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Crustal Study Based on Integrated Geophysical and Petrological Investigation in Poonch Division, Azad Jammu and Kashmir

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Abstract: This study examines the tectonic framework and mineral potential of the Poonch Division in Azad Jammu and Kashmir through an integrated geophysical and petrological approach. Situated within the tectonically active Hazara-Kashmir Syntaxis (HKS), the region is profoundly shaped by the ongoing convergence of the Indian and Eurasian plates, an orogenic process that has driven the formation of the Himalayas. This tectonic regime has resulted in extensive crustal shortening, faulting, and uplift, leading to the deformation of Phanerozoic sedimentary sequences and the development of complex thrust fault systems. Gravity and magnetic surveys were employed to delineate subsurface structures and identify zones of potential mineralization. Gravity anomalies correspond with major tectonic features such as the Riasi Thrust and Khaigala Fault, indicating significant density contrasts in the subsurface. Magnetic data revealed anomalies associated with elevated concentrations of magnetic minerals, suggesting the presence of heavy mineral assemblages likely deposited in molasse environments. Petrographic analysis of samples from the Kamlial, Chinji, and Nagri formations reveals a heterogeneous mineralogical composition, indicating a mixed provenance from igneous, metamorphic, and sedimentary sources. The integration of geophysical and petrological data facilitates a comprehensive understanding of the subsurface geology and mineral distribution in the study area. The results highlight the region's complex tectonic evolution and substantial mineral potential. These findings not only enhance the geological understanding of the Poonch Division, but also support its prospects for sustainable mineral exploration and resource development. Realizing this potential could significantly contribute to national economic growth.

Keywords: Hazara-Kashmir syntaxis, tectonic framework, gravity and magnetic surveys, mineral potential petrological analysis, subsurface geology.

Introduction

The collision of the Indian and Eurasian plates is one of the most significant tectonic events, forming the Himalayas and the Tibetan Plateau, and fundamentally altering regional geodynamics (Dewey & Bird, 1970; Molnar & Tapponnier, 1975). The Indian plate, originally part of Gondwana, separated from Madagascar and drifted northward, leading to a collision with the Eurasian plate about 55 million years ago (Molnar & Tapponnier, 1975). This convergence, at a rate of around 45 mm/year (Sella et al., 2002) has generated a series of structural complexities, including faulting and thrusting, particularly across the Indus Suture Zone (ITSZ), Main Boundary Thrust (MBT), and Hazara-Kashmir syntaxis (Burg & Podladchikov, 2000; Wang et al., 2001).

The tectonic pressures created high mountain ranges and deep crustal structures, producing the distinct syntaxial bends at the eastern and western extremities of the Himalayas, such as the Nanga Parbat syntaxis in the northwest (Gansser, 1964). The immense crustal shortening and complex deformation in the region result in substantial mineral potential, particularly within Pakistan's northern territories. Geophysical methods, including gravity and magnetic surveys, are key to detecting density and magnetic anomalies related to ore deposits, geothermal reservoirs, and structural changes (Nabighian et al., 2005). Gravimetric and magnetic surveys help to map subsurface features, such as hydrothermal systems and mineral-rich zones (Criss & Champion, 1984; Hanna, 1969). Additionally, petrological analyses using microscopic methods to examine the mineral composition and structure of rocks provide crucial insights into regional geological history and mineralization processes (Wang et al., 2024; Bo et al., 2015).

In Pakistan, the mineral industry remains underdeveloped despite significant coal, copper, gold, and gemstone resources (Farah et al., 1984). Challenges include outdated technology, limited infrastructure, and policy constraints. Yet, areas like Azad Kashmir, particularly the Poonch region, hold promising mineral reserves essential for economic growth (Kazmi & Jan, 1997). The crustal shortening happens along the distinct thrust as a result of the ongoing convergence of the Indian and Eurasian plates (Najman, 2006). This involves the Indian crust's shortening and under thrusting beneath the Eurasian and lateral isolation along a large transform fault that forced material eastward. This impact caused the Kohistan Island Arc to get sandwiched between the Indian and Eurasian plates. This impact also produced the Himalayan Mountains (Rustam et al., 2003). An integrated geophysical and petrological approach in the region could reveal new prospects, enabling sustainable mineral development and addressing Pakistan's economic and industrial needs (Carranza, 2008; Roonwal, 2018).

The geological study based on petrographic and geochemistry in the southeast of study area was carried out in Mirpur division (Zaheer et al, 2023). This study investigates tectonic dynamics and mineral potential in Rawalakot and surrounding areas, aiming to support resource-driven growth and improve understanding of the geotectonic framework.

Materials and Methods

The study area lies in the division Poonch, Azad Jammu & Kashmir, Pakistan, in the Sub Himalayas, a part of the Hazara Kashmir syntaxes. The area lies between longitudes 73° 40′ 0″ to 73° 50′ 0″ E and latitudes 33° 40′ 0″ to 33° 50′ 0″ to N (Fig.1). There is a variety of topography in the area with steep hills and valleys surrounded by a diverse landscape that averages 1500 meters above sea level. The research area is under the influence of Sub Himalayas (DiPietro et al., 2021; Mughal et al., 2016).

Therefore the structures found in the area are due to the tectonic activities (Bossart et al., 1988). Throughout the region, minor anticlinal and synclinal folding is common. The tectonic forces that have been activated are observed in these formations. Structural characteristics and geometry of the Murree Formation are a function of density difference between shale and sandstone strata of the Murree Formation. It is normal for strata to have strike and dip directions ranging from northeast to southwest which belong to the broad geological and tectonic context of the Himalayan Mountains on the northern part of the Indian subcontinent. As seen in Figure 1, the main lithological unit is the Kamlial Formation (Middle to Early Miocene) which is characterized by purple gray to dark red sandstones with purple-red mudstones and conglomerate intercalated with them.

The Murree Formation (Miocene) covers the upper part of this area. Northern Pakistan, situated along the Indo-Eurasian collision zone, hosts a complex tectonic and mineralized landscape shaped by the breakup of Gondwana, northward movement of the Indian plate, and successive collisions along the Indus Suture Zone (Molnar & Tapponnier, 1975; Allegre et al., 1984; Chatterjee, 1992; Reeves & De Wit, 2000). Previous geophysical investigations have identified major fault systems such as the MBT, MFT, KBT, and BBF, as well as mineralization in the Kohistan Island Arc linked to Fe, Mn, Cu, and Ni deposits (Rustam et al., 2003, 2016; Shah et al., 2020).

Studies elsewhere have shown the effectiveness of integrating geophysical, geochemical, and petrographic methods for detecting mineralized zones (Farzamian et al., 2022; Loukola-Ruskeeniemi et al., 2023). However, such integrative approaches remain underexplored in northern Pakistan. This study addresses this gap by applying combined geophysical and geochemical methods to evaluate the region's mineral potential and support future exploration and economic development.

Geological Setting

The study area lies within Core of Hazara Kashmir Syntaxis (HKS). The main tectonic features such as thrust faults in and around the study area include Salt range Thrust/ Main Frontal thrust, Main Boundary Thrust, Riasi Thrust, Jhelum Strike slip Fault, and Muzaffarabad Fault. Geological mapping of the study area was assessed based on the maps of the Geological Survey of Pakistan (2004) (Sheet No. 43, G/14, Scale 1).

It is supported by satellite images and field observations (50,000). However, stratigraphical units of Precambrian to Quaternary age units are observed in the study area, which are highly deformed due to active deformation zones and linkage with thrusts and faults. Main Boundary Thrust (MBT) separates Sub Himalayan molasses at the core of the HKS and pre molasse Lesser Himalayan at the Limbs of HKS. Geological map indicates the prevailing rocks of Cenozoic and Precambrian age as well as their representation in the study area.

The Rawalpindi group includes Murree Formation of Early Miocene and Kamlial Formation of Middle to Early Miocene representing marine to the continental transition of sedimentation immediately after the closure of Neotethys. From younger to older stratigraphic units, present in the study are explained. Poorly sorted conglomerates consisting of pebbles and boulders of sedimentary, igneous and metamorphic rocks indurated in sandy or clayey matrix constitute Mirpur Conglomerates of Pleistocene age. Siwalik Group consists of Dhok

Pathan Formation of Early Pliocene to Late Miocene age comprising fine to medium grained sandstone of grayish color, medium to thick bedded with silty clay in lower, and in the upper part it contains lenses of conglomerates. In the study area, the Rawalpindi Group overlies Dhok Pathan Formation. Geological succession with description of each rock units of the study area to the local surroundings is given in Table 1.

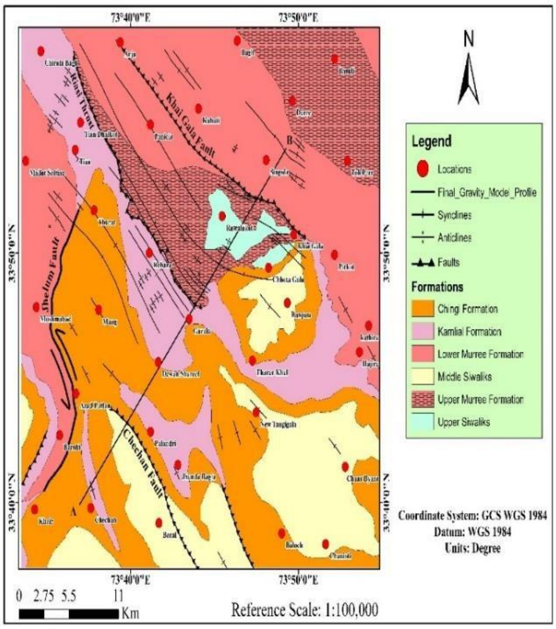

Fig. 1 Geological map of the study area.

Results and Discussion

This section provides the result based on the integrated geophysical and petrological studies keeping in view the objectives of the research and the discussion present the detail of results with comparison to the various previous studies conducted in the area. Gravity and Magnetic interpretation have been caried out in mandatory with the earlier admitted structural and geological information (Rustam et al., 2016, 2018; Latif, 1970, 1973; Rustam, 1994; Rustam et al., 2003; Valdiya, 1980; Wadia, 1931).

Qualitative Interpretation

For qualitative interpretation map of the study area like Bouguer anomaly, Regional and Residual anomaly. Free Air anomaly, average Crustal Thickness, Total Magnetic intensity, Regional and Residual Magnetic Intensity, and Reduce to pole Magnetic Intensity were created.

Bouguer anomaly map of the study area: The Bouguer anomaly map of the project area has been created in Geosoft Oasis Montaj software using minimum curvature at the scale of 1:4.1, with contour interval of 5 mGal (Fig. 2). Different contour closures are shown by the Bouguer anomaly map. The comparatively high gravity contours closure, between -190 mGal to -186 mGal, indicated the presence of high-density material in the southern part of the area between Baral to Palandri. Whereas in the Southeast of this zone, the second zone developed with comparatively low gravity relief. This zone trend in the southeast to northeast direction between Baloch and Rawalakot area and suggested the comparatively medium density rocks. The area between Baral and Palandri the NW-SE contours trend demarcated the Chechan fault. The rocks lie in the footwall of Chinji Formation having high density. In the central part between Dewan Shareef to Mang this zone also suggests the presence of some high-density rocks.

In the north and northeastern part of the Mang and Rawalakot area's the low gravity contours closure trending in the NW-SE to E-W directions confirm different thrust faults like Riasi thrust and Khaigala thrust. The rocks in this area are highly imbricated, the density of rock in this region decreases due to intense deformation like faulting and fracturing. The NW-SE contours trend in Garala suggested the presence of Riasi thrust. Whereas in the NNE part of Rawalakot the N-S contours trend demarcated Khaigala fault. The very low gravity relief in the northeastern periphery of the area in Toliper area is suggested the presence of very low-density material near the Shaheed Gala fault or BBF.

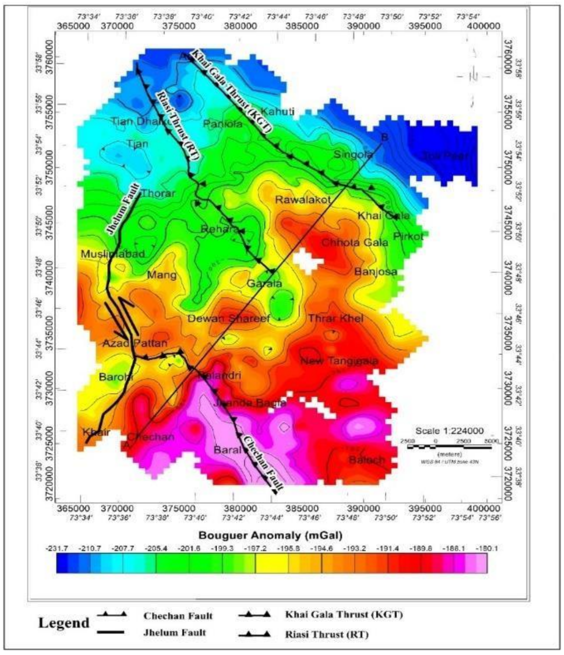

Fig. 2 Bouguer anomaly map of the study area.

Regional bouguer anomaly of the study area: Using minimum curvature technique, we have created the regional Bouguer anomaly map in Geosoft Oasis Montaj, already described software.

In some cases, the regional Bouguer anomaly is separated from the regular Bouguer anomaly by the upward continuation filter, using both contour interval of 1 mGal. Over the regional Bouguer Anomaly the clear contour trend is in the SE-NW direction. Figure 3 shows the regional Bouguer anomaly map which shows broad regional gravity trends in the gravity variations ranging from -216.1 mGal to -184.2 mGal. In the northern part of the study area contours indicating NE-SW trends between Singola and Paniola whereas between Paniola to Thorar contour trend is from SE to SW. Generally, the gravity decreases towards NNE directions. The aggregate pattern observed in this structural trend is consistent with the presence of large-scale subsurface structures, possibly associated with crustal thickening or deep-seated tectonic features.

Gravity anomalies in the northwestern areas, especially the aspect of Tian Dhalkot and Kohala areas are low as compared to other area and may indicate the presence of low-density materials as such could be associated with sedimentary sequence or deeper crustal root. On the contrary, southeastern portion has higher gravity values, around Khair and Baral as well, characteristically indicate more dense formations, possibly associated with uplift of basement rocks, structural highs or the births. Significant tectonic forces exert an overall gravity gradient across the region, and steep contour gradients near Garala and Pirkot indicating possible active fault zones or major geological boundaries.

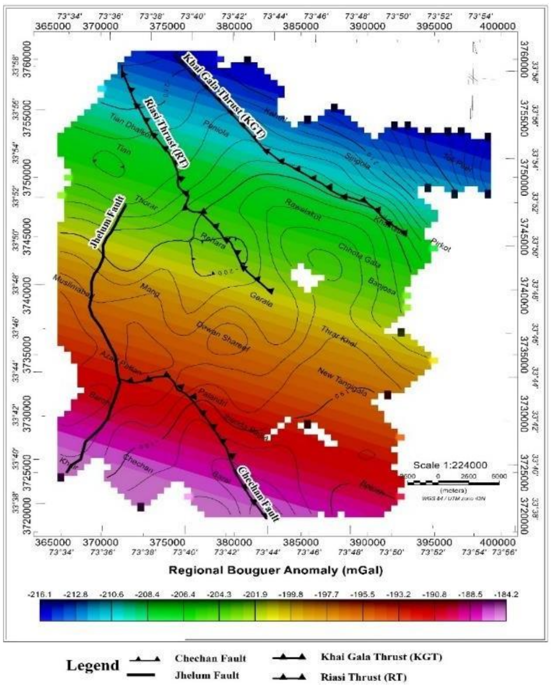

Fig. 3 Regional Bouguer Anomaly map of the study area.

With critical insights into the regional deep structural framework provided, the distribution of density contrasts at a broader scale is provided through the regional Bouguer anomaly map.

Residual bouguer anomaly of the study area: The regional Bouguer anomaly map has been created in the already described Geosoft Oasis Montaj software by means of minimum curvature technique. The upward continuation filter has been applied for the separation of regional Bouguer anomaly from the Bouguer anomaly with the contour interval of 1 mGal. The residual Bouguer anomaly map that represents gravity variations from -18.1 mGal to 14.5 mGal (Fig. 4).

The general contour trend on the Bouguer anomaly map is in the NE-SW direction. The Residual Bouguer anomaly map is classified into three main zones i.e., the northeastern zone, central zone, and the southwestern zone. The northeastern zone consists of one high gravity zone (H1) at Chouta Gala which indicates the high-density rocks i.e., middle Siwalik's of Late-Miocene to Middle-Miocene age.

The high gravity value in this zone is also due to the presence of Khai Gala Fault and Riasi Thrust extending from north to east. In the northeast of the (H1) zone lies the medium gravity zone (M1) between New Tanggala and Thara Khal. The medium gravity values in this zone represents the medium density rocks such as Chingi Formation of Early to Late Miocene age and Kamlial Formation of Early Miocene to Middle Miocene age. In the northern part of the study area the medium gravity zone (M2) is developed at Paniola. This medium gravity zone also indicates the presence of some medium density rocks such as Lower Murree Formation of Eocene age.

These positive anomalies probably result from uplifted basement rocks or faulted rocks. The low gravity anomalies over the western and northwestern parts, around the Muslimabad, Rehara and Thorar represents the (L1) gravity zone at Barohi area, implying the presence of low-density material, perhaps linked to the sedimentary sequences or highly deformed zones. Based on steep gravity gradients between Garala and Dewan Sharief, possibly tectonic boundary or fault zones indicate important differences in subsurface structure. One negative contour closure (L2) is also developed at the Toli Per.

The gravity values in this part of the study area ranges from the -18.1 mGal to -5.8 mGal. The low gravity gradient in this part is due to very low-density rocks of Miocene age Murree Formation.

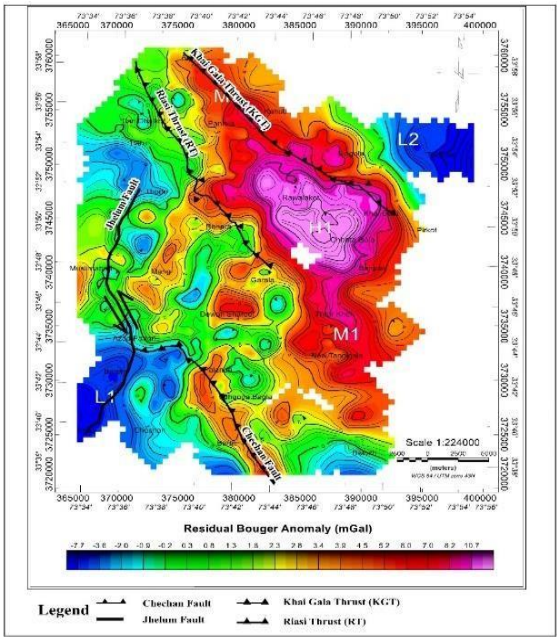

Fig. 4 Residual Bouguer Anomaly map of the study area.

Total magnetic intensity: The Total Magnetic Intensity (TMI) distribution across a region in the Hazara area is overlain with major tectonic features, including the Chechan Fault, Jhelum Fault, Riasi Thrust (RT) and Khai Gala Thrust (KGT), shown in the first map. Magnetic anomalies in a range from low (–492.4 nT) to high (110.3 nT), with blue and purple areas representing low intensity of magnetic, and red, pink, and yellow areas indicating high magnetic intensity (Fig. 5).

The central and southern areas have the highest values and are concentrated around Azad Patta, Dewan Shar, Barari and Garala. These regions of high intensity may reflect highly magnetic rocks or igneous intrusions or tectonically uplifted magnetic formations. Relatively low magnetic intensity is shown in the northern and eastern portion of the map, near Rawalakot, Kahuti, and Singola, which may be related to less magnetically active lithologies or deeper sources.

The Chechan Fault and Riasi Thrust, correspond to notable changes in magnetic intensity interpreted as tectonic displacement, uplift of magnetic basement rocks, or juxtaposition of different lithologies with different magnetic properties. The sharp gradient in the magnetic intensity in the magnetic field curve between the high and low values near Khai Gala and Pirkot indicates that the Khai Gala Thrust is a prominent boundary. Structural faults likely control the framework that governs the distribution of magnetic anomalies, whereas the magnetic highs along the southern section might represent subsurface tectonic features which uplifted magnetic unit closer to the surface.

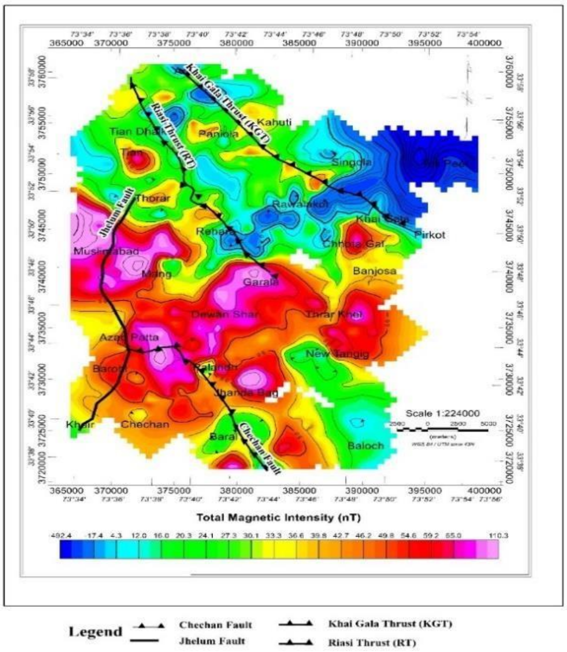

Fig. 5 Total magnetic intensity (nT) map of the study area.

Reduction to pole total magnetic intensity map: Reduced to Pole (RTP) Total Magnetic Intensity, showing the magnetic anomalies with the regional magnetic inclination removed for what would be observed at the magnetic pole (Fig. 6). This processing removes dipolar anomalies and aligns them directly over source, facilitating easier interpretation. However, the present RTP map is still quite wide in the range of magnetic values from -36.8 nT to 78.6 nT. As in the TMI map the highest anomalies (in pink and red) are concentrated in southern and central parts, including around Garala, Dewan Shareef, and Azad Pattan.

The source of these anomalies appears to be shallow and robust, and could be high-magnetic-content rocks, the mafic or ultramafic units associated with deformational tectonic events, or magnetic minerals. All three faults align with significant gradients in the magnetic field, which suggest they have played a role in shaping the regional tectonic framework and perhaps with the emplacement of magnetically different rock bodies. Reduction to pole transformation enhances the visibility of the magnetic highs and lows, particularly a magnetic low (in blue) in the northeast around Singola and Gala Peet that may indicate the presence of nonmagnetic lithologies or deeper sources in that region.

Magnetic contrasts exist between the regions near the Khai Gala Thrust and the Riasi Thrust, possibly due to tectonic juxtaposition of different lithological blocks of differing magnetic property. In some areas, the magnetic intensity contrasts are caused by thrusts which apparently coax magnetic anomalies closer to the surface.

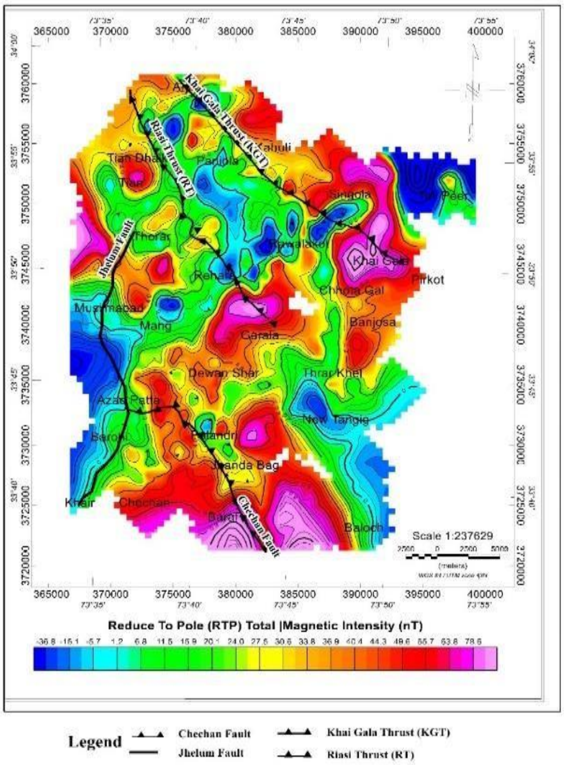

Fig. 6 Reduce to Pole (RTP) Total Magnetic Intensity (nT) map of the study area.

Regional magnetic intensity: This map provides the Regional Magnetic Intensity of a region that is tectonically active, with magnetic anomalies ranging from (-102.6) nT to (76.2) nT, represented by a gradient of cool blue to warm pink hues. The variations here show the effects of lithology, structural deformation, and tectonic activity on the magnetic properties of underlying rock formations. Areas of higher magnetic intensity (red, pink hues) correspond to the Jhelum Fault and the Chechan Fault, which are seen in the southwestern part of the map (Fig.7).

Its presence therefore suggests the presence of magnetically susceptible rocks, potentially uplifted basement material, such as iron rich lithologies or metamorphic units. In particular, the Riasi Thrust (RT) and Khai Gala Thrust (KGT) in the northern and central part of the region correspond to lower magnetic intensities (blue and green hues). It therefore suggests the dominance of weakly magnetic or nonmagnetic rocks, mostly sedimentary sequences or deeply buried metamorphic unit, under compressional tectonic settings.

In fact, the abrupt change in the sharp magnetic gradient along the fault line, especially along the Chechan Fault, indicates the sharp change of the subsurface condition, and therefore suggests that the fault lines can play a major role in the formation of the tectonic boundaries. Higher magnetic intensity may occur where denser, magnetically active rocks occur in association with igneous or metamorphic processes, and may correlate with the area near the Jhelum and Chechan Faults. The northern (Toli Peer and Khai Gala) region, however, has low magnetic values due to young sedimentary cover.

The variation in this area highlights the way in which faults and thrusts define the geological framework of the region, and in controlling the distribution and exposure of different rock types. Moreover, the alignment of magnetic gradients with fault systems implies that these are active tectonic zones in the regional deformation pattern.

The magnetic data is highly valuable for understanding the regional subsurface lithology and tectonic evolution. The origin of the higher magnetic anomalies is probably uplifted or exposed basement blocks, whereas the lower values are sedimentary units covered by over thrusting. The combined influence of Jhelum Fault, Chechan Fault, Riasi Thrust and Khai Gala Thrust emphasizes that interaction between faulting, thrusting and surface mass distribution creates a tectonically dynamic area. The map, using WGS 84 / UTM zone 43N projection and scaled at 1: Using 224,000, we have an excellent tool for regional geological interpretation to inform our understanding of crustal deformation and tectonic evolution.

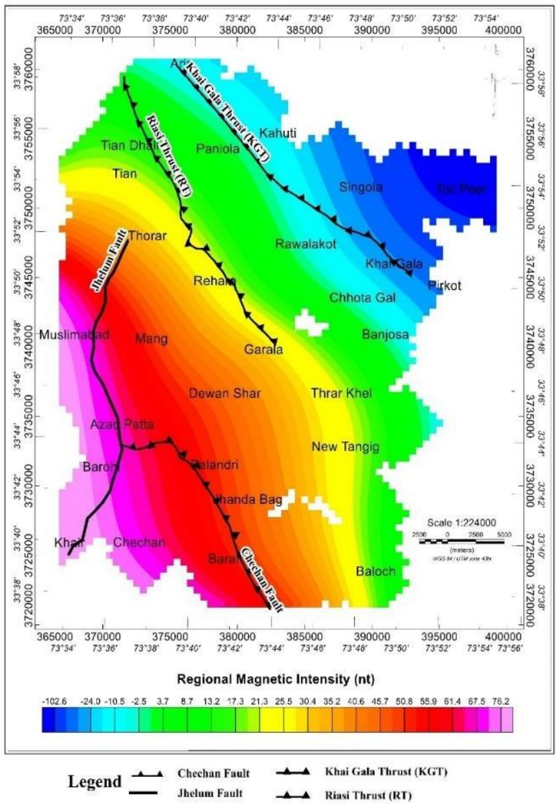

Fig. 7 Regional Magnetic Intensity (nT) map of the study area.

Residual magnetic intensity: The third map presents the residual magnetic intensity, showing more localized anomalies to determine smaller scale subsurface structures. Values of residual anomalies run from deep blue (very low), all the way to bright pink (very high). Like the previous image the map highlights the same fault systems, but at a greater magnification, and illustrates addition information about localized magnetic anomalies. The residual magnetic anomalies in the Palandri, Dewan Shareef, and Azad Pattan regions are strong positive, suggesting the possibility of local rocks having high magnetic contrasts, i.e., basalts and some metamorphic rocks (Fig. 8).

Unlike those, reserved areas like Toli Peer, Chechan, and Baloch have much lower residual magnetic intensity that might argue for the presence of sedimentary basins and/or less magnetized rocks. Residual anomalies are aligned with known fault locations including the Chechan Fault and Khai Gala Thrust indicating they may be responding to tectonic activity, deformation and the presence of magnetic materials in the subsurface along the fault zones.

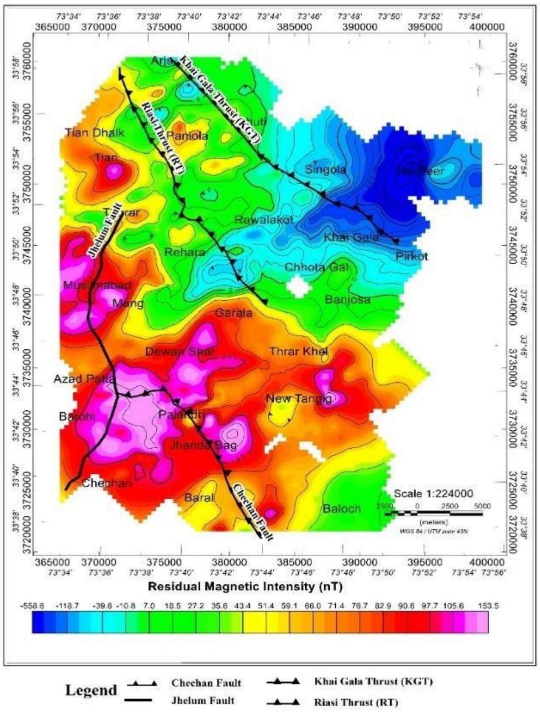

Fig. 8 Residual magnetic intensity (nT) map of the study area.

Quantitative Interpretation

Crustal thickness: The region's total crustal thickness (kilometers) in color gradient from deepest blue to brightest pink, depending on crustal depth (Fig. 9). The thickest parts of the crust concentrated in the near the northern and the northeastern parts, and their thickness more than 45 km, can be phenomena of Arja near Kahuti and Singola. Moderate crustal thickness from 40 to 43 km appears in central and southern mapped area, especially in the area around Palandri, Rawalakot and Garala, in green to yellow colors. Thinner crust, around 38–40 km, is observed in southwestern areas subjected to Chechan, Khair and Baral (Fig. 10).

The crustal thickness distribution in the region suggests the crust of the northern part may be subjected to even greater tectonic stresses, in part because of the proximity to faults undergoing the ongoing crustal shortening and thickening due to thrusting. Second, crustal thickness variation could be even further evidence for variations in the tectonic plates or blocks of the region.

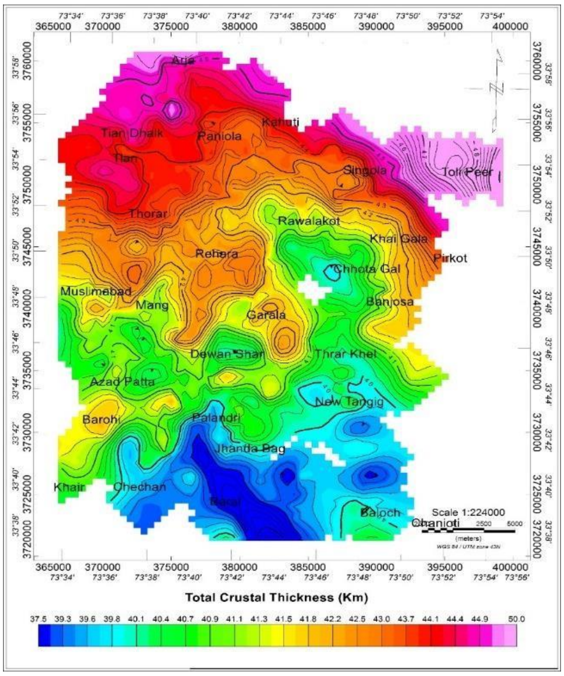

Fig. 9 Total crustal thickness map of the study area.

Gravity modelling: The gravity model along profile A-B/ (Fig. 2) selected from Chechan to Singola is 32.5km in length. Using observed and calculated gravity data, the presented model illustrates the structure of a 2D gravity profile for a region with complex geological formations and fault systems. The modeled gravity response compared to the observed gravity anomalies is shown above in purple and blue respectively to evaluate the fit between measured and predicted data in the upper section of the modeling response (Fig. 10). The minor differences between the two curves imply good correlation between the geological model and the subsurface characteristics. The stratigraphic layers and fault systems are represented beneath the gravity profile. Each geological formation is color coded and described by a legend of units. For example, different formations defined in the model include the Upper Murree, Lower Murree and

Kamlial Formation, together with other units such as Kuldana Formation, Carbonates, Salt Range Formation, Chinji Formation and the Crystalline Crust of Indian shield. In this area the strata have been folded and faulted. Such type of deformation has been significantly deformed due to tectonic forces. Major fault systems such as the Chechan Fault, Riasi Thrust and Khaigala Fault are shown by dashed lines which denote major structural discontinuity in the area. This geological model computed different geological prisms faults and local sedimentary basin in the area.

The present model also depicted the deeper structures such as the Crystalline Crust of Indian shield and upper Moho. At the base of the model, the Moho represents the transition between the Earth's crust and the upper mantle, an important boundary in probing crustal thickness and tectonic process patterns in the region. Depending on the material properties of each layer, the color variations within the formations and fault zones correspond to density variations (in g/cm³). For example, within certain layers, specific density values of -0.4 to -0.7 g/cm³ occur, while the density variations of upper Moho with crystalline crust and Moho is at 0.30 g/cm³.

The geological model computed on the basis of gravity data depicted different geological prism and thrust system between Chechan in the SW and Singola in NE. The first prism consists of Chinji Formation has been computed between 0 – 1.41 km. The density contrast of this prism with crystalline crust of Indian shield is -0.55g/ cm³ after this prism the Kamlial Formation of older age is thrusted over the Chinji Formation, and developed the local fault which is extended up to Kuldana Formation. The prism of Kamlial Formation computed between 1.41 – 2.65 km, density contrast of this prism with crystalline crust is -0.4 g/cm³. The third prism also consist of Chinji Formation computed between 2.65 – 5 km and the density contrast assigned to this prism with crystalline crust of Indian shield is -0.58 g/cm³. This prism has comparative low density due to presence of high shale contents and fractures. The fourth prism consist of Middle Siwalik's which computed between 5 - 7.5 km. The density contrast of this prism with crystalline crust is 0.54 g/cm³, and this prism shows the faulted contact with the younger Chinji Formation.

The fifth prism of Chingi Formation computed with 7.5 – 8.61km and the density contrast assign to this prism with crystalline crust is again -0.55 g/ cm³.The sixth prism again consist of Kamlial Formation computed between 8.61 –10 km. The density of this prism with crystalline crust is -0.4 g/cm³. The seventh prism again consist of Chinji Formation computed with 10 – 12.68 km and the density of this prism with crystalline crust is -0.55 g/cm³. The eight prisms of Kamlial Formation computed between 12.68 – 18.22km and the density of this prism with crystalline crust is -0.4 g/cm³. This prism shows the faulted contact with the ninth prism of upper Murree Formation which extended from 8.22 – 23.34km and the density of this prism is -0.58 g/cm³.

The tenth prism consist of upper Siwalik's computed between 23.34 – 25.79 km and the density contrast this prism with crystalline crust is -0.04 g/cm³. The second last prism computed between 25.79 – 28 km and the density contrast of this prism is -0.57 which developed the faulted contact with lower Murree Formation which extended from 28 -32 km and density contrast of this prism with crystalline crust is -0.48 g/cm³. The model also computed the Kuldana Formation which have the density contrast of -0.55 g/cm^3 with crystalline crust under the Siwaliks and Murree formations.

The carbonates of Eocene to Cambrian age are also computed under the Kuldana Formation. The thickness of these carbonates are 2.8 to 3 km and density contrast assign to -0.38 g/cm^3. The Salt Range Formation of Precambrian age is computed under the thick layer of carbonates. The density contrast assigned to this formation is -0.7 g/cm^3. The 38km thick crystalline crust of Indian shield is extended throughout the study area. The model also computed the upper Moho which have the density contrast of 0.3 g/cm^3.

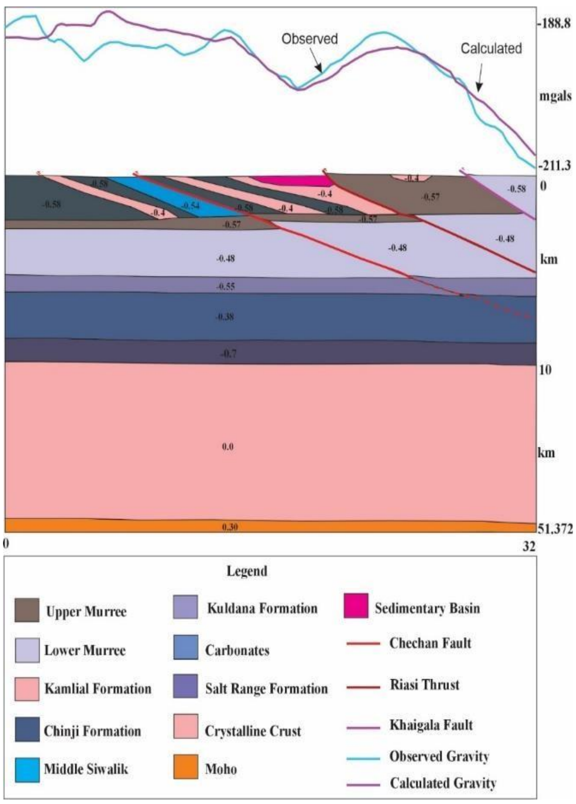

Fig. 10 Gravity modeling of the study area.

Petrography and Mineral Potential

The sandstone of the Nagri Formation exhibits a diverse mineralogical composition indicative of a complex provenance (Fig. 11). The presence of quartz, a highly resistant and stable mineral, suggests significant contributions from mature continental sources, likely dominated by weathered crystalline rocks. The occurrence of epidote and monazite points to inputs from igneous and metamorphic terrains, specifically those associated with moderate-grade metamorphism and intermediate igneous rocks. Zircon, often sourced from igneous rocks, further supports a contribution from eroded crystalline bedrock, particularly of felsic origin. The occurrence of muscovite suggests a derivation from metamorphic or granitic sources, indicative of sedimentary recycling or contributions from mica-bearing schists and granites.

Finally, fougerite, a rare iron-bearing mineral, points towards specific geochemical conditions, potentially related to localized diagenetic processes or the presence of reducing environments during sediment deposition. The sandstone of the Chinji Formation displays a mineral assemblage indicative of a complex and multi-sourced provenance (Fig. 12). The presence of both monocrystalline and polycrystalline quartz suggests contributions from stable continental crust as well as recycled orogenic sources, where quartz may have undergone multiple cycles of deposition and reworking. Hematite, often formed under oxidizing conditions, points to a depositional environment influenced by weathering processes, possibly indicating a fluvial or terrestrial setting.

The inclusion of chert and volcanic clasts suggests input from both sedimentary and volcanic sources, indicating the proximity of volcanic arcs or eroded volcanic terrains. The occurrence of tourmaline and garnet, typically associated with metamorphic rocks, signifies contributions from high-grade metamorphic terrains, likely from eroded metamorphic belts. Ilmenite and epidote point towards mafic or intermediate igneous and metamorphic sources, while zircon, a highly durable mineral, underscores contributions from felsic igneous rocks or recycled sedimentary rocks.

Collectively, these mineralogical components suggest that the Chinji Formation sandstone was sourced from a tectonically active region, incorporating materials from igneous, metamorphic, and sedimentary (Fig. 13). The abundance of monocrystalline quartz suggests a significant input from stable continental crust, potentially originating from older, weathered crystalline rocks.

The presence of plagioclase indicates derivation from igneous rocks, particularly those of intermediate to mafic composition, such as andesites or basalts, which are less resistant to weathering and suggest relatively short transport distances or rapid deposition after erosion. Epidote, commonly associated with low- to moderate-grade metamorphic rocks or hydrothermal alteration, points to a metamorphic component in the provenance, possibly indicating eroded metamorphic belts or areas undergoing tectonic uplift.

Overall, the mineral composition of the Kamlial Formation sandstone suggests a mixed source, with significant input from igneous terrains, likely influenced by active tectonism, and contributions from weathered metamorphic and stable continental sources, with evidence of both volcanic activity and prolonged sedimentary recycling. The sandstone of the Kamlial Formation presents a mineralogical composition that reflects a provenance dominated by contributions from both igneous and metamorphic sources. The sandstone of the Dhok Pathan reveals a complex provenance, reflecting contributions from both igneous, metamorphic, and recycled sedimentary sources (Fig. 14).

The presence of abundant monocrystalline quartz suggests significant input from mature continental sources, likely from stable cratonic areas or recycled sedimentary rocks. The occurrence of monocrystalline quartz with stylolite, a feature formed through pressure dissolution during diagenesis, points to compaction and deep burial processes, suggesting a history of multiple sedimentary cycles or significant tectonic stress. The presence of plagioclase indicates an igneous source, likely intermediate to mafic in composition, suggesting relatively short transport before deposition due to its susceptibility to weathering.

Tourmaline, a mineral commonly associated with high-grade metamorphic rocks, indicates contributions from metamorphic terrains such as schists or gneisses. Hematite, often formed under oxidizing conditions, points to weathering in a terrestrial or fluvial environment. The inclusion of sandstone clasts signifies the reworking of older sedimentary rocks, suggesting sediment recycling, while the presence of mica schist reflects contributions from metamorphic sources, particularly those with low to medium-grade metamorphism.Altogether, the Nagri Formation sandstone reflects a diverse and multi-sourced provenance, with contributions from igneous, metamorphic, and recycled sedimentary materials, shaped by tectonic activity and sedimentary rework.

The present study carried out in the Poonch division based on the integrated geological, petrological and geophysical investigation. In this area no such type of work had been caried out. The geological study based on petrographic and geochemistry in the south east of study area caried out in Mirpur division (Zaheer et al, 2022). Different workers caried out the geological study in the north and northwest of the study area (Baig & Lawrence, 1987; Lefort, 1975). Only few workers caried out the geophysical survey in the north and northwest of study area and demarcated MBT, PT, IKSZ and BBF. Rustam and Ali (1997) demarcated the Jhelum strike slip fault between Tian and Muzaffarabad city.

The present study based on qualitative and quantitative interpretation also depicted the Jhelum strike slip fault near Azad Pattan. The study also suggested that MBT, PT and IKSZ are not existing in this area however the BBF lies in northeastern periphery of the area. The different thrust faults have been depicted between Chechan to Singola. These thrust fault from south to north are Chechan fault, Riasi fault and Rawalakot-Khaigala fault. The geological study based on gravity and magnetic data suggested that these thrust faults which lie in the study area are dipping in northeast direction. The geological model suggested that these all faults are thin skinned except the Khaigala fault which joins the thick skinned BBF between Rawalakot and Singola. Mostly the Siwalik's rocks are present in the study area. Some units of Kamlial Formation are also demarcated in this area which formed the faulted contact with Siwalik rock. In the north of Riasi fault mostly the Murree formation is occurring. In the north and northeast of Rawalakot, Khaigala fault developed within the Murree Formation. The rocks of lower Murree are thrusted over the rock of upper Murree formation along this fault.

The crustal thickness computed near Azad Pattan is 10 km whereas in Singola area the thickness extended up to 11 km. The thickness of sedimentary wedge increases from south to north due to stacking of different thrusts sheets along different thrust faults. These thrust faults have been developed due to compressional stresses which are being generated by the collusion of Indian and Eurasian plates. These thrusts faults are trending in the NW-SE direction parallel to the eastern limb of Hazara Kashmir Syntaxis and developed due to SW and SE transportation of eastern and western limbs of HKS, respectively. The crystalline crust of Indian shield is dipping at an angle of 35˚ NE.

Previous workers demarcated the Riasi thrust between Kotli to Palandri and Kohala area as a single fault (Coward & Butler, 1985; Khan et al., 2016; Najman, 2006; Powell & Conaghan, 1973). The present study suggested that lower Chechan fault is an extension of Jhelum strike slip fault whereas all thrust system lies between Palandri and Singola join with detachment. These all-thrust faults are developed due to compressional stresses and are offshoots of the Riasi thrust fault. The active nature of faults in the study area imbricated the sedimentary wedge. The cyclic deposition of sandstone, mudstone and shale in Murree formation and clays in Siwalik rocks in future will play a significant role in the landsliding.

The two earthquakes occur in February 2024 near Rawalakot and Davi Gali along the Rawalakot Khaigala fault suggested that this fault is tectonically very active. The seismicity slickenside and imbrications also suggested the area is tectonically very active. The earthquake focal mechanism solution (Hameed et al., 2023) also indicates the SW and SE oriented stresses in core of HKS. These stresses are generating the seismicity near the apex and core of the HKS, then stresses are produced due to collision of Indian and Eurasian plates. These stresses will trigger the long term and medium-term earthquakes in the study area.

The petrographic study indicates that heavy minerals like zircon, monazite, ilmenite, and tourmaline are commonly found in the sandstone of the Himalayan molasse sequence of the Poonch Division. Zircon ($ZrSiO_4$) is found in the sandstone of Chinji and Nagri Formations. It is known for hosting a wide range of trace elements and rare earth elements (REEs) due to its ability to substitute zirconium (Zr) in its crystal lattice. Common trace elements found in zircon include hafnium (Hf), uranium (U), thorium (Th), yttrium (Y), niobium (Nb), tantalum (Ta), and phosphorus (P). Zircon is also a significant host for both light and heavy REEs, such as cerium (Ce), neodymium (Nd), samarium (Sm), dysprosium (Dy), erbium (Er), ytterbium (Yb), and gadolinium (Gd), with a preference for heavy REEs (HREEs) (Lukács et al., 2018) Monazite, another important heavy mineral found in the sandstone of Nagri formation, contains various trace elements including strontium (Sr), barium (Ba), rubidium (Rb), zirconium (Zr), uranium (U), thorium (Th), lead (Pb), and nickel (Ni). Monazite is also a significant carrier of REEs such as cerium (Ce), neodymium (Nd), and lanthanum (La) (Farzamian et al., 2022).

Ilmenite ($FeTiO_3$), a common accessory mineral derived from igneous and metamorphic rocks found in the sandstone of Chinji Formation, probably contributes trace elements such as vanadium (V), chromium (Cr), magnesium (Mg), manganese (Mn), nickel (Ni), and cobalt (Co). Although ilmenite itself does not typically host significant amounts of REEs, small concentrations of cerium (Ce) or yttrium (Y) may be present in some complex mineral assemblages (Míková et al., 2014) Tourmaline found in the sandstone of Dhoak Pathan Pormation. It is a boron silicate mineral group, is notable for accommodating a wide range of elements in its structure. It can contain trace elements such as lithium (Li), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), magnesium (Mg), nickel (Ni), cobalt (Co), and lead (Pb). Although tourmaline is not a primary REE-bearing mineral, small amounts of REEs like cerium (Ce), yttrium (Y), and lanthanum (La) have been reported in some varieties, particularly in complex pegmatites (Míková et al., 2014).

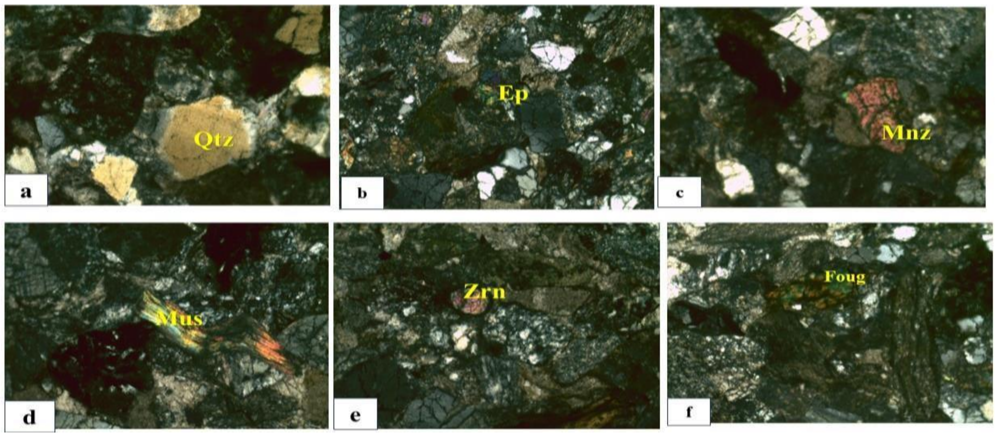

Fig. 11 Photomicrograph of sandstone of Nagri Formation showing a) quartz (Qtz), b) epidote (Ep), c) monozite (Mnz), d) muscovite (Mus), e) zircon (Zrn), f) fougerite (Foug).

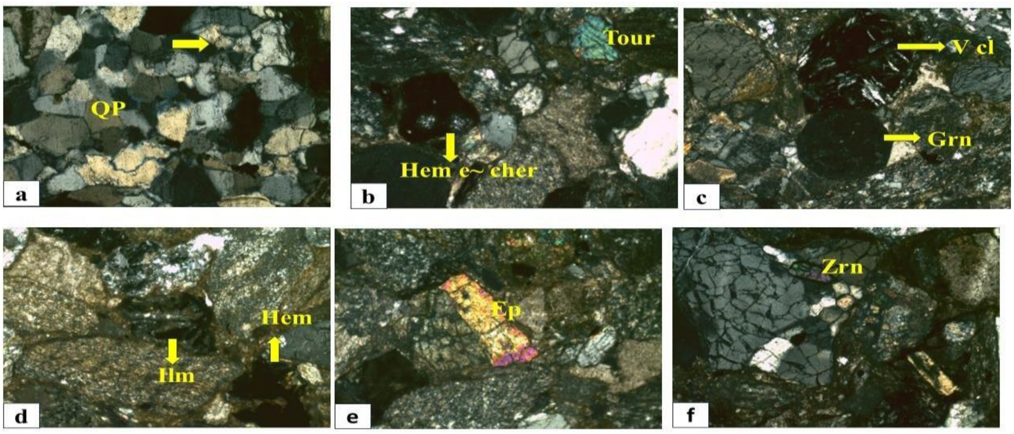

Fig. 12 Photomicrograph of sandstone of Chinji Formation showing a) polycrystalline quartz (QP), b) Hematite with chert (Hem e~ Cher), Tourmaline (Tour), c) Volcanic clast (Vc), Granet (Grn), d) Ilmunite (Ilm), Hematite (Hem), e) Epidote (Ep), f) Zircon (Zr).

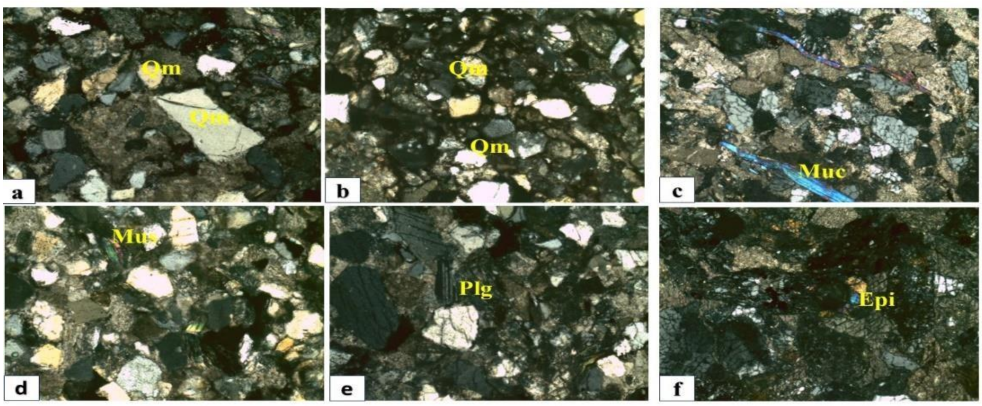

Fig. 13 Photomicrograph of sandstone of Kamlial Formation showing a, b) Monocrystalline quartz (Qm), c, d) Muscovite (Mus), e) plagioclase (plg), f) Epidote (EP).

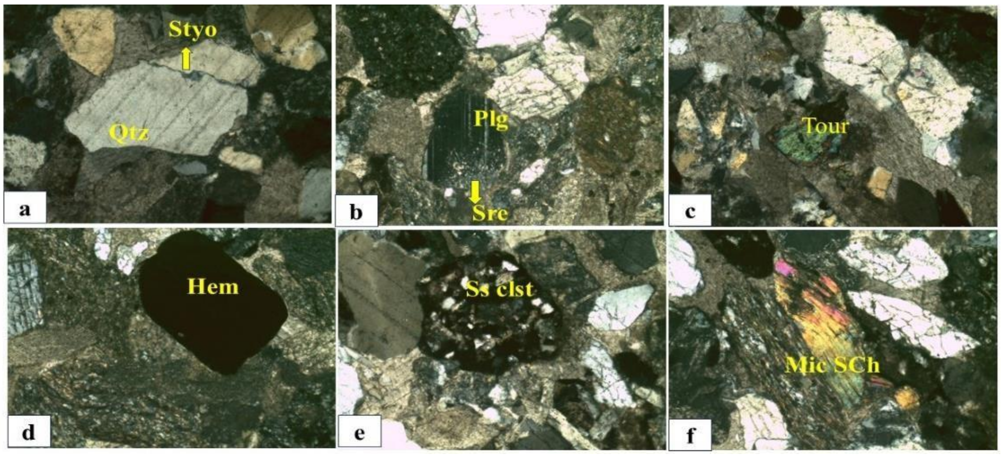

Fig. 14 Photomicrograph of sandstone of Dhok Patan showing a) Stylolite feature (Styo), quartz (Qtz), b) plagioclase (Plg), Sericite (Sr), c) Tourmaline (Tour), d) Hematite (Hem), e) sandstone clast (Sc), f) Mica schist (Mic Sch).

Conclusions

On the basis of geological and geophysical investigation the following conclusions are drawn:

1. The study identifies a north-south trending Jhelum strike-slip fault extending between Chechan and Azad Pattan, indicating the continuity of the fault from Tian to Muzaffarabad.

2. Multiple thin-skinned thrust faults, including the Chechan and Riasi faults, were observed, with the thick-skinned BBF fault reactivated post-Indian-Eurasian collision, unlike the thin-skinned faults that formed due to compressional forces from this collision.

3. The findings show no evidence of the Main Boundary Thrust (MBT), Panjal Thrust (PT), or Indus-Kohistan Suture Zone (IKSZ) within the study area, while all observed thrusts are active, NE-dipping, and pose earthquake and landslide hazards.

4. Petrological analyses highlight diverse mineral assemblages across formations, with potential hydrocarbon-bearing carbonates, sediment recycling processes, and economically significant mineral resources which may contribute to Pakistan’s socioeconomic development.

Statements and Declarations

The authors declare that there no financial interests/personal relationships which may be considered as potential competing interests.

Conflict of Interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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