

Frontal structural style of the Khisor Range, northwest of Bilot: Implications for hydrocarbon potential of the north-western Punjab fore deep, Pakistan

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Abstract

Khisor Range of the Trans-Indus ranges is a south-vergent fold-thrust belt that defines an east-west to north-northeast trending structural geometries and protrudes southward into the northwestern Punjab foreland deep. This range is characterized by east-west to north-northeast trending parallel to en echelon, plunging anticlines and synclines pairs that observed asymmetric to overturn in the form of fold train and dominantly southeast vergent. The frontal foothills of the Khisor Range comprise a latest partially emergent thrust fault named as Khisor Thrust. Surface projection to depth of the emergent structural elements suggests a thin-skinned structural mechanism for evolution of the Khisor Range where gliding horizon for the frontal thrust sheet being located within the Nilawahan Group rocks of Permian age at a maximum depth of 3~4 km. The structural growth of the Khisor Range is dominantly attributed to the south directed transferal deformation mechanism along the basal detachment horizon being observed at the foot of the Permian Warchha Sandstone. Along this basal detachment surface the Warchha Sandstone emplaced over the Siwalik Group rocks southeastward on top of the northwestern frontier of the Punjab Foreland. Thrusting generally commenced subsequent to deposition of the Siwalik Group rocks, for the reason that these rocks involved in the latest thrusting phase. The Khisor Range front is the latest and dynamic frontal fracture zone of the northwestern Himalaya where deformation proceeds in the course of southward progression. The Khisor Thrust demarcates the northwestern proximity of the Punjab Foreland and is predominantly underlain by the shallow marine rocks of Permian to Triassic age in the region of Bilot. The stratigraphic framework of the Khisor Range is significantly associated and correlative with the Surghar and Salt ranges with some exceptions. Permian strata of the Khisor Range comprise on Nilawahan and Zaluch groups rocks, where the top of the Nilawahan Group consists of the Sardhai Formation and bottom of the Zaluch Group consists of the Amb Formation. The Sardhai Formation observed 40m thick and consists of dark gray to blackish gray and black carbonaceous shale while the basal parts of the Amb Formation consists of dark gray carbonaceous and calcareous shale of more than 20m thick, which is conflicting to the stratigraphic setting of the Surghar and Salt ranges. The structural geometries and stratigraphic framework of the Khisor Range suggests that the northwestern Punjab fore deep is pertinent for the hydrocarbon exploration as thick carbonaceous shale facies of both formations are feasible potential source rocks.

Keywords: Khisor Range; Structural geometries; Bilot; Permian strata; Punjab fore deep; Hydrocarbon exploration.

1. Introduction

The Trans-Indus extension of the Salt Range is composed of the Surghar-Shinghar, Marwat-Khisor, Pezu and Manzai ranges “which form an “S” shaped double re-entrant and surrounds the Bannu Basin” (Fig. 1). These ranges represent the western part of the northwestern Himalayan foreland fold-and-thrust belt that formed by progressive south-directed decollement-related thrusting of the sedimentary cover sequence of the

Indian Plate during the ongoing collision between India and Eurasia Plates (Stocklin, 1974; Stonely, 1974; Molnar and 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 et al., 1987; Patriat et al., 1984; Beck, et al., 1995; Opdyke, et al., 1988; Blisniuk et al., 1998). 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.

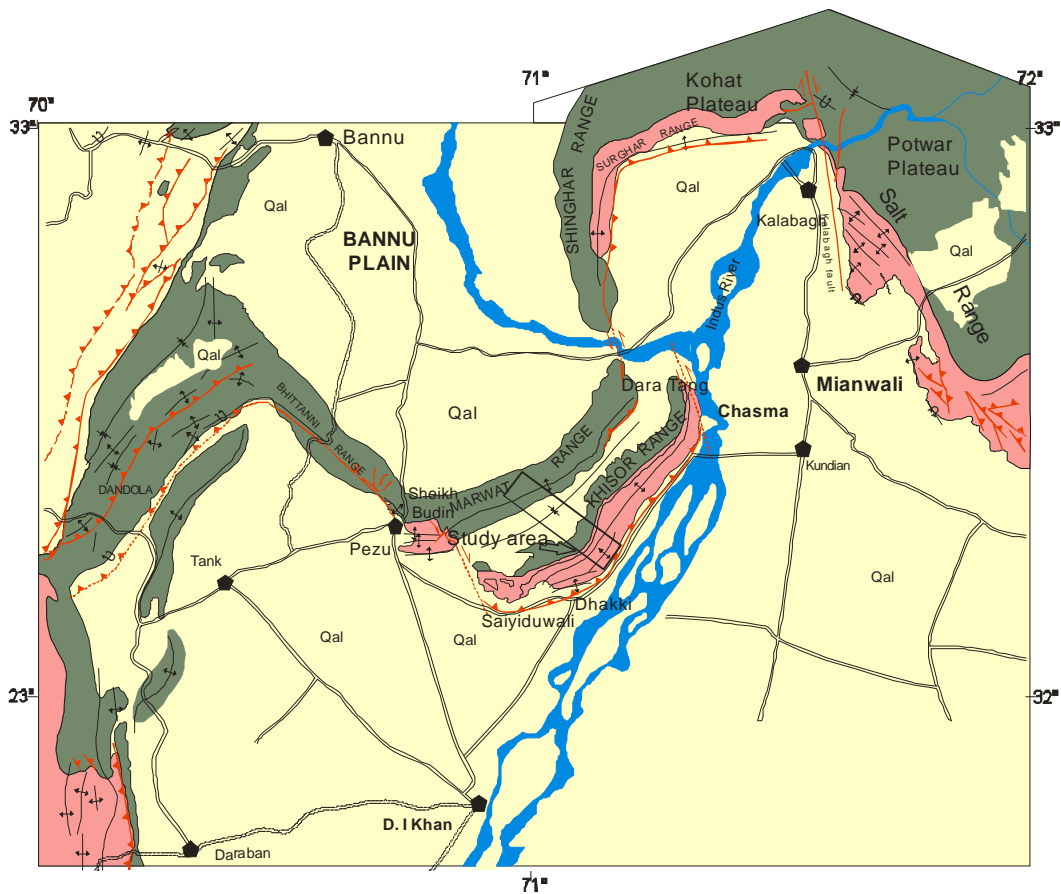


Fig. 1. Regional geological map of the Trans-Indus Ranges, showing the study area.

The Marwat-Khisor Range of the Trans-Indus Ranges defines north-northeast trending fold and thrust belt “which separates the north-western Punjab foreland to the southeast from the southern deformed fold thrust belt”. Collectively, the Marwat-Khisor ranges represent the deformed and mobile outskirts of the Bannu Basin to the north-northwest where the non-outcropping rocks of this basin observed uncovered and well deformed. The Marwat-Khisor Ranges are divided in the middle by a broad elongated structural feature named as Abdul Khel Syncline (Fig. 5). From south to north, three major tectonic elements that define the active foreland deformation belt of North Pakistan are as follows: (1) the Punjab foreland (2) the Salt and Trans-Indus ranges (3) the Kohat-Potwar Plateau and the Bannu Basin Stonely, R.L. (1974). This study deals with one of the fringing belts of Himalayas that is the central portion of the Marwat-Khisor ranges which make the inner part of the Trans-Indus ranges (Fig. 1). The study area is lying northwest of Bilot, D.I. Khan between longitude $70^{\circ}58'00''$ and $71^{\circ}11'00''$ E and

latitude $32^{\circ}14'00''$ and $32^{\circ}27'00''$ N to border it. These ranges are bounded to the north by the Bannu Basin and to the southeast by the Indus River. The Punjab forelands demarcate the southern frontier whereas the northwest boundary is marked by the Sheikh Budin hills (Fig. 1). The study area is characterized by fractions of the Marwat-Khisor ranges constitutes the south westernmost part of the Himalayan foreland basin of North Pakistan. It is characterized by the presence of roughly north to northeast-trending structural features. The fold structures are generally asymmetric, plunging and are mostly associated with the underlying decollement related thrust faults system. A major south-vergent thrust fault has been recognized all along the frontal foothills of the Khisor Range where the Permian strata thrusts southward against the Punjab foreland. Structural geometries of folds and thrust faults within the area indicate that a major regional decollement surface underlie these ranges that have played a major role in its tectonic architecture. The detachment-related thrust-

transferral regime has allowed north-south differential accommodation in the southeast margin of the Khisor Range (Alam, 2008). The Permian succession of the Khisor Range comprised of a thick sequence of carbonates and mixed carbonate-siliciclastic rocks representing a wide variety of shallow marine to deltaic environments of deposition. This stratigraphic sequence along with relevant structural geometries suggests an important petroleum system comprised of potential source, reservoir and seal rocks for the oil and gas generation and accumulation (Alam, 2008).

2. Regional stratigraphic setting

The stratigraphic sequence of the Marwat-Khisor ranges divides into the following three major stratigraphic horizons.

2.1. Precambrian crystalline basement rocks

The Precambrian Crystalline Basement is not exposed in this area but exposed towards the southeast in the form of Sargodha Basement High.

2.2. Shallow marine Permian and Mesozoic

This pre-orogenic platform sequence is mapped in the Khisor Range. The Mesozoic strata exposed in the western portion and Permian in the eastern portion of the Khisor Range.

2.3. Cenozoic, Late Tertiary (Neogene to Quaternary)

Syn-orogenic foreland basin deposits are mapped in the Marwat Range, mostly at the northern flank of the Khisor Range and at some locations in the frontal portion of the Khisor foothills.

Paleozoic to Mesozoic stratigraphic sequence is well exposed northwest of Saiyiduwali, in the Khisor Range. The Cambrian age rocks are exposed at the bottom of the succession that comprises Khewra Sandstone, Kussak, Jutana and Khisor Formation (Fig. 2) Top of the Cambrian sequence is occupied by the Permian rocks that comprise of the Nilawahan and Zaluch Group.

The Nilawahan Group consists from bottom to top the Tobra Formation, a tillitic deposit

overlying Warchha Sandstone 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 that consist of Amb Formation, Wargal Limestone and Chhidru Formation. The Permo-Triassic boundary is observed at the contact between the Permian Chhidru Formation and the Triassic Mianwali Formation of the Musa Khel Group. The Tredian Formation overlies the Mianwali Formation, the lower part of the formation consists on silty beds and the upper part comprises on thick-bedded sandstone. The upper profile of the succession consists of the Kingriali Formation. This formation consists of dolomitic marl and shale, and is unconformably overlain by the Siwalik Group rocks in the Khisor Range. The Musa Khel Group is well exposed in the west and extends up to north of Saiyiduwali but further eastwards it does not make its way to the surface. In the entire Khisor Range along the strike, The Jurassic in the west, Triassic in the center and Permian rocks in the east are unconformably overlain by the Nagri, Dhok Pathan and Soan formations, of Siwalik Group. These nonmarine molasses facies represent the erosional products of southward advancing Himalayan thrust sheets. The Marwat Range lies immediately south of the Bannu Basin and outcropping in the form of broad anticline known as the Marwat Anticline. It is entirely composed of Siwalik Group rocks (Fig. 3) representing the 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. The influence of the advancing orogenic front on the foreland sedimentation becomes more pronounced during the deposition of the Siwalik Group as compared to Rawalpindi Group because the axis of the Siwalik depocenter shifted southward, resulting in the formation of middle/upper Siwalik in the Marwat-Khisor ranges (Pilgrim, 1926; Fatmi, 1973). Paleozoic to Cenozoic sedimentary section of the mapped area is comprised of a series of mechanically competent and incompetent units that appear to have defined the locations of regional and local detachment horizons as well as the structural geometries of large and small scale folds. Mechanically competent units are separated by the shale and marl rich facies that have

permitted both interbeds slip between the more competent sequences and the evolution of low to

moderate angle thrust faults and detachment tectonic habitats.

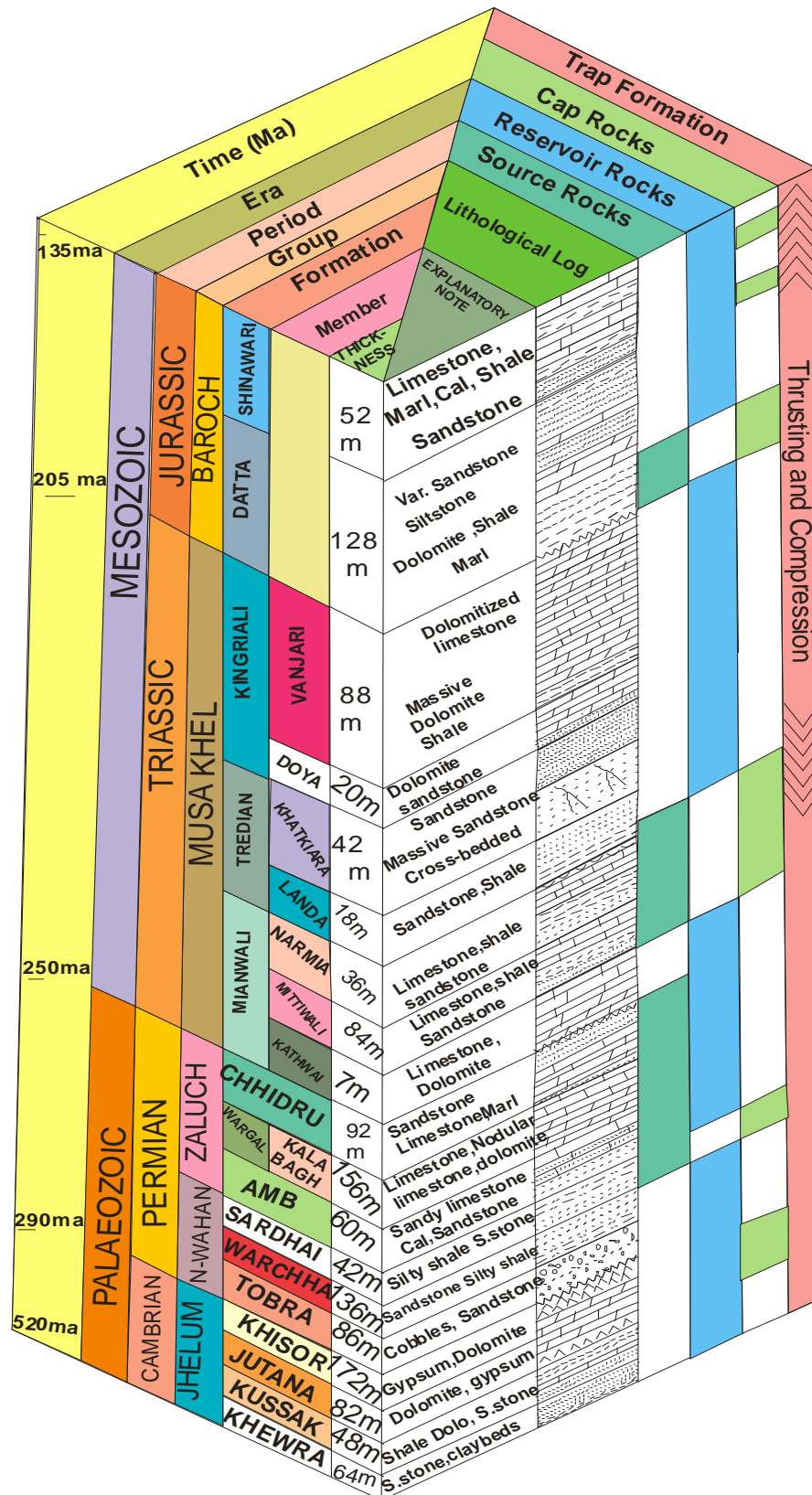


Fig. 2. Anticipated petroleum system in the Marwat-Khisor ranges.

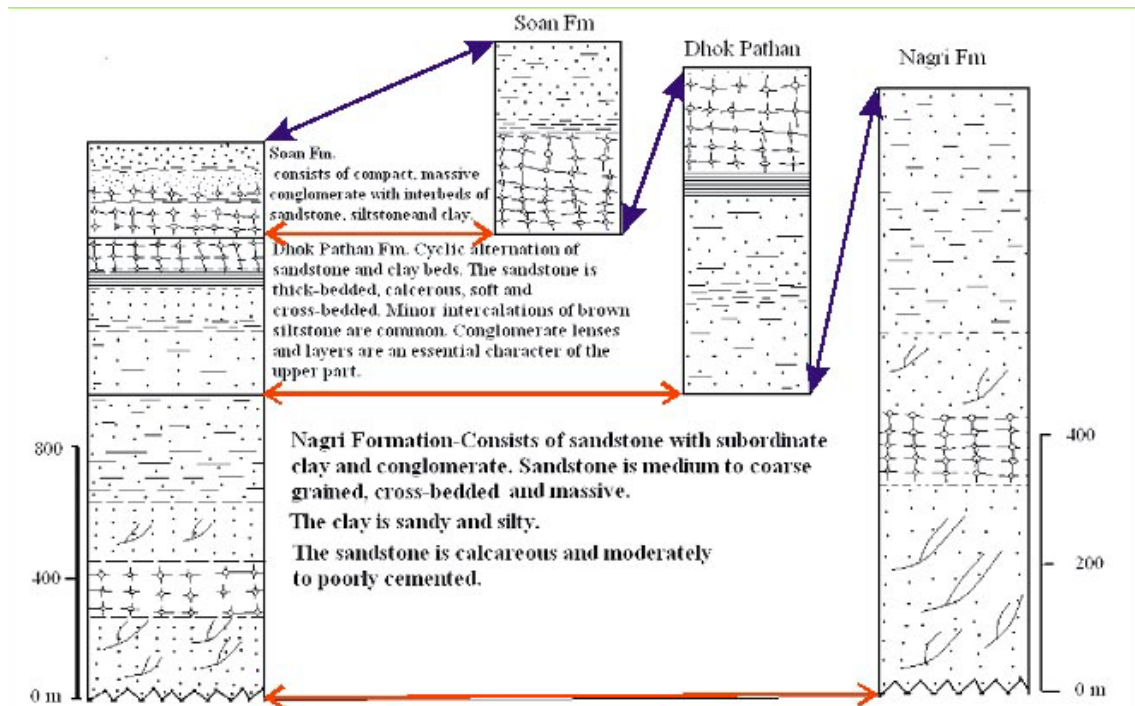


Fig. 3. Generalized columnar section of Swalik Group rocks exposed in the study area.

3. Structural geometries

Structure of the mapped area is characterized by the presence of roughly NNE trending (Fig. 4). North-northeast trend observed for the structural elements of the Khisor Range with asymmetric, overturned and plunging structural geometries. Most of the mapped structures define east-southeast vergence in the Khisor Range and southeast vergence system in the Marwat Range.

All of the macro-scale asymmetric folds observed overturned along their forelimbs and define southeast vergence mechanism. Overturned forelimbs generally dip between 45° and 75° , although dips values as low as 13° have been observed along the northern margins of the Khisor and Marwat ranges in the Siwalik Group rocks. Major structural features are mapped from southeast to northwest in the sequence as Khisor Thrust and Bilot fore thrust in the foothills of Khisor Range followed by the Bilot Anticline and syncline along with intervening small scale folds. In the sequence mapped the Dhupsari Anticline and syncline and Mir Ali Anticline. Abdul Khel Syncline, which demarcates the northwestern boundary of the Khisor Range and southeastern boundary of the Marwat Range.

3.1. Fold structures

The largest anticlinal fold mapped in the Marwat Range is the Marwat Anticline. This anticline is bounded to the southeast by the Abdul Khel Syncline and to the northwest by the Bannu Basin. The back limb of this anticline is composed of rocks of the Dhok Pathan and Soan formations whereas the forelimb constitutes the strata of the Dhok Pathan Formation only. The Nagri Formation is exposed in the core of anticline. The southeastern limb of the anticline dips to the northwest at a moderate to steep angle (50° ~ 75°) whereas its northwestern limb dips gently to the northwest (15° ~ 44°). On the basis aforesaid attitude data the Marwat Anticline is considered to be an overturned anticline with south vergence geometry. The Abdul Khel Syncline has been mapped immediately to the northwest of the Mir Ali Anticline. The Mir Ali Anticline and Marwat Anticline bound this syncline to the southeast and northwest respectively. The Soan Formation is well exposed at the north-western limb of syncline while the same formation is absent at the southeastern limb due to erosion associated with deformation. Fold geometries indicate that its southeastern limb dips gently to the northwest whereas its north-western limb dips steeply to the

southeast making the overall sectional geometry overturned for the Abdul Khel syncline. The Mir Ali Anticline is mapped about 5 km northwest of the Bilot. Axial trend observed in the north-northeast and is thus identical in fashion to the Abdul Khel Syncline. Its map extension along the axial trend is more than 5 km. Its southeastern limb is comprised of the rock of Chhidru Formation whereas its northwestern limb comprises of the rocks of Chhidru and Mianwali Formation, unconformably overlain by the

Siwalik strata. The southeastern and northwestern limbs dip gently to the southeast and northwest respectively, attributing south asymmetry. The Dhupsari Syncline towards southeast and is associated with the north-western limb of the Dhupsari Anticline. The trend of the fold axis of this synclinal is north-northeast. The Mir Ali Anticline has the highest structural relief compared to other fold structures and exposes the Kingriali dolomite in the apex of fold hinge.

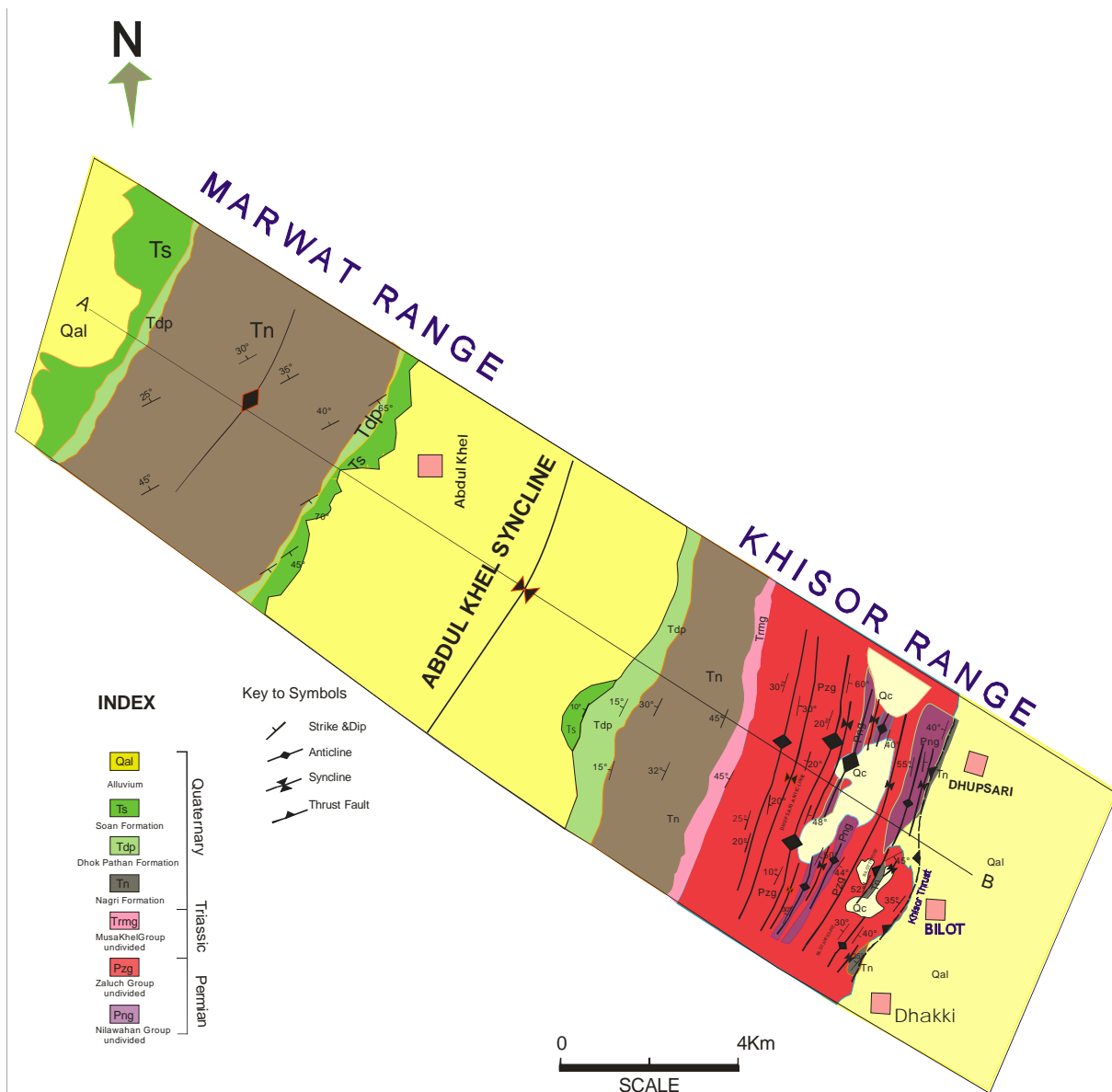


Fig. 4. Geological map of the Marwat-Khisor Ranges, Dhakki-Bilot, D.I. Khan.

3.2. Fault structures

Two prominent southeast vergent northwest dipping thrust faults have been observed and mapped in the foothills of the southeastern Khisor Range north-east of Bilot village. Bilot fault has been mapped 2 km northeast of the Bilot village and northwest of the Khisor Thrust. It strikes north-northeast not much laterally extended. Along this fault the Permian rocks in the hanging wall are thrust over the Nagri Formation in its footwall (Fig. 4) On the basis of surface structural geometries it appears to be an imbricate splay fault associated with the frontal Khisor Thrust. The Khisor fault is a frontal thrust which is partially exposed along the frontal slopes of the Khisor Range. It is well exposed west of Bilot, and Dhupsari villages, providing good outcrop exposures. All along the map trace of the Khisor thrust, the Permian strata constitutes its hanging wall thrust over the Siwalik Group rocks in the footwall. It is dominantly oriented north-northeast and dips moderately toward the northwest (Fig. 4). The outcrop characteristics of this fault suggest that it is south-vergent fore thrust detached at the base of the Permian rocks (Alam, 2008).

4. Emergent structural style

Two phases of deformation, that are earlier normal faulting followed by south verging thrust faulting, are considered to be regionally expressed and most probably affected the entire present-day NW Himalayan thrust front according to Blisniuk, et al., (1998). They suggest that earlier deformation was probably of thick-skinned extensional style related to syn-orogenic flexure of the Indian Plate during the late Miocene. It was followed by Plio-Pleistocene south-directed thrusting along the present-day thrust front related to outward growth of the NW Himalayan thrust wedge. However, because of the lack of detailed information, the subsurface structural style including the nature of basal decollement, depth to the decollement and fold-thrust styles underneath the Marwat-Khisor ranges is still poorly understood. Therefore a detail structural transect of the mapped area has been constructed to understand the tectonic architecture of the region in depth.

4.1. Structural transect AB

A Structural cross section was generated along line AB (Fig. 5) across the Marwat-Khisor ranges. This transect line AB is oriented north-northwest in both the Marwat-Khisor ranges. From northwest to southeast along the section line the Marwat Anticline depicts high side anticlinal closure associated to a major ramp from basal detachment surface. The dip of its back limb shows the dip of the underlying ramp, whereas its forelimb is steeply southeast dipping and is related to the tip line of the fault where movement on the fault is apprehended below the forelimb of the anticline. Southeast of the Marwat Anticline lies the Abdul Khel Syncline that is believed to be a flat-syncline between two successive ramps. Along this transect the southern most part of the range front is occupied by the Nilawahana and Zaluch Group rocks that exhibit small scale, consistent fold sequence of synclines and anticlines, characterized by very short wavelengths of less than half kilometer. Along this transect, deformation is mostly concentrated in the frontal margin of the Khisor Range and makes the hanging wall strata of the Khisor Thrust. Khisor Thrust appears as south facing and emplaces Permian rocks of the Zaluch Group over the Siwalik Group strata in the southern frontier of the Khisor Range (Fig. 5). NNW of the frontal Khisor Thrust the Bilot thrust was marked along the cross section line AB. Along this fault the Permian rocks thrust over the Nagri Formation of the Siwalik group rocks.

North-northwest, the Bilot Thrust is south verging fore thrust and is believed to be a splay fault that emerged from the shallow level flat underneath the Khisor Range in order to accommodate shortening within the hanging wall sequence of the Khisor Thrust. The intervening folds between the thrust faults and Abdul Khel Syncline are open to moderately tight and asymmetrical, having short wavelengths.

Structural style depicted along transect clearly indicates that this part of the Marwat-Khisor ranges has developed as a south directed fold-thrust transferal system, detached from the regional basal decollement. The deformational geometries observed along the section line mostly in the form of ramp-flat trajectory.

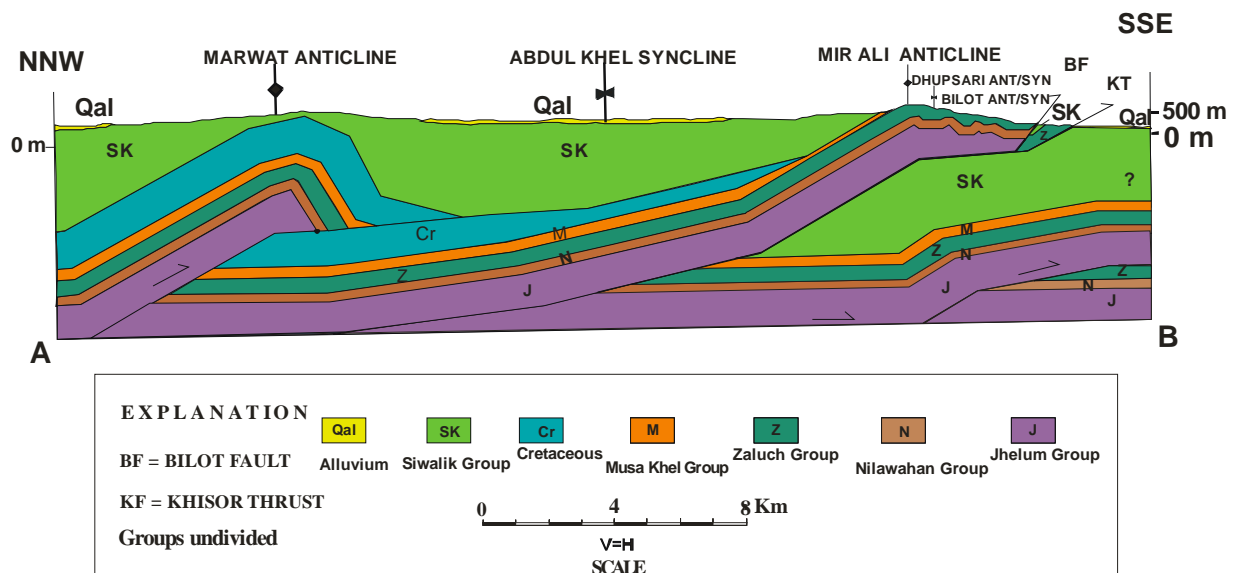


Fig. 5. Shows the structural transect along line AB of the figure 4.

5. Hydrocarbon potential of the north-western Punjab foreland

Compressional tectonics associated with the Indian and Asian plate collision has modified the Tertiary (Riaz, 1998). The first oil well was drilled at Kundal, northern Punjab in 1866. However, the first commercial oil discovery was made at Khaur, northern Punjab, in 1916 in the Potwar Plateau. Discovery of good quality gas at Sui, Balochistan in 1952 was another milestone in the exploration history of the country. To date several significant oil and gas provinces have been discovered in the southern and northwestern part of the country that shows the absolute potential of hydrocarbon in the foreland basins of Pakistan.

Jhelum Group and Cretaceous rocks are exposed towards the western terminus of the Khisor Range little bit beyond the study area. The Permian succession of the Khisor Range comprises a thick sequence of carbonates and mixed carbonate-siliciclastic rocks representing a wide variety of shallow marine to deltaic environments of deposition (Alam, 2008). The stratigraphic sequence constitutes an important petroleum system (Fig. 2), comprised of potential source rocks such as Sardhai Formation of Nilawahan Group of Permian age that dominantly consists of carbonaceous shale. The Sardhai Formation is 50 m thick towards northeast of Bilot that can serve as excellent source medium for

hydrocarbon generation. Beside the Sardhai Formation the lower part of the Amb Formation of the Zaluch Group also comprises thick beds of carbonaceous shale whereas its upper part consist of thick beds of sandstone, providing an equal opportunity as reservoir and source medium for the desired expectation. Seal rocks can be considered as Mianwali Formation that dominantly consists of shale overlain by thick overburden of the Tredian and Kingriali formations of Triassic age and Datta and Shinawari formations of Jurassic age that is in turn unconformably overlain by Siwalik Group rocks. Prerequisites for hydrocarbons generation and accumulation such as reservoir and source rocks are present throughout the mapped area along the sealing horizon to prevent the escape of oil and gas, in the form of thick shale beds. The structural system is thin-skinned related to convergent plate tectonic habitat as basement is not involved in the structural configuration of the area.

5.1. Source rocks

The potential source rocks observed in the area comprise of thick black shale of thickness upto 40 to 50 m in the sardhai Formation. Likely thick shale horizon observed in the lower part of the Amb Formation that can be considered as potential source medium. Thick bedded to massive, highly fossiliferous limestone beds in the Amb Formation, Wargal Limestone and Chhidru Formation of Permian age can be considered as less significant

source medium and play significant role as thick overburden upon the potential medium.

5.2. Reservoir rocks

Clastic and non-clastic reservoir rocks have been observed throughout the mapped area (Fig. 4). The Warchha sandstones and Tredian Formation offer valuable clues to the potential character of the fluid content. Among the fragmental clastic rocks sandstone, and siltstone are by far the most common reservoir rocks and these sediments are the basic constitution of the Tobra Formation of the Nilawahan Group that is a probable potential reservoir medium. The Warchha Sandstone is fragmental reservoir rock, where oil does occur commercially in rocks of

continental or non-marine origin. Non-marine sediments with porosity, permeability, adequate impermeable cover and favorable trap conditions should not be overlooked as potential encouraging reservoir rocks.

Out of the carbonates the Wargal Limestone and Chhidru Formation are the most significant reservoir rocks for petroleum accumulation. The Wargal Limestone dominantly consists of thick bedded to massive, partly sandy limestone and dolomite. These rocks are highly fractured and fossiliferous (Fig. 2) and are suitable as reservoir assets. Similarly the Chhidru Formation consists of medium to thick-bedded sandstone and fractured sandy limestone that provides a good reservoir perspective.



Plate 1 and 2 shows the blackish carbonaceous shale beds in the Sardhai Formation.

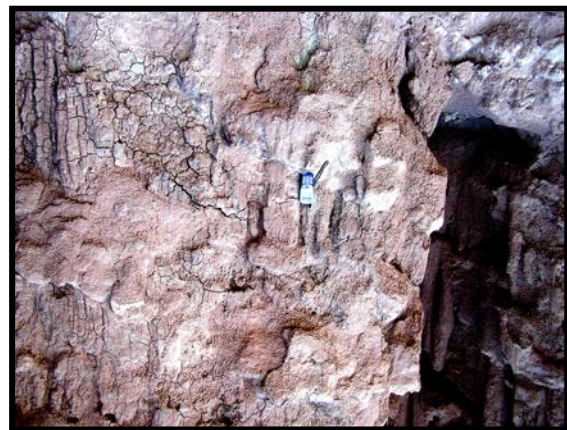


Plate 3 and 4 shows the Warchha Formation



Plate 5 and 6 shows the Mianwali Formation

5.3. 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 to act as effective cap rocks. The Mianwali Formation of the Triassic age is dominantly composed of shale that might be characterized as good cap rocks. Note the source rocks the Sardhai and Amb Formations underlying the cap rocks.

5.4. Hydrocarbon traps

Fold and thrust belts are significant areas for hydrocarbon exploration and exploitation. Out of the petroleum traps the fault-related anticlinal culminations are regarded as the most prolific structural traps. The Marwat-Khisor ranges define a south verging; thin-skinned deformed fold thrust belt where the structural style is characterized by decollement related thrusting associated with contemporaneous fault bend folding. Several major anticlinal folds of such nature have been mapped in the area that is ideal for entrapment of oil and gas. Based on these structural observations and similar stratigraphic lithologies and their array can be predicted for the non-outcropping rocks underneath the northwestern Punjab Foreland Basin that are still poorly explored parts of the foreland fold and thrust belt of north Pakistan. These lithological units may provide excellent stratigraphic traps for the retention of Hydrocarbon bodies.

6. Discussion

Geological mapping along with structural analysis and construction of the balanced structural transect indicates that the frontal foothills of the Khisor Range is underlain by a regional structural detachment horizon located at the base of the Permian Nilawahan Group. The emergent structural elements oriented in the north northeast in the Khisor Range and north-east in the Marwat Range indicate horizontal compressional stress being commenced and observed from northwest. This interpretation is consistent and supported by the presence of north-northeast trending structural geometries and south to southeast vergent compressional structures. Whereas the maximum strain along the foothills of the Khisor Range observed in the form of frontal thrust. This thrust is also southeast vergent and northwest dipping consistent to the interpretation of south directed tectonic transport regime. In consequence of this horizontal tectonic compression differential accommodation shortening observed along the structural transect AB (Fig. 5). Deformation intensity and crustal shortening observed high southeastward in the frontal margin of Khisor Range where the deepest and non-outcropping rocks of the Marwat Range protrude southeast against the Siwalik Group rocks in the form of a tectonic wedge. This differential and intense crustal shortening indicates the nonappearance of the cushion horizon below the foothills of the Khisor Range. Therefore the north-northwest tectonic shortening

across the Marwat-Khisor ranges may be comparable with some extent to that estimated for the western Salt Range, which is located within the identical compressional structural regime. The Khisor Thrust is therefore interpreted as a frontal thrust that separates the uplift and southeast vergence of the Khisor Range in the south from the relatively undeformed Punjab foreland in the northwest. Based on these structural observations and interpretations comparable stratigraphic framework can be envisaged for the undeformed and non-outcropping rocks underneath the northwestern Punjab Foreland Basin. The exposed lithological units across the Khisor Thrust in the Khisor Range are consistent with the interpretation of hydrocarbon generation and accumulation. The northwestern margin of the Punjab foreland deep along the Khisor Range in the vicinity of Bilot needs to be explored for hydrocarbon potential in the region.

7. Conclusions

Geological mapping of the study area indicates that this structural province is characterized by north-northeast-trending, asymmetric to overturned structural elements show southeast vergence. Structural geometry reveals that thin-skinned deformed fold-thrust assemblages control the entire structural system of the Marwat-Khisor ranges. Most of the macro-scale anticlines constitute the hanging wall thrust sheet of the emergent and non-emergent thrust faults in both the ranges. Analysis of the structural geometries of large-scale structural features and the construction of a balanced cross section indicate that the mapped area is underlain by a regional detachment surface located within the incompetent fraction of the Permian Nilawahan Group. This basal detachment surface is gently dipping northwards by 2° – 3° . Differential shortening observed in both ranges indicate the intensity of deformation towards the southeastern margin of the mapped area. Deformation occurred along the frontal structures postdates deposition of the Siwalik Group facies, representing Plio-Pleistocene southeastward propagation of the latest structural ramps in the form of ramp-flat geometry (Alam, 2008). Hydrocarbon potential toward the northwestern outskirts of the Punjab foreland is promising in light of the proximal appropriate lithological units exposed in the

Khisor Range. Prerequisites for the generation and accumulation of hydrocarbon are present in the form of source, reservoir and cap rocks which construct an anticipated petroleum system in the region.

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