International Research Journal of Earth Sciences _____ISSN 2321 – 2527
Vol. **9(1),** 20-31, February **(2021)** *Int. Res. J. Earth Sci.*

Review Paper

Geological Investigation of 5.6 M_W Mirpur Earthquake, Northwestern Himalayas, Pakistan

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Available online at: www.isca.in
Received 11th September 2020, revised 30th November 2020, accepted 11th January 2021

Abstract

A devastating earthquake of 5.6 M_w occurred in the Kashmir Himalayas at the axis of Hazara Kashmir Syntaxis on September 24, 2019 caused massive destruction. The tremors were felt in a radius of ~100km with damage taking place in area of 700km^2 including life losses. The epicenter was located near Mirpur, Kashmir at a depth of 10km, whereas a peak ground acceleration in the range of 0.35g within limits of <0.0017 to>1.24g. The earthquake affected area lies at the fold axis of Hazara Kashmir Syntaxis, which is major structural antiform involved in different orogenic episodes and tectonic phases since Precambrian. The Mirpur Earthquake is resultant of an onward collision between Indian and Eurasian plates on a main thrust fault (i.e., Samwal Fault) in the epicentral region. The seismogenic Samwal Fault is extending as WNW-ESE exposed near Samwal Village with a surface rupture and sporadic slope failures appearing at various places. The fault plane is dipping SW at the eastern end and NE at western side. This study applying the remote sensing techniques which used to analyze the causative fault by using Landsat Imagery and Digital Elevation Model in correlation with the fieldwork observations. The Samwal Fault was delineated, based on morphological peculiarities and straightness on the satellite imagery, which marked a major topographic front in the study area. The main characteristics associated with 2019 Mirpur Earthquake is the liquefaction induced lateral spreading along the Upper Jhelum Canal, which caused an extensive damage to infrastructures. The other damages were mainly occurred along the main fault line, which caused human fatalities due to the damaging of infrastructures. The factors responsible for the damages are foundation failure, lack of structural integrity and inappropriate construction material.

Keywords: Mirpur earthquake, Western Himalaya, Surface Rupture, Seismo-tectonics, Samwal Fault.

Introduction

The Earthquake is recognized as major natural disaster, causing devastation and compound hazards around the globe. It is an unpredictable disastrous event which effects the human population over hundreds-thousands of square kilometers. The earthquake has a severe impact on society, infrastructure facilities and disrupts the economic situation of the region. The aftereffects, related to seismic ground trembling significantly rise in area, where, population is dense with poor infrastructure. For this reason, a proper identification of earthquake characteristics and associated secondary hazards is essential for preventive measures and disaster mitigation strategy in affected area.

According to USGS, in the afternoon of 24th September, 2019 at 11: 01(UTC) an earthquake struck western Himalayan region in Mirpur, Jammu & Kashmir. The epicenter (33.106°N, 73.766°E) of shallow focus earthquake (10km deep) was located at 07km SSE of Mirpur City, Jammu & Kashmir (Figure-1). This medium earthquake had generated seismic moment of 5.6 M_w and estimated Mercalli Intensity of VII[1]. The tremors were felt in the radius of 100km among Kashmir territory, Punjab (India, Pakistan) and northern region of India. The city of Mirpur is situated ~460m altitude and is connected through major GT-Road (Lahore-Peshawar) at the locality of Dina (District Jhelum). The area is situated at 35km from Dina and 136 km from Islamabad.

According to the situation report of National Disaster Management Authority (NDMA) dated on October 5, 2019, high level structural failure produced in the Mirpur area which causes 39 fatalities and injured 746. Approximately 15,000 buildings including houses, shops, schools, hospitals, cattle head etc. were damaged[2]. A major road connecting Mirpur to Jatlan along the Upper Jhelum Canal (UJC) is completely damaged

including 06 bridges as a result of liquefaction and almost 200 vehicles were destroyed in the said earthquake. A medium range of shallow landslides were generated in the rupture area of fault trace; however, at a distance from main rupture zone, sporadic failures were spotted at few places. The present study is an attempt to deal with the post-earthquake geological settings and field based geo-technical investigations of the earthquake affected areas.

The western Himalaya depicts the dynamic nature of Himalayan orogeny characterized by major tectonic structures, encouraging high seismicity in the region[3,4]. The Kashmir region lies in Indus-Kohistan Seismic Zone, which is believed as the source of shallow to medium seismicity in the area. The recent major earthquake of M_w 7.6, near Muzaffarabad is the evidence for high potential future earthquakes[5]. The current seismic event in the Mirpur region paid attentions to geoscientist community, to undertake the detail analysis of seismogenic source. The natural process and climatic conditions can have adverse impact on ground water resources after a strong ground vibration[6,7]. The lack of scientific dataset (seismic hazard map, geotectonic map and geotechnical studies) and vulnerability to disaster awareness and mitigation plans increases the risk of social insecurities in population[8]. Therefore, investigating the source of earthquake and elements at risk needs to be identified for formulating a mitigation strategy. This study highlights the relationship of geological structure with earthquake activity, and their associated characteristics and damages initiated as consequence of strong ground vibration.

Geology and tectonic setting

The epicenter of Mirpur Earthquake (ME) is located in a severely deformed and complex domain that includes different orogenic events and tectonic stages, mainly divided into three tectono stratigraphic terrains[9]. The northern tectonicunit constituents the Trans-Himalayan Tectonic, Eurasian Plate (Karakoram Block) incorporating the sedimentary rocks of Paleozoic to Mesozoic with plutonics of Cretaceous to Miocene. The Main Karakorum Thrust (MKT) demarcates the northern segment of Kohistan Island Arc (KIA) separating it from Eurasian block, whereas, the Main Mantle Thrust (MMT) marks its southern edge with Indian Plate[10] (Figure-1). The KIA encompasses the intrusive rocks of Late Cretaceous to Eocene, and calc-alkaline volcanics, metamorphics, and minor metasediments. Furthermore, in south, the Kashmir basin represents an assemblage of basic volcanics, metamorphic complexes of variegated grades, granitic pluton and quaternary deposits. In the adjoining Potwar Basin all other packets are present except basic volcanics and high-grade crystallines. The final stages of Himalayan orogeny have exposed the basement rocks in foreland belt with subsequent fluvial stacking in superimposed basins towards south[11].

About 2,400km long Himalayan range was formed about 50-65 Ma ago[12] due to collision of Indian Plate (south) and Eurasian Plate (north). This mountain range is considered as the youngest and distinguished feature of continent-continent convergence around theworld[13-17]. The most spectacular element of the Himalayan orogeny is the western Himalayan Syntaxis, which is flanked on either side by Peshawar Basin and Kashmir Basin[18] (Figure-1).

Tectonically, the Samwal Fault (SF**)** is present adjacent to the fold axis of Hazara Kashmir Syntaxis (HKS). HKS is considered as prominent tectonic structure in the western extremity of Himalaya, and controlling the structural setting of the area, and holds an important role with regard to its stratigraphic and structural setup[19] (Figure-2). The HKS is an antiformal structure, which is convex to the hinterland and concave to the foreland, created due to bending of thrust sheets around northwest trending to northeast trending thrusts[20]. These thrust sheets are bounded by Salt Range Thrust (SRT), Panjal Thrust (PT) and Main Boundary Thrust (MBT). The Jhelum Fault present in the western extremity of HKS shows the active nature of sinistral faulting (Figure-2). The south-eastern limb and the core of HKS are imbricated and folded to form a regional fold and thrust belt, where as, at Balakot-Muzaffarabad area the syntax is quite narrow and gradually widen out southward[21]. The earthquake triggered area is located in the Jhelum Re-entrant, a major tectonic feature in the outer Himalayas of Pakistan, bounded to the east and northeast by the MBT and Riasi Fault, while the north-easternend of SRT lies in the west (Figure-2). The Tertiary cover sequence of the Indian Plate is folded and faulted during the Late Tertiary Himalaya norogeny. The Himalayan deformation is represented in the form of southwest or northeast verging, southeast plunging and a symmetric folds and southwest directed thrusts. Different regional scale folded structures with minor folds and faults in the structural conformity to the major structures were reported[21]. The project area mainly consists of Dhok Pathan and Soan formations with quaternary alluvium covering majority of the area (Figure-3).

Seismotectonic setup: Seismic activity in South Asia is supposed to be an outcome of the Indo-Eurasian collision. The estimated movement of the Indian Plate is 4-6cm/year towards the north-west[23]. The subsequent collision has generated many fractures in Indian Plate, resulted in various segmentation of structures under Kashmir Basin, which is identified as the Indus-Kohistan Seismic Zone[3,5]. Based on homogeneous tectonic and seismic characteristics, the area has been categorized into following sub-seismic zones – i. MBT ii. Potwar iii. Punjab iv. Salt Range v. Riasi vi. Hazara (Figure-4). These seismic zones were evaluated as active due to distribution of considerable seismicity. The tectonic setup indicates that this earthquake affected areais located within active seismotectonic zone i.e. Riasi Seismic Zone. The Samwal Fault is identified as the possible cause of 2019 Mirpur Earthquake (Figure-2, 3). Previously, a devastating earthquake of 7.6M_W was reported along the Bagh-Balakot Fault (BBF) within the HKS on 8th October 2005[5].

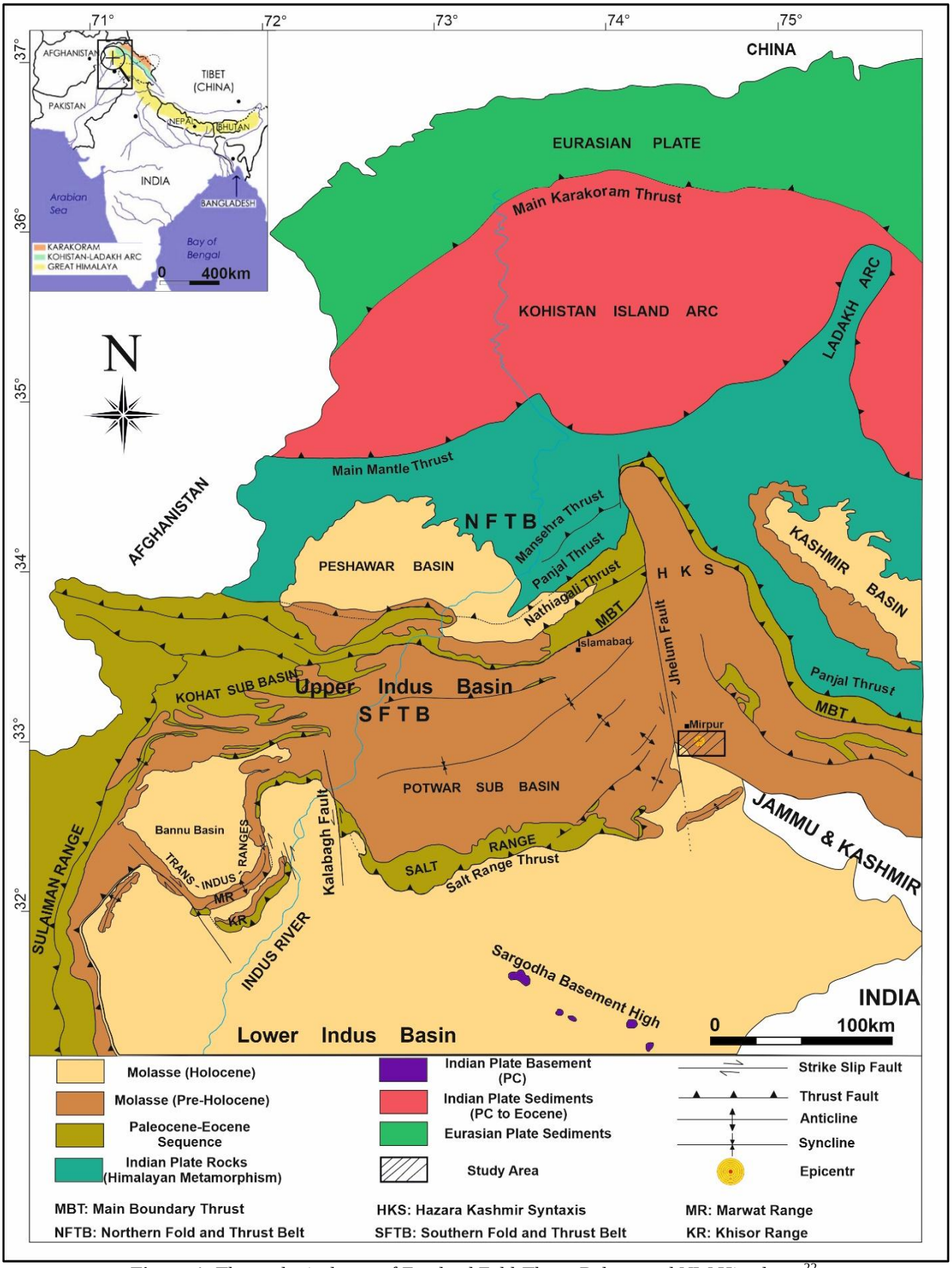

Figure-1: The geological map of Foreland Fold-Thrust Belt around NW Himalayas[22].

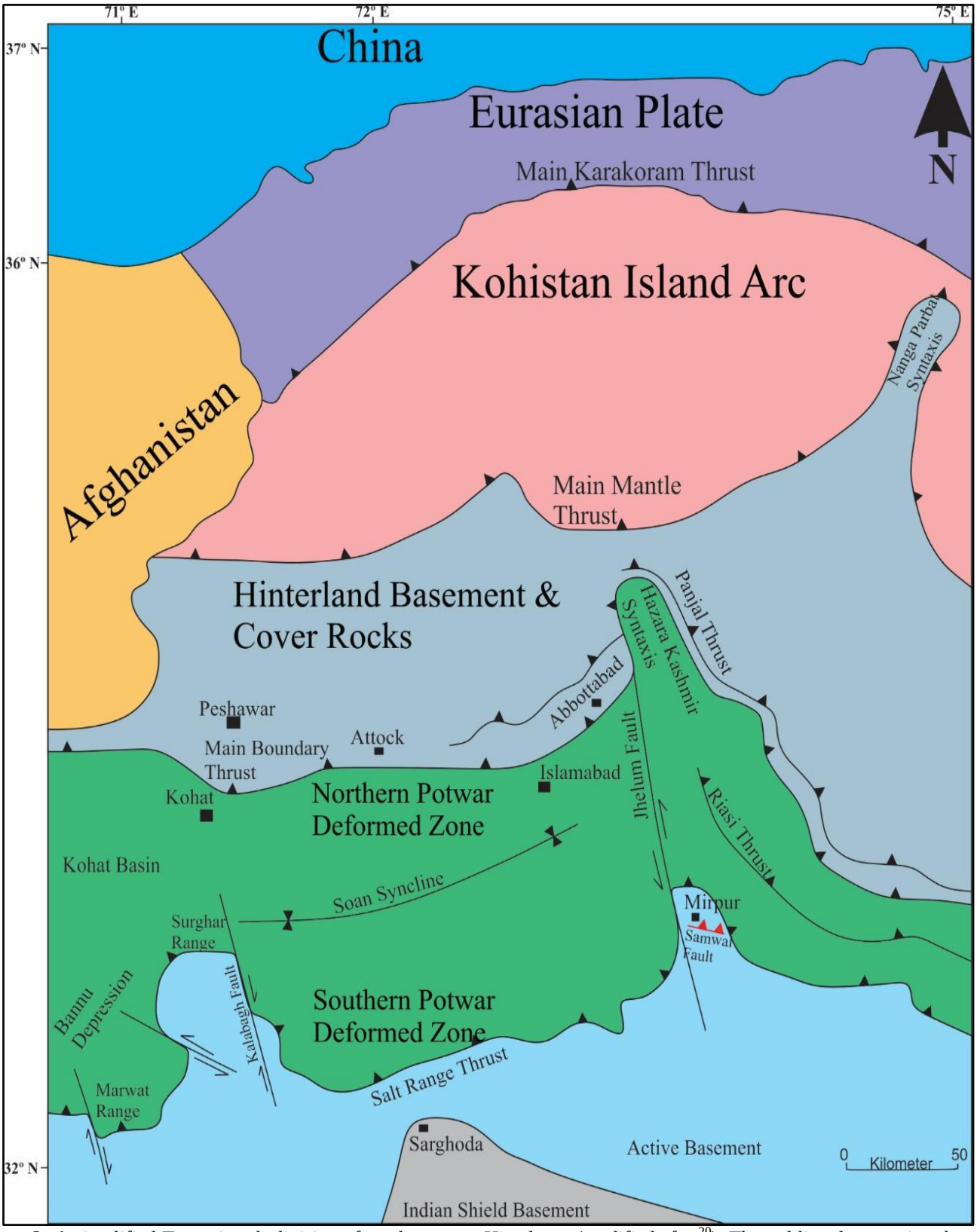

Figure-2: A simplified Tectonic sub-division of north-western Himalayas (modified after[20]). The red line demarcating the main fault line, i.e. Samwal Fault.

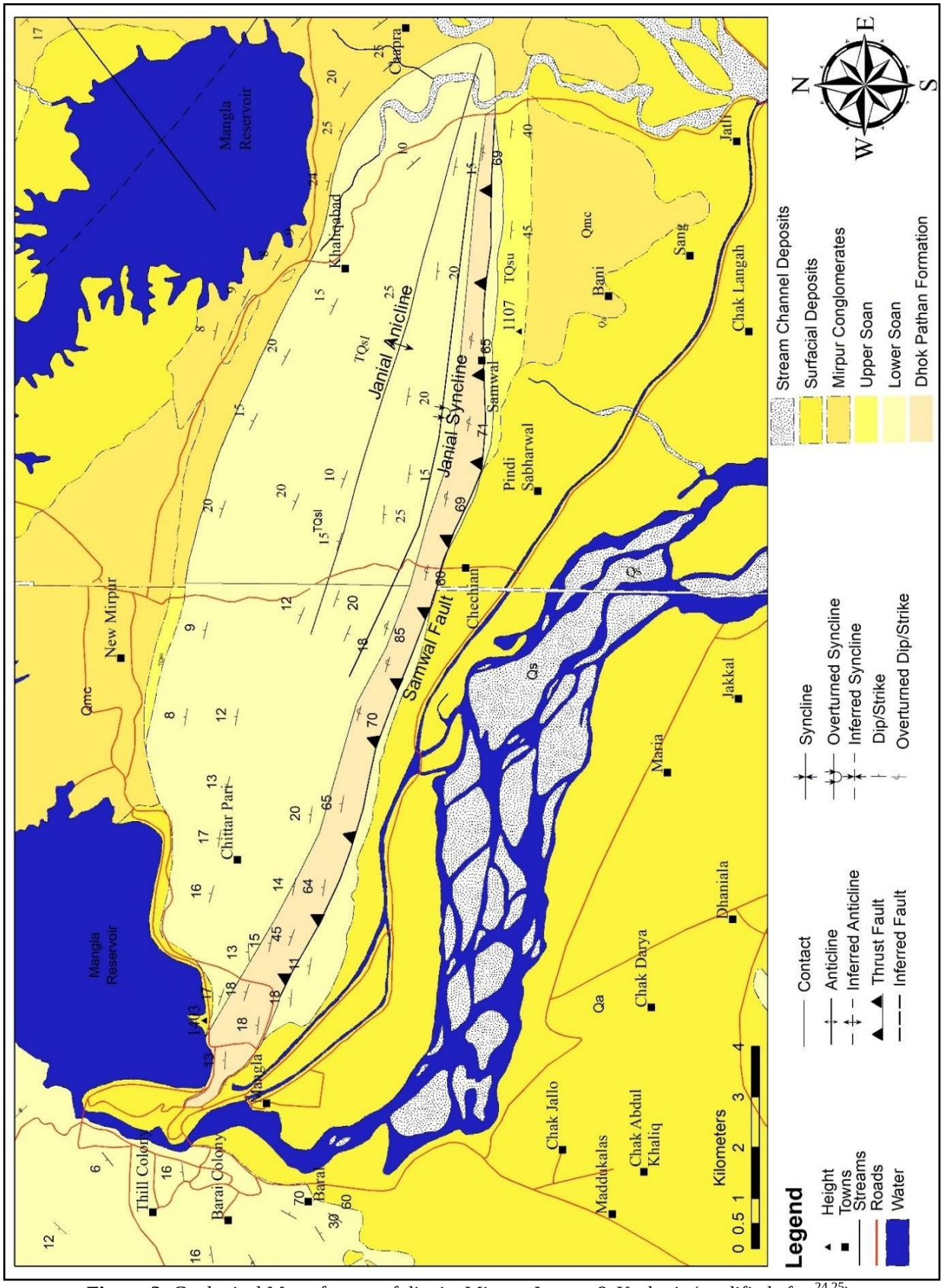

Figure-3: Geological Map of a part of district Mirpur, Jammu & Kashmir (modified after[24,25]).

As per the report of Pakistan Metrological Department (PMD), there cent earthquake of 24th September 2019 lies in moderate seismic intensity zone with Peak Ground Acceleration (PGA) in the range of 0.35g within limits of <0.0017 to > 1.24g, indicating damages to infrastructure near the epicenter[1]. This earthquake of 5.6M w is generated from a depth of 10km that released of around 1010KJ and is equal of about 1000tons of TNT being exploded under ground.

According to the seismic events data (1953-2018) provided by the PMD, the Jhelum Fault (maximum considered earthquake = 7.6) and Dil Jabba Thrust (maximum considered earthquake = 7.0) are the most critical seismotectonic features passing very near to the Mirpur and major seismic events are aligned along these faults (Figure-4). The distribution of seismic events within focus shows that major concentration of the seismic events is within the upper 30km crust, especially the events with M_w>5. The seismicity linked to this event demonstrate that seismic waves generated at shallower depth in the proximity of this region exhibit strong earthquake hazard.

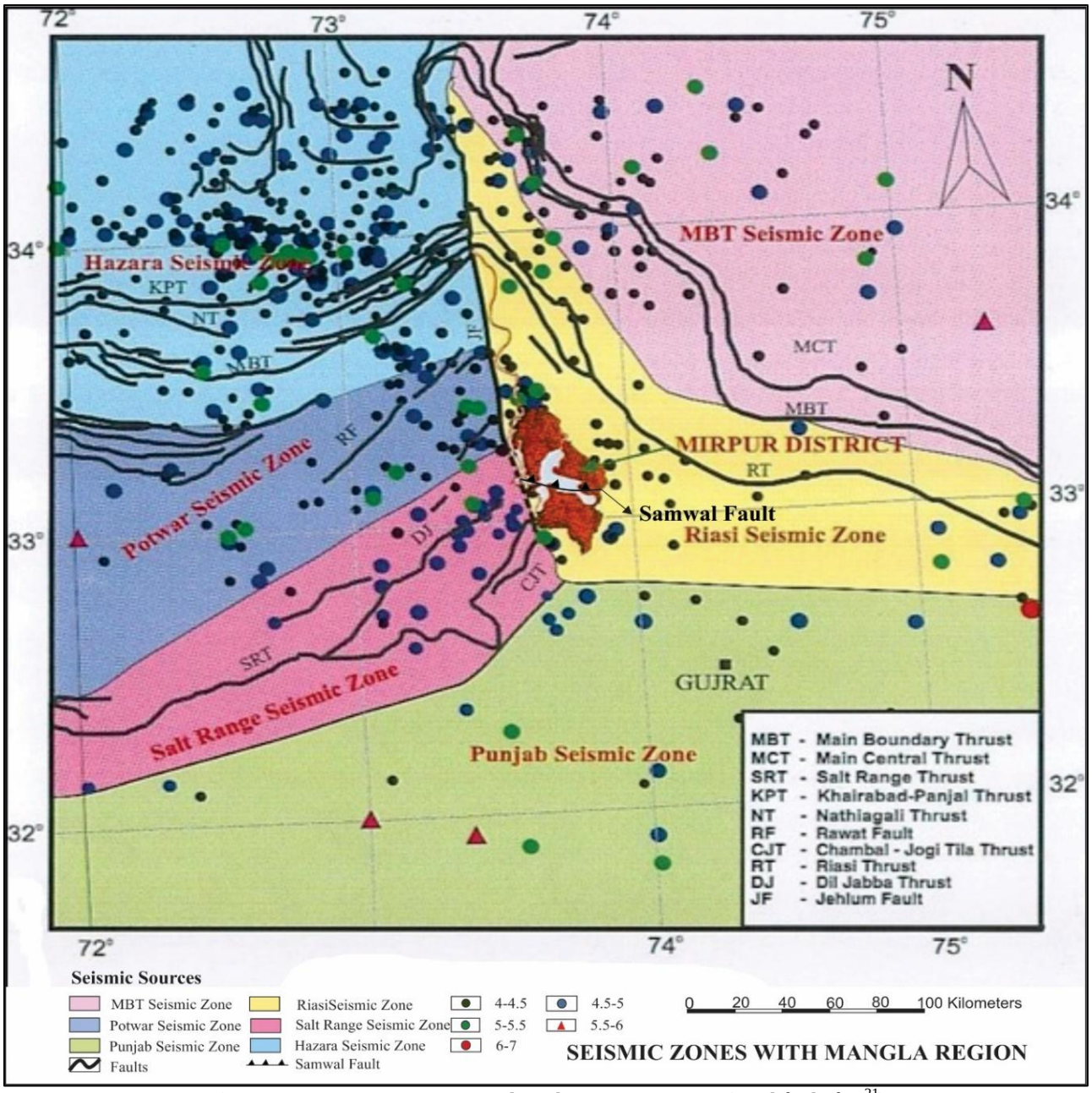

Figure-4: Seismic zones surrounding the Mirpur District (Modified after[21]).

Faulting characteristics and surface deformation: The SF, a major NW-SE trending structure in the study area is likely the source of ME 2019. It lies approximately 5km south of the Mirpur City and forming a major topographic front in the area (Figure-5 and Figure-6). Field observations and geological studies suggested that the SF is a high angle dip-slip fault ranging from 45º to 85º NE. It emplaces the Dhok Pathan Formation of Miocene over the lower part of Soan Formation at places. At the eastern end of SF, the rocks were overturned and forming an overturned syncline with in the upper part of Soan Formation in the hanging wall, whereas, rocks were dipping normally (NE) at the western portion. The So an formation (600 m) and Recent deposits lies in the footwall of SF (Figure-1), which includes sheared rock with brittle deformation and drag folds. The brittle deformation includes breccias and gouge. The drag folds show sense of shear along fault that present at the base of hanging wall block show southwest directed thrusting along SF. The longitudinal extent (exposed) of SF is about 20 km, starting from Jari Kass in the east to the Mangla Colony in the west (Figure-6).

The identification of structural geometries and their kinematics portray an important aspect for evaluating structural development of any region. The surface manifestation is the first indication that signifies the structural changes[8]. The existence of manifestations, correlated with their faults beneath the surface. Faultzone was delineated based on morphological peculiarities and straightness on the satellite imagery. In this research, study of remote sensing for fault analysis has been done by utilizing Landsat-8 imagery[26] and Digital Elevation Models[27] that were processed digitally. The results of image analysis indicate there is one morphological straightness dominant direction of NW-SE (Figure-6).

A major fault trace was exposed near the Samwal Village. This rupture lies on the faulted contact between Dhok Pathan and Soan formations (Figure-7). However, a crack opening was calculated 01 m at maximum point, whereas, the evidences of slip sense (i.e. slicken slides) were not clear because of heavy rainfall occurred after the main shock. Many other small-scale cracks and opening were encountered along the fault line with frequent landslide phenomena (Figure-8).

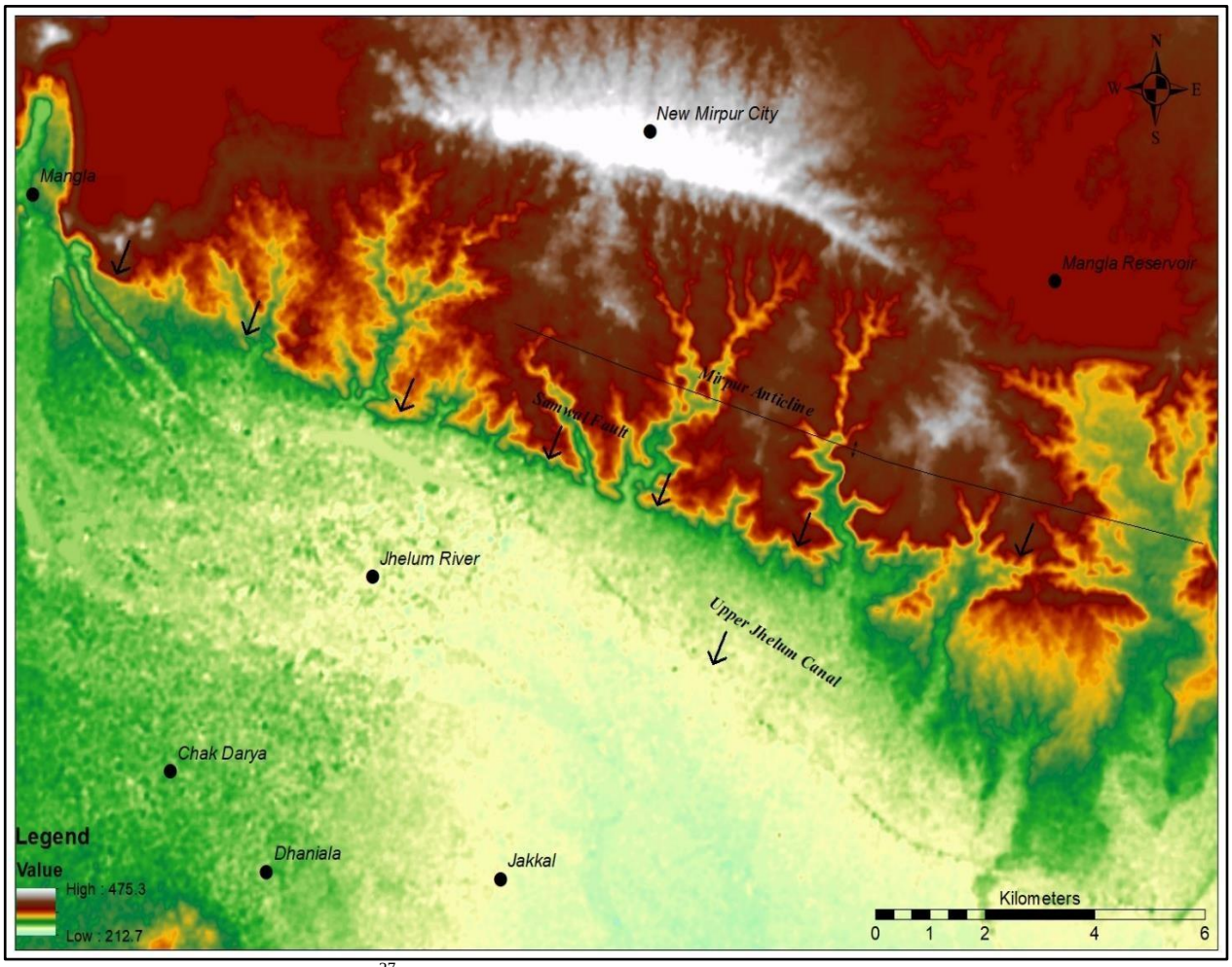

Figure-5: Digital elevation model (DEM)[27], illustrating major topographic front in the study area delineating the Samwal Fault (shown by arrows).

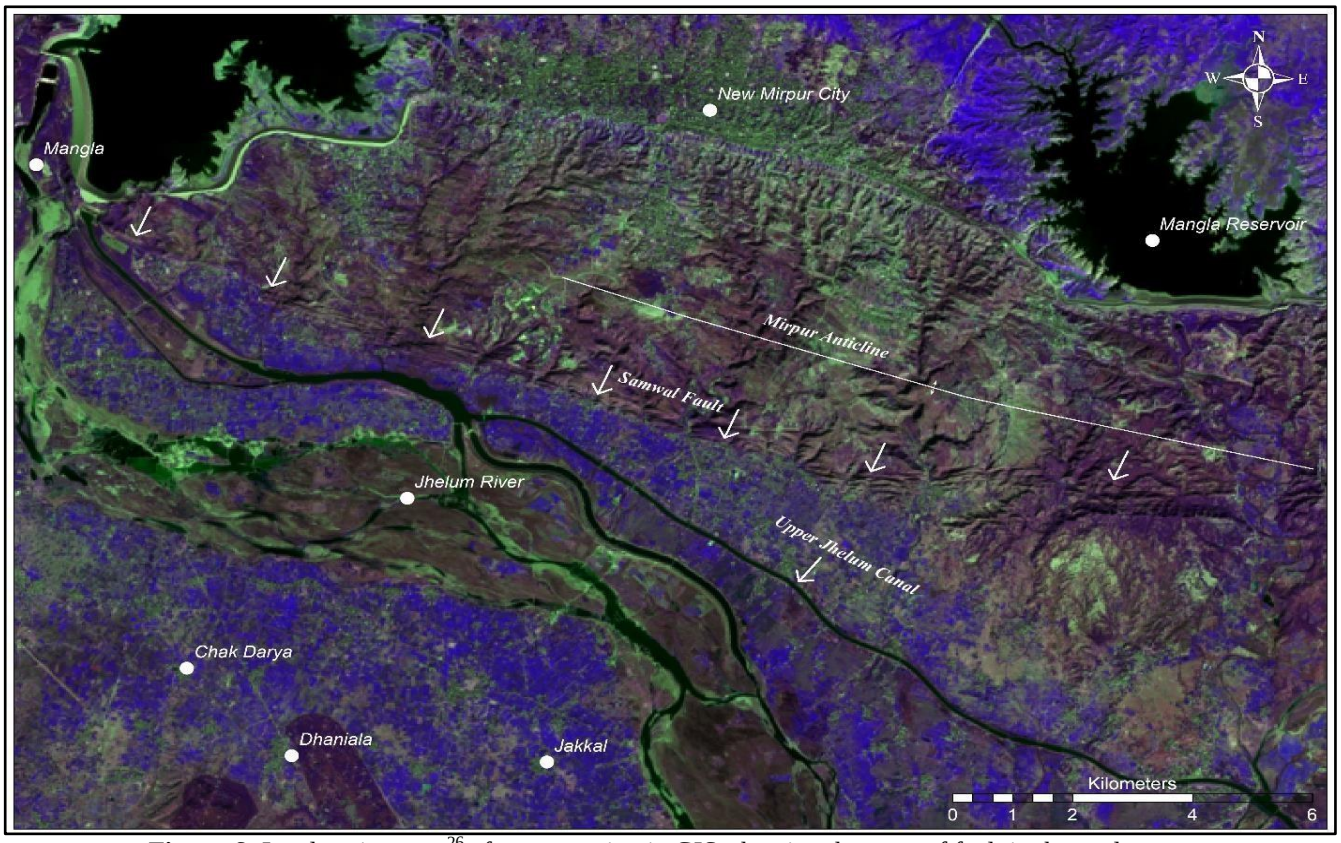

Figure-6: Lands at imagery[26] after processing in GIS, showing the trace of fault in the study area.

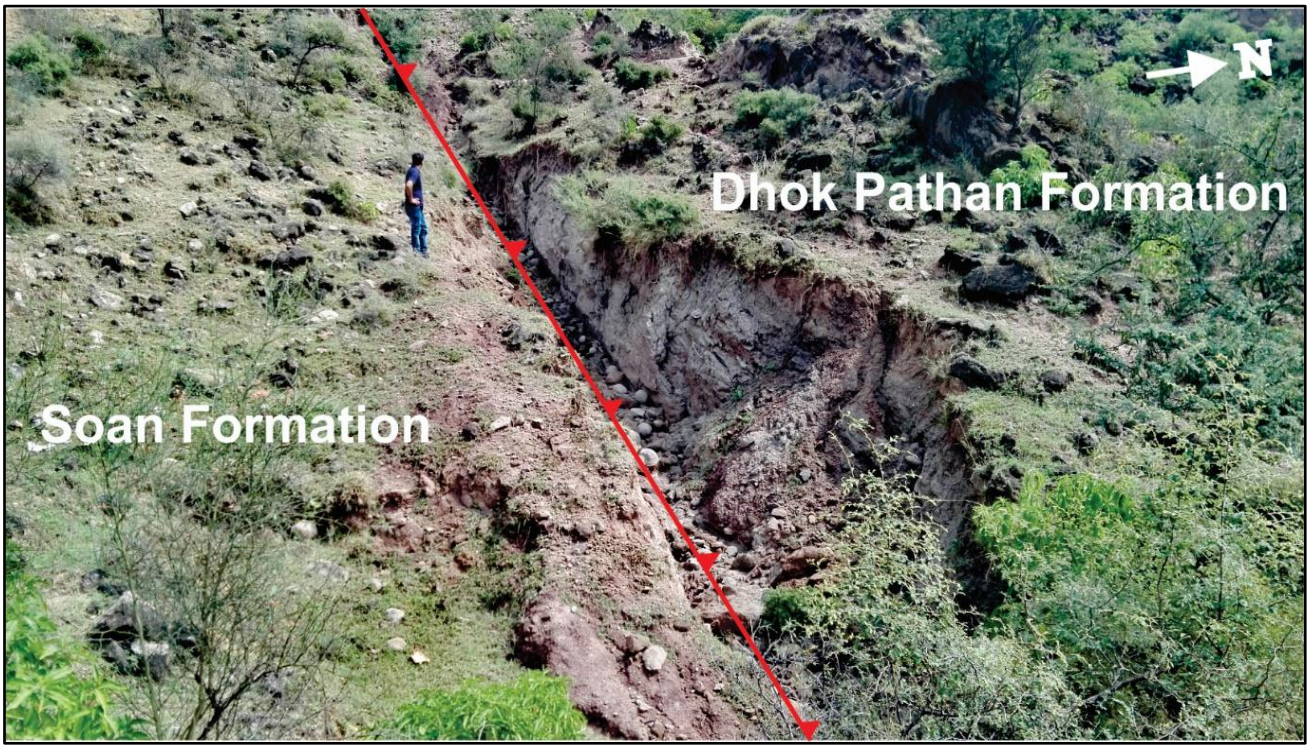

Figure-7: Field photograph showing the faulted contact between Dhok Pathan and Soan formations near Samwal Village, while this red line indicating the possible fault plane along which ME of 2019 occurred.

Geo-Technical field observations

Infrastructure damaged: The earthquake has caused a number of human fatalities due to crumbling of buildings, because they are lacking of proper foundations and selection of poor construction materials i.e. aggregate, cement, sand, water, steel, and admixture or their proper combination (concrete-mix-design). As a consequence of this, buildings did not withstand against the lateral earthquake forces. Most of the earthquake-prone developing countries including Pakistan are facing such sort of serious problems. These problems are becoming diverse because of population expansion, financial insecurities, insufficient stock of wood, steel, cementing material, and poor knowledge of earthquake characteristics etc.

Following aspects were observed in the study area, which caused the significant damages: i. Defects in foundation stability, selection of construction materials proportion (concrete- mix-design), and to some extent structural configuration, reported including asymmetrical geometry, both in plan and elevation. In addition to this, cracks and fissures were turned up on buildings wall, floor and on the roof are the main factors responsible for damages. ii. The failure observed in the foundation is mainly initiated as a result of liquefaction induced by lateral spreading of loose soil, ground water pockets or soil settling due to ground shaking. iii. The poor understandings of reliability in structural components are one of the major reasons of damage. Greater thickness of the roof's slab exceeding the standard specifications acted as a catalyst to fall down during the adverse event of earthquake. iv. Faulty construction materials with inadequate skilled labor in structure building, etc. resulted in infrastructure failure.

Infrastructures built on unconsolidated materials are quite disturbed near the epicenter of earthquake. Failure of buildings are owing to poor selection of construction materials and ignoring foundation's importance to withstand superstructure. Infrastructure is more disturbed nearby the proximity of the water bodies (Figure-9, Figure-10).

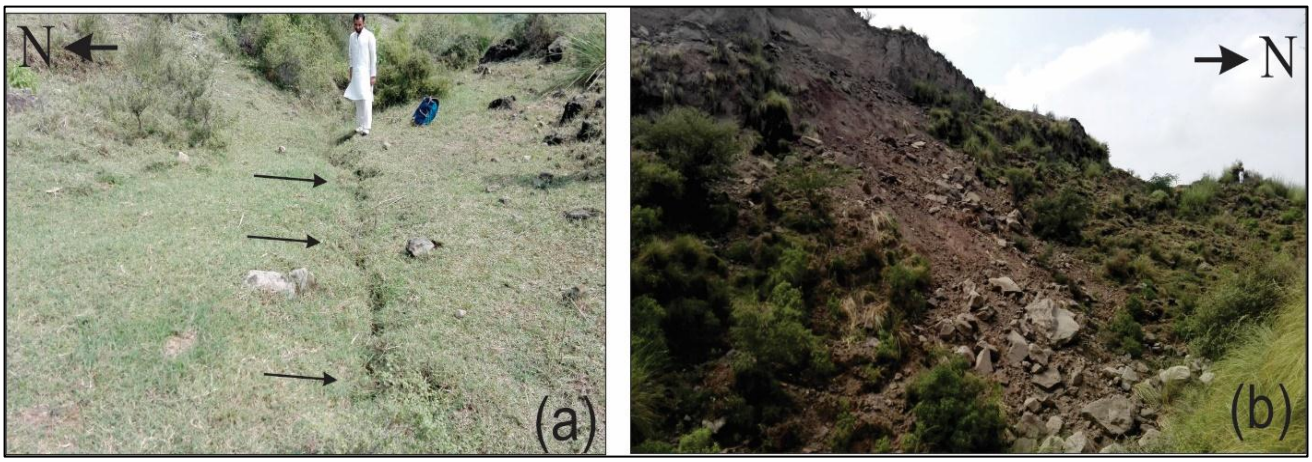

Figure-8: A field photograph (a) illustrating a minor rupture of about 6" width associated with the Samwal Fault while (b) showing land sliding along the fault line in the study area.

Figure-9: Field photographs (a) and (b) showing a collapsed house due to ground shaking at Jatlan and Samwal villages, respectively.

Figure-10: Field photographs showing (a) the liquefaction induced lateral spreading along the embankment of UJC (b) cracks in abutment of Dab Bridge (c) vehicle damaged by the collapse of boundary wall (g) Manda Bridge collapse (e) the Bani Bridge after earthquake (f) the displacement of abutment of Sang Bridge.

Effects on groundwater conditions: The earthquakes with strong ground shaking effects the hydrogeologic conditions of the region, especially in the proximity to earthquake epicenter[10]. As a result of door-to-door survey, reported by the affected people that the maximum number of subsurface wells produces muddy water or becomes dry, whereas, at some places it began pouring near the fault line (i.e., Samwal Sharif, Mirpur due to ground motion). Furthermore, the earth's movement break down the subsurface pipelines and other hydrological supply lines beneath the ground.

In this regard, sometimes new springs are originated but, not observed/reported during our preliminary study of the earthquake struck areas. Likewise, decrease in spring discharge was reported by locals. Bringing forward, the current scenario of aftermath, damages to the existing wells were observed.

Discussion: In this study, overall view of geology, tectonics, and seismicity of 2019 ME was depicted, whereas, structural deteriorations and foundations failures related to geotechnical engineering with probable adverse impacts on buildings were also described. It is generally accepted that the earthquake energy released along new or existing fault gives the idea of earthquake mechanism[8,10]. The preliminary field investigation suggest that the maximum deformation was concentrated along the fault zone, in the form of surface trace. The seismic intensity of ME demonstrate that the ground vibration near epicenter have caused wide spread infrastructure damages. The peak ground acceleration for ME was inferred in the range of 0.35g within limits of <0.0017 to >1.24g. Seismic deformation associated with this event indicate that slope failures were induced due to ground shaking overcoming the shear strength of material (cobble-soil). Moreover, the unconsolidated superficial deposits were spread out horizontally in most of the affected area, which caused considerable damages in Mirpur District. While, the deterioration in many bridges suggest that the durability of bridges with substantial structural architect can't sustain for longer period under strong seismic shaking. The mass movement in the form of soil failures were detected in the proximity of major topographic front in the south of Mirpur

City. However, at various places some failures are linked to surface rupture of the triggering fault i.e. Samwal Fault. This study suggests that the observed deformation requires further geophysical and structural investigation to monitor the future trend of seismicity in Mirpur region.

Conclusion

The earthquake of 5.6 M_w occurred at the fold axis of HKS, represented by the Jhelum Re-entrant south of the Kohistan Island Arc. The preliminary field observations for fault analysis, reveals that the surface rupture of <1m follows the main seismogenic fault trace i.e. Samwal Fault. The Landsat image interpretation conclude that the morphological peculiarities and straightness on satellite data confirms the fault related tectonic landform. Similarly, the major topographic front observed in DEM suggest the presence of this fault in the study area. The field investigation in earthquake epicentral area demonstrate that the intensity of ground motion has induced sporadic slope failures and liquefication in unconsolidated alluvial layers. The phenomena of liquefaction have induced lateral spreading along the Upper Jhelum Canal (unlined), resulting in destruction major roads, several bridges, and other infrastructure. The anticipated human causalities were associated with crumbling of faulty constructed buildings, which couldn't resist during sudden ground shaking. The maximum damages in infrastructure were seen where foundation's geology is comprised of unconsolidated materials -or- poor selection of construction materials/ their combination (aggregate, cement, steel bars, sand, water and admixture). The field study indicates that the non-compliance of building codes and lack of geologic/geotechnical investigation before construction has prompted the severe damages to civil infrastructure during the earthquake event in the study area.

Acknowledgements

The sincere gratitude of authors goes to the Director General, GSP (Ministry of Energy) for his keen interest to dispatch an advance team to Mirpur, Jammu & Kashmir and cooperation during the various phases of compilation of report. The manuscript benefited from the critical reading, valuable suggestions for improvement and imparting professional knowledge pertaining to geological framework by Dr. Rubina Firdous (Director Incharge, Northern Area Directorate, Islamabad).

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