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Evaluating Fold-Thrust Structures and Hydrocarbon Potential in the Western Marwat-Khisor Ranges and Sheikh Budin Hills, North Pakistan

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Abstract

The Marwat-Khisor Range, part of Pakistan's Himalayan frontal fold-thrust belt, showcases thin-skinned tectonics driven by north-south crustal shortening from the Indo-Asian collision. This work presents the structural style, geometries, and potential of the hydrocarbon in the western part of the Marwat Khisor and Sheikh Budin hills. The key structures include the south-divergent thrust sheets, asymmetric folds, and active faults (e.g., Khisor Frontal Thrust) juxtaposing Cambrian strata against younger sediments. Recent deformation near Dhupsari shapes the Punjab foredeep basin, accumulating synorogenic deposits having Permian-Triassic marine sequences that correlate with adjacent ranges. The notable units have shale with high organic content that is rich in carbon, as seen in the outcrop. These units are the Amb Formation and the Sardhai Formation of Permian Age. Based on outcrop observations, these units can act as source rock in the area. The Reservoir potential exists in porous Permian sandstones (e.g., Warchha Sandstone), sealed by Triassic evaporites. The Structural traps (anticlines, fault compartments) and thick carbonate overburden enhance hydrocarbon retention. This system mirrors productive analogs in the Potwar Basin, suggesting significant untapped potential. Recommended exploration includes 3D seismic surveys and geochemical analysis to target areas where mature source rocks align with structural complexity. The region is positioned as a promising frontier for hydrocarbon development, having source, reservoir, and cap rocks within Pakistan's fold-thrust belt.

Keywords: Himalayan Frontal Ranges; Structural Architecture; Punjab Foredeep; Hydrocarbon prospects.

1. Introduction

This study signifies the structural and stratigraphic appraisal of the frontal Himalayan ranges comprised of the Marwat-Khisor Ranges (MKR) and Sheikh Badin Hills (SBH), which constitute the southwestern segment of the Trans-Indus Ranges (TIR), north Pakistan (Stocklin, 1974; Stonely, 1974; Malnor and Tapponier, 1975; Alam et al., 2014; Rehman et al., 2016; Rehman et al., 2024). The study area encompasses 855 sq km, shown in squares in (Fig. 1). Pakistan contains the northwestern edge of the Indian lithospheric plate. Since the Eocene, these tectonic elements of the Indian Plate have been contractile and thin-skinned and occur along the northern and northwestern margins of the Indian Plate due to the Subduction of the Indian Plate underneath the Eurasian Plate (Blisniuk and Sonder, 1998; Rehman et al., 2017, 2024). As thick sheets of sedimentary rock were thrust across the Indian Craton, the IP continued to subduct, resulting in the Himalayas and a sequence of foreland fold-and-thrust belts

(Achache and Patriat, 1984; Kemal, 1991; Beck et al., 1995). The Salt and TIR of north Pakistan are considered to be the itinerant borders of the Kohat and Potwar plateaus. These frontal flanks of the Himalayan Orogeny are generally distinguished by décollement-related structural assemblages. These structural elements are indeed responsible for the accommodation of shortening within these orogenic belts (Baker et al., 1998; Burbank et al., 1989; Ahmad, 2003, 2008; Rehman et al., 2022a, b). It seems that the thrusting between the Salt ranges is dominated by the north-dipping normal faults that involve the basement and which localize thrusting (Pennock et al. 1989). A similar style of structure has been construed in the frontal Himalayan ranges and most likely in the present study area and the Kohat plateau (Parwez, 1992).

This study aims to comprehensively evaluate the geometry, kinematics, and evolution of fold thrust structures in the Western Marwat Khisor Ranges and Sheikh Budin Hills through integrated geological mapping, structural modelling, and stratigraphic analysis to constrain subsurface architecture and deformation history. To assess the hydrocarbon potential of the area by analyzing structural traps, reservoir–seal configurations, source rock characteristics, and petroleum system elements, thereby identifying viable exploration leads and reducing geological risk.

This study also deals with the frontal peripheral belts of the Himalayas, the MKR and SBH, which make the central part of the TIR (Fig. 1). The Bannu Basin and the Indus River encircle these ranges on their northern and southern borders, respectively. The Bhittani Range marks the northwest border, while the Punjab forelands define the southern border (Fig. 1) (Shah, 2009). The prominent structural features of the area are generally north-to-northeast trending, asymmetric, plunging, and frequently related to the ramp-flat trajectory mechanism. An important southward-dipping leading-edge thrust has been identified throughout the frontal boundaries of the researched area. This thrust has caused layers from the Cambrian to Permian periods to be pushed southwards against the Punjab flatlands. The folding and faulting patterns observed in the locality suggest the existence of a deep-seated basal decollement underlying the region, which has been a principal agent in shaping its structural form. This system of detachment-driven thrust faulting has facilitated differing levels of tectonic adjustment in the southeastern fringe of the Khisor Range (Alam, 2008). The Permian layers of this area are characterized by a substantial sequence of mixed carbonates and siliciclastic-carbonate strata indicative of a range from shallow marine to deltaic depositional settings. Together with the associated structural features, these rock sequences indicate a noteworthy petroleum system with the requisite source, reservoir, and cap rocks that are essential for the genesis and entrapment of oil and gas (Alam, 2008).

2. Stratigraphic Framework

Geologic mapping in the area led to a good understanding of the stratigraphy that includes Cambrian to Middle Jurassic platform sequences unconformably overlain by Plio-Pleistocene fluvial molasse sediments of Siwalik Group rocks (Fig. 2). The platform sequences become thicker towards the western portion of the Khisor Range and west to east in the SBH (Johnson et al., 1986; Khan et al., 1988). Towards the western terminus of the Khisor Range, northwest of Saiyiduwali, a significant stratigraphic profile of the Paleozoic and Mesozoic rocks is mapped.

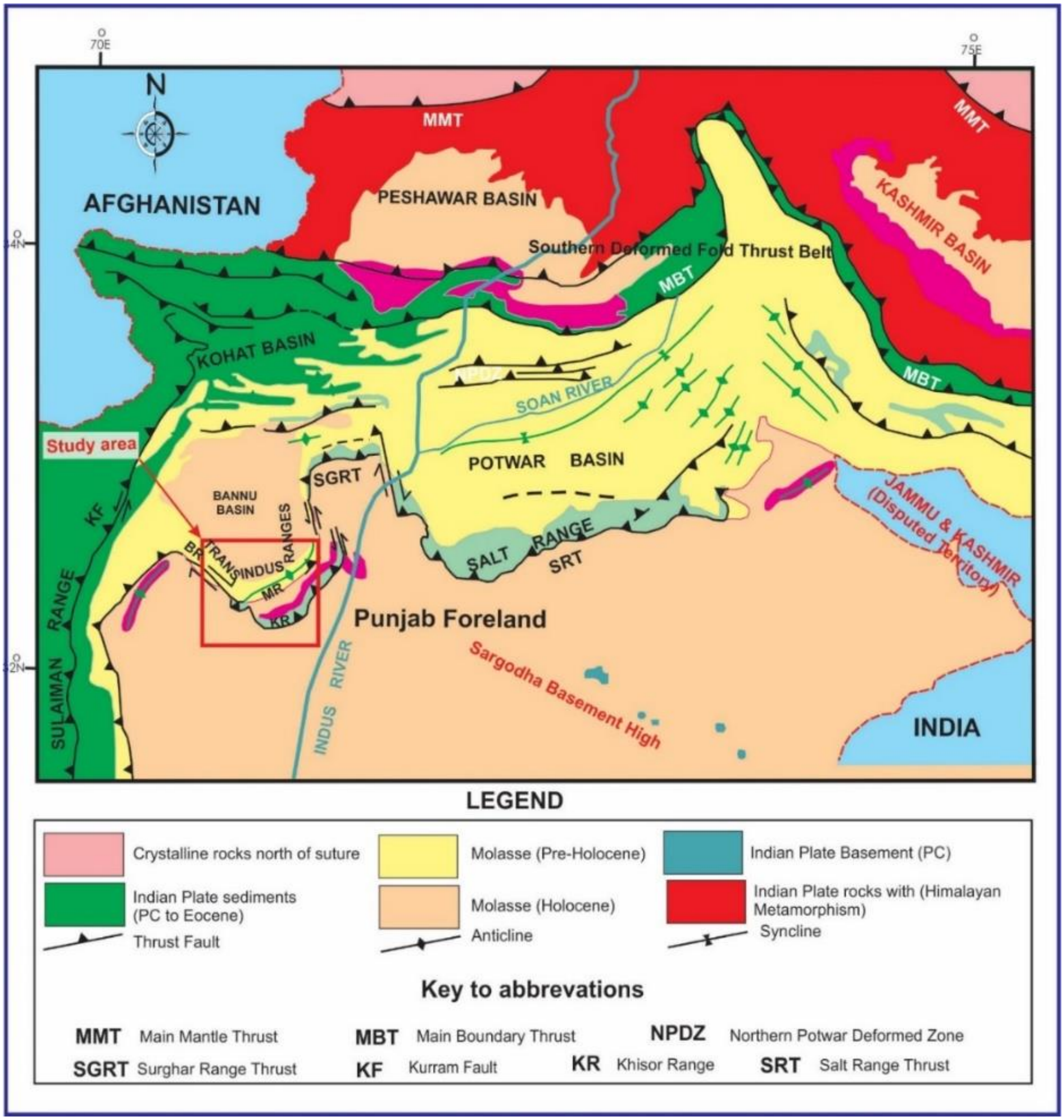

Fig. 1. Geological map of the TIR, insets show the location of the study area (Rehman et al., 2022a).

The stratigraphic successions were studied along the Saiyiduwali, Paniala, and Dhupsari sections in the Khisor Range, as shown in Fig. 2. The oldest rocks are in the form of the Khewra Formation, Kussak Formation, Jutana Formation, and Khisor Formation, which are located in the Saiyiduwali section (Figs. 2-3). The Khewra Formation sandstone is purplish-brown in color, thickly bedded with coarse clay bands, and the upper section of the sandstone is filled by concretionary layers. Above this is the Kussak and Jutana Formation, which is sandy, dolomitic, and glauconitic-rich. The Khisor Formation, which is composed primarily of gypsiferous marl interspersed with shale, gypsum, and dolomitic strata, lies on top of the grey, massive Jutana Formation. A thick succession of Permian rocks lies on top of the Cambrian strata made up of the Nilawahan and Zaluch Groups (Fig. 2). The Tobra Formation, a tillitic deposit, comprises the base of the Nilawahan Group, while the Warchha Sandstone, which lies above it, is made up of a clastic unit in the form of red-colored shale and sandstone. The Sardhai Formation comprises carbonaceous, silty shale with tertiary, intermittent layers of sandstone. The formation is composed of dense laminated beds of bluish-black to pitch-black carbonaceous shale. The Zaluch Group consists of a mixture of siliciclastic and carbonate rocks found within the lower Amb Formation and the upper Chhidru Formation. In the transitional zone between the Amb and Chhidru formations, there exists a prominent carbonate unit, the Wargal Limestone, which forms rugged cliffs. This geological formation contains various fossils such as brachiopods, crinoids, bryozoans, and corals. There is a well-exposed contact between the Permian Chhidru Formation and the Triassic Mianwali Formation in the area near Saiyiduwali, which is of the Musa Khel Group (Alam, 2008). Above the Mianwali Formation lies the Tredian Formation, characterized by a silty lower section and an upper portion comprised of sandstone with distinct bedding. Beyond this, we encounter the Kingriali Formation, consisting of dolomite, dolomitic limestone, marl, and shale. Notably, an unconformity separates the Kingriali Formation from the overlying rocks of the Siwalik Group in the Khisor Range. To the west, the Musa Khel Group is extensively exposed, extending north of Saiyaduwali. Here, Jurassic rocks are found in the western region, followed by Triassic rocks in the central area, and Permian rocks in the eastern region. These rocks are unconformably overlaid by the Siwalik group rocks (Fig. 2).

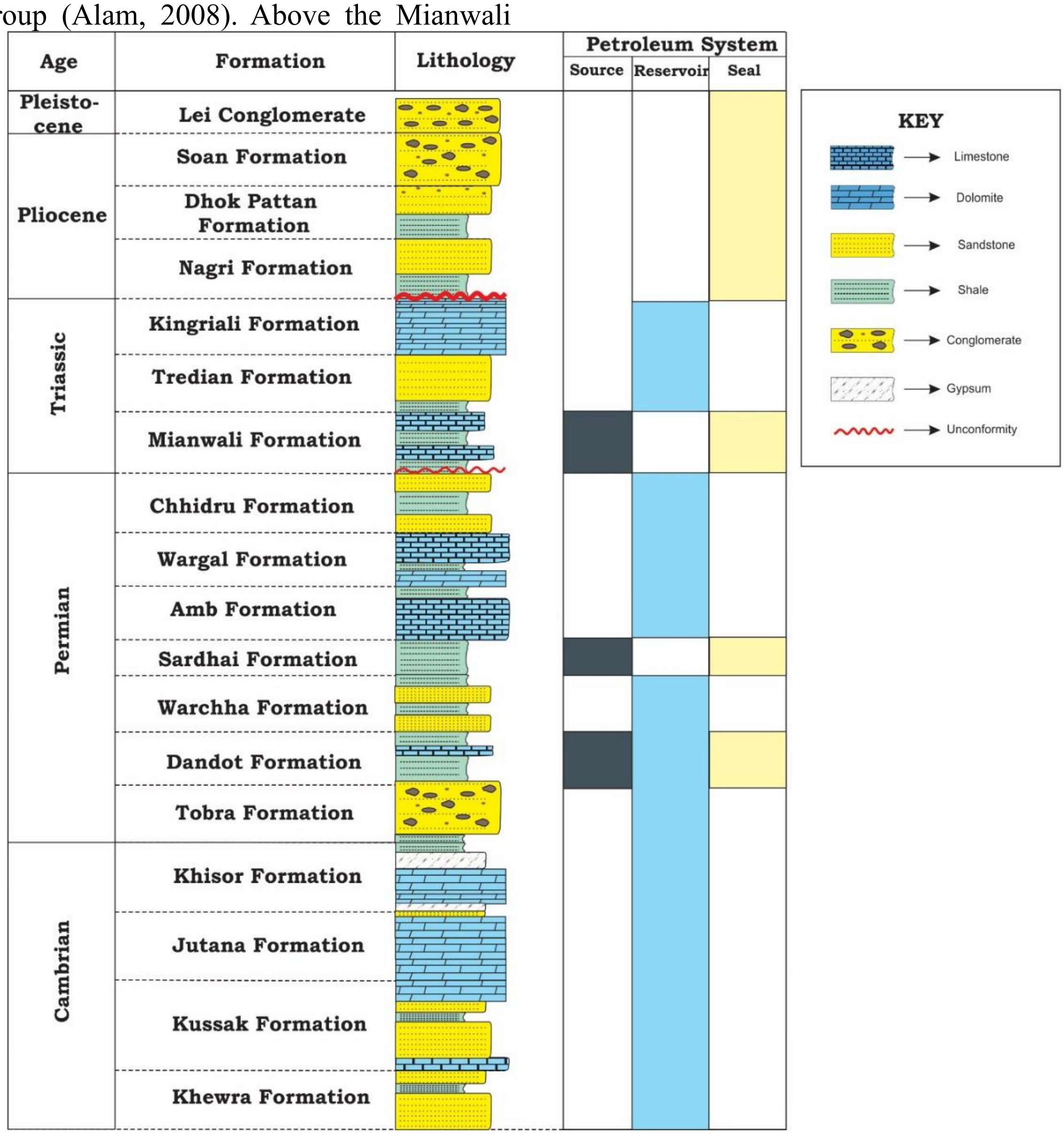

Fig. 2. Stratigraphic profile and anticipated petroleum system of the study area (after Alam, 2008).

3. Structural Framework

This study deals with the structural synthesis of the study area, which is located in the southwestern TIR. These ranges are a fundamental geological section of a regional fold-and-thrust belt that describes the geology of the outer margins of the Himalayas orogenic zone (Fig. 1). The structural style and tectonic uplift of this area are primarily ascribed to the youngest deformation mechanism of the frontal sub-Himalayan orogeny. To elucidate the hydrocarbon potential of the region, in-depth structural studies have been conducted to better comprehend the structural framework. The northern extension of the studied strata towards the Kohat plateau contains proven hydrocarbon reservoirs and has yielded significant commercial discoveries to date, whereas the recently studied structural province has only been marginally explored for the intended purpose. The present structural interpretation of the Khisor Range reveals that this range is comprised from west to east of elevated and prominent structures, namely the Paniala, Saiyiduwali, and Dhupsari anticlines (Kazmi and Rana, 1982; Alam, 2008).

The northwestern boundary of the Khisor Range is marked by the SBH of the Marwat Range toward the west (Fig. 1). The Khisor Range is divisible into four wide-ranging and discrete anticlines, which display unlike setting to the range. The SBH consists of a singular, broad Chunda Anticline that extends westward to the westernmost point of the Marwat Range. Current geo-structural mapping in the region reveals that these anticlines are characterized by structural variation along trend, but are bounded to the south by a principal frontal thrust fault (Kazmi and Rana, 1982).

4. Methodology

The current field studies comprised geo-structural mapping and litho-stratigraphic studies being conducted in the frontal Himalayan ranges, that is, the Marwat Khisor Range (MKR) and Sheikh Budin Hills (SBH). In this study, a detailed geological map was prepared along with balanced structural transects right-angle-oblique to the outcropping structural trend of the area at the scale of 1: 50,000 (Fig. 3). The Google Earth and CorelDRAW software were used for the graphic work if the map preparation to the completion. Identification of structural styles, their kinematics, inferred geometries, and possible depth to the basal detachment beneath the Paniala, Saiyiduwali, and Dhupsari anticlines in the Khisor Range, and the Chunda Anticline in the SBH. Field traverses have been made across the axes of major structures exposed in the area to collect structural and stratigraphic outcrop data. Studied the subsistence character and upset of faults that were mapped in the area and their impact on the structural evolution of the Paniala, Saiyiduwali, Dhupsari, and Chunda anticlines in the area. The balanced structural transects across the structural trend of the study area are prepared to describe their structural mechanism along with their subsurface structural geometry at the depth of potential reservoir horizons.

5. Results

5.1 Structural Synthesis of Khisor Range

The eminent physiographic features that have been mapped in the Khisor Range from west to east are described as follows:

5.1.1 Paniala Anticline

It is an important structural aspect of the western plunging terminus of the Khisor Range and constructs the hanging ramp sheet of the Khisor Frontal Thrust. This structural element has been studied in depth as a vital rock configuration from the perspective of petroleum detection. For the corroboration of its geometric pattern, the structure has been traversed at various places across and along its strike profile. Attitude data acquired along with both limbs designate that its back limb is rather steeper than its forelimb. Its fold axis is northwest plunging and trends in a sub-latitudinal fashion (Fig. 3). This anticline is a comparatively short amplitude feature as compared to the Saiyiduwali and Chunda Anticline. Based on structural attitude data, it is interpreted as being slightly asymmetries towards the north. Along the west-dipping extremity of this anticline, Jurassic rocks are thrust southwestward over Siwalik Group rocks of the Nagri Formation via a lateral ramp. The structural information gathered along the back/northern flank of the anticline ranges from 55° to 70°. The angular unconformity between the Shinawari and Nagri formations is in the range of 3° to 5°. The dip values persistently increase further north of this hiatus and become as gentle as 10°~15°. The southern/forelimb of this anticline slopes gradually to the south and is characterized by a pair of small-scale east-west trending synclines and anticlines with short amplitudes. The syncline is parallel to the Paniala Anticline and plunges northwestward. This structural element is composed primarily of the Triassic Tredian and Kingriali Formations. A small-scale anticline is mapped towards the southwestern end of the western Khisor Range, containing the Mianwali Formation in its core and the Kingriali Formation in its southwestern limb, both of which abruptly dip to the southwest to form the hanging wall sequence of the Khisor Frontal Thrust. The Paniala Anticline reveals the Permian Zaluch Group rocks overlain by the Triassic and followed by the Jurassic rocks in an unconformable turn. The Jurassic rocks are unconformably overlain by the Siwalik Nagri Formation along the rear limb and western lateral extremity of the Paniala Anticline.

5.1.2 Saiyiduwali Anticline

This particular geological feature holds significant importance as the foremost anticline identified along the southern foothills of the western Khisor Range. It is situated adjacent to the Paniala Anticline, which stretches from west to east along the same range. The lateral extent of this anticline's mapping can be traced for more than 5 kilometers. The northern or back limb of the Saiyiduwali Anticline exhibits the most pronounced structural relief, particularly at the point where the Chhidru Formation sits atop the range. The distinctive feature of the Saiyiduwali Anticline lies in its back limb, which comprises Cambrian to Permian rock strata. However, its anterior portions and forelimb have undergone erosion, except for the eastern and western sections, where both limbs of the anticline remain relatively unaltered (Fig. 3). The deformation of this anticline's back limb has resulted in conspicuous folded structures within the Triassic Musa Khel Group rocks. Within the central area of the Saiyiduwali Anticline, one will encounter Cambrian strata, specifically the Khewra, Khussak, Jutana, and Khisor Formations of the Jhelum Group. Overlying this sequence are the Tobra Formation, Warchha Sandstone, and Sardhai Formation of the Nilawahan Group. Moving further upwards, the rocks belonging to the Zaluch Group consist of the Amb Formation, Wargal Limestone, and Chhidru Formation. These rocks are overlain by the Triassic strata of the Musa Khel Group, encompassing the Mianwali and Tredian Formations, as well as the Kingriali Dolomite unconformably. Subsequently, these Triassic strata are unconformably covered by the Nagri Formation of the Siwalik Group.

5.1.3 Dhupsari Anticline

This anticline is the eastern continuation of the Saiyiduwali Anticline along the range front, located about 5 kilometers northeast of Dhupsari towards the eastern Khisor Range. This anticline's structural tendency is north-northeast, similar to the Saiyiduwali Anticline. The length of the map or the trend of the axis takes over 10 km. The Permian Nilawahan Group strata are present in the core of the Dhupsari Anticline (Fig. 4).

5.1.4 Fault Constitution

The fault surfaces are inadequately exhumed in the earth as compared to fold structures in the area. Overall, three different fault surfaces have been recognized in the area. One regional-scale fault has been observed and mapped all along the southern margins of the Khisor Range as a fore thrust. The second fault has been observed in the form of a lateral ramp toward the western plunging end of the Khisor Range sited southwest of Paniala Village. The third fault surface has been mapped toward the frontal boundaries of the SBH as the Sheikh Badin fore thrust.

5.1.5 Khisor Thrust

The Khisor forethrust is located toward the outside edge of the Khisor Range. This is the youngest, one of the eminent and key front-bounded tectonic slices in the Khisor Range. It is a continuation of the youngest tectonic event in the Sub-Himalayan orogenic belts. It is the extension of an active Himalayan deformational episode that skirts the entire Salt and TIR of north Pakistan (Fig. 3). The Khisor forethrust is observed to be a blind or partially emergent thrust slice in the western Khisor Range except at one locality near Paniala village, where the Datta Formation is thrust westward in a hanging wall against the Nagri Formation in a footwall as a lateral ramp (Fig. 5). Considering its established orientation, the Khisor Thrust is responsible for the clear and visible geological outcrops in the east. Its predominant trend is deduced to be east-west, and it undergoes a transition towards the north-northwest in the vicinity of Paniala. In this region, the Jurassic rocks of the Datta Formation are inclined laterally, effectively overlying the Siwalik Group belonging to the Nagri Formation (Figs. 3 and 5).

5.1.6 Paniala Fault

The Paniala fault has been mapped and located southwest of the Paniala Village, trending N05ºW/70ºNE, where the Datta Formation of Jurassic laterally ramped over the Nagri Formation. The second judgment concerning the lateral ramp is that the Siwaliks lying along the shoulder of the Datta Formation had been displaced along the Strike-Slip fault from the southern limb of the western Khisor Range and juxtaposed laterally to the Datta Formation along the right lateral strike-slip fault between Paniala and SBH (Fig. 3 & 5).

5.1.7 Dhupsari Thrust

Within the range, the Dhupsari Thrust fault has been located 1 km to the southwest of the Dhupsari Village and to the northwest of the Khisor Thrust. With little map extension, it impacts the north-northeast. The Nagri Formation in the footwall of this fault is shoved over by the Permian Amb Formation in the hanging wall layers. According to the attitude information, this fault might be an imbricate splay slice that is consistent with the frontal Khisor Thrust sheet. It seems southeast veering (Malnor and Tapponier, 1975) (Fig. 3).

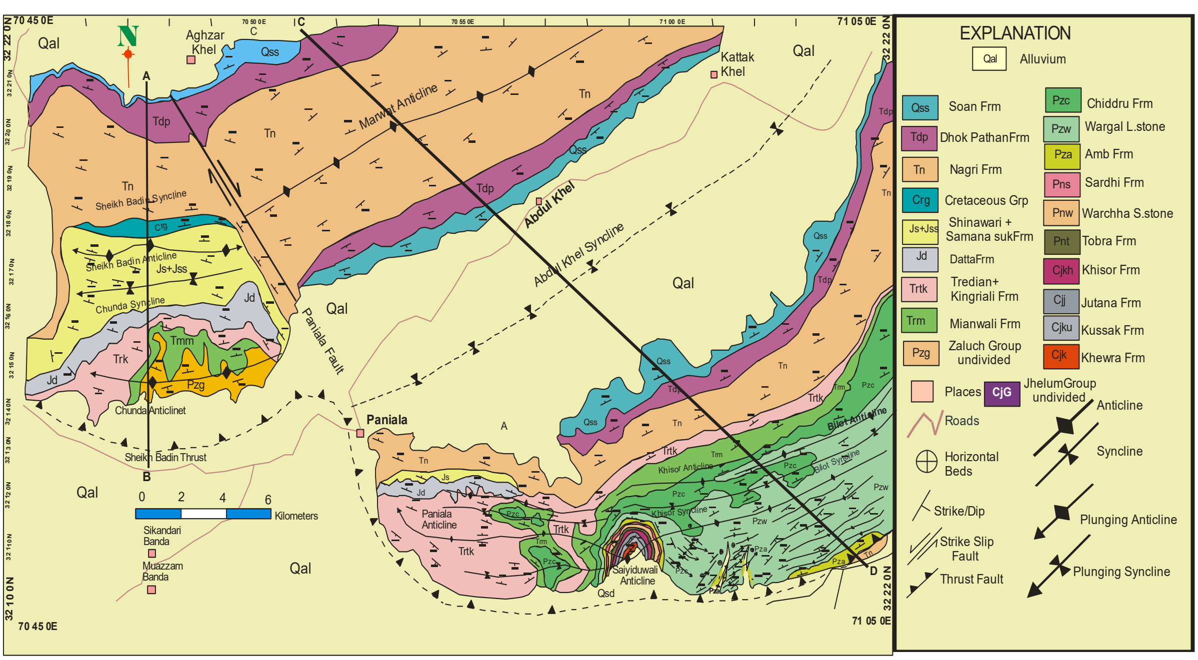

Fig. 3. Geological map of the Marwat-Khisor Range (MKR), Sheikh Budin Hills (SBH), and Trans Indus Ranges (TIR), North Pakistan (This study).

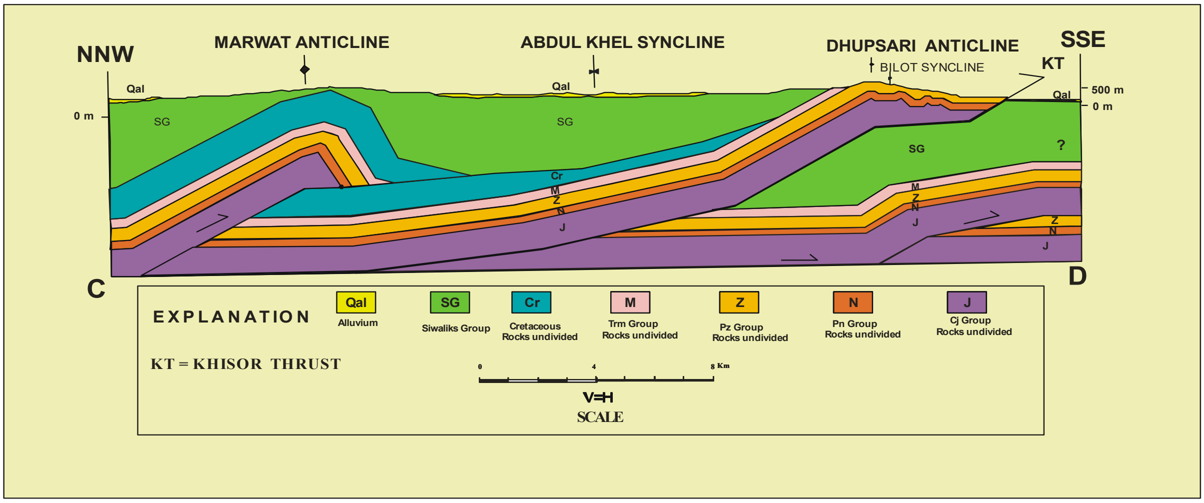

Fig. 4. Structural transect along line CD of the geological map of Figure 3. ("J" represents the Jehlum group, "N" represents the Nilawahan Group, "Z" represents the Zaluch Group, "M" represents the Musakhel Group, "Cr" represents the Cretaceous rocks, "SG" represents the Siwalik group rocks.

Fig. 5. South-looking view of the outcrop exposure of the Paniala Lateral Ramp, where the Datta Formation of the Jurassic is laterally thrust over the Nagri Formation (Person for scale, 170 cm).

5.2 Structural Synthesis of Shekih Budiun Hills (SBH)

The structural elements that have been mapped in the SBH of the Marwat Range are described in detail as follows;

5.2.1 Sheikh Badin Anticline

This anticline is a key structural element of the northern expanse of the SBH (Fig. 6). It is a northwester-southeast type of structural oriented feature that is defined to the northwest by the Pezu Anticline and to the east by the Marwat Anticline. This structure is laterally extended for more than 8 km. Jurassic rocks of the Samana Suk Formation are entrapped in the core of this anticline. Siwalik Group rocks are unevenly overlain by Cretaceous strata, including those from the Chichali and Lumshiwal formations, which are exposed towards the limbs. The right lateral Paniala Fault separates the anticline's eastern and northern ends, respectively. This feature has a northern limb that dips gently (22° to 25°) towards the north and a southern limb that dips moderately to steeply (35° to 65°) towards the south, slightly overturning the anticline.

5.2.2 Chunda Anticline

This is the range front anticline, located toward the south of the Chunda Syncline. Permian Zaluch Group rocks are exposed in its core (Fig. 6). It is a doubly plunging anticline and characterized by an east-west trending fold axis. It has a broad northern limb exposing Permian to Jurassic sequence, whereas its southern limb has been battered and exposed exclusively of Permian Zaluch Group rocks.

5.2.3 Sheikh Badin Thrust

The Sheikh Badin forethrust is the youngest and analogous structure to the Khisor Range frontal thrust and represents the major frontal deformational phase in the SBH (Fig. 3). This frontal thrust originated as a blind or partially emergent thrust toward the anterior perimeter of the southern SBH. Based on its inferred trend, the Sheikh Badin Thrust is to be an east-west-oriented forethrust that switches to north-northwest toward the western terminus of the SBH (Fig. 3).

5.2.4 Structural Construal

A couple of broadly gapped structural cross-sections have been drawn in the MKR and SBH. The cross-sectional lines AB and CD of Fig. 3 were constructed for a better understanding of the surface behavior of various formations and also to understand the kinematics and structural relationship among various folds and fault structures. It would be useful to recognize structural and stratigraphic variations across the trend in the outcropping rocks. The salient structural features are shown on the cross-sections and are discussed in detail below.

Section CD

This structural transect alongside line CD of Fig. 3 reveals the intersection of both the MKR. This section is northwest-southeast oriented in the MKR. Along the section line from north to south, the Marwat Anticline represents an uplifted anticlinal feature associated with a thrust ramp generated and detached from basal décollement. The back limb inclination of the structure is associated with the underlying ramp gradient; on the other hand, its forelimb is inclined steeply towards the south and is interrelated to the tip line of the fault. Under the forelimb of this anticline, the slide movement along the ramp is observed. The Abdul Khel Syncline, which is supposed to be a flat syncline between the two succeeding ramping anticlines, is located south of the Marwat Anticline.

The structural disturbance is regularly found along this transect along the Khisor Range's front edges. The hanging wall ramp of the Khisor Thrust is made up of these deformed strata. On the southern side of the Khisor Range, this thrust is south-facing and emplaces the Permian rocks of the Zaluch Group over the Siwalik Group (Fig. 4). A small-scale thrust fault has been identified along the cross-sectional line CD, north of the frontal Khisor Thrust. The Permian rocks of the Amb Formation are juxtaposed against the Nagri Formation in this thrust fault's hanging wall, which is known as the Dhupsari Thrust. To accommodate shortening within the hanging wall sequence of the Khisor Thrust Sheet, the Dhupsari Thrust, a south-facing fore-thrust, is thought to have formed from the shallow level flat beneath the Khisor Range. The Abdul Khel Syncline and the two succeeding thrust faults are separated by folds that are open to moderately tight, asymmetrical, and have short wavelengths.

A south-directed fold-thrust system disconnected from the local basal décollement has developed in this area of the MKR, as shown by the structural style presented along the transect. The section line's mapped faults primarily follow ramp-flat trajectories.

Section AB

The structural transect along line AB is north-south oriented, nearly at right angles to the structural trend of the exposed strata mapped in the Chunda section (Fig. 6). The Chunda Anticline is a south-facing, rather asymmetric anticline that shows its highest structural uplift in this section, exposing a Permian to Jurassic sequence in the core. The southern/forelimb of the anticline dips steeply toward the south and defines the hanging wall strata of the Sheikh Badin Frontal Thrust, whereas the northern/back limb of the anticline dips moderately to steeply. From the patterns of the many structures produced in the SBH, it can be deduced that the cross-section line is roughly aligned to the north-south-directed tectonic transport track. The southern limb of this anticline is demarcated by an open Chunda Syncline that evolved in the Jurassic rocks of the Sa-mana Suk Formation. The contiguous Sheikh Badin Anticline is a key structural element of the northern flank of the SBH (Fig. 3). This anticline is bounded to the east by the Marwat Anticline. At about 8.0 kilometers, its lateral extension after the axial trend is seen. Rocks from the Jurassic to the Cretaceous are present in the anticline's core. Overall, the cross-sectional structural deformation is similar to that seen throughout the previous cross-section.

5.3 Hydrocarbon potential

The Tertiary sequence has been affected by compressional tectonics associated with the collision of the Indian and Asian plates. Recent exploration of many significant hydrocarbon geostructural provinces in Pakistan's south and northwest demonstrates the country's foreland basins' unexplored petroleum potential (Kadri, 1995; Riaz, 1998). The Khisor Range has thick sequences of carbonates and mixed carbonate-siliciclastic rocks from the Cambrian, Permian, and Cretaceous periods that reflect a wide range of shallow marine to deltaic depositional settings (Alam, 2008). An important petroleum system is developed by the stratigraphic sequence (Fig. 2). The sealing horizon, which takes the shape of thick shale beds, as well as reservoir and source rocks, are present across the mapped region as prerequisites for the formation and accumulation of hydrocarbons.

Due to the absence of a basement in the structural arrangement of the area, the structural style is thin-skinned and related to the habitat of convergent plate tectonics. The mapped structural geometries are also engendering appropriate entrapments for the accumulation and retention of hydrocarbons.

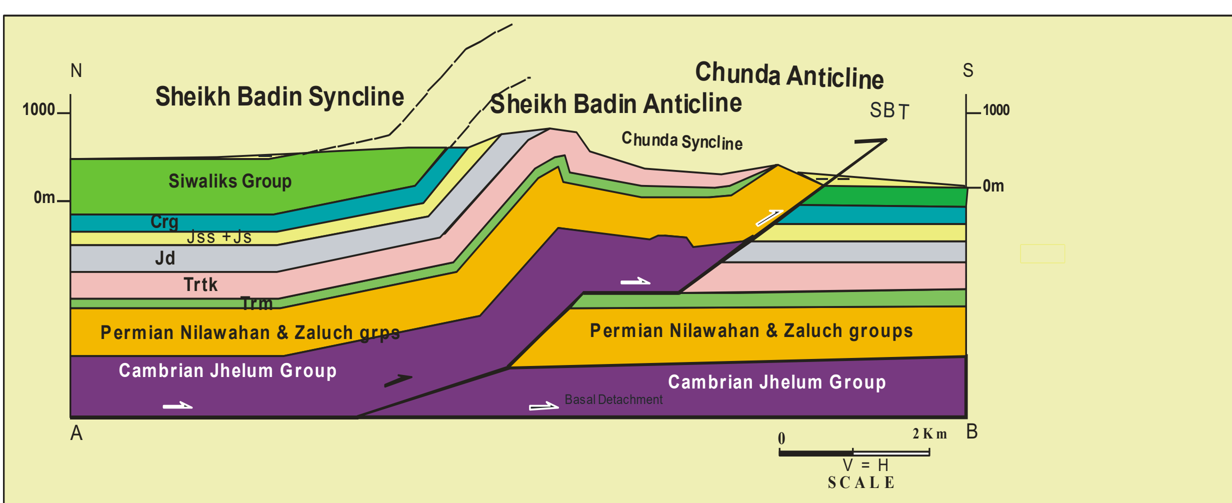

Fig. 6. Structural cross-section along line AB of Figure 3 (The codes in cross-section are as follows: "Trm" is Miawali Formation; "Trtk" is Tredian and Miawali Formation; Jd is Datta Formation; "Jss" is Samana Suk Formation, and Js is Shinawari Formation; Crg is for Cretaceous rocks).

5.3.1 Source rocks

The Sardhai Formation's dense black shale, measuring up to 40 to 50 m in thickness, makes up the possible source rocks seen in the region (Fig. 7). There is probably a thick shale horizon in the Amb Formation's lower section that serves as a comparable possible source medium. In the Amb Formation, Wargal Limestone, and Chhidru Formation of the Permian, thick-bedded to massive, extremely fossiliferous limestone beds can be viewed as a less significant source medium and also play a key function as thick overburden onto the prospective medium. Early Permian Tobra, Dandot, Warchha, and Sardhai shales yield TOC values of 0.55–1.05% and thermally immature to mature Type III kerogen suitable for gas-prone hydrocarbons (Ahmad et al., 2019). Further east in the Raniganj sub-basin (Damodar Valley, India; Gondwana-Tethys transition), Permian Barakar, Barren Measure, and Raniganj carbonaceous shales (TOC up to several %) derive from felsic sources in a continental rift, with mixed terrestrial-marine organic matter supporting oil/gas generation (Saqib, 2025).

5.3.2 Reservoir rocks

The mapped area contains both clastic and nonclastic reservoir rocks (Fig. 3). The Warchha Sandstone and Tredian Formation offer insightful hints about the possible composition of the fluid. The Tobra Formation of the Nilawahan Group, which is a likely prospective reservoir medium in the area, is made up primarily of these sediments and is by far the most common reservoir rock among the fragmental clastic rocks. The Warchha Sandstone is a reservoir rock with fragments, and it is one of the few rocks with continental or non-marine origins where oil is economically present. Non-marine sediments like the Datta Formation should not be discounted as possible attractive reservoir rocks because of their porosity, permeability, appropriate impermeable cover, and ideal trap conditions (Fig. 7).

The Wargal Limestone and Chhidru Formation are the most significant reservoir rocks for petroleum accumulation among the carbonates. Dolomite and limestone in deep, bedded to enormous, occasionally sand-like formations make up the Wargal Limestone. These rocks are ideal as reservoir assets because they are heavily fragmented and fossiliferous (Fig. 2). Like the Chhidru Formation, which also has a good reservoir, it contains of medium and thick-bedded sandstone and fractured sandy limestone.

5.3.3 Cap rocks

An impermeable medium is crucial for stopping leakage, seepage, and migration of hydrocarbons. Shale and evaporites, which have fine-grained compositions, frequently function well as cap rocks. Shale that may be said to be a fine sealing medium makes up the majority of the Triassic Mianwali Formation. Remarkably, the cap rocks are underneath the source rocks, the Sardhai and Amb Formations.

5.4 Stratigraphic Traps

Fold and thrust belts around the globe are regarded as significant hydrocarbon exploration and extraction regions. The anticlinal culminations that are associated with the fault are considered to be the most prolific structural petroleum traps. The MKR characterizes a south-verging, thin-skinned, deformed fold-thrust belt that is characterized by décollement-involved ramped faulting and forced folding that occurs contemporaneously. Several significant anticlinal folds of this nature have been mapped in a location that is ideal for hydrocarbon sequestration. On the basis of these structural observations, analogous stratigraphic lithologies and their distribution can be predicted for the rocks beneath the northwest Punjab Foreland Basin that are not exposed. This portion of the foreland and thrust belt in northern Pakistan must be investigated. These stratigraphic horizons could serve as important stratigraphic traps for the retention of hydrocarbon bodies.

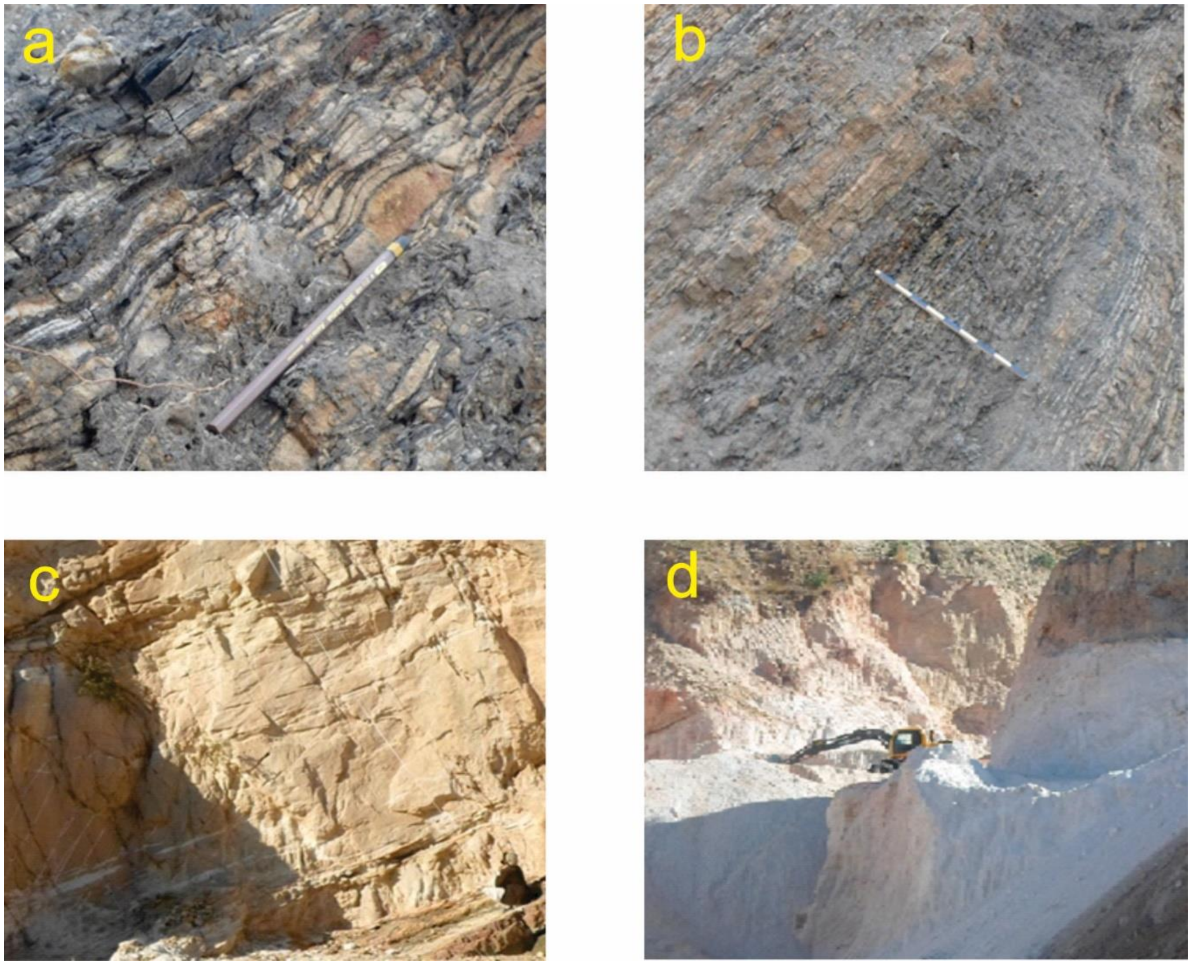

Fig. 7. a & b) Dark gray to blackish to dark black thin-bedded source rocks of the Sardhai Formation; c & d) Friable to weakly cemented and porous silica sand of the Datta Formation, a reservoir horizon.

5.5 Structural traps

The combination of stratigraphic and structural framework is likely producing a significant petroleum system in the region (Fig. 2). Current geological investigations in the study area reveal the potential existence of structural traps in the western Khisor Range. On the frontal extremities of the Chunda and Dhupsari Anticline, comparable prospects are anticipated. In addition to anticlinal structures, the Abdul Khel Syncline near Abdul Khel village is structurally bounded by a couple of larger fault-bend folds, i.e., the Marwat Anticline in the Marwat Range and Khisor Anticlinorium in the Khisor Range, which could be explored by penetrating the Jurassic Datta Formation, which contains sandstone with promising reservoir potential. In the western Khisor Range, rocks ranging in age from Cambrian to Jurassic are well exposed, rendering a petroleum system anticipated on both the northern and southern flanks of the area due to the existence of structural trapping tendency.

6. Discussion

The Khisor Range and Sheikh Badin Hills (SBH) evolved primarily through contractile deformation associated with Himalayan frontal tectonics, characterized by east-west trending fold-thrust systems (Hemphill and Kidwai, 1973). Key structures include five anticlinal culminations, Paniala, Saiyuduwali, and Dhupsari in the Khisor Range, and Sheikh Badin and Chunda in the SBH—all controlled by thrust-related folding. These anticlines formed during emplacement of the Khisor and Sheikh Badin Thrusts, driven by displacement along a décollement surface at the base of Cambrian Jhelum Group strata, particularly within the Khewra Sandstone. Folding and thrusting progressed southward, generating fault-bend anticlines with localized structural complexities, such as the north-vergent Paniala Anticline influenced by a blind rearward thrust. Structural geometries reveal detachment surfaces beneath Cambrian units, facilitating thin-skinned deformation. Incompetent shale layers (Amb and Sardhai Formations) acted as glide horizons, enabling south-directed tectonic transport. Thrust sheets exposed Permian Wargal Limestone but remain rooted in deeper Cambrian strata. Deformation timing postdates Pliocene-Pleistocene Dhok Pathan Formation deposition, constraining activity to pre-Siwalik phases.

Critical elements of a petroleum system, organic-rich source rocks (Permian shales), reservoir units (Cambrian-Permian sandstones/carbonates), structural traps (anticlines), and seals (Triassic evaporites/Cretaceous carbonates)—are present. The alignment of deformed stratigraphic units across thrust sheets underscores hydrocarbon potential, particularly in the northwestern Himalayan foreland basin's frontal margins near Paniala and SBH. Detailed subsurface investigation is recommended to evaluate trap integrity and migration pathways in this prospective hydrocarbon province.

The Khisor Range-Sheikh Badin structural style exemplifies thin-skinned fold-thrust belts typical of Himalayan frontal deformation, comparable to the adjacent Salt Range and Surghar Range, where south-vergent anticlines develop above Permian basal detachments at 3-4 km depth (Ahmad et al., 2003). Worldwide analogs include the Sub-Andean fold-thrust belt of Bolivia and Peru, where Cambrian-Ordovician sandstones form basal detachments overlain by Paleozoic carbonates and shales, generating fault-bend folds with proven hydrocarbon traps (e.g., gas fields in the San Alberto trend; Lacombe et al., 2019). Similarly, the Zagros Simply Folded Belt (Iran) features Permian-Triassic décollements enabling thin-skinned thrusting of Mesozoic carbonates over Tertiary foreland, with shale horizons (e.g., Dashtak evaporites) serving as principal glide planes (McQuarrie, 2004). These systems share the Khisor Range's characteristics of post-Pliocene reactivation, duplex-style thrust sheets, and integrated petroleum systems preserved in frontal anticlines.

7. Conclusions

This study has led to the following conclusions;

1. Structural Style: The region exhibits a thin-skinned deformation regime characterized by fold-thrust assemblages, with detachment surfaces localized within the Jhelum Group strata, as inferred from surface geometries and balanced cross-sectional restorations.
2. Tectonic Regime: Compressional and transpressional tectonics dominate, impacting Paleozoic and younger lithostratigraphic units, with primary contractional deformation post-dating the Late Pleistocene, constrained by deformation truncating late Miocene-to-Pleistocene sedimentary sequences.
3. Basal Décollement: A regional-scale detachment horizon underlies the Jhelum Group, serving as the sole fault (sole décollement) from which thrust systems propagate; structural projections via kink-plane bisecting-angle methodologies confirm an undeformed basement, restricting deformation to supradetachment strata.
4. Deformation Mechanisms: Shortening is accommodated through sequential frontal ramping along the basal décollement, generating fault-bend folds and fault-propagation folds, with syn-tectonic hanging-wall synclines reflecting progressive strain partitioning.
5. Fault Geometry: Thrust faults exhibit classic staircase trajectories, flat-ramp-flat architectures, with ramp segments inclined at moderate-to-steep angles, transitioning into shallow detachments within mechanically weak horizons.
6. Hydrocarbon Potential: The petroleum system components, source rocks, reservoir units, and sealing lithologies are structurally juxtaposed across thrust-

related closures, anticlinal traps, and fault-dependent geometries, affirming the area's viability for hydrocarbon accumulation.

Author's Contributions

Iftikhar Alam conceptualized the research, concept development, led structural fieldwork, and manuscript drafting; Nazir-ur-Rehman performed the data analysis. Shuja Ullah and Afrasiab contributed to the experimental design and formatting. Yousuf Haroon evaluated hydrocarbon potential and exploration implications. Subhan Ullah and Abdul Hakim Shah performed the CorelDRAW work and prepared the figures, and Maria Kaleem provided the proofreading of the manuscript.

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