Pakistan Journal of Hydrocarbon Research
Vol. 17, (June 2007),p.103-114, 08 Figs. 03 Table.

Fracture Network Analysis of Samana Anticline: A Fault-related fold at the front of Samana Range, Orakzai Agency, NWFP, Pakistan

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Abstract

Samana Anticline is a well developed fault-related fold exposed along the front of Samana Range with its southern limb thrust over the Paleocene-Eocene rocks of the Kohat Basin. The Samana Anticline hosts a carbonate and sandstone rock assemblage of Jurassic to Paleocene age with a well developed fracture network including three basic forms that are extension, shear and pressure solution seams of meso-macroscopic scale. Extension fractures, predominantly oriented at high angle to the bedding surfaces can be distinguished into two orthogonal sets that are parallel and transverse to the fold axis. The shear fractures observed along the Samana Anticline define a conjugate set trending northeast and northwest. Almost all the bedding surfaces within Jurassic-Paleocene rocks are characterized by well developed stylolites. Fractures density calculations reveal that it is greatest at fold culmination followed by forelimb and back limb which implies that fracture porosity and connectivity is greatest at the hinge area of Samana Anticline. The entire fracture network bears close spatial coordination with Samana Anticline suggesting that their genesis is syn-folding and the Samana Anticline has itself evolved as a flexural slip fold. The Samana Anticline can serve as a case example for the type of fracture system that should have been developed in similar anticlinal closures underneath Kohat Plateau.

INTRODUCTION

Layer parallel shortening, the first response to regional stress, manifests itself in the formation of penetrative regional fracture sets (Cloose, 1961; Geiser, 1988 and Nickelsen, 1979) Since these nucleate at very low stress, early in a region's tectonic history, they could be present well before the onset of hydrocarbon generation and provide both pathways and barriers to migration. Multiple sets of fractures develop as stress orientation change over time.

Permeability in many carbonate reservoirs is largely dependent on the fracture systems. Fractures often develop in predictable pattern in folds. As folds evolve, other processes may operate to complicate fracture pattern and the physical characteristics of fractures. Evaluating the geometric configuration of the fracture system in a proven reservoir structure is essential for optimized exploration and exploitation drilling and efficient reservoir production. Exploratory and production wells take advantage of fractures porosity and permeability. A known practice is to drill fold hinges to take maximum advantage of enhanced fractures development. However, in argillaceous limestone, pressure solution develops under very low confining pressure and frequently accompanies fracturing. Fractures are quickly filled by carbonate deposition, and either limb may exhibit greater fracture porosity than the hinge. In such cases, cemented fractures along the axial plane act as barrier to hydrocarbon migration and divide the reservoir into forelimb and back limb domains of different reservoir pressure and oil/water or gas/water contacts.

Several stratigraphic horizons have proved to be potential reservoirs underneath the northwestern foreland basin of North Pakistan such as Lumshiwal-, Hangu- and Lockhart Formation. For optimized drilling and production it is obligatory that the surface outcrops of these reservoirs should be analyzed for their fracture system. Samana Anticline was chosen for this study because (a) its geometry is typical of a fault-related fold (b) it exposes the Lumshiwal formation of Cretaceous age while Hangu and Lockhart Formation of Paleocene age that are regionally important reservoir units and (c) it offer accessible outcrops covering a broad range of structural positions. The purpose of this study is an assessment of orientation and size characteristics of fracture systems at locations throughout the Samana Anticline in order to evaluate the fractures density, connectivity and dimensional parameters and its role in secondary permeability and porosity.

For this purpose several fracture measurement stations were established at different locations including the limbs and crest of Samana Anticline within the Lumshiwal, Hangu and Lockhart Formation. Attempts were made to concentrate on selecting measurement stations on bedding surfaces; however at few locations, data was also collected on bedding perpendicular exposures as well. The fracture data was collected at various locations using area measurement techniques. At each measurement station, the orientation, trace length and aperture of all visible fractures that are totally or partially within the defined measurement area was determined. These fundamental field data was used to fulfil the above-mentioned objectives.

GEOLOGICAL SETTING OF SAMANA ANTICLINE

The Samana Range along with Kohat Fold Belt is located in the Lesser Himalayas of North Pakistan, a product of the enduring collision between the Eurasian and Indian plates in the middle to late Eocene (Molnar and Tapponier, 1975; Stocklin, 1974 and Stonely 1974) It defines an east-west trending fold-thrust belt system that separates the meta-sedimentary rock assemblages of Peshawar Basin in the north from the platform to Plio-Pleistocene sediments of the Kohat Fold Belt (Figure 1).

Samana Anticline is the southern most of the enechelon fold assemblages that characterize Samana and Kohat Range. This fold is wide with a half wavelength of about 5 km

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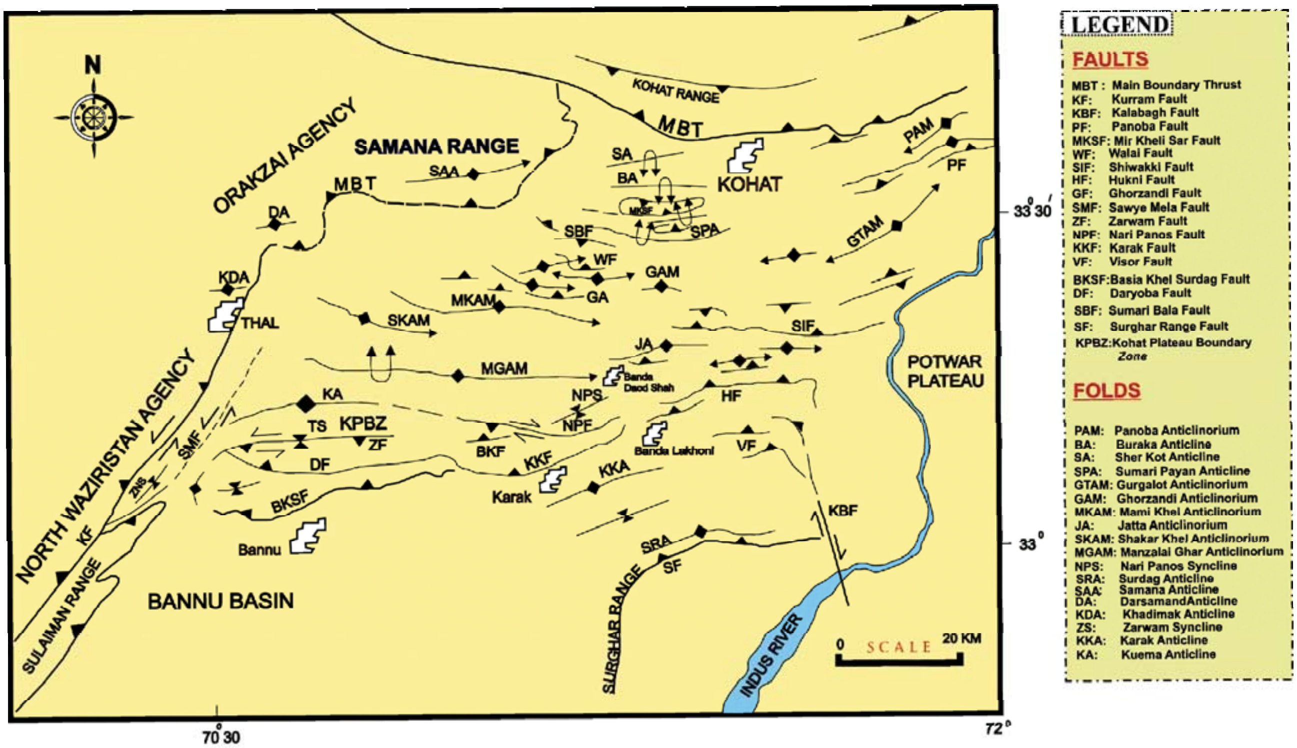

Figure 1- Structural Map of the Kohat Plateau modified after Ahmad et al., 2004.

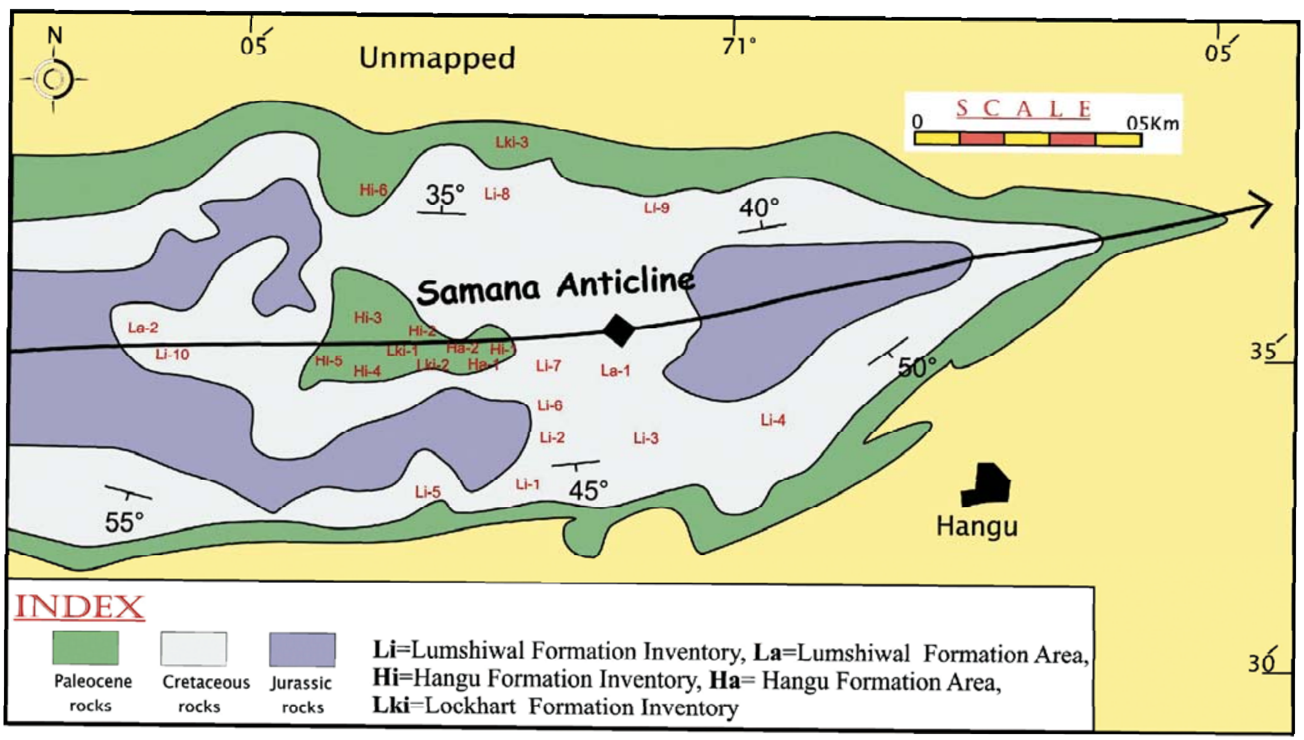

Figure 2- Geological map of the Samana Anticline showing location of the Measurement Stations.

and a strike length of more than 20 km in the study area (Figure 2). The fold axis is sub horizontal and trends east west which is parallel to the regional structural trend of the Kohat Belt (Ahmad et al. 2004). Ahmad et al. 2004 interpreted Samana Anticline to be a fault propagating anticlinal fold detached at the level of Jurassic rocks. The altitude data along this fold suggest a southwards asymmetry.

GENERAL CHARACTERISTICS OF FRACTURE DEVELOPMENT

The detailed account of parameters that characterize the fracture pattern of Lumshiwal-, Hangu-and Lockhart Formation exposed at the surface of Samana Anticline is given in table no.1 to 3. Three basic forms of macroscopic scale deformational features are observed along the Samana Anticline: extension or opening-mode fractures (joints and veins), shear fractures and pressure solution seams (stylolites).

Extension fractures are the most common of these fractures on Samana Anticline and are well developed in almost every outcrop of the Lumshiwal-, Hangu- and Lockhart Formation. Shear fractures are predominantly oriented at high angle to bedding, and commonly form in two distinct sets of orientation. These two different sets appear to be geologically contemporaneous. The majority of the fracture aperture is in the range of 0 .1 to 0.2 mm. Bedding-parallel pressure solution stylolites are well developed within all the three selected reservoir horizons that are Lumshiwal-, Hangu- and Lockhart Formation (Figure 3).

Fractures commonly do not terminate at bedding contacts as none of the three reservoirs display distinct mechanical layering with regard to fracture development. Fractures with finite aperture are occasionally filled with mineral cement that is dominantly calcite and quartz as well. Calcite and quartz cements coexist in many fractures within the sandstones of Hangu-and Lumshiwal Formation.

DIMENSIONAL CHARACTERISTCS OF FRACTURES

Twelve measurement stations were established in Lumshiwal Formation, with six on forelimb, four on crest and two on back limb (Figure 2). In Hangu Formation six measurement stations were established, out of which five are located on crest of the Samana Anticline and one on its fore limb. Two stations were analyzed on the crest of Samana Anticline within the Lockhart Formation and only one locality was available for measurements along the back limb of Samana Anticline. These stations represent a variety of structural positions through the Samana Anticline. Extension fractures are the most common of all types of fractures and generally occur as two distinct sets (Figure 4). One of the set is roughly aligned parallel to the axial trend of the fold that is east-west and the other set is roughly oriented transverse to the fold axis that is north-south. Both these orientation sets are better developed in terms of number and length. No consistent timing relationships are suggested between abutting and cross cutting fracture orientation nor does mineral cement in the fractures indicate a temporal distinction between different orientation sets.

Throughout the forelimb of Samana Anticline the dominant orientation set observed within Lumshiwal Formation include extension-mode fractures oriented nearly transverse to the fold axes that is ENE (Figure 4). Using the abc-coordinate reference frame for folds this fracture system is an ac-orientation set (Figure 5). On the forelimb another extension-mode fracture orientation set is well developed and corresponds to the bc-orientation set.

Throughout the crest of Samana Anticline the fracture orientation measured within Lumshiwal-, Hangu- and Lockhart Formation share more or less similar structural trends. Two distinct sets of extension-mode fractures that are transverse and sub parallel to the axial trend of Samana Anticline characterize it and correspond to ac- and bc-orientation sets. Another couple of distinct shear-mode fractures sets characterise the crest of this anticlinal fold and define conjugate fracture system and are oriented NW and NE.

FRACTURES CONNECTIVITY

The connectivity of fracture networks developed across Samana Anticline is investigated by tracing fractures in photographs taken at measurement stations within the Lumshiwal-, Hangu- and Lockhart Formation (Figure 6). This analysis clearly demonstrates that fractures at all of the measurement stations within Lumshiwal-, Hangu- and Lockhart Formation are linked to form an extended connected fractures network. The impact of fractures density and scaling on the connectivity of these fracture system is negligible and the connectivity is a scale invariant phenomenon within all the three reservoirs exposed within the Samana Anticline. Fractures throughout Samana Anticline are developed in distinct orientation sets. At any particular location, one set is generally dominant in terms of numbers and length. The directional character of the connectivity that results from these non-random fracture orientations will be expectedly much higher in the direction of the dominant fracture orientation. However, it can be inferred that the extension-mode fractures that are oriented east-northeast and north-northwest are characterised by high trace lengths and should be the best for conductivity and transmissivity of hydrocarbons within all these three reservoirs underneath the Kohat Plateau.

FRACTURES DEVELOPMENT VS. STRUCTURAL POSITION

One of the primary intentions for this study was to evaluate variations in fracture development as a function of structural position. The data obtained on Samana Anticline provide the material for a case study of fracture patterns.

A) Fracture Orientation vs. Fold Geometry

Stearns, 1967 proposed that fold axis parallel (bc) and fold axis orthogonal (ac) are the dominant orientation trends for extension fractures and pointed out that these specific trends are related to the stress fields associated with the folding process. Further, where shear fractures are common, they form in conjugate sets symmetric around the same orientation trends. Extension as well as shear-mode fractures through out the map extension of Samana Anticline are in agreement with Stearns model of fracture geometry (Figure 7).

Table 1 - Dimensional characteristic of individual Fracture sets within Lumshiwal Formation Samana Anticline measurement stations.

Station	Set	So	N	π	ρ(cm-1)	τ (cm)
Li-1	1	**070/25**	19	052/60	0.24	1,242
	2	………..	7	095/74	………..	………..
	3	………..	6	045/22	………..	………..
Li-2	1	**080/35**	12	310/80	0.28	357
	2	………..	7	80/70	………..	………..
	3	………..	7	160/75	………..	………..
Li-3	1	**090/30**	12	320/45	0.2	583
	2	………..	21	120/73	………..	………..
Li-4	1	**070/35**	15	202/69	0.22	639
	2	………..	4	0707/38	………..	………..
Li-5	1	**060/20**	16	073/59	0.19	556
	2	………..	7	040/76	………..	………..
Li-6	1	**058/20**	16	115/75	0.65	1,004
	2	………..	2	310/53	………..	………..
	3	………..	6	070/52	………..	………..
Li-7	1	**090/20**	27	300/46	0.14	609
Li-8	1	**180/50**	4	165/73	0.14	609
	2	………..	5	140/40	………..	………..
	3	………..	10	110/50	………..	………..
	4	………..	8	020/65	………..	………..
Li-9	1	**090/10**	16	110/66	0.19	3,819
	2	………..	10	010/67	………..	………..
	3	………..	9	000/46	………..	………..
Li-10	1	**230/10**	3	170/72	0.26	737
	2	………..	4	160/76	………..	………..
	3	………..	4	050/75	………..	………..
	4	………..	15	Oct-78	………..	………..
LA-1	1	**000/000**	6	270/73	0.18	561
	2	………..	8	160/80	………..	………..
LA-2	1	**090/10**	15	360/76	………..	………..
	2	………..	8	280/74	………..	………..

So= Original Bedding, π = Mean Fracture Set Orientation,
ρ = Fracture Density & τ = Cumulative Trace Length.

Table 2 - Dimensional characteristic of individual fracture sets within Hangu Formation, Samana Anticline measurement stations.

Station	Set	So	N	π	ρ(cm-1)	τ (cm)
Hi-1	1	**295/20**	16	205/78	0.11	911
	2	………..	3	010/77	………..	………..
Hi-2	1	**260/35**	12	140/74	0.23	627
	2	………..	8	020/80	………..	………..
	3	………..	10	090/74	………..	………..
	4	………..	2	065/75		
Hi-3	1	**000/000**	19	120/85	0.38	1,092
	2	………..	10	175/74	………..	………..
	3	………..	16	210/74	………..	………..
	4	………..	6	330/80	………..	………..
Hi-4	1	**090/30**	18	180/85	0.41	1,167
	2	………..	11	090/82	………..	………..
	3	………..	7	220/64	………..	………..
Hi-5	1	**065/30**	14	270/59	0.43	860
	2	………..	12	180/72	………..	………..
	3	………..	9	150/78	………..	………..
Hi-6	1	**100/45**	8	010/65	0.15	1,230
	2	………..	7	350/77	………..	………..
	3	………..	5	090/52	………..	………..
	4	………..	8	003/68	………..	………..
HA-1	1	**000/000**	27	290/77	0.14	609
	2	………..	2	210/76	………..	………..
HA-2	1	**290/15**	30	165/73	0.09	1,546
	2	………..	29	230/75	………..	………..

So= Original Bedding, π = Mean Fracture Set Orientation,
ρ = Fracture Density & τ = Cumulative Trace Length.

Table 3 - Dimensional characteristic of individual fracture sets within Lockhart Formation,Samana Anticline measurement stations.

Station	Set	So	N	π	ρ(cm-1)	τ (cm)
Lki-1	1	**180/15**	11	110/78	0.26	737
	2	………..	9	270/76	………..	………..
	3	………..	8	320/75	………..	………..
	4	………..	6	350/74		
Lki-2	1	**110/30**	12	010/68	0.54	700
	2	………..	24	290/52	………..	………..
	3	………..	14	225/70	………..	………..
	4	………..	6	040/75	………..	………..
Lki-3	1	**280/40**	4	360/78	0.13	1,081
	2	………..	30	160/55	………..	………..
	3	………..	13	030/65	………..	………..

So= Original Bedding, = Mean Fracture Set Orientation,
ρ = Fracture Density & = Cumulative Trace Length.

Figure 3- Bedding parallel Stylolites within Lumshiwal, Hangu and Lockhart Formations.

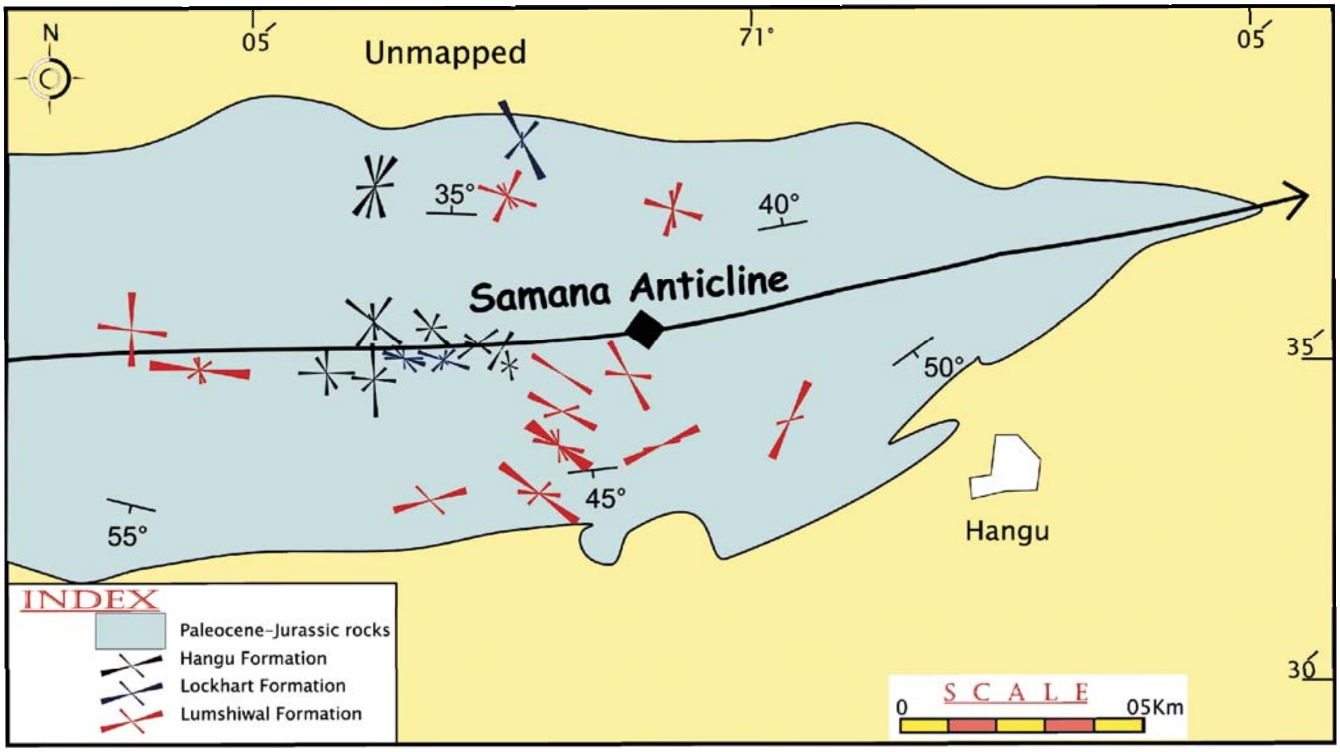

Figure 4- Geological map of Samana Anticline showing diagrams of the various Measurement Stations.

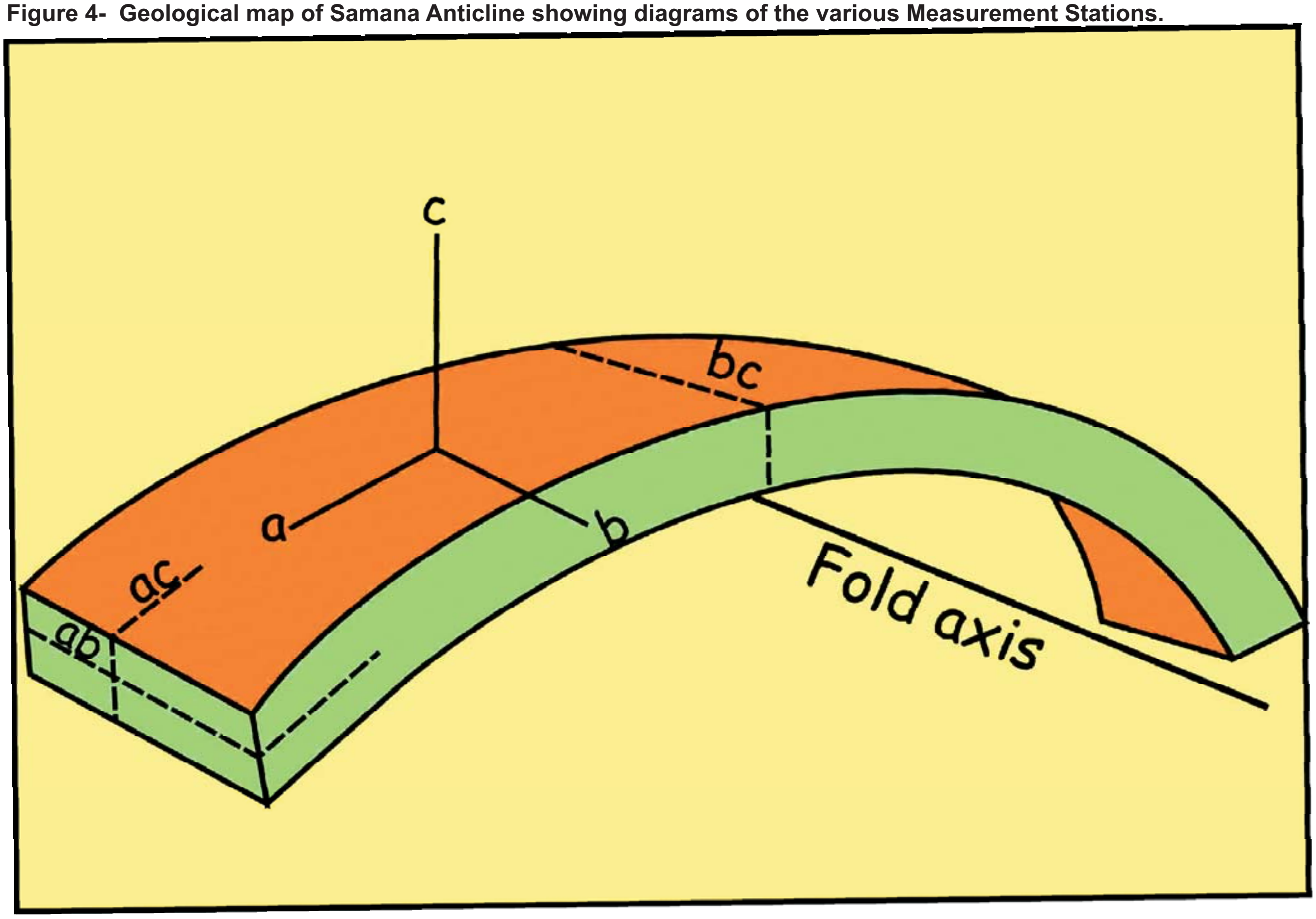

Figure 5- Abc-Coordinate System for folds after Hancock 1985.

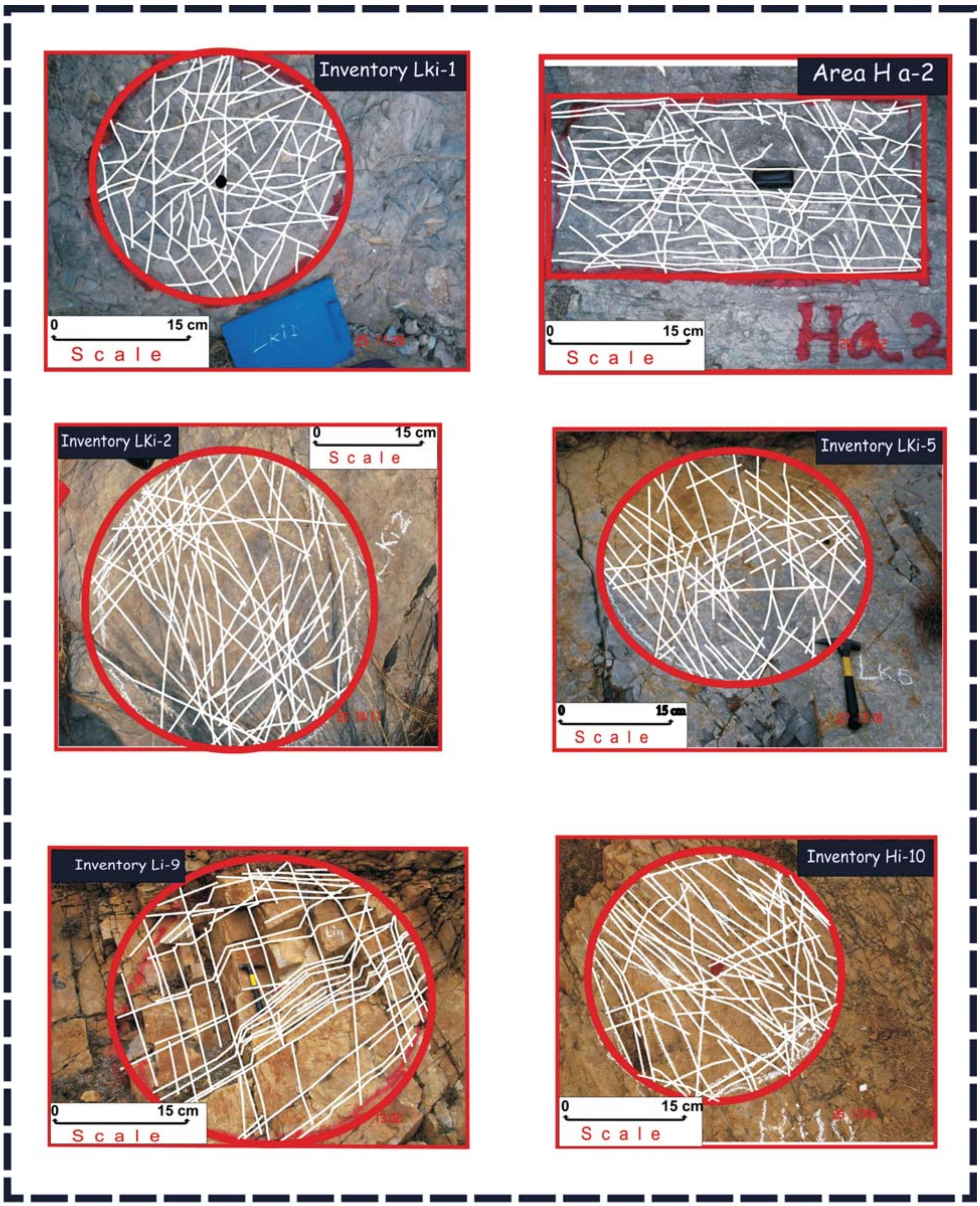

Figure 6- Diagram showing Fracture connectivity at various Measurement Stations along Samana Anticline.
Li= Lumshiwal Formation Inventory, Hi= Hangu Formation Inventory,
Ha= Hangu Formation Area, Lki= Lockhart Formation Inventory

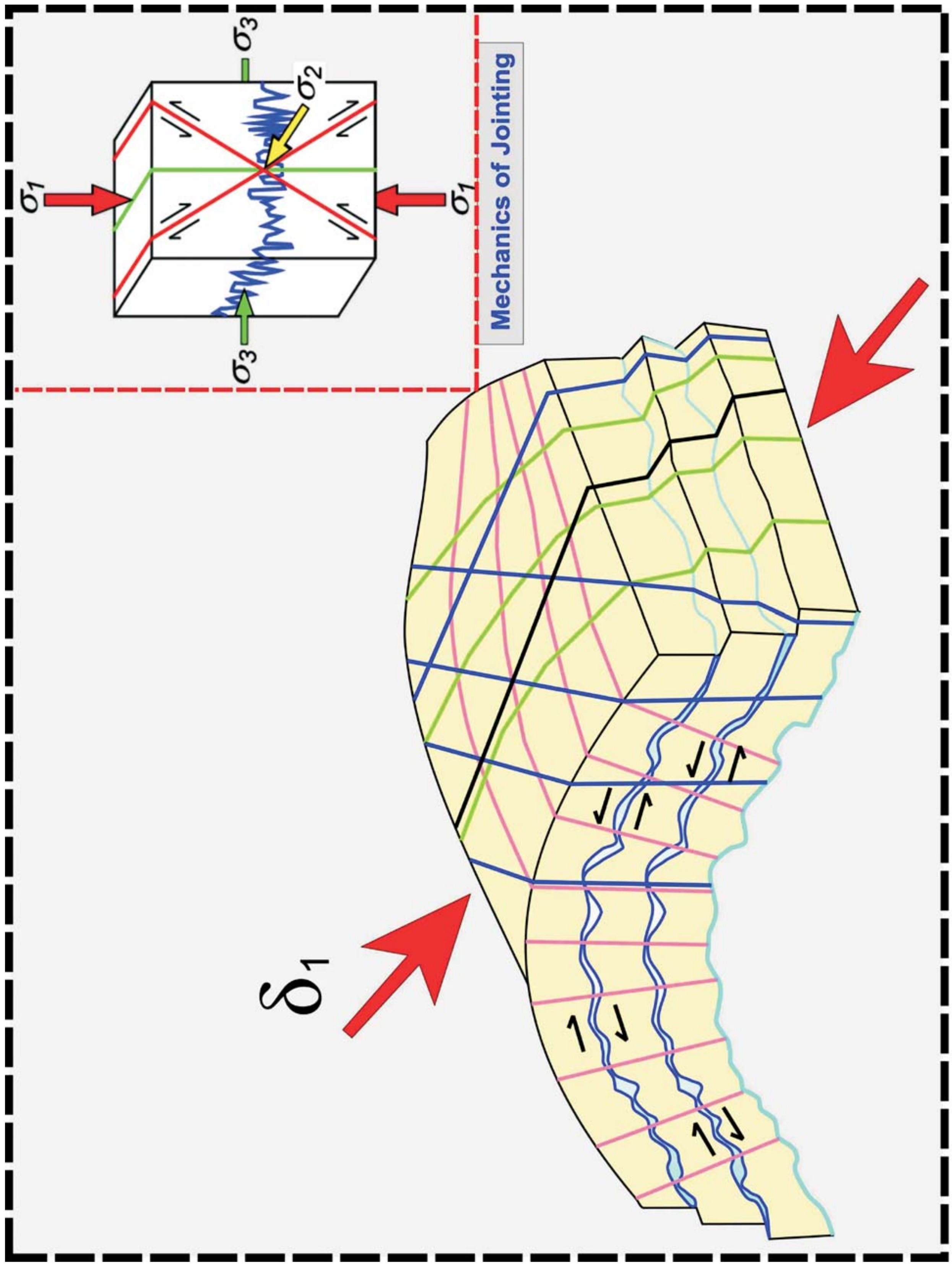

Figure 7- Fracture Geometry of the Samana Anticline.

B) Fracture Density vs. Fold Geometry

A common approach for predicting fracture density and aperture from fold geometry is the procedure called as radius of curvature technique. This approach based on the analysis of Murray, 1968 which relates fracture aperture directly to the degree of flexure that the bed of interest has undergone: the sharper the flexure, the greater the fracture aperture and density. Murray, 1968, assumed that (a) fracture aperture and density will increase with increasing strain and that (b) bending of the beds is the dominant strain-producing process in folded rocks. The data from Samana Anticline is in agreement with Murray, 1968 assumption. It has been found that fracture density is high at the crest of Samana Anticline, followed by the limbs (Figure 8). However, it has been found that the fracture density on the fore-limb of the Samana Anticline is characterised by greater fracture density as compared to the back limb.

C) Fracture Network Transmissivity vs. Fold Geometry

A fracture network facilitating reservoir drainage must be connected and the component fractures must be reasonable conductive on a production time scale for the reservoir fluids. Based on the dimensional character of fractures in Samana Anticline, fracture density appears to be the most critical factor for development of good fracture connectivity. According to Murray, 1968 there is a directly proportional relationship between fracture density and connectivity. Raising fracture density will enhance fracture connectivity. At most of the measurement stations on Samana Anticline a single dominant fracture orientation trend is evident, although there may be one, two, or three distinct but subordinate orientations sets which are parallel and transverse to the fold axis. The connectivity evaluation demonstrates that this fracture alignment imparts a significant directional character to the predicted connectivity orientation. The fracture density distribution data on Samana Anticline indicates that the fold hinge is the area of maximum connectivity followed by fore limb and back limb.

DYNAMIC AND KINEMATIC ANALALYSIS OF JOINTS ASSOCIATED WITH SAMANA ANTICLINE

The fractures data collected at various measurement stations within Lumshiwal-, Hangu- and Lockhart Formation bears a close geometric coordination with the orientation properties of the Samana Anticline (Figure 7). The Samana Anticline is found to be an east west trending, south facing asymmetric fold. It exposes a thick sequence of sedimentary rocks Jurassic to Paleocene age and mechanically defines a single competent structural lithic unit. Competent structural lithic units when subjected to compressional forces generally deform by the process of flexural slip folding. Joints that develop during the process of flexural slip folding are found to be of three types: a) cross joints which are oriented nearly perpendicular to the fold axis b) parallel joints that are sub

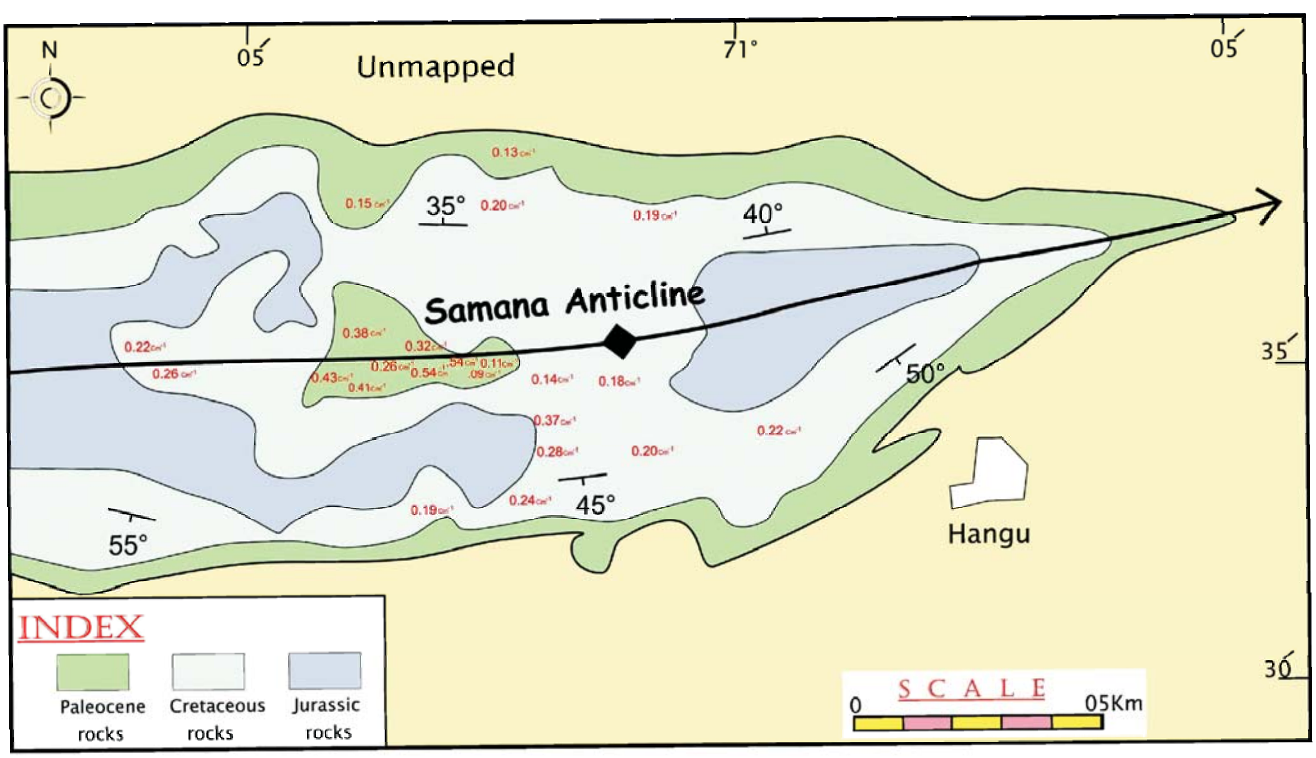

Figure 8- Geological map of the Samana Anticline showing the distribution of fracture density.

parallel to the fold axis and c) oblique conjugate joints that bear an oblique relationship with the fold axis (Figure 7). The fracture data clearly suggests that Samana Anticline has been deformed by the process of flexural slip folding whereby cross joints shows hinge parallel elongation. These are mostly filled, clearly expressing stretching.

Parallel joints are regarded as the most important for the reservoirs permeability and porosity, because these are generally planar and continuous. When strata are deeply buried and horizontally compressed, elastic strain is stored in the rocks. The energy may remain pent-up in the rocks for long periods despite some degree of jointing. When strata with stored energy are raised from deeper levels by thrusting, the strata are permitted to expand in response to progressively decreasing confining pressure. High confining pressure can as well contribute significantly to the development of fractures. Elevated fluid pressure can permit tensile stresses to exist at depths as large as 4000 meters and the tensile stress can overcome the inherently weak tensile strength of rocks to produce fractures.

All the data sets prepared for the Samana Anticline clearly suggest that all these fractures are synfolding tectonic fractures that developed synchronously as Samana Anticline evolved through time.

NATURE OF BEDDING SURFACES AND THEIR ROLE IN POROSITY AND PERMEABILITY

Throughout the map extension of Samana Anticline bedding surfaces observed within all the three formations that are Lumshiwal-, Hangu- and Lockhart are found to be characterized by stylolites (Figure 3). Bedding parallel stylolites are the result of the pressure induced dissolution of host rock in the presence of its own pore fluids when a sedimentary pile is quickly buried due to rapid sedimentation above it. The geologic record of the Kohat Plateau shows that the non-outcropping Jurassic to Paleocene rocks along with Eocene rocks were quickly buried under thick piles of molasse that is the product of Himalayan exhumation.

Bedding parallel stylolites in its undeformed state will look like jig saw puzzle with no voids. But if such a sequence is subjected to the process of flexural slip folding, which is found to be the case in the structural evolution of Samana Anticline, then a few mm bedding slip is most likely going to produce significant voids that could be critical in storage and flow of hydrocarbons.

CONCLUSIONS

The fracture network characteristics observed in Samana Anticline serve as a case example of the type of fracture system that should have developed in similar anticlinal closures underneath Kohat Plateau. The fractures developed throughout this structure bears close geometric correlation with its geometric properties and suggest that it has been evolved as a result of flexural slip mechanism. Fracture density is the primary factor affecting connectivity and porosity and is found to be highest at the fold culmination followed by forelimb and back limb. The conductive fractures are dominantly extension mode, east- northeast and north-northwest oriented and bedding parallel stylolites within all the three reservoirs Lumshiwal-, Hangu- and Lockhart Formation. The connectivity directions are dominantly east west and north south.

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Received Feb. 22, 2008, revised September 10, 2008 and accepted October 28, 2008. First the paper was presented in Annual Technical Conference of PAPG - SPE held in Islamabad, Pakistan, March 27-28, 2007 and published in its proceedings. Now the paper is being published after subjecting it to refereeing process outlined by Higher Education Commission , Islamabad, Pakistan.