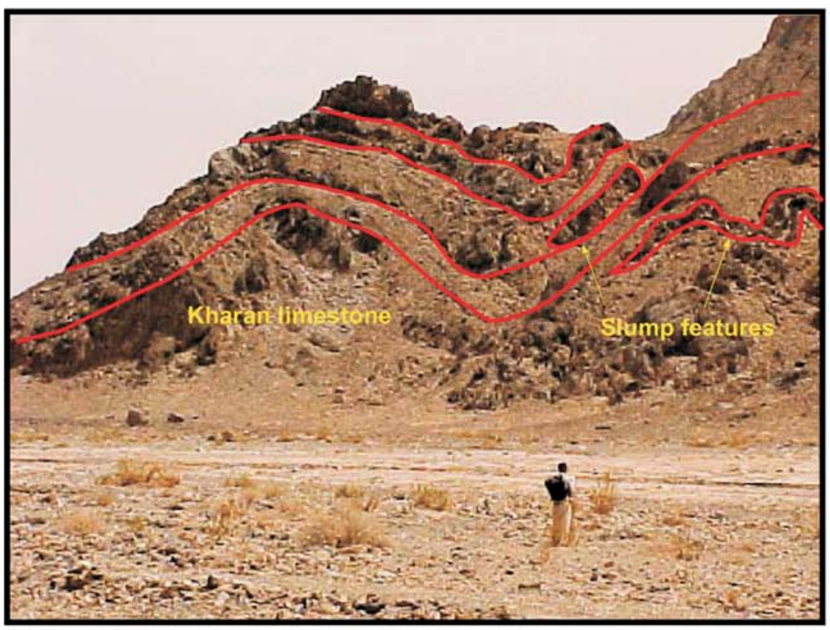

Plate - 7 (b)
Slump features within Kharan Limestone indicating the deposition in an unstable basin and subsequent development of slump and gravity slides.

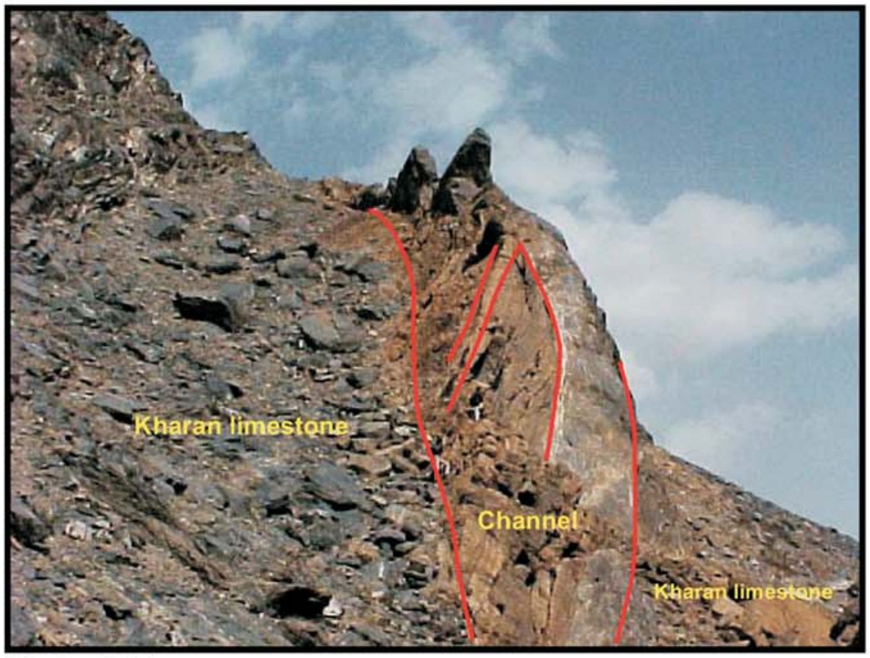

Plate - 8 (a)
Channel filled limestone and recycled sediments in basal part of Kharan Limestone.

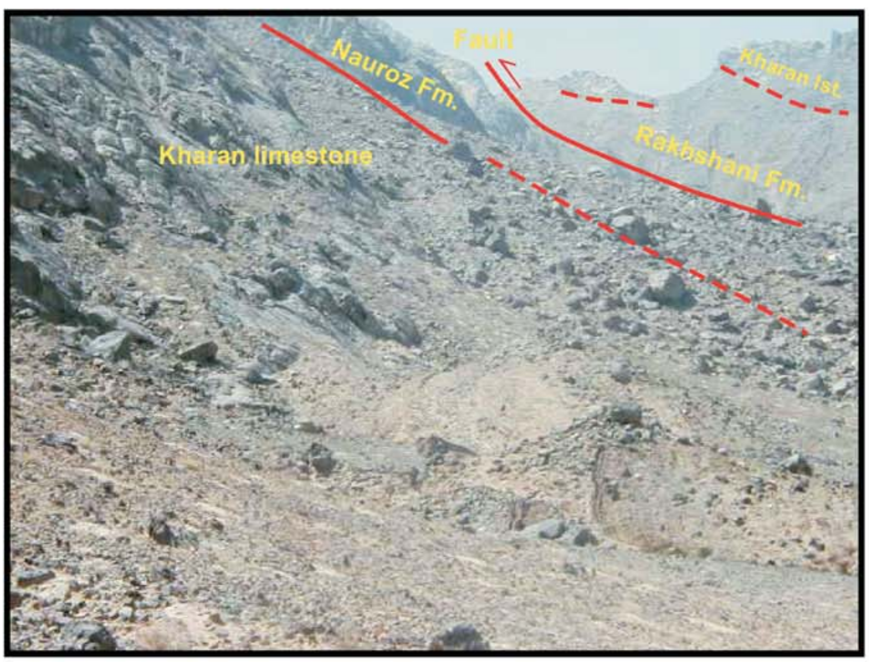

Plate - 8 (b)
Stratigraphic contact of Nauroz Formation and Kharan Limestone exposed in the northern limb of Eri-Kalak kink fold. Camera facing west.

Plate - 9 (a)
Undulating surface at top most part of Kharan Limestone. This is near the contact between Kharan Limestone and Nauroz Formation. The slickensides show the movement at the time of faulting. Location : 28^{o} 39' 24'' N / 65^{o} 09 ' 21'' E, Alt=938m.

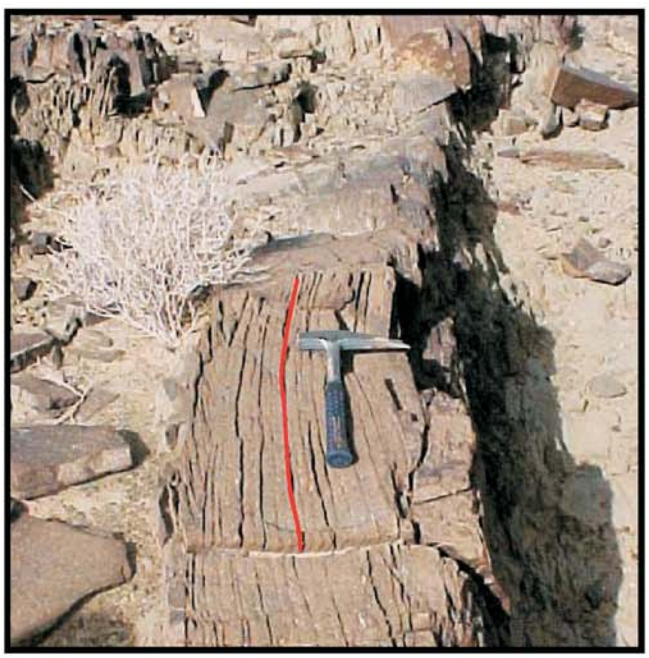

Plate - 9 (b)
Cross Bedded sandstone of Nauroz Formation.

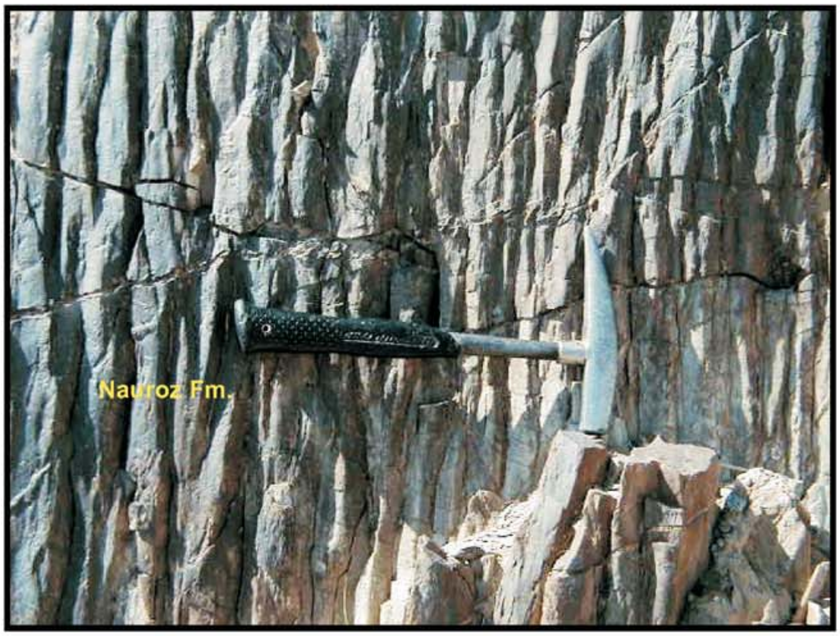

Plate - 10 (a)
Straight crusted ripples striking 110^{o} / 64^{o} at the top of sandstone bed in Nauroz Formation. The current direction follow direction (Hammer Head) from NE to SW.

Plate - 10 (b)
Greenish grey cleaved shale of Nauroz Formation. Camera facing south. Location Coordinates : 28^{o} 39' 30'' N / 65^{o} 09' 46'' E.

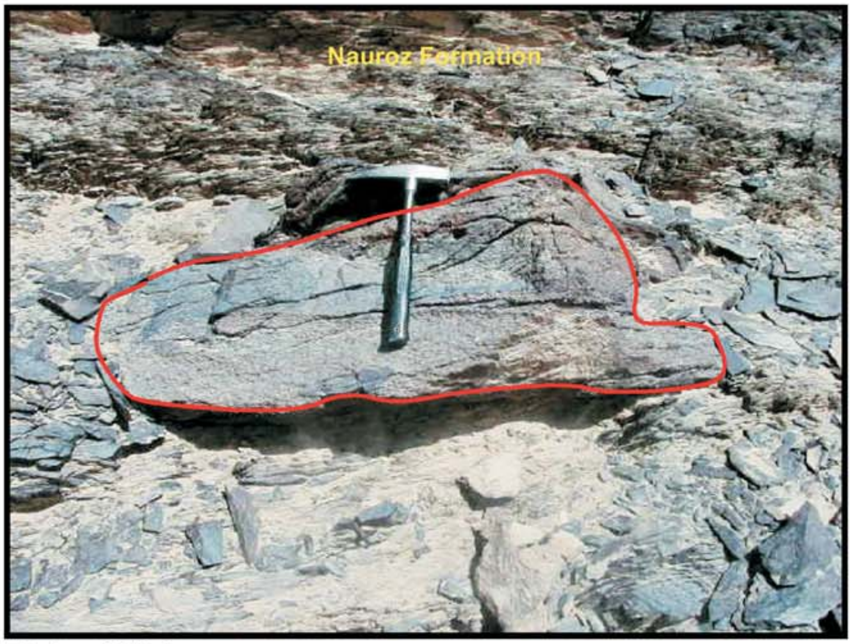

Plate - 11 (a)
Exotic Limestone in Nauroz Formation. Location : 28^{o} 39' 30'' N / 65^{o} 09' 46'' E.

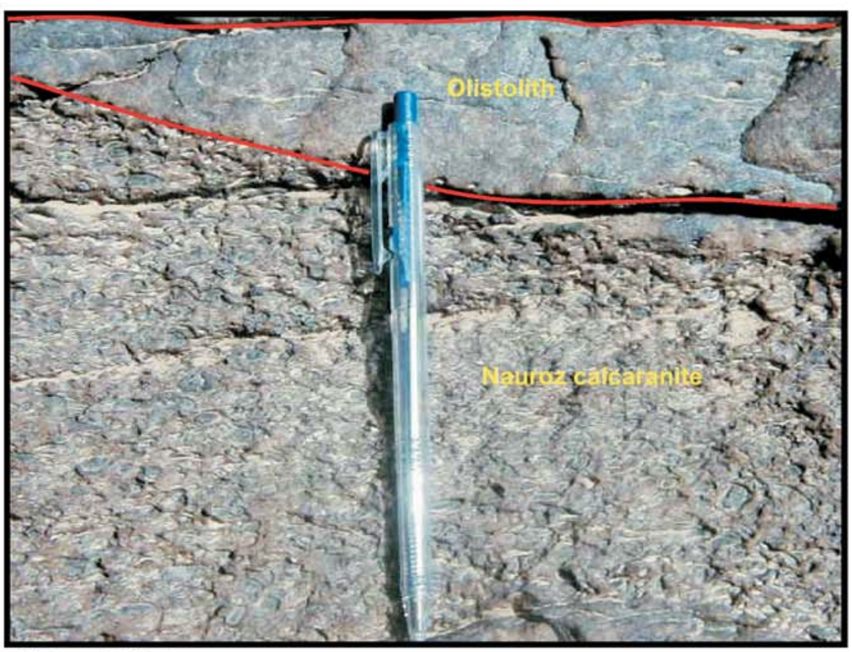

Plate - 11 (b)
Olistoliths within calcaranite development in Nauroz Formation. Location : 28^{o} 39' 30'' N / 65^{o} 09' 46'' E.

Plate -12 (a)
Limestone channel deposits in Nauroz Formation. Limestone is rich in fossils, creamy, buff, light brown, hard, crystalline. Location 26° 45' 49.15" N / 65° 35' 25.76" E.

Plate -12 (b)
Closeup view of limestone channels deposits in Nauroz Formation. Location 26° 45' 49.15" N / 65° 35' 25.76" E.

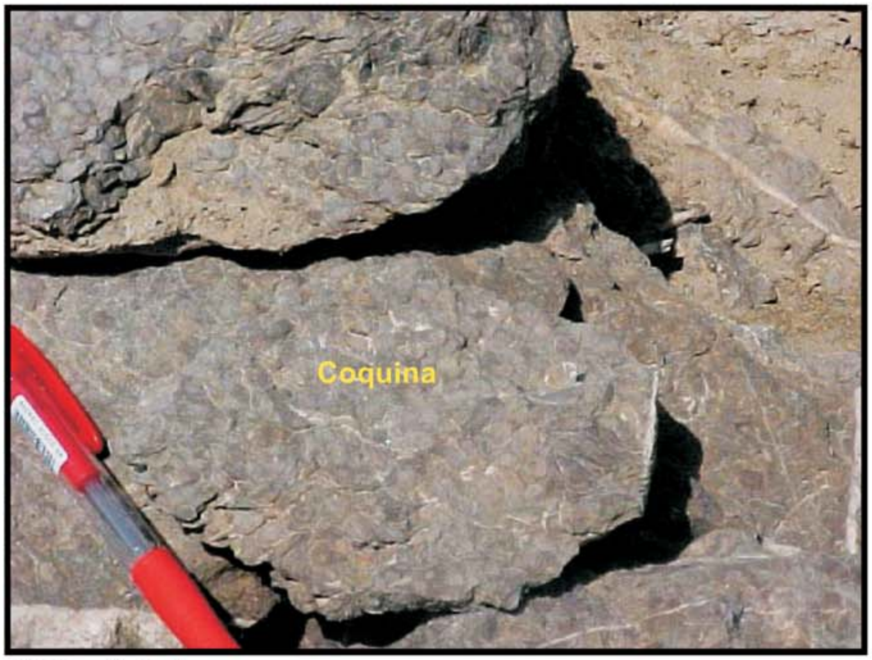

Plate - 13 (a)
Coquina horizon in Nauroz formation indicating shallow depositional setting.

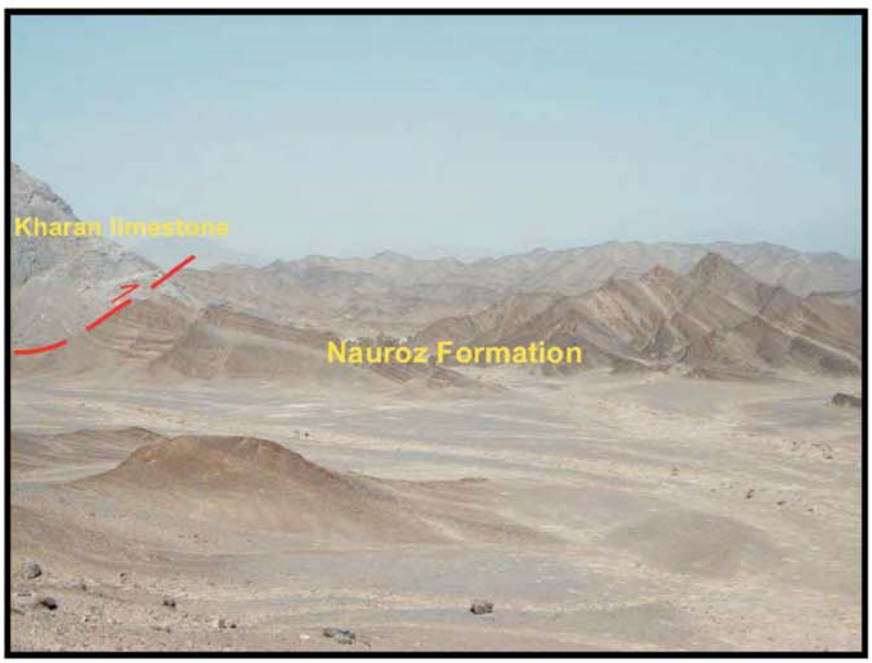

Plate - 13 (b)
Nauroz Formation over thursted by Kharan Limestone . Location : 28^{O} 39' 38'' N / 65^{O} 12 ' 39'' E.

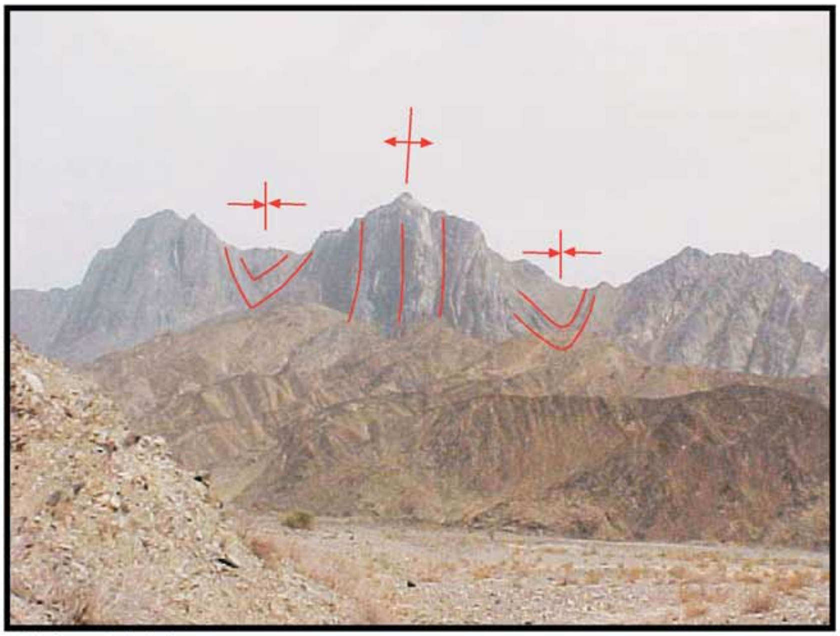

Plate - 14 (a)
Two closed spaced synclines in Rakshani Formation.

Plate - 14 (b)
Isoclinals fold, involving Rakhshani Formation and Kharan Limestone. Camera facing west-east. Location : 28° 30' 53'' N / 64° 48' 52'' E, Altitude=810m.

commercial quantity. An example is the Cook Inlet Basin of Alaska, from where more than one billion barrels of oil equivalent has already been produced.

An oil seep was reported at Kwash by HSC in1961. However, subsequently search by Hydrocarbon Development Institute of Pakistan (HDIP) and several other exploration companies could not confirm the presence of this or any other oil seepage. Based on field data gathered by PPL and previous studies the depositional setting of the Palaeogene succession in Kharan forearc sub-basin indicates that there are favorable conditions for the occurrence of potential source-, reservoir- and cap-rock assemblages and a viable petroleum system. Tectonic development of the basin also shows progressive decrease in the structural complexity southward of Raskoh range resulting in the likely occurrence of less complex structural traps of considerable pool size.

The details regarding the source rock nature and occurrence, reservoir facies development, regional seal in the area and likely entrapment situation are discussed in the proceeding sections.

SOURCE ROCKS

Fetid smell of freshly broken Kharan Limestone indicates contents of hydrocarbon generating organic matter. The basal part of Kharan Limestone is composed of wackstone, which seems relatively better host of organic matter than the upper part of the formation. However, initial geochemical analysis from these horizons shows TOC up to 0.22% with genetic potential of 0.12 gm/ton, which are low values. Generally as a result of intense weathering the organic matter is easily oxidized and therefore, low TOC of surface sample may not reflect their actual organic richness preserved in the subsurface. It may be added here that limestone containing as low as 0.3% TOC are considered source rock capable of generating hydrocarbon. Therefore, we expect that subsurface Kharan limestone may exhibit better TOC contents and genetic potential.

Dark colored shale, interpreted to be deposited in slope environment occurs in the middle and lower part of Rakhshani Formation. This depositional setting is conducive for accumulation and preservation of organic matter. Since Rakhshani Formation has experienced intense compaction due to subduction tectonics, its organic matter seems to be partially transformed into graphitic carbon which limits the genetic potential of the formation. One sample shows TOC up to 1.98% but pyrolysis results show no hydrocarbon generation potential. This may be due to its proximity to the volcanic belt. However, under the Kharan desert it may have a better genetic potential.

SOURCE ROCK POTENTIAL

A total number of 77 samples were collected from different lithostratigraphic units in the Kharan area for the evaluation of potential source rocks. Geochemical results of 8 random surface samples from various lithofacies in Kharan are tabulated in Table 2 .

Table-2- Geochemical Analysis of samples from various Lithofacies Samples of Kharan Area.

Sr. No.	Sample No.	TOC (%)	GP (kg/ton)
1	**KN-4/KL-9/03**	0.23	0.12
2	KN-4/KL-15/03	0.18	-
3	KN-4/KL-17/03	0.12	-
4	**KN-5/RS-6/03**	1.98	0.07
5	KN-5/RS-9/03	0.19	-
6	KN-5/RS-12/03	0.17	-
7	KN-5/RS-25/03	0.37	-
8	**KN-5/RS-33/03**	0.50	0.02

The TOC of these samples do not depict their true organic richness due to the fact that there is a very thick weathering zone which has resulted in oxidation of organic matter in the surface samples. As may be seen that organic matter in most of these samples has been found oxidized. Considering the depositional environment and present weathering zone, it can safely be assumed that the un-oxidized organic matter would increase substantially with depth below the weathered zone.

SOURCE ROCK MATURITY

The genetic potential (gP) and hydrogen index (HI) of one sample of Kharan Limestone and two samples from Rakhshani Formation show very low values indicating insignificant source rock potential. However, Tmax values of Kharan Limestone indicate an early stage of maturity. Production Index (PI) for Kharan Limestone also coincides with other geochemical parameters. Values of Production Index (PI) for Rakhshani Formation show a range indicating the possibility of hydrocarbon generation (Table-3).

Table-3- Source Rock Maternity Analysis of Kharan Limestne and Rakshani Formation.

Sample No.	Tmax	PI	HI	GP
KN-4/KL-9/03	436	0.33	34	0.12
KN-5/RS-6/03	364	0.83	4	0.07
KN-5/RS-33/03	-	1.00		0.02

The available analytical data does not help in evaluation and defining the potential source rock in the area. However, the field geological observations and paleo-geographical development of the sub-basin indicate that there exists a good chance for the accumulation of marine and terrestrial organic matter.

The basin modeling of Kharan sub-basin shows that the Kharan Group is within mature oil generation window at a depth of around 3000m, whereas the Rakhshani Group is within oil to gas generation window at a maximum depth of 5500m. The basin modelling results are supported by the presence of Kwash oil seepage, which proves that the source rock must be or had been within the oil maturity window in order to generate the oil.

Figure 6 shows the geothermal gradient and sedimentary fill map (Raza, 1991).

The area south of Kharan has a maximum sediment thickness of 15,000m whereas, in the north of Kharan area, the maximum sediment thickness is in order of 5,000m. There for, a modest thickness (maximum of 6,000m) of sediment was used for the basin modelling. Although the source rock samples from Raskoh show that the source rock is over-mature but this is likely to be due to the close proximity of the igneous bodies. It is important to mention here that temperature has an exponential effect on source rock maturity and hydrocarbon expulsion.

Figure 7 shows the burial history curve and maturity window from basin modelling and petroleum system of Kharan sb-basin.

RESERVOIR ROCKS

The sediment fill of the basin includes marginal carbonate buildups (Kharan Limestone) within which carbonate reservoirs are normally developed. The Kharan Limestone is dark gray to brownish gray, occasionally highly fossiliferous and reefoid and has a fetid smell. Its thickness varies greatly and has been measured up to 400m in the Eri Kalag area (Table-1).

Lithologically the upper part of Kharan Limestone is mainly grainstone and is partially dolomitized and partially dedolomitized. The grainstones generally have some intergranular porosity as well as vuggy porosity due to dedolomitization.However, the porosity/permeability analyses of few samples from the upper part of Kharan Limestone indicate development of very little porosity in the dolomitized/dedolomitized horizons. Despite the very low intergranular porosity and permeability, the Kharan Limestone may still be considered as a potential reservoir rock in view of a) its nodular nature; b) development of large vugs due to dissolution of dolomitic zones and c) fractures developed due to deformation (Plate-15a and b). As pointed out earlier, Kharan Limestone is deposited in marginal settings of the basin, where generally early diagenesis lead to dolomitization providing chances for development of adequate vuggy porosity. In several sections we have noticed several zones of dolomitization in the upper part of Kharan Limestone. Further prospective part in the carbonates buildups could be the reefal zones developed along the paleo-highs.

The upper part of Rakhshani Formation comprises gritty sandstone, conglomerate and fine to coarse grained sandstone interbedded with shale. Normally such horizons exhibit good porosity/permeability. However the analysis of three samples from Rakhshani Formation and its equivalent facies in the west show very negligible results.

The upper part of Nauroz Formation is dominantly composed of quartz arenite of considerable thickness. The sandstones are medium to coarse grained and well sorted. These sandstones can also serve as potential reservoir if interbedded shale horizons can provide sufficient seal.

RESERVOIR ROCKS CHARACTERISTICS

A total of 54 samples were collected to analyse reservoir characteristics of sandstone horizons of Nauroz and Rakhshani formations and dolomitic limestone of Kharan Limestone. The analyses of 10 samples indicate very low porosity and permeability of these horizons (Table 4).

Table 4- Poroperm Analysis of Nauruz and Rakhshani Formation and dolomite limestone of Kharan.

Stratigraphic Xns / Fm / Lithology	k (mD)		Ø (%)
	Horz.	Vert.	
KN–4/KL-7/03/Lst	1.20	0.92	0.80
KN-4/KL-11/03/Lst	0.89	0.93	0.90
KN-5/RS-11/03/Sst	0.57	0.97	0.97
KN-6/KL-17/03/Lst	0.63	0.97	0.91
KN-TG/KL-1/03/Lst	0.59	0.90	0.92
KN-TG/KL-1/03/Lst	0.57	0.89	0.70
KN-8-JD/-24/03/Sst	0.59	0.93	0.88
KN-8-JD/-31/03/Sst	0.57	0.82	0.88
KN-7/KL-18/03Lst	0.58	0.94	0.89

REGIONAL TOP SEAL

Intraformational shale horizons of Rakhshani Formation can be considered to be the cap rocks over its sandstone and conglomerate horizons.

The thick shale horizons of the lower part of Nauroz Formation are considered to constitute an effective seal over the dolomitized upper part of Kharan Limestone.

STRUCTURAL TRAPS

Forearc basins generally contain abundant, fault controlled structural traps. The traps in our case are due to the subduction of Arabian Plate under the Eurasian Plate. In this tectonic environment we observe mostly thrust blocks and thrusted folds (Figure 8). However, the structural style within the Kharan area, as determined by structural cross sections and 2D seismic of OGDCL (Figure 9), indicates that the tectonic deformation is progressively decreasing southward from Raskoh to Kharan desert area and the tight folds and high angle reverse faults are becoming less common southward. It is therefore interpreted that less complex structural traps would occur below Kharan desert.

Surface anticlines seen in the field indicate the presence of structural traps of considerable lateral extent up to 15 km and 1.75 km wide (from Geological map). Kharan Limestone and Rakhshani formations are exposed in the cores of uplifted anticlinal structures, which are separated by broad synclines. Fold closures are relatively

Plate - 15 (a)
Kharan Limestone; nodular nature, fractured and filled with calcite veins. Calcite may be filled because of dolomitic limestone dissolution.

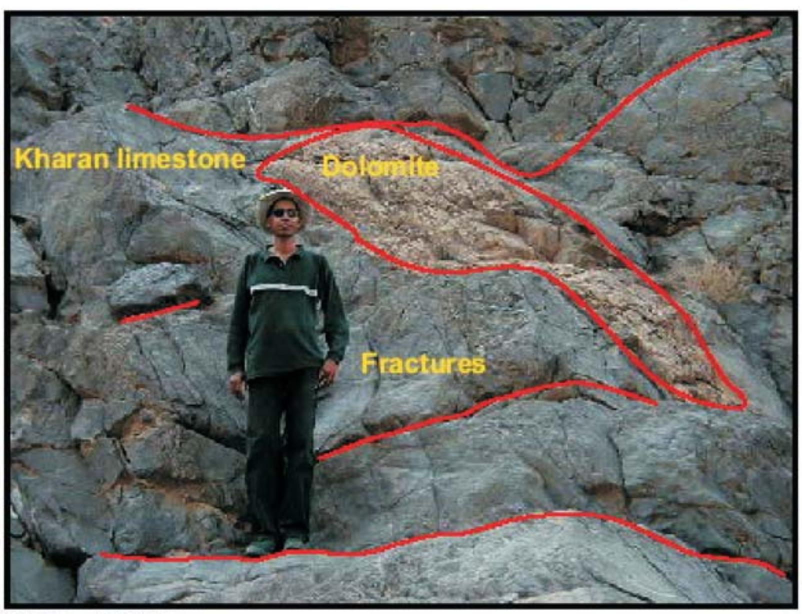

Plate - 15 (b)
Fractured pattern in Kharan Limestone. The strike and dip of the pattern is N 64^{o} E / 70^{o} N. Fractures are low angle and filled with dolomite. Location : 28^{o} 29' 15'' N / 64^{o} 40 ' 50'' E., Alt=926m.

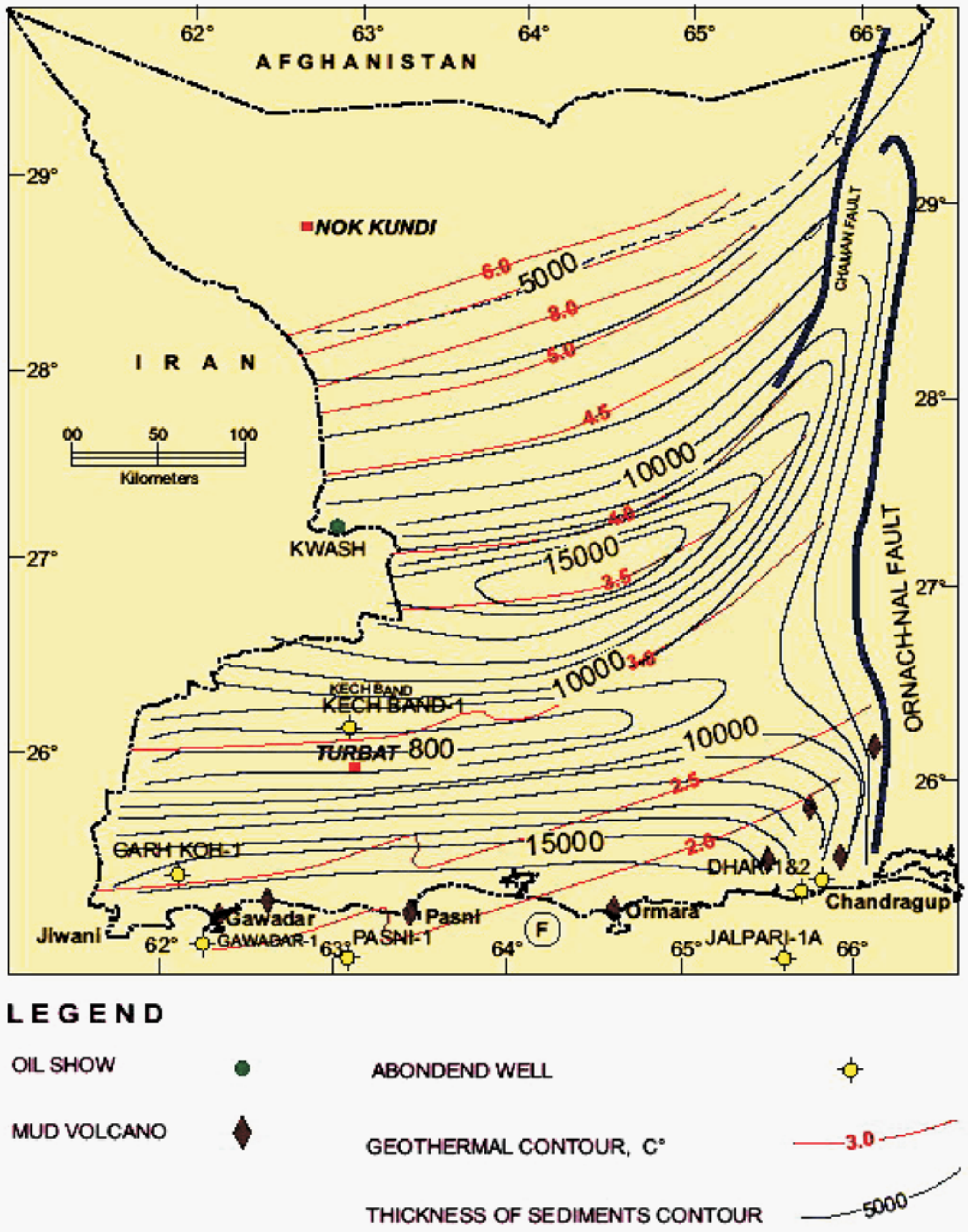

Figure 6

1- Geothermal Gradient Map has been adopted after Raza et al, 1991.
2- Sedimentary Fill Map has also been adopted from Raza et al, 1991, (Modified after Kemal, Raza and Chohan, 1982).

Figure 7a

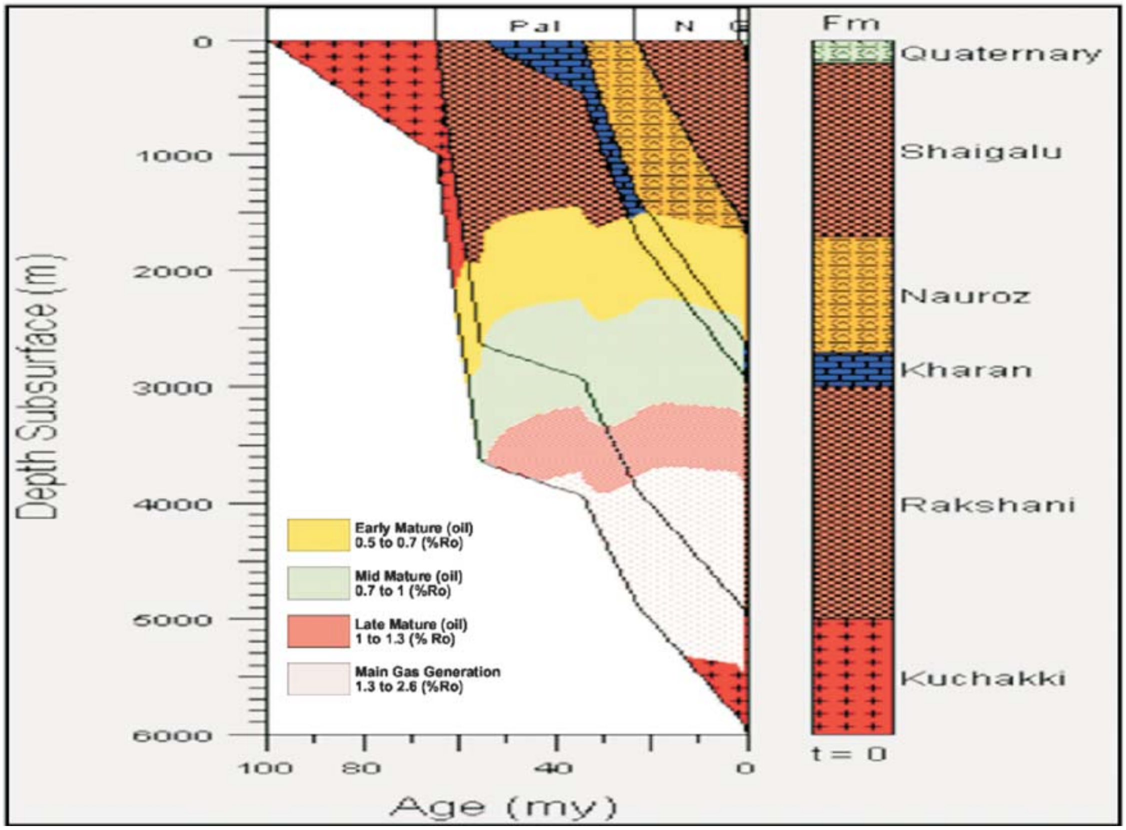

Figure 7b

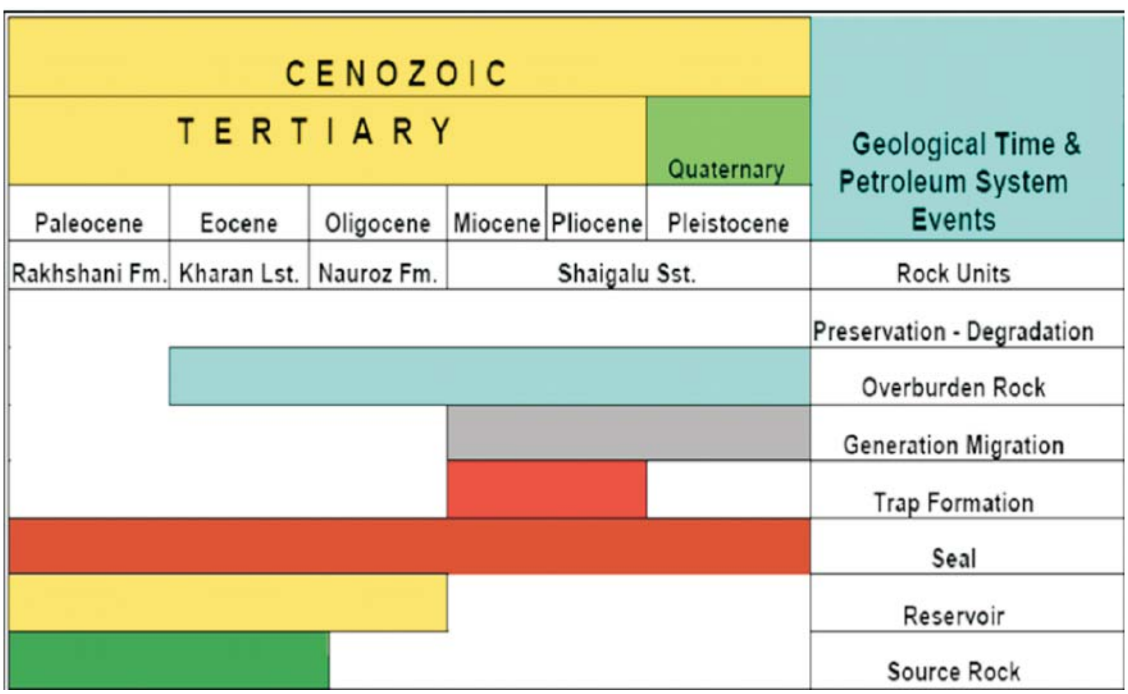

Figure 7-(a) Burial History Curve and Maturity Window of Kharan Forearc Sub-basin (b) Petroleum System of Kharan Forearc Sub-basin (Midified after Murphy, 1999).

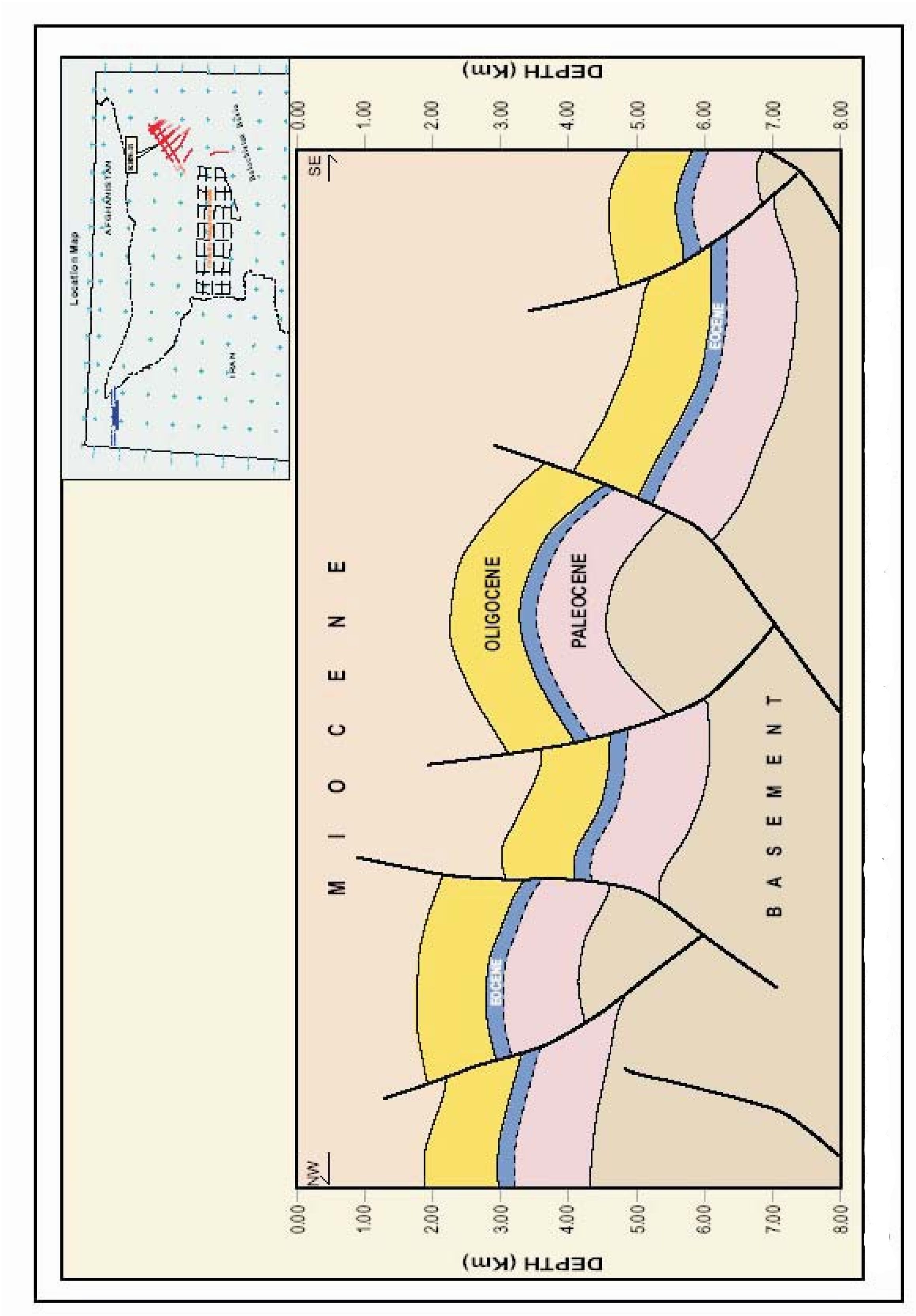

Figure 8- Structural Styles in Kharan Forearc Sub-basin (Based on Aeromag Data of Murphy, 1999.

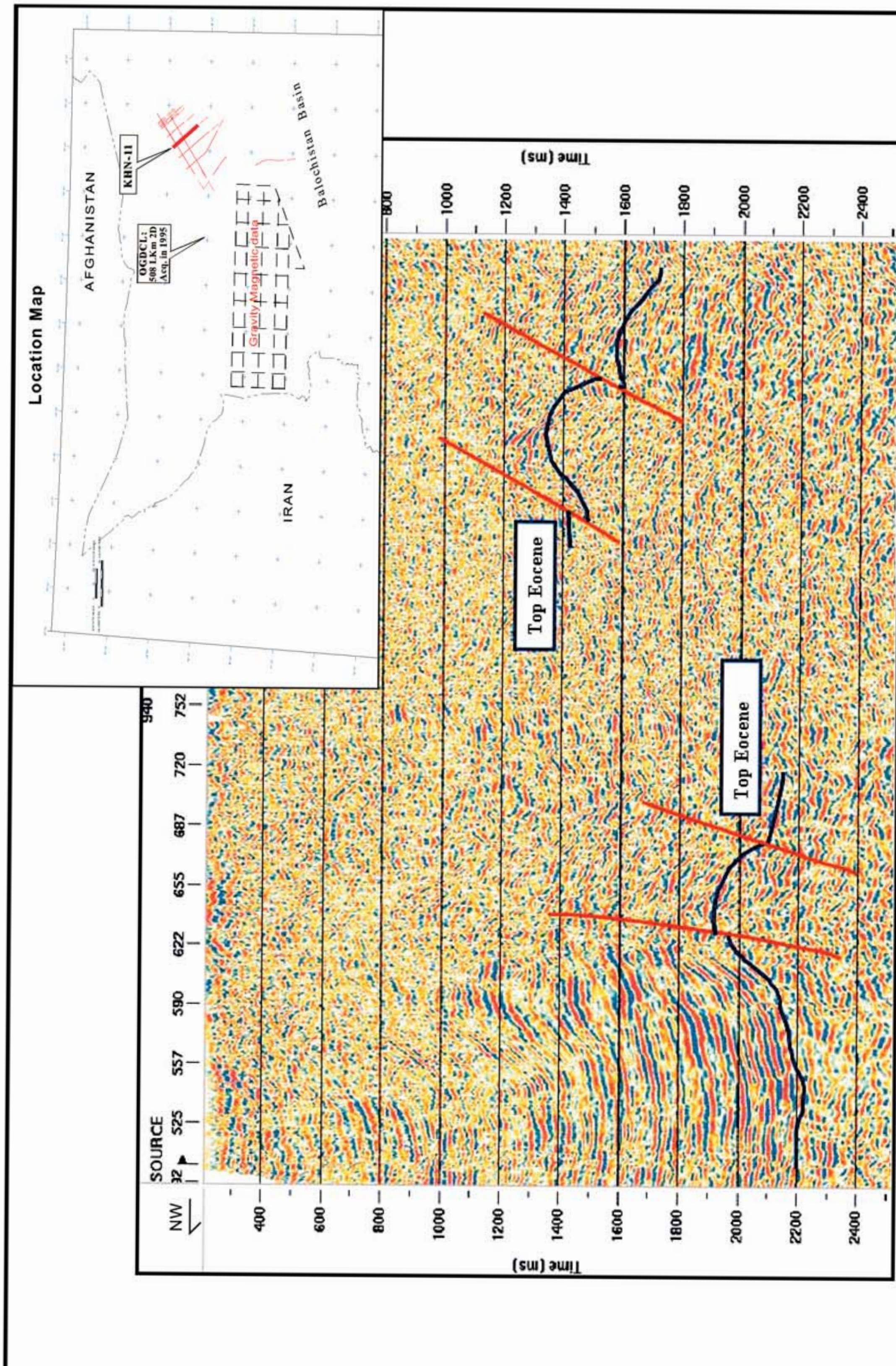

Figure 9-2D Seismic Line KHN-11 across Nauroz Block acquired by OGDCL in 1995.

common in Kharan Limestone and lower horizons level throughout the Kharan region. Folds close in both directions, but predominately with a small plunge angle in the east. Such structures in subsurface could be identified when the hanging wall is cut off the top surface of a massive limestone beneath shale; or when the leading edge of a limestone thrust wedge in shale occurs.

GRAVITY & MAGNETIC INTERPRETATION (After MPOC and Rafferty et al., 2000)

The gravity, magnetic and the subsequent modelling of these data were carried out by Carson Services Incorporated (Carson, 1999) and ARK on behalf of Murphy Pakistan Oil Company (MPOC) in 1999. The gravity and magnetic interpretation reports are available and a detailed account is also given by Rafferty et. al, 2000 in their paper on Kharan Basin. This section only gives a brief summary and compilation of the above reports and the avid reader is requested to go through the above references for more details.

Major geological and structural elements of Kharan forearc basin were delineated using the Carson airbone-gravity and magnetic survey by Murphy Pakistan Oil Co. (MPOC). The data were acquired in 1999 by MPOC from Carson Services Incorporated over the Kharan area, south of 28° N. The lines were flown in a NESW and NWSE orientation with spacing of 6km and the grid coinciding with the regional dip and strike direction. A total of 8772 line kilometers of magnetic data and 7359 line kilometers of gravity data were recorded with expectancy to resolve anomalies greater than 3 kilometers. Figure-3 shows the gravity and magnetic grid.

The Carson Bouger gravity map was produced using a Bouguer density of 2.67 gm/cc for terrain correction. The Bouguer gravity map and its mathematical residuals show similar characteristics. The maps show values ranging from -50 millligals in the north to -110 milligals in the south west. A broad low frequency high, trending EastWest is seen in the northern limit of the survey with 30 milligal's value. This high is located south of the Raskoh range and under the Kharan depression. To the south and the east along the north Siahan Ranges a broad gentle low is observed with distinct gravity gradient. Positive and negative anomalies associated with Cretaceous oceanic basement highs and lows (thrusts / back thrusts?) are seen, once the regional gradient is cancelled.

The gravity maps show low frequency positive anomalies along the northern section indicating a shallow mafic crystalline basement. In the south, negative gravity anomalies are indicating a probable deep oceanic type crystalline basement.

The northern high observed on the gravity and magnetic data may be the remnant island arc system (Amiri Belt) of intrusive basement and ophiolitic rocks buried under Tertiary sediments. In the NW corner, the high frequency magnetic high anomaly may be caused by shallow Quaternary volcanics associated with Cenozoic magmatism of Koh-I-Sultan to the north.

Near the Washuk, in the eastern part of the survey area, a relatively narrow but long, asymmetric positive anomaly appears. Its segmented NE-SW strike is interpreted to be a thrusted basement block, parallel to the Siahan Range. The segmentation is due to several smaller and younger faults trending parallel to the Chaman Fault Zone with several elongated narrow lows.

The predominant strike direction in the central part of the survey varies from E-W to NW-SE towards Iran. The large negative anomaly located in the southwest could be interpreted to represent a sedimentary basin.

The merged magnetic anomaly map shows a regional NE-SW trend similar to the gravity map. A suture zone, interpreted from the large, long wavelength magnetic anomaly straddling around 28°N is thought to represent a major intra- basement magnetically susceptible body.

The residual magnetic anomaly map shows significant variability in magnetic receptiveness within large broad trends. The residual magnetic anomaly map is useful for the identification of near surface igneous rock and magmatic bodies. The high frequency narrow residual anomalies to the north of 28°N are interpreted as igneous rocks.

Using the depth modelling, the magnetic basement in the northwest is estimated to be very shallow, in around 2 kilometers depth. This basement represents volcanic bodies and possible lava flows. Whereas in the central part of the basin, the depth of this basement is up to 7Km deep. The Eulers depth estimates for the igneous basement were used for constraining the gravity data in the profile modelling and ARK modelled two profiles, mostly constrained by surface geology. The main objective of the modelling was to ascertain the nature and thickness of sediments in the area. Both profiles suggested that the forearc sediments within Kharan basin have high density values (2.63 2.67 gm/cc) and the modelling suggest that the section lying above the suture zone contains high density sediments.

Figure 8 shows the structural styles based on the aeromagnetic data.

WORLD ANALOGUE

In a trench-arc system such as that of the Balochistan basin, forearc basins are considered to have the best petroleum prospects. An example is the Cook Inlet basin of Alaska with total oil and gas recoverable reserves of over 3 billion barrels of oil equivalent (25 oil and gas fields). It has produced 1.3 billion barrels of oil and 9.3 Tcf of gas. Its mean undiscovered resource potential (onshore and offshore) is estimated at 1.4 billion bbl (0.2 billion m3) of oil and natural-gas liquids and 2.3 Tcf (65 billion m3) of gas (IHS).

Kharan forearc basin is analogous to Cook Inlet basin of Alaska, in terms of exponentially wide trench-arc gap, (250-300 km) and the relatively simplicity of tectonic style. Cook Inlet basin produces from Eocene, Oligocene and Miocene reservoirs and similar age equivalent reservoir are found in Kharan forearc basin.

Figure 10a shows the location map of Cook Inlet basin, Alaska (Web).

In the Cook Inlet, oil seeps were first noted by Russian explorer's in 1850s on Iniskin Peninsula and the exploration wells first drilled near seeps found crude oil. Commercial oil first discovered at Swanson River field (Richfield Oil, July 1957) and the first Cook Inlet oil production (Swanson River) began in 1958. The largest Cook Inlet oil field, McArthur River was discovered in 1965: estimate 1.5 billion barrels.

Oil production peaked in 1970 at 82 MMBO per year and the oil production in 2002 was 11.5 MMBO per year. Similarly, Gas was first encountered during exploration for oil in 1950s and the first and largest commercial gas discovery was at the Kenai field by Unocal in October 1959. First Cook Inlet gas production began in 1961 and Gas production peaked in 1994 at 311 BCF gas with more then 9 TCF gas, produced to-date and 2 TCF proven gas reserves remaining.

Figure 10b shows reserves from Alaska with comparison on reserves from Cook Inlet (Web).

The petroleum system of Cook Inlet basin with Jurassic source rocks, Eocene, Oligocene and Miocene reservoir rocks, timing of source rock maturation, structuration and migration is shown in Figure 10c (Web). This could very well apply to Kharan, except that there are no Jurassic rocks known in this area. However, since the sedimentary cover is very thick, even the younger source rocks are expected to be mature and to have generated hydrocarbons as shown by the basin modelling results (Figure 7).

POTENTIAL AREAS

As discussed earlier in the section on exploration history of the basin, the frontal region of the Raskoh and Kharan forearc region remained one of the least studied parts of the Balochistan basin, and therefore neither the overall structural geometries of the region, nor their prospectivity and hydrocarbon potential were clearly understood prior to the initiation of the present exploration program. It was therefore critical, during this phase of hydrocarbon exploration within the study area, to conduct basic geologic programs, including structural and stratigraphic analyses. As initially defined by PPL, the purpose of the structural field program was to conduct an initial reconnaissance survey in order to determine those areas of greatest structural prospectivity for hydrocarbon exploration and to make a series of traverses at suitably spaced distances for understanding structural geometries across the region to recognize areas of prospectivity.

In this context southern and south-eastern part of the basin has been classified as a potential area for further exploration. This is based on the following field observations.

The lower part of Kharan Limestone exhibits depositional environments suitable for accumulation and preservation of organic matter. Thus giving rise to a potential source rock. Its upper part has reservoir characteristics developed due to the presence of nodular beds and large vugs resulting from late stage of diagenetic dolomitization and dedolomitization. First laboratory results cannot fully support this view at present.

In Raskoh range, Kharan Limestone is more than 400m thick and extends for about 100 km in east-west direction. The OGDCL seismic lines show that it is thickening to the south below the northern part of plains (Figure 3).

Relatively simple structural traps can be expected in the area of interest. From field evidence it can be deducted that structural complexities decrease progressive southward.

The area is away from the center of igneous activity at Raskoh geanticline. As such the impact may not be detrimental on maturity of organic matter.

The aeromagnetic and gravity data over this area show a considerable thickness of the sedimentary pile over the basement rocks.

CONCLUSIONS / RECOMMENDATIONS

Kharan area is classified as the forearc region of Balochistan basin which is analogous to several oil and gas producing region elsewhere in the world. It is compared with the highly prolific Cook Inlet Basin. We consider that the central part of the forearc sub-basin is a potential area for oil and gas exploration as there is a sufficiently thick sedimentary sequence, which may have source potential, reservoir characteristics and cap rock capability.

Paleogeography and sedimentary depositional environments prevailing in Kharan area during Paleogene are considered conducive for deposition of organic matter in anoxic conditions to develop suitable source rock horizons. It is interpreted that the low organic contents found in surface samples of Kharan Limestone are due to weathering. However, low TOC values are approaching the minimum limit of 0.3% TOC for classifying Kharan Limestone as a potential source rock. Therefore, we expect that Kharan Limestone in subsurface may contain better TOC contents and a better genetic potential. There are some horizons in the lower part of Rakhshani Formation, which show graphitic carbon contents. This may be due to its proximity to the volcanic Raskoh area. However, under the Kharan desert it may have a better genetic potential preserved.

There may be several horizons with reservoir characteristics in vast thickness of clastic sediments and marginal carbonate in the Cenozoic succession of the Kharan forearc sub-basin. The field study indicates that upper part of Kharan Limestone is mainly grainstone and is partially dolomitized and dedolomitized. The porosity measurements of few samples indicate very low values of intergranular porosity as well as permeability for this horizon. It may be noted that quantifying porosity and likewise permeability in naturally fractured carbonate reservoir is always considered as a compounding problem due to

Figure 10a

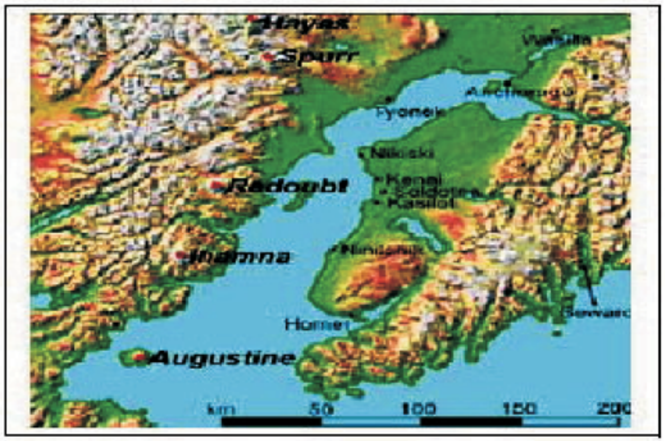

Figure 10b

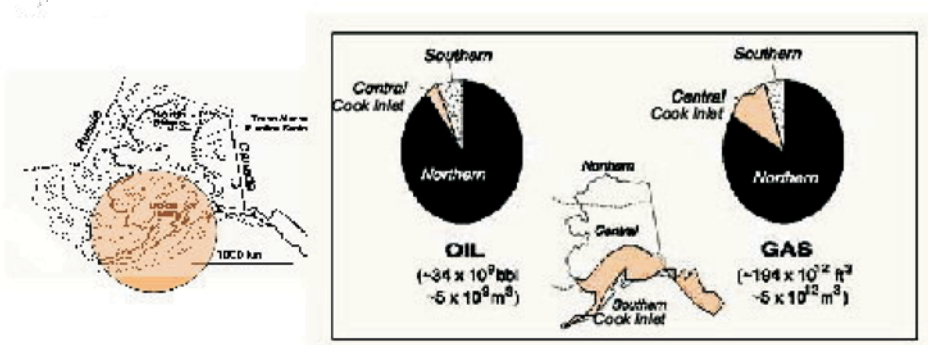

Figure 10c

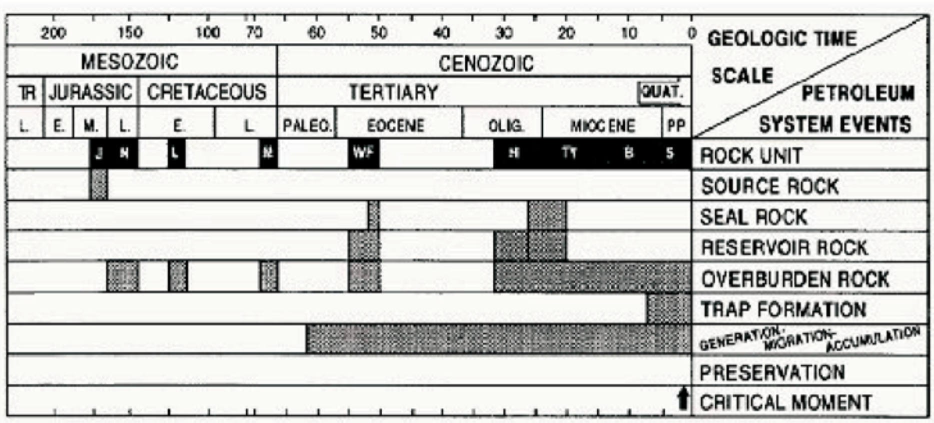

Figure 10- (a)-Location Map of Cook Inlet Basin, Alaska (Web).
(B)- Comparison of Cook Inlet Field Resources Vs. Alaska (Web), and
(c)- Total Petroleum System Chart of Cook Inlet Basin (Web).

variability in diagenetic processes affecting intergranular porosity. However, we understand that the presence of large vugs and nodularity in the upper part of Kharan Limestone could qualify it as a promising reservoir rock.

The gritty sandstone and conglomerate in the upper part of Rakhshani Formation are likely to have good porosity and permeability.

The medium to coarse grained and well sorted quartzarenite of considerable thickness occurring in the upper part of Nauroz Formation is another potential reservoir in the Kharan stratigraphic succession.

There is no dearth of structural traps in the area as the compressional tectonics due to subduction results in the development of large elongated structures. As discussed earlier, the less complicated structures are likely to occur in the Kharan desert area.

It is recommended that before undertaking further exploration in Kharan forearc sub- basin, gravity and magnetic surveys covering the desert area should be carried out to determine the depth to basement, and hence the thickness of overlying strata.

As mentioned earlier the central and eastern part of the Kharan forearc sub-basin appears prospective for oil and gas exploration.

A comprehensive depositional model of Kharan Limestone is required to be constructed by integrating data of geological field works, seismic and other data available with different companies.

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