FRACTURE PARTTERN ANALYSIS ALONG THE HAZARA KASHMIR SYNTAXIS, PAKISTAN

BY

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Abstract: *Fractures are the cracks or breakage within a compacted rock unit caused by brittle deformation and they play a major role in reservoir characterization. Major aim of the study is to perform fracture analysis to interpret paleo stresses and to define the orientation of maximum (σ1) intermediate (σ2) and (σ3) minimum principal stresses. Data was collected along the Main Boundary Thrust, Nathia Gali Thrust and western limb of Hazara Kashmir Syntaxis, NW Himalayas, Pakistan, by using circular inventory method. A total of 34 circles were drawn for different Mesozoic and Tertiary rock units at various locations. Fracture data includes orientation (strike and dip) of fractures, length of fractures, aperture (opening and filling of fractures) and density of fractures which describe the abundance of fractures. The interpretation of fracture data within the win-tensor program results in rose diagram and R. Dihedron diagram representing prominent (σ1) NW-SE orientation along the Main Boundary Thrust and western limb of Hazara Kashmir Syntaxis, some strike-slip components were also observed due to local stress effects within the study area. The results represent a compressional regime due to the collisional phase of Indian and Eurasian plates.*

INTRODUCTION

Fracture analyses are of different types such as outcrop analysis, core analysis, log analysis and curvature analysis but the present study deals with outcrop analysis. Fracture outcrop analysis describes the regional scale fracture distribution, their sizes and morphology.

In general fracture is a term typically used to emphasize that something is broken or any breakage crack in a rock. Any sort of mechanical crack or breakage occurs in a rock formation is known as fracture such as joints and faults. Fractures are the commonly developed structures and can develop when rock is too competent to withstand stress or due to the brittle failure in a rock. Carbonate reservoir fractures are important as they have an effective influence on reservoir rock properties such as porosity and permeability of a carbonate rock (Aghli et al. 2014).

During study, data was collected in field at different stations along Main Boundary Thrust (MBT), Nathia Gali Thrust (NGT) and western limb of Hazara Kashmir Syntaxis (HKS), Pakistan. Almost 34 circles were traced at different locations on different rock units. Several conventional methods and techniques are available for the collection of data in the field such as inventory circle method, scanline method and rectangular method (Jadoon, 2005). Mostly the circular inventory method is used as it is accurate and helpful in improving the efficiency to acquire data in the field. Parameters for fracture patterns observed and analyzed within the outcrop are circle diameter, fracture length, density, aperture, and fracture orientation. Secondly, stress tensors are also calculated from fracture data that has been gathered from the 34 inventory circles. This whole process requires a software interpretation, for the calculation of fracture plane directions and to know about paleo-stresses. Complete interpretation was carried out within a user-friendly program Win-tensor.

The Himalayan chain is a result of collision between Indian and Eurasian plate (Tahirkheli, 1979). The northward movement of Indian plate resulted in crustal shortening, forming geological structures, folds, and thrusts belts (Lillie et al. 1987; Ghazanfar, 1993).

Study area is located along MBT, NGT and western limb Hazara Kashmir Syntaxial zone (Fig.1). It consists of Lesser Himalayas and Sub Himalayas separated by Main Boundary Thrust. This area is represented by a thrust zone that places the older metamorphosed rocks over younger unmetamorphosed rocks. NGT overlies MBT towards North. Punjal Thrust overlies the Nathia Gali Thrust and merges within MBT along the core of HKS, and it is in the North-East corner of Pakistan between Mirpur and Muzaffarabad. It comprises of broader geological structures of Himalayas which makes an abrupt hair pin bend (Ghazanfar et al. 1986; Greco, 1993).

HKS is a complex tectonic zone and its axial zone is defined by the stack of thrust sheets forming a loop around its axis (Fig. 3). Precambrian to Neogene sedimentary, volcanic, and metamorphic rocks, Cambrian or early granitic rocks are exposed in Hazara Kashmir Syntaxial zone and its proximity. These rock units are punctuated by many unconformities. Axial zone of HKS has NNW direction and is covered by 1700m thick Murree Formation. It truncates the Murree Formation in east, west and north direction. Murree thrust is present on both limbs of Hazara Kashmir Syntaxis as MBT (Treloar et al. 1989, 1990, Greco, 1991). MBT circles around Hazara Kashmir Syntaxial Zone, this south verging thrust Fault terminates in Jhelum fault and bend southward towards Balakot.

Around Muzaffarabad, Precambrian, Cambrian, and Paleocene sedimentary rocks are exposed in an overturned and cross-folded anticline

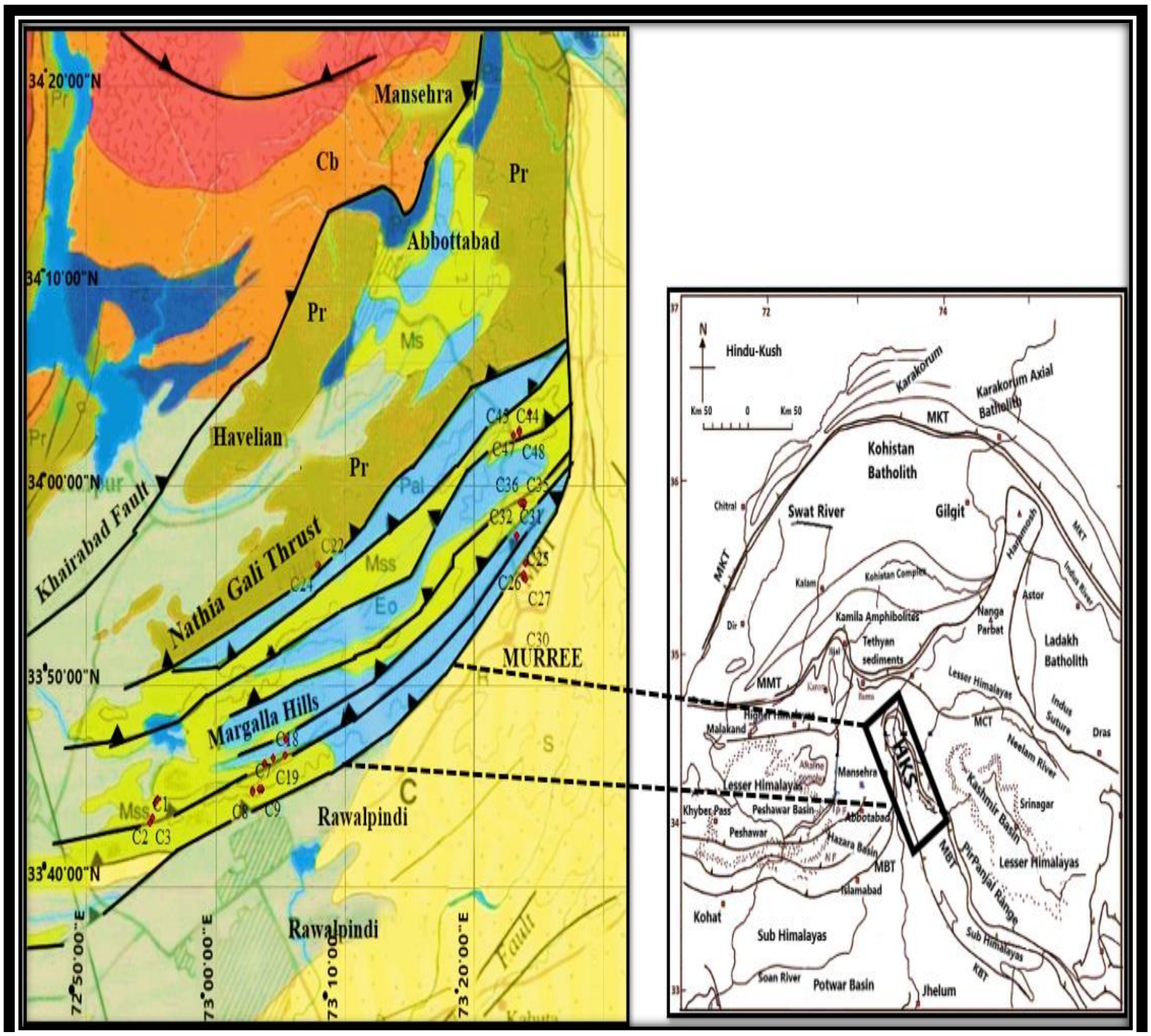

Fig. 1 (a) Location map of the study area. (b) Regional geological map of Northern Pakistan along with tectonic setting showing the study area Modified after Ahsan and Chaudhary (2008).

which thrusts in south west direction along Muzaffarabad fault. The dip of this fault is about 2025° East and this fault has brought older rocks towards west over Paleocene Limestone and Muzaffarabad Formation (Calkin et al. 1975). In north Balakot Hazara Kashmir Syntaxis bends towards north east Kaghan and beyond into Nanga Parbat Haramosh region where it is called as Nanga Parbat Syntaxis (Coward, 1985).

MATERIALS AND METHODS

The method used in study is circle inventory method. It is an easy and reliable method to perform fracture analysis. In this method a circle of a known and predetermined radius of about 40cm-100cm or less than 3 m is drawn and measured on the exposed surface of a rock unit containing fractures (Davis, 1996). Similarly, many circles are traced around selected fractures for analysis to measure the orientation, length, aperture, density (number of fractures) of each fracture within a circle. Orientation, length, and width of fractures are measured by using brunton, measuring tape and simple mathematical ruler and for coordinates global positioning system (GPS) is used. When required parameters of a fracture are measured within a circle then that circle is marked by chalk to avoid the problem of repetition.

Fractures

Fracture is a term used to emphasize that something is broken or cracked, in rocks fracture is a wide term including faults and joints developed due to brittle failure in rocks. They can form due to external tectonic or internal thermal stresses and are commonly developed structures, as they are found in all competent rocks with an increasing porosity and permeability factors.

MODES OF FRACTURE

Mode I

This mode is known as opening or tensile mode (Fig. 2). In this type, extension occurs in a cracked surface, and stress is perpendicular to the fracture surfaces (Lawn and Wilshaw, 1975). It is the most common mode type of fractures and develop within σ1 stress plane.

Mode II

A sliding mode or shear mode (Fig. 2) where shear stress is parallel to the surface having cracks and perpendicular to the fractured surface front. In this mode fracture surfaces displace parallel to each other.

Mode III

It is known as tearing mode (Fig. 2) in which shear stress act parallel to the fracturing surface and it is also parallel to the fracture front. Mode II and Mode III are oriented parallel to the sigma II stress.

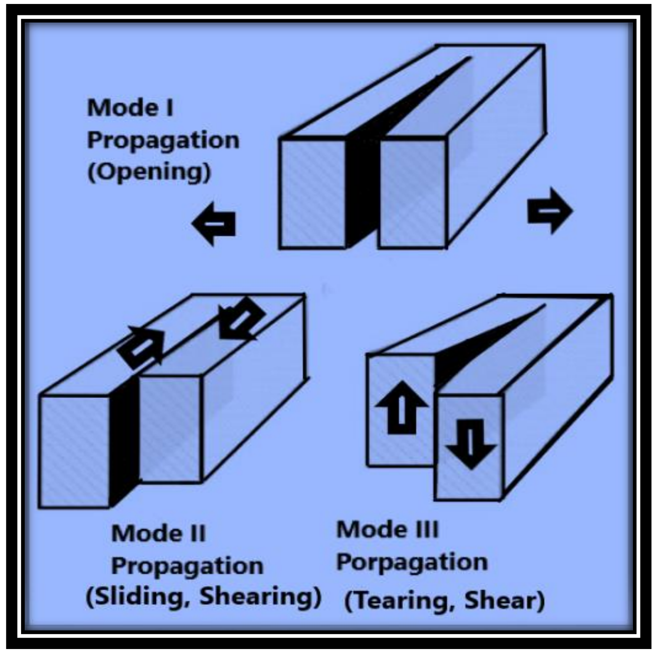

Fig. 2 The three displacement modes of fractures (Gudmundsson, 2011).

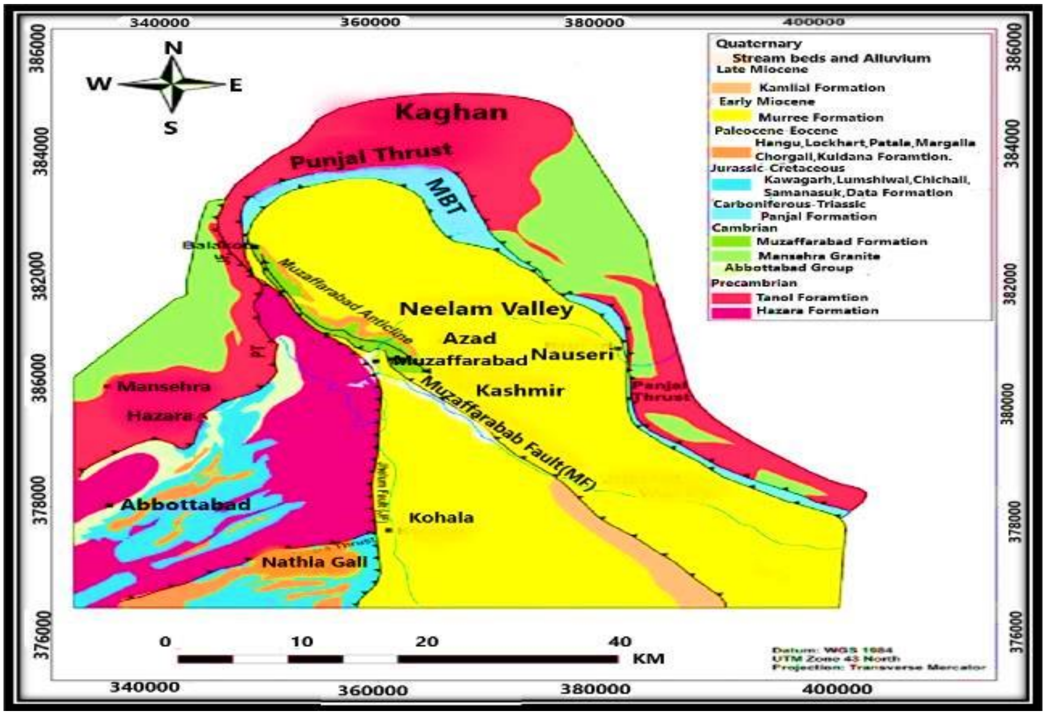

Fig. 3 Geological map of Hazara Kashmir Syntaxis (modified after Wadia 1931, Calkin et al. 1975; Baig and Lawrence 1987; Hussain et al. 2004).

FRACTURE PARAMETERS

Fracture Orientation

It exhibits connection of a fracture with its environment, defined as fracture plane by its dip angle and strike (Van Golf- Racht, 1982; Wang, 1992; Fossen, 2010). Generally, in fracture analysis strike is examined by rose diagram. The tectonic fractures can be bedding fractures, oblique fractures, and vertical fractures.

Fracture Density

Generally, observations show that dense strata with lamination have high density fractures. Fracture density describes the abundance of fractures present at a working station (Davis, 1996). Evaluation and measurement of fracture density can be done in numerous ways that is: total cumulative length of all fractures within a given volume of rock area of the circle. (Jadoon et al, 2003). According to Davis (1996) fracture density measurement along with circle inventory method is the sum of lengths of all fractures present in an inventory circle divided by an area of the circle. The equation is:

Fracture Density = $\mathbf{\Sigma\, L}/\,\boldsymbol{\pi r^2}$

Where, r = radius of the inventory circle

ΣL= Cumulative length of all fractures

Fracture Aperture

Fracture aperture also known as “fracture width” is generally an opening of a fracture and exhibits distance between fracture walls. Aperture depends upon host lithology, minerology, and the nature of normal and local stresses. It mainly plays a very significant role in determining fractures porosity and permeability for a reservoir (Van Golf-Racht,1982 Wang, 1992).

Fracture Length

Fracture length is a distance to which a fracture can be traced and interpreted. It depends upon the area occupied by fractures at a sampling station within the inventory circles. Length of fractures varies depending upon their different sizes. Large fractures have length up to meters with small associated fractures.

Fracture Porosity

Porosity is defined as the total ratio of voids within a rock to the bulk volume of the rock. It represents fracture opening area or void spaces.

Basically, porosity also represents connectivity of the fractures. It is derived from aperture, length, and density of a fracture at a given station (Jadoon et al, 2003). The formula for determination of fracture porosity in the inventory circle method is:

$$\textbf{Porosity} = (\mathbf{1/A})\sum^{N}{}_{\mathbf{1=1}} \cdot (\boldsymbol{L_i} \times \boldsymbol{W_i})$$

i = Index to classify each fracture in an inventory circle

Li = Length of the fracture

Wi= Width of the ith fracture

N = Fractures number present in the inventory circle

A = area of inventory circle

A comprehensive data was gathered by circular inventory method then interpreted within Wintensor software. This program is used for reconstruction of paleo-stresses from structural data. Data is entered from excel sheets or by formatted text files. There are many modules used within Wintensor program for interpretation of data such as stereonet, rose diagram, optimization, PBT method, right dieder method, rotational optimization method, mohr Diagram. The modules used for interpreting and processing of data collected for this study are rose diagram , stereonet and right dihedron method. Wintensor is developed and organized within two links data worksheet and processing worksheet. Different data parameters are present for each type of data set within the software. Data format selected for this data interpretation is 31/4.

RESULTS AND DISCUSSION

A very precise observation of the inventory circle data gathered in field survey is given as following:

Circle-1

Inventory circle of 50 *cm* diameter was drawn and maximum fractures within this circle were traced on the Margala Hill Limestone. It consists of sedimentary carbonate rock of Eocene age and is a nodular limestone. Margala Hill Limestone is a very good reservoir and is producing oil and gas in Potwar region. Dip direction of the bedding was towards SW and its strike direction was N 10° E. Most of the fractures are closed and filled with calcite and those which are showing opening they are having aperture range from 01-1.9*cm*. It comprises of two fracture sets. Set 1 is represented by blue color and Set 2 is represented by orange color (Fig. 4). Mostly fractures in set 1 are representing the

blue color and Set 2 is represented by orange color (Fig. 4). Mostly fractures in set 1 are representing the EW direction and are older than set 2 fractures which are younger and showing NS direction (Fig. 5).

Formation: Margala Hill Limestone

Circle diameter: 50*cm*

Lithology: Limestone

Area of the circle =πr^2, r is radius of the circle

Area of the circle:7850cm^2

Fracture Sets: 2 (Set1blue, Set2 orange)

Prominent trend: NW-SE

Fracture density= Total length/ Area of the circle, =0.0088cm^{-1}

Total\Cumulative length=69.6 *cm*

Table 1. Fracture Parameters of circle 1.

Fracture No.	Length	Aperture
1	10	0.1
2	8	0.1
3	12.5	0.5
4	2.8	0.9

Fig. 4 Fracture pattern and their sets within circle 1.

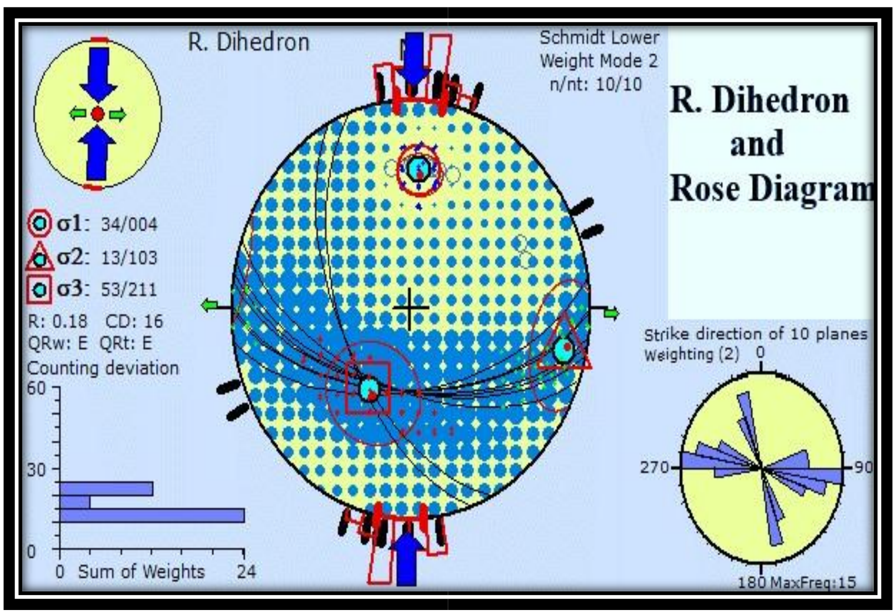

Fig. 5 Right dihedron and Rose diagram showing fractures and their stresses orientation of circle 1.

Circle-2

Circle was drawn on thin to medium bedded Lockhart limestone (Fig. 6). It comprises of light grey nodular limestone. Lockhart limestone act as a good reservoir for the generation of hydrocarbons in upper Indus Basin. It is a brittle type of limestone showing many fractures and joints within it. Circle diameter of about 60 *cm* was drawn covering prominent fractures. Dip of the bedding is 59°NE and strike is NW-SE. Aperture of these fractures ranges from 0.2 to 0.8*cm*.

Circle contains three fracture sets. Set 1 is the prominent fracture set having direction NNE-SSW (Fig. 7) whereas the Set 2 and Set 3 are the less prominent.

Formation: Lockhart limestone

Circle Diameter: 60*cm*

Lithology: Limestone

Area of circle: 11304 cm^2

Fracture Sets: 3 (Set 1 blue, set 2 orange, Set 3 yellow)

Prominent trend: NNE-SSW

Fracture density = 0.02490088 cm^{-1}

Cumulative length = 282 *cm*

Fig. 6 Fracture pattern and their sets within circle-2 drawn on Lockhart limestone.

Table 2. Fracture Parameters of circle 2.

Fracture No.	Length	Aperture
1	26	0.29
2	37	0.8
3	40	0.3
4	20	0.6
5	8	0.31
6	29	0.69
7	18	0.25
8	13	0.6
9	52	0.5
10	39	0.3

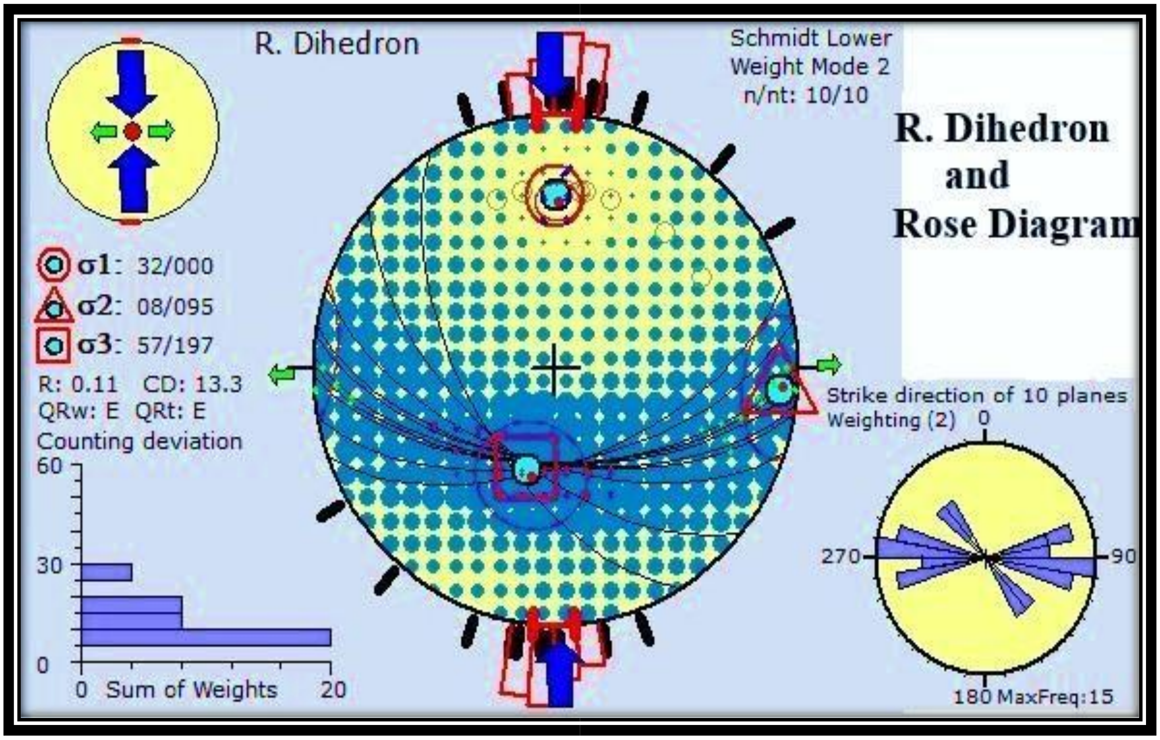

Fig. 7 Right dihedron and rose diagram showing fractures and their stresses orientation of circle 2.

Circle-3

Circle of about 100*cm* diameter was drawn on the outcrop of Samana Suk Formation covering prominent 5-10 fractures. At location, the formation consists of light grey to dark grey medium bedded limestone showing weathered brownish grey color. Dip direction of the bedding is 69°SE and strike are about N 45 E. It consists of three fracture sets. fractures opening ranges from 0.1 to 1.81*cm*.The most prominent is Set 1 then Set 2 (Fig. 8) and the least dominant set is Set 3 showing only one type of fracture orientation. They have prominent NE-SW direction (Fig.9).

Table 3. Fracture Parameters of circle 3

Fracture No.	Length	Aperture
1	73	1.81
2	24	0.15
3	52	1.13
4	20	0.7
5	98	2
6	56	2.9
7	50	2.65
8	34	1.6

Formation: Samana Suk Formation

Circle diameter: 100*cm*

Lithology: Limestone

Area of circle: 31400 cm^2

Fracture Sets: 3

(Set 1 blue, set 2 orange, Set 3 yellow)

Prominent Trend: NE-SW

Fracture density = 0.016 *cm*

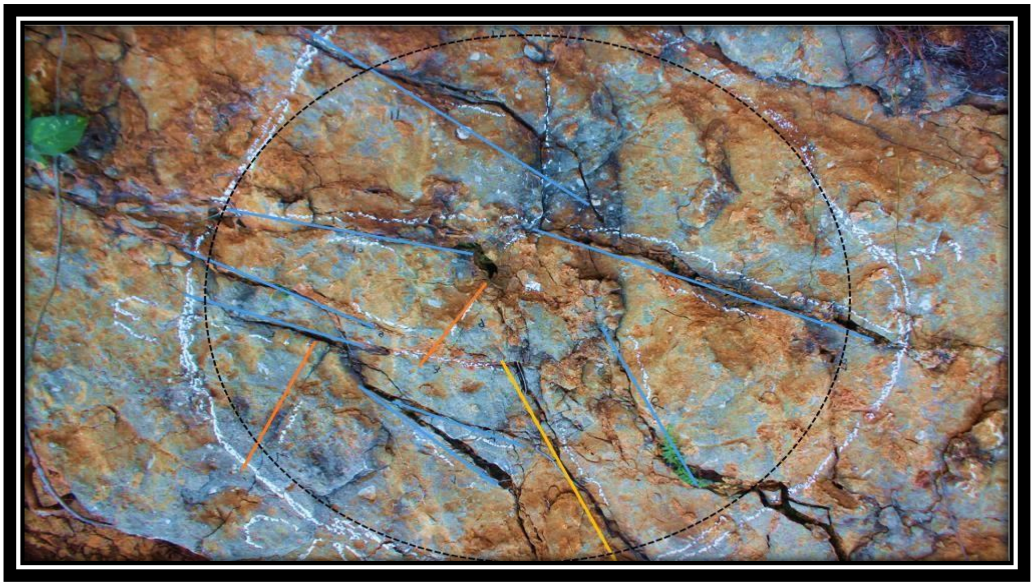

Fig. 8 Fracture pattern and their sets within circle-3 drawn on Samana Suk Formation.

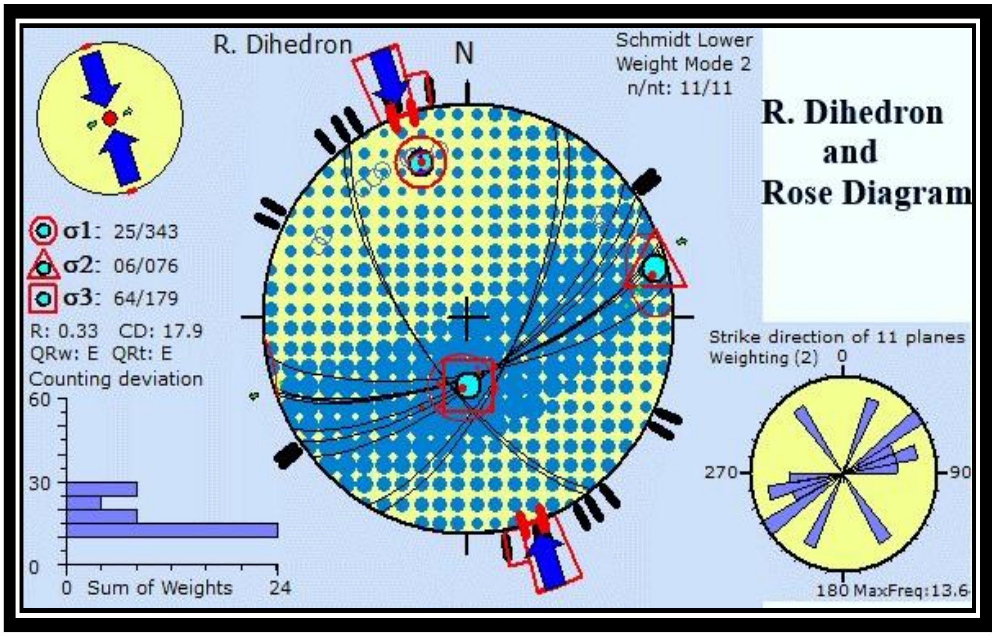

Fig. 9 Right dihedron and rose diagram showing fractures and their stresses orientation of circle 3.

Circle-4

A circle with a diameter of 50 *cm* was drawn on Lumshiwal Formation. The rock unit at the location consists of rusty brown to light grey compacted sandstone, showing weathered yellow brown color (Fig. 10). It is considered as a good reservoir with respective to hydrocarbon prospect. The fracture aperture is from 0.23-1.5*cm*. Circle consists of four prominent fracture sets including 5-15 fractures. Set 1 and Set 3 are the most notable fractures sets whereas Set 2 and Set 4 are less. The strike direction of the bedding is N 79°E and it dips towards NW. Maximum fractures direction is NE-SW (Fig. 11).

Formation: Lumshiwal Formation

Circle diameter: 50*cm*

Lithology: Sandstone

Area of circle: 7850 cm^2 , Cumulative length= 172 *cm*

Fracture Sets: 4 (Set 1 blue, set 2 orange, set 3 yellow,
Set 4 green)

Prominent trend: NE-SW

Fracture density = 0.0219 cm^{-1}

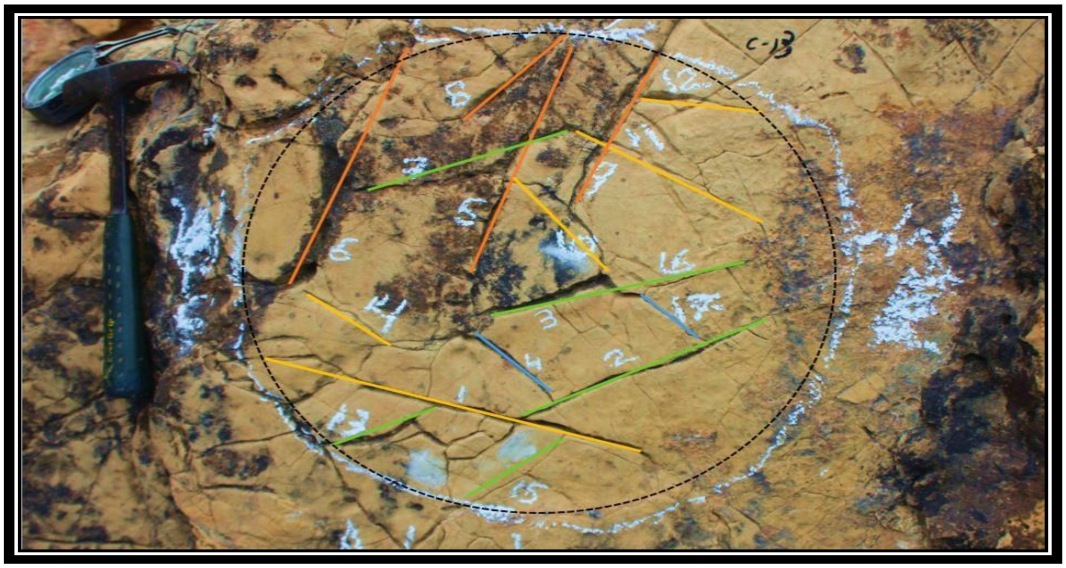

Fig. 10. Fracture pattern and their sets within circle 4

Table 4. Fracture parameters of circle 4.

Fracture No.	Length	Aperture
1	28	0.8
2	24	0.5
3	12	0.6
4	8	0.9
5	24	0.6
6	26	1.5

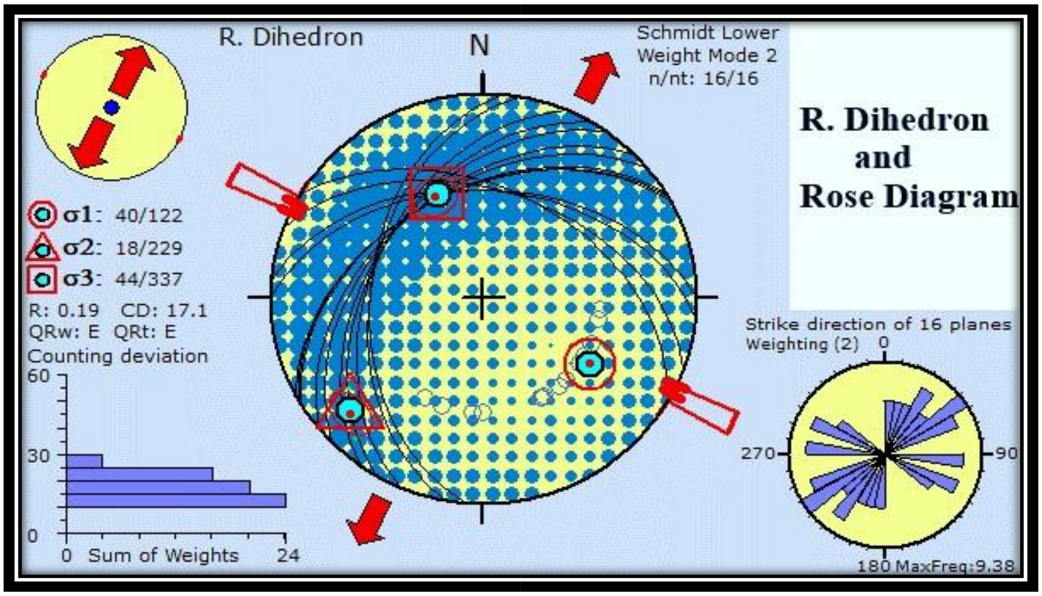

Fig. 11 Right dihedron and Rose diagram showing fractures and their stresses orientation of circle 4.

Circle-5

The circle was traced from Lockhart Formation at location it was thin to medium bedded. Formation comprised of partially nodular light grey to dark grey limestone. It acts as a source and reservoir in the upper Indus basin. A circle of diameter 50 *cm* was drawn covering maximum fractures almost 5-10 and their sets. Fractures were grouped in two sets as Set 1 and Set 2. Set 1 is represented in blue and Set 2 is represented in orange color (Fig. 12). The direction of the bedding dip is NE and strike direction is about N 56° W. Prominent trend is NE-SW (Fig.13).

Formation:

Lockhart Limestone

Circle diameter: 50*cm*

Lithology: Limestone

Area of circle: 7850 m^2

Fracture Sets:

2 (Set 1 blue, Set 2 orange)

Prominent trend: NW-SE

Fracture density = 0.0124 cm^{-1}

Cumulative length = 98 *cm*

Table 5. Fracture Parameters of circle 5.

Fracture No.	Length	Aperture
1	28	0.2
2	22	0.96
3	15	0.2
4	12	0.4
5	16	0.4
6	5	0.5

Fig. 12 Fracture pattern and their sets in circle-5.

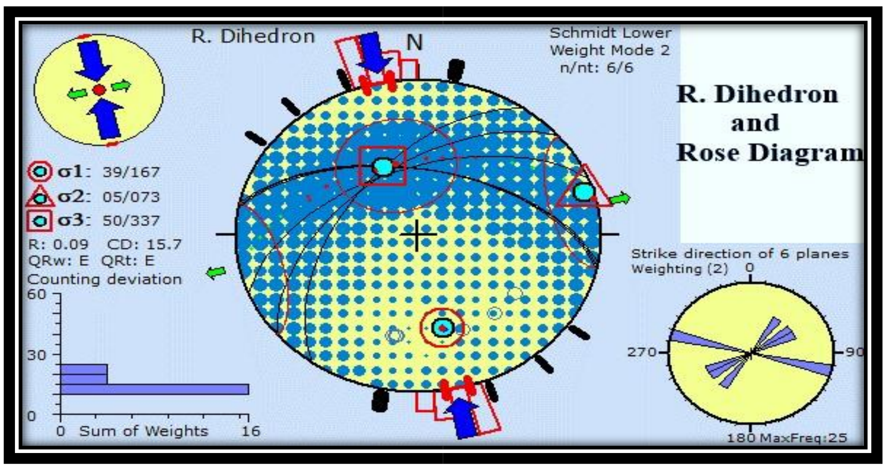

Fig. 13 Right dihedron and Rose diagram showing fractures and their stresses orientation of circle -5.

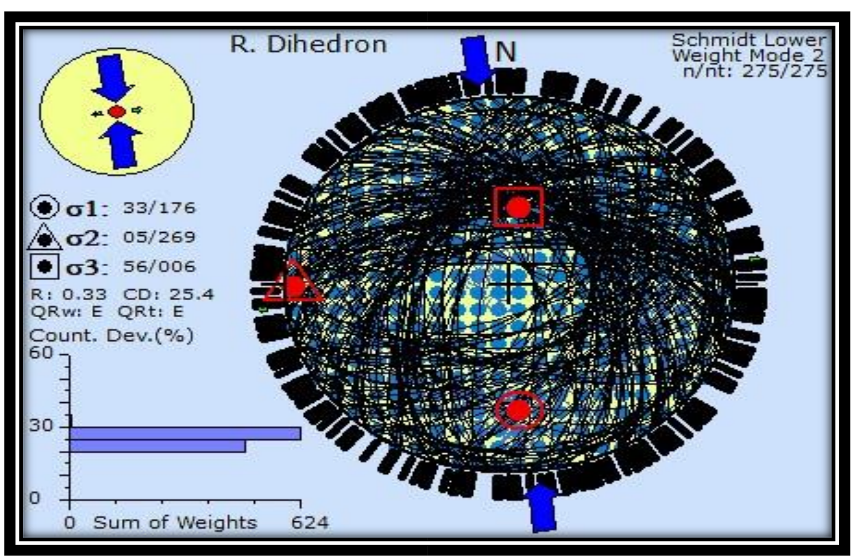

Fig. 14 Right dihedron diagram of total 34 circles showing compressional regime within study area.

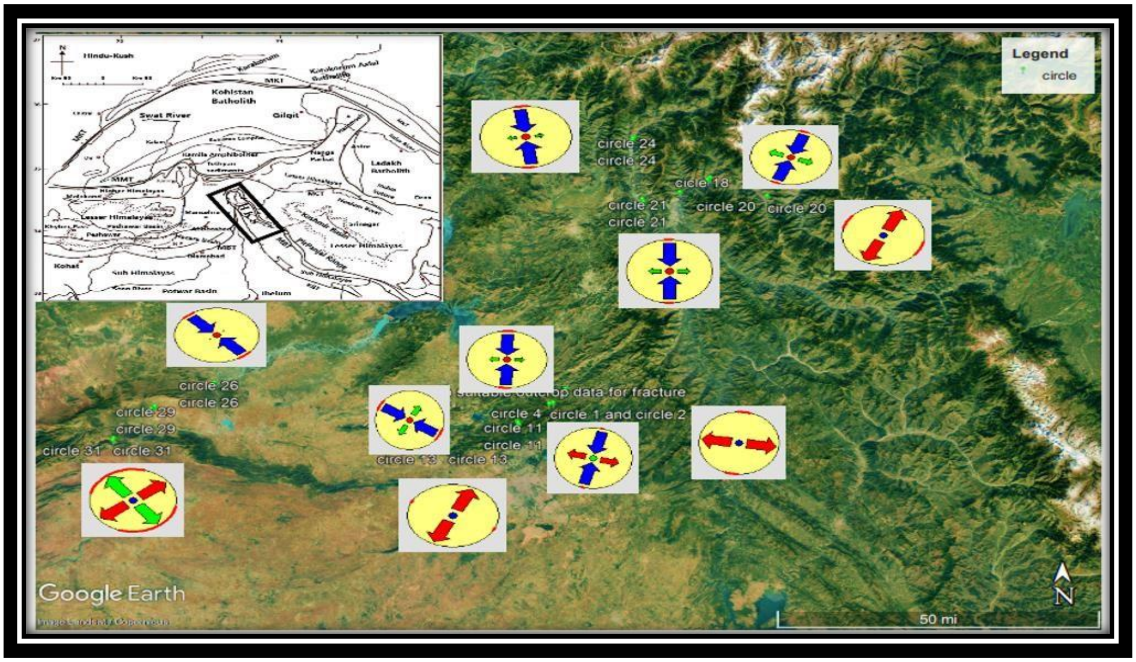

Fig. 15 Google Earth map showing the location of collected circle data within study area.

Stress Analysis

Fracture orientation mainly depends upon principal stresses, data for analysis plotted in rose diagram which provides a visual evaluation of stress orientation with respect to the data information placed within software (Baitu et al., 2008). The maximum principal stress is sigma 1, sigma 2 is intermediate stress and sigma 3 is the least principal stress with minimum direction of stress. There are two prominent sets of fractures observed, i.e., Set-1 NW-SE and Set2 NE-SW at the study area. $\sigma1$ and $\sigma2$ stress direction is horizontal whereas $\sigma3$ stress orientation is vertical in the compressional fractures (Jadoon, 2003).

Paleostress analysis is basically determination of stresses and their direction (orientation). The tectonic regime of theses stresses can be required by mechanical and tectonic responses including fracturing, faulting, folding and the relationship between tectonics and sedimentation (Angelier, 1994). Anderson describes that the principal stresses ($\sigma1$) is a maximum stress, ($\sigma2$) is intermediate stress and ($\sigma3$) is minimum stress.

Fracture data collected from the field is along the HKS covering the segment of MBT. Mostly data gathered for fracture analysis was collected from Cretaceous, Paleocene, and Eocene rock units. Different fracture patterns include shear fractures (parallel to bedding surface) are parallel to intermediate stress (Jadoon, 2003) the extensive fractures which are (perpendicular to bedding surface) (Billings, 1972). The fractures observed from different localities were divided into different sets, showing opening and somewhere completely/partially filling of calcite.

According to Nelson (1989) dense and compacted sheared fractures develop along the major structural features. As discussed here, mostly fractures represent NE-SW orientation of compacted and dense fractures pattern and these results explain compressional regime along the MBT. According to Billings (1972) shear fractures are oblique to the maximum principal stress $\sigma1$.

Results represent that the $\sigma1$ is horizontal which shows compression in the HKS area as according to Anderson (1905) $\sigma3$ is vertical and $\sigma1$ is horizontal in compressional area where thrusts and fractures are developed. As HKS represents highly dense structure composed of thrust sheets, due to the substantial stresses which were applied during the Eurasian and Indian plate collision. Due to this collision, many thrusts were developed and MBT is one of them. So, results from fracture pattern and their orientation represents a compressive stress regime along the Hazara Kashmir Syntaxis.

CONCLUSIONS

The laminated, dense, compacted, and brittle lithology is generally observed within the formations showing highly dense and complex fractures within the field area. That gives a comprehensive understanding of fractures patterns, their orientation, length, density, aperture, and stress regime. The paleo stress inversion results indicate that σ1 is horizontal. The prominent trend of fractures is in NW-SE direction and some fracture in NE-SW are observed along the HKS. During the study, some strike-slip components were also observed. In study area the overall tectonic regime is compressional.

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