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Regional Geodynamic Implications of Proterozoic Volcanic and Metasedimentary Sequences in The Kirana Hills, Punjab, Pakistan

Talal Ahmed[1,2] and Iqra Hassan[2,3]

[1]Department of Earth and Environmental Sciences, Bahria University Islamabad, 44000 Pakistan
[2]Earthocity Research Innovation Centre, Earthocity Islamabad, 45200 Pakistan
[3]Department of Geological Engineering, UET Lahore, 54890 Pakistan

Corresponding author ttalal.pg@gmail.com
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Abstract - The Proterozoic volcanic and metasedimentary sequences of Kirana Hills, Punjab, Pakistan, provide critical insights into the region geodynamic evolution of the northwestern margin of The Indian Shield. This study investigates the region stratigraphy, structural framework, and lithological variations of The Kirana Complex, and analyzes fracture studies to reconstruct regional geodynamic processes. The aim of this research is placed on understanding how volcanic and metasedimentary assemblages, along with deformation patterns, reflect the tectonic settings and subsequent crustal evolution of the area dated back to approximately 870 ± 40 million years. The studied region field investigations, geological mapping, and fracture analyses were combined with factor-mapped datasets. Fracture characterization was performed using circle inventory methods for the three sites to quantify structural orientation, density, porosity, and permeability. The rose diagram interpretation for the fracture analysis study was performed using permeability, and using the circle inventory method to understand tectonic deformation and fluid movement. The findings suggest that the region is exposed to Proterozoic sequences of volcanic rocks dominated mostly by rhyolite, basalt, dolerite, quartzite, and volcanogenic slates of mostly Hachi Volcanics and Mach Super Group with distinct evidence of multiple magmatic and tectono-metamorphic phases. Field evidence of felsic-mafic associations, mineralization (hematite, limonite, micaceous hematite, jasper, and bornite), and other alterations highlight fluid-rock interaction and multiple shifts of mineralization. The fracture studies show (i). Hadda Quartzite shows N-S oriented conjugate fractures associated with compressive stress and migration of paleo-fluids; (ii). In the Buland Hill Formation, there is evidence of radial and concentric fractures around volcanic vents with mineralized joints that indicate signs of hydrothermal activity; and (iii). The Foliation-aligned fractures of The Asianwala Formation suggest the related foliation-based shear deformation. Taken together, these characteristics point to the existence of an initial history of extensional regimes associated with continental rifting, then compressional reworking and progressive deformation. This work lies in its integration of fracture analysis study with regional structural and lithological studies and mapping of site characterization during the field analysis. This approach refines existing models of Kirana by linking fracture-controlled fluid migration to broader geodynamic processes.

Keywords: Kirana-Malani Basin, Volcanic Deposits, Metasedimentary Deposits, Fracture Analysis Studies

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Introduction

Several geological features are scattered throughout the region of Punjab, and The Kirana Hills found in the north of the province are some of the oldest geological formations. These hills belong to The Kirana Group, and are mainly formed of Precambrian basement complex rocks, which offer valuable data on the formations and even the tectonic movements of the region. The system of Precambrian basement predominantly consists of granite and granitic gneiss, and has undergone a quite distinguishable metamorphic transformation consequent to tectonic activity. This region has a nearly entirely crystalline base of igneous and metamorphic rocks that are covered with layers of sedimentary deposits that indicate the tectonic geological construction of this region over periods of millions of years. Studies have revealed that The Kirana Hills are structurally rugged, especially given the fault, fold, and shear zones that dominate the area (Davies and Crawford, 1971). Shah (1977) pointed out that the main structural trends exhibited in The Kirana Hills are steeply dipping faults and fractures, which suggested heavy tectonic activities in the area for a long time. This structural deformation is believed to have been caused by The Indian-Eurasian Plate convergence that produced the Himalayan orogenic cycle which to date still exerts compression force on the region (Gansser, 2017). These structural configurations are an interesting topic to explore the regional tectonics of the subcontinent, specifically within The Kirana Hills (Gansser, 2017).

Kirana Hills have also an interesting stratigraphic sequence that has evoked scholarly interest. Most stratigraphic works about the area have concentrated on the sandstone, conglomerates, and shale formations overlying the basement complex. Field studies of Kochhar (1998) revealed that The Kirana Hills show a multifacies succession and deposited in fluvial-lacustrine conditions; episodic changes in provenance fed by coarse-grained materials which predate increased tectonic activity and associated sedimentary provenance. The appearance of sedimentary rocks in this sequence can allow us to work towards reconstructing the paleoenvironment and depositional history of the region (Alam *et al*., 1992). Accessibility to the area has also boosted the application of geochronological analysis of Kirana Hills in the further understanding of its geological formation. Literature and research conducted using radiometric dating techniques like U-Pb zircon dating expect the basement rocks in this part of Pakistan to be more than one billion year old a fact that makes them among the oldest rocks in the entire country (Ghosh *et al*., 2022). These structures form part of the large-scale cellular fabric of The Punjab Shield that incorporates other smaller Precambrian outcrops such as The Salt Range and Hazara Hills. It is essential to understand the temporal aspects of these formations to reconstruct the tectonic framework of northern Pakistan and synthesize more general information about the geological history of The Indian Plate.

These studies provide a valuable understanding, but there are several critical gaps remain behind, the first is the structural configuration of The Kirana Hills, and its relation to Himalayan foreland deformation is not fully resolved. In second, the provenance and depositional environments of the overlying sediments remain insufficiently quantified (might be due to geogenic factors and mining activities), particularly regarding the response to regional tectonic pulses. Third, despite geochronological advances, there is limited integration of structural mapping, stratigraphic analysis, and isotopic dating to reconstruct the temporal and geodynamic evolution of this shield fragment. This study aims to bridge these gaps by conducting an integrated investigation of the region combining the detailed study of the formations by characterizing stratigraphic changes in the localities to better understand the variation changes and studying the trend of structural trends by performing fracture analysis studies. The novelty of this study lies in its integration of fracture analysis study with regional structural and lithological studies and mapping of site characterization during field analysis. This approach refines existing models of Kirana by linking fracture-controlled fluid migration to broader geodynamic processes.

Structure and Tectonics

Kirana Hills lie in a tectono-morphologically volcanic zone of The Himalaya related to the convergence of the Indian and Eurasian lithospheric plates, and characterized by prominent structural folds, faults, and lineaments. These structural features contain much useful data on the tectonic history of the region, because paleo-tectonic events are recorded by them at the time of their formation, and these include structures related to The Himalayan movement. This form of structural configuration infers that the region has undergone previous compressional stress and strain as common with orogenic tracts (Ghosh *et al*., 2022). This knowledge is vital to constructing models of seismotectonic activity and evaluating seismic hazards, because The region is situated near active faults (Chaudhry *et al*., 2022). The tectonic map of the region is shown in Figure 1.

Besides structural analysis, stratigraphic work is also very important in understanding the depositional setting and sedimentary successions of The Kirana Hills. These sedimentary covering rocks above the basement rocks are sandstone, conglomerate, shale deposits which indicate fluvial and lacustrine environment of deposition, that has undergone various tectonic and transformation for geological time (Kochhar, 1998). These ancient sequences of reefs give geologists an ability to look at past climates, tectonic activity, and erosion rates and thus, replicate the paleo-environmental conditions of the area. Analysis of such sediments composition and grain size and their orientation can provide the geologists with the conclusions about the provenance of the materials that were delivered to the basin as well as more general conclusions about the

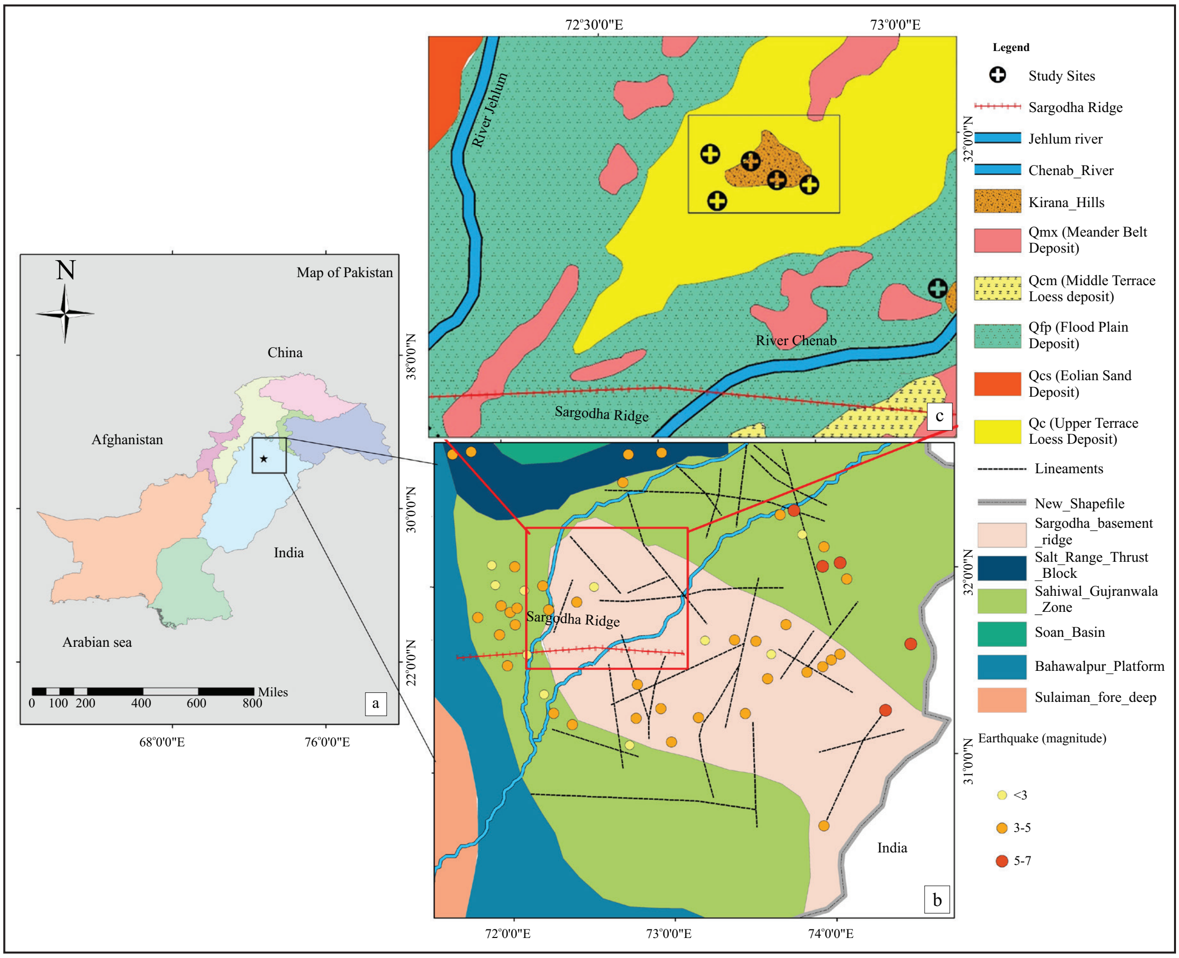

Figure 1. Tectonic-geomorphic framework of the studied area showing tectonic features and surrounding structural elements; (a) Geographical location of Pakistan indicating the regional locality of the studied area; (b) Geological-tectonic configuration highlighting Sargodha Ridge, SRT block, Platform(NW), Foredeep (SE) and associated structural lineaments. Earthquake epicentres illustrating seismic activity along the basement ridges and thrust systems; (c) Enlarged view of the studied area showing geomorphological units indicating Kirana Hills (є), meander belt deposits (Qmx), middle terrace loess deposits (Qcm), floodplain deposits (Qfp), eolian sand deposits (Qcs), and upper terrace loess deposits (Qc).

tectonic activity within the region (Davies and Crawford, 1971).

Regional Geodynamics

The Proterozoic volcanic and metasedimentary sequences of Kirana Hills record significant tectono-thermal and magmatic events that reflect the broader geodynamic framework of northwestern Indian Shield (Deb, 2014). These lithological assemblages indicate an episode of volcanism, sedimentation, and subsequent metamorphism associated with rifting, subduction, and possible collisional processes during The Proterozoic in an igneous suite of Kirana-Malani (Kumar and Sharma, 2021). In Pakistan, the geodynamic shift highlights the role of Kirana Hills as tectonic window of Aravalli Ranges, along the northwestern margin of Gondwanian fragments (Bhatti *et al*., 2017; Pant *et al*., 2020). Geochemically, volcanic members can be mantle-based magmas, associated with continental rift conditions, and metasedimentary units preserve signatures of basin, and subsequent deformation (Khan *et al*., 2017). Similarly, a recent research conducted by Ali *et al*. (2025) provides an in-depth discussion of the Neoproterozoic Sharaban Formation by combining field observations with petrographic analysis, the use of geochemical methods (XRD, SEM), isotopic studies, seismic imaging, and regional data. The geodynamic evolution of Kirana (KMB) starts in different stages; (a) stage 1; refer to rifting and volcanism stage ~870 Ma in which extensional tectonics initiated rift related volcanic activity (Verma and Greiling, 1995), (b) stage 2; refer to volcano-sedimentary deposition in which there is accumulation of volcaniclastic and metasedimentary sequences take place (Sharma, 2004) (c), stage 3; refer to compression and fracturing in which the regional compression is caused by deformation, fracturing and folding (Chaudhry *et al.*, 1999) (d), stage 4 refers to fluid migration and mineralization in which hydrothermal fluids circulated along fractures, depositing calcite and quartz veins and the last stage (Gansser, 2017), (e) stage 5 refers to the present structural framework in which erosion and tectonic uplift produced isolated hillocks and deformed rock assemblages (Davies and Crawford, 1971).

Geological Setting and The Studied Area

Kirana Hills are an important geological feature with major patterns of stratigraphy and tectonism. These hills are part of The Kirana Group. The basement complex includes Precambrian granitic and metamorphic rocks that interact with sedimentary layers. The structural style of The Kirana Hills has drawn the interest of geologists for decades. The models of these structures can help interpret the tectonic history of the region and the formation of The Indian Plate (Davies and Crawford, 1971). This region is not only a powerful archive of the geological past of the India region, but it is also a prime example to comprehend the fundamental mechanics of continental tectonics and strata building (Valdiya, 2015). The Kirana volcanics are an integral part of the world largest felsic volcanic field known as Malani Volcanics occupying tracks along the northwestern flank of the great Aravalli Mountain ranges with scattered outcrops extending from Tosham in Haryana to other places in northern districts of Rajasthan. Thus, Kirana Malani may be described as a volcanoplutonic province characterized by the widespread Late-Proterozoic tectono-magmatic activity (spanning over 950 Ma to 550 Ma) with distinct rhyolitic flows and associated granites (Chaudhry *et al*., 2022). The volcanic suites belong to tholeiitic basalt andesite-rhyolite magma association (Ahmad, 2000). The volcanics are interbedded with intercalations of volcanogenic sediments and tuffs. The overlying metasedimentary units are Tuguwali phyllites and Asianwala quartzites respectively (Alam, 1987). These upper Proterozoic rocks are made up of rift-related bimodal volcanics and volcaniclastics, which are overlain by low-grade coarsening metasediments that go higher. Heron (1913) also classified Kirana exposures as part of the Precambrian basement. Farah *et al.* (1977) conducted comprehensive gravity investigations, and determined that rocks exposed in Pakistan in Kirana (Punjab) and Nagar Parker (Sindh) are components of an NW-SE buried ridge of the "Indian Shield". Furthermore, the Punjab exposures were fault-bound steep horst complexes. Jan *et al.* (2022) interpreted magnetic data and identified Kirana (Pakistan) and Tusham and Rajasthan exposures (India) as part of a NW-SE buried ridge of the Indian Shield. Kazmi and Jan (1997) also classified Kirana rocks as part of The Indian Shield. Chaudhry *et al.* (1999), Ahmad and Chaudhry (2008), and Khan *et al.*, (2009) conducted extensive research in the area, and concluded that Kirana igneous and metasedimentary rocks can not be correlated with rocks from India's Vindhyan Basin, and thus are not part of The Aravalli orogen, which is part of The Indian Shield. Instead, they are part of a rift-related tectonomagmatic upper proterozoic bimodal volcanic, hypabyssal, and clastic metasedimentary sequence. Davies and Crawford (1971) dated the igneous activity between 850 and 750 Ma. The igneous activity may be linked to the breakup of The Rodina Supercontinent and the opening of The Mozambique Basin as a result of the rising Mantle Plume (Chaudhry *et al.*, 1999). The regional geological map (Figure 2) shows The Precambrian outcrops (ϵ) associated with volcanic-metasedimentary sequences, representing The Precambrian shield fragments. These rocks have undergone multiple phases of deformation and metamorphism, pointing to their association with The Proterozoic orogenic cycles.

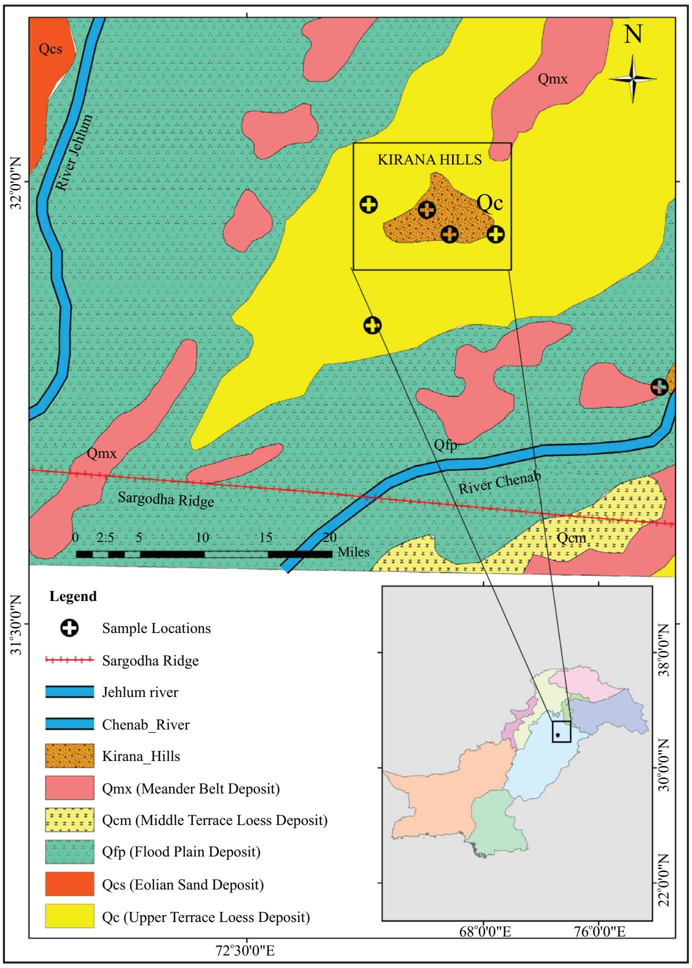

Figure 2. Geological map of the region, showing Kirana Hills (ϵ) exposure shaded in brown, marking Proterozoic sequences of volcanic and metasedimentary rocks forming resistant inselbergs within Punjab Plains. These basement exposures are surrounded by Quaternary deposits of Upper Terrace (Qc), Flood-plain deposits (Qfp), and middle terrace depoists (Qcm), along with recent sand deposits (Qcs) and meander deposits (Qmx), which reflect alternating fluvial, Aeolian, and loessic depositional regimes linked to the river. The Sargodha Ridge (dashed line) represents
a basement uplift influencing sedimentary architecture and fluvial patterns.

They form the resistant topography in contrast to the surrounding Quaternary cover. The crystalline basement is surrounded by unconsolidated deposits reflecting fluvial, aeolian, and loess sedimentation controlled by The Chenab and Jhelum Rivers; Qc (Upper Terrace Loess Deposit) - widespread yellow deposits indicating wind-blown silt accumulated during arid climatic phases. Qfp (Flood Plain Deposit) - Riverine alluvium from Chenab and Jhelum Rivers, deposited during periodic flooding events. Qcm (Middle Terrace Loess Deposit) - The loess of intermediate ages which represents the humid-arid climatic changes. Qcs (Eolian Sand Deposit) - Aeolian or wind sorted sand, implying desert-type wind regimes. Qmx (Meander Belt Deposit) - meandering river sands and silts, the variability of the alluvial history of the tributaries of the Indus.

The studied Formations and units are located in the vicinity of Kirana Complex, and the part of KMB (Kirana-Malani Basin) of NE Gondwana. The region is bounded by different local scattered hills and Chenab River to the northeast. The localities of the study perspective in consideration are Pindi Rasool Village, Shaheenabad, and Sharaban Village in Sargodha District, and Chota Darbar Choti in Chiniot District, Punjab Pakistan. The map of the studied area shown in (Figure 3) represents major lithological units, including rhyolites, quartz-wackes, volcanogenic slates, quartzites, dolerites, slates (hatched grey) of Asianwala, conglomerates (dotted yellow) of Chak 112, and lithic grey units (cross-hatched pattern) in various studied formation across the region.

Material and Methods

Different outcrops have been observed in the multiple sections of Kirana Hills. The observed sections are based on the field methods, which is the primary investigation of the outcrop, to study its geology, structural markings, dip, strike, source of mineralization, and sample collection. The each studied outcrop is followed by the same methodology, at first the true north (bearing) was measured using hand compass, then Global Positiong System (GARMIN eTrex 10) was utilized

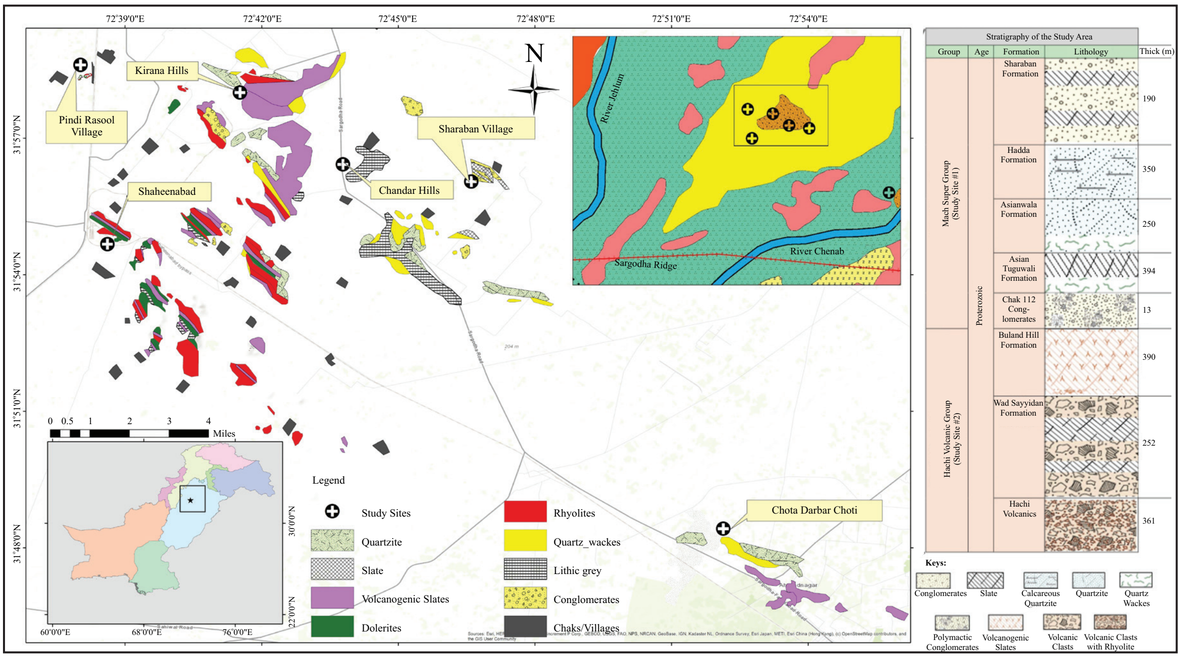

Figure 3. (a) Geological map of the studied area, showing distribution of major lithological units, including rhyolites (red), quartz-wackes (yellow), volcanogenic slates (purple), quartzites (dotted green), dolerites (green), slates (hatched grey), conglomerates (dotted yellow), and lithic grey units (cross-hatched pattern); (b) Stratigraphy of rhe studied area representing lithostratigraphic succession, subdivided into two primary groups: Hachi Volcanic Group and Mach Super Gropup of the Kirana Volcanic Zone.

for measuring the latitude and longitude of each outcrop, the best technology in field geology to map the north taking exact configuration of the type locality coordinates according to (Adero, 2023). Each outcrop was examined using standard field techniques (measuring tape was utilized to measure the extent of the outcrop, hand lens was used to examined the grain size, field photographs are acquired using the photophone, and the sampling from each outcrop was done using geological hammer, dip and strike for each outcrop was measured using Brunton compass). This is the standard and best field technique utilized in the field observation by many geologists and a practical guide for exact readings (Lisle *et al*., 2011; Barnes and Lisle, 2013; Gregory, 2022). The rose diagram interpretation for the fracture analysis study was performed using GeoRose 0.5.2 version software. This software is very potent in terms of fracture analysis studies and earthquake mapping projections, utilized in many studies (Anteneh *et al*., 2022; Han *et al*., 2024). The stereographic plane projection (using equal area and angle) were plotted using InnStereo beta6 software. This version of stereographic projections for analyzing the fracture studies in the outcrop is reported in study by many researchers and best utilized by (Derbyshire, 2021; Staneczek *et al.*, 2022). The methodological framework for all the studies performed is shown below in Figure 4.

Results

Field Observations

Studied Site 1

In this section, various outcrops were observed, the type locality for this study section is Pindi. The geological name for this section is Qilla Hills, as referenced by Khan (2000) and Khan *et al*. (2009). These are basically scattered and isolated hills (Alam, 1987). The area shows inverse tectonics or basin inversion (relates to the relative uplift of a sedimentary basin or similar structure as a result of crustal shortening. This normally excludes uplift developed in the footwalls of later extensional faults, or uplift caused by mantle plumes). The oldest rocks (Neoproterozoic age) are exposed at this region. In this section the majority of rocks are volcanic which are formed by sudden cooling of magma as when they are in contact to the surface exposure. The two differential magma composite rock exposure have been observed (light colour shows felsic origin and dark colour shows mafic origin). The section was divided into two packages, the lower and upper, but in this section, the lower package has been observed, named as Hachi Volcanics after Alam *et al*. (1992).

Rhyolite

The studied outcrop was Rhyolite (Figure 5a), the rock exposure belongs to Hachi Volcanics. The Hachi Volcanic Group mainly comprised thick sequence of volcanics and volcaniclastic rocks. The volcanics are dominantly acidic to intermediate in composition and mainly include rhyolite, rhyolitic tuff, andesite, dacite, and dacitic tuff. The surficial (weathered) colour observed for this sample was yellowish white, and after sampling the fresh (polished) colour observed was light yellow (Figure 5a). The light colour is due to its felsic origin within the volcanic complex. Adjacent to this outcrop there was the exposure of a small intect unit of Cherty Quartzite, the Quartz lens-like structural feature is also present in the outcrop (Figure 5b). The outcrop also shows the conjugate joint sets (Figure 5c). The rock samples also showing the dendritic (flower-like) patterns due to manganese intrusion in rhyolite (Figure 5d). Marking its lateral extent, there was a slight variations in the colour as the outcrop also shows the differential magma process, the dark colour observed in the sample, is due to the change of mineral composition (hematite mineralization) shown in (Figure 5e).

Basalt and Dolerite

The studied outcrop was basalt (Figure 5f), the rock exposure belongs to Buland Hill Formation within The Hachi Volcanics, the lateral extent of this measured outcrop was 34 m in thickness. It is the small exposure, and the basalt shows a phaneritic texture, and phenocrysts are present

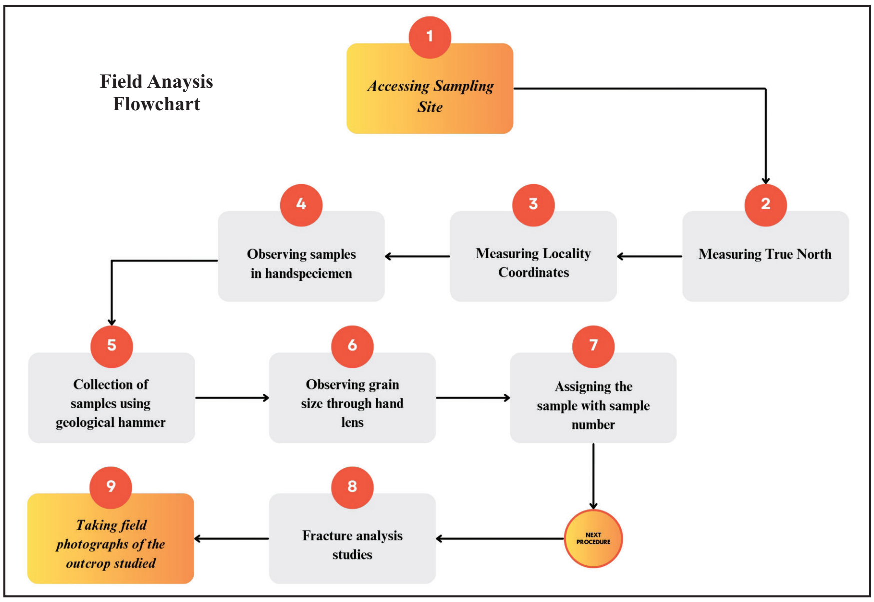

Figure 4. Methodological framework for the field analysis.

in that outcrop (Figure 5f). Basalt also shows a change in colour variation due to the presence of olivine minerals (Figure 5g). Columnar joints are present in the basalt showing a high rate of deformation and structural complexities (Figure 5i). Quartz veins (contact) was also observed in the basalt (Figure 5h). The contact between basalt and dolerite was observed during the observation taken at this outcrop. The dolerite outcrop shows salt and pepper texture due to the presence of pyroxene minerals (needle-like minerals observed under hand lens) shown in Figure 5j. The textural appearance of dolerite was medium grained, and sample was higly weathered due to the operational activities over there (blasting was observed during the observation). Dolerites are typically black to green in colour, and are widely exposed on The Hachi, Shaheenabad, and Hachi Hills. They undergo autometasomatic transformation and eventually metamorphosis into lower greenschist facies. These rocks are fine to medium-grained and frequently blastoporphyritic, however hypidioblastic texture may also be seen (Alam, 1987).

The basalt outcrop was also subjected to the change in colour as previously observed in the rhyolite. The colour change is due to hematite mineralization, but in the basalt sample the rate of mineralization and solution intrusion is high as shown in Figure 5k. The outcrop was also there were too many joined patterns, and the sets of joints were observed and measured there. Basalt mostly shows the patterns of conjugation in joints, but in between the patters the sigmoidal joints was also observed, the geometry of conjugate joints (Figure 5l) aligned in between (20-60^o), and sigmoidal joints (Figure 5m) aligned in between (10-20^o) in sets.

The last outcrop in this studied site shows rocks belonging to the Green Schist Facies further to The Buchan Facies Series. In the present study, a simple thin section of chlorite was seen, and its mineralogical grade was apparent and generally low. The most obvious and significant feature of this outcrop is the boudin structure (series of sausage shape fragments) formed due to ductile deformation, and this is an important feature in identifying ductile deformation processes (Alam, 1987) (Figure 5n). The outcrop shows green colouration due to the mineral chlorite, which is the dominant mineral within this area. Chert and basaltic xenoliths were also noted, adding to the already diverse geology of this region. The information can provide the metamorphic and tectonic events that shaped the area. The Buchan Facies Series of regional metamorphism is characterized by the presence of andalusite, and sometimes cordierite, in intermediate-grade mineral assemblages indi-

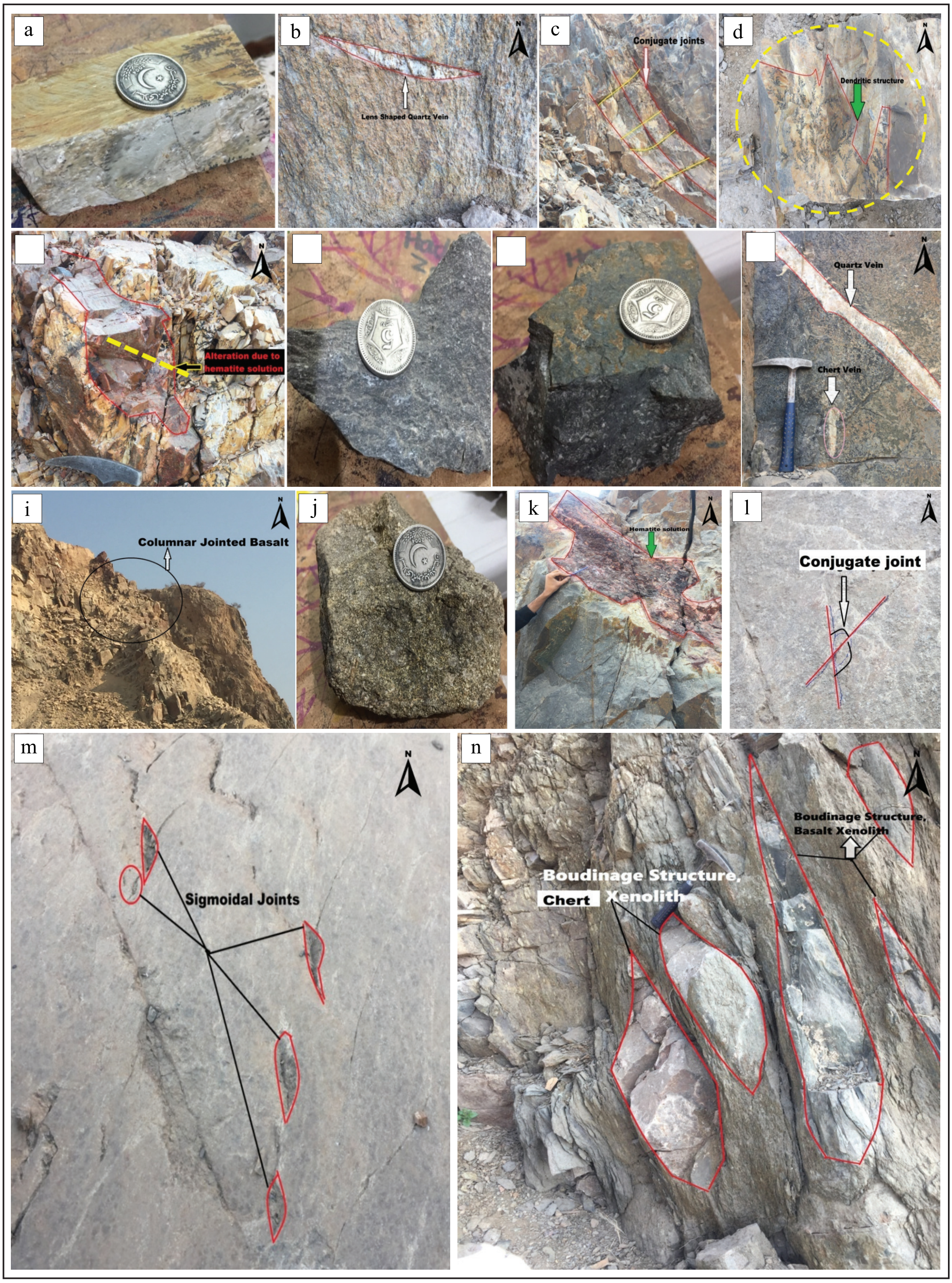

Figure 5. Field photographs; (a) Rhyolite sample, (b) lens-shaped quartz vein in rhyolite, (c) Conjugate joints sets, (d) Dendritic patters in rhyolite; (e) Alteration in observed outcrop due to hematite mineralization (solution); (f) Basalt sample; (g) Change in colour due to pyroxene mineralization; (h) Quartz and chert vein in the sample; (i) Columnar joints in the observed outcrop; (j) Pyroxene needle like minerals in dolerite sample; (k) Basalt with hematite mineralization; (l) Sets of conjugate joints in outcrop; (m) Sets of sigmoidal joints in outcrop; (n) Outcrop shows xenolith of Basalt and Chert, in boudinage structure at Chak 100 N.

Figure 6. Field photographs; (a) Rhyolite sample replacement with fluids; (b) Rhyolite outcrop exposure at Shaheenabad; (c) Quartz vein observed in the outcrop; (d) Pinch-out Swell structure in rhyolite; (e) Outcrop exposure of tuffaceous or volcanogenic slates in sharp contact with basalt and rhyolite; (f) Outcrop of basalt showing quartz veins and mineralization of micaceous hematite at Shaheenabad; (g) Microgranite sample; (h) Basalt xenoliths in microgranites, observed exposure at Shaheenabad.

cating that the conditions of metamorphism were at lower pressure and along a higher metamorphic field gradient than that recorded in the Barrovian facies series metamorphic rocks.

<u>Studied Site 2</u>

Rhyolite

The studied outcrop was rhyolite (Figure 6a) as observed in the previous section. The outcrop belongs to the same Hachi Volcanics, and the studied site was Kirana Hills near the railway crossing. In this outcrop the mineral chemistry is changed (approximately all the outcrop is subjected to mineralization by hematite enrich solution) shown in Figure 6b. At this outcrop, several joints was identified within the rhyolite. Assessment of the available dimensions using a measuring tape suggests that the rhyolite covers a dimension length of about 4 to 5 m. When observing it under a hand lens, it becomes evident that this rock has a porphyritic texture - large crystals surrounded by fine grains. Further, a quartz vein (Figure 6c) averaging 12 inches in thickness was observed in the rhyolite layer with its strike parallel to the surface layer. The outcrop also shows the pinch-out swell structure (Figure 6d) in the rhyolite area, wherein rhyolite has been deformed into quartz-filled vein again indicating structurally and minerals built up at the site.

Basalt with Hematite Mineralization

Mineralogical characteristics became significant at Shaheenabad outcrop in Kirana Hills, showcasing distinctive geological characteristics in that area. Micaceous hematite appears together with Buland Hill Formation basalt rocks inside quartz veins (Figure 6f). The micaceous hematite materials showed a platy texture and metallic sheen, existing between quartz and the dark basalt in a visually contrasting way. The geological setting indicates active geological processes that might have resulted from hydrothermal activity during mineralization.

The outcrop showed the presence of calcite veins in its basalt strata which could be verified by acid testing methods. An acid reaction proved calcite existence to show that basalt experienced secondary mineralization through the intrusion of mineral-rich fluids while crystallizing. These calcite veins within the basalt highlight the geochemical interactions between volcanic rock and circulating fluids, further illustrating the outcrop complex geological history (Chaudhry *et al*., 1999). These exposures at Shaheenabad in The Kirana Hills offer very important data about the tectonic-mineralogical growth of this area. One is exposed to consolidated lava, quartz, and calcite interagency, and the discovery of micaceous hematite suggests a multiphase-tectonic-mineralization history of igneous as well as aqua-thermal post crystalline movements.

<u>Studied Site 3</u>

Tuffaceous or Volcanogenic Slates

The tuffaceous or volcanogenic slates of The Buland Hill Formation, part of the Hachi Super Group are well exposed at Shaheenabad within The Kirana Complex. They mainly consist of volcanic ashes; mostly of fine-grained material altered and more or less metamorphosed to slaty textures (Figure 6e). These rocks are volcanic in origin as indicated by the tuffaceous constituent, derived from pyroclastic deposits which are the result of volcanic activity in earlier geologic past.

Low-grade metamorphic features show prominent evidence in the slates in terms of foliated structures and obvious signs of tectonic stress after deposition was exerted on them (Figure 6e). Volcanogenic slates of The Buland Hill Formation can give much necessary information about the tectonic-volcanic setting of the area since the post-tectonic volcanic activity was succeeded by the compressional and metamorphic phase in the development of The Kirana Complex. These rocks act as reference points of the volcanism that has shaped the geology of this region as evidenced by sedimentary and igneous formations.

Microgranite Dykes

The studied outcrop was microgranite (Figure 6g), which are the small extent exposure of Wad Saiydan Formation of Hachi Volcanics or Super Group. The exposure at Shaheenabad shows fine-grained texture, and these microgranites are the intrusion within the thick unit of basalt of Buland Hill Formation, as due to the extensional regime there is overlapping seen in the outcrop. Xenoliths of basalt was also observed under the hand lens. The microgranite and microgranitic dykes exposed within the basalt of The Kirana Hills particularly at Shaheenabad represent interesting aspects of the magmatic history at the locality. Microgranite is a fine-grained intrusive igneous rock containing mainly quartz, feldspar, and minor portions of mica akin to granite but coarser than it because of relatively rapid cooling of the magma (Shah, 1977).

At Shaheenabad these microgranitic dykes splay across the surface of the basalt suggesting that the microgranite was injected into older basaltic rocks. This suggests that after the formation of the basalt, later activity triggered the emplacement of the more felsic microgranite along fractures within the solidified basalt leading to the formation of dykes. These dykes are usually lighter in colour than the basalt, and they are also more resistant to weathering and erosion; thus they stand out in the field. The presence of microgranite dykes cutting across the outcrop of the basalt indicates multiple phases of magmatic activity in The Kirana Hills, which came against the background of mafic (basaltic) magmatism succeeded by felsic (granitic) intrusions. The application of this relationship is to constrain the tectonic and magmatic history of the region to understand the chronological association of volcanic and intrusive events in the region. The nature of the dykes is also microgranitic, and the exposures therefore represent a record of the geological history of The Kirana Complex and the changing magmatism.

<u>Studied Site 4</u>

In this study section, various outcrops were observed. The type locality for this study section is Chak 112 N, and the geological name for this type locality is Chandar Hills (Alam *et al*., 1992). The area also comprised Mach Super Group after (Khan *et al*., 2009). The Chandar Hills present interesting geological characteristics with considerable tectonic, stratigraphic, and formation attritions. Located tectonically, The Chandar Hills are in a part of the region that has been greatly subjected to deformation due to past tectonic activities, which in turn exposes distinguishing forms of folds, faults, and traces. This deformation is well expressed regarding the position and organization of rock units within the hills. In terms of geology, the area is characterized by an extensive sequence of metamorphic and igneous rock types suggesting highly active geology. Essential structures include the existence of volcanic and sedimentary units, and separated by lava flows, volcanic ashes which indicate that the area was formerly active volcanically. The configuration in Chandar Hills comprises metavolcanic rocks, slates, and quartz, which are features of The Kirana Group. Interest in studying such formations gives an understanding of the ancient conditions for the formation of the territory now occupied by The Chandar Hills, including volcanic activity and sedimentation. As studied in the previous sections, this was the lower package of The Mach Super Group, but in this locality all studied sites observed were of the upper package comprised moslty of Chak 112 Conglomerates Asianwala Formation, Hadda Quartzite, and Sharaban Formation.

Quartzite

The studied outcrop was quartzite (Figure 7a), metamorphosed form of sandstone. The outcrop exposure belongs to Asianwala Formation of Mach Super Group. The surficial (weathered) colour of this outcrop was yellowish grey, and after sampling the fresh (polished) colour observed was light grey. The outcrop shows the hematite veins along with the stock work deposits (Figure 7b). The yellowish colour in quartzite is due to the presence of Limonite (Figure 7a). Tectonically and structurally the outcrop is highly fractured. At the far proximal part of the outcrop quartz vein was also observed (Figure 7c), alluvium deposits (Figure 7a) present at the top of the exposure striking N40º W, which marks the recent deposits in the region. The outcrop was diping 44º SW.

Slates

The studied outcrop was slates (Figure 7d), which are fine-grained metamorphic rocks, metamorphosed from the shales. These slates have been formed from low-grade metamorphic

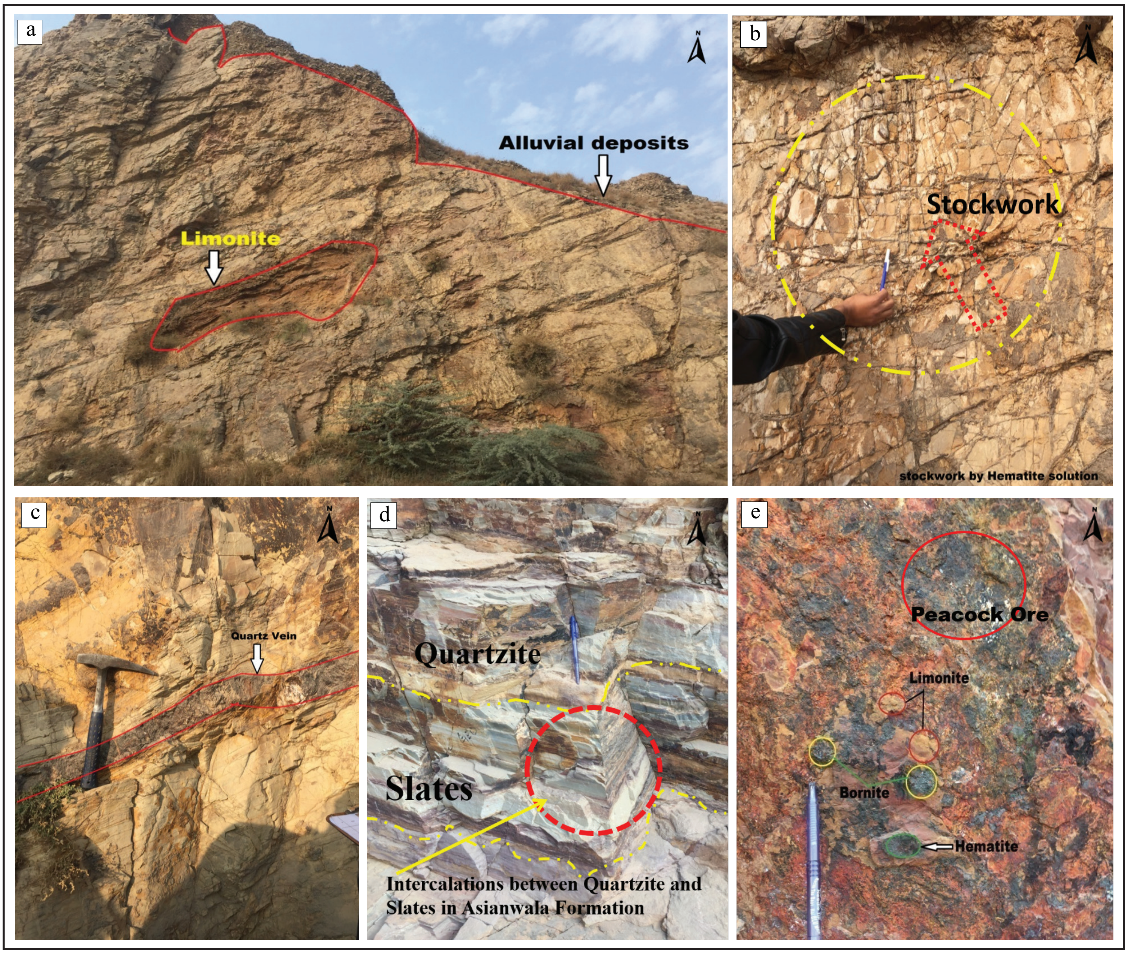

Figure 7. Field photographs; (a) Outcrop exposure of quartzite of Asianwala Formation with its contact with recent deposits; (b) Stockwork deposits form in quartzite due to hematite solution; (c) Quartz vein in quartzite; (d) Outcrop exposure of slates of Asianwala Formation interclated with quartzite, the greenish appearance in slates is due to the presence of clorite mineral; (e) Presence of limonite, hematite, and bornite minerals in Asianwala Formation.

transformation of clayey sedimentary rocks, and bear witness to their tectonic evolution under pressure at relatively low temperature that characterize regional metamorphism. The slates of the Asianwala Formation contain a variety of colours, which was from grey to greenish-grey, and fresh (polished) colour after sampling was light grey. This is due to the mineral differences present in the formation, mostly the constituent of chlorite and mica. These slates exhibit well developed foliation (Figure 7d), showing the exposure in high compressional tectonic regime.

Mineral Chemistry of Asianwala Formation

The Asianwala Formation particularly contains significant quartzite outcrop, in terms of its mineral assemblage, exposed at Chandar Hills. The formation is enriched in minerals like limonite, hematite, and bornite.

Limonite

Limonite is oftenly not a true mineral. It is the mixture of hydrated iron oxide minerals, limonite typically forms due to the process of weathering and oxidation of Fe minerals oftenly sederite and hematite, under the conditions where water and oxygen exposure are (Shah, 1977). Limonite form in the formation shows yellowish brown to dark brown colour, and after sampling the fresh colour observed was light yellow (Figure 7e). Limonite staining or coatings are often visible on fracture surfaces or in pore spaces within quartzite, giving the rock a distinctive brownish-yellow appearance. This suggests an interaction between iron-rich fluids and the quartzite host rock, which could have occurred in surface or near-surface conditions.

Hematite

Hematite, (Fe_2O_3) an iron oxide mineral with no water in its structure, it's the abundant iron oxide mineral formed in a stable geological environment (Liang *et al*., 2024), and in the Kirana Complex, its form under the oxidizing conditions of the parent rock (igneous or metamorphic) (Shah, 1977). In most of the geological settings in The Kirana, hematite is exposed in the form of thin coating or streaks (Figure 7e), resulting to the reddish look of the soils and rock exposures in the region. In this region, especially hematite, appearance results to the oxidative environment or due to the groundwater interaction, but it does not affect the stability of the mineral in the exposed outcrop.

Bornite

Bornite, a copper iron sulfide mineral, is oftenly known as the "Peacock Ore" (Figure 7e) due to its purplish blue textural appereance as its exposure to direct sunlight and air (Shah, 1977). Bornite is mostly found in hydrothermal veins and porphyry copper deposits, from its Cu-rich fluids. Its presence in The Asianwala Formation suggest that the outcrop is exposed to fractures and cavities where these Cu-rich fluids penetrate, or the outcrop experienced some level of hydrothermal alteration, but the possible geochemical environment suggest the interaction of the fluids movement in the past, as the extent of mineral is not up to larger scale.

<u>Studied Site 5</u>

Quartzite

Unit 1

The studied outcrop was quartzite (Figure 8a). The outcrop exposure belongs to Sharaban Formation of Mach Super Group. This Formation mostly consist of Quartzite and Intraformational conglomerates, these conglomerates are also known as Chak 112 Conglomerates, the quartzite of Sharaban Formation oftenly shows convolute banding (Figure 8b). This is due to high mineralization present in this area, for that reason they are called black mountains or black outcrops. Conglomerates shows sharp contact between the quartzite (Figure 8c), as observed different source transported grains was observed in these conglomerates, the limestone grains are predominant (Figure 8d).

Unit 2

The studied outcrop was also quartzite, but in this unit the quartzite colour is differentiated. Here, the conformable contact have been observed between the Sharaban Formation and Hadda Quartzite (Figure 8e). The presence of pebbly conglomerates in this unit is more, as in the previous unit. Ripple marks (Figure 8h) and convolute banding (Figure 8i) was also observed in this unit. The sedimentary dyke was seen in this unit intruding in the dyke, cross cutting perpendicular to the unit (Figure 8f), the measurement taken for the dyke was 13 cm in width and 12 ft. long. The presence of potholes was also observed in this unit (Figure 8j) and caving structures in Sharaban Formation (Figure 8g) due to the surficial weathering. Overall analysis put in consideration was that this whole zone is a suspect to weathering rate in the recent past as a lot of sedimentary cover was observed over the top.

Quartzite

The studied outcrop was Quartzite (Figure 8k). The outcrop exposure belongs to Hadda Quartzite of the Mach Super Group. The weathered colour observed for this outcrop was greenish black, and after sampling the fresh colour observed was dark grey. The outcrop shows Anastamosal structure that was filled with calcite (Figure 8k). The outcrop is enriched in two mineralizations, the dark greenish black colour is due to Micaceous Hematite (Figure 8l) and red colour in quartzite is due to the presence of jasper (Figure 8o), it is the red variety of quartz. The dogtooth spar structure was also observed in the outcrop (Figure 8n). At the proximal end part of the outcrop there was cave (Adit) present, the presence of hematite was

Figure 8. Field photographs; (a) Quartzite outcrop of Sharaban Formation; (b) Convolute banding in quartzite; (c) Contact between quartzite and conglomerate; (d) Pebbly conglomerate sample showing limestone grains; (e) Contact present between Sharaban Formation and Hadda Quartzite; (f) Sedimentary dyke in quartzite; (g) Poth holes due to weathering; (h) Ripple marks; (i) Convolute banding in quartzite; (j) Cave-like structure in Sharaban Formation; (k) Outcrop showing contact between quartzite and rhyolite in the formation; (l) Anastamosal strcture with calcite filling; (m) Micaceous hematite in Adit; (n) Jasper in Hadda Quartzite; (o). Dog toothspar structure in quartzite.

abundant there, measuring the outcrop of 28 m thick. This is due to stockworks occuring in the rhyolite that fills the hematite solution with time in the quartzite, due to shearing stress and tectonics (Figure 8l).

Mineral Chemistry of Hadda Formation

The Hadda Formation contains significance in terms of its mineral assemblage, particularly in quartzite outcrop exposed at Sharaban Village, the formation is enriched in minerals like micaceous hematite and jasper.

Micaceous Hematite

Micaceous hematite or specular hematite is a hematite with a mica or flaky structure of appearance. Micaceous hematite has the same chemical composition as ordinary hematite, but it forms in thin layer under petrographic observation, reflective scales or plates that have a metallic sheen and are layered (Chaudhry *et al*., 1999). Micaceous hematite is the hematite that has developed in environments where the iron oxides deposit in the layers and the process occurs under conditions of metamorphism or chemical deposition. The presence of micaceous hematite suggests that iron-enriched fluids were involved in interaction with silicate minerals, and hematite formed in the micaceous manner. Imenefit can be seen sometimes as thin layers or as inclusions in fracture zones, the quartzite outcrop has a silvery to tarnished look in some isolated sections into streaks or sheets of mica Late movers, the Hadda Quartzite fluoresces pale blue under short wavelength UV light. This mineral indicates that solutions with high concentrations of iron came into contact with the quartzite through regional metamorphism or hydrothermal activities, and deposited in the manner of micaceous hematite.

Jasper

Jasper is a microcrystalline quartz of silicon dioxide (SiO_2), often containing iron oxides or other mineral inclusions imparting red, brown, yellow, and green colour. Jasper often occurs due to the process of silicification, where silica-bearing solutions penetrate the surrounding rock material and deposit quartz incorporating the colouring agents - iron oxides (Chaudhry *et al*., 1999). In Hadda Quartzite these inclusions therefore give it, its cloudy and coloured appearance, making it different from other semiprecious quartz such as the agate or the chalcedony. Only in general terms jasper usually originates from the silification process which is a phenomenon where silica saturated solution solution penetrates adjacent rock material, and settles as quartz including impurities like iron oxide.

Studied Site 6

In this study section, researchers observed various outcrops. Observed, the type locality for this study section Chota Darbar Choti is located near Chenab Nagar. The area comprises Hachi Volcanics and Mach Super Group. The area has a very limited outcrop exposure. outcrop, but the lateral extent is large, followed by the two main lithologies. The area is enriched in mineral potential like bornite, chlorite, hematite, magnetite, and jasper.

Quartzite

The studied outcrop was quartzite (Figure 9c), and the outcrop exposure belongs to the Asianwala Formation of Mach Super Group after (Khan, 2000). The weathered colour observed for this outcrop is black to reddish black in colour, and after sampling the fresh colour observed was greyish black. The fracture was observed in the quartzite and mainly the fractures are filled with the hydrothermal solution.

Volcanogenic Slates

The studied outcrop was volcanogenic slates (Figure 9b). The outcrop exposure belongs to Hachi Volcanics. These slates formed a sharp contact with quartzite (Figure 9a), and at its basal part they have contact with the sedimentary deposits mainly conglomerates. These conglomerates have clasts of volcanogenic material, but mostly pebbly appereance in quartzite (Figure 9c). These slates are important, because they constitute the low-grade metamorphic equivalents of volcanic rocks,

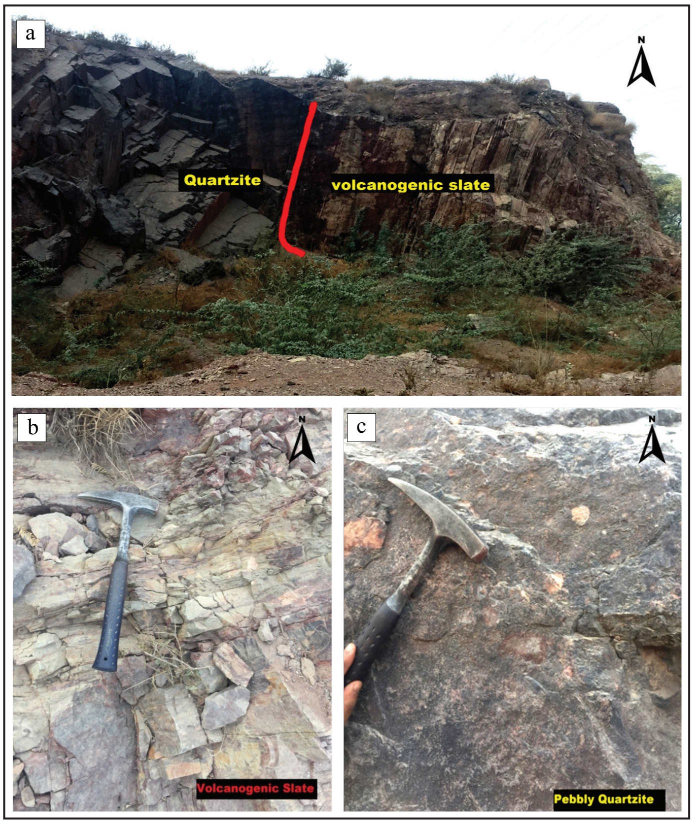

Figure 9. Field photographs; (a) Contact between quartzite and volcanogenic slates; (b) Outcrop showing volcanogenic slates; (c) Volcanic clasts in quartzite also known as pebbly quartzite.

and the study of these rocks offers information on the tectono-thermal evolution of the Kirana Hills. At the same time, it is possible to find clear indications of volcanogenic slates to determine the previous volcanic activity and the character of the volcanic source.

The various mineral samples were collected from the studied site (Figure 10) showing minerals (economic), and hydrothermal source minerals from The Kirana Hills, are mostly of this type locality.

They are closely associated to the regional geological framework of the volcanic and metasedimentary zone. The presence of bornite alongside hematite and associated iron oxides indicates mineralization processes strongly controlled by hydrothermal activity within the tectonically deformed volcanic and sedimentary sequences. In this zone, the quartzite host rocks act as rigid frameworks, where hematite occurs as clusters and nodules, reflecting metasomatic replacement and fluid-rock interaction. The widespread development of hematite nodules and clusters points to oxidizing conditions during fluid circulation, which facilitated the precipitation of iron oxides within both volcanic and sedimentary units. Bornite, as observed in hydrothermally altered zones near the Chenab Nagar area, reflects sulfur-rich reducing conditions where copper-bearing hydrothermal fluids interacted with the iron-rich volcanic assemblages, producing localized copper sulfide mineralization.

Regionally, the volcanic and metasedimentary terrain of The Kirana Hills is characterized by mafic to felsic metavolcanics interbedded with quartzites, phyllites, and dolerites, which provide both the structural conduits and geochemical traps for mineralizing fluids. Iron mineralization, dominated by hematite, represents the oxidized end-member of these processes, while the occurrence of bornite highlights the localized transition to sulfide facies in structurally favourable zones. The interaction of hydrothermal fluids with silica-rich host rocks further enriched the system, producing hematite-quartz associations and en-

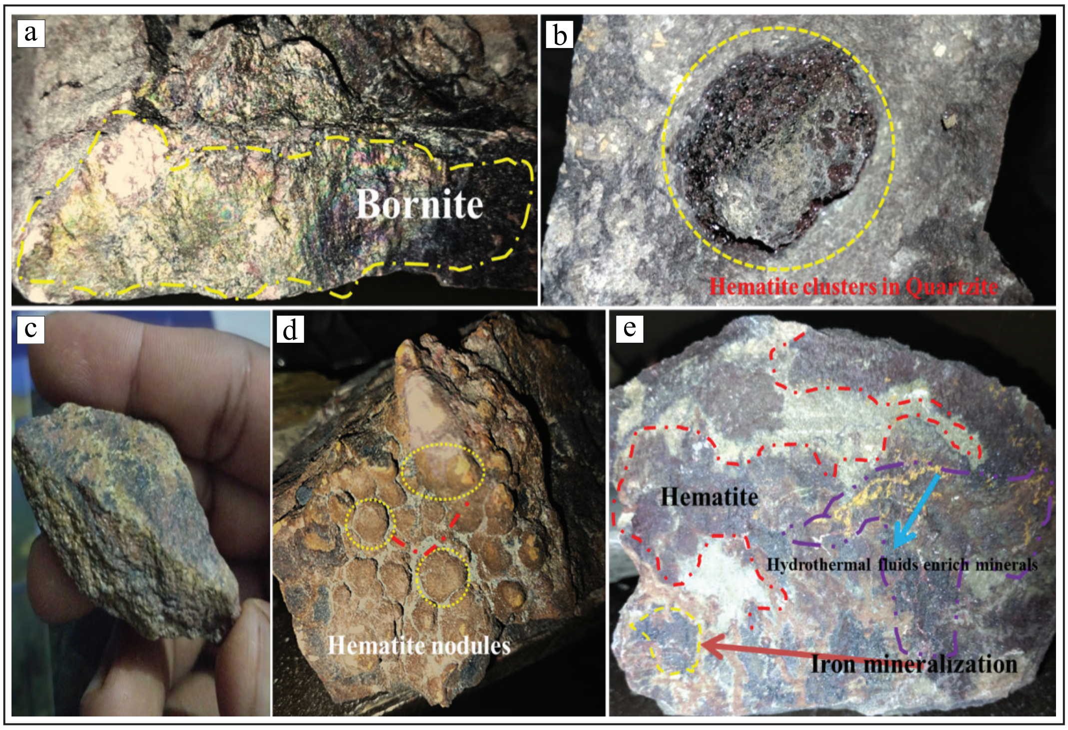

Figure 10. Hand specimens; (a) Bornite sample; (b) Hematite clusters in quartzite; (c) Limonite with hematite alterations and fluid replacements; (d) Hematite nodules; (e) Hematite sample with iron mineralization and hydrothermal fluids enrichments.

hancing the metasomatic replacement processes. Collectively, these mineral occurrences in The Kirana Hills signify a multi-phase mineralizing history associated with Precambrian tectonothermal events, where iron oxide and sulfide mineralization developed in close association with the volcanic and metasedimentary sequences.

Fracture Analysis Studies

A fracture is any separation in the geological formation, mostly in the form of joint or fault that separates or disintegrate the rock into two pieces. Analysis of fracture distribution in sedimentary and igneous rocks reveals much about the tectonic transitions and the protracted history of deformation in a locality (Khan *et al.*, 2009). In Kirana, mostly fractures develop due to compression or the inversion tectonics (shearing mechanism). All the formations studied in the field observations shows fracture and intense deformation. Three sites was studied for the fracture analysis, which was performed using circle inventory method. This method allows a systematic collection of orientation data in a limited area, to be used for statistical analysis and frequency diagrams. A circle of known diameter is predetermined on a bedrock surface, where maximum numbers of joints are exposed. Then, the orientation and trace length of each joint within the circle are measured. The measure of joint density is the summed length of all the joints within an inventory circle, divided by the area of the circle. The locality of Qilla Hills shows intense deformation rate and the fracture observed in the outcrop are disputed. For the Chandar Hills area the fracture analysis was conducted using ten sets of samples in the outcrop, while two other fracture studdies was conducted using ten to twelve datasets in Sharaban and Shaheenabad area, and for the last locality eighteen sets was considered for the analysis, to check the mode of deformation.

In Hadda Quartzite, conjugate fractures are well-developed and parallel to regional compressive stresses. Such fractures give information about the main directions of the tectonic forces that influenced the quartzite outcrops. Within the Asianwala Formation, shear fractures are correlated with shear deformation and tension gashes. Veins of the secondary minerals including quartz along the fault planes are an indicator of progressive deformation and mineralization bursts. The Buland Hill Formation shows calcite and quartz filled joints which suggest that fluid movement occurred along the fracture plane. These ideas will be reinforced, where other mineral fills are preserved. It is in the development of the joint sets that the paleo-fluid movements were active in the formation growth, that must be recognized to gain a better understanding of the post depositional tectonic histories of the area.

Interpretation

The analyzed fractures (Figure 11) in Hadda Quartzite (studied at site 1) are dominantly of compression that is reflected by N-S oriented fractures indicating stress fields related to regional plate tectonics. Fractures in the Asianwala Formation (studied at site 2) are parallel to foliation and show features suggestive of low-grade metamorphism. The orientation of fractures that are found within this formation corresponds with observed shear zones, suggesting that the zone is influenced by strike-slip faulting. Faults in the Buland Hill Formation (studied at site 3) are associated with past volcanic activity, and include both radial and concentric fractures to the main volcanic vents. Subscribing to the assumption that the pinch-and-swell quartz veins mark multiple stages of extension followed by compression, it can be inferred that the observed structures were influenced by syn-depositional tectonic events. Fracture studies from Hadda Formation (studied at site 4) in Sharaban Village reveals a well-developed system of discontinuities, characterized by variable orientations, widths and associated features. The fracture length with a predominant orientation trend (145°-240°) suggests a dominant NW-SE to WSW-ENE fracture trending, likely associated

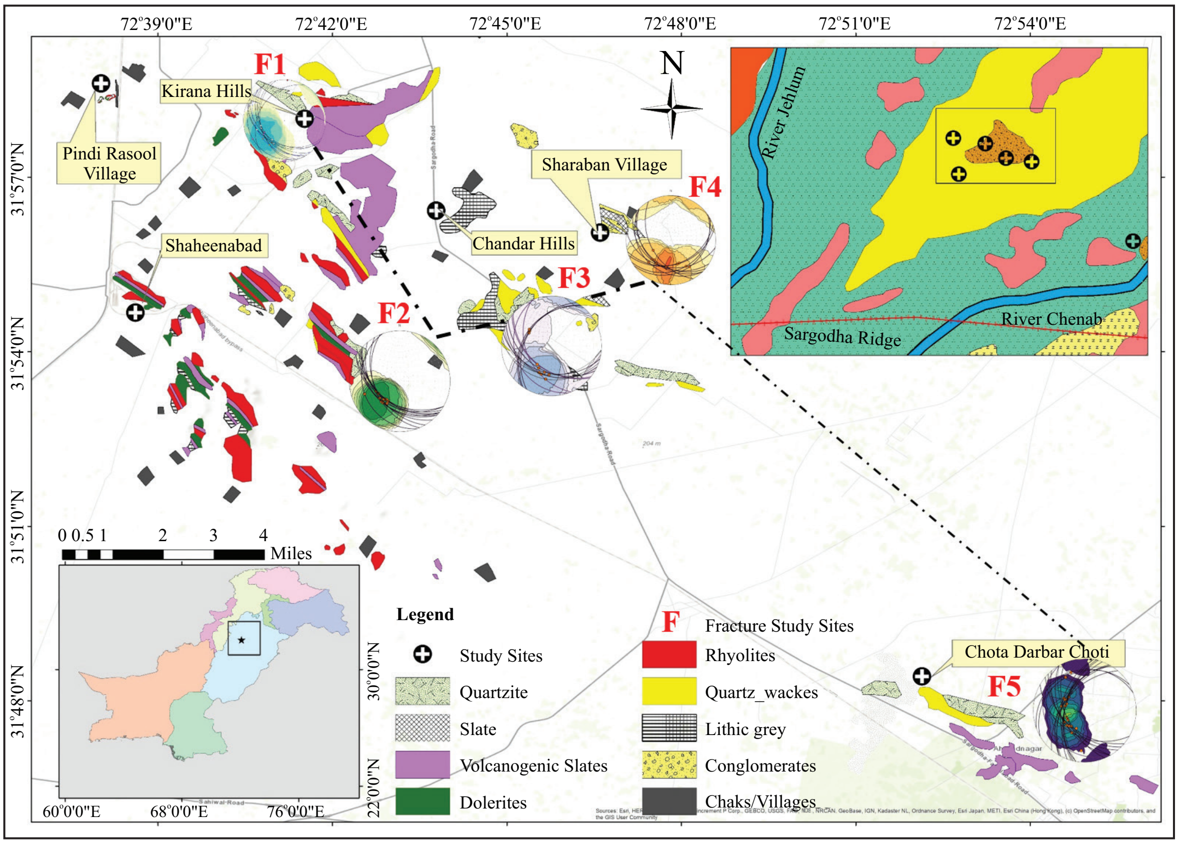

Figure 11. The map displays five fracture studied sites distributed across different geological units within the studied area. Stereonets at each site location indicate the orientation data collected for fracture analysis.

with regional tectonic stresses of Kirana Hills. The fracture data from volcanogenic slates (studied at site 5) exhibits a highly heterogeneous but well-connected network of discontinuities. The fracture orientations predominantly cluster around trends (225°-300°), with dips indicating NW-SE orientation. These orientations are consistent with tectonic compression and shear stresses commonly associated with Precambrian basement structures of the regime.

Analysis

During field observations, the selected outcrop at each studied site was selected to perform the analysis, using circle inventory methods, the circle was drawn using the marker. After that the fracture was marked, for each frature, its width, oriented length and trend and plunge was The f calculated, the same analysis was performed for all the site studied. The following equations was utilized for calculating the fracture density, its porosity, and permeability. The fracture density is shown in Equation 1, fracture porosity is shown in Equation 2, and permeability is shown in Equation 3.

For calculating F.D.:

$D_f = \sum F_l / A$ .... (1)

For calculating F.P.:

$\Phi_f = V_f / A$ .... (2)

For calculating F.K.:

$K_f = Wi^3 / 12$ .... (3)

The analysis from the fracture studies suggest that the fracture orientations show consistent patterns across the observed formations in the studied sites. The trend shows the bi-orientation in both phases (NW-SE) mainly in three studied sites and WNW-ESE in one studied site, based on the observed rose diagram (see Figures 12-16). Most

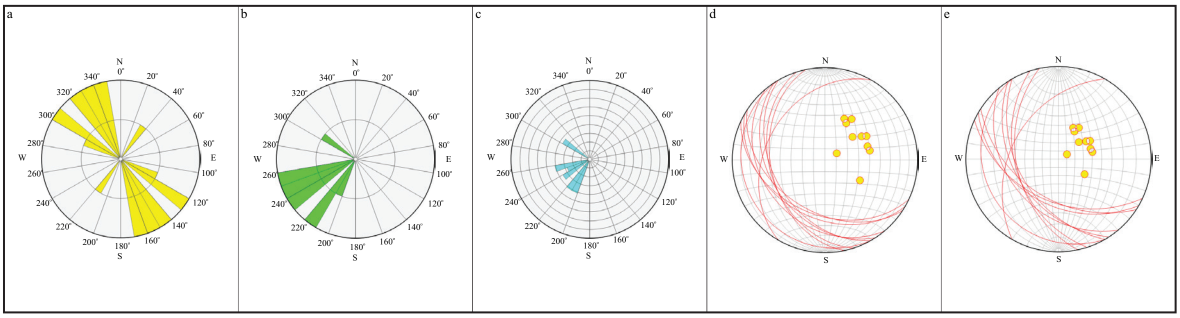

Figure 12. Fracture analysis studies for site 1 – Photographs showing; (a) Rose diagram using strike data. (b) Rose diagram using trend data. (c) Rose diagram using plunge data. (d) Stereographic projection suing equal area. (e) Stereographic projection using equal angle.

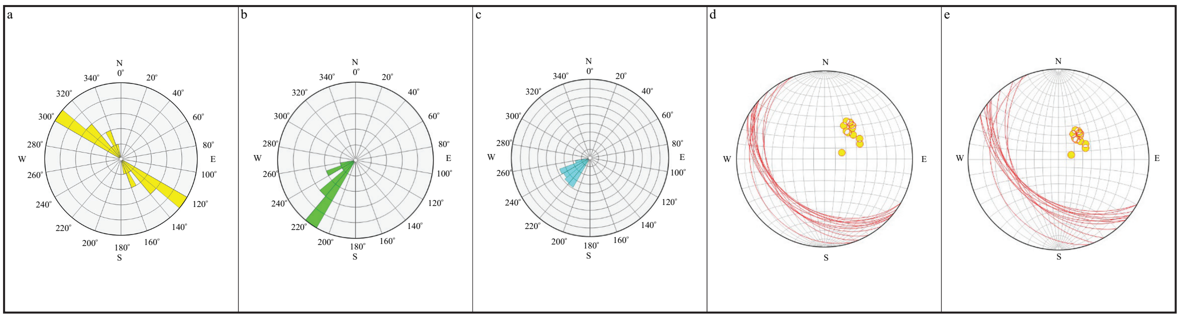

Figure 13. Fracture analysis studies for site 2 – Photographs showing; (a) Rose diagram using strike data. (b) Rose diagram using trend data. (c) Rose diagram using plunge data. (d) Stereographic projection suing equal area. (e) Stereographic projection using equal angle.

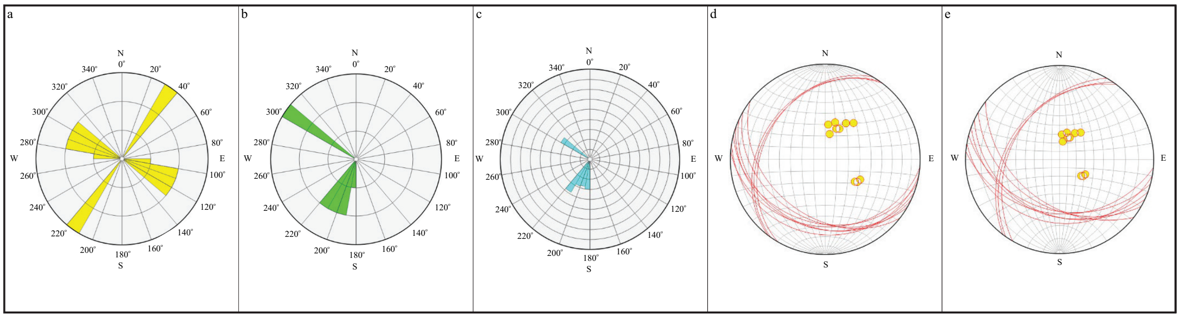

Figure 14. Fracture analysis studies for site 3 – Photographs showing; (a) Rose diagram using strike data. (b) Rose diagram using trend data.(c) Rose diagram using plunge data. (d) Stereographic projection suing equal area. (e) Stereographic projection using equal angle.

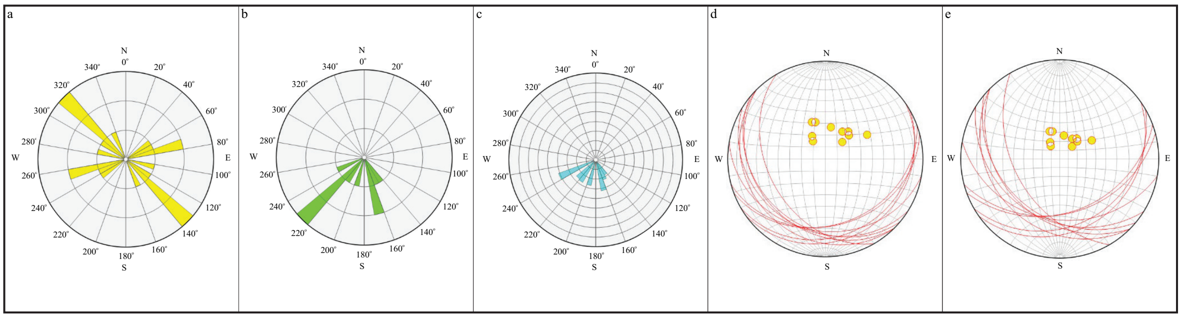

Figure 15. Fracture analysis studies for site 4 – Photographs showing; (a) Rose diagram using strike data. (b) Rose diagram using trend data. c) Rose diagram using plunge data. (d) Stereographic projection suing equal area. (e) Stereographic projection using equal angle.

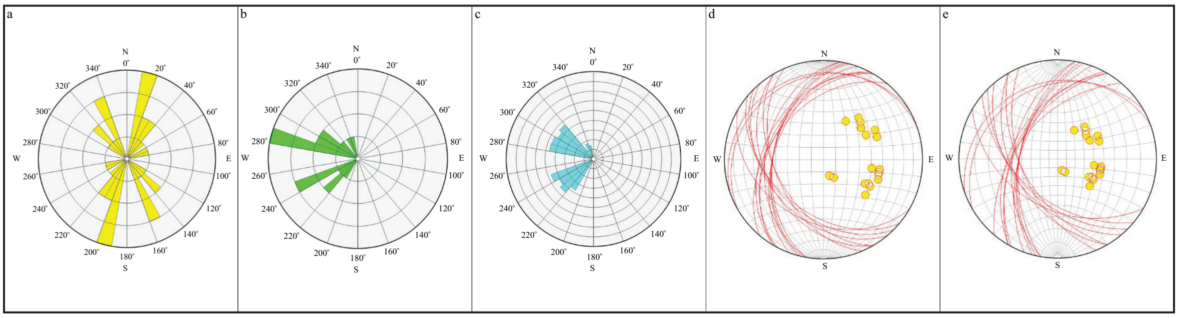

Figure 16. Fracture analysis studies for site 5 – Photographs showing; (a) Rose diagram using strike data. (b) Rose diagram using trend data. (c) Rose diagram using plunge data. (d) Stereographic projection suing equal area. (e) Stereographic projection using equal angle.

fractures in the regime show moderate to steep plunges roughly between (14°-50°), but several plunge also show steep plunge (40°-50°) mainly observed in studied site 1 and some fractures in studied site 3 and the maximum of 50° in site 5 (fracture studies Tables 1-5). These steep plunges indicating oblique or high-angle joint sets are also explained in the study conducted on Taku schist in Malaysia by (Ali *et al*., 2008). These sets are likely related to steep, brittle fracture sets formed under compressional-to-transpressive regimes. This analyis was also studied in detailed research conducted on paleostress inversion and outcrop fracture analysis of the brittle deformation along Main Boundary Thrust in NW Himalayas by Ahsan *et al.* (2021). Measured fractures widths range from ~0.1-2.6 cm in site-to-site variations. The majority are subcentimeter to centimeter

Table 1. Fracture characterization data for measured fractures in studied site 1. The table presents comprehensive geometric and hydraulic properties including fracture length (cm), trend (degrees from north), plunge (degrees below horizontal), aperture width (cm), fracture density (fractures per unit length), fracture porosity (dimensionless ratio of fracture void space to total rock volume), and fracture permeability (dimensionless coefficient representing fluid flow capacity through fracture networks)

Fracture No.	Fracture Length (cm)	Trend	Plunge	Fracture Width (cm)	Fracture Density	Fracture Porosity	Fracture Permeability
F1	44	240º	12º	0.1	0.44	0.0044	0.0083
F2	21	237º	39º	0.3	0.21	0.0063	0.0025
F3	37	210º	38º	0.4	0.37	0.0148	0.0053
F4	38	258º	41º	0.7	0.38	0.0266	0.0285
F5	17	252º	40º	0.8	0.17	0.0136	0.0426
F6	32	240º	43º	0.2	0.32	0.0064	0.0006
F7	30	213º	44º	0.5	0.30	0.0150	0.0104
F8	14	230º	32º	0.5	0.14	0.0070	0.0104
F9	24	300º	36º	0.5	0.24	0.0120	0.0104
F10	30	205º	41º	0.6	0.30	0.0180	0.0108

Table 2. Fracture characterization data for measured fractures in studied site 2. The table presents comprehensive geometric and hydraulic properties including fracture length (cm), trend (degrees from north), plunge (degrees below horizontal), aperture width (cm), fracture density (fractures per unit length), fracture porosity (dimensionless ratio of fracture void space to total rock volume), and fracture permeability (dimensionless coefficient representing fluid flow capacity through fracture networks)

Fracture No.	Fracture Length (cm)	Trend	Plunge	Fracture Width (cm)	Fracture Density	Fracture Porosity	Fracture Permeability
F1	24	250º	17º	0.3	0.24	0.0072	0.0022
F2	31	247º	36º	0.1	0.31	0.0031	0.0008
F3	32	220º	41º	0.2	0.32	0.0064	0.0016
F4	34	218º	41º	0.3	0.34	0.0102	0.0022
F5	29	222º	33º	0.9	0.29	0.0261	0.0202
F6	42	240º	38º	0.6	0.42	0.0252	0.0009
F7	39	210º	41º	0.6	0.39	0.0234	0.0009
F8	34	210º	36º	0.2	0.34	0.0068	0.0016
F9	26	230º	35º	0.7	0.26	0.0182	0.0274
F10	33	215º	42º	0.9	0.33	0.0297	0.0202
F11	30	222º	39º	0.6	0.30	0.0180	0.0009
F12	32	218º	33º	0.8	0.32	0.0256	0.0213

Table 3. Fracture characterization data for measured fractures in studied site 3. The table presents comprehensive geometric and hydraulic properties including fracture length (cm), trend (degrees from north), plunge (degrees below horizontal), aperture width (cm), fracture density (fractures per unit length), fracture porosity (dimensionless ratio of fracture void space to total rock volume), and fracture permeability (dimensionless coefficient representing fluid flow capacity through fracture networks)

Fracture No.	Fracture Length (cm)	Trend	Plunge	Fracture Width (cm)	Fracture Density	Fracture Porosity	Fracture Permeability
F1	28	190°	22°	0.2	0.28	0.0056	0.0018
F2	36	200°	28°	0.4	0.36	0.0144	0.0032
F3	41	185°	30°	0.7	0.41	0.0287	0.0245
F4	39	195°	33°	0.3	0.39	0.0117	0.0021
F5	26	205°	29°	0.5	0.26	0.013	0.0152
F6	31	210°	36°	0.6	0.31	0.0186	0.0068
F7	38	218°	40°	0.8	0.38	0.0304	0.0221
F8	27	305°	34°	0.2	0.27	0.0054	0.0015
F9	34	307°	32°	0.9	0.34	0.0306	0.0198
F10	30	300°	35°	0.4	0.3	0.012	0.0041

scale (0.2-0.9 cm), but studied site 5 includes and exceptional aperture with of measured fracture no.14 (2.6 cm) due to high activity of hydrothermal fluids movement as seen in many outcrop of this studied site, and contains various mineral assemblages along the contact with Hadda Quartzite. This fluid movement interaction in deformed rock is explained in the study by Witherspoon *et al*. (1980) for validation of cubic law in fluid mechanics of rocks.

Table 4. Fracture characterization data for measured fractures in studied site 4. The table presents comprehensive geometric and hydraulic properties including fracture length (cm), trend (degrees from north), plunge (degrees below horizontal), aperture width (cm), fracture density (fractures per unit length), fracture porosity (dimensionless ratio of fracture void space to total rock volume), and fracture permeability (dimensionless coefficient representing fluid flow capacity through fracture networks)

Fracture No.	Fracture Length (cm)	Trend	Plunge	Fracture Width (cm)	Fracture Density	Fracture Porosity	Fracture Permeability
F1	25	145°	18°	0.2	0.25	0.005	0.0012
F2	33	150°	22°	0.5	0.33	0.0165	0.0142
F3	29	212°	27°	0.3	0.29	0.0087	0.0024
F4	40	190°	27°	0.7	0.4	0.028	0.0208
F5	36	220°	30°	0.6	0.36	0.0216	0.0095
F6	32	165°	32°	0.4	0.32	0.0128	0.0032
F7	28	225°	28°	0.8	0.28	0.0224	0.0186
F8	35	160°	33°	0.5	0.35	0.0175	0.0124
F9	30	155°	26°	0.6	0.3	0.018	0.0108
F10	38	240°	41°	0.9	0.38	0.0342	0.0256

Table 5. Fracture characterization data for measured fractures in studied site 5. The table presents comprehensive geometric and hydraulic properties including fracture length (cm), trend (degrees from north), plunge (degrees below horizontal), aperture width (cm), fracture density (fractures per unit length), fracture porosity (dimensionless ratio of fracture void space to total rock volume), and fracture permeability (dimensionless coefficient representing fluid flow capacity through fracture networks)

Fracture No.	Fracture Length (cm)	Trend	Plunge	Fracture Width (cm)	Fracture Density	Fracture Porosity	Fracture Permeability
F1	70	340˚	14˚	0.4	0.70	0.2800	0.0053
F2	51	247˚	49˚	0.6	0.51	0.3060	0.0108
F3	17	300˚	40˚	0.3	0.17	0.510	0.0023
F4	28	298˚	43˚	0.6	0.28	0.1680	0.0108
F5	27	280˚	41˚	0.2	0.27	0.0540	0.0007
F6	36	280˚	48˚	0.4	0.36	0.1440	0.0053
F7	33	283˚	48˚	0.4	0.33	0.1320	0.0053
F8	34	210˚	37˚	0.5	0.34	0.1700	0.0130
F9	29	220˚	46˚	0.5	0.29	0.1450	0.0130
F10	20	285˚	48˚	0.6	0.20	0.1200	0.0108
F11	12	290˚	49˚	0.7	0.12	0.0840	0.0204
F12	12	248˚	50˚	0.8	0.12	0.0960	0.0427
F13	44	330˚	17˚	0.3	0.44	0.1320	0.0023
F14	50	230˚	41˚	2.6	0.50	1.3000	0.1758
F15	51	225˚	44˚	0.3	0.51	0.1530	0.0023
F16	44	240˚	41˚	0.3	0.44	0.1320	0.0023
F17	50	310˚	46˚	0.2	0.50	0.1000	0.0003
F18	32	300˚	45˚	0.6	0.32	0.1920	0.0108

Discussion

The study analyzes different outcrops and structures of Kirana Hills area which has an inverted tectonic environment and with a long geological history. The Kirana, comprises Pre-cambrian bimodal volcanism consitted of basalt, andesite, and rhyolites, volcanoclastic and hypabassal intrusive rocks overlain by low grade metasedimentary sequences. The analysis of these rocks were done in recent past by Jamil and Sheikh (2012) as they have studied the geodynamics and behaviour of Neoproterozoic reservoirs in Pakistan. Similarly, the study conducted by Ahmad and Chaudhry (2008) focuses on the geochemical characterization of rocks by observing the field and sample collection in different parts of Kirana. As in this stud, the same localities have been studied, but there the field extent also includes the Hachi Hills covering NE-SW of the region, where mine quarries have been established by the government at the time of observations. This succession spans over ~870 Ma, consistent with the Late Proterozoic rifting and plume-related magmatism are linked to the breakup of the Rodinia supercontinent and the formation of the Mozambique Ocean

(Davies and Crawford, 1971, Chaudhry *et al*., 1999; Ahmad and Chaudhry, 2008). Similarly, these sequences are also documented in other studies of Neoproterozoic rifting by Gaucher and Sprechmann (2009) and Gaucher *et al*. (2009).

This study confirms the stratigraphic framework across the observed sites (type localities) demonstrating spatial continuity of volcanic flows, tuffs, and overlying metasediments in the Kirana Hills. This consideration was also documented by in a stratigraphic research report by (Bhatti *et al*., 2017), while structural characterization was well documented in similar studies of the region by Deb (2014) and Chaudhry *et al*. (2022). The recent studies in the Kirana documented the metasedimentary sequences and the role of soft sedimentary deformation in this region (Ali *et al*., 2025). In this field observation, most of the localities show structural styles related to basin inversion and high rate of shear deformation, resulting in fault-bounded geometry. This analysis and observation aligns with gravity and magnetic interpretations done in Kirana region (Farah *et al*., 1977; Jan *et al*., 2022) supporting the analysis, and also supports the mechanism that Kirana is not associated with Vindhyan orogenic belt sequences, but from their own rift related tectonomagmatic province as explained in this study and in past by Khan *et al*. (2009). In relation to geodynamics aspect of this study, Kirana is associated with multiphase tectonothermal events. Early felsic volcanism and ryolitic intrusion (hematite enrich solutions) as seen in studied site 1, this particular aspect of change, was also reported in the study by Alam *et al*. (1992), Chaudhry *et al*. (1999), Chaudhry *et al*. (2022). Similarly in the area of Chandar Hills and mostly NW trend of Kirana region, the sill-dyke intrusion was commonly seen along with micrograniteS, indicating evolving magmatic flux. This influence was characterized and defined first in study by Davies and Crawford (1971) suggested this mechanism related to progressive lithospheric thinning, and Khan *et al*. (2017) reported as crustal melting. Moreover, the identification of chlorite-bearing greenschist and Boudinage structures in site 1 (Qilla Hills) implies syn-volcanic or tectonic extension and in some literature as hydrothermal activity consistent with evolving rift settings. This assemblage in specific zones of Kirana associated with Qilla and Chandar Hills were also documented with mineral assemblages and petrographic characterization study conducted by Chaudhry *et al*. (2021), and tectonic links in these mineral assemblages were reported in a research condcuted on Proterozoic sedimentary cycles and Paleo-magmatism by Spaggiari (2014). The presence of rhyolitic-volcanoclastic facies transitioning into fiolated tuffaceous slates and associated mineralization (hematite and bornite) in different sites mainly in Asianwala Formation at Chandar Hills and in Chenab Nagar area, suggest that the deformation, fluid flow, and metasomatism occur during and after magmatic activity. The flow mechanism of hydrothermal activity was also documented in these specific areas of Kirana except the new studied area (Chenab Nagar) in this field by Alam *et al.* (1992), Chaudhry *et al*. (1999), and Chaudhry *et al*. (2022). The observation related to hydrothermal mineralization and fluid pathways in this study suggests that observed hematite alteration zones, quartz, and calcite bearing deposits mainly associated with Hadda Quartzite. Bornite occurences and liminoite coatings in Asianwala Formation and jasper mineralization in Sharaban Formation are all associated with these migration pathways of hydrothermal enrichments. The oxide and sulfide mineral assemblages occured in the strucutrally controlled zones. This zones are described in other studies as lenses, veins, and fractures by Cathles (1981), Caine *et al*. (1996), Bons (2000), and Chaudhry *et al*. (2022). Such widespread iron oxide ± copper sulfide mineralization in Neoproterozoic volcanic terranes has parallels in the eastern Saharan orogenic belt (Bouabdellah and Slack, 2016; Abdel-Karim *et al*., 2024). The field observations and field photographs suggested that crystalline Kirana outcrops are encircled by Quaternary alluvium and aeolian deposits. These sedimentary deposits sequences are mostly observed in Sharaban Village, associated with conglomerates and mud deposits of fluvial environments which were also studied in detail by Ali *et al*. (2025) associated with soft sedimentary deformed structures of Sharaban Formation in Sharaban Village. This aligns with regional geomorphic models where resilient bedrock knobs in the Punjab Plains punctuate extensive loess mantles derived from the fluvial sources (Clift, 2022; Inam *et al.*, 2022). The juxtaposition of resistant Proterozoic basement and unconsolidated Quaternary cover highlights The Kirana Block tectonic and geomorphic significance (Inam *et al*., 2022).

The fracture studies performed in different sections across the sampling sites, provides important insights into tectonic stresses, deformation type and mechanism associated with fracture analysis, along with the fluid flow regimes of the volcanic-metasedimentary terrane of the region. The observed fracture orientations display consistent NW-SE and WNW-ESE trending with plubging dominant at the moderate to steep slope, reflecting regional compression regime of Kirana in comparison to these trends observed. The structural configuration was also briefly determined as the compressional tectonics in studies by Davies and Crawford (1971), Shah (1971), Chaudhry *et al*. (1999), and Khan (2000). These fracture sets are consitent with the inversion tectonics, which are also previously documented in the research by Khan *et al*. (2009) where crustal shortening and basin inversion processes are thought to have generated conjugate and oblique fracture systems. Although there is not much consideration put in concern regarding the fracture studies of this area, the geochemical characterization of the fluids and their reflectance on the rocks was studied by Ahmad and Chaudhry (2009) and Hassan and Haq (2025). The predominance of steep plunges (40°-50°) in the studied sites 1, 3, and 5 suggests brittle fracture under high differential stresses, with a feature are also documented in schsitose and volcanic terranes such as Taku Schist of Malaysia (Ali *et al*., 2008). Similarly, the connection between conjugate joint system in rhyolites and quartzite at sites 1 and 2 matches the paleostress inversion studies conducted along MBT in NW Himalayas. The brittle fracture shows the evidence of compressional and transpressional regimes (Ahsan *et al*., 2021). In terms of lithological control, fractures in rhyolites and basalt (sites 1-2) are predominantly associated with conjugate sets and mineralized veins. Whereas volcanogenic slates (site 3) and quartzite (sites 4-5) show fracture system aligned with foliation and shear zones. This reflects lithological dependency in fracture systems and propagation. Ductile slates can handle shear deformation, while brittle quartzites form steep fracture sets that are more likely to transmit fluids. Researchers have noted similar effects in granitic and metamorphic areas around the world. Here, differences in mechanical properties push fracture growth (Gudmundsson, 2011; Scarpato, 2013). Overall, the detailed field observations and analysis presented in this study contribute to a better understanding of the complex tectonic, volcanic, and metasedimentary history of The Kirana Hill region, which has been shaped by a multiphase geological evolution.

Conclusions

In this study, field investigations were carried out at six studied sites, revealing the complex tectono-magmatic development of the region. The field data suggest that the volcanic sequence within The Hachi Volcanics shows a magmatic range from mafic to felsic compositions at studied sites 1 and 2. The presence of rhyolite, basalt, and microgranite dykes indicate multiple phases of magmatism, starting with early mafic volcanism followed by more evolved felsic intrusions. The observed textural variations, such as porphyritic in rhyolite and phaneritic in basalt, along with structural features like columnar joints and conjugate fractures, provide evidence for different cooling rates and emplacement conditions. The microgranite dykes cutting through basaltic units in Shaheenabad confirm the polymagmatic nature of the complex. This suggests episodic magmatic activity during The Precambrian, which constrains the timing of magmatic events and points to an extended period of crustal melting and differentiation.

The metamorphic assemblages range from lower greenschist to Buchan facies conditions, indicating different pressure-temperature regimes during regional metamorphism. The presence of volcanogenic slates associated with well-developed foliation structures shows low-grade metamorphic changes of primary volcanic materials under compressive stress. The significant hydrothermal mineralization observed throughout the studied area has both scientific and economic importance. However, its potential is limited until 3D geological software and proper magnetic geophysical surveys are used for future assessments. The mineral assemblages, including hematite, limonite, bornite, micaceous hematite, and jasper, indicate multiple phases of fluid-rock interaction under varying oxidation conditions. The iron oxide mineralization (hematite-limonite) points to oxidizing hydrothermal conditions in The Chandar Hills and Sharaban Village. Meanwhile, the presence of bornite in the Asianwala Formation suggests localized reducing sulphide facies mineralization. This shift between oxidation states reflects the complex hydrothermal development, and indicates the potential for Cu-Fe ore deposits, especially in structurally controlled areas near Chenab Nagar. Fracture studies show a systematic pattern of deformation across all examined formations at different sites. The main NW fracture orientations align with regional compressive stress fields, consistent with transpressive tectonic regimes.

However, limitations remain, including the absence of radiometric dating, geochemical and isotopic data characterization, and subsurface geophysical characterization using electrical resistivity survey and electric tomography method. These limitations restrict the chronological resolution or depth of interpretation. Future research should integrate isotopic geochronology, stable isotope and fluid inclusion studies, discrete fracture network modeling, and subsurface geophysical surveys to refine tectonic placements and assess the economical mineral potential. These all studies were done in the past but with limited resources and limitation geological data because of the complex tectonic regime and isolated hills.

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