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Assessing The Impact Of The Main Boundary Thrust On Landslide Dynamics: Insights From The Western Limb

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ABSTRACT

Due to its particular geotectonic setup and resultant terrain, the northern Pakistan has witnessed landslides as one of the major geohazards posing a permanent threat to life, infrastructure and socio-economic setup. The link between geological fault lines and landslides is well-established by researchers. The current study encompassing the landslides in a segment of the western limb of the Main Boundary Thrust (MBT) aims to look into the behavior of landslides along the MBT and role of MBT in landsliding. Field work was carried out for data collection regarding landslide parameters; kinematic analysis was carried out to indicate the failure pattern in outcrop while soil samples were collected for Atterberg limits, an empirical method was applied to assess the slope stability. Local communities were interviewed to record the landslide history and past behavior. Field observation, rock strength classification, terrain analysis and soil testing reveal that MBT and its associated factor like spring water and rock discontinuities along with anthropogenic activities are the main threat to slope stability. In addition, the much-projected higher precipitation in northern Pakistan associated with the climate change scenario has a higher potential to accelerate the landslides along MBT. The situation will be worsened by growing anthropogenic activities caused by increasing population on mountain slopes.

Keywords: Landslides, Main Boundary Thrust (MBT), climate change

INTRODUCTION

Landslides being one of the major hazards faced by the mountainous communities in northern Pakistan, not only pose a threat to human life and infrastructure but also disrupt the socio-economic setup in the affected communities. Studies have established a direct relationship between tectonic lineaments and landslide spatial distribution (Getachew & Meten, 2021; Kaneda et al., 2008; Sadiq et al., 2021; Torizin et al., 2017). The current work presents the outcome of landslide investigation along the Main Boundary Thrust (MBT) under the approved Public Sector Development Programme (PSDP) project "Pakistan National Research Program on Geological Hazards (Earthquakes & Landslides), Data Acquisition along Active Faults and Identification of Potential Landslide Hotspot Zones". Owing to the higher concentration of landslides along the MBT, the current study aims to investigate the characteristics of landslides, and to assess the role of MBT in destabilizing the mountain slopes with an objective to better understand the forces behind slope failure. The findings will not only assist the researchers and planners to devise a strategy to cope with landslide issues in the area of interest but also to effectively use that information for landslide risk reduction in other areas with similar terrain and tectonic setup.

STUDY AREA

The study area comprises about 32 km stretch of the western limb of MBT from Birote in Abbottabad District to Lohargali in Muzaffarabad. The studied landslides are located on the right bank of Jhelum River in the bordering areas of Abbottabad and Muzaffarabad districts. Figure 1 presents the location map of the study area.

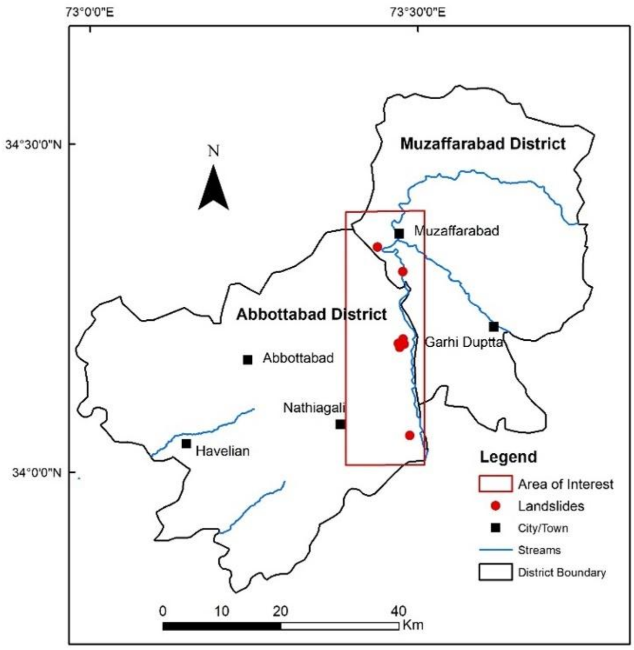

Figure 1: Location map of the study area.

REGIONAL GEOLOGY AND LOCAL GEOLOGICAL SETTING

The area lies in the Main Boundary Thrust (MBT) zone; MBT is a thrust fault developed during the Cainozoic shortening of Indian Plate (Mugnier et al., 1994). In general, tectonic deformation in northern Pakistan is younger as we move toward foreland (Jadoon et al., 1997). The Balakot-Bagh Fault (BBF) responsible for the 2005 Kashmir Earthquake has been associated with the MBT by some authors (Khan et al., 2021; Tahirkheli, 2010) while others associate the BBF with Medlicott Wadia Thrust (MWT) lying south of the MBT (Thakur et al., 2010). MBT separates the Tertiary rocks of Sub Himalaya from the pre-Tertiary strata of Lesser Himalaya (Thakur et al., 2010). In the investigated area, the MBT is characterized by thrusting of older formations like Kuldana, Patala, Lockhart, Kawagarh, Samana Suk and Hazara Formations over the Murree Formation. The Hazara Formation consists of slate, phyllite, and shale with minor occurrences of limestone and graphite layers. Slate and phyllite are green to dark green and black, but are rusty brown and dark green on weathered surfaces. Some thick-bedded, fine to medium-grained sandstone is also present. The Murree Formation is a sequence of sandstone, shale, mudstone and clay (Calkins et al., 1975).

MBT plays a crucial role in shaping the geological landscape of the area, as it is pivotal for the uplifting, folding of rocks, faulting patterns, and potential seismic activity; it is an important feature to consider when studying the geological prospect of geohazard: terrain evolution and tectonic activity due to MBT has a noteworthy impact on landslide phenomenon (Kothyari et al., 2012; Nath et al., 2021).

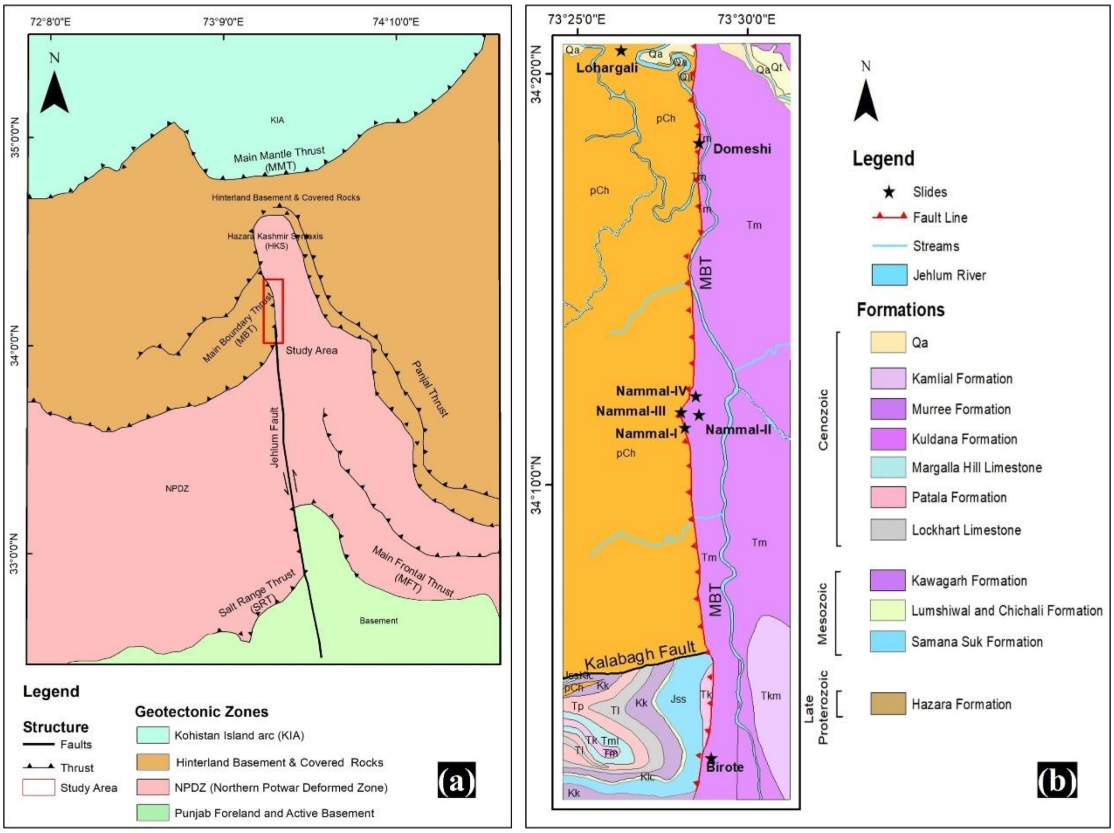

Figure 2(a): Regional tectonic setup, the red rectangle depicts the investigated area; modified after (Ghaznavi et al., 2011; Hussain et al., 2004; Zaheer et al., 2022). (b): Geology of the investigated area with landslides marked on the map; modified after (Ghaznavi et al., 2011; Hussain et al., 2004).

Table-1: Names and locations of the studied landslides.

Sr. No.	Name	Location		District
1	Birote Landslide	34° 3' 23.22"N	73°29' 15.36"E	Abbottabad
2	Nammal-I Landslide	34°11'25.41"N	73°28'20.24"E	Abbottabad
3	Nammal-II Landslide	34°11'44.92"N	73°28'44.67"E	Abbottabad
4	Nammal-III Landslide	34°11'48.23"N	73°28'12.85"E	Abbottabad
5	Nammal-IV Landslide	34°12'11.95"N	73°28'38.43"E	Abbottabad
6	Domeshi Landslide	34°18'22.00"N	73°28'38.00"E	Muzaffarabad
7	Lohargali Landslide	34°20'36.00"N	73°26'18.00"E	Muzaffarabad

MATERIALS & METHODS

Field survey was conducted to collect the data, seven landslides were studied out of which five fall in the Abbottabad district while the two in Muzaffarabad. Table-1 presents the names and locations of the landslides in tabular form.

Information about landslide parameters like lithology/material composition, discontinuity data, hydrological conditions and element at risk were collected through field visits in the area of interest; soils were tested in the laboratory to determine the Atterberg limits. Temporal variation in Google Earth images was utilized to trace the past history of landslides where possible. Moreover, the local communities were interviewed to gather information about landslide origin, history and resultant damages.

FIELD OBSERVATIONS

Birote Landslide

Birote Landslide was triggered by heavy rainfall in July 2021 while the rains in February 2022 reactivated it. The area in general faces the slope stability issues due to presence of MBT. Heavy precipitation further aggravates the issue as unplanned growing population on mountain slopes has disrupted the natural drainage system. It is an old landslide located in the Murree Formation with a slope angle of about 25° and facing south-west direction; the latest activity is a partial reactivation induced by water infiltration (Figure 3). Presence of the old landslide has also been confirmed by the community through a narrative passed on from one generation to another; the narrative relates the boulders in Figure 3(b) to an old landslide event. The slide deposits from recent episode include huge boulders and matrix posing a potential threat to human lives and infrastructure (Figure 4).

The latest landslide activities have been triggered by water infiltration. Waste water from surrounding areas is drained in the landslide body through a concrete channel. The volume of inflowing water increases many-fold during heavy showers. In addition, the houses located in the landslide zone don’t have a proper drainage system, waste water from domestic use is drained into un-lined septic tanks that infiltrates the slopes. Erosion by Khaner Kas stream at the toe of the old landslide zone (Figure 4) may facilitate the phenomenon of mass wasting in future although it is not a major contributor in the current situation.

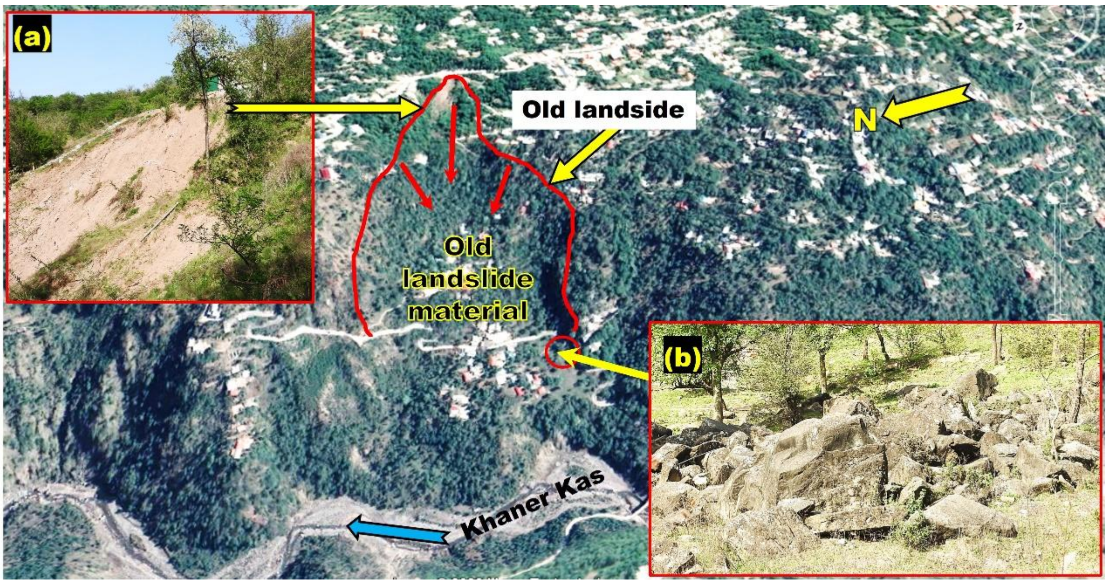

Figure 3 An old landslide in Birote Kallan (a) current main scarp of the landslide (b) boulders rolled down the slope in some old times.

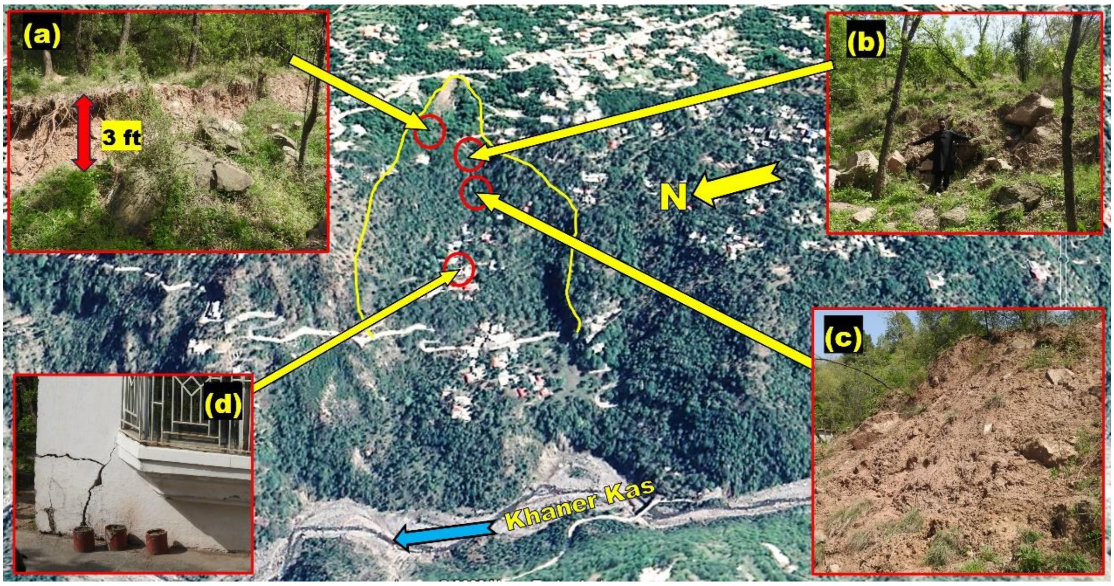

Figure 4: Series of mass movement events presented on Google Earth imagery. (a) about 3 feet settlement (b) slide material (c) fresh landslide (d) cracks developed in a house.

Nammal-I Landslide

The landslide was triggered due to slope disturbance by a road cut in 2002; since then, the slope has never been stable. This landslide is located along the road near Nammal village, just at the boundary between the Murre and Hazara Formations, with a slope angle of about 23° facing toward NE direction. The road gets frequently blocked by the landslide during/after rainfall. Water permanently oozes out through the strata resulting in erosion of the shale. Three to four houses are at risk at the top of the slope whereas one house has been completely damaged. Dimensions of the landslide are 100 × 150 m^2, dominant lithology is mainly overburden and shales of Murree Formation.

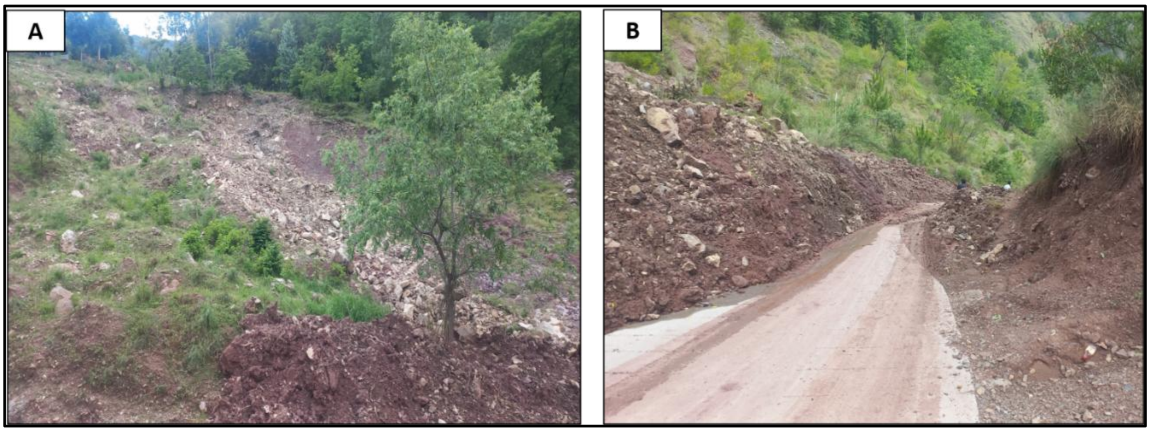

Figure 5. The road is frequently blocked due to a Nammal-I landslide along the road (A) view of the landslide body (B) road blockage at the toe of landslide.

Nammal-II Landslide

The landslide was initially triggered after rain in January 2021, then it continued to expand and its current dimensions are approximately 220 x 530 m^2; it has a slope angle of 24° and aspect in the NW direction.

Its upslope progression poses a threat to the nearby houses. The landslide is situated in Murree Formation; here, the major portion comprises shale with thin to medium-bedded sandstone interbedded at places. The main inducing factor of landslide is the MBT fault zone along with the fragile nature of shales of the Muree Formation. Secondly, water seepage from a local spring, house sewerage, and precipitation further aggravated the situation. In Figure 6, the satellite image of April 2021 doesn't show any visible signs of the landslide whereas the May 2023 field photograph shows the huge landslide in the area.

The existence of the spring just above the landslide initiation point in January 2021 suggests the hydrologic triggering of the landslide. The landslide is accelerating at a very high pace; it has gained a length of about 500 meters in two years and the crown is still shifting upward. Huge cracks along the flanks of the landslide suggest a future enlargement potential of the landslide.

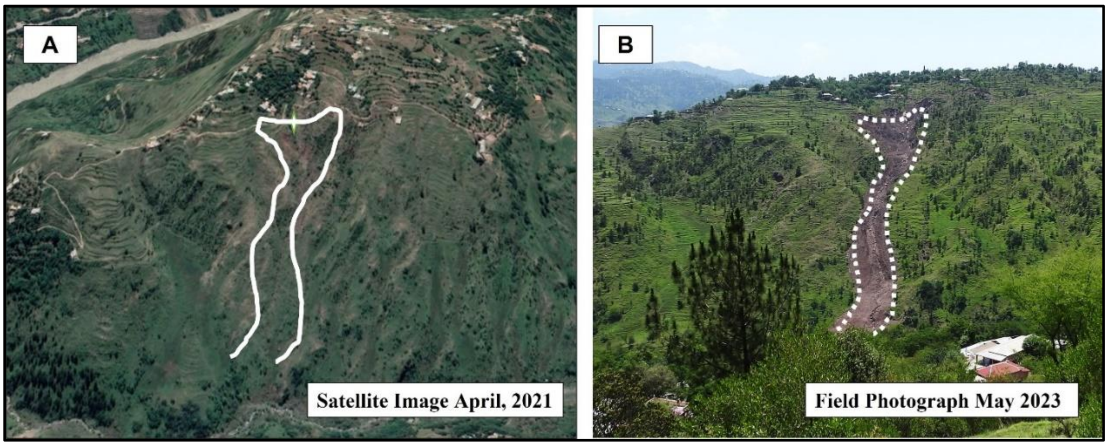

Figure 6. The landslide was triggered in January 2021 (A) landslide is not visible in the April 2021 satellite image (B) May 2023 photograph clearly shows the landslide.

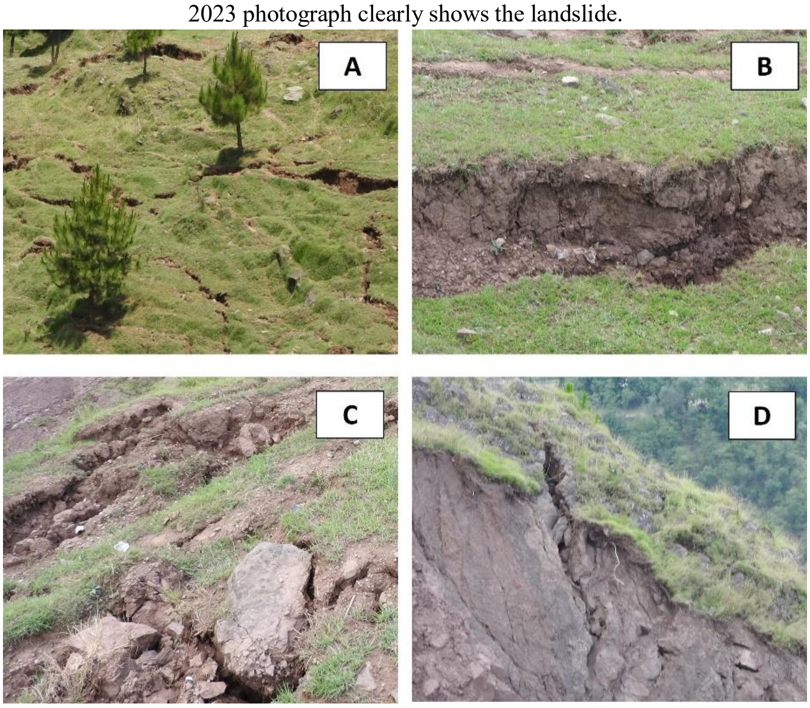

Figure 7. (A) Network of cracks along the right flank of landslide (B) vertical displacement near the landslide crown (C) cracks and settlement along the left flank (D) another crack passes across the left flank.

Nammal-III Landslide

Nammal-III landslide is located in the slates of Hazara Formation; it has a slope angle of 52° and aspect in the SE direction with an approximate dimension of 300 x 100 m^2; it partially blocked the road and has the potential to block it in the future. It is relatively older landslide; although no one from the local community remembers the actual year of landslide event but they informed that it was triggered sometime around 1995. Local community couldn't provide information about the triggering factor but structural discontinuities developed by proximity to the MBT seem the major contributing factor.

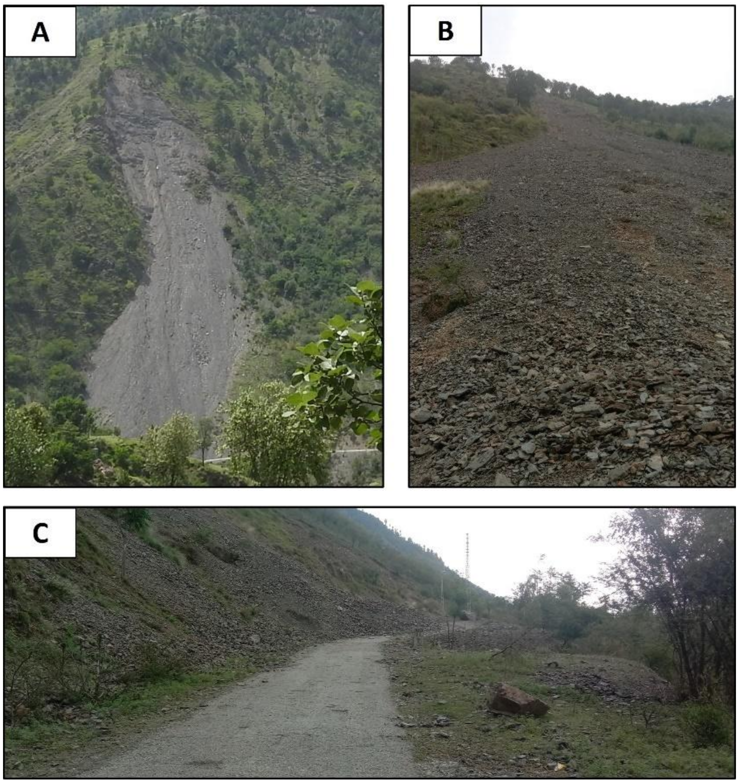

Figure 8. Nammal-III landslide in Salkhala Formation (A) an overview of the landslide (B) a close up of the landslide accumulation zone (C) road partially blocked by the landslide.

Nammal-IV Landslide

This landslide is situated just north of the Landslide-II, on the opposite side of the stream. Although this landslide was triggered in January 2020, a year before the trigger of the Landslide-II but its rate of progression has been lower than that of the Landslide-II. Its slope has an angle of 25° and faces SE direction. The houses are located at some distance from the landslide crown, so there is no direct water infiltration from septic tanks/sewerage water. However, there is a spring at its crown which is a source of water infiltration into the landslide body. In the long run, the permanent infiltration due to spring water and domestic water on its upslopes may adversely affect the slope stability causing the possible re-activity of the landslide.

Figure 9: Nammal-IV landslide, just opposite to the Nammal-II landslide.

Domeshi Landslide

The landslide is located on right bank of Jhelum River, opposite side of Muzaffarabad Kohala Road, near Domeshi village. The landslide event occurred by the start of August 2023 and its triggering factor was heavy rainfall just days before the event. The slow movement allowed the population for evacuation avoiding any life loss although ten houses were completely destroyed along with a metaled road and agricultural land. This earth slide with surface area of 450×250 m² has a slope angle of about 34° and faces towards SE direction. The fault line passes through the landslide body with its crown lying in the Hazara Formation and toe in the Murree Formation. Some water springs in the body of the landslide have stopped flowing after the slide. The slide material continues to move downslope in steps, slowly and gradually.

Figure 10: Crown of Domeshi Landslide located in the Hazara Formation.

Lohar Gali Landslide

Lohar Gali landslide is located near Lohar Gali village along Muzaffarabad Garhi Habibullah road. Here, the slope angle is 43° aspect is southeast. This landslide has been reported as more than 50 years old, as the exact date of initiation is not known. Although the slide remained partially active after the initial triggering but 2005 Kashmir Earthquake severely reactivated it. It occasionally blocks the road during rains. About eight houses have already been relocated while another 20 are at risk. It is translational earth slide in slates of Hazara Formation; thinly laminated slates are crushed and highly weathered; dimension of the sliding zone was measured to be 270×90 m^2. There are number of inducing factors: at first landslide triggered due to road cutting; secondly, MBT is also passing nearby whereas water infiltration/seepage from human settlements and agricultural lands has also been observed. Cracks are visible at the crown and the right flank.

Figure 11: A view of Lohargali Landslide from Muzaffarabad-Garhi Habibullah Road.

TERRAIN ANALYSIS

ALOS PALSAR, high resolution terrain corrected, 12.5 m resolution, Digital Elevation Model (DEM) by Alaska Satellite Facility (ASF) was downloaded from ASF's website (https://search.asf.alaska.edu/) to carry out terrain analysis with two components i.e., slope angle and slope aspect. Surface tools from the Spatial Analyst Toolbox of the Esri ArcMap 10.8.2 were used to carry out the said analysis.

DISCONTINUITY ANALYSIS

Discontinuity data was conducted by window sampling methods using ISRM guidelines (N. Barton & Bar, 2015; N. R. Barton, 1978; N. R. Barton & Grimstad, 2014) from outcrop in the surroundings of failed slopes (Table 2). The data was collected from Nammal-II and Nammal-III landslides; it is the location where we have a cluster of four events i.e., Nammal-I, Nammal-II, Nammal-III and Nammal-IV landslides. It was not possible to collect the discontinuity data from other landslides because of the absence of outcrop with reliable joint sets as some of the landslides comprise overburden material or soft/crushed lithology.

Kinematic Analysis

The data was plotted in DIPS (RocScience) to assess the kinematic stability analysis and mode of failures for the relevant slopes.

Q-Slope Analysis

Orientation, spacing, persistence, infilling of the joints was also noted for the rock mass classification. Q-Slope empirical method (Bar & Barton, 2017) was used to assess the stability of slopes corresponding to Hazara and Murree Formations.

Table 1: Orientation data plotted for stereographic projection

Murree Formation (Nammal-II Landslide)		
Joint	Dip	Dip Direction
Slope Face	24	11
Joint-I	70	301
Joint-II	34	104
Joint-III	46	19
Hazara Formation (Nammal-III Landslide)		
Joint	Dip	Dip Direction
Slope Face	52	158
Joint-I	61	276
Joint-II	49	175
Joint-III	22	93

Table 3: Discontinuity data collected from Hazara and Murree Formations.

Rock Unit	**Joints**	**Spacing (mm)**	**Persistence (m)**	**Aperture (mm)**	**Roughness**	**Undulation**	**Infill**	**Seepage**	**No. of sets**
Hazara Fm.	J1	300	45	10	Smooth	Planar	Clay	Damp	3
	J2	550	70	16	Rough	Stepped	Clay	Damp	3
	J3	650	35	23	Smooth	Stepped	Clay	Damp	3
Murree Fm.	J1	60	38	5	Rough	Undulating	Silt and Clay	Damp	3
	J2	120	10	2	Rough	Undulating	Clay	Damp	3
	J3	350	16	5	Rough	Undulating	Clay	Damp	3

Rock quality designation (RQD) was calculated through joint volumetric count (J_v) by a relationship presented by Palmstrom, 2005.

$$RQD = 110 - 2.5\ J_v$$

J_v represents the total number of joints per cubic meters which are calculated by the spacing of joints by following relationship (Bar & Barton, 2017; Palmstrom, 1982, 2005).

$$J_v = \sum_{i=1}^{j} (1/S_i)$$

The following empirical formula was used for slope assessment (Bar & Barton, 2017)

$$Q = RQD/J_n \times (J_r/J_a \times J_o) \times J_w/SRF$$

RESULTS AND DISCUSSION

Five out of seven landslides have occurred in the Murree Formation while only two landslides i.e., Nammal-III and Lohargali landslides were observed in the Hazara Formation (Table 4). This emphasizes that Murre Formation is the most vulnerable lithologic unit to landslides. This lies exactly in line with the previous studies which suggest that owing to its lithology and lithological variations, the Murree Formation is generally prone to landslides in favorable conditions (Sadiq et al., 2021; Torizin et al., 2017). Moreover, landslides in the Murree Formation have happened on gentle slopes ranging between 23°-34° whereas the landslides in Hazara Formation have steep slopes with angles of 43° and 52° (Figure 12(a) and Table 4). This probably refers to the incompetent lithology of Murree Formation unable to withstand steep angles particularly under the stressful influence of MBT. Four out of seven landslide events happened on slopes with south-east direction while one each in the south-west, north-east and north-west direction. Out of four landslides with south-east aspect two have occurred in the Murree Formation while the remaining two in the Hazara Formation; the probable reason for the dominance of southeast aspect is the fact that current landslides are restricted to the right bank of Jhelum River, if we would include the area along the left bank, then the trend might be different; a dataset with a greater number of landslides may offer a better solution. Proximity to MBT along with its associated phenomenon like springs, shearing, and discontinuities are the major and common inducing factors in almost all of the observed landslides (Table 4).

The stereographic projection on DIPS with 24/11 slope orientation of Murree Formation at Nammal-II (Figure 13) depicts that the joint intersection in this zone doesn't present any probability of failure; the main reason is the gentle slope angle. The Nammal-III discontinuity data collected from the Hazara Formation also presents three joint sets intersecting the slope face having the orientation 52/158; projected sets show a probability of failures along joints (Figure 14). 6 out of 43 intersections offer the 13.95% probability of plane failure whereas 118 out of 903 intersections present 13.07% probability of wedge failure. Moreover, the probability of direct and oblique toppling is 1.11% and 3.65% respectively. The reason for absence of any failure scenario in the Murre Formation is not due to its strength but due to its low angle which exhibits its weak lithology. As discussed earlier, Murree Formation is more prone to slope failure than other formations. The shales being the incompetent lithology are prone to failure, particularly when moist.

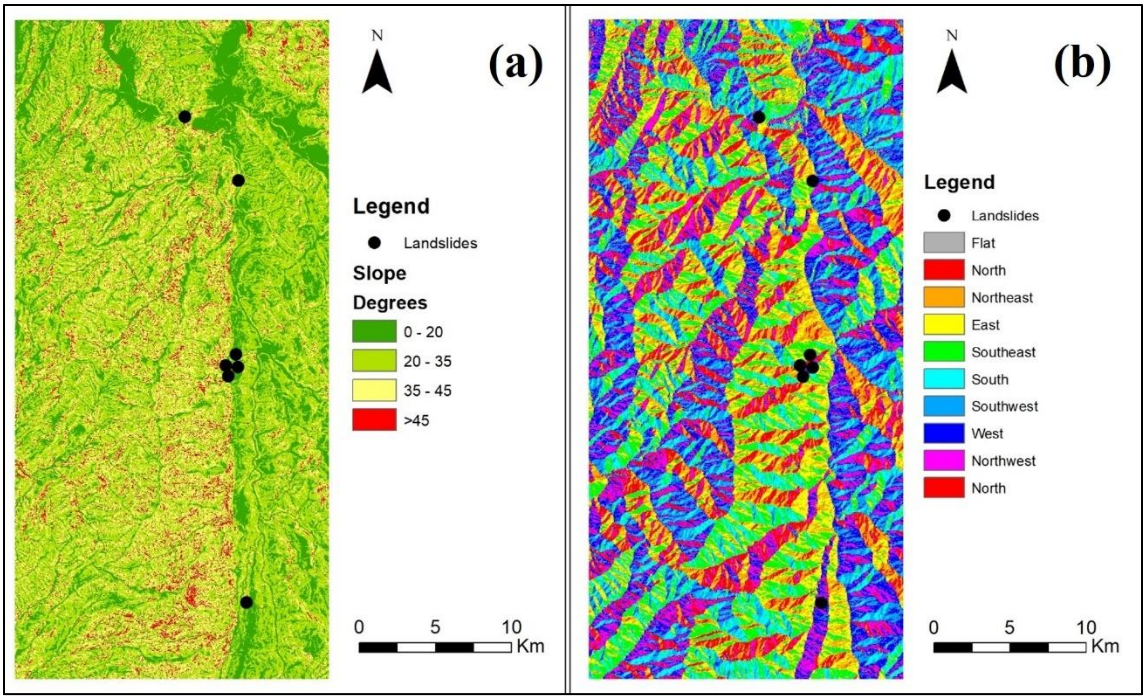

Figure 12 (a): Depiction of slope angle against the landslide locations (b): slope aspect of the landslide surfaces.

Table 4: A summary of lithology, slope angle, slope aspect, triggering factor of the observed landslides.

Sr. No.	Landslide	Lithology	Slope Angle	Slope Aspect	Driving forces
1	Birote	Murree Fm.	25°	SW	MBT, rain, anthropogeny
2	Nammal-I	Murree Fm.	23°	NE	MBT, water springs
3	Nammal-II	Murree Fm.	24°	NW	MBT, water spring anthropogeny
4	Nammal-III	Hazara Fm.	52°	SE	MBT, discontinuities
5	Nammal-IV	Murree Fm.	25°	SE	MBT, precipitation, spring
6	Domeshi	Murree Fm.	34°	SE	MBT, precipitation
7	Lohargali	Hazara Fm.	43°	SE	Road cutting, MBT, rain, anthropogeny

The laminated structure and alternating layers create weak planar surfaces within the rock mass that can serve as potential slip surfaces during landslides. However, sandstone in the Murree Formation is known to exhibit a certain level of resistance to landslides compared to shale. Its resistance to landslides can be attributed to several factors; for example, coarser arenaceous grains provide a more stable and interlocking structure by exhibiting a good permeability, allowing water to flow through the rock mass more easily. The presence of discontinuities, bedding planes, or structural complexities within the sandstone can still influence the stability of slopes. The Hazara Formation being the competent lithology maintains relatively steeper angles and its discontinuities offers more intersection with the slope face resulting in a number of failure mechanisms. While the presence of slates, phyllites, and related metamorphic rocks within the Hazara Formation can contribute to its overall resistance against landslides, it is important to consider other factors such as geological structures, slope geometry, and local environmental conditions when assessing landslide hazards. Detailed site investigations and geotechnical assessments are necessary to evaluate the stability and potential risks associated with the Hazara Formation.

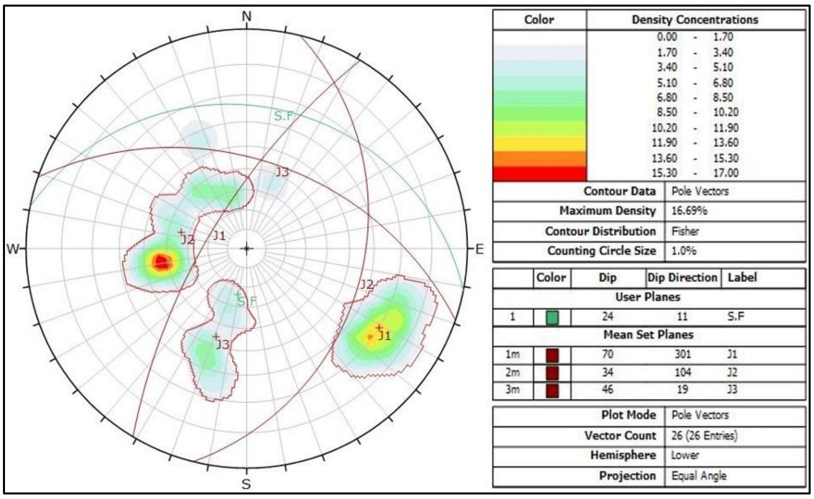

Figure 13: Stereographic projection for Murree Formation.

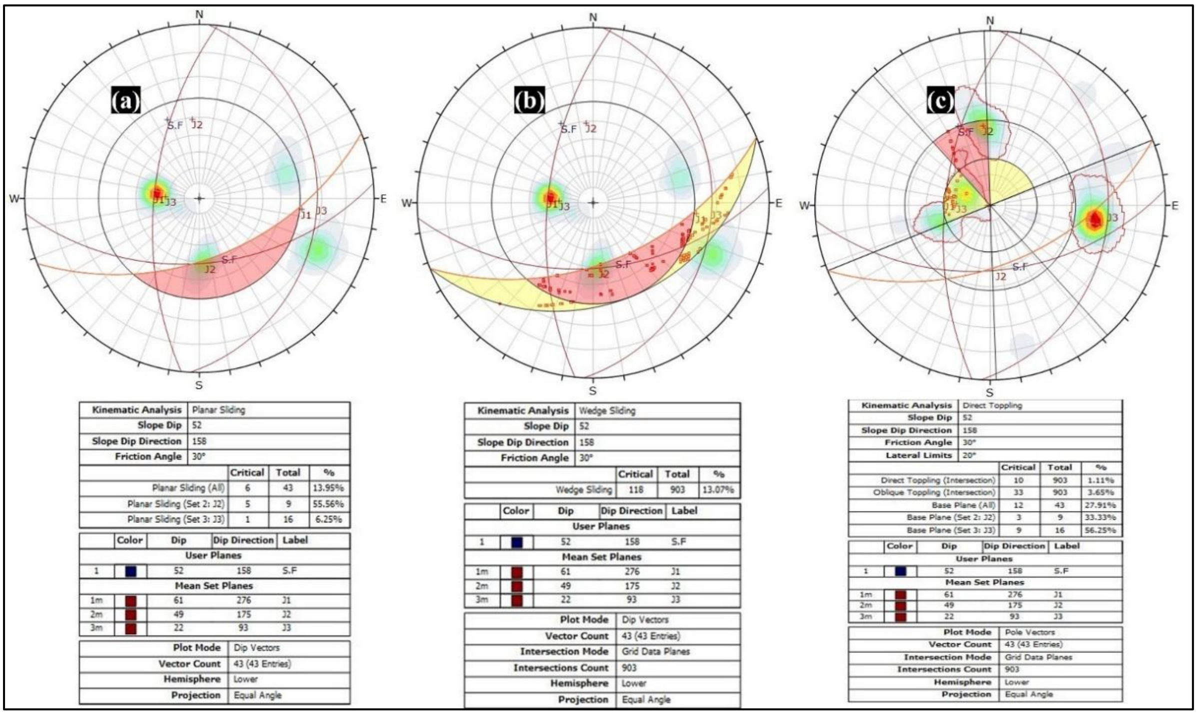

Figure 14: Kinematic Stability analysis for mode of failure in Hazara Formation (a): planar failure (b): wedge failure (c): direct toppling.

The slope stability assessment using Q-Slope method presents a value of 0.03 for Murree Formation with 35° as the angle where slope would be stable; the existing slope angle of 24° suggests it as a stable slope (Table 5). Similarly, the Q-slope value of 0.43 has been calculated for the Hazara Formation with 58° as the angle where slope would be stable; again, the existing slope angle of 52° suggest a stable slope. Although the method declares the slopes angles of both Murree and Hazara Formations in the stable zone but we have observed a number of landslides in a limited area. It means that there is some other driving force for the landslides to occur, and this force is not much dependent on the slope angles. We can see that the Q-Slope stability chart (Figure 15) puts the Hazara Formation in the stable zone while Murree Formation in a zone where the slope stability is uncertain. So, the driving force surpasses the barrier of slope angle and have caused extensive landsliding in the area: as discussed earlier, MBT and its associated factors constitute the force that has driven slope failure in the study area.

Table 5: Q-Slope assessment of the slopes of Hazara and Murree Formations.

Unit	RQD	Jn	Jr	Ja	Jo	Jw	SRFa	SRFb	SRFc	Q-Slope	Angle
Hazara Fm	65	12	2	3	1	0.6	5	5	2	0.43	58
Murree Fm	18	9	1.5	3	1	0.3	10	10	8	0.03	35
RQD – Rock Quality Designation, Jn – Number of joints, Jr – Joint roughness Ja – Joint alteration Jo- Orientation factor, Jw – water factor, SRF – Stress reduction factor											

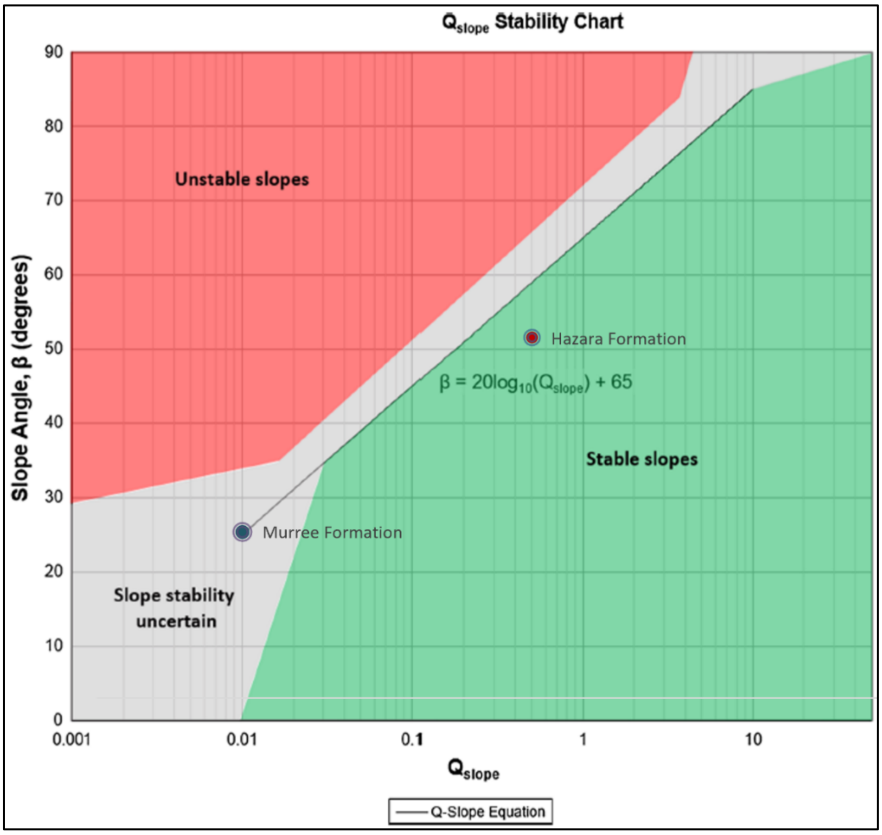

Figure 15: Q-slope stability chart.

Water springs are very common in the area, most likely because of proximity to the major fault line; almost all of the landslide bodies have one or more springs in or near the landslide body. Excessive rains further aggravate the situation by either triggering new landslides or reactivating older landslides. Also, water infiltration from anthropogenic activities like septic tanks, improper drainage of waste water and excessive irrigation water further deteriorates the situation. This destructive role of excessive water in slope failure is a particular point of worry as experts have projected an increase in the monsoon rains in Pakistan due to climate change scenario (UNDP, 2017). Studies suggest that increase in rainfall will accelerate the process of slope failure and it will trigger more landslides and debris flows (Jakob, 2021; Sadiq et al., 2024). In addition, ever-growing population will enhance the negative impacts of anthropogeny on landslides.

Moreover, the results of Atterberg Limits (Table 6) of the soil samples collected from the landslide sites declare the soils as clay and clayey silt. The results show that with the exception of Nammal-II landslide, the soils in general are low plastic that are more susceptible to landslide. It's also worrisome that the MBT is the driving force that have destabilized Nammal-II landslide which is neither unstable as per Q-Slope classification nor a low plastic lithology. It means that these driving forces would be more catastrophic if the current scenario is disturbed by much anticipated high-intensity, high duration precipitation in future.

Table 6: Results of Atterberg Limits for soils collected from the landslide sites

Name	**Liquid Limit (%)**	**Plastic Limit (%)**	**Plasticity Index (%)**	**USCS Classification**
Birote	29.5	21.8	7.7	CL
Nammal-II	38	16.6	21.4	CL
Domeshi	21	14	7	CL-ML
Lohargali	18	13	5	CL-ML

Conclusions

The study area has witnessed extensive landsliding along the MBT; the Murree Formation owing to its incompetent lithology is more prone to landsliding than other lithologies; it is too weak lithology to maintain steeper slope angles with the exception of its sandstone bed which offers resistance to slope failure. Murree Formation contributed 5 out of 7 landslides (i.e., 71.4%) whereas Hazara Formation is much stronger than the Murree Formation. Proximity to MBT and causative factors associated with the MBT are the major driving force behind landslide occurrence in the area. Water infiltration and seepage along the fault line have proven to be very important factor that destabilized the slopes along the MBT. Certain studies suggest that climate change phenomenon will increase the rainfall in Pakistan that will trigger more landslides in its mountainous terrain; it is further going to deteriorate the problems with slope stability in northern Pakistan. Additionally, the anthropogenic factor is also anticipated to trigger more landslides in future. The researchers and the planners need to devise strategies to face the looming threats of accelerated landsliding in mountainous terrain.

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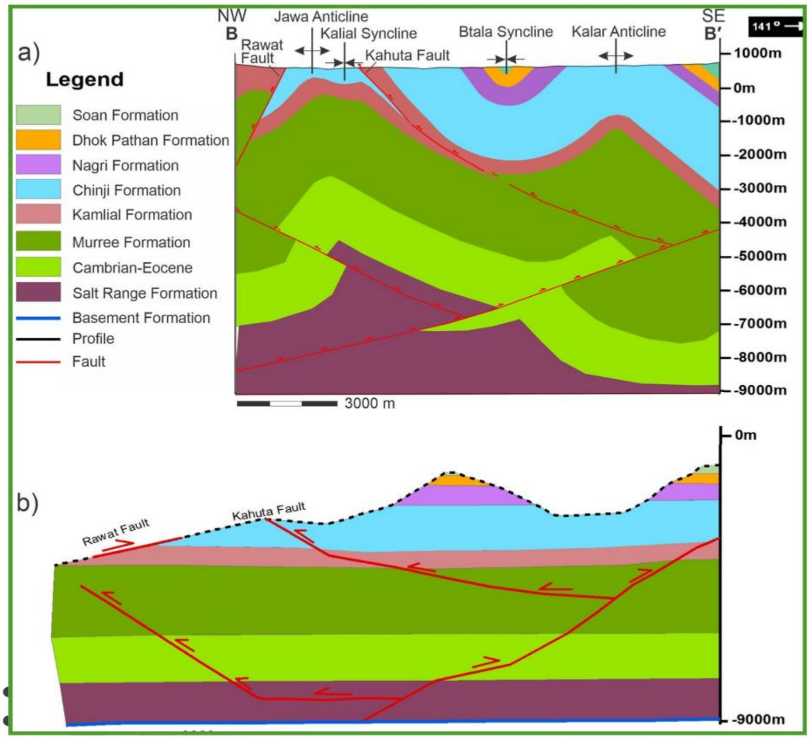

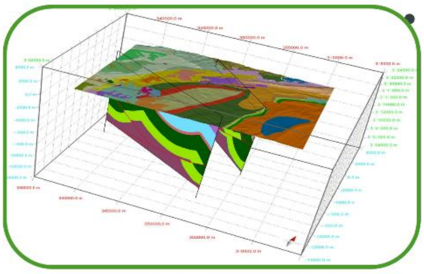

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