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Fold-thrust Style and Fluid Reservoir Potential of Eocene Sakesar Limestone: Sothern Surghar Range, Trans-Indus Ranges, North Pakistan

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Abstract

The Surghar Range western extension of the Trans-Indus ranges constitutes the southeastern frontal fold-and-thrust belt of the Kohat Plateau. This structural province is comprised of various local to regional scale anticlines right from Serkia-Mitha Khattak to Kutki areas. The existing range-front anticlinal trend is well-built along the east-west trending segment of the Surghar Range. These anticlinal features reveal infantile tendency from east to west and unearthing the platform rock sequences ranging from Permian to Eocene which is unconformably overlain by the Mitha Khattak Formation equivalent facies to the Rawalpindi Group. This facies in turn has overlain by the fluvial sediments of Siwalik Group. Overall three major anticlines have been mapped from west to east as the Mitha Khattak, Makarwal and Malla Khel Anticline. Differential stratigraphic levels are exposed in cores of these anticlines which proved excellent prospect to be potential hydrocarbon reservoirs horizons. The Eocene Sakesar Limestone has been selected for details studies of his fractures and joints analysis. The Sakesar Limestone exposed along the range front making fraction of the frontal limbs of different anticlines. Various fractures networks and joints pattern has been observed in the Sakesar Limestone at different localities reveal high secondary porosity and permeability. Most of the secondary tectonically induced and primary diagenetic opening and ruptures planes are interconnected and tenders proficient conduit lattice for munificent circulation of fluids in the Sakesar horizon. Origin of fractures and joints growth is mainly associated to force folding in response to the compressional, transpressional and trans-tensional deformation being observed in the region. The studied anticlines reveal that they are the product of fault-bend and fault-propagation folding tender excellent structural fluid trapping philosophy. The range frontal flanks reveal that different level of strata thrust against the foredeep showing inconsistency in the subsurface level of basal detachment horizon which is too hopeful for the construction of structural traps at various levels. Blending of the structural style of the area with the sedimentary structural features of the Sakesar Limestone of Surghar Range urges that this structural province is significantly associated to make hydrocarbon reservoir potential at the stratigraphic level of Sakesar Limestone.

Keywords: Surghar range; Deformation style; Sakesar limestone; Reservoir potential; Tectonic; Diagenetic fractures

Introduction

Surghar Range is the outer most fold-and-thrust belt of the sub-Himalayas making the easternmost extension of the Tran-Indus ranges (TIR) bifurcated by the KaIabagh fault system from the western Salt Range of North Pakistan [1]. The range follows east-west structural trend along the sothern margin of the Kohat plateau and switches to north-south trend along the easternmost flank of Bannu Basin (Figure 1) [2]. Along the range front the non-outcropping Permian to Eocene rocks underneath the Kohat and Bannu Basin are exposed at surface. The range displays arcuate structural style in plan and exhibits distinct mountain forefront geometries along its map trace. It is characterized by south facing structures along its east-west trending segment. Whereas the north-south trending segment of the range is dominated east vergent fold-thrust assemblages. The whole range displays bidirectional structural trend, north-south toward its sothern terminus to Malla Khel and oriented east-west from Malla Khel to its eastern terminus up to junction of KaIabagh Fault Zone, making two broad segments. The north-south segment is composed of Siwalik sequence penetrated in progression by Eocene to Jurassic rocks from south to north in the proximity of Malla Khel village across the Baroch Nala section. The north-south oriented segment of the range is dominated by east facing structural geometries in additional to west vergent active back thrusting and tectonic wedging [3]. Previous work is mostly attributed to stratigraphy, economic geology and geological mapping of the Surghar Range [2,4,5] where as its outer eastern flanks of the north-south segment and southeast flanks of the east-west segments has been remained unaddressed since long. Sothern part of the north-south oriented segment is dominantly controlled by the uplifts of Siwalik sequence where Chinji Formation is exposed in the core of Qubul Khel Anticline. Near Sirkai a broad anticline has been mapped in the Siwalik sequence where Mitha Khattak Formation and Sakesar Limestone are thrust in the hanging wall over the Dhok Pathan Formation in the footwall. The structural geometries of east-west oriented segment are characterized by south facing overturned concentric anticlinal folds with a prominent south vergent thrust fault. The Sakesar Limestone is exposed and mapped along three major anticlinal folds right from northwest of Sirkia Village to Baroch Nala. These anticlines have been designated from south to north as Mitha Khattak, Makarwal and Malla Khel anticlines. The frontal limbs of these folds are thrust over Siwaliks Group rocks toward Punjab Foredeep. This thrust fault is observed laterally extended along the foothills of the range from Sirkia to the eastern terminus of the Surghar Range. Transpressional tectonics is the significant structural style of the north-south trending segment while overturned concentric folding and thrust faulting is the dominant structural mechanism of the east-west trending segment of the range. Maturity in deformation style and variable stress regimes are observed from sothern plunging end to the eastern termination of the range all along the structural pathway in the form of tectonic progression, structural growth, maximum crustal shortening and unearthing of Paleozoic-Mesozoic rocks of the cover sequence. Maturity in the

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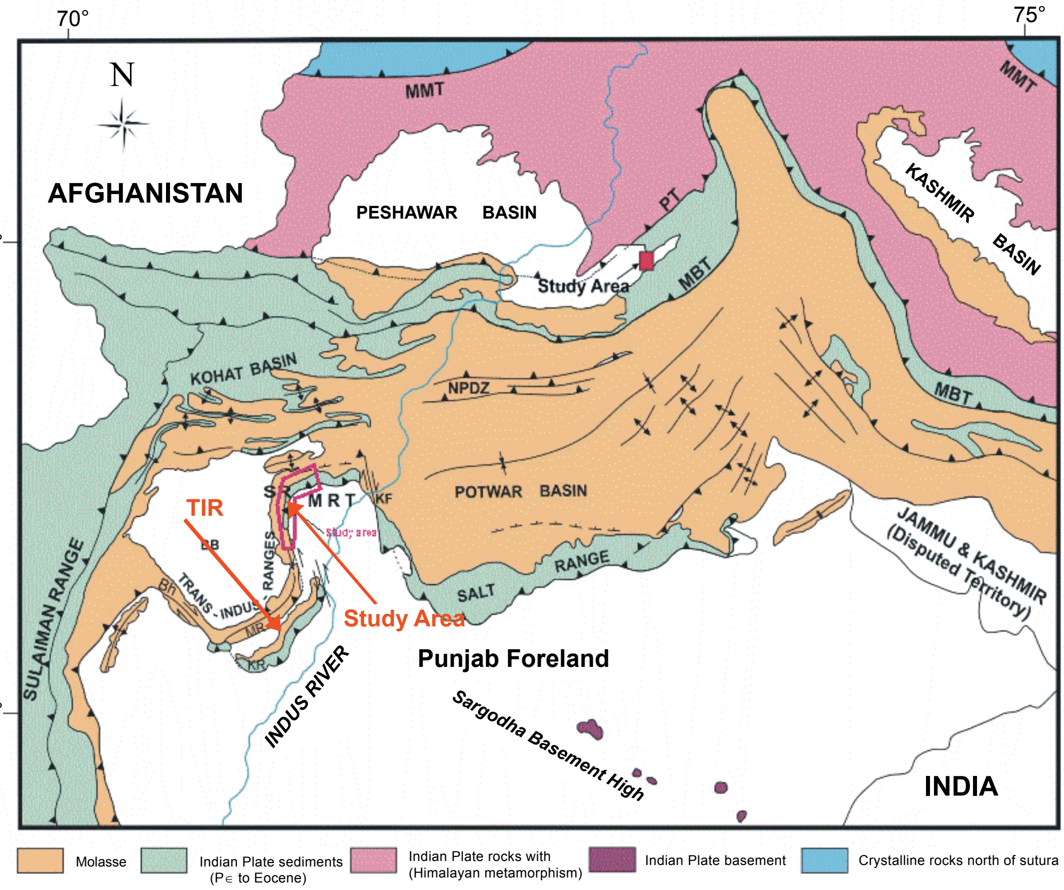

Figure 1: Regional geological map showing the TIR and study area.

tectonic phases and exhumation of the older strata from interior to surface is well predictable. Sakesar Limestone has been studied for their reservoir potential by considering the growth of natural fractures and joints network developed attributable to the tectonic and diagenatic processes. The fractures network and their distribution are important parameter and essential prerequisite for the potential hydrocarbon reservoir. Connected fractures have been observed which provide high permeability for the carbonate reservoirs and eventually helpful for the enhancement of yield.

Geological setting

Pakistan occupies the northwestern structural province of the subducting Indian lithospheric plate underneath the Eurasian Plate. This global tectonic event has produced compressional and transpressional tectonic elements since Eocene on the northern and northwestern fringes of Pakistan. Continual under thrusting of the Indian Plate since Cretaceous created the amazing elevated mountain ranges of Himalaya and a series of foreland fold-and-thrust belts as thick sheets of sedimentary origin and thrust over the Indian Craton [6].

The Trans-Indus extension of the Salt ranges is composed of several frontal ranges creates an "S" shaped double re-entrant and surrounds the Bannu Basin (Figure 1). These ranges symbolize the western fraction of the northwestern Himalayan foreland fold-thrust belt that produced by continual south-directed décollement-related thrusting of the Indian Plate crust during long-term collision between India and Eurasia [7-10] crustal architecturing normally advanced southward with time space. The youngest and latest sothernmost fracture zone has transpired along the forefront thrust mechanism contiguous to the Trans-Indus ranges (Figure 2) [11,12]. The current study area is the easternmost extension of the TIR. Along the Surghar frontal fault Paleozoic to Cenozoic platform sequence is thrust southward over the undeformed Quaternary sediments of the Punjab Foredeep. The TIR characterized the foremost deformational front of the Kohat fold-thrust belt and Bannu Basin in North Pakistan. Consequently, the tectonic mode is generally observed thin-skinned for the outcropping structures.

Stratigraphic setting

During field studies, it has been observed that the eastern and southeastern flank of the Surghar Range is comprised of Permian to Eocene platform sediments unconformably overlain by Plio-Pleistocene fluvial sediments (Table 1). The platform sediments become thicker and more complete from west to east along the range. In western part of range, northeast of Malla Khel in Baroch Nala and east of Pannu in the Chichali Nala excellent sections ranging in age from Permian to Miocene are exposed. The stratigraphic successions were studied along these sections of the range as shown in Table 1.

In this area, the base of stratigraphic succession is occupied by the Permian Zaluch Group rocks of Wargal Limestone overlain by the Chhidru Formation. This succession is occupied by the Triassic sequence of Musa Khel Group rocks of Mianwali, Tredian and Kingriali

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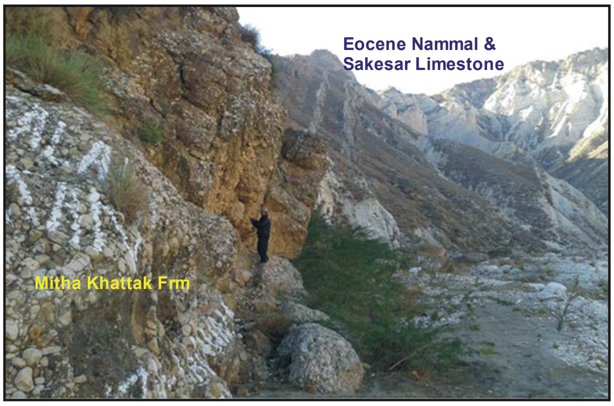

Figure 2: Photograph showing Mitha Khattak and Eocene formations exposed in MKA.

Era	Period	Epoch	Group	Formation
Cenozoic	Tertiary	Pliocene	Siwalik	Dhok Pathan
				Nagri
				Chinji
		Miocene	Equ. Rwp GP	Mitha Khattak
		Eocene	Chharat	Sakesar limestone
				Nammal
		Paleocene	Makarwal	Patala
				Lockhart Limestone
				Hangu
Mesozoic	Cretaceous	Early	Surghar	Lumshiwal
				Chichali
	Jurassic	Late	Baroch	Samana Suk
		Middle		Shinawari
		Early		Datta
	Triassic	Late	Musa Khel	Kingriali
		Middle		Tredian
		Early		Mianwali
Paleozoic	Permian	Late	Zaluch	Chhidru
				Wargal Limestone

Table 1: Stratigraphic framework of Surghar Range [5].

Dolomite overlying the Jurassic that include Datta, Shinawari and Samana Suk Formation. On top the Cretaceous sequence is mapped and comprised of Chichali and Lumshiwal Formation unconformably overlain by Paleocene sequence that comprised of Hangu, Lockhart and Patala formations. In turn the sequence is overlain by the Eocene Nammal Formation and Sakesar Limestone which is unconformably overlain by the Mitha Khattak Formation and Siwaliks Group rocks.

Methodology

Before performing fieldwork relevant literature was extensively reviewed to acquire knowledge regarding the geological setup of the study area. In the field I have studied the lithologic composition, primary and secondary structural features and stratigraphic position of the Sakesar Limestone in the exposed stratigraphic succession of the area. For the purpose conducted several stratigraphic/structural traverses across the range for the preparation of structural geological map of the area. Traverses were planned in the east-west and north-south directions in the western and eastern domains approximately right angle to the trend of the outcrops of the range. Besides studying the physical properties of the exposed Sakesar Limestone, detailed structural data regarding strike and dip of bedding and, faults and attitudes of the fold axes were collected and correlated with each other in order to establish the pattern of the various structures.

Reservoir potential of eocene horizon

The following prominent fold structures have been mapped from south to northeast toward the frontal flanks of the Surghar Range exposing Eocene horizon comprised of Sakesar Limestone. Medium to thick beds of the Sakesar Limestone make the hanging wall ramp of the frontal thrust sheet against the Siwaliks sequence in the footwall toward the Punjab Foredeep. The Sakesar Limestone is developed throughout the Surghar Range is a hard prominent cliff-forming formation. The limestone horizon maintains a relatively uniform character all over the area. It consists of white to whitish gray, greenish gray to gray, nodular, medium to thick bedded limestone with alternate thin marl beds. Cherts concretion and nodules are frequently observed in middle and upper part of the limestone. The whole limestone is well fossileferous, highly fractured, jointed, moderate to rationally cavernous, and visible to measurable beds disjointing have been observed in the outcrop exposure. Random joints and fissures have been observed along the bedding planes making the horizon well porous and permeable. Interconnected joint net observed on the outcrop level. The morphology of the interconnectivity of the joints/fractures sets enhanced the rate of fluid flow inside the medium. Visually observed that the area falls in higher fracture density. Thickness of the Sakesar Limestone in the Landa Psha section is 128 meters whereas in the Makarwal section of the Surghar Range is 300 meters [13]. Thickness reported 220 meters in Chichali section and 600 meters at Makarwal area [5]. Physical characteristics including its lateral extension, thicknesses, primary and secondary connected and unconnected fractures fabricates its permeability and storage capacity of the formation is appropriate and in hand basic parameter for the reservoir potential of the horizon. Its lower contact with the Nammal Formation and upper contact with the Chinji Formation both comprised of thick shale beds making the seal horizons, observed conformable and unconformable respectively. The Sakesar Limestone evolved in open marine carbonate depositional environment [14] during early Eocene.

Mitha Khattak anticline (MKA)

This anticline is mapped north of Mitha Khattak village and comprised of rocks of the Siwaliks Group underlain by the Eocene Sakesar Limestone and Nammal Formation. The Eocene rocks are underlain by the Paleocene Patala Formation and Lockhart Limestone. Base of the Lockhart Limestone is not exposed in the core of MKA. This is an east facing and south plunging prominent structural of the area [15]. The eastern limb is steeply dipping to southeast to make the anticline is overturned.

The fluvial and Siwaliks Group rocks composed of Mitta Khattak and Chinji formations. The Mitta Khattak Formation dominantly consists of dark brown thick bedded sandstone at the top and 8 to 9 m thick, compact and well cemented cobble gravels conglomerate beds of coarsening upwards sequence observed at base of formation, representing unconformity. The Mitta Khattak Formation could be equivalent facieses of the Rawalpindi Group. Structural trend of the beds is N10~15°E and dipping at an angle of 75°~80°SE. Thick horizon of the Sakesar Limestone observed fractured and jointed making a potential reservoir format for the accumulation of hydrocarbon in this structure (Figure 3).

Joints data

Joints data has been collected on the eastern limb of the MKA

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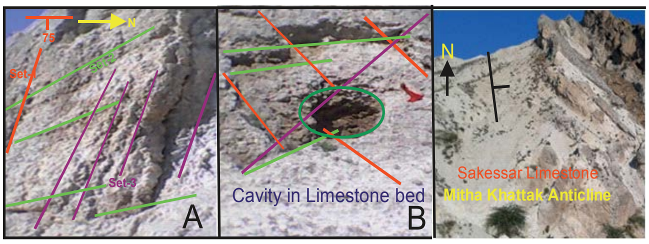

Figure 3: Photographs showing Joint system in Sakesar L.s eastern limb of MKA.

on the exposed beds of Sakesar Limestone observed highly fractured tectonically and diagenatically. Tectonically induced three different joints sets have been observed and acquired data of each parameter which is tabulated in Table 2.

The surface exposure of Sakesar Limestone observed highly fractured, jointed, vugy and showing nodulation. Visible and splitted bedding planes, longitudinal and transverse joints pattern, chicken wire net fractures and existence of elliptical to circular holes right angle to strike make the horizon encouraging reservoir for fluid circulation as well as potential storage compartment (Figure 4).

Karandi anticline (KA)

Rocks exposed on the eastern limb of KA are the Mitha Khattak and Chinji formations. The Eocene Nammal Formation and Sakesar Limestone are thrust eastward on the Mitha Khattak Formation in the hanging wall. The oldest formation exposed in core of the KA is the Cretaceous Lumshiwal Formation, where base of the Lumshiwal Formation is not exposed in the core. General trend of the strata is N5°~10°W and dipping steeply toward 80°SW. Tectonically induced Joints trend and other diagenetic apertures up to13 cm diameters, data has been acquired of the Sakesar Limestone to reveals its reservoir potential capability in the region. The obtained data is tabulated in Table 3.

The Sakesar Limestone is medium to thick bedded showing prominently bidirectional joint pattern with some visible circular to semicircular openings. The fracture density visually observed high at the outcrop level. The same density is expected to be existed at the subsurface level because these ruptures are the product of diagenetic as well as tectonic process. In view of, the Sakesar Limestone will be considered virtually as potential reservoir for the accumulation of hydrocarbon in the Surghar Range (Figure 5).

Malla Khel anticline (MKA)

The Malla Khel Anticline is located northwest of Malla Khel village. It is a prominent structural feature of the region. The frontal limb of the anticline is overturned. The back limb of the anticline gently dipping to northeast while its forelimb is asymmetrical to overturned and dipping at high angle ranging from 80°-85° northeast, the oldest Datta Formation is exposed in its core. In frontal flank Eocene strata are thrust in a hanging wall ramp over Siwaliks in the footwall ramp. Geometry of the anticline revealed as fault bend-fold (Figure 6).

General structural orientation of beds is N05°~10°E and steeply dipping to 80°~88°NW~NE. Secondary induced joints/fractures trend along with diagenatically produced openings data has been acquired along the frontal limb of anticline of the Sakesar Limestone to reveal its fluid reservoir potential in the Surghar Range. The collected data is tabulated in Table 4.

The surface exposure of the Sakesar Limestone observed remarkably fractured, jointed by penetrative strain with the creation of open bedding planes. Some major dissolution of the primary minerals observed in the form of cavities (Figure 7) which is responsible for the

S. No	Strike	Dip	Length m	Spacing m	Opening m	No of Joints
Set -1	N70°~80°E	50°~60°NW	01~3.0	0.5~1.0	0.001~0.002	25
Set -2	N20°~30°W	35°~40°SW	0.5~1.0	1.0~3.0	0.001~0.0015	27
Set-3	N30°~ 40°W	50°~65°SW	02~4.0	0.30~0.7	0.005~0.01	10

Table 2: Showing joints trend dimensional data of the Sakessar Limestone, MKA.

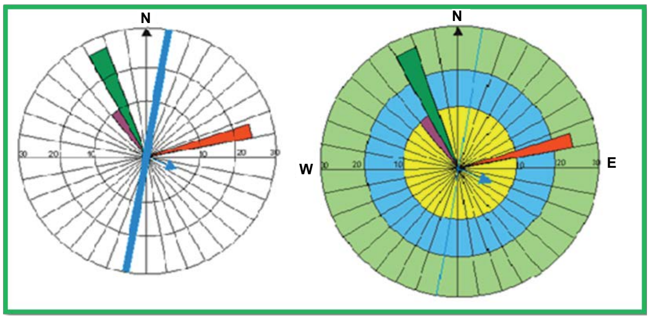

Figure 4: Joints rose diagram along with structural trend data eastern limb of MKA.

S. No	Strike	Dip	Length m	Spacing M	Opening M	No of Joints
Set -1	N68°~75°W	70°~80°SW	0.3~2.0	0.2~0.5	0.001~0.002	12
Set -2	N20°~25°E	50°~56°SE	0.5~4.0	1.0~3.0	0.01~0.15	15
Set-3	N55°~ 60°E	50°~65°NW	0.5~3.0	0.5~1.5	0.01~0.03	12

Table 3: Showing joints trend dimensional data of the Sakessar Limestone, MKA.

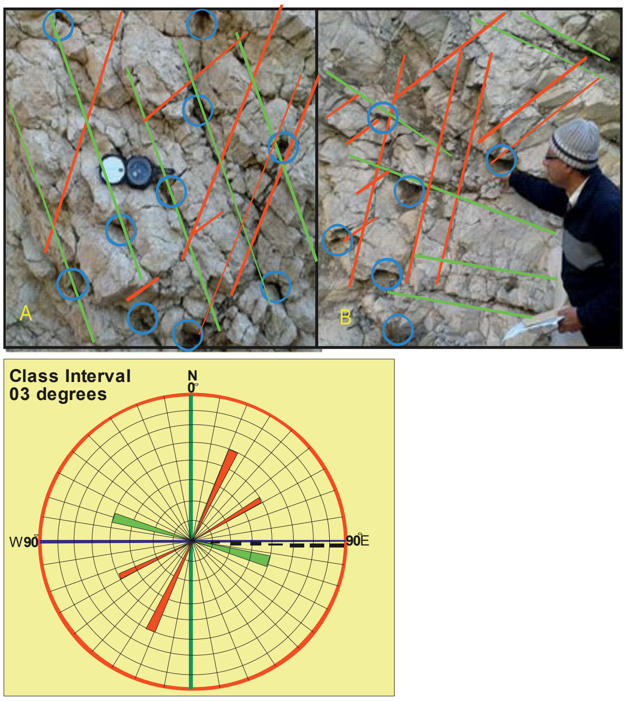

Figure 5: Showing fractured Sakesar Limestone with joints rose diagram of KA.

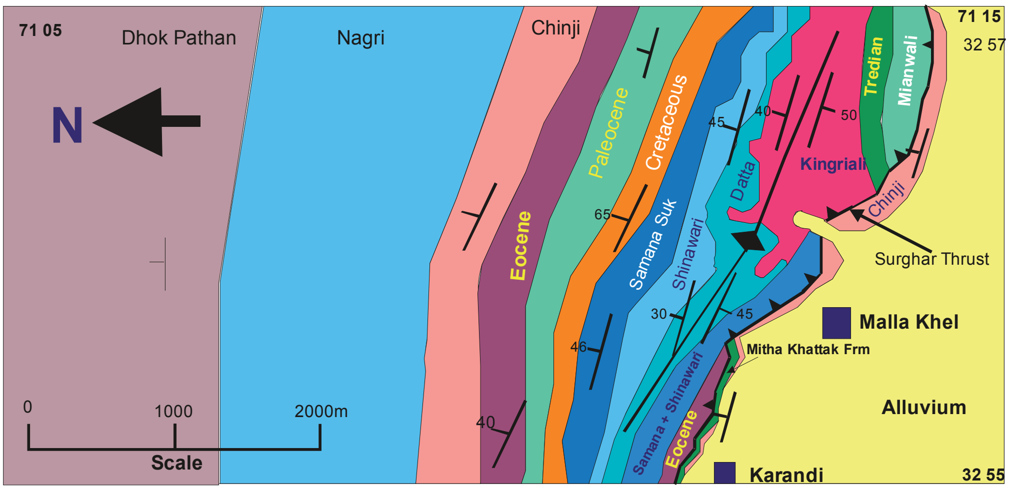

Figure 6: Geological map of the Karandi and Malla Khel areas of Surghar Range.

S. No	Strike	Dip	Length m	Spacing m	Opening m	No of Joints
Set -1	N40°~60°W	65°SW~Vert	0.2~1.0	0.5~ 2.0	0.001~0.0015	15
Set -2	N20°~25°E	30°~40°SE	0.5~2.0	0.5~1.5	0.002~0.004	18
Set-3	N60°~65°E	70°~75°NW	0.5~2.5	0.5~2.0	0.01~0.03	12

Table 4: Joints trend and diagenetic apertures in the Sakesar Limestone, MKA.

Figure 7: Photographs showing overturned Malla Khel Anticline, Surghar Range.

enchantment of permeability of the desired horizon. These fractures are observed interconnected with each other to make a net of conduits for the fluent flow of fluids in the studied horizon (Figure 8).

Discussion

Tectonics and structural deformations in the Surghar Range is younger proportional to the northern mountain belts of the inner Himalayas. This outermost frontal fold-and-thrust belt of the sub-Himalayas is comprised of latest tectonic and local to regional scale structural features well developed in the frontal flanks of the range. The mapped folds and faults are the product of compressional to transpressional tectonic regime. The Surghar Range is an arcuate feature and bounded all along its periphery by the combination of major thrust and local scale strike slip faults. The younger segment of the range is north-south oriented whereas the well-grown segment of the range is east-west oriented. The Sothern plunging terminus of the range is bounded by the Kundal strike-slip fault whereas the eastern terminus of the range is bounded by the Kalabagh fault system. The northwestern boarder is demarcated by the Karak Thrust fault and the southeastern perimeter is decoupled by the Surghar Range forethrust. The in-between compartmentalized area is comprised of small to large sized force folds being the product of fault-bend and fault-propagation compressional phenomenon. The oldest Paleozoic sequence of Permian rocks is cropped out along the frontal thrust sheet and protrudes southeastward against the Punjab foredeep. In structural route from south to east along the range different stratigraphic horizons have been exhumed along the frontal ramp reveals detachment flux from the prime basal décollement. The Eocene strata towards south and Permian strata toward east along the range front have thrust over Siwaliks in the footwall ramp. The outcrop exposure of the rocks along the range front is remarkably fractured and jointed. The Sakesar Limestone of Eocene has been selected for detailed fractures analysis to show its hydrocarbon reservoir potential along the eastern and southeastern flanks of the range.

Conclusion

The structural defects have been observed in the Sakesar Limestone and found that they are the products being induced diagenatically and tectonically during depositional and post depositional phases respectively. The tectonically secondary induced fractures are

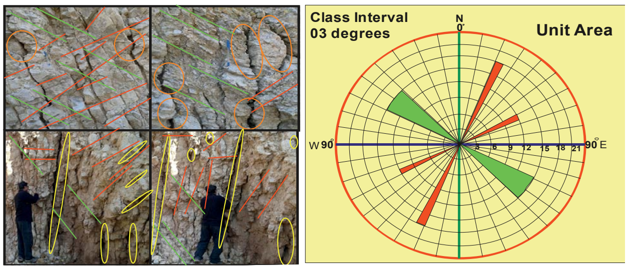

Figure 8: Fractures in Sakesar Limestone along with rose diagram, Malla Khel Anticline.

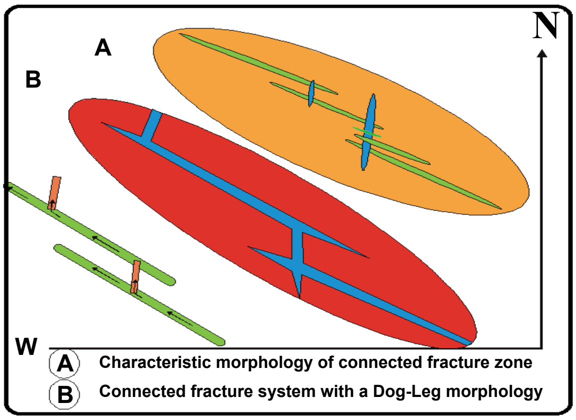

Figure 9: Showing characteristics of connected and dog-leg fracture morphology [15].

elongated reveal systematic and preferred orientations, joint spacing and joint openings/apertures. Three different joint sets have been observed at the three different observatory stations at three different anticlines along the range front shown high fracture densities. Some of the unsystematic/random joints and fractures have also been observed at each location raises the reservoir capability of the Sakesar horizon. The diagenetic apertures are generally shown on the photographs in the form circles, because they are more or less spherical in appearance. The sizes of sphere and their openings are significantly larger than the secondary tectonically induced fractures. The inner diameter walls of the spheres are uneven, rough and harsh and reveal the dissolution of some unstable minerals masses subsequent to their deposition.

The differences in fracture directions that might disclose differences in the regional tectonic stress patterns between the two time periods. Most of the joint patterns are observed interconnected with each other and give dog-leg morphology (Figure 9). Visually the fracture density in the Sakesar Limestone horizon observed greater in the east-west trending segment as compare to the north-south trending segment of the range. These fractured rocks facilitate the fluid storage capacity and transmissivity along the medium to enhance the reservoir quality of the Sakesar Limestone. That's why one of the most essential prerequisite for the hydrocarbon accumulation is in hand in the Surghar Range, Trans-Indus Ranges of the outer Himalayan orogenic province.

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