# Structural Architecturing of the Western Khisor Range, North of Saiyiduwali: Implications for Hydrocarbon Prospects, KPK, Pakistan

Iftikhar Alam* and M. Waseem Khan

Atomic Energy Minerals Centre, Lahore, Pakistan

*Email: iakhattak40@yahoo.com

**Abstract**. Western Khisor Range segment of the Trans-Indus ranges is a south-vergent, east-west trending fold-thrust belt that protrudes southward into Himalayan foreland deep. The frontal flanks of range are characterized by east-west trending parallel to enechelon, plunging local anticlines and synclines structures. General structural style of folds was observed asymmetric to overturn and dominantly south vergent. The frontal outskirts of the study area is demarcated by a youngest partly emergent thrust fault named as Khisor Thrust. Outcrops projection to subsurface of the structural features suggests a thin-skinned tectonic mechanism for growth of the western Khisor Range where gliding surface for the frontal thrust sheet being located within the Cambrian rocks of Jhelum Group at a maximum depth of 4km. The structural evolution of the western Khisor Range is generally ascribed to southward directed thrust transferral system along the basal décollement being observed at base of the Cambrian Khewra Sandstone. Along this detachment horizon the Khewra Sandstone emplaced over the Recent alluvium and boulder bed deposits. The Khisor Thrust fault bulldozed the fore limb of the Saiyiduwali Anticline and demarcates the north-western proximity of the Punjab Foredeep. The Khisor Thrust sheet is predominantly comprised of the shallow marine rocks of Paleozoic to Mesozoic, laterally extended along the range. The stratigraphic framework of the western Khisor Range is considerably related and correlative to the eastern Trans-Indus and Salt ranges. Cambrian strata of the western Khisor Range comprise of Jhelum Group where its apex is underlain by the Permian Nilawahan and Zaluch groups rocks, consists of the Sardhai and Amb formations. The Sardhai Formation was observed 50m thick and consists of dark gray to blackish gray and black carbonaceous shale while the lower constituents of the Amb Formation contains dark gray carbonaceous and calcareous shale up to 30m thick, which is favorable setting for hydrocarbon potential of the area. Blending of structural style and stratigraphic framework of the western Khisor Range urges that the south-western foredeep in proximity of Saiyiduwali is significantly associated for the hydrocarbon research, as thick carbonaceous lithofacies of both formations are viable potential source rocks.

**Keywords:** Décollement, Khisor thrust, thin-skinned tectonics, hydrocarbon potential.

## Introduction

The study area is lies northwest of Saiyiduwali, D.I. Khan between geodetic coordinates of longitude 70º58′00″ and 71º04′00″E and latitude 32º10′00″ and 32º20′00″N to border it. It is bounded to north by the Marwat Range and to southeast by the Indus River; the north-western boundary is marked by the Sheikh Badin Hills (Fig. 1).

Khisor Range represents central part of the Trans-Indus ranges and south-western part of the foreland fold-and-thrust belt of the north-western Himalaya being product of the progressive south-directed décollement-related thrusting of cover sequence of the Indian Plate during ongoing collision between Indian and Eurasian Plates (Stocklin, 1974; Stonely, 1974; Molnar, & Tapponier, 1975). Following the convergence of the Kohistan Island Arc (KIA) and the Indian Plate at the site of the Main Mantle Thrust (MMT) (Yeats and Hussain, 1987; Patriat & Achache, 1984; Beck, 1995; Khan et al., 1988; Blisniuk & Sonder, 1998; Alam, 2008; Alam et al, 2014). The southernmost and youngest frontal fractural zone observed in the form of thrusting that occurred along the frontal thrust system bordering the Trans-Indus Ranges.

The western Khisor Range is the south-western most extension of the Trans-Indus and Salt ranges of north Pakistan that appears as an elongated fold-thrust belt (Fig. 1). The range follows in general an east-west structural trend while bordering southern flanks of the Marwat Range, bifurcated in middle by a broad parallel Abdul Khel Syncline. It is an active range forefront and produces different structural styles preserved in the outcropping strata. The western east-west trending division of the Khisor Range reveals that its growth in the form of a frontal ramp related thrust sheet generated above the basal décollement being observed within the Paleozoic-Mesozoic sequence and exhumed as frontal thrust fault named as the Khisor Thrust. The hanging wall of the Khisor Thrust is moderate to tightly folded making local scale structural features toward eastern part of the mapped area; whereas the western part is comprised of large scale structural elements include the Saiyiduwali and Khisor anticlines being generated as fault-bend folds. Forelimbs of the frontal folds had been damaged and eroded during propagation and depositional environments. The stratigraphic sequence along with relevant structural geometries suggests an essential petroleum system comprised of structural and stratigraphic traps, potential source, reservoir and cap rocks favorable for the oil and gas generation and accumulation perspective

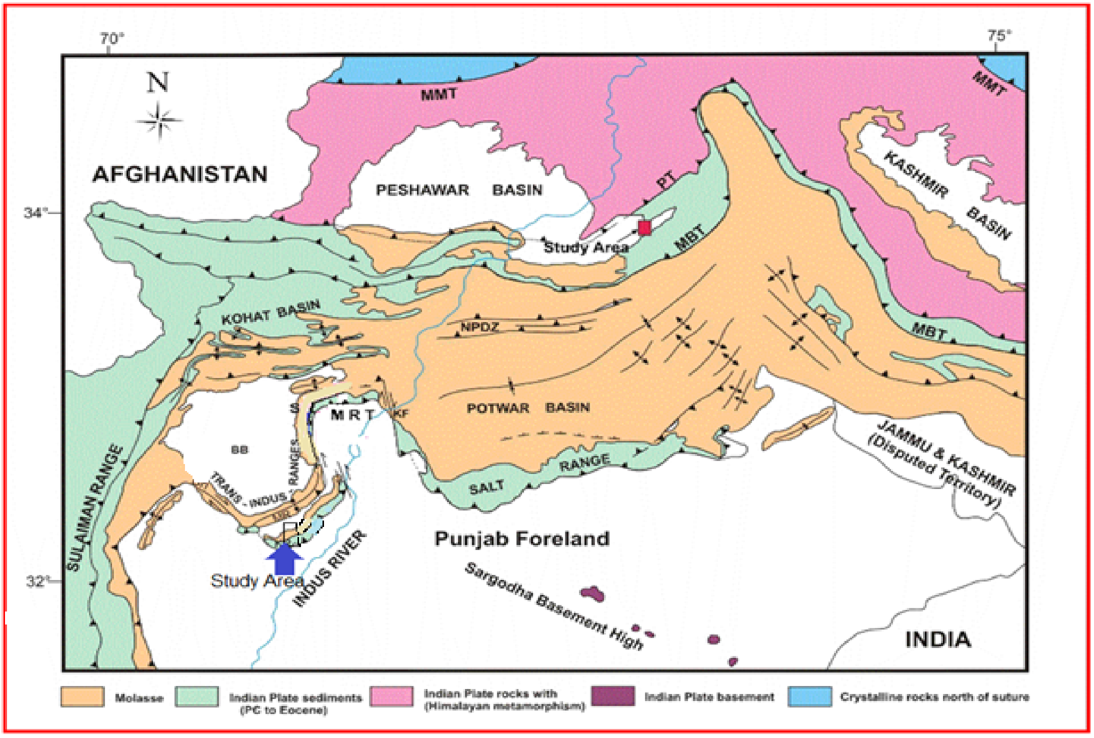


Fig. 1 Regional geological map showing the Trans-Indus ranges and study area.

exhumation phase of the Khisor Thrust. Footwall of the thrust fault observed concealed in the subsurface. Structural geometry of the Khisor Thrust along forefront suggests that it is the last phase of the ramp-flat trajectory commenced from the basal décollement. The fault surface is undetectable and covered under thick alluvium and boulder fans. The western Khisor Range generally reveals south verging structural style that protrudes south-eastward over foredeep in the south (Fig. 1).

Structural geometries of folds and thrust fault within the area indicate that a major regional décollement surface underlie the range that played a key role in its tectonic architecture. The detachment-related thrust-transferral system has allowed north-south differential accommodation in the southeast margin of the western Khisor Range (Alam, 2008). Permian rocks of the Khisor Range comprised of a thick sequence of carbonates and mixed carbonate-siliciclastic rocks indicating an extensive variety of shallow marine to deltaic (Alam et al., 2014).

## 2. Stratigraphic Framework

The exposed stratigraphic sequence of the western Khisor Range is comprised of Cambrian to Neogene horizons. The oldest rocks outcropping belongs to Paleozoic-Mesozoic sequence well exposed northwest of Saiyiduwali in the western Khisor Range. The Cambrian rocks are exposed at the base of succession that comprises Khewra Sandstone, Kussak, Jutana and Khisor Formation (Fig. 2). Top of the Cambrian sequence is unconformably overlain by the Permian rocks that comprise of the Nilawahan and Zaluch groups. The Nilawahan Group consists from bottom to top the Tobra Formation, a tillitic deposit overlying Warchha Sandstone which is mainly composed on siltstone and silty shale. The Sardhai Formation consists of carbonaceous silty shale and sandstone bands. This group is overlain by the Zaluch Group rocks and consist of Amb Formation, Wargal Limestone and Chhidru Formation. The Permo-Triassic boundary is marked at the contact between the Chhidru Formation and Mianwali Formation of the Musa Khel Group. The Tredian Formation overlies the Mianwali Formation, the lower part of the formation consists of silty beds and the upper part comprises of thick-bedded sandstone. Top of the sequence consists of the Kingriali Formation. This formation is unconformably overlain by the Siwalik Group rocks and comprised of the Nagri, Dhok Pathan and Soan formations. These nonmarine molasses facies represent the erosional products of southward advancing Himalayan thrust sheets and development of a terrestrial foreland basin that contained generally south-flowing fluvial systems, including the Paleo-Indus River, which were derived from the Himalayas during Pliocene till present (Pilgrim, 1926; Fatmi, 1973; Danilchik and Shah, 1987; Alam et al., 2014).

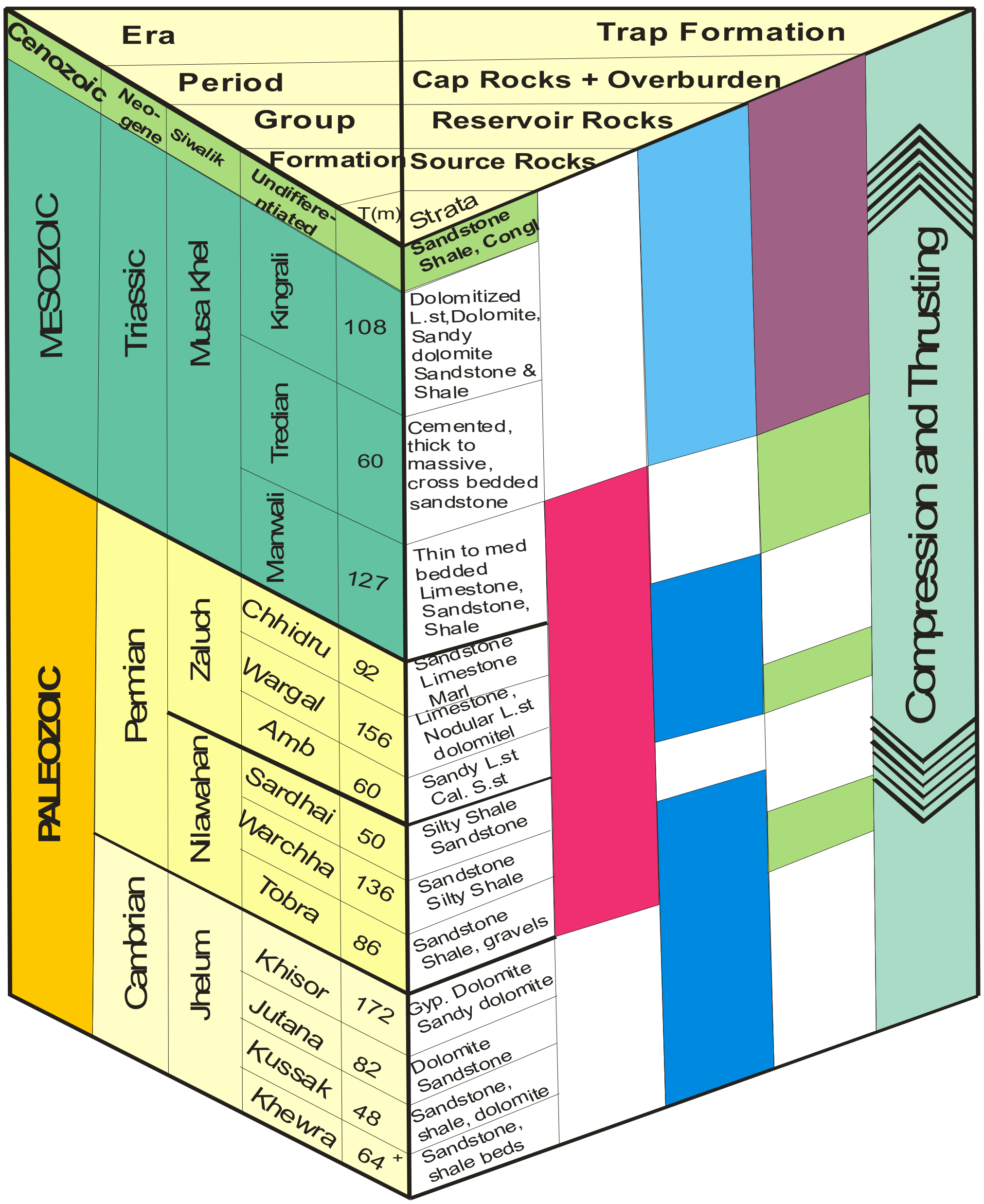


Fig. 2 Anticipated petroleum system of the western Khisor Range.

## 3. Structural Architecture

Structural elements of the mapped area generally define east-west trend with southeast vergence mechanism (Fig. 3). Geometrically the macro-scale fold structures observed asymmetric to overturn along their frontal flanks and moderately plunging along their map extension.

Overturned forelimbs are commonly dipping at angle between 40º and 70º, although dip values observed as low as 13º along northern margins of the western Khisor Range in the Siwalik sequence. Key structural elements mapped in sequence from south to north as Khisor Thrust followed by the Saiyiduwali Anticline, Khisor Syncline, Khisor Anticline and Abdul Khel Syncline which demarcates the northern periphery of the mapped area. Concentration of small scale intervening folds is observed along the eastern segment of the study area.

### 3.1 Fold Structures

The following four major fold structures mapped in the western Khisor Range in sequence from south to north as:

**Saiyiduwali Anticline.** It is the largest fold structure mapped toward western terminus of the western Khisor Range and it can be traced for a distance of more than 5 km along its map trace in the east-west direction. This anticline is bounded to the north by the Khisor Syncline and to the south by the Khisor Thrust Fault. The northern flank of this fold attains greatest structural relief, where Chhidru Formation occupies hinge zone of the fold. The topographic expression of this structure is mainly attributed to its back limb which consists of Cambrian to Permian rocks, whereas its forelimb has been eroded and does not crop out with the exception in the east and west, where both of the anticlinal limbs are found intact (Fig. 3). The back limb of this fold is moderately deformed producing shallow folded structures, well developed in the Musa Khel Group rocks of the Triassic age. The oldest rocks entrapped in the core of Saiyiduwali Anticline include Khewra Sandstone, Kussak, Jutana and Khisor Formation of the Jhelum Group overlain by the rocks of Tobra Formation, Warchha Sandstone and Sardhai Formation of the Nilawahan Group of lower Permian. Further upwards the rocks of Zaluch and Musa Khel Group of upper Permian and Triassic overlie this sequence and are in turn unconformably overlain by the Siwalik Group rocks of Nagri Formation (Fig. 4).

**Khisor Syncline.** This syncline appears very next to the Saiyiduwali Anticline toward north and is associated with the northern limb of the Saiyiduwali Anticline. The trend of the fold axis of this syncline is east-west oriented. Both limbs dip at diverse angles toward core of syncline, producing an asymmetrical geometry. The southern limb of this syncline comprises the same rock units as that of the northern limb of the Saiyiduwali Anticline whereas its northern limb consists of the rocks of the Chhidru Formation.

**Khisor Anticline.** This fold is located northeast of the Saiyiduwali Anticline, and is characterized by an east-west trending fold axis. Both limbs of the anticline are dipping slightly at different angles creating the anticline asymmetric in shape. The southern limb consists of rocks of the Chhidru Formation while the northern limb consists of Chhidru Formation overlain by Musa Khel Group rocks of Triassic which are unconformably overlain by the Siwalik Group rocks (Fig. 5). The Khisor Anticline has the highest structural relief compared to other fold structures and exposes the Kingriali dolomite at apex of fold hinge and forms the Kingriali peak where the western Khisor Range achieves its highest elevation.

**Abdul Khel Syncline.** This synclinal fold has been mapped immediately to the north of the Khisor Anticline. The Khisor Anticline and Marwat Range bound this syncline to the south and north respectively. The Soan Formation is well exposed at the southern limb of syncline and core of the structure is filled with disintegrated sand due to erosion associated with deformation. Fold geometries indicate that its fold axis is east-west oriented and laterally extended all along the map extension.

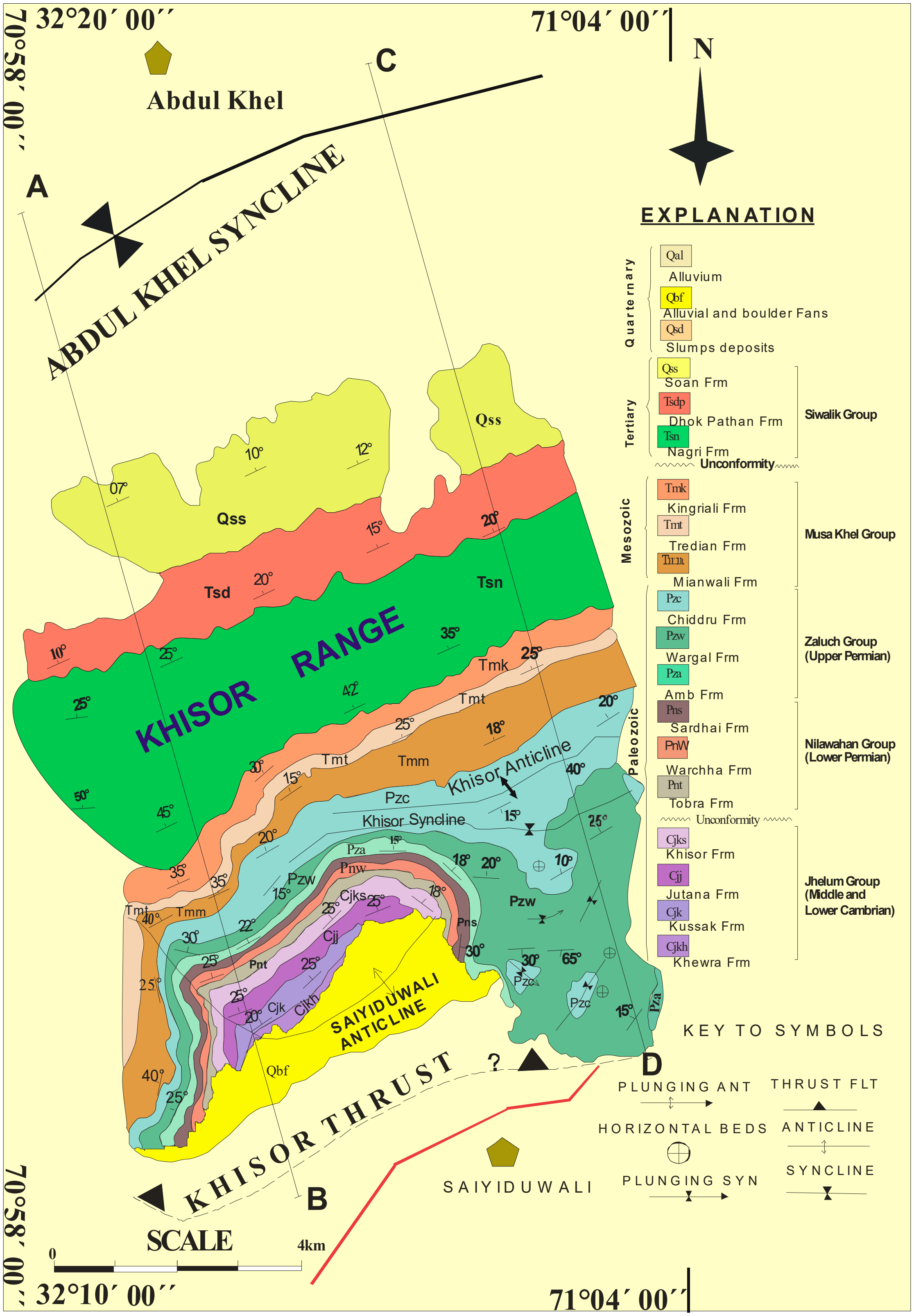


Fig. 3 Geological map of the western Khisor Range, Saiyiduwali, D.I. Khan.

### 3.2 Fault Structure

One prominent southeast vergent northwest dipping thrust fault observed and mapped in the frontal foothills of the western Khisor Range north of Saiyiduwali village named as Khisor Thrust Fault (Fig. 4 & 5). The Khisor fault is a forefront thrust which is partially exposed along the frontal slopes of the Khisor Range (Alam, 2008 & Alam et al, 2014). It is well exposed east of Saiyiduwali village and providing excellent outcrop exposures. All along the map trace of the Khisor thrust, Cambrian to Permian strata constitutes its hanging wall thrust ramp over the alluvium and Siwaliks in the footwall. It is dominantly oriented east-west and dips moderately toward the northwest (Fig. 4 & 5). The outcrop characteristics of this fault suggest that it is south-vergent forethrust detached at different stratigraphic levels ranging from base of the Cambrian to Permian rocks (Alam, 2008).

### Structural Synthesis

Two different episodes of tectonic activities were reported for the structural evolution of the region. Normal faulting prior to generation of south facing thrust faulting, modified the contemporary northwest Himalayan thrust front (Blisniuk et al., 1998). Basement related thick-skinned extensional tectonics associated to syn-organic flexure of the Indian plate of late Miocene followed by the south-directed thrusting of the cover sequence in Plio-Pleistocene, responsible for the generation of outward growth of thrust wedge along the outskirts of the outer Himalaya.

Couple of viable structural transects have been constructed on the basis of projection of surface structural data into the subsurface to recognize the tectonic architecture, characteristic features of the basal detachment horizon and fold-thrust geometries of this structural province.

## 4 Structural Transect AB

A structural transect along line AB (Fig. 4**)** has been constructed across (Fig. 3). This transect is oriented north-northwest in the north to south-southeast in the south toward the western terminus of the range. This transects cross cut all the significant structures of the region and portrays the overall structural geometry of (Fig. 3). It is nearly right angle to the structural trend of the exposed lithological units. From south to north the back limb of Saiyiduwali Anticline occupies the hanging wall strata of the Khisor thrust, whereas its forelimb has been eroded. The basal strata cropping out in the core of this anticline is the Jhelum Group overlain by Permian rocks. Subsurface projection of the structural geometries indicates that this anticline is underlain by a basal detachment horizon located at the base of Khewra Sandstone of lower Cambrian. The Salt Range Formation is not exposed in the study area, thus, the basal regional detachment surface below the Saiyiduwali Anticline may exist directly above the basement crystalline rocks of Precambrian age. The Saiyiduwali Anticline is interpreted as a fault-bend forced fold related to frontal ramping from the basal décollement. This transect depicts that this part of the western Khisor Range has been uplifted as a result of a south directed translation. A pair of folds is mapped north of the Saiyiduwali Anticline in the Permian and Triassic strata in the form of Khisor Syncline and Khisor Anticline. Both are symmetrical structural features. North of the Khisor Anticline in the vicinity of Abdul Khel village a broad and open syncline is mapped and designated as Abdul Khel Syncline.

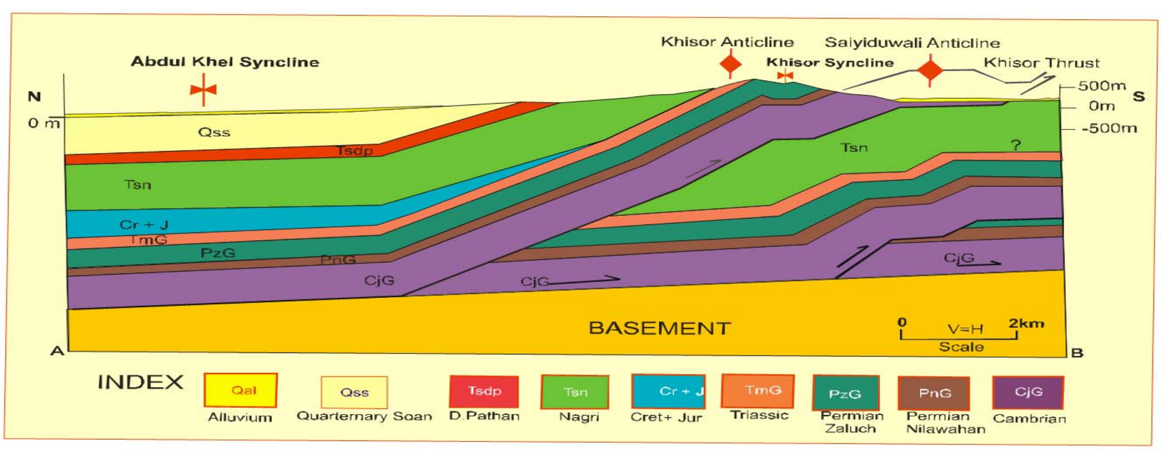


Fig. 4 Shows the structural transect along line AB of the Fig. 3.

## 5. Structural Transect CD

The structural cross-section along line CD (Fig. 5) of the Fig. 3 crosses the eastern flank of the study area and is located northeast of Saiyiduwali village. Along this transect the southernmost part of the range front is occupied by the Permian Wargal Limestone that displays a small scale, continuous fold train structure of synclines and anticlines characterized by short wavelengths of less than 1km. The Khisor Anticline is the most prominent fold structure of transect and makes the main topographic expression of the western Khisor Range. Most of the dip values along the cross sectional line are moderate to gentle especially to north of the Kingriali peak indicating the shallowness of the folds. The subsurface projection of attitude data along the structure reveals that the Khisor Anticline is the result of a ramp emanating from the regional detachment surface. All the small-scale structures in the Wargal Limestone towards the southern margin of the range front are associated with translation above a flat, generated due to the flattening of the major ramp underneath the Khisor Anticline. The ramp from the basal décollement finally ramps out at the site of the Khisor Thrust above the southward-propagating wedge of the cover sequence. Along line CD the major ramp anticline, that is Khisor Anticline, exposes the Zaluch Group rocks of Permian in its core and its southern limb is comparatively steeper than its northern limb. Projection of the surface data and cut-offs along the frontal thrust suggests that the basal detachment surface exists below the Khewra Sandstone of Jhelum Group rocks at about 3~4 km depth. Structural style depicted along transects clearly indicates that this part of the Khisor Range evolved as a south directed fold-thrust transferral system, detached from the regional basal decollement. The deformational geometries are observed along the section lines mostly in the form of ramp-flat trajectories

### Hydrocarbon Potential

Compressional and associated tectonics regime related to collision of the Indian and Asian plates has modified the Tertiary sequence of the foredeep. Discovery of the first commercial oil well at Khaur north-western Potwar was made in 1916. Up to present plentiful and significant oil and gas structural provinces have been discovered in the southern, north-western and north-eastern part of the country that reveals the absolute potential of hydrocarbon in the northern plateaus, fold-thrust belts and foreland basins of Pakistan.

Rocks ranging in age from Cambrian to Cretaceous are well exposed in the western Khisor Range making an anticipated petroleum system both toward the northern and southern flanks of the range.

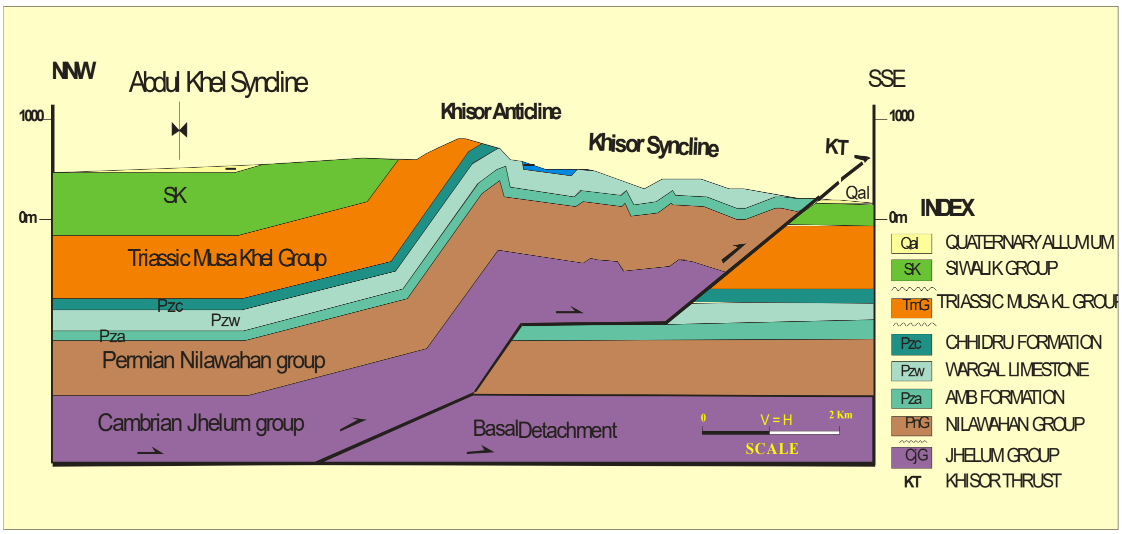


Fig. 5 Shows the structural transect along line CD of the Fig 3.

The Permian sequence of the mapped area consists of carbonates and mixed carbonate-siliciclastic horizons signifying an extensive range of shallow marine to deltaic depositional setting (Alam, 2008 & Alam et al, 2014). The exposed stratigraphic succession along with structural framework almost certainly generates an imperative petroleum system in the region (Fig. 2). This system is comprised of potential source rocks such as Sardhai Formation of Permian that predominantly consists of blackish to dark black carbonaceous shale. The Sardhai Formation is 50m thick that can provide as excellent source for hydrocarbon generation. Basal horizon of the Amb Formation of Permian also comprises of thick beds of carbonaceous shale overlain by thick beds of sandstone, contributing an equal chance as reservoir and source medium for the desired prospect. Mianwali Formation of Triassic can be considered as seal horizon that frequently composed of shale overlain by thick overburden of the Tredian and Kingriali formations that in turn unconformably overlain by Siwalik Group rocks. Ground rules for generation and accumulation of hydrocarbons such as source and reservoir rocks both exist in the entire mapped area in conjunction with the sealing rocks to check the escapement of hydrocarbon, in the form of thick shale beds. On the basis of surface observation the local structural system is as thin-skinned rather than thick-skinned, related to contractile plate tectonic environments (Alam et al., 2014).

## Requisite rocks availability

The potential source medium is observed in the lower Permian sequence and comprised of thick blackish gray to dark black shale of thickness 50m present in the Sardhai Formation. Comparable thick shale horizon mapped at lower level of the Amb Formation that can be favourable potential source medium. Thick bedded to massive, well fossileferous limestone horizons in the Amb Formation, Wargal Limestone and Chhidru Formation of Permian can also be considered as less significant source rocks and these rocks play important role as thick overload above the potential medium.

Detrital to non-detrital reservoir rocks packages frequently observed in the mapped area (Fig. 3). Massive sandstone bodies mapped in the Warchha and Tredian Formation suggests imperative indications to the potential nature of fluid content. Among the fragmental clastic rocks, sandstone and siltstone are considered the most frequent reservoir medium. These sediments are essential ingredients of the Tobra Formation of lower Permian which is an apparent potential reservoir medium. The Warchha Sandstone is fragmental reservoir medium, where oil does occur commercially in rocks of continental or non-marine origin. Non-marine sediments with porosity, permeability, sufficient impervious cover and useful trapping environments would not be ignored as potential promising reservoir medium. Beside non-carbonates the carbonates of Wargal Limestone and Chhidru Formation are also considered as significant reservoir medium for hydrocarbon accumulation. These formations are well fractured, jointed and fossiliferous, diagenetically and tectonically and are appropriate as reservoir resources.

Crystalline to very fine grained rocks for instance evaporites or shale have the tendency to serve as effectual cap horizons to stick migration, leakage and seepage of hydrocarbons from reservoir medium, therefore impervious horizon is imperative to cap the saturated medium. The Mianwali Formation of Triassic is generally composed of shale that can be considered as suitable cap rocks above the potential source rocks of Sardhai and Amb formations.

## Hydrocarbon Traps

Foreland fold-thrust-belts are considerable environments for the exploration and exploitation of oil and natural gas all over the world. There are various important petroleum traps including the structural traps. The existence of forced folded and fault-related anticlines are considered as the most useful structural traps in the study area. The mapped locality and its lateral extension recognizes a south to southeast verging; thin-skinned deformed fold-thrust belt where the structural mechanism is dominantly controlled by basal detachment-related fore thrusting associated with concurrent fault-bend folding (Alam et al., 2014). Some principal anticlinal structures of desired disposition mapped in the area that are exactly appropriate for the entrapment of hydrocarbon. Observations based on outcrop structural interpretation and comparable lithologies and their combination can be envisaged for the non-outcropping rocks below the north-western foredeep which are still inadequately explored division of the foreland fold and thrust belt of northwest Pakistan. Beside the structural traps the existing lithological constituents of the area also contribute toward constituting useful and significant stratigraphic traps for the retention of fluids.

## Discussion

Geological mapping in conjunction with structural architecturing and construction of couple balanced structural cross section interprets that the fore flanks of the western Khisor Range is underlain by a regional décollement horizon positioned at the base of the Cambrian Jhelum Group rocks. Most of the outcropping structural features east-west oriented and south to southeast verging reveal horizontal compressional stresses being originated and observed from northwest. These analyses are rather reliable and supported by the existence of east-west trending structural geometries and south to southeast vergent compressional structures. Whereas the greatest strain is observed along the western terminus of the western Khisor Range in the shape of frontal thrust. This thrust sheet is southeast vergent and northwest dipping consistent to the philosophy of south-directed tectonic transferral regime. In result of contractile deformation a differential stratal telescoping observed along the structural transects AB and CD (Fig. 4 & 5). Intensity of strain and telescoping of the cover sequence observed lofty in the Saiyiduwali Anticline where the deepest rocks of Cambrian exposed to surface constructing a frontal tectonic wedge. Variation of deepness has been observed in level of the basal décollement along the range front. This differential and intense structural deformation represents skinny or nonexistence of salt situation beneath the western Khisor Range. The Khisor Fault is therefore categorized as a fore thrust that detached and separated the range from comparatively undeformed north-western foreland deep toward northwest. The exposed lithological units across the Khisor Thrust in the western Khisor Range are consistent with the interpretation to construct a hydrocarbon kitchen in the area. The north-western outskirts of foreland deep along the Khisor Range in the locality of Saiyiduwali needs to be investigated for hydrocarbon potential in the region.

## Conclusion

Geological mapping of the structural province of western Khisor Range indicates that this part of the Khisor Range is characterized by east-west trending, asymmetric to overturned structural features reveal southeast vergence toward the foreland basin. Structural architecturing in the western Khisor Range shows that this region is comprised of thin-skinned deformed fold-thrust assemblages which copes the whole structural mechanism of the region. The mapped major anticlinal folds constitute the hanging wall strata of the exhumed and non-exhumed thrust faults in the area. Structural synthesis of the prominent structural features and construction of the balanced cross sections interpret that this structural province is underlain by a principal basal décollement horizon sited below the Khewra Sandstone of lower Cambrian. Outcrop structural data and structural transects reveal that this basal décollement horizon is gently dipping northwards by 2°~3°. Intensity of deformation and amount of stratal shortening observed more toward the south-eastern outskirts of the mapped area. Hydrocarbon potential toward the north-western environs of the foreland deep is due to existence of suitable lithofacies in the study area. Essentials which are needed for making the hydrocarbon kitchen are present in the form of source, reservoir and cap horizons that generate an expected petroleum system in the region.

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