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Fracture connectivity, porosity and permeability evaluation of the Sakesar Limestone around the Surghar Anticline, Kohat Plateau, Pakistan

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ABSTRACT

The ENE trending Surghar Anticline is located in the Surghar Range. Stratigraphy ranging in age from the Jurassic to Eocene is nicely exposed in the Anticline. This thick sedimentary sequence is unconformably overlain by the fluvial molasses sediments of the Siwalik Group deposited during the Himalayan Orogeny. The Surghar Anticline exposes hydrocarbon bearing formations, which elsewhere are concealed by the younger sediments in the Kohat and Potwar foreland Basins. The potential reservoir rocks of the Sakesar Limestone of Eocene age are nicely exposed along northern and southern limbs of the Anticline. Detailed fracture analyses indicate that the formation is predominantly characterized by extension mode fractures followed by shear mode conjugate fractures. The ENE and NNW trending fracture sets are sub-parallel and orthogonal to the ENE trending Surghar Anticline axis respectively. Overall fracture density is greatest at the fore-limb than the back-limb. The fracture connectivity and porosity-permeability calculations demonstrate that various fractures at all stations within the formation are connected and imparting high secondary porosity and permeability.

These fractures could potentially provide pathways to hydrocarbon circulation to suitable trap structures. The prominent fracture network both geometrically and genetically related to the Surghar Anticline.

INTRODUCTION

Fractures are the common geologic feature of deformed terrains (Koehn et al., 2005; Herman, 2005). They immensely improve permeability and porosity of hydrocarbon reservoir rocks. In carbonate rocks secondary fractures related with fold and thrust belts are critical to permeability and porosity. Quantification of fractures parameters such as density, size, distribution, connectivity and geometric characteristics are important in hydrocarbon reservoir structures for the assessments of hydrocarbon flow and storage. The Surghar Anticline is a well-exposed surface Anticline located in the Surghar Range that rims the southeastern proximity of the Kohat Basin (Figure 1; McDougall and Hussain, 1991, Ahmad et al., 1999). It defines the youngest deformational front of the Himalayan orogenic belt in North Pakistan and is dominated by ENE-WSW and N-S trending structures (Figures 1 and 2). The fold and thrust assemblages depict thin-skinned

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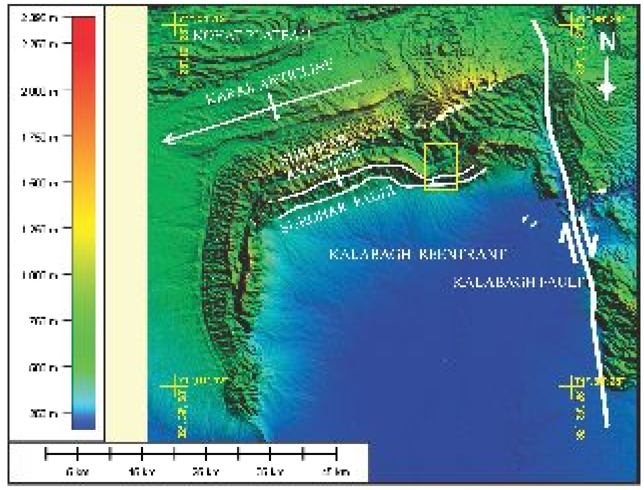

Figure 1. DEM (Digital Elevation Model) of the Surghar Range and Mianwali Re-entrant,showing present day structural grain of the region. The inset shows location of the study area.

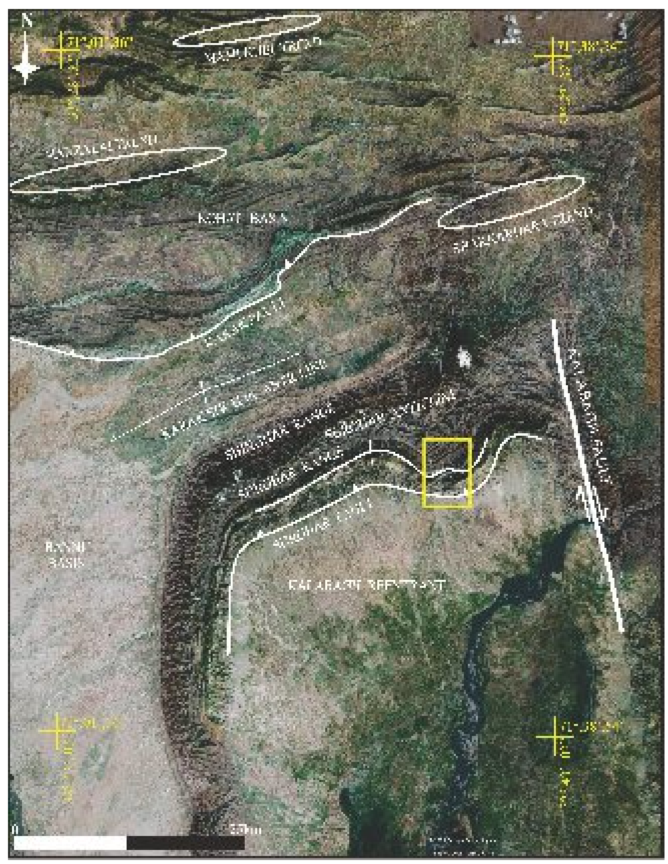

Figure 2- Satellite Image of the Surghar Range, showing major structural features. Rectangle shows the location of study area.

deformation style and have been mainly evolved as a result of frontal ramping from a regional basal decollement (see for detail Ahmed 2003).The Surghar Anticline has been interpreted to be a fault propagating fold that forms the major topographic expression of the ENE-WSW trending domain of the Surghar Range in the vicinity of Chichali Nala. The axial trace of the Anticline is ENE-WSW and is consistent with the regional structural trend of the Surghar Range (Ahmed 2003). The anticlinal core provides an excellent exposure of platform sediments ranging in age from the Jurassic to Eocene, unconformably overlain by the fluvial molasse sediments of the Siwalik Group rocks. Several stratigraphic horizons exposed in the core of the Surghar Anticline have been proved as potential reservoirs within the Kohat and Potwar Basins (Ahmed et al., 1999). This paper explains in much detail the overall fractures behavior of the Sakesar Limestone of the Eocene age, which could be a potential reservoir in the Kohat and Potwar Basin.

DATA

Oriented data were collected from the Sakesar Limestone exposed at the northern and southern limbs of the Surghar Anticline (Figure 3). Most of the data were collected on bedding surfaces plus some on the steep bedding face. The fracture data were measured at various stations using line

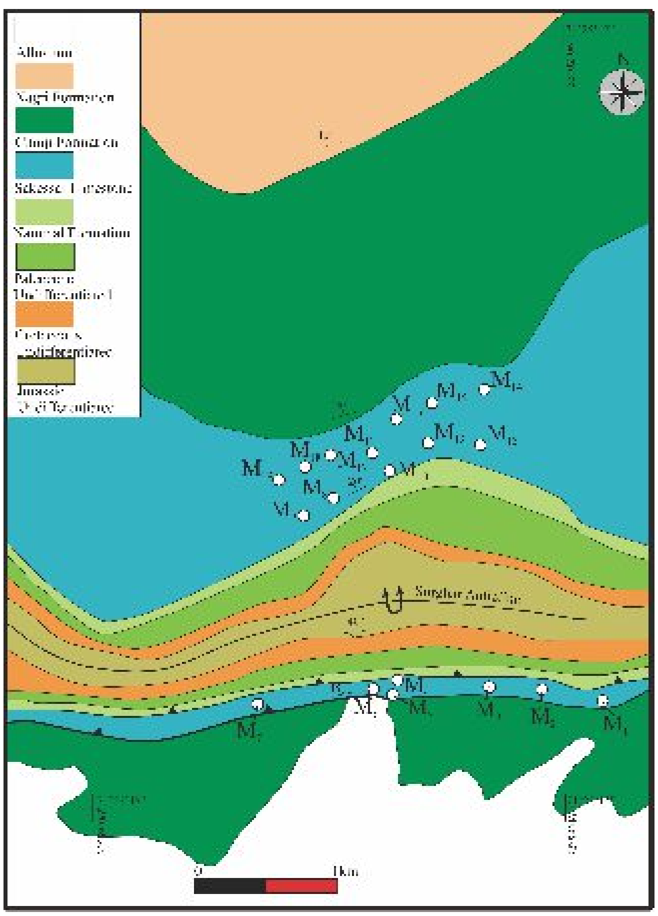

Figure 3 - Geologic Map of the Surghar Range showing fracture inventory points on the Sakesar Limestone along Surghar Anticline.

traverses (scan line) and inventory techniques. The measurement area was chosen wider than the mean fracture trace length. Preferably the dimensions of the individual stations were in the range of 1 to 5 m^2, with an average area of about 1m^2. At each measurement station, trace length, aperture and orientation of all exposed fractures within the measurement circle or that intersect the traverse line were determined.

GEOLOGICAL SETTING

The Surghar Range makes the eastern part of the Trans-Indus Ranges of the Sub-Himalayas. The ENE-WSW structural trend of the Surghar Range, which makes the southern margin of the Kohat Basin changes to N-S trend along the eastern flank of the Bannu Basin (Figures 1 and 2). It exposes the Jurassic to Paleocene sequence, which elsewhere concealed by the younger sedimentary sequence of the Kohat, Bannu and Potwar Basins (Figure 4). The range exhibits arcuate geometry in plan and display contrasting mountain front geometries along its trace. The ENE-WSW and N-S trending structures in the range are dominated by south and east verging structures respectively. It also consists of west verging active back thrusting and tectonic wedging. The back-limb of the Anticline is shallowly dipping towards north whereas its fore limb is dissected by couple of south verging fore-thrusts along the entire mapped area (Ahmed 2003). The core of the Surghar Anticline is completely occupied by the Jurassic rocks. Along the frontal faults Eocene rocks are thrust southwards over Chinji Formation of the Siwalik Group rocks (Figure 3). The structural analyses at of the Surghar Range are important to assess the sub surface structural style of the Kohat, Bannu and Potwar Basins as no rocks older than Paleocene crops out in these basins. It is believed that the recent success of oil and gas wells in the Kohat Basin needs better understanding of its subsurface structures and fractures characteristics that can be best accomplished by the structural understanding of the Surghar Range.

STRATIGRAPHY

Figure 4 showing the exposed stratigraphy of the study area. The stratigraphy of the region has been established by the Geological Survey of Pakistan (Fatmi, 1973; Shah et al., 1977) and Petroleum exploration companies working in the Trans-Indus Ranges. The Late Permian to Miocene age platform and fluvial stratigraphic sequences have been established in the region from the surface and sub-surface exposures.

QUANTITATIVE FRACTURES NETWORK ANALYSIS

Fractures are produced in rocks during a variety of geological conditions including burial, tectonic loading and uplift. It is very hard to discern a particular fracture to its specific origin. However, in general fractures play an important role in rock mass characterization and flow parameters such as porosity and permeability. Fractures analyses is a critical tool in hydrocarbon exploration and exploitation because these are responsible for enhancing the

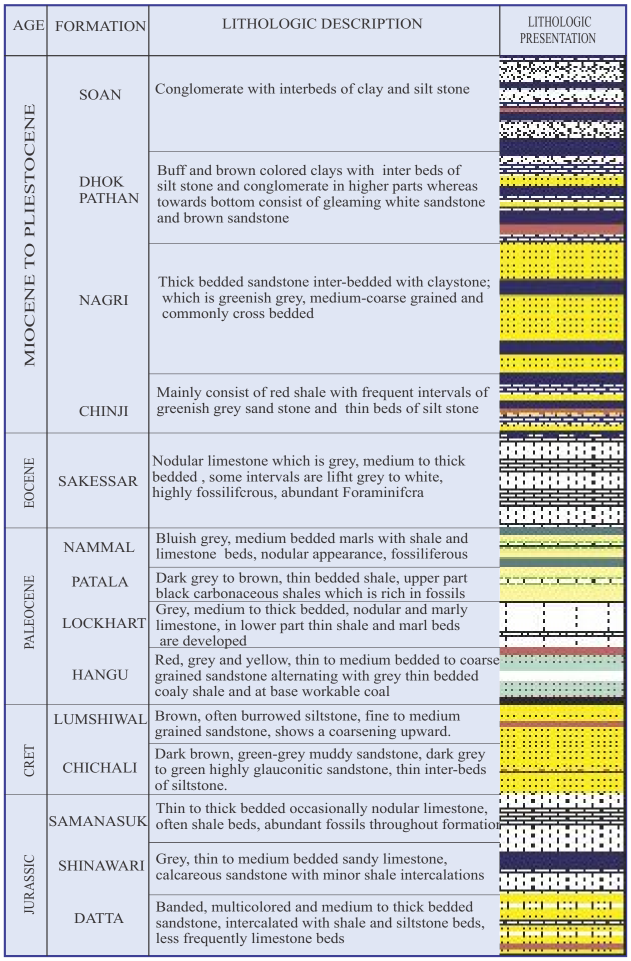

Figure 4 - Generalized stratigraphic sequence of the Surghar Range.

reservoir porosity and permeability.

Fractures present within the hydrocarbon bearing rocks are generally the product of burial and tectonic loading due to the fact that the reservoirs are usually deeply buried. Therefore fractures generally exist before the generation of hydrocarbon and provide pathways for hydrocarbon accumulation within a reservoir. Establishing the geometric characteristics of fractures in a proven reservoir structure is vital for hydrocarbon exploration and effectual reservoir production. Fractures often develop in predictable manner around fold structures (Anderson 1951; Engelder and Geiser, 1980; Ahmed 2003; Ramsey and Chester 2004). Genetically two types of fracture evolve during a single folding event, one parallel to the hinge line of the fold while the other form orthogonal to the hinge line. However, in multiply deformed rocks secondary deformation events may complicate the fractures pattern across a fold. Therefore, establishing the fracture pattern in a basin, which has future hydrocarbon prospects, is vital. We thoroughly carried out detailed fracture analyses at the outcrops, which expose the Sakesar Limestone, to understand the fracture network of the formation in areas where it is not exposed and concealed by the younger sediments. Fracture data were collected from 19 measurement stations (Figure 3). Fault related folds and easily accessible outcrops located on fore-limb and back-limb of the Surghar Anticline provide a wealth of information on all fractures networks and structures present in the area (Figure 5).

Fracture Characteristics

The parameters that describe fractures patterns of the Sakesar Limestone exposed in the flanks of the Surghar Anticline are given in Table 1. Meso-scale extension-mode fractures and shear fractures were studied all along the Surghar Anticline. In terms of abundance the extensional fractures are the dominant and well developed at all measurement stations. Shear fractures with two distinct sets, which appear to be geologically coeval oriented at moderate angles to bedding.Two distinctive orthogonal sets of extension mode fractures are present across the Surghar Anticline. The Sakesar Limestone does no show mechanical variation across the dip due to which the fracture sets cross cut bedding of the formation without any deflection.

Table 1- Dimensional characteristics of individual fracture set, of the Surghar Anticline, "N" is Number of fractures, So is dip amount and dip direction at the measuring stations and Area is station measuring area, DF Fracture Density in m/m^2, ΔP is Persistence of fractures, ΔW Aperture in meters and Kf is Fracture Permeability in (m^2).

Station	Fracture sets	No.	Azimuth	S_o	Area(m^2)	DF m/m^2	ΔP (m)	ΔW (m)	Kf (m^2)
M_1	1	9	20	30/NE	1.130	17.115	0.650	0.060	0.0003000
	2	8	80	70/SW			0.530	0.040	0.0001333
	3	4	50	73/NE			0.360	0.074	0.0004563
M_2	1	19	39	46/NE	3.140	12.669	0.520	0.090	0.0006750
	2	11	73	83/NE			1.082	0.055	0.0002563
	3	29	69	79/NE			0.621	0.060	0.0002966
M_3	1	11	50	61/NE	0.785	23.370	0.545	0.075	0.0004631
	2	8	83	43/NE			0.613	0.044	0.0001595
	3	15	63	70/NE			0.496	0.056	0.0002651
M_4	1	42	53	61/SE	0.502	81.975	0.463	0.057	0.0002676
	2	19	212	61/NE			0.680	0.075	0.0004631
	3	21	39	59/NE			0.420	0.090	0.0006750
M_5	1	40	50	55/NE	3.140	18.088	1.025	0.072	0.0004260
	2	15	240	40/SW			0.616	0.083	0.0005787
	3	10	30	50/NE			0.656	0.066	0.0003630
M_6	1	40	65	48/NE	1.530	43.128	0.928	0.077	0.0004883
	2	15	210	45/SW			1.409	0.057	0.0002733
	3	10	38	53/NE			0.775	0.057	0.0002733
M_7	1	10	150	50/SE	1.312	16.692	0.690	0.130	0.0004083
	2	13	250	80/SE			0.454	0.055	0.0002556
M_8	1	16	180	60/NW	1.200	16.361	0.569	0.093	0.0007130
	2	7	70	55/NE			0.433	0.065	0.0003521
M_9	1	16	180	60/NE	0.960	17.786	0.469	0.058	0.0002815
	2	7	70	55/NW			0.382	0.062	0.0003247
M_{10}	1	13	150	70/SE	1.130	19.416	0.531	0.060	0.0003000
	2	9	140	50/SE			0.778	0.051	0.0002177
	3	15	30	50/NE			0.536	0.056	0.0002651
	4	10	140	35/SE			0.600	0.053	0.0002297
M_{11}	1	5	220	40/SW	1.538	9.363	0.700	0.072	0.0004320
	2	6	110	60/NE			0.983	0.075	0.0004688
	3	9	140	50/SE			0.556	0.061	0.0003112
	4	7	40	40/NE			0.367	0.080	0.0005333
	5	3	340	40/NW			0.833	0.027	0.0000593
M_{12}	1	40	270	80/SW	0.502	50.159	0.415	0.053	0.0002319
	2	12	240	50/SW			0.483	0.041	0.0001389
	3	5	120	60/SE			0.560	0.060	0.0003000
M_{13}	1	15	349	58/NE	2.000	8.850	0.575	0.049	0.0002028
	2	6	345	54/SW			0.463	0.046	0.0001754
M_{14}	1	14	49	65/SW	1.530	7.404	0.450	0.051	0.0002143
	2	6	49	60/NW			0.455	0.047	0.0001855
M_{15}	1	6	75	62/NW	0.780	20.712	0.383	0.038	0.0001225
	2	3	138	60/SW			0.378	0.037	0.0001131
M_{16}	1	16	334	46/NE	3.140	6.408	0.795	0.048	0.0001880
	2	6	292	45/NW			0.467	0.038	0.0001225
	3	5	37	42/NE			0.920	0.030	0.0000750
M_{17}	1	17	48	66/NW	0.715	23.646	0.447	0.048	0.0001892
	2	7	115	68/SW			0.467	0.038	0.0001225
M_{18}	1	10	80	65/NW	2.280	8.372	0.604	0.055	0.0002521
	2	6	264	55/SW			0.541	0.047	0.0001836
M_{19}	1	13	329	47/NE	1.760	9.726	0.754	0.048	0.0001957
	2	7	298	73/SW			0.674	0.057	0.0002669
	3	5	37	43/NW			0.520	0.066	0.0003630

Dimensional Nature of Fractures

19 measurement stations were chosen in the Sakesar Limestone, 7 on fore-limb and 12 on back-limb of the Surghar Anticline (Figures 3 and 5). These stations are widely spread at the back and fore limbs of the Surghar Anticline for maximum coverage of the fracture pattern. Extension fractures generally occur in two separate sets (Figure 6). The ENE-WSW fracture set is sub-parallel while the NNW-SSE fracture set is orthogonal to the Surghar Anticline axis. In fore-limb the distinct opening mode fractures are followed by the shear mode fracture sets. The back-limb is dominated by extensional mode fractures. The shear mode fractures are less prominent at the back-limb as compare to the fore-limb of the Anticline.

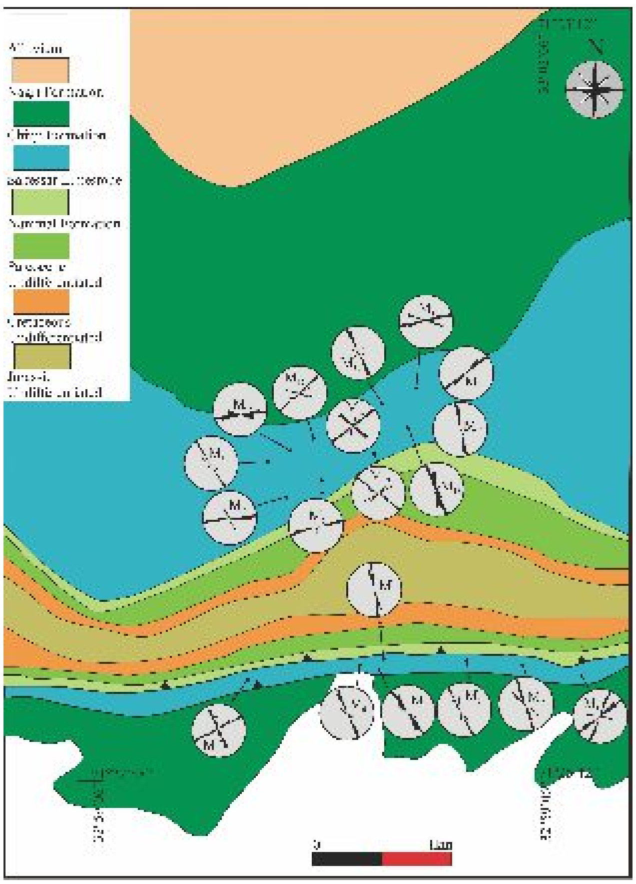

Figure 5- Geological map of the Surghar Range showing rose diagrams at the measurement stations.

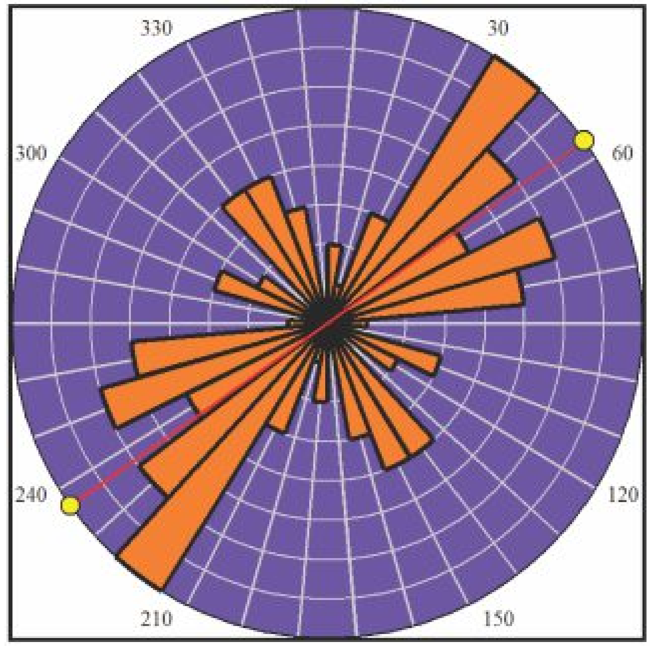

Figure 6- Rose diagrams showing fracture orientations of the Surghar Anticline.

Fracture Connectivity

Fracture connectivity can be estimated from the ratio of intersection and isolated fractures. The fractures connectivity developed along the Surghar Anticline is established by marking fractures on the oriented photographs taken at the exposed outcrop of the Sakesar Limestone at fore and back limbs. This study clearly demonstrates that various fractures at all measurement stations within the Sakesar Limestone are connected and establish a well developed fractures network (Figures 7 and 8). The following formula provides a practical way to estimate fracture connectivity within a grid cell. Fracture with a cell are interconnected have dual porosity if Hƒ < D 2. Where Hƒ is the average fracture spacing within the cell and D is the cell size, D could be the area of measuring station and Hƒ was calculated for the selected measuring station and is found less than D2 for each measuring station thus showing high ratio of interconnected fracture network (Table 2).

Connectivity of the Sakesar Limestone fracture network is not affected by the density and scaling. The connectivity is a scale invariant phenomenon within the formation. Fractures throughout the Surghar Anticline are present in distinct orientation sets. At any specific location, one set is dominant over the other (Figure 6).

Table 2- Cell size and average fracture spacing in measuring stations along the Surghar Anticline.

Station	Cell Size (m^2)	Average fracture Spacing (H*f*)
M_7	0.785	0.046
M_8	3.14	0.209
M_3	1.312	0.08
M_5	1.2	0.11

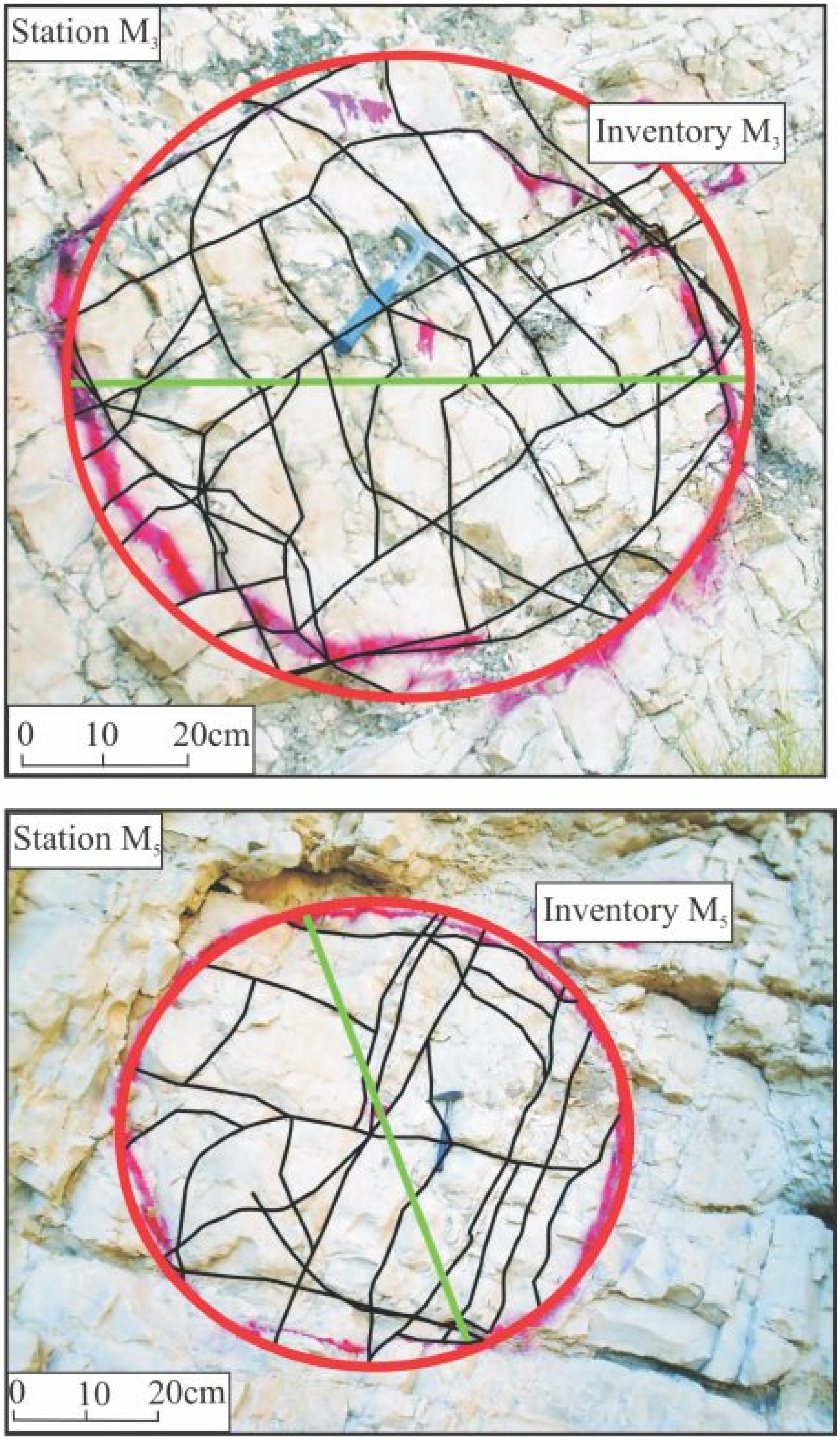

Figure 7- Line diagram showing fracture connectivity at stations M3 and M5 with in the Sakesar Limestone, along the Surghar Anticline.

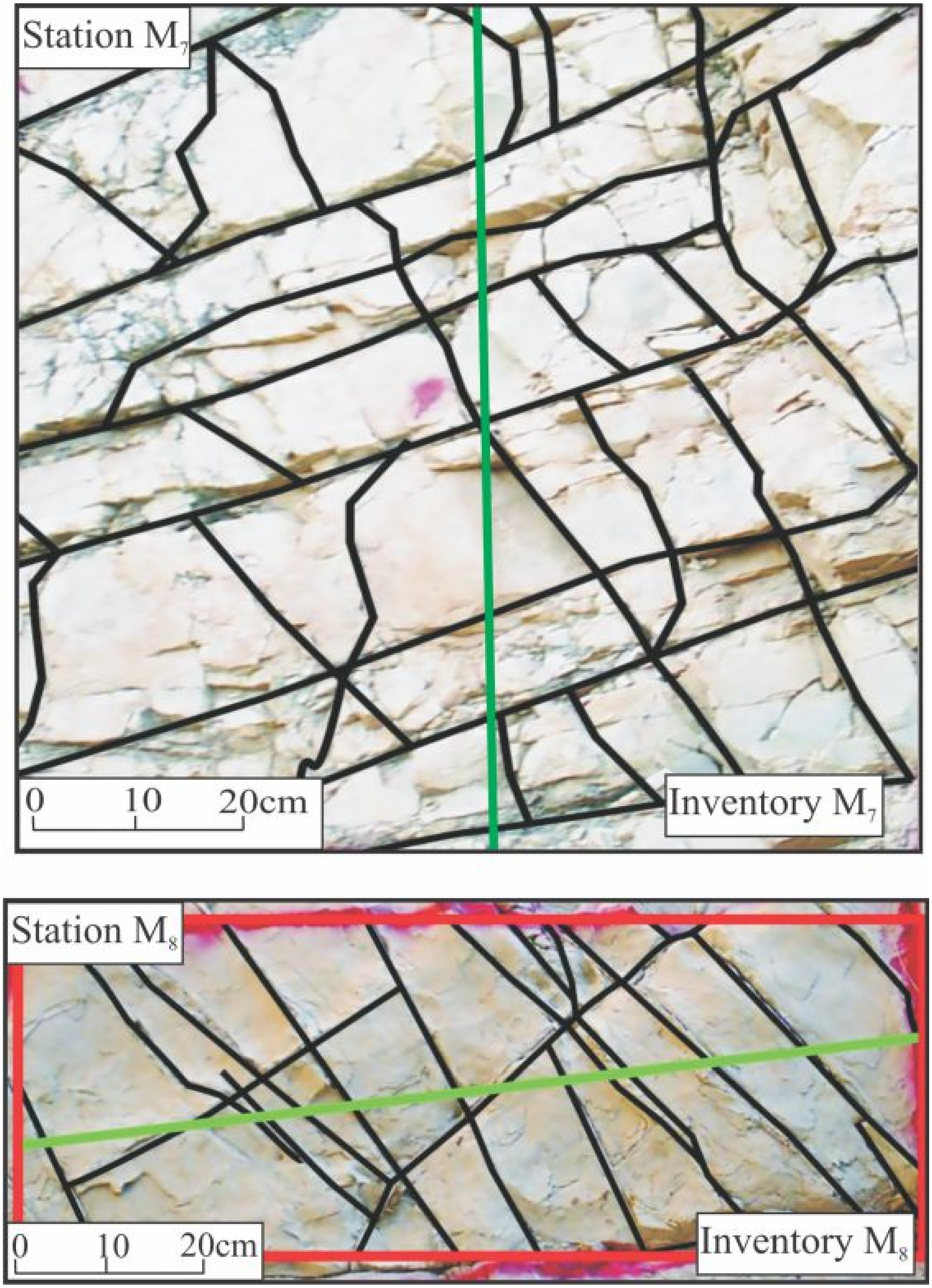

Figure 8 - Line diagram showing fracture connectivity at stations M7 and M8 Sakesar Limestone, along the Surghar Anticline.

Fracture Permeability

Permeability of individual fractures, Kf is related to the hydraulic fracture aperture (Snow, 1969),

Kf = w2/12 ....(i)

Where "Kf" is permeability of fractures in m^2, "w" is the aperture in meters. Fracture permeability for individual fracture sets at all measurement stations within the Sakesar Limestone was performed. Maximum permeability was calculated ~0.00 14083 m^2 at measuring station M7 (Table 1) at the fore-limb of the Surghar Anticline. The average permeability of all station was ~0.0003 194 m^2 .The permeability trend is found to be higher at the fore-limb having an average value of 0.0004327 m^2, whereas at the back-limb it is comparatively low with an average value of ~0.0002534 m^2 (Table 1).

Fracture permeability can be expressed in Darcy, as

1 Darcy = 9.869233×10^{-13} m²

On the basis of fracture permeability, conductivity of fluids can be calculated by the following mathematical formula,

Cƒ = g w2 / 12μ...................................(ii)

Where Cƒ is hydraulic conductivity (m/s), Kƒ is fluid density(kg/m^3) and μ is fluid viscosity, or it can be written as

Cƒ = g Kƒ / μ..................................... (iii)

Fracture Porosity

The fracture porosity in the Sakesar Limestone along the Surghar Anticline was calculated at selected measurement station located at the fore and back limbs. Fracture porosity can be calculated as,

= w / d..(iv)

Where "w" is the fracture aperture and "d" is the distance between fractures. The porosity calculated is higher in the fore-limb as compared to back-limb (Table 3).

Effective Permeability

Effective permeability (Kef) is given by

Kef=Kf w/d or Kef = Kf ....(v)

It shows that effective permeability (Kef) is directly proportional to fracture permeability (Kf) and porosity. Effective permeability was calculated for measuring stations along fore-limb and back-limb of the Surghar Anticline which is shown in Table 4.

Fracture Permeability vs. Structural Position

One of the main objectives of present study is to assess the fluctuations in fracture formation in connection to regional structure. The fracture data from the Surghar Anticline give insight of the fractures pattern in the following manner:

Fracture Orientation vs. Fold Geometry

According to Stearns (1967) fractures develop in predictable manner in association with fold axis. Two extension mode fracture sets that include a parallel (bc) and an orthogonal (ac) to fold axis are the dominant orientation trends. He mentioned that stress fields related to the folding process control the main trends of fracture sets across the fold. Furthermore, shear fractures usually appear in conjugate sets symmetric around the same orientation trends. The major extension and shear-mode fractures are developed in the study according to the Stearns model of fracture geometry (Figure 9).

Table 3 - Average distance between individual fractures, aperture of fractures and porosity of various measurement stations in the Sakesar Limestone along the Surghar Anticline.

Station	Avg.Distance (m)	Aperture(w)	φ (Porosity)
M_7	0.1700	0.1118	0.6576
M_8	0.1873	0.1305	0.6966
M_3	0.1447	0.1032	0.7132
M_5	0.1908	0.1632	0.8552

Table 4 - Fracture permeability (Kf), porosity (φ) and effective permeability (Kef) at selected measuring stations.

Station	Fracture Permeability(Kf)	φ (Porosity)	Effective Permeability(K_{ef})
M_7	0.000832	0.6576	0.000547
M_8	0.000533	0.6966	0.000371
M_3	0.000296	0.7132	0.000211
M_5	0.000456	0.8552	0.000390

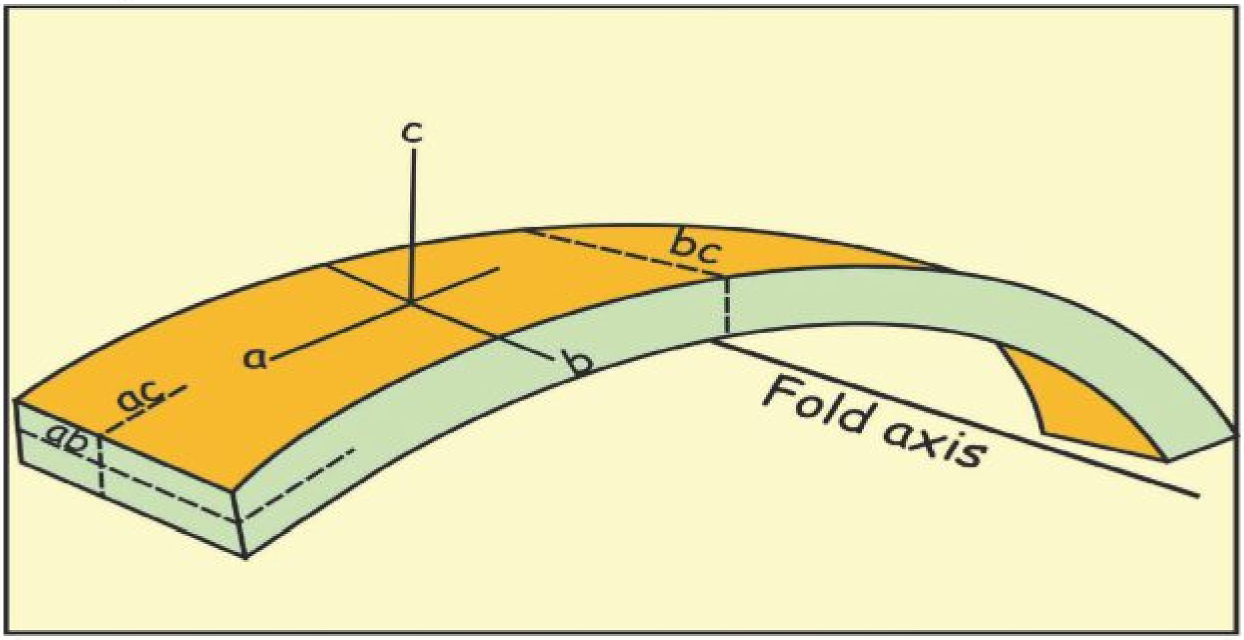

Figure 9 - ABC-Coordinate System for folds after Stearns (1967).

Fracture Permeability Versus Fold Geometry

Connected fracture network effective improves the reservoir drainage pattern. Fracture density associated with the Surghar Anticline is the main factor for fracture Connectivity within the study area. According to Murray (1968) the fracture density is related in direct proportional with connectivity. The connectivity evaluation (Table 1) demonstrates that the fractures measured at back-limb and fore-limb along the Surghar Range is predominantly interconnected and bears good permeability values. However the fore-limb displays greater permeability values as compared to the back-limb because the fore-limb is intensely deformed.

Stress And Strain Analysis Of Fractures Associated With Surghar Anticline

Fractures data collected from 19 measurement stations within the Sakesar Limestone have a firm geometric resemblance relation with the Surghar Anticline (Figure 10). The Surghar Anticline is an ENE-WSW trending and south facing. It exposes sedimentary rocks ranging in age from the Jurassic to Eocene. It also exposes the following three types of fractures that developed during flexural slip: (a) Transverse fractures are orthogonal to the fold axis, (b) Longitudinal fractures are sub-parallel to the fold axis and c) Conjugate fractures are oblique to the fold axis (Figure 11). The structural style of the Surghar Anticline clearly suggests that it has been developed by flexural slip folding (cf. Ahmed 2003). Transverse and longitudinal fracture sets respectively developed fold axes parallel and perpendicular dilations across the Surghar. These fracture sets, which are formed during the main folding phase of the Surghar Anticline, are vital to enhance the reservoir secondary permeability and porosity.

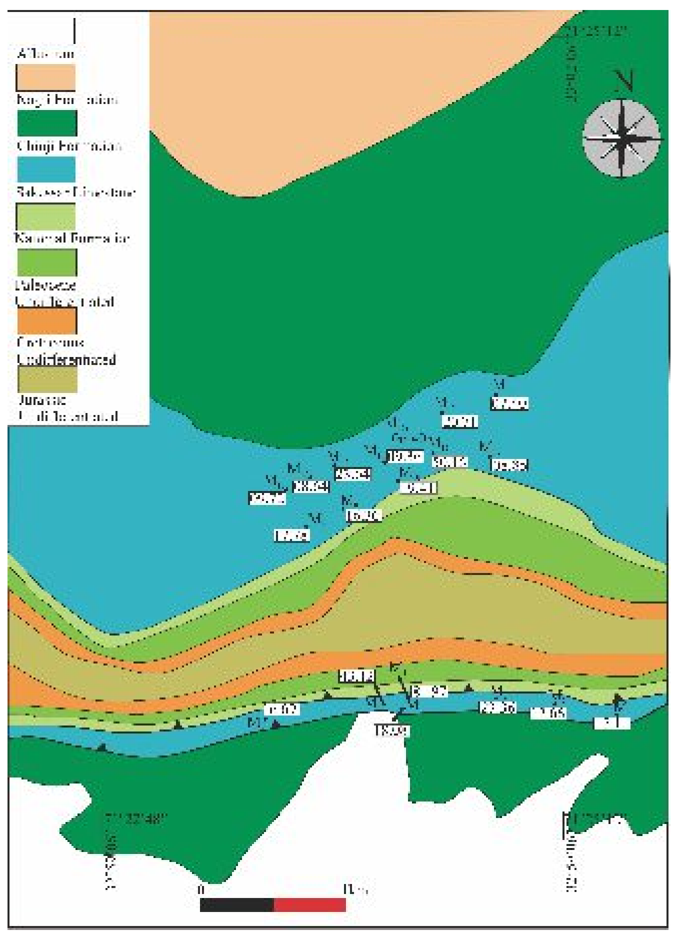

Figure 10 - The map showing density distributions of fractures at back and fore limbs along Surghar Anticline.

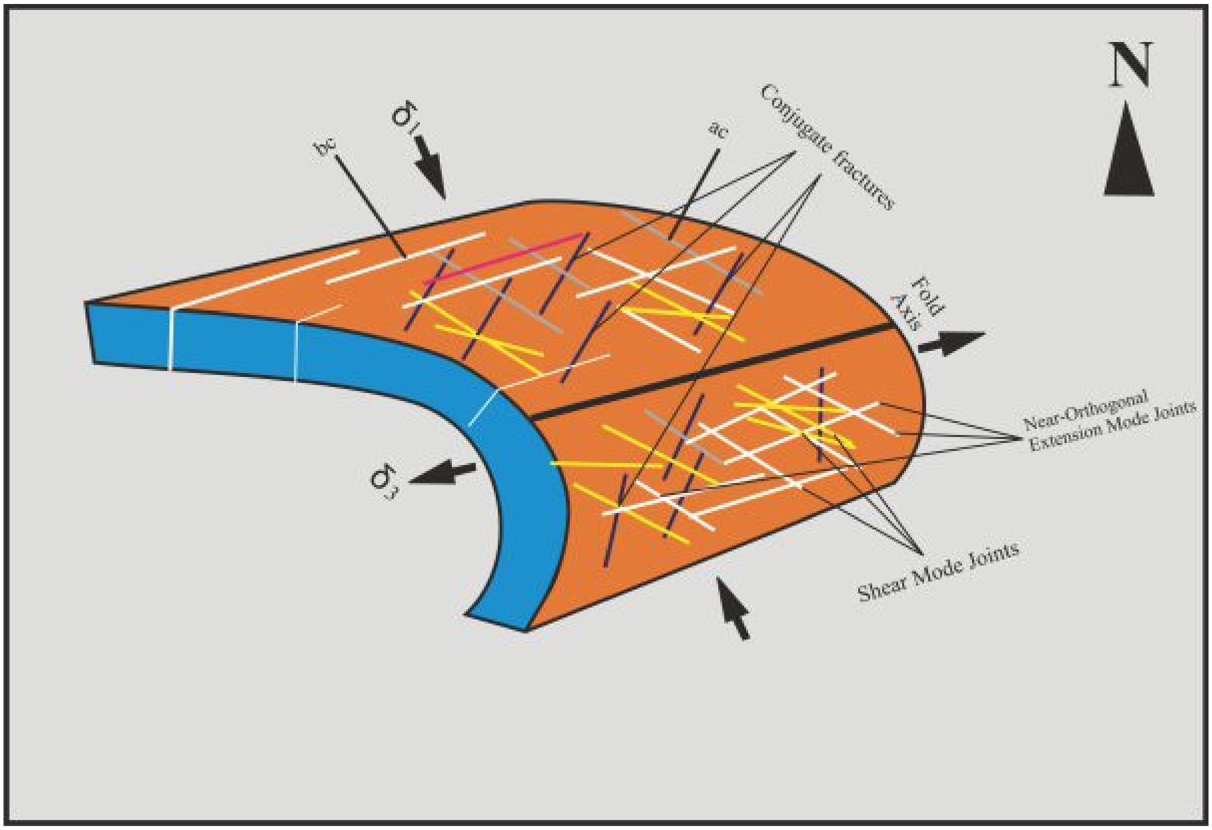

Figure 11- Schematic diagram showing geometric relationship of prominent fracture sets associated with the Surghar Anticline. The inset equal area rose diagram illustrates orientation of all fracture sets. Near-orthogonal σ1 and σ3 illustrating principal stress directions that developed extension mode fractures within the Surghar Anticline.

CONCLUSIONS

- The dominant fractures orientation sets observed within the Sakesar Limestone exposed along the limbs of the Surghar Anticline include a pair of distinct opening mode followed by a shear mode conjugate pair.
- The Surghar anticline Anticline fracture sets and geometric elements similarity Anticline suggest a syngenetic link between them.
- The fracture network, which was observed in the Surghar Anticline indicates that the similar fracture network might have been developed in an identical manner underneath the Kohat, Bannu and Potwar Basins.
- Fracture density is found to be highest at the forelimb due to intense deformation.
- ENE-WSW and NNW fractures are interconnected and conductive.
- The porosity and permeability analyses indicate that the observed fracture sets impart high porosity and permeability to the Sakesar Limestone and if similar fracture system exists at the deeper level, the Sakesar Limestone may acts as a potential reservoir for the accumulation of hydrocarbons.

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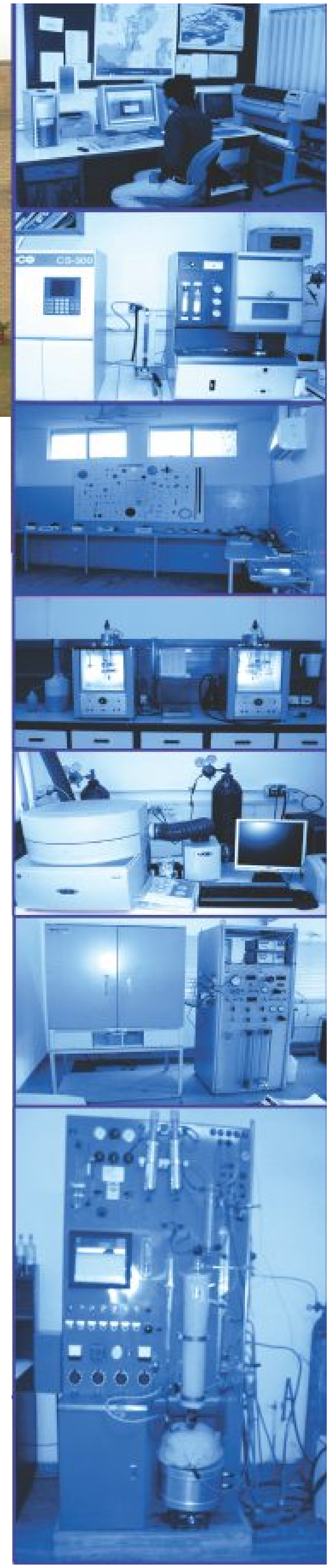

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Quality Assessment of Blending/Reclamation Plants
Quality Assessment of Depots of Various Marketing Companies

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Evaluation of CNG Equipment
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Operation of HDIP's Four Model CNG Refueling Stations

PUBLICATION AND INFORMATION DISSEMINATION:

Pakistan Energy Yearbook
Pakistan Journal of Hydrocarbon Research

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