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Hydrocarbon Prospects of Karak anticline, NW Pakistan: Myths and Facts

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ABSTRACT

The Karak anticline (KA) is a prominent structural high of the southern Kohat Basin in northwest Pakistan. In recent past the Kohat Basin has emerged as a prolific hydrocarbon bearing province of the country. In 1977-78,Texas Gulf drilled an exploratory well Karak-1 to test Eocene carbonate reservoir. The well was abandoned within Siwaliks at the depth of 4459 meters. Since then the exploration chapter remained closed on the assumption that Siwaliks are enormously thick and the reservoir is too deep. This paper discusses issues related to hydrocarbon prospectivity of the KA incorporating redefinition and reinterpretation of the data. Current field investigations reveal that the KA is about eighteen kilometers long, running ENE-WSW, is a well-defined, slightly asymmetrical fold with a relatively broad crest. The closures to the NW, west and along the southern flank are well marked. The fold is cut on the north eastern boundary by the Mitha Khel Fault, which is steeply north dipping. The attitude data on the limbs of KA suggest the presence of a subcrop, south facing thrust fault. The seismic definition of the fold is in harmony with the surface data and depicts two prospective highs at the level of Eocene related to subcrop fault: one in the hanging wall with Eocene top at 3300m depth from ground level and the second one in footwall with Eocene top at 4700m depth from ground level. Geo-seismic transect constructed across the KA depicts that Karak-1 well was placed around 800 m south of the hanging wall prospect and penetrated the steeply dipping forelimb, the subcrop fault and repeated sequence of Siwaliks and was abandoned approximately 200m above the footwall high. Reported oil and gas seepages, kerogen shales (oil shales) associated with gypsum, faint film of oil (about 1 mile NW of Karak), and discoveries in the adjoining areas indicate that KA lies within the hydrocarbon province and, since the anticline is bounded by well-marked structural lows, it would be expected that any petroleum generated in the structural lows would have migrated updip, into the likely reservoirs in the anticline. The Bannu Plain is the hydrocarbon kitchen for KA. The reservoir rocks beneath the KA include Eocene Sakesar Limestone and Paleocene Lockhart/Hangu formations which are the main producing horizons of the oil fields in adjoining areas.

INTRODUCTION

Throughout the world, peripheral foreland basins of orogenic belts are conspicuous features of convergent plate tectonic habitat and have proved to be potential areas for hydrocarbon exploration. In North Pakistan the Kohat- Potwar fold and thrust belt along with its associated frontal ranges, which are Salt and Trans-Indus ranges represent the foreland fold-thrust belt of northwestern Himalayan mountain chain (Figure 1). The geographic boundaries of the Kohat Fold and Thrust Belt are marked by Kohat Range in the north and northeast, Indus River in the east, Surghar Range in the southeast, Bannu Basin in the south and Samana Range in the northwest (Figure 1 and 2). The Kohat foreland basin is currently the site of intense hydrocarbon exploration activity as it has observed several major hydrocarbon discoveries around Manzalai, Mami Khel, Makori and Shakkardara areas (Figure 3). These discoveries also enhance the hydrocarbon potential of the neighboring areas that are still untapped frontiers. One such area lies in the southeastern part of the Kohat Basin where a potential structural high is present within the Siwalik sediments (Figure 1 and 3). Exploration activities in the Kohat region started during 1970-71 when Attock Oil Company acquired exploration license on the KA proper. They did some preliminary geological work in the area with no follow up of seismic survey activity. The Karak area was later on acquired by Texas Gulf for hydrocarbon exploration.

During 1977-1978 an exploratory well namely Karak-1 on the KA was drilled. The well was abandoned at 4459 meters depth within lower Siwaliks. Later on, the area was licensed by Occidental Petroleum during 1980-81. They conducted some limited seismic campaign on the KA and quit without drilling the structure. Since then little attention has been paid to this important high. This paper is an attempt to re-evaluate the hydrocarbon potential of this important structure through detailed field investigations and reinterpretation of the available subsurface data acquired by Occidental Petroleum.

In order to elucidate the structural aspects of the Karak area detailed field work was conducted. Useful information on the structural behavior of the KA and its relationship with the Surghar Range front in the south and the northern bounding Mitha Khel Fault was collected. Detailed geological mapping was conducted on the Surghar Monocline in the south to establish an accurate control for drawing the geological cross section over the region.

GEOLOGICAL SETTING

The Karak area is part of the east-west trending Kohat Basin which had been influenced by the southward progression of Himalayan deformation during late Miocene (Pivnik, 1992). The Kohat Basin is bounded to the north by the

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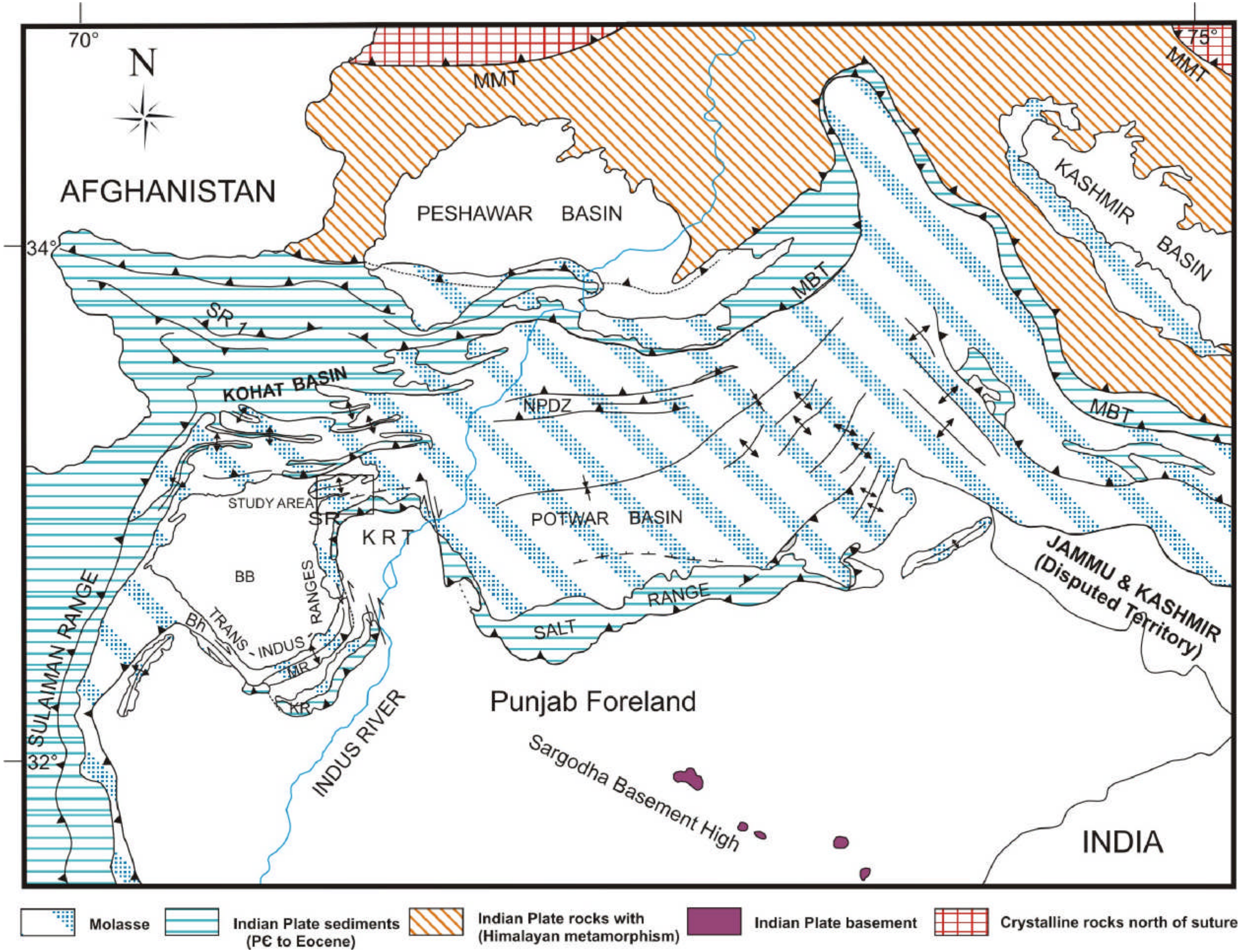


Figure 1 - Generalized geologic map of the NW Himalayan foreland fold and thrust belt (modified after Kazmi and Rana, 1986). Inset shows the location of study area. MMT: Main Mantle Thrust, MBT: Main Boundary Thrust, NPDZ: Northern Potwar Deformed Zone, KR: Khisor Range, BB; Bannu Basin, KRT: Kalabagh Re-Entrant, MR: Marwat Range, BH: Bhittani Range, SR: Surghar Range and SR 1: Samana Range.

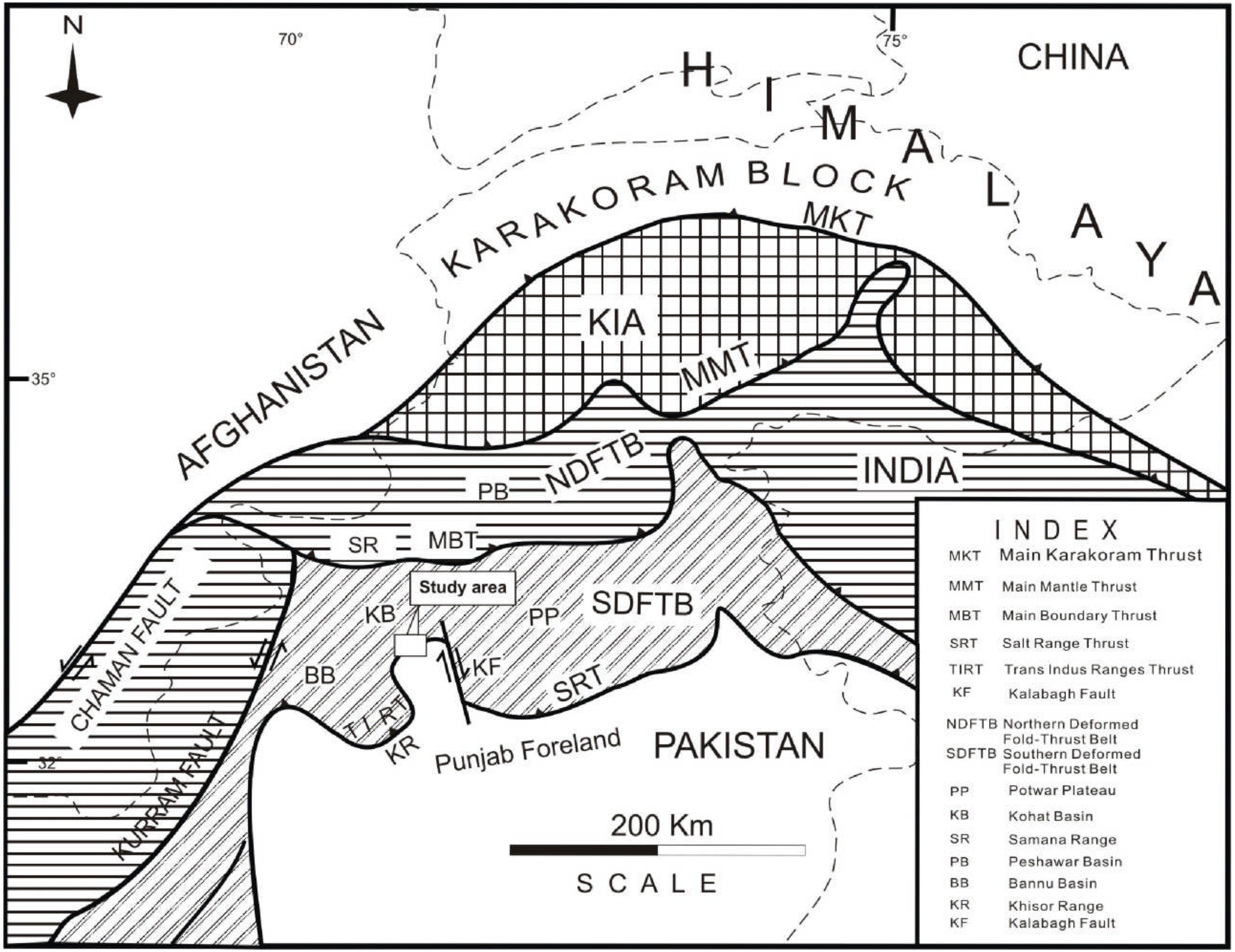


Figure 2 - Tectonic map of North Pakistan, showing major structural features (modified after Ahmad, 2003).

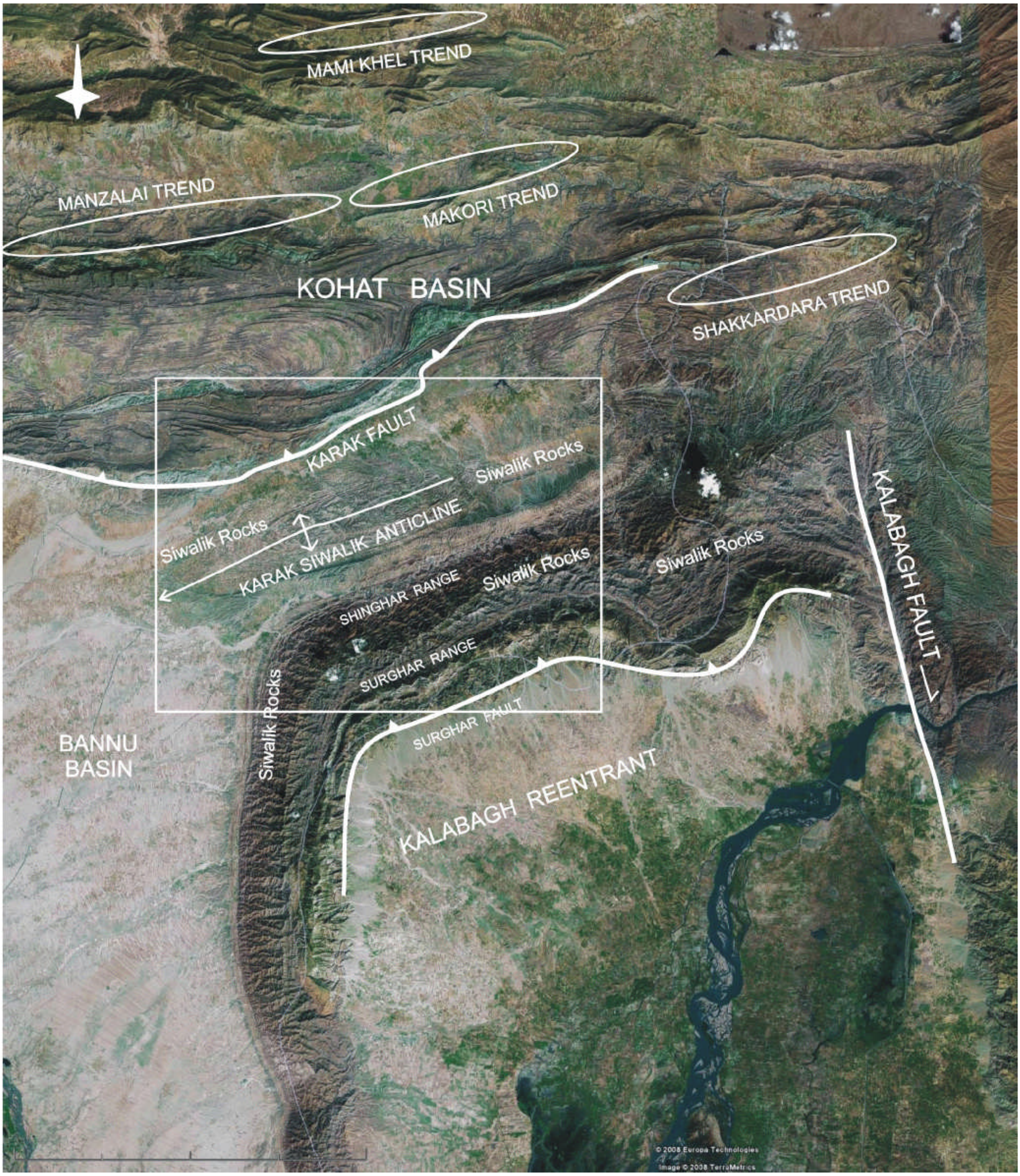


Figure 3 - Satellite image of the Kohat Basin showing proven hydrocarbon trends and location of the study area.

Main Boundary Thrust (MBT) (Figure 2). MBT carries highly deformed Mesozoic rocks of Kohat Range in its hanging wall over the Eocene-Miocene sediments of Kohat Basin located in the footwall (Yeats & Hussain, 1987).

Towards west (Figure 2), the Kurram Fault juxtaposes highly deformed Mesozoic rocks of Samana, Darsamand, Tal and North Waziristan Agency with the Eocene to Miocene sediments of the Kohat Plateau (Ahmad, 2003). The southeastern boundary of the Kohat Basin is Surghar Range where Mesozoic rocks are emplaced southwards over the Kalabagh Re-Entrant of Punjab foreland in the south (Ahmad et al., 1999).

The tectonic history of Kohat Basin is well preserved in the outcropping rocks (Meissner et al., 1974 and 1975, Pivnik, 1992, (Pivnik and Wells 1996). The Kohat Basin exposes Paleocene to Eocene sedimentary rocks comprising limestone, shale, evaporite, sandstone and conglomerate deposited in a restricted deep marine environments, Pivnik and Wells 1996(Figure 4). Soon after the deposition of the Middle Eocene, the initial phase of Himalayan orogeny commenced and the sea receded from Kohat Basin leaving a fluviatile and lacustrine environment in the region. This event is marked by a widespread regional unconformity, which is overlain by enormously thick detrital material deposited in a fluviatile and lacustrine environment of sedimentation because of a mighty river flowing down the rising Himalayas to the north, pouring its material in the molasse basin of Kohat.

Tethyan Ocean sediments ranging in age from Paleozoic to Eocene are exposed along the frontal Surghar Range representing an essentially shallow marine continental shelf environment ranging from brackish and fresh water to lacustrine and estuarine conditions (Figure 5). This cycle of slow sedimentation was occasionally interrupted by localized block uplifts, often of prolonged period leading to hiatus and disconformity. The close of Eocene sedimentation period witnessed the first phase of regional uplift belonging to the Himalayan orogeny. This uplift affected our region, and hence no sediments of upper Eocene or Oligocene are seen in the area.

The Himalayan uplift from early Miocene to Pleistocene times lead to the emergence of the Himalayas in the north. The area to the south, comprising the Potwar-Kohat Basin, underwent continuous subsidence to form marginal troughs and furrows, filled by clastic, fluviatile Siwalik sediments, and bounded in the south by the upland region of Sargodha High.

STRUCTURE OF THE KOHAT BASIN

At the close of Tertiary Era, the earth movement of considerable magnitude, defining the final phase of Himalayan orogeny, affected the entire area and led to the development of numerous folds and complicated fault systems of the Kohat Basin. In areas where evaporites occur, the structural features as seen today are further complicated by the plasticity and piercing character of these sediments (Meissner et al, 1974 and 1975; Pivnik, 1992; Sercombe et al, 1994 and Ahmad, 2003). Several folds, accompanied by thrusts, back thrusts and wrench faulting, belonging to the late Pliocene/early Pleistocene orogeny occur in the Kohat Basin. The structure of the Kohat Basin generally follows an east west trend. However, there is a prominent swing in the general trend towards west and south east of the basin. The arcuate nature of the outcrops in the region is fairly open and broad within Kohat Basin, while in the Surghar-Shinghar area to the south and Kalabagh hills in the south east the loop of the folded chains becomes more arcuate. Three contrasting models explain the structural genesis of the outcropping rocks in the Kohat Basin. One of these models depicts the structures within the exposed rocks as part of a passive roof thrust that is translating northwards in a thin-skinned fashion. This passive roof thrust is underlain by an active wedge of south-directed thrust slices of Pre-Tertiary stratigraphy that form a passive roof duplex (McDougal and Hussain, 1991 and Abbasi and McElroy, 1991). The second model suggests that the structural evolution of the Kohat Basin has been greatly influenced by strike-slip faulting related to thick-skinned deformation. These strike-slip faults are not recognizable at the surface but are deep-rooted in the basement and expose themselves as anticlinal trends in the Eocene cover (Pivnik, 1992; Pivnik and Sercombe, 1993 and Sercombe et al., 1994 a and b). A third model for the structural genesis of Kohat Basin suggests that the surface structures do not mimic the subsurface structures and decollement related thrusting within Paleocene and older rock tips at the base of Eocene sequence. Eocene rocks are mainly deformed by disharmonic folding further complicated by shale/evaporate diapirism (Ahmad, 2003).

KARAK ANTICLINE

Structural investigations at surface are quite crucial in order to elucidate the geometry at depth especially in the areas where there is a structural mismatch between the surface and underlying structures. Complex structures at surface do not mimic the underlying simple structures and vice versa. Detailed field investigations were carried out around Karak area in order to understand the structural style of the KA. The fold hosts rocks of Nagri Formation in its core and is well exposed south of Karak (Figure 6). The anticlinal axis here runs ENE-WSW in the central and western area, while its course changes towards NE-SW in the east. To the northeast it is tectonically terminated against the Mitha Khel Fault (Figure 6). On the southern side the anticline is bounded by Banghar Syncline where the rocks of Soan Formation host its core. The trend of Banghar Syncline here also follows the same general trend as that of Karak Anticline to the north, and like the anticlinal axis the synclinal axis also terminates against the Mitha Khel Fault further to the east. The Karak Anticline is not sharply folded, but at the surface has a broad crest with dips to the north of the crest axis not more than 05° about one kilometer away from crest axis, whilst along the axis itself the beds are almost horizontal. These low dips characterize the entire trace of the fold axis. However, on the south side of the axis the zone of low dips is relatively narrow, thus making the structure south facing (Figure 6).

Along the northern flank of the fold the dips progressively increase towards the Mitha Khel Fault where a maximum of 48° is recorded on the outermost bed of the fold in contact with Mitha Khel Fault. The southern limb is relatively steep with

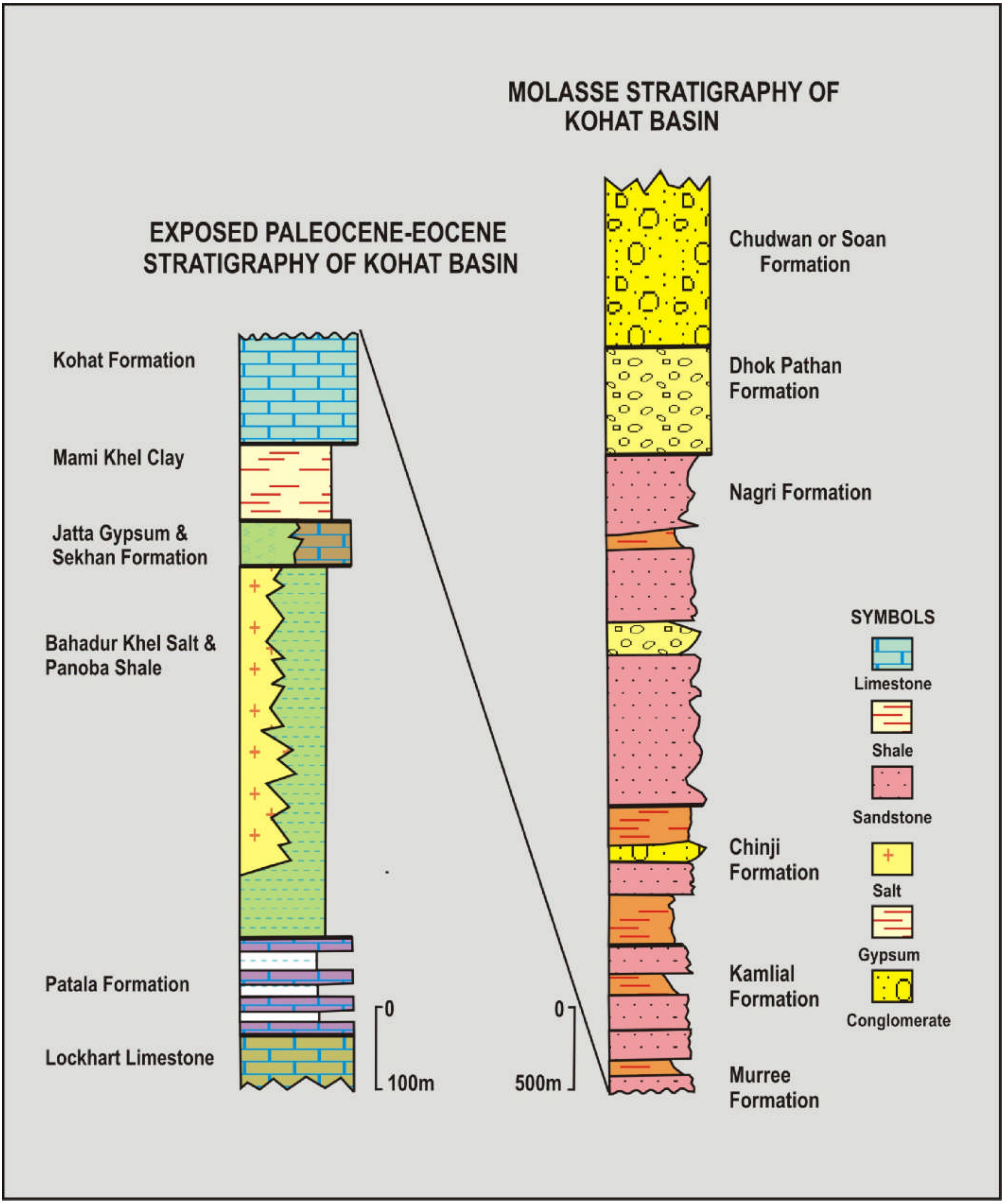
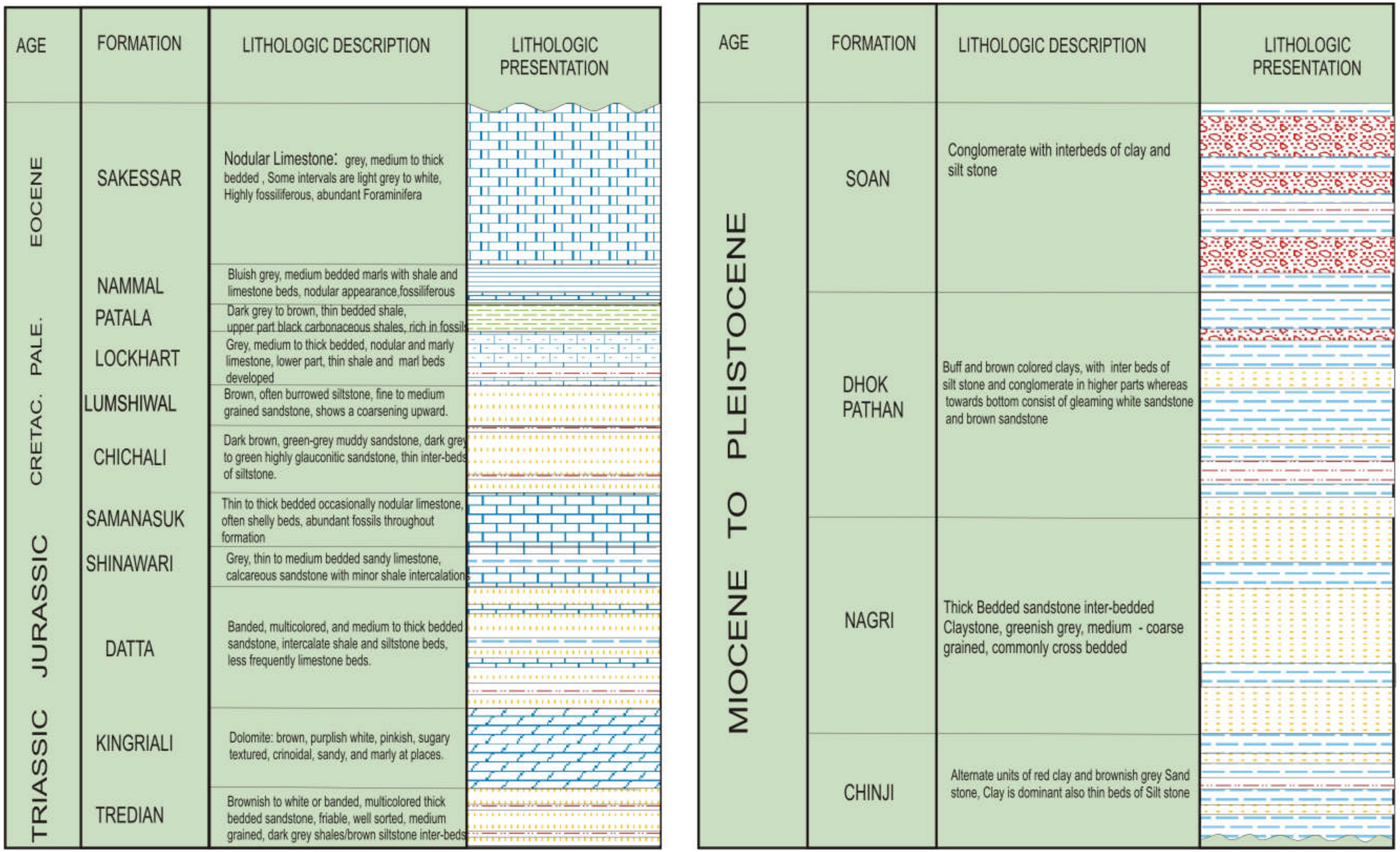


Figure 4 - Composite lithostratigraphic column of the Kohat Basin (after Ahmad, 2003).



AGE	FORMATION	LITHOLOGIC DESCRIPTION	LITHOLOGIC PRESENTATION
EOCENE	SAKESSAR	Nodular Limestone: grey, medium to thick bedded , Some intervals are light grey to white, Highly fossiliferous, abundant Foraminifera	
	NAMMAL	Bluish grey, medium bedded marls with shale and limestone beds, nodular appearance,fossiliferous	
PALE.	PATALA	Dark grey to brown, thin bedded shale, upper part black carbonaceous shales, rich in fossils	
	LOCKHART	Grey, medium to thick bedded, nodular and marly limestone, lower part, thin shale and marl beds developed	
CRETAC.	LUMSHIWAL	Brown, often burrowed siltstone, fine to medium grained sandstone, shows a coarsening upward.	
	CHICHALI	Dark brown, green-grey muddy sandstone, dark grey to green highly glauconitic sandstone, thin inter-beds of siltstone.	
JURASSIC	SAMANASUK	Thin to thick bedded occasionally nodular limestone, often shelly beds, abundant fossils throughout formation	
	SHINAWARI	Grey, thin to medium bedded sandy limestone, calcareous sandstone with minor shale intercalations	
	DATTA	Banded, multicolored, and medium to thick bedded sandstone, intercalate shale and siltstone beds, less frequently limestone beds.	
TRIASSIC	KINGRIALI	Dolomite: brown, purplish white, pinkish, sugary textured, crinoidal, sandy, and marly at places.	
	TREDIAN	Brownish to white or banded, multicolored thick bedded sandstone, friable, well sorted, medium grained, dark grey shales/brown siltstone inter-beds	

AGE	FORMATION	LITHOLOGIC DESCRIPTION	LITHOLOGIC PRESENTATION
MIOCENE TO PLEISTOCENE	SOAN	Conglomerate with interbeds of clay and silt stone	
	DHOK PATHAN	Buff and brown colored clays, with inter beds of silt stone and conglomerate in higher parts whereas towards bottom consist of gleaming white sandstone and brown sandstone	
	NAGRI	Thick Bedded sandstone inter-bedded Claystone, greenish grey, medium - coarse grained, commonly cross bedded	
	CHINJI	Alternate units of red clay and brownish grey Sand stone, Clay is dominant also thin beds of Silt stone	

Figure 5 - Generalized stratigraphic column of the Surghar Range in the vicinity of Kutki and Chichali Pass area (after Ahmad et al., 1999).

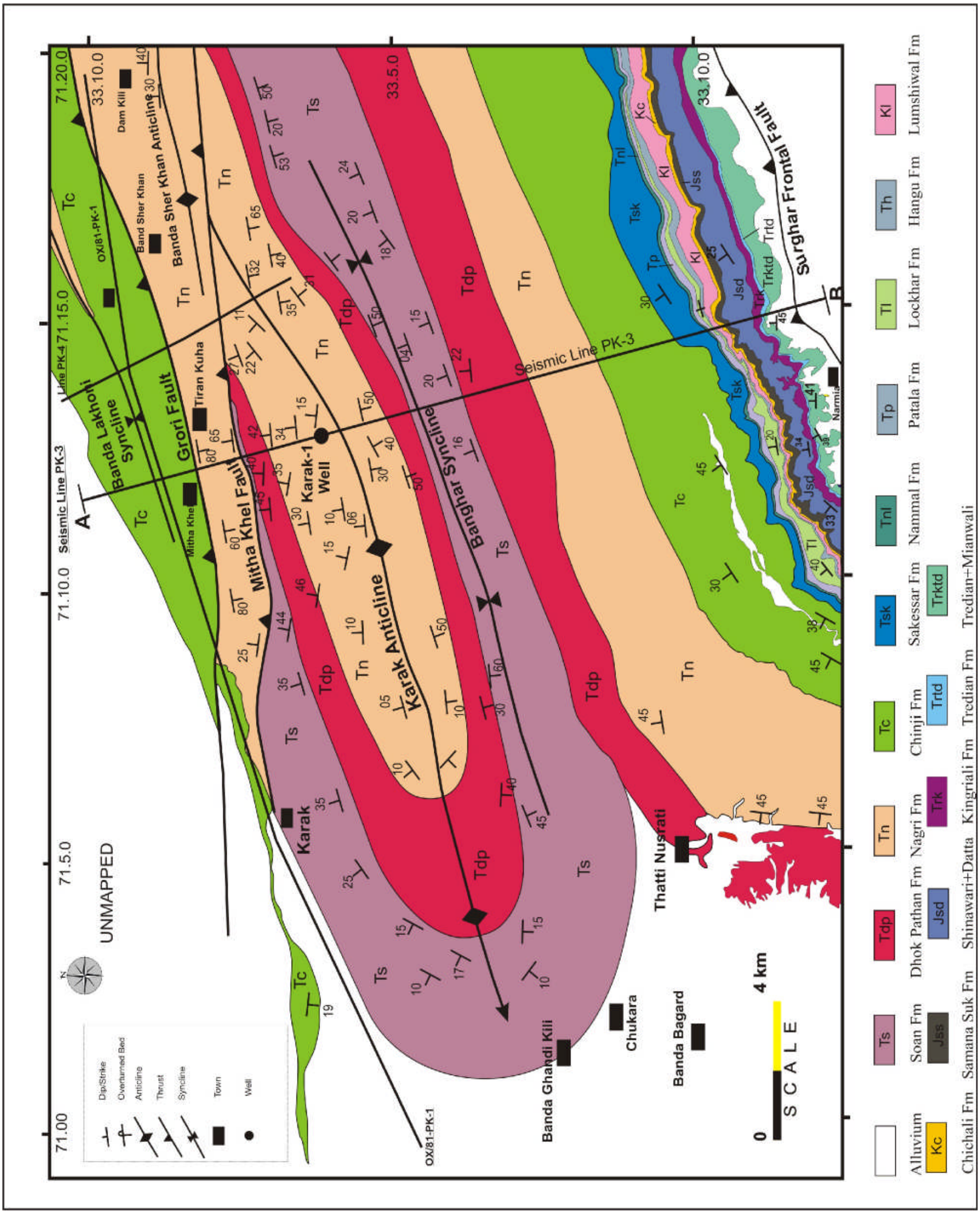


Figure 6 - Geological Map of the Karak area.

dips ranging from 50-60°. The KA shows a prominent plunge of about 10-15° towards WSW in the western outcrops which decrease to about 8° in the extreme west (Figure 6).

Two near parallel faults are mapped on the northern side of KA. Presumably they have a common origin. The northernmost is the Grori Fault which in outcrops is marked by steep dips and is often marked by the development of small scale folds and intense shearing. The Mitha Khel Fault demarcates the northern flank of the KA and is found to be a high angle thrust fault. There is a lack of concordance and absence of correlation in the structural trends on the up thrown side with that of the down thrown side showing that the thrust might also be accompanied by some lateral translation as well.

South of the Banghar Syncline lies the Surghar monocline that moderately to steeply dips northwards. The Surghar monocline forms the hanging wall succession of the frontal bounding Surghar Fault which juxtaposes Permian to Triassic age rocks against the Siwaliks in the south.

SUBSURFACE STRUCTURAL STYLE

The structural style of the KA and adjoining area is summarized by describing a north-northwest trending dip line. The location of geological transect is chosen in alignment with the available seismic data in order to validate the subsurface structural geometry of the region (Figure 7). Surface data was detailed along the available seismic line for extrapolation purpose as the seismic image is of poor quality due to the complex nature of deformation. The seismic data was acquired by OGDC for Occidental Petroleum Inc. in 1981 over KA as 48 fold data using dynamite as a source. This data displays fair quality in shallow as well as in the deeper horizons.

The structural transect along line A-B is oriented northnorthwest, almost parallel to the regional tectonic transport direction (Figure 6). Banda Lakhoni Syncline appears in the extreme north, which is a symmetrical synclinal structure in sectional view. The southern limb of this syncline is cut by Grori Fault, which is a steep, North dipping south verging thrust, bringing rocks of Chinji Formation in the hanging wall over Nagri Formation in the footwall. South of the Grori Fault lies another high angled thrust, called Mitha Khel Fault (Figure 7). This is also north dipping, south verging steep thrust emanating from the basal decollement, thrusting the rocks of Nagri Formation over the rocks of Soan and Dhok Pathan formations in the footwall (Figure 7). The basal decollement is estimated to be located at a depth of around 8200 meters and 7500 meters in the northern and southern parts of the section respectively with a regional dip of around 2-3° towards the north.

Further south to the Mitha Khel Fault, the KA appears in the section. This is an asymmetrical anticline with a steeper and shorter forelimb and comparatively longer and gentler back limb both in map and sectional views. The seismic data interpretation clearly suggests (Figure 8 a and b) that the KA is developed on the hanging wall of a blind thrust, emanating from the basal decollement and terminating in the upper Siwaliks, offsetting the core of the Banghar Syncline lying to the south of the KA. The Banghar Syncline is a tight asymmetrical synclinal feature, cored by rocks of Soan Formation having steeper northern limb and gentler southern limb in sectional view. Further southwards, the section depicts the huge Shinghar-Surghar monocline, developed on the hanging wall of the main Surghar Frontal Thrust. The limb of this monocline is quite extensive and north dipping (Figure 7).

The Surghar Frontal Thrust is a south verging fault, originated from the basal decollement and is shallow dipping in the deeper parts and become progressively steeper near the surface. Along this fault Mesozoic and the underlying older rocks of the Surghar Range are thrust southwards over the quaternary deposits of the Punjab foreland. This geo-seismic transect indicates that Karak-1 well was placed around 800 m south of the hanging wall prospect and penetrated the steeply dipping forelimb, the subcrop fault and repeated sequence of Siwaliks and was abandoned approximately 200m above the footwall high.

PETROLEUM SYSTEM

The essential ingredients of the petroleum system of Karak area are summarized in Table 1. The basic requirements for hydrocarbons generation and accumulation such as reservoir and source rocks are believed to be present underneath the KA along with the sealing horizon to prevent the escape of oil and gas, in the form of thick shale beds at various levels. Jurassic to Paleocene succession exposed along the Surghar Range comprise a thick sequence of sandstone, carbonates, claystone and mixed carbonate-siliciclastic rocks representing a wide variety of shallow marine to deltaic environments of deposition. The stratigraphic sequence constitutes an important petroleum system, including multiple source, reservoir and sealing horizons.

Claystone of marine nature is found to be the most fertile source rocks throughout the world, thus the potential source rocks underneath study area would be Datta and Shinawari of Jurassic age, Chichali Formation of Cretaceous age and Patala Formation of Paleocene age.

The Source rock potential of rock samples from outcrops in the Marwat-Khisor ranges and well cuttings from Marwat-1 and Pezu-1 wells was determined by Hydrocarbon Development Institute of Pakistan (HDIP) for Pakistan Petroleum Limited (PPL) by analyzing these samples geochemically (HDIP Report, 1992). Some of the basic geochemical data (vitrinite reflectance, organic richness, genetic potential and hydrocarbon Index etc) has been extracted from the above-mentioned report in order to highlight the source potential of some of the formations in the region, which is given in Table 2.

The Samana Suk, Datta, Lumshiwal and Lockhart Formation are the most potential reservoirs for the entire study area however for the KA proper the drillable reservoir would be Sakesar Formation of Eocene age. To seal the leakage, seepage and migration of hydrocarbons, impermeable horizons are essential. Fine-grained rocks such as shale or evaporite have the tendency as effective cap rocks. The Paleocene, Eocene and Miocene succession of the study area comprise thick shale horizons and are the potential sealing horizons underneath the study area.

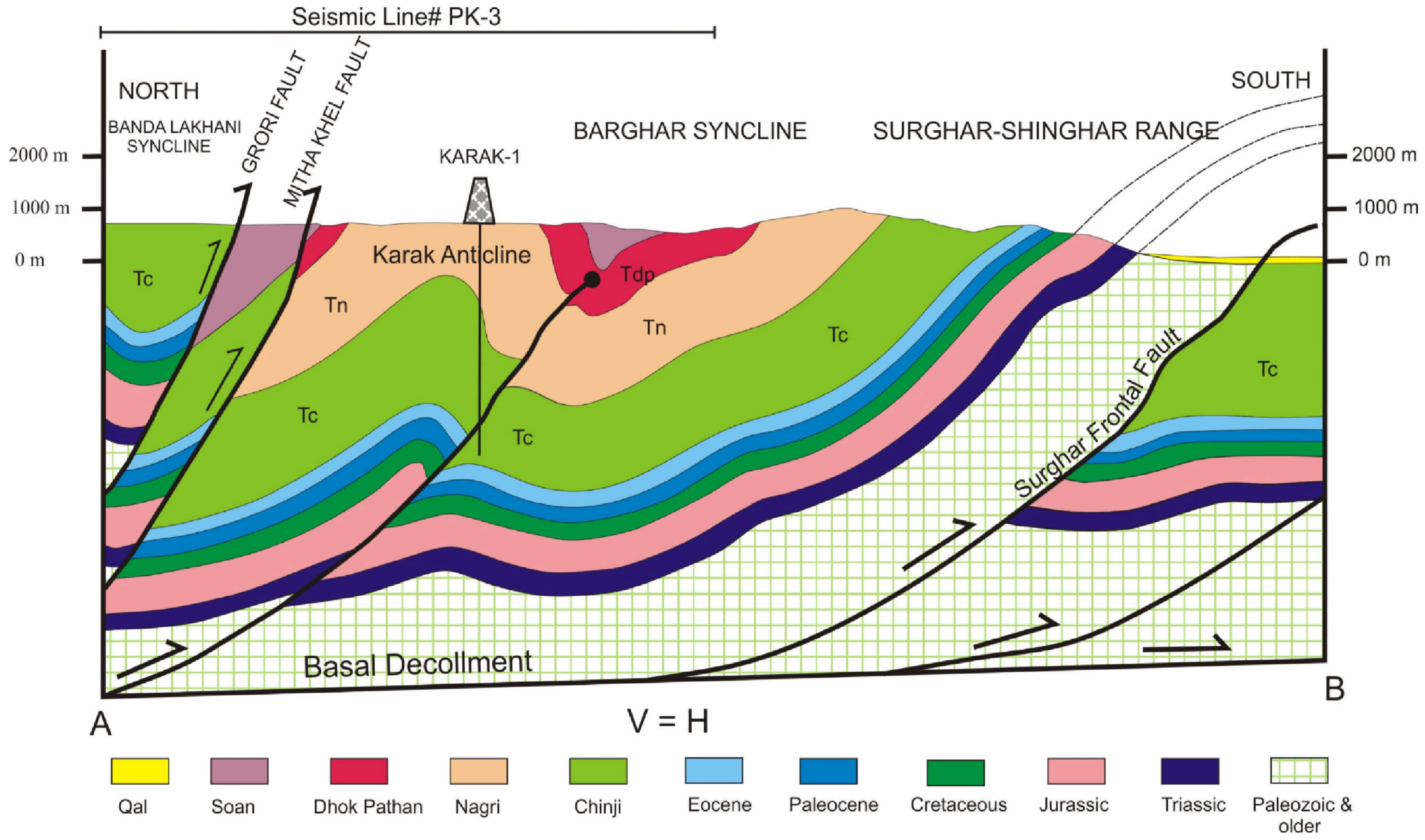


Figure 7 - Geological cross section along line AB of Figure 6

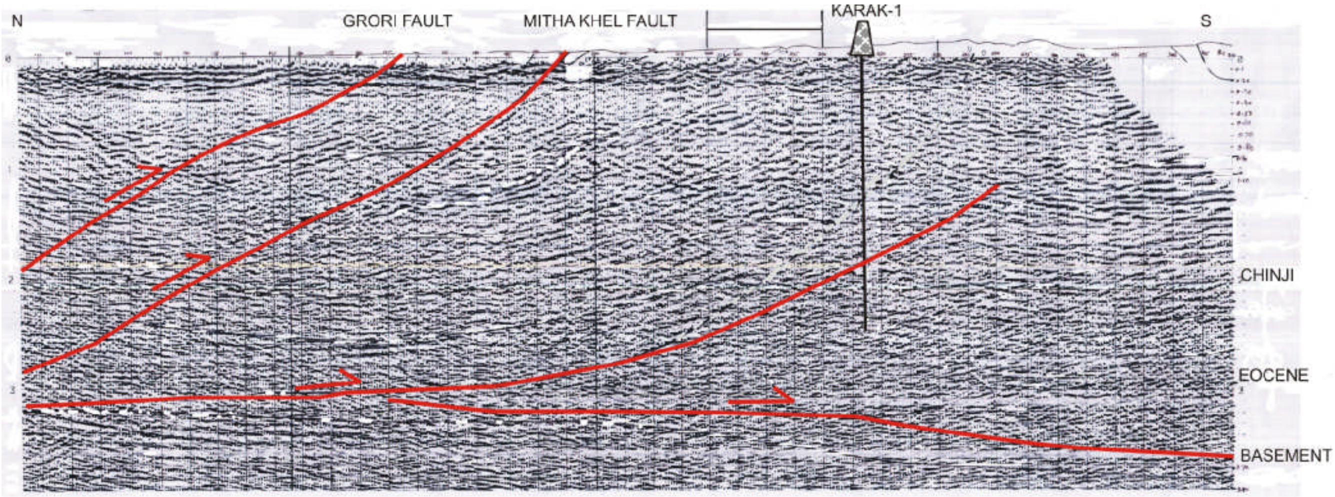


Figure 8a - Seismic section along line # 811-PK-3 with major faults interpretation.

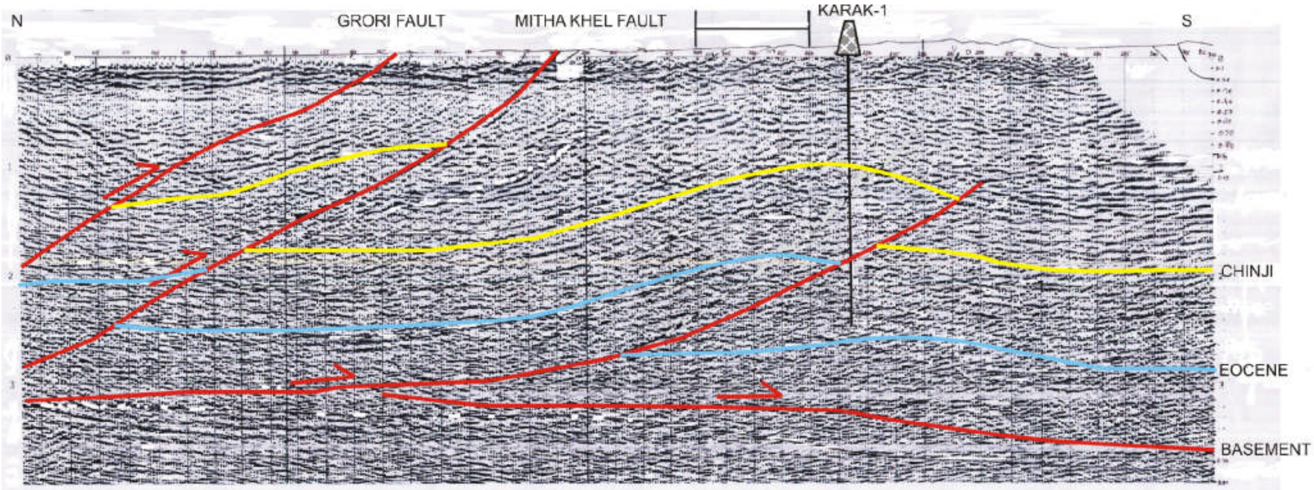


Figure 8b - Seismic section along line # 811-PK-3 showing various formation tops and structural style.

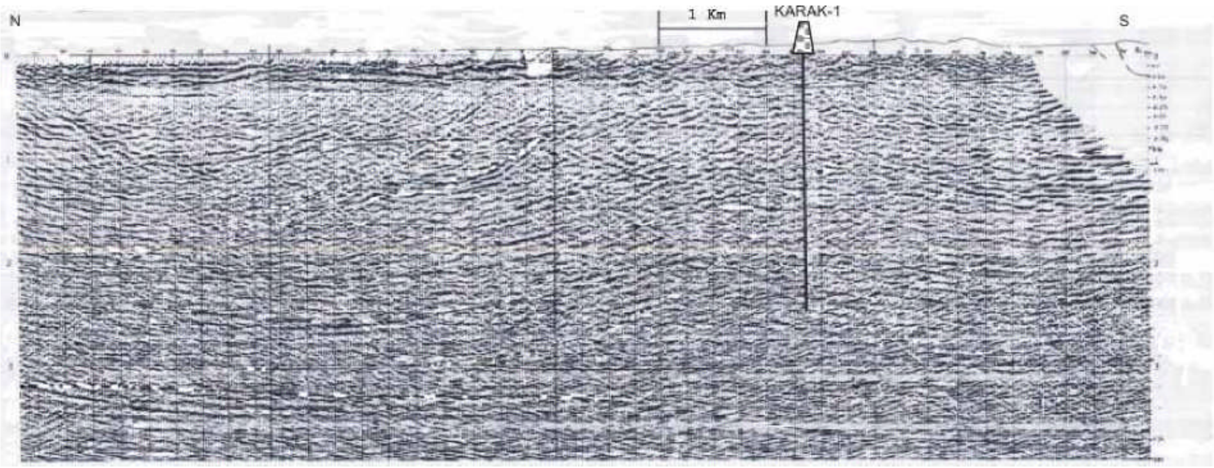
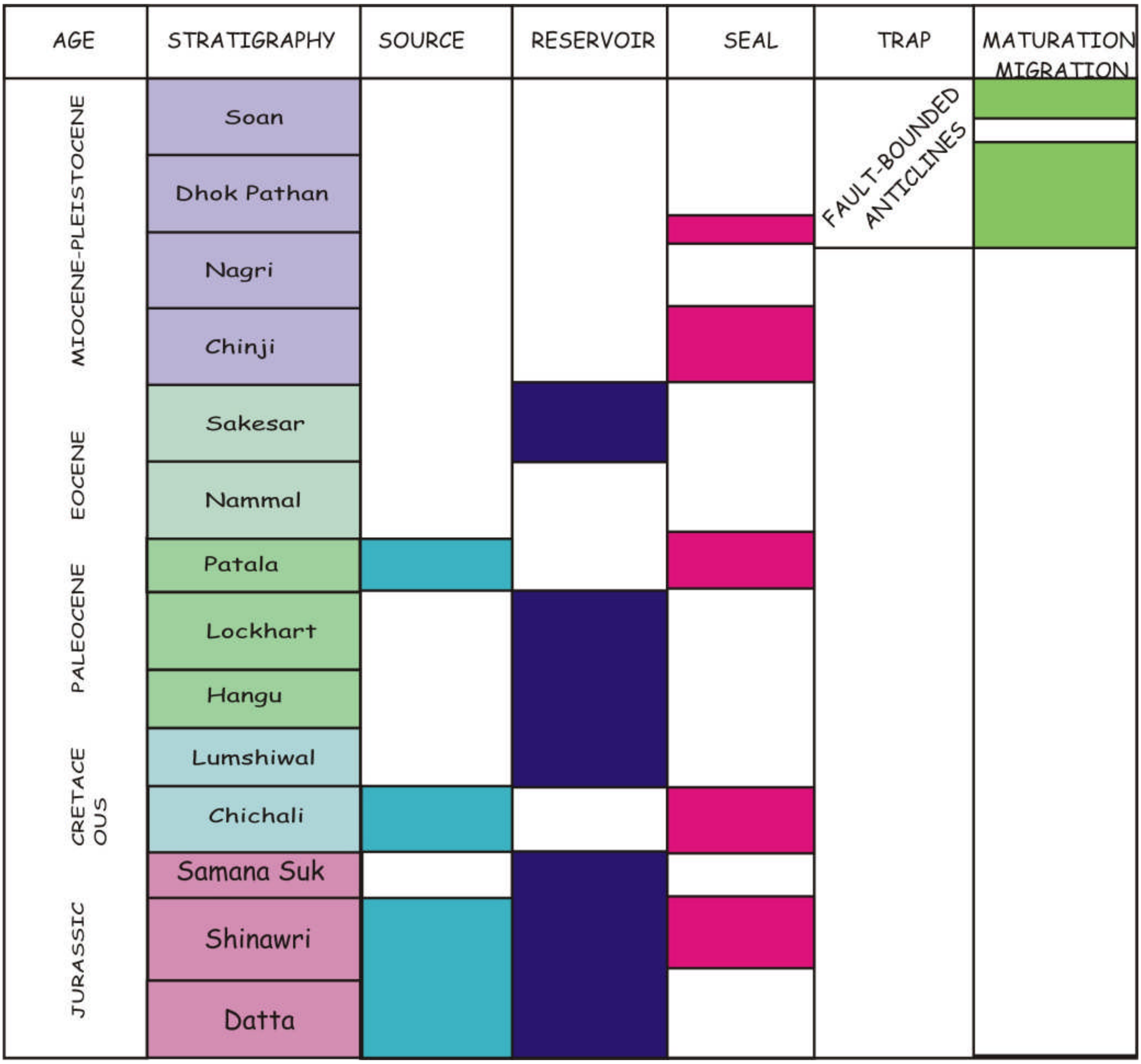


Figure 8c - Un-interpreted Seismic section of line # 811-PK-3

Table 1- Petroleum system of Karak area



AGE	STRATIGRAPHY	SOURCE	RESERVOIR	SEAL	TRAP	MATURATION MIGRATION
MIOCENE-PLEISTOCENE	Soan				FAULT-BOUNDED ANTICLINES	🟩
	Dhok Pathan			🟥		🟩
	Nagri					🟩
	Chinji			🟥		
EOCENE	Sakesar		🟪			
	Nammal					
PALEOCENE	Patala	🟦		🟥		
	Lockhart		🟪			
	Hangu		🟪			
CRETACE OUS	Lumshiwal		🟪			
	Chichali	🟦		🟥		
JURASSIC	Samana Suk		🟪			
	Shinawri	🟦	🟪	🟥		
	Datta	🟦	🟪			

The surface geology clearly indicates that the study area comprises a south verging, thin-skinned deformed fold and thrust belt structural system, where the structural style is characterized by decollement related thrusting associated with concurrent fault bend folding within the hanging walls that are forming potential traps. Fault-bend folds have a so-called ramp-flat geometry. Thrusts mostly propagate along zones of weakness within a sedimentary sequence, such as mudstones or salt layers, these parts of the thrust are called flats.

If the effectiveness of the decollement becomes reduced the thrust will tend to cut up the section to a higher stratigraphic level, until it reaches another effective decollement where it can continue as bedding parallel flat. The part of the thrust linking the two flats is known as a ramp and typically forms at an angle of about 15°-30° to the bedding. Continued displacement on a thrust over a ramp produces a characteristic fold geometry known as a ramp anticline or more generally as a fault-bend fold.

DISCUSSION AND CONCLUSIONS

The central Kohat Basin has been successfully drilled for hydrocarbons and the exploratory as well as development wells have revealed the extremely complex nature of tectonics in the area. It is well documented that within the Kohat Basin surface structures do not mimic the subsurface structures. The northern and central parts of the Kohat Basin are more tectonised as compared to that of the southern Kohat Basin mainly due to the presence of Paleogene salt that does not extend up to the Karak area in the south (Ahmad, 2003). The KA is located to the immediate south of the central Kohat Basin. An environment separating saline basin in the north from the normal marine conditions in the south towards Surghar Range is expected to have prevailed over the area.

Several oil and gas seepages along the Oligocene unconformity are found within the Surghar monocline near

Table 2 - Laboratory results highlighting source rock potential of some rocks in the region

AGE	FORMATION	AREA/WELL	VR%	TOC %	GP kg/t	HI mg/g
Cambrian	Khisor Fm	Marwat-1	0.65	0.48-0.90	<1-11.5	170-1280
Cambrian	Khisor Fm	Khisor Range	-	0.77	1.2	150
Permian	Sardhai Fm	Marwat-1	0.68	0.28-0.73	<1	-
Permian	Sardhai Fm	Khisor Range	0.75	0.96-2.30	<1	-
Triassic	Mianwali Fm	Marwat-1	0.56	0.50	1.9	380
Jurassic	Shinawari Fm	Marwat-1	0.51	0.52	<1	-
Jurassic	Shinawari Fm	Marwat Range	0.34	1.50	<1	-
Cretaceous	Chichali Fm	Marwat Range	0.39	1.24	<1	-
Cretaceous	Chichali Fm	Pezu-1	0.62	0.50-1.24	1.2-1.7	130-250
Cretaceous	Lumshiwal Fm	Marwat Range	0.31	1.10-1.50	<1	-
Eocene	Jatta Gypsum Shales	Kohat Area	0.65	0.50-1.16	<1-1.4	130-160

Malakhel and Chichali pass area (Ahmad, 2003). After the drilling of Karak-1 well on this structure, a kind of mystery was associated with this area. Several companies licenced this area during different times and after retaining it for 2-3 years, relinquished it due to low prospectivity.

The Karak Anticline being a well-developed surface feature, has been validated on the basis of seismic data to have structure at the level of Eocene-Paleocene. Keeping in view the well-established petroleum system of the area, Karak Anticline is worth-exploring as the mystery now appears to have been resolved.

In the following, a structural development model for the region is proposed. The thin-skinned deformation is related to a regional structural detachment, probably located at the contact between the crystalline basement and Paleozoic sediments. Projection of fold geometries within the exposed rocks requires buried anticlinal structures at the base of Eocene sequence in order to equalize the amount of shortening. The subsurface fold geometries present within the Mesozoic-Paleocene rocks are interpreted as fault propagation folds developed in response to the motion along the thrust splays from a regional basal decollement. The rheological contrast between the base of Eocene succession and the sub-cropping Mesozoic-Paleozoic sequence has played an important role in determining the contrasting structural styles within the exposed and subsurface rocks. It is believed that the presence of a thick sequence of Panoba-Ghazij shale at the base of Eocene has defined the zone of strain partitioning between surface and subsurface structures where the subsurface structural system is migrating southwards in response to the Himalayan deformation. The Paleozoic to Mesozoic rocks are deformed by low angle listric thrust splays and give rise to fault propagation folds within the overlying rocks. The timing of deformation is interpreted to be late Pliocene-Pleistocene in age (Blisniuk et al, 1998).

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