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Hydrocarbon Prospectivity of the Bhittani and Northern Sulaiman ranges, North-West Himalayas, Pakistan

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ABSTRACT

The Bhittani and northern Sulaiman ranges are integral part of the Himalayan foreland fold-thrust belt that surrounds the northwestern apex of Tank Reentrant of the North Western Frontier Province (NWFP), Pakistan. Despite several significant oil and gas discoveries in the southern and northwestern segments of the Himalayan foreland fold-thrust belt, Bhittani and northern Sulaiman ranges are still challenging frontiers for petroleum explorationists. This article is an attempt to address the geological risk of the area through the concept of hydrocarbon system and play. Critical review of the available literature and geological fieldwork in the region depicts that all the potential parameters of a working "hydrocarbon play" that are source, reservoir, trap/seal, timing and migration, exist underneath Bhittani and northern Sulaiman ranges. The petroleum system is high impedance, characterized by multiple reservoirs and sealing horizons that are likely to be charged by multiple source rocks. Surface structural style shows that en-echelon anticlinal closures developed within the hanging walls of Jandola, Bhittani and Domanda faults are potential drillable prospects. The presence of a regional hydrocarbon kitchen is well supported by the stratigraphic record of the area. Whereas, the discovery of Savi Ragha within the Sulaiman Range has clearly established a working hydrocarbon system i.e. optimum timing of hydrocarbon generation, migration and entrapment.

INTRODUCTION

The Himalayan foreland fold-thrust belt of NWFP Pakistan includes Kohat fold-thrust belt along with its associated frontal ranges that include Surghar-Shinghar, Marwat-Khisor, Manzai, Bhittani (Trans-Indus ranges), Northern Sulaiman Range and the D.I. Khan Plain in the south (Figure1). This entire belt is a geologically defined compressional structural domain and encompasses an area of over 15,000 square kilometers.Until to date six discoveries of oil and gas along with four dry wells within Kohat fold-thrust belt in the north and seven in the south have been made in this domain. The recent discoveries have proved the maturity, migration and entrapment of the hydrocarbons in the region and demands reappraisal as for as the complex structural evolution of the Himalayan fold-thrust belt, Bannu depression and the D.I.Khan Basin is concerned.

The hydrocarbon prospectivity of a sedimentary basin is primarily based on the knowledge of geology and in particular on the concept of hydrocarbon system and play. The prospectivity process begins with addressing the geological risk which is established through play concept (Otis & Schneidermann, 1997). The play concept includes four key elements that are source, reservoir, trap/seal and the dynamics (timing and migration). All these elements together define a petroleum system and all these elements must be in place in time and space such that a petroleum accumulation can occur (White, 1993 & Magoon, 1989).

Fold and thrust belts of the world have been explored for hydrocarbons since more than a century with mixed results and are still challenging frontiers for hydrocarbon search despite the high exploration costs. Though the seismic data have contributed a lot to the understanding of the complex geometries in the fold-thrust belts, challenges are still there for exploration geologists.

Exploration for hydrocarbons in the Himalayan foreland fold-thrust belt of NWFP, Pakistan has been an important part of oil and gas companies exploration strategies in Pakistan during the last 50 years. Based on the recent discoveries in the central Kohat fold belt, has given an increasing demand for hydrocarbons and the continued expectations of finding big hydrocarbon reserves in the Himalayan foreland fold-thrust belt.

This paper addresses the hydrocarbon prospectivity of Bhittani and Northern Sulaiman ranges that is still a challenge for hydrocarbon exploration and provide answers to the queries related to the evaluation of different geological risks.

REGIONAL SETTING OF BHITTANI & NORTHERN SULAIMAN RANGES

The geodynamic processes of sea floor spreading, continental drift and collision tectonics resulted in the formation of a pronounced global feature that is the Himalayas surrounding the Indo-Pakistani subcontinent (Figure 2).

Four regional faults systems that are Main Karakoram Thrust, Main Mantle Thrust, Main Boundary Thrust and Trans-Indus Ranges Thrust subdivide the Pakistani Himalayas into five litho-tectonic domains, which are characterized by distinctive stratigraphy and physiography. From north to south these gross geological belts are Karakoram Block, Kohistan Island Arc, Northern Deformed Fold-Thrust Belt, Southern Deformed Fold-Thrust Belt and Punjab Fore deep (Ahmad et al,2005).

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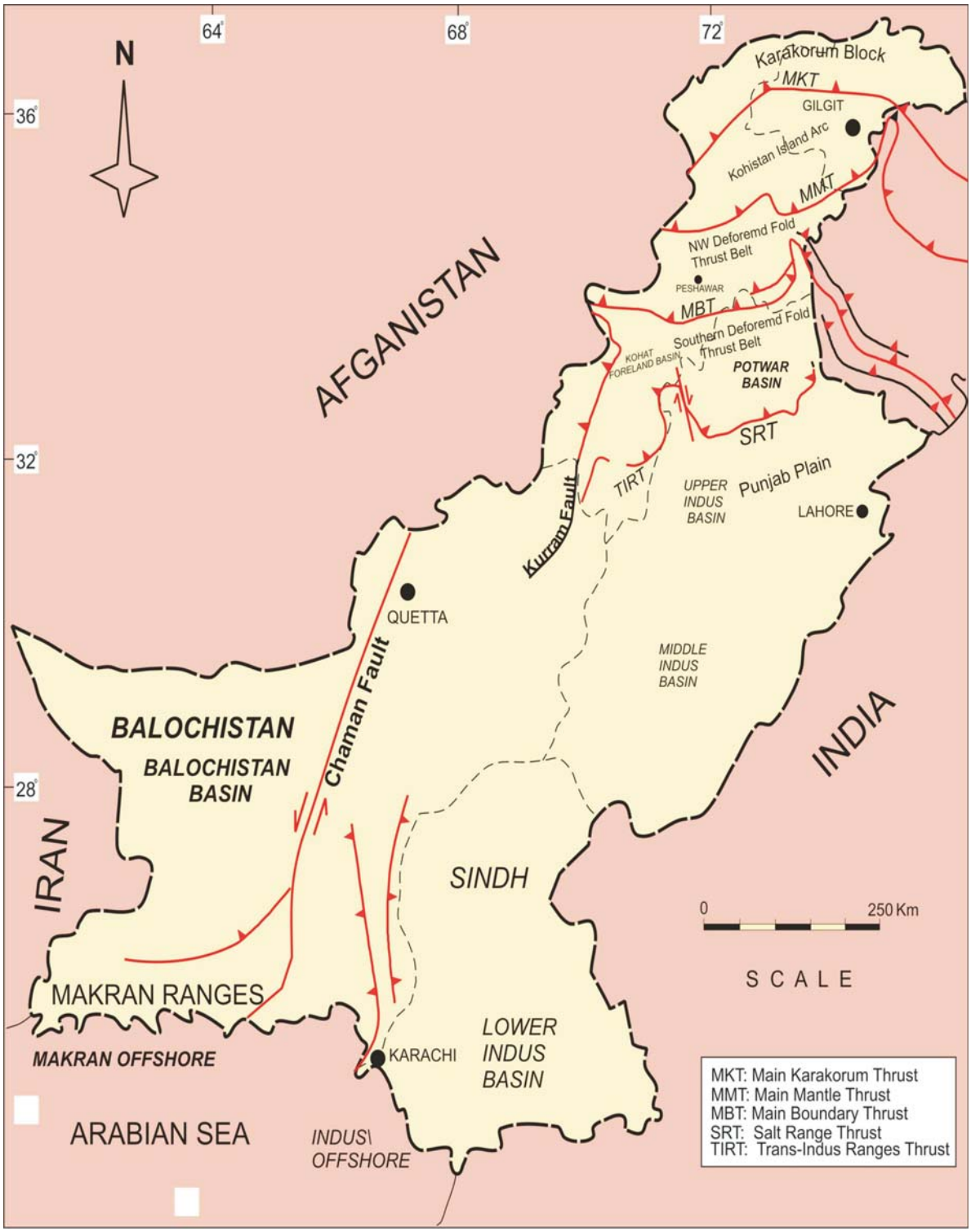

Figure 1- Tectonomorphic map of Pakistan, showing the location of Kohat Foreland Basin (Modified after Kazmi & Rana, 1982).

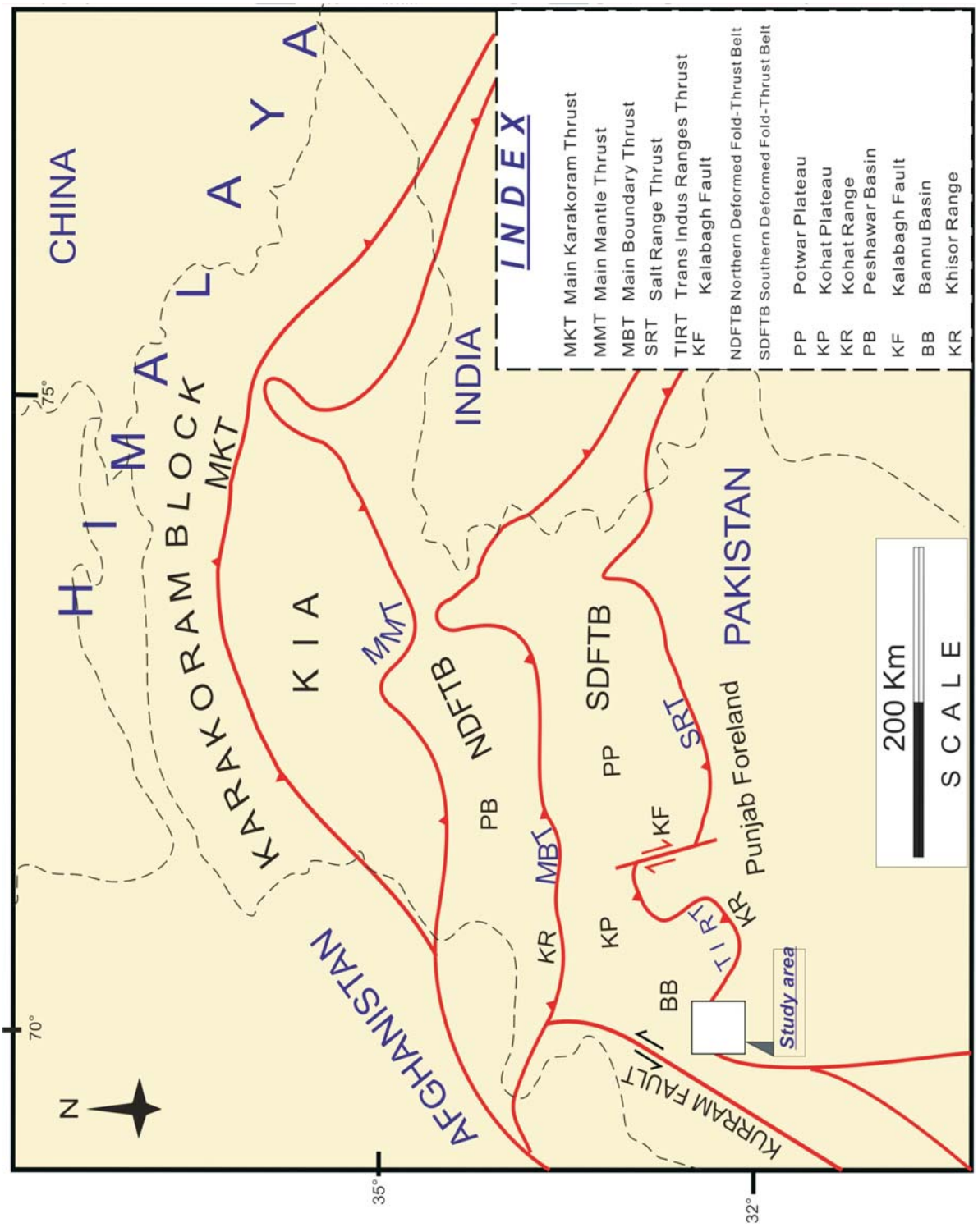

Figure 2- Tectonic map of North Pakistan. Inset shows the location of study area.

The Northern Deformed Fold-Thrust Belt comprises deformed sedimentary, meta-sedimentary and igneous rocks. This belt stretches from Kurram area in the west near Afghan border up to the Kashmir basin in the east. The Northern Deformed Fold-Thrust Belt is bounded by Main Boundary Thrust (MBT) separating it from the southern deformed fold and thrust belt (Figure 2). The MBT extends along the front of the Northern Deformed Fold-Thrust Belt around Hazara-Kashmir Syntaxis. It carries the pre-collisional Paleozoic & Mesozoic sedimentary and meta-sedimentary rocks of the Northern Deformed Fold-Thrust Belt in its hanging wall and post-collision folded Miocene foreland-basin deposits in its footwall (Yeats et al 1984) and is comprised of a series of parallel or en-echelon thrust faults (Pivnik & Wells, 1996). According to Iqbal and Baig (2007), the nature of MBT is not clear in Pakistan along the hill ranges. However, there is little doubt about the existence of a frontal thrust system boarding the hill ranges and separating the Northern Deformed Fold Thrust Belt from the Southern Deformed Fold Thrust Belt. The usage of the word MBT is still retained in this paper based on the fact that it is the most commonly used name for the frontal thrust system along the hill ranges in Pakistan.

The Southern Deformed Fold-Thrust Belt rims the Himalayan mountain belt from Ganges Delta in India up to the Makran area in the south in Pakistan. It is oriented east-west and switches to north south along the western border of Pakistan defining a major oroclinal deflection in structural trend. It is underlain by a thick pile of fluvial sediments and was the main depocenter of the synorogenic sediments influx, which started in early Miocene. In NWFP the Himalayan fold thrust is divisible into two tectono-stratigraphic provinces that are the east west trending Kohat-Potwar plateau along with its associated frontal ranges and the north south trending Northern Sulaiman Range. The proposed study area that is Bhittani and Northern Sulaiman ranges along with the D.I.Khan Basin defines the north western apex of Indo-Gangetic fore deep .The Indo-Gangetic fore deep rims the southernmost extension of Himalayan mountain chain in India and Pakistan (Figure1&2). It is overlain by unconsolidated Quarternary sediments and is the present day depocenter for the eroded debris from the Himalayan chains in the north.

STRATIGRAPHIC FRAMEWORK

The Bhittani and Northern Sulaiman ranges are composed of Jurassic to Eocene carbonate, sandstone and shale sequences (Figure 3). In the Sulaiman Range the oldest exposed rocks belong to Sulaiman Limestone Group (Table 1). This sequence is disconformably overlain by Sembar Formation, Parh Limestone, Mughal Kot Formation and Pab Sandstone of Cretaceous age (Hemphil & Kidwai, 1973). In the Sulaiman Range the Sembar Formation consist of more than 330 meters thick sequence of dark grey claystone with interbeds of dark color limestone and sand beds towards the base. The overlying Parh Limestone is dark grey; medium to thick bedded and is about 400 meters thick. The Mughal Kot Formation disconformably overlies Parh Limestone and consists of shaley limestone that is dark grey to blue towards the base of formation. It becomes sandy towards top and consists of thick-bedded argillaceous sandstone interbedded with claystone.

The Cretaceous sequence is in turn disconformably overlain by a thin succession of Paleocene age Dungan Formation. Dungan Formation in the Northern Sulaiman Range is composed of dark grey, thick bedded limestone towards the top and bottom with some sandstone horizons up to 5 meter thickness in the middle part. The Paleocene succession is conformably overlain by Eocene rocks that include Ghazij Shale at the base followed by Baska Shale and Kirthar Formation towards top. The Eocene succession is dominantly shale in the lower part comprising Ghazij and Baska Shale and becomes calcareous towards top comprising Kirthar Formation. The Eocene succession is in turn disconformably overlain by clay stone, siltstone and sandstone of Chitarwata Formation of Oligocene to Miocene age.

A thick succession of molasse sediments of Miocene to Plio-Pleistocene age belonging to Siwalik Group disconformably overlies Chitarwata Formation in the study area. The lithology of Siwalik Group rocks is represented by Vihowa, Litra and Chaudwan formations and consists of an interbedded sequence of fluviatile sandstone, clay and siltstone.

PLAY CONCEPT

Until to date several significant oil and gas pools have been discovered in the southern and northwestern part of Pakistan that shows the potential of hydrocarbon in the foreland basin of Pakistan. The stratigraphic sequence constitutes an important petroleum system, including multiple source, reservoir and sealing horizons (Figure 4). Pre-requisites for hydrocarbons generation and accumulation such as reservoir and source rocks are present throughout the Bhittani and Northern Sulaiman ranges along with thick shale providing sealing horizons to prevent the escape of oil and gas, at various levels. Jurassic to Paleocene succession of the Bhittani and Sulaiman ranges comprises thick sequences of carbonates, claystone and mixed carbonate-siliciclastic rocks representing a wide variety of shallow marine to deltaic environments of deposition.

SOURCE ROCKS

Based on the fact that claystone of marine nature has been found to be the most fertile source rocks through out the world, the potential source rocks underneath Bhittani and Sulaiman ranges would be Sembar Formation and Parh Limestone of Cretaceous age. The lithostratigraphy of Sembar is dominated by dark colour claystone that is about 330 meters thick. The Parh Limestone also contains claystone interbedded with limestone in its lower and middle parts. The third prolific source is believed to be the Sulaiman Group rocks of Jurassic age as it is found to be about 1200 meters thick sequence of limestone and contains several horizons of claystone in its middle part. The Sembar Formation and Parh Limestone are well proven source through out the Sulaiman and Kirthar ranges in the middle and lower Indus Basin of Pakistan (Quadri, 1980).

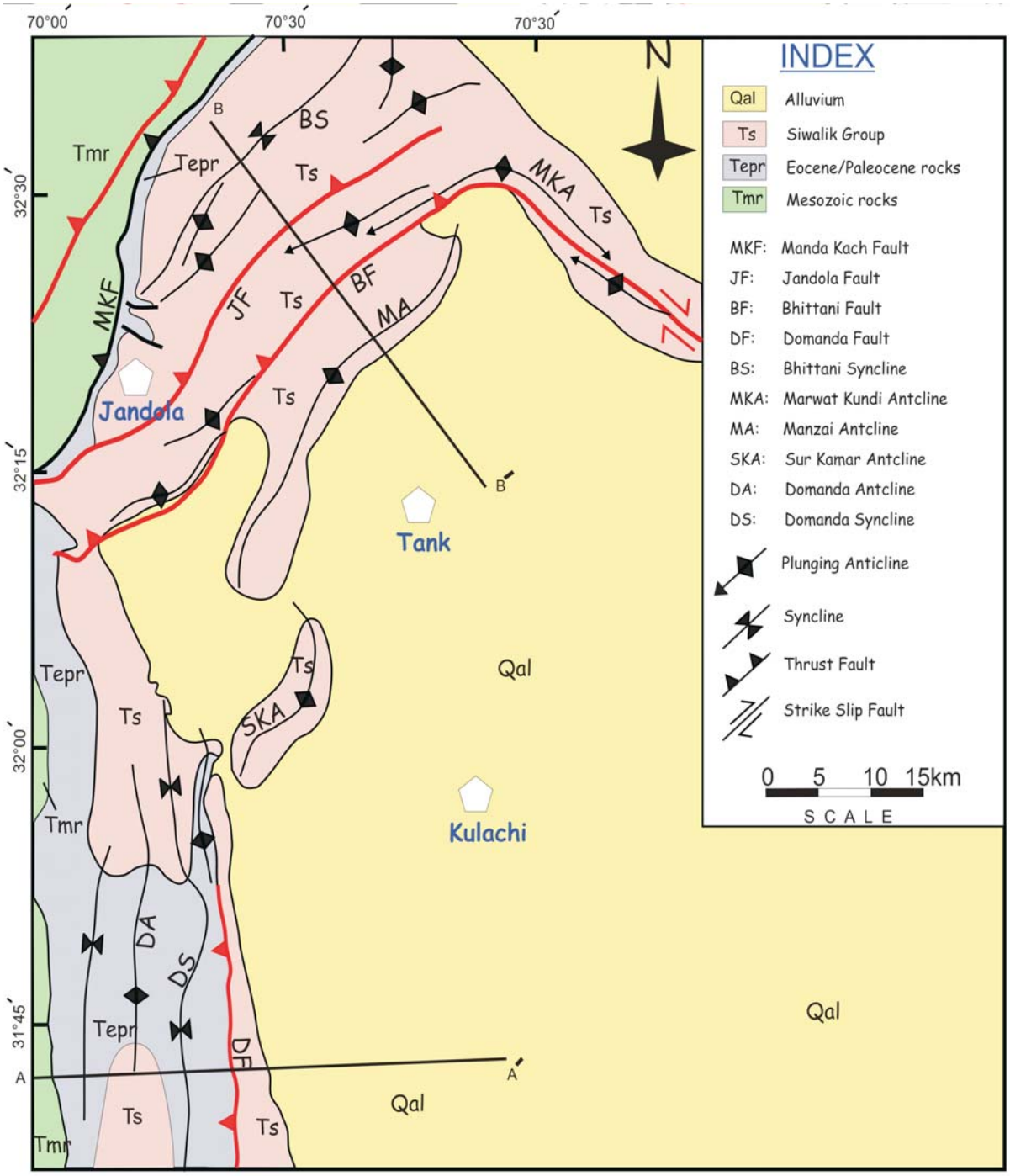

Figure 3- Generalized Geological map of Northern Sulaiman & Bhittani ranges, modified after Hemphil & Kidwai (1973).

Table 1-Stratigraphic frame work of the Bhittani and Northern Sulaiman ranges.

System	Series	Group	Formation
QUARTERNARY	Pliocene-Pleistocene	Siwalik Group	Chaudwan Formation
			Litra Formation
			Vihowa Formation
TERTIARY	Oligo.-Mioc		Chitarwata Formation
	Eocene		Kirthar Formation
			Baska Shale
			Ghazij Shale
	Pliocene		Dungan Formation
MESOZOIC	Cretaceous	Upper	Pab Sandstone
			Mughal Kot Formation
			Parh Limestone
		Lower	Sembar Formation
	Jurassic		Sulaiman Limestone Group

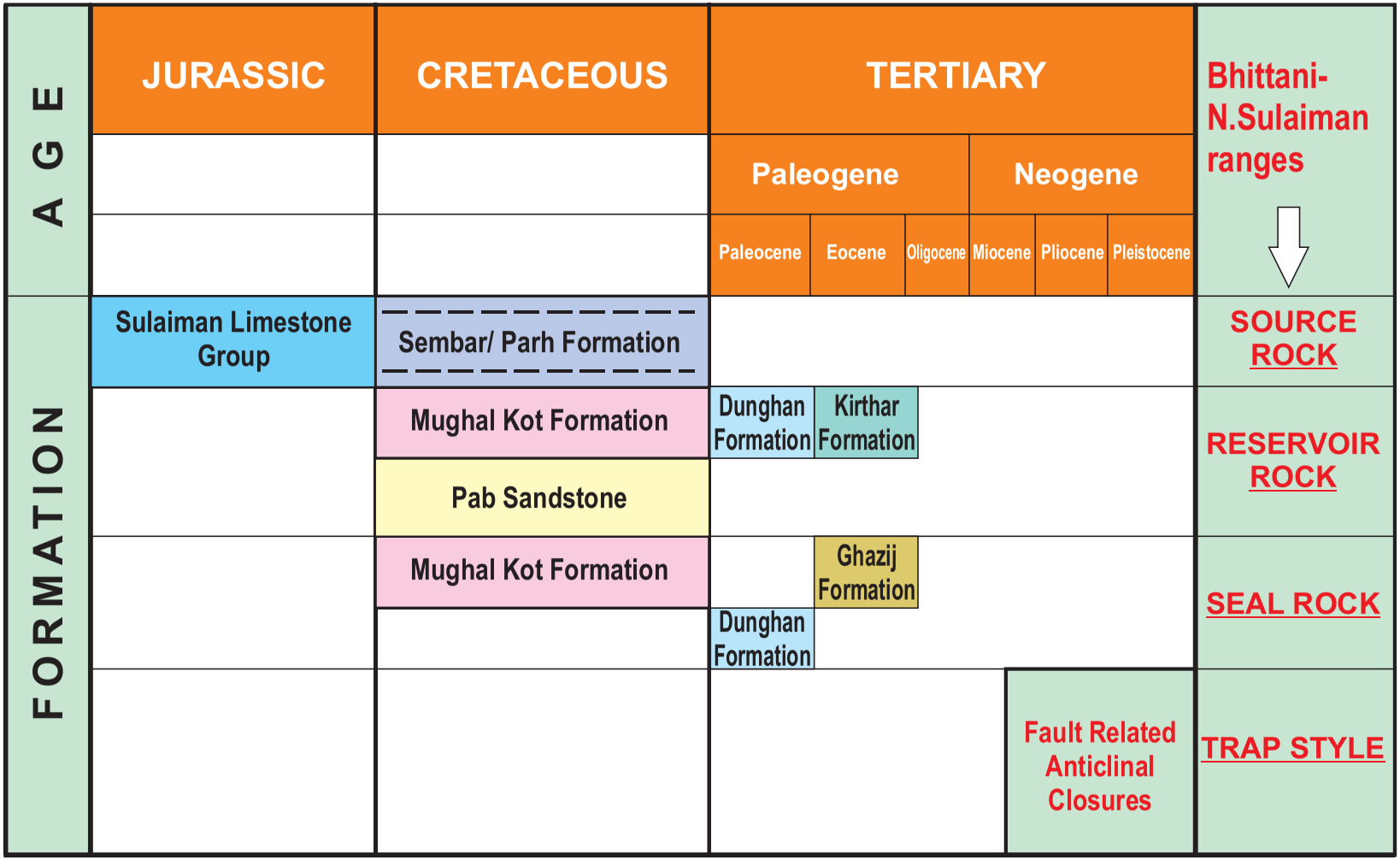

Figure 4- Petroleum System of the Bhittani and Northern Sulaiman ranges.

RESERVOIR ROCKS

Clastic and non-clastic reservoir rocks are well developed throughout the Sulaiman Range and underneath the Bhittani Range. The Pab Sandstone along with the sand horizons within the Mughal Kot Formation are the most potential reservoirs for the entire study area. Beside these the fractured carbonates of Dungan and Kirthar formations can be considered as encouraging reservoirs as well. The Pab Sandstone is well proven reservoir throughout the Sulaiman and Kirthar ranges in the middle and lower Indus Basin whereas the Ranikot sandstone is the main reservoir in Savi Ragha that lies south of the study area (Quadri, 1980).

CAP ROCKS

To seal the leakage, seepage and migration of hydrocarbons, impermeable horizon is essential. Fine-grained rocks such as shale or evaporites have the tendency as effective cap rocks. The Paleocene and Eocene succession of Bhittani and Northern Sulaiman ranges comprise thick shale horizons and are the potential sealing horizons underneath these ranges.

STRUCTURAL STYLE AND HYDROCARBON TRAPS

Fold and thrust belts throughout the world are the most significant areas for hydrocarbon exploration and exploitation. Out of the petroleum traps, fault-related anticlinal culminations are regarded as the most prolific structural traps. The surface geology of the study area is depicted in Figure 3 and is dominated by two regional scale north-south trending thrust faults. One of these faults is Domanda Fault that skirts the eastern margin of Northern Sulaiman Range, detached at the base of Ghazij shale and marks the tectonic boundary between Sulaiman Range in the west and D.I.Khan Basin in the east (Figure 5). The hanging wall cutoffs observed along the entire fault trace are not older than Ghazij Shale whereas the footwall cutoffs are not older than the Litra Formation of the Siwalik Group. The hanging wall structural style is dominated by a series of north south trending en-echelon folds.

The second regional scale structure is the Jandola Fault that characterizes the southern limb of Bhittani Syncline and juxtaposes Siwalik Group rocks against each other (Figure 6). The hanging wall of this fault also carries a series of north northeast trending en-echelon folds mostly detached at the base of Siwalik Group rocks.

The surface geology clearly indicates that the Bhittani and Northern Sulaiman ranges define an east verging; thin-skinned deformed fold thrust belt structural system where the structural style is characterized by decollement related thrusting associated with concurrent fault bend folding within the hanging wall and is high impedance system (Demaison & Huizinga, 1991) related to convergent plate tectonic habitat.

Considering the structural and stratigraphic aspect of the Bhittani and Northern Sulaiman ranges, it is believed that potential anticlinal culminations of en-echelon nature are present all along the hanging walls of Domanda and Jandola faults along the entire traces of these faults (Figure 5 &6).

Mechanically, the stratigraphy of the Bhittani and Northern Sulaiman ranges is divisible into a lower competent group including Paleocene and older rocks and an upper competent group including Kirthar and Siwalik Group rocks with thick horizon of clay of Eocene age that forms an intervening mobile horizon. This mobile horizon must have behaved diapirically and logically should serve as fold detachment for the folds within Eocene and younger rocks and the underlying folds must have behaved disharmonically with respect to the folding within the upper competent group. The hanging wall anticlinal culminations developed due to fault bending and or propagation within the lower competent group are of prime importance for hydrocarbons exploration and exploitation. Based on these structural observations similar structural styles can be predicted for the non-outcropping rocks underneath the Dera Ismail Khan Basin that is still poorly explored parts of the foreland fold and thrust belt of North Pakistan.

OVERVIEW OF THE CHARGE AND DYNAMICS

In every petroleum system the principal constraint to petroleum richness is the adequacy of the generative subsystem, which must be powerful enough to provide sufficient petroleum charge to migration-entrapment subsystem. If there is no petroleum generation in the subsurface, then all of the other necessary requirements of a petroleum system like structure, reservoir and seal lose relevance (White, 1993 & Magoon, 1989). The regional charge of the study area can be worked out if the Source Potential Index (SPI) of the source rock is calculated. The SPI is usually obtained from exploration wells and measured stratigraphic sections. As, at present stage this kind of data is not available but from the literature review it is quite obvious that the probable source rock that is Sembar Formation is more than 330 meters thick and is quite extensively developed in the basin. Thus the total amount of petroleum available for entrapment, which has been expelled from the regional kitchen, should be high enough to fill commercially viable structures.

As the migration and expulsion processes of a petroleum system are relatively inefficient, the existence of petroleum accumulations requires focused drainage from large volumes of source beds into volumetrically much smaller traps. Lateral oil migration along the bedding of continuous, permeable carriers is an important migration mechanism. However, reservoirs cannot function as efficient lateral drains unless they are continuously overlain by unbreached sealing lithologies (White, 1993 & Magoon,1989). These beneficial reservoir-seal associations are often regionally extensive where marine transgressive sequences rest on marine transgressive sediments. In the proposed study area the sandstone of Pab is found to be regionally widespread permeable carrier as well as reservoir overlain by claystone within Dungan Formation and the large scale lateral drainage is possible.

It is important to identify secondary migration pathways for a petroleum system as it decides that whether hydrocarbons will be dispersed or concentrated once they are expelled from the source beds. Secondary migration style is tectonically

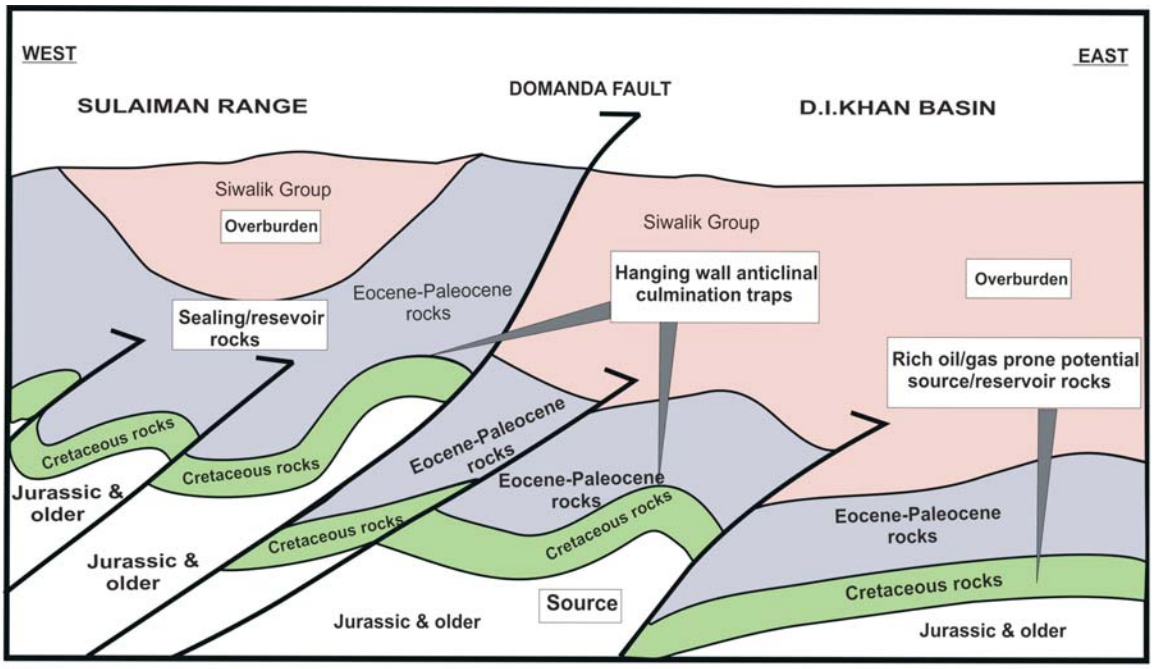

Figure 5- Schematic cross section along AA ́of figure 3 showing conceptual play model.

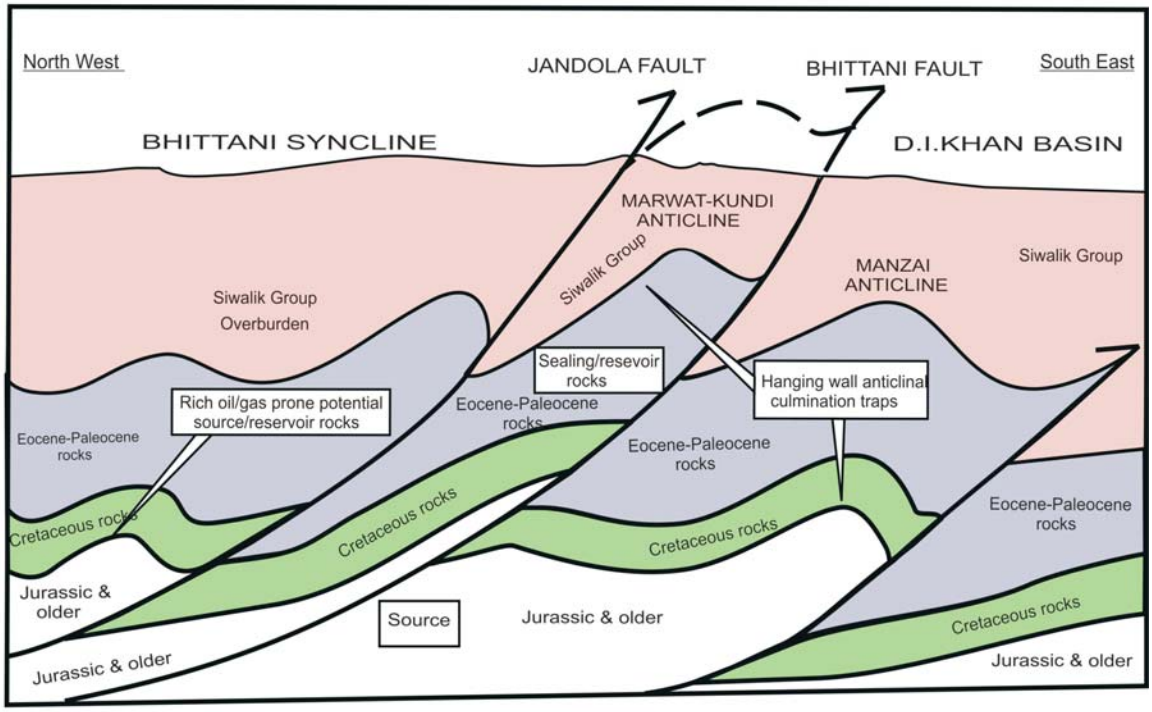

Figure 6- Schematic cross section along BB ́of figure 3 showing conceptual play model.

controlled and is predictable from the broad structural and stratigraphic fabric of a basin (White, 1993 & Magoon, 1989). The regional structural style of the study area block is thin-skinned decollement-related thrusting along with fault related anticlinal closures in the hanging wall. The thrust faults in its history act both ways that is sealing and non-sealing and always provide important drainage pathways for the upward movement of hydrocarbons to accumulate in the hanging wall anticlines.

Thrust timing and sequence determine whether hydrocarbons will be trapped within the thrust belt or escape ahead of the advancing thrust front. If hydrocarbons move faster than the thrust front, oil and gas generated beneath the advancing thrust belt will migrate up dip of foreland sediments to stratigraphic and structural traps. Such is the case with oil generated beneath the Kohat fold thrust belt in the upper Indus Basin and Sulaiman and Kirthar ranges in the middle and lower Indus basins. The stratigraphic sequences involved along the thrust faults within the study area suggest that the timing of deformation for the structural evolution of this part of foreland basin is Plio-Pleistocene. The discovery of Savi Ragha along the same trend is a clear indication of the optimum timing of hydrocarbons generation, migration and entrapment within the Bhittani and northern Sulaiman ranges.

CONCLUSIONS

The chance of success of finding hydrocarbon accumulations in a frontier sedimentary basin is primarily dependent on providing answers to the following queries; a) Does the hydrocarbon charge exist? b) Does the structure exist? c) Does the seal exist? d) Does the reservoir exist? Based on the comprehensive synthesis of the geological setting of the Bhittani and northern Sulaiman ranges addressed in this article, it can be concluded that the answer to the above queries is yes and there is little doubt in the presence of working hydrocarbon mechanism and a fair chance of discovery in the region.

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