Mountain Front Structural Geometries And Their Implications For Understanding The Detachment Tectonics And Oroclinal Bending Along The Eastern Salt Range, Pakistan

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ABSTRACT: This research aimed to investigate the structural variations of a major thrust fault in the Himalayan foreland fold and thrust belt. The study utilized field, radon concentration, and satellite imagery data to analyze surface and subsurface deformation patterns along the eastern part of the Salt Range Thrust (SRT). The research area was divided into a less deformed western part with east-west trending structures and a highly deformed eastern part. The study addressed the controversial behavior of the SRT near the Jalalpur area, where opposite directions of vergences along the same trend line have remained an unsolved question. The results revealed a sequence of tectonic events, starting with the formation of the SRT as a south-verging major thrust fault, followed by another episode of stresses, with maximum principal stress axes (σ1) oriented in the NW direction, resulting in tight oroclinal bending in the SRT and the formation of the Jalalpur back-thrust. The back-thrust was identified as the most recent deformational event, thrusting the Salt Range Formation onto Miocene rocks in Jalalpur valley. The study also identified the presence of the northeast-southwest trending Karangal bach-thrust, dividing the western and eastern parts. Additionally, a transformation from the Karangal back-thrust to the Choa fore-thrust indicated the presence of a sinistral strike-slip fault near Choa Saidan Shah Village. The research findings suggested that the SRT is an active fault-zone, supported by higher values of radon gas emission and readings showing multiple points of higher values on the surface expression of the SRT.

KEYWORDS: Structural Geology, Salt Range Thrust (SRT), Foreland Tectonics, Orocline, Active Fault Zone.

INTRODUCTION

The research is carried out in the south-eastern part of Salt Range Potwar Plateau (SRPP), which and is a part of sub-Himalayas in North Pakistan (Dipietro and Pogue, 2004). The research area lies between 32˚36′00" to 32˚52′00" N and 72˚48′00" to 73˚28′00" E and stretched between the Kallar Kahar village in the west and Jalalpur village in the east covering a part of central and the eastern Salt Range. The Salt Range-Potwar Plateau (SRPP) covers an area of ~ 18,000 km2, hosting some of the major regional tectonic feature i.e., Main Boundary Thrust (MBT) and an imbricated North Potwar Deformed Zone (NPDZ) at north, Soan-Syncline and Salt-Range Thrust (SRT) towards the south, Jhelum Strike Slip Fault at east and Kalabagh Strike Slip Fault at west (DiPietro and Pogue, 2004; Drewes, 1995; Gee, 1980).

The southern region of the SRPP exhibits a characteristic behavior of a frontal thrust, where the Precambrian rock is brought over the Miocene rocks by the Salt Range Thrust (SRT). The study area demonstrates a regional east-west trend with sinusoidal bending towards the western half. The SRT serves as the primary structural lineament governing the regional tectonics of the SRPP. However, the behavior of the SRT undergoes significant changes towards the eastern part of the study area, particularly in the vicinity of the Jalalpur area, giving rise to a well-known oroclinal structure with opposite directions of vergences, characterized by back-structures with hinterland-ward vergence (back thrust) along a common trend line (Puniya and Mukherjee, 2021; Bose and Mukherjee, 2019). This phenomenon has posed a perplexing challenge, as the behavior of the SRT along this loop has been subject to controversy. In the Jalalpur area, the SRT undergoes a sudden bend towards the north, partially concealed by alluvium, and re-emerges near the Pind Sawika area. This study, based on meticulous field observations and cross-sectional analyses, sheds light on the structural complexities associated with thrusting along the oroclinal bending of the SRT. Moreover, it elucidates the structural characteristics of the study area by constructing subsurface cross-sections. Notably, the research identifies the eastern prominent north-south oriented regional thrust fault, referred to as the Jalalpur Back-Thrust, which was previously considered to be the oroclinal extension of the SRT but exhibited an unclear shift in the direction of vergence along the common trend line in the Jalalpur area.

By resolving structural ambiguities and providing a comprehensive understanding of the oroclinal bending of the SRT, this research significantly contributes to the existing knowledge. Additionally, the study highlights the active nature of the SRT as an active fault zone based on radon gas emissions detected along the SRT at various locations. These findings enhance our understanding of the tectonic processes in the study area and contribute to the broader understanding of the Himalayan foreland fold and thrust belt.

TECTONICS SETTINGS

The collision of the Indian and Eurasian plates has resulted in the formation of the Himalayan Mountain System, serving as a prime example of an active collisional orogeny (Dewey and Bird, 1970; Lefort, 1975; Mukherjee 2013 & 2015; Basit et al., 2023). The interaction between these two continents has led to the development of prominent regional faults, which play a crucial role in understanding the orogenic evolution of the Himalayan ranges (Zanchi and Gaetani 2011; Angiolini et al., 2013). The ongoing collision between the Indian and Eurasian plates has caused deformation and sediment deposition in the foreland basin of the Himalayan orogeny, dating back approximately 55 million years (Powell, 1979; Raynolds and Johnson, 1985; Klootwijk et al., 1985; Treloar et al., 1991; Beck et al., 1995; Dutta et al., 2019). In Pakistan, the platform covers strata and foreland sedimentary successions of the foreland thrust belt, which spans approximately 130 kilometers, have been detached and transported southward along two major thrust faults: The Main Boundary Thrust (MBT) and the Main Frontal Thrust/Salt Range Thrust (SRT) (Coward and Butler, 1985; Butler et al., 1987; Lillie et al., 1987; Treloar et al. 1992; Nazir et al., 2020; Ali et al., 2021).

The presence of ductile evaporites of Precambrian age beneath the Salt Range-Potwar Plateau (SRPP) serves as a basal zone of décollement for regional thrusting above the Precambrian basement (Seeber and Armbruster, 1979; Butler et al., 1987; Jaumé and Lillie 1988; Pennock et al., 1989). Along these weak and ductile evaporites, the foreland thrusting of the Salt Range Thrust Sheet, with a minimum shortening of 20 kilometers, has occurred (Lillie et al., 1987; Baker et al., 1988). At the surface, the thrust is characterized by a north-dipping section of Precambrian to younger sedimentary successions (Gee, 1980 & 1989), while subsurface observations indicate that the thrust ramps over pre-existing normal faults in the Precambrian basement rocks (Baker et al., 1988). In the central Salt Range, the flat-on-flat portion of the Salt Range thrust sheet has remained undeformed, while it is highly deformed and imbricated to the north of the Soan Syncline in the footwall of the MBT, known as the North Potwar Deformed Zone (NPDZ) (Jadoon and Frisch, 1996). Paleomagnetic dating of unconformities, stratigraphic evidence, and sediment-accumulation rates suggest that the SRT fault has remained active for approximately 5 million years, specifically between 2.1 million and 1.6 million years ago (Burbank et al., 1986; Johnson et al., 1986; Baker et al., 1988; Burbank and Beck, 1991). The eastern part of the Salt Range-Potwar Plateau (SRPP) exhibits considerably more deformation compared to the central SRPP, which may be attributed to variable evaporite thicknesses in both regions (Johnson et al., 1986; Jadoon and Frisch, 1996; Burbank et al., 1986; Johnson et al., 1986; and Burbank and Beck, 1989) proposed that stress accumulation preceded thrusting along the Salt Range Thrust in the eastern SRPP. However, (Pennock et al., 1989) argued that the thick layer of evaporites in the central SRPP provided a favorable zone for décollement with internal symmetrical deformation. Overall, the tectonic setting of the Himalayan Mountain System and the associated regional faults offer valuable insights into the ongoing orogenic processes and the geological evolution of the area.

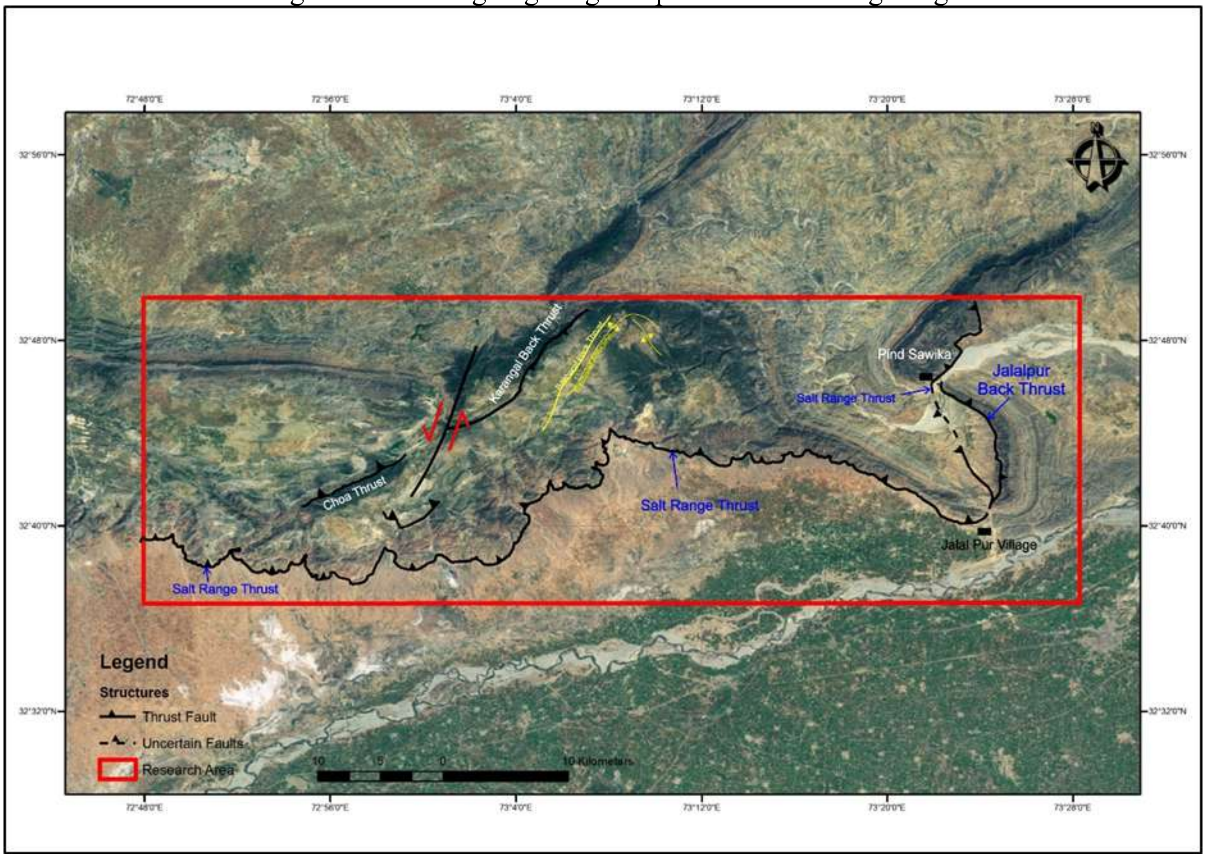


Fig. 1. A generalized geologic map showing various structural elements in and around the study area with Google Earth imagery of study area showing different faults (modified after Gee, 1989).

STRATIGRAPHY OF THE EASTERN SALT RANGE

The eastern Salt Range exhibits a stratigraphic sequence ranging from Precambrian to Late Tertiary sedimentary successions. The oldest rock unit exposed in the area is the Salt Range Formation, with Precambrian age, although its base is not directly visible at the outcrop. Sub-surface geophysical data has revealed the presence of basement rocks beneath the Salt Range Formation (Gee, 1989). Overlying the Salt Range Formation are thick sequences of shallow marine clastic rocks belonging to the Jhelum Group. These include formations such as Khewra, Kussak, Jutana, and Baghanwala, which are of Cambrian age (Noetling, 1901; Fatmi 1973; Yeats and Hussain, 1987; Qureshi et al., 2023).

The eastern Salt Range also exposes Early-Permian rocks, represented by formations such as Tobra, Dandot, Warcha, and Sardhai of the Nilawahan Group. However, the rocks of Late Permian are absent, indicating a significant Nonconformity (Basit et al., 2023). The complete strata of the Mesozoic Era are also missing, indicating another major Nonconformity in the eastern Salt Range. Paleocene rocks in the study area consist of formations from the Makarwal Group, including Hangu, Lockhart, and Patala formations. These are overlain by formations from the Chharat Group, such as Nammal, Sakesar, and Chorgali, which are of Early Eocene age (Qureshi et al., 2019). The interval between the Charat and Rawalpindi Group rocks represents a significant Nonconformity in the eastern Salt Range. The Rawalpindi Group, which is of Early Miocene age, overlies the Chharat Group and includes formations such as Murree and Kamlial. These formations are further overlain by sediments of the Siwalik Group. The general stratigraphy of the eastern Salt Range is summarized in table 1.

MATERIALS AND METHODS

A field excursion was conducted to study the stratigraphy and structural characteristics of a specific area. Various field data collection methods were employed, including recording attitudes data, marking sedimentary contacts with GPS coordinates, measuring topography, assessing radon concentrations, and taking field photographs. The dip-strike measurements and sedimentary contact locations were plotted on Google Earth and exported to ArcGIS to create a detailed geological map. Additionally, move 2018.1 software was used to construct subsurface cross sections, which helped in understanding the geological complexities and subsurface features of the study area. Overall, the field excursion provided valuable insights into the area's stratigraphy and structure, aided by the use of advanced software tools/

Table 1. Generalized stratigraphy of the Eastern Salt Range (after Gee, 1989)

AGE	GROUP	FORMATION	LITHOLOGY	THICKNESS(m)	DESCRIPTION
Miocene	Siwaliks	Dhok Pathan		Approx. 2500	Red-brown clays with grey sandstones:and conglomeratic
		Nagri			Greenish-grey sand stones and clays
		Chingi			Bright red clays with sand stones
	Rawalpindi	Kamlial			Massive red and brown sandstones,dark red clays
		Murree			Massive sandstones,dark red and purplish clay shales
Eocene	Charat	Chorgali		100	Olive-green shales with bedded limestones
		Sakesar			Massive and nodular limestones with marls
Paleocene	Makarwal	Patala		80	Green shales with coal seam and thin limestones
Permian	Nilawahan	Warcha		180	Red and light coloured sandstones,clay interbeds
		Dandot			Olive-green sandstones and shales with limestone beds
		Tobra			Conglomeratic sandstones and boulders
Cambrian	Jhelum	Baghanwala		100	Blood-red shales and sandstones with salt pseudomorphs
		Jutana		70	Massive dolomite and dolomitic sand stones
		Kussak		80	Grey and purplish shales and glauconitic sand stones
		Khewra		180	Massive maroon sand stones with maroon shales
Eo-cambrian		Salt Range		800-2000	Red gypseous marl with rock salt,gypsum-dolomite above
Precambrian		Indian Shield			

RESULTS AND DISCUSSIONS

Geological Mapping

A surface geologic map is prepared at 1:50,000 scale by the integration of field outputs (dip-strike data), previous maps and Google Earth Imagery (Fig. 2). The map shows a very complicated structural pattern along the east-west length of the SRT. In a regional perspective, the western part of the study area is less deformed than the eastern part where SRT bends oroclinally.

Based on deformation depicted from map relationships, the study area can be divided into two zones divided by Karangal Back Thrust, Choa Thrust and their associated strike slip faults (Fig. 3). Low lying series of anticlines and synclines within the Eocene rocks occupies the north-western part showing mild deformation. This east west trending series of folds abruptly terminates against a west-northwest verging thrust fault known as Karangal Back Thrust (Fig. 2). The Karangal Back Thrust has brought the Precambrian sequence over the Miocene rocks (Fig. 4d). The Karangal Back Thrust transforms into the southeast verging Choa Fore-Thrust juxtaposing the Cambrian sequence against the Miocene rocks. Both Karangal Back Thrust and the Choa Fore-Thrust follow the same linear trend and divide the study area into eastern and western deformational zones (Fig. 3).

Western Deformational Zone (WDZ) represents the typical fold and thrust belt, which fits best in the regional tectonic setting of Pakistan as well as of the SRT. The east-west trending fold axes and the south verging faults nicely fit with the tectonic jigsaw of the Indian-Eurasian collision (Fig. 2). In contrast to the west, the Eastern Deformational Zone (EDZ) represents more complications and challenges where two major tectonic stress vectors seem to play their role in fabricating the surface expressions of rocks. The eastern zone not only demonstrates the north south tectonic compression but also shows the evidences of east-west compression. The orientation of three major back thrusts in the study area including the west-northwest verging Karangal Back Thrust, Basharat Back Thrust and the Jalalpur Back Thrust clearly define the west verging tectonic stress vector. This concept is advocated by the presence of refolded anticlinal axes of Basharat Anticline and its associated smaller anticline towards east (Figs. 4 a, b, c). The map relationships show that the Basharat Anticline initially was originated from the north south compression of Indian collision but was later on refolded into a broad regional anticline having north-south axis (Fig. 2). Towards the east of Basharat Anticline the north-south oriented Kotal Kund Syncline rests in the valley formed due to the oroclinal bending in the SRT (Fig. 2).

The map evidences reflect that the SRT initially formed as a result of north-south compression and then the eastern part of the SRT started experiencing the westward push bending the SRT to > 1200 degrees. The continued westward stresses then created the Jalalpur Back Thrust, which was formerly given the name of Chambal Ridge by Yeats et al. (1984).

The southern half of the area has also shown normal faults which are formed due to gravity collapsing (Figs. 5a-b). The gravity faulting is because of salt diapirism, which shows that the rocks which are exposed on the surface are no more under the influence of tectonic compression. A south verging overturned fold is present in the south-western half which is in flow with the transport along SRT. Numerous plunging folds are also observed throughout the area with other minor near surface small scale deformational features i.e., intra denominational thrust faults, normal faults and graben structures (Figs. 2,4,5). In conclusion, the surface geologic map of the study area reveals a complex and intricate structural pattern along the SRT. The map highlights distinct deformational zones divided by prominent thrust faults. The Western Deformational Zone (WDZ) showcases a typical fold and thrust belt consistent with the regional tectonic setting, while the Eastern Deformational Zone (EDZ) presents greater complexities with evidence of multiple tectonic stress vectors. The map also depicts various fold structures, thrust faults, and gravitational collapse features, providing valuable insights into the geological evolution of the area. Overall, this comprehensive geologic map serves as a valuable resource for understanding the tectonic history and structural style of the study area.

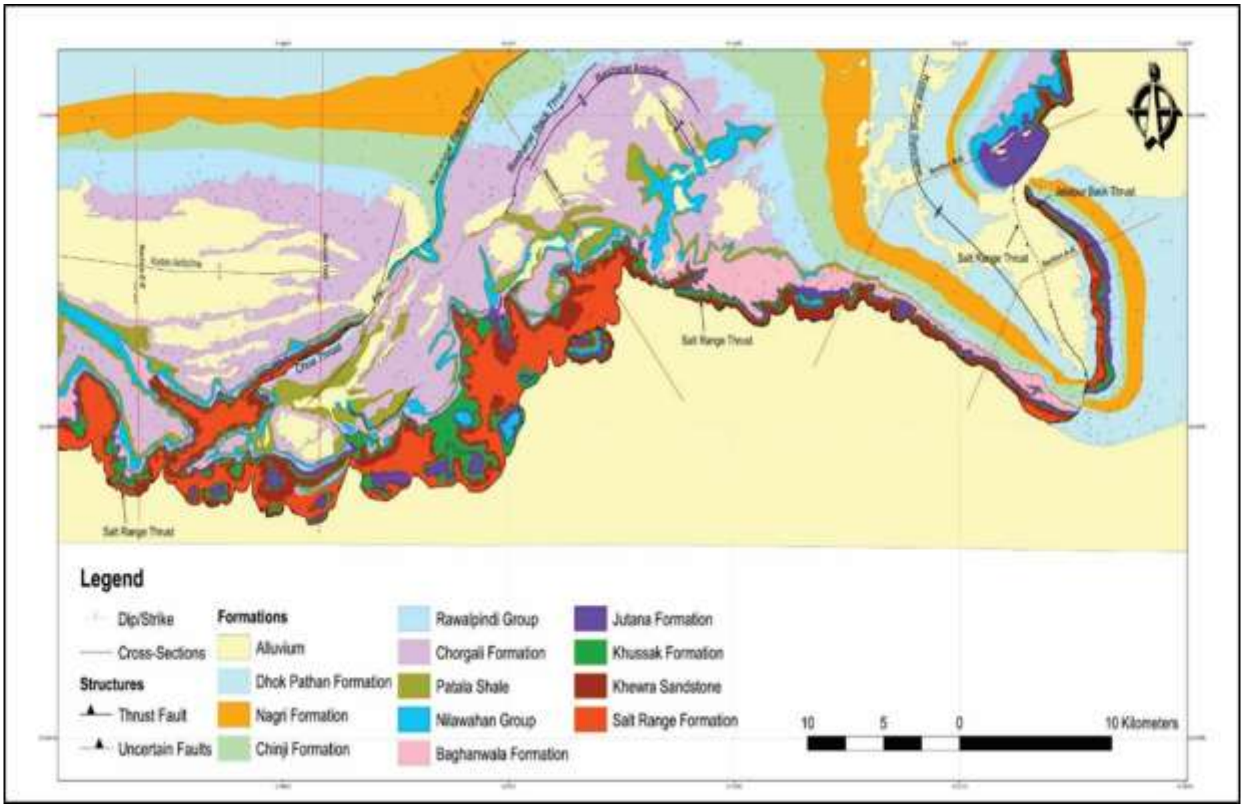


Fig. 2. Geological map showing structural elements and stratigraphic units of study area at 1:50,000 scale.

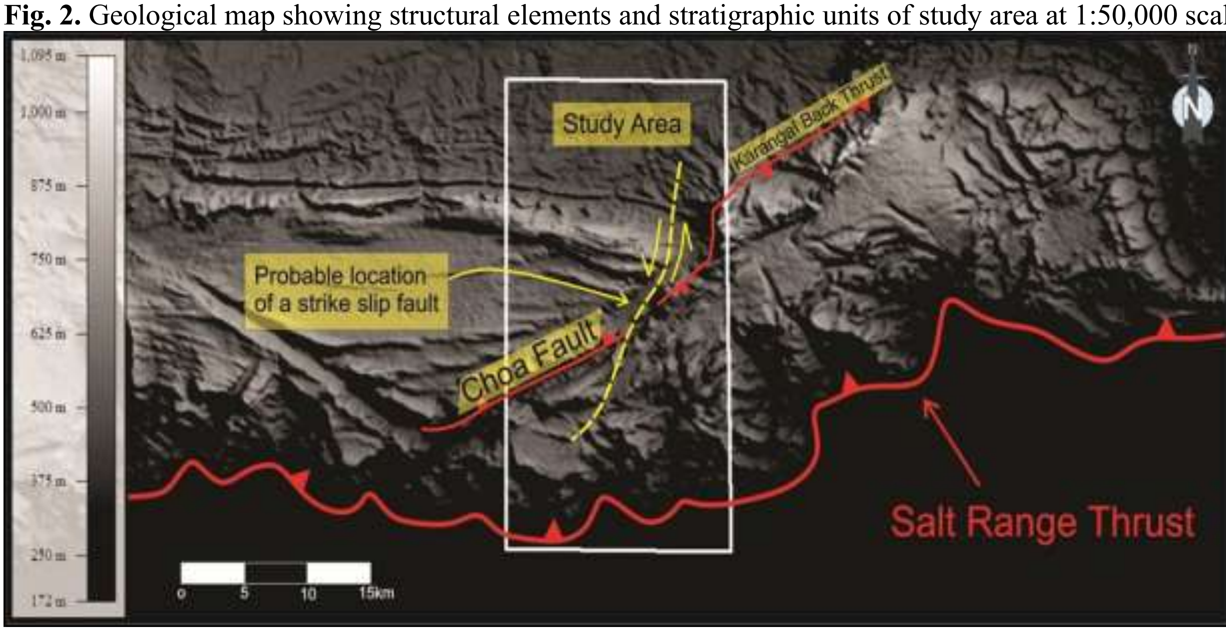
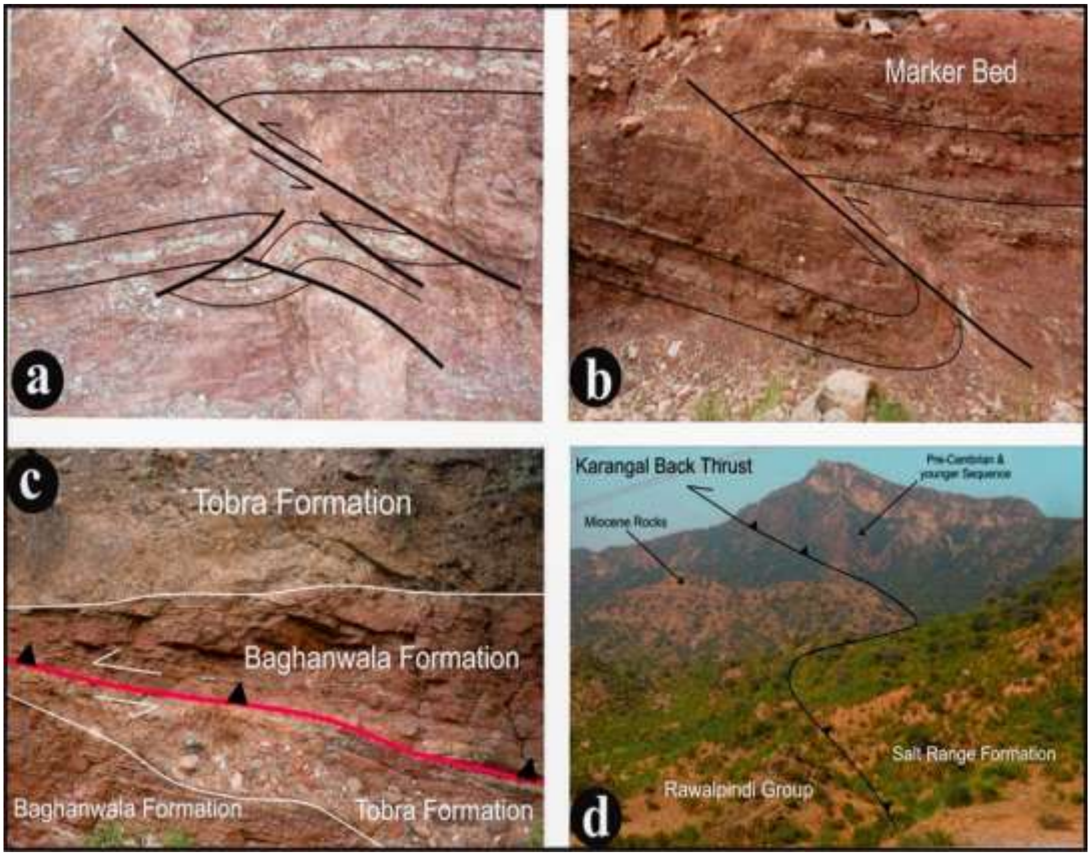
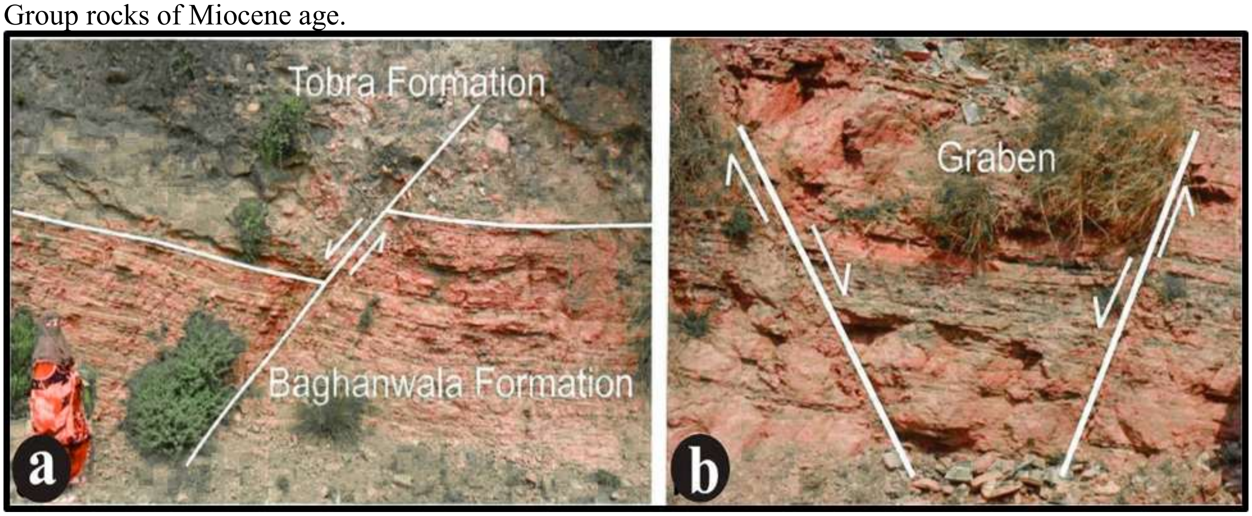


Fig. 3. DEM (digital elevation model) imagery showing the division of Eastern Deformational Zone (EDZ) and Western Deformational Zone (WDZ) separated by Karangal Back-Thrust and Choa Fore-Thrust and their associated strike slip fault.



Figs. 4a-d Field photographs showing **(a) (b)** Intra-formational thrust faults in Baghanwala Formation **(c)** Intra-formational thrust fault, thrusting Baghanwala Formation (older) over Tobra Formation (younger) **(d)** Karangal Back Thrust along which Precambrian Salt Range Formation is thrusted over Rawalpindi Group rocks of Miocene age.



Figs. 5a-b Field photographs showing **(a)** Normal faulting at the contact of Baghanwala Formation and Tobra Formation **(b)** Graben structures in Baghanwala Formation.

Geological Cross Sections

Five geological cross-sections have been rendered based on acquired data to comprehend the subsurface dynamics of the mapped structures. These sections are constructed utilizing attitude data obtained from outcrops. Each cross-section intersects the Salt Range Thrust (SRT) at various points, revealing changes in the behavior of the SRT, as well as its associated folded and thrust-related geometries. The displacement along the SRT has caused the Precambrian-Cambrian sequence to override the younger sequence. All faults in the area exhibit a listric geometry, with steeper dips near the surface that gradually flatten as we move deeper. Eventually, they become sub-horizontal to horizontal and merge with the basal decollement at the level of the Salt Range Formation (Figs. 6-7). Notably, the sections covering the eastern part of the study area display more pronounced deformation compared to those in the western sections.

In cross-sections AA/ and BB/, the subsurface behavior of the tightly folded SRT can be observed, along with the presence of the Jalalpur Back Thrust. Both cross-sections also exhibit the NW-SE-oriented Kotal Kund syncline (Figs. 6a-b). Cross-section CC/ represents the central part of the study area, where the Karangal and Basharat back-thrusts, as well as the SRT, can be observed. Cross-section DD/ is located in the eastern part of the area and is perpendicular to the general trend of formations. The northern part of this area experiences less deformation as there is no major faults present. Based on the degree of deformation, this cross-section can be divided into three zones: the northernmost zone is occupied by the Katas Anticline, followed by the south-verging Choa Fore-Thrust, and finally the SRT along section DD/ (Fig. 7b). The north-dipping limb of the Katas Anticline is steeper, while the south-dipping limb is gentler. Interpreted from the inter-limb angle, this anticline represents a gentle fold. The core of the anticline contains the Salt Range Formation, while the Eocene rocks are exposed at the surface. This anticline is classified as a roll-over fold or a drag fold (Mukherjee, 2014) caused by the fault. Additionally, a blind thrust emerges from a depth of 4000 meters and terminates in the Nilawahan Group. Furthermore, another north-verging blind back-thrust is associated with this fault, giving rise to a pop-down structure (Fig. 7b). The core of the anticline contains the Salt Range Formation, while the Eocene sequence is exposed on the surface. There is also a blind south-verging fore-thrust responsible for the juxtaposition of the Precambrian sequence over the molasse sediments. This fault dissipates within the Chinji Formation of the Siwalik Group. The stratigraphic package above this fault folds due to roll-over drag forces (Fig. 7c). Salt Range Thrust in all sections as a major thrust fault and Basharat Anticline, Basharat Back Thrust and Karangal Back Thrust in CC/, Choa Fore-Thrust and Katas Anticline in DD/ and EE/. Various blind thrust faults are also common in this part.

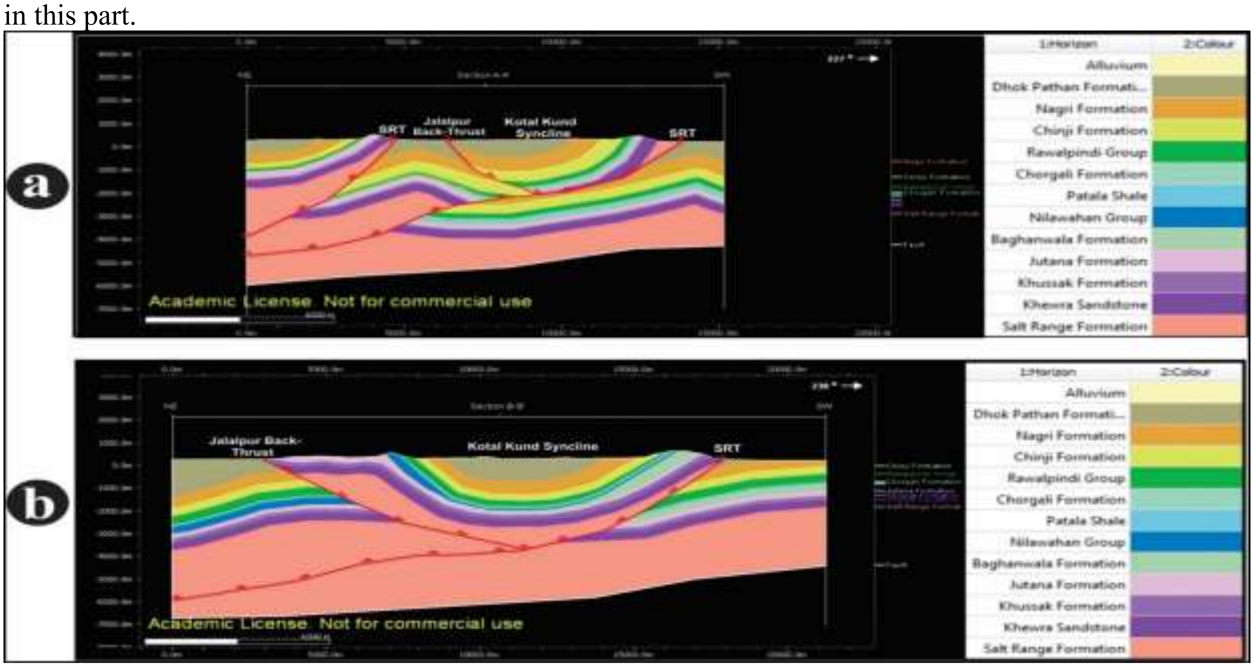
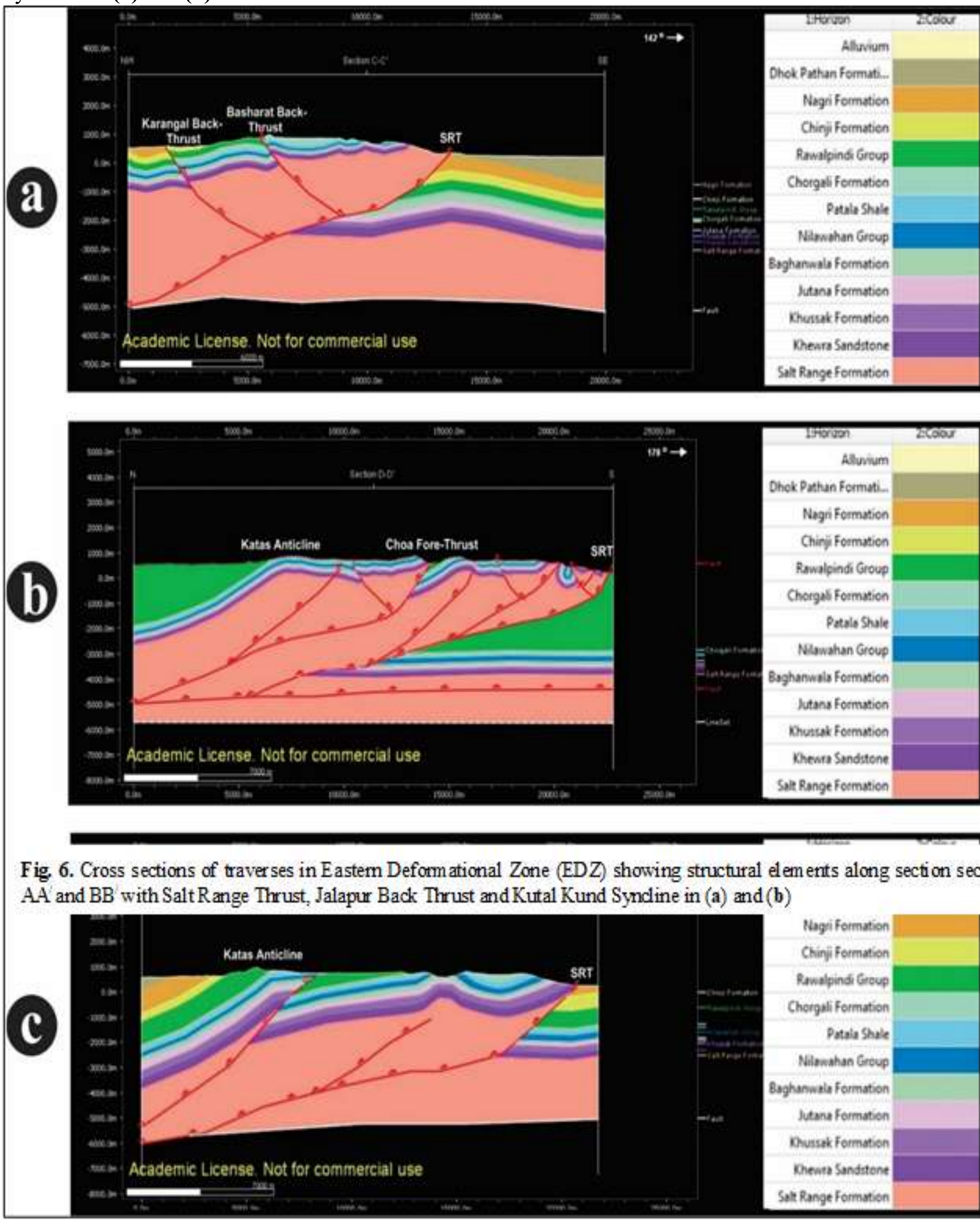


Fig. 6. Cross sections of traverses in Eastern Deformational Zone (EDZ) showing structural elements along section sections AA/ and BB/ with Salt Range Thrust, Jalapur Back Thrust and Kutal Kund Syncline in **(a)** and **(b)**



Figs 7a-c: Cross sections of traverses in central part of study area and Western Deformational Zone (WDZ) showing structural elements along section sections CC, / DD/ and EE/ with Salt Range Thrust in all sections as a major thrust fault and Basharat Anticline.

Radon Concentrations measurement

The soil-gas radon emission measurement survey was conducted across the SRT in the month of February, 2022, because the weather was relatively dry and suitable for conduction of soil-gas test in the study area. SRT was the target fault to compute its associated radon activity. Keeping in view the overall trends of the structural lineaments it can be easily inferred that the north-south oriented regional stress vector is responsible for this uplift. The impact of these compressional stresses is visible at all scales including meso and megascopic examinations. Along this fault, rocks of the Precambrian Salt Range Formation are thrusted over the Punjab Platform sequence.

For measuring the concentration of radon, the SRT was traversed along five different lines where the streams provided easy way to move across the range and the valley preferably cut perpendicular to the range (Fig 8). The location of measuring stations is given in the Table 2. The traverses were made at a lateral distance of ~500 m away from each other whereas the consecutive points for measurements along the same traverse were kept ~100 m apart. Radon concentrations data is displayed in the Table 2. A broad range of readings have been calculated along these traverses with systematic highs along the surface expression of the SRT (Fig. 9a).

Along every traverse it is noticed that the readings can be divided into three broad zones. One of them is the peak itself which shows the activity along the fault. The other zone is the zone of moderate emission which may indicate towards the span of the fault zone. The third zone refers to inactive zone with very little radon emission (Figs. 9a-b). Radon emission decreases as moving away from the major fault (Amponsah, et al., 2008; Sun et al., 2018) so as the case with SRT but it has been noticed that two or more higher values along the same traverse (Dandot Village) have also been recorded which indicate a broad fault zone in the study area (Fig. 9a). Along AA/ it is characterized by two high values which indicated the Jalalpur Back Thrust and SRT. The reading along Jalal Pur Back-Thrust is relatively higher than the reading taken along SRT which indicates the Jalal Pur Back-Thrust is the recent most deformational event in eastern part of study area. In the section BB/ the single peak of high value indicates only one deformational feature towards the south i.e. SRT. In section CC/ near Gharib Wala Section, the higher values of radon emission than SRT, are due to the recently evolved Basharat Back Thrust in the central part of study area. In western part, a minor difference between the values of Randon concentration along same traverse section in DD/ and EE/, indicates a broad fault zone (Fig. 9b).

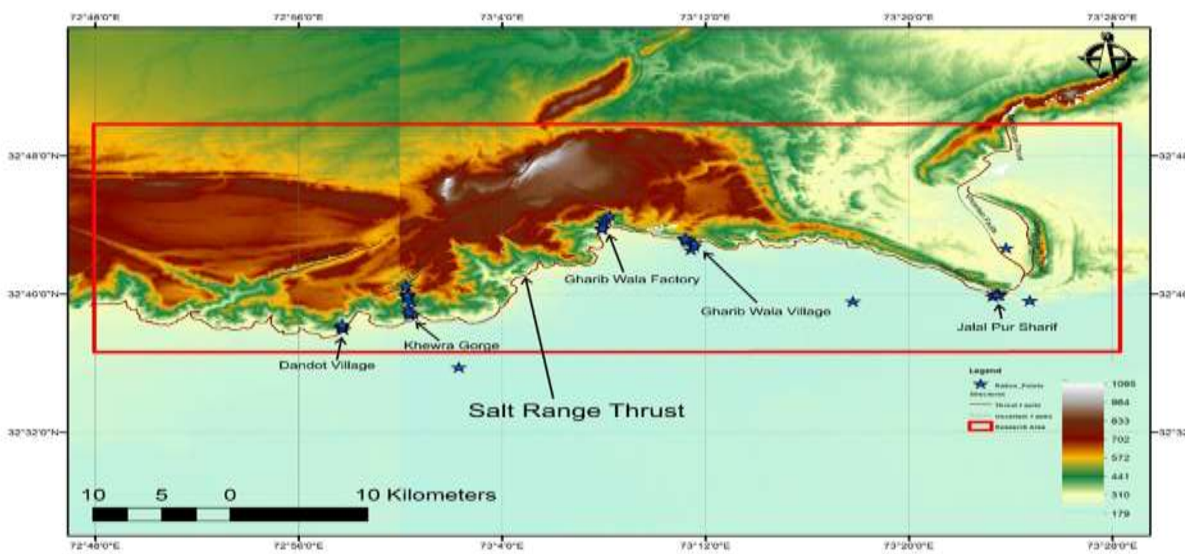
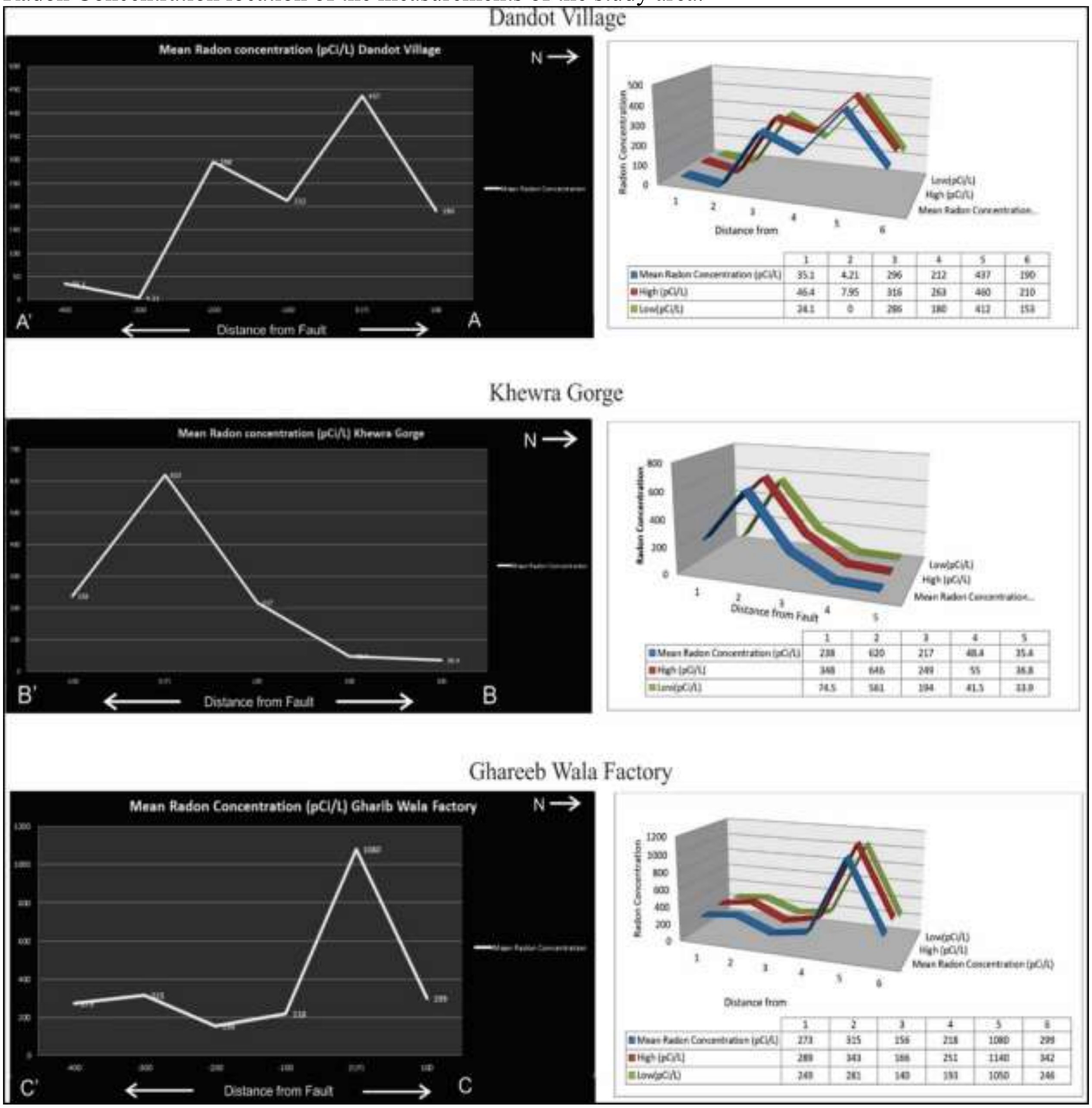


Fig 8: Digital elevation model (DEM) of the study area, a. map view of the DEM with inset showing the Radon Concentration location of the measurements of the study area.



Figs. 9a-b. Graphical representation of concentration of Radon gas emission with low, high and mean values of concentration along three traverse sections in Khewra Gorge, Dandot Village and Ghareeb Wala Factory, (b) Graphical representation of concentration of radon gas emission with low, high and mean values of concentration along two traverse sections in Ghareeb Wala Village and Jalalpur Sharif.

Table 2. Radon flux measurements recorded in study area.

Locality	Coordinates	Mean Radon Conc. pCi/L	High pCi/L	Low pCi/L
Khewra Gorge	N 32°39′13.6″ E 73°00′19.0″	238	348	74.5
	N 32°39′34.6″ E 73°00′25.3″	35.4	36.8	33.9
	N 32°39′49.4″ E 73°00′18.4″	620	646	561
	N 32°39′58.2″ E 73°00′16.2″	48.4	55	41.5
	N 32°39′0.70″ E 73°00′17.6″	217	249	192
Dandot Village	N 32°38′58.4″ E 73°00′22.2″	35.1	46.4	24.1
	N 32°38′49.8″ E 73°00′30.8″	4.21	7.95	0
	N 32°37′57.8″ E 72°57′46.0″	296	316	286
	N 32°38′03.3″ E 72°57′46.6″	212	263	180
	N 32°38′0.81″ E 73°57′41.8″	437	460	412
	N 32°38′15.7″ E 73°57′43.2″	190	210	153
Gharib Wala Village	N 32°42′34.4″ E 73°11′25.5″	342	360	323
	N 32°42′46.1″ E 73°11′17.3″	355	383	337
	N 32°42′46.4″ E 73°11′34.6″	222	244	199
	N 32°43′03.4″ E 73°11′25.5″	517	541	492
	N 32°43′08.3″ E 73°11′10.2″	495	527	479
	N 32°43′14.0″ E 73°11′12.2″	370	440	330
	N 32°43′44.8″ E 73°07′55.1″	273	289	249
	N 32°43′49.7″ E 73°07′56.6″	315	343	281
	N 32°44′06.2″ E 73°07′57.3″	156	166	140
	N 32°44′12.3″ E 73°07′58.8″	218	251	193
	N 32°44′22.2″ E 73°08′05.4″	1080	1140	1050

	N 32°42′33.4″ E 73°08′14.3″	299	342	246
Jalalpur Sharif	N 32°42′40.2″ E 72°25′49.0″	182	194	171
	N 32°39′37.7″ E 73°24′45.3″	114	122	105
	N 32°29′52.5″ E 73°23′17.9″	182	194	171
	N 32°39′57.7″ E 73°23′24.3″	290	306	270
	N 32°40′00.4″ E 73°23′32.0″	276	289	265

CONCLUSIONS

In conclusion, this study provides valuable insights into the deformational characteristics and structural complexity of the study area, particularly focusing on the Eastern Deformational Zone (EDZ) and the Western Deformational Zone (WDZ). By distinguishing these two zones based on their distinct deformation styles and intensities, the research enhances our understanding of the tectonic processes at play.

The WDZ is characterized by relatively less deformation, with an east-west trending fold axis and south-verging thrust faults. This deformational pattern aligns with the regional tectonic setting of Pakistan and the South Rehman Range (SRT), representing a typical fold and thrust belt. The prominent structure in the WDZ is the Katas Anticline, exhibiting steeper north-dipping and gentle south-dipping limbs.

In contrast, the EDZ displays a more complex and deformed nature, influenced by two major tectonic stress vectors. The first stress vector is west to northwest verging, indicating east-west compression, while the second stress vector is south-verging, suggesting north-south compression. Major structures identified in the EDZ include the Basharat Back-Thrust, Basharat Anticline, Kotal Kund Syncline, and Jalalpur Back-Thrust.

The WDZ and EDZ are delineated by the Karangal Back-Thrust and Choa Fore-Thrust, along with their associated strike-slip faults. These faults serve as boundaries between the two deformational zones, further emphasizing the structural heterogeneity in the study area.

Furthermore, the presence of higher radon gas emissions along the SRT suggests its active fault nature. The occurrence of multiple high values along the same traverse indicates the existence of a broad shear zone rather than a discrete fault line. This finding highlights the significance of considering the broader tectonic framework when assessing the fault activity and seismic hazard potential in the region.

Overall, the conclusions drawn from this research contribute to our understanding of the tectonic and deformational processes within the study area. The identification and characterization of distinct deformational zones, along with the recognition of major structures and fault boundaries, provide a foundation for further investigations and have implications for seismic hazard assessment and geotechnical considerations in the region.

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