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Geomorphological Processes and Landforms in the Indus Valley Between Hemiya to Khalsi in Leh District, Ladakh India

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Abstract: ***The current study attempts to identify and describe the geomorphological processes and landforms in the Indus Valley, from Hemiya to Khalsi villages in Leh, Ladakh. The study area under investigation was mapped through a field Survey as well as by using Google Earth images, LANDSAT data, and ASTER DEM data. Mass-wasting, fluvial, glacial, and gravitational processes are recognized as playing a significant role in shaping the landscape of the study area. Twenty-one different resultant landforms of glacial, fluvial, and gravitational origin have been identified and mapped. These processes and landforms are well distributed across 163 long stretches along the northern and southern slopes, with distinct geological structures exposed in some places. The geomorphological map prepared based on field survey, field observations, and satellite data serves the purpose of the study as it gives a detailed and synoptic picture of the current and past geological processes, paleo-landforms, and the vulnerable spots of geological risk and geomorphic hazards.***

Keywords: Indus valley, Alluvial fan, Braided channel, Glacial valley, Debris flow, Scree

1. Introduction

Earth landforms have their own distinct physical shape, size, and composition and are the result of certain geomorphic processes and agents (Wei Luo et al., 2004). Geomorphic processes comprise all those physical and chemical changes caused by internal and external forces that impact the earth's surface and are involved in the development of landforms, while the geomorphic agent (fluvial, glacial, wind, and waves) is a mobile medium that erodes, transports, and deposits the material on the earth's surface. (Kennedy, 2003). The Himalayas of northern India comprise several mountain ranges, including the Trans-Himalaya, the Greater Himalayas, the Lesser Himalayas, and the Siwalik's. The Quaternary period has seen strong orogenic movements in the Himalaya. The Himalayan Mountain ranges are the result of the ongoing collision between the Eurasian and the Indian plates, which began 50 million years ago. Other processes that contribute to the formation of the Himalayas include glacial and related activities, the huge rivers that drain the Himalayas, mass movement, weathering, and aeolian processes. (Owen, 2014). Ladakh, situated in the Trans-Himalaya region of northern India, is known for its stunning mountain landscapes and cold desert environment. The region is tectonically active due to its location along the Indus Suture Zone (ISZ), which signifies the collision edge between the Indian and Eurasian plates (Thakur & Mishra, 1984). This suture zone, is a fault line where these huge plates have connected, resulting in ongoing seismic activity, such as earthquakes and landslides (Searle et al., 1988). From a geographical perspective, the region is significant due to its unique physiography and its location in one of the highest altitude habitable regions in the world. Previous works in this region are mainly based on geological structure, tectonostratigraphic, paleo landscape features, and Quaternary deposits. Ladakh has vast Quaternary deposits, of fluvial, paleo- lacustrine, glacial and aeolian origin. (Namga & Nayak, 2024b). Research works in the study area are mainly focused on landforms such as paleolake (Nag et al., 2016; Mujtaba et al., 2017; Nag & Phartiyal, 2016; Kotlia et al., 1998; Sharma & Chaudhri, 2021) Fluvio- lacustrine deposit's (Kotlia et al., 1997; Mathur & Kotlia, 1999; Phartiyal et al., 2004) Sand ramps (Kumar et al., 2016) Fluvial terraces (Blöthe et al., 2014; Kumar & Srivastava, 2017). According to our extensive literature survey to date, there has been no systematic and organized description and analysis of landforms in this region. A detailed description and analysis of landforms and processes operating in this region are required to understand how these landforms formed and what processes affect them. This allows us to judge better where to build structures and how these landforms will evolve, and moreover, will help in mitigating various hazards. The present study attempts to identify, describe, and map the various geomorphic processes and their resultant landforms in the Indus valley between Hemiya to Khalsi village, Leh, Ladakh.

2. Study Area

The total area under consideration is 4659 sq. km, with a total length of 163 km in the Indus Valley between Hemiya (33.270 N Latitude and 78.42º E longitude) to Khalsi villages (34.32º N latitude, 76.87º E longitude) in Leh District, Ladakh, India. The Indus Valley lies between two mountain ranges the Ladakh batholith in the north and the Zanskar Tethys Himalayan in the south, and altitudes ranging between 3000 m to 6500 m. The Indus River, which is the backbone of Ladakh, flows in a southeast to northwest direction in the Indus Valley along the Indus Suture Zone. The annual average rainfall in Leh is less than 100 mm, and more than 50 percent is in the form of snow. The temperature in Leh may vary from 34.8 c during summer and drops to as low as -27.9º c in winter, and the annual daily temperature is between 7 to 8º c (Chevuturi et al; 2018).

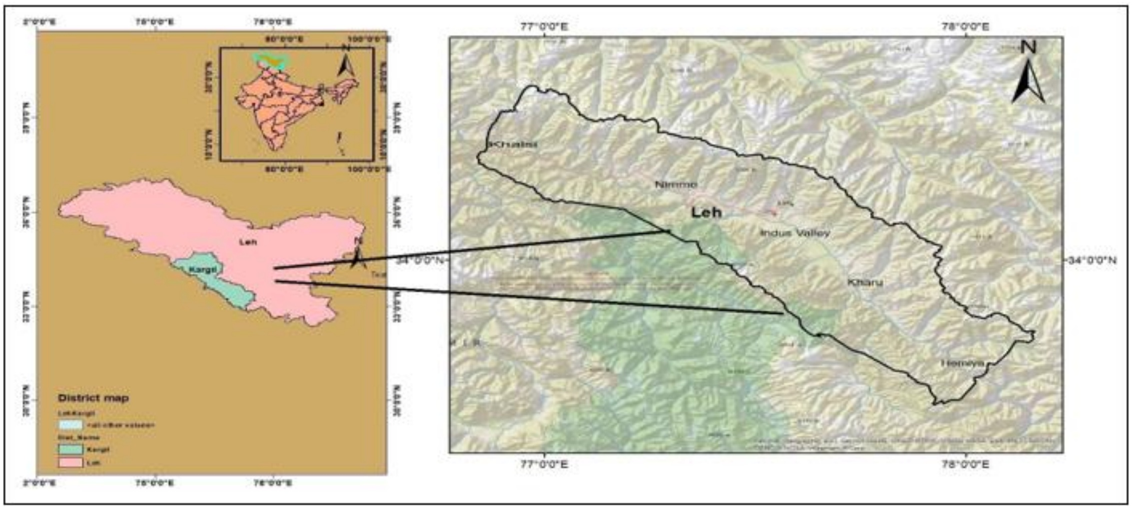


Figure 1: Location of the study area.

3. Methodology

Before preparing the geomorphological map, a base map of the study area was prepared. The geomorphological landforms of the area, spanning a 163 km long stretch from Hemiya to Khalsi, were mapped through a field Survey as well as by using Google Earth images, Landsat data, and ASTER DEM data. The ASTER DEM with 30 m resolution, high-resolution Google Earth images, and Landsat-ETM+ 30 m resolution imagery were all obtained and digitally processes. The geomorphic features were interpreted using typical visual interpretation factors such as tone, texture, colour, pattern, shape, and association. The features of the landform were physically verified using ground checks after visual interpretation to confirm the accuracy of the geomorphological map, which was created using satellite images in open GIS software. A longitudinal valley profile was created using Google Earth to determine the channel gradient between Hemiya and Khalsi, while the cross-sectional profile of the river valley was generated using the ASTER DEM (30-meter resolution) in ArcGIS software.

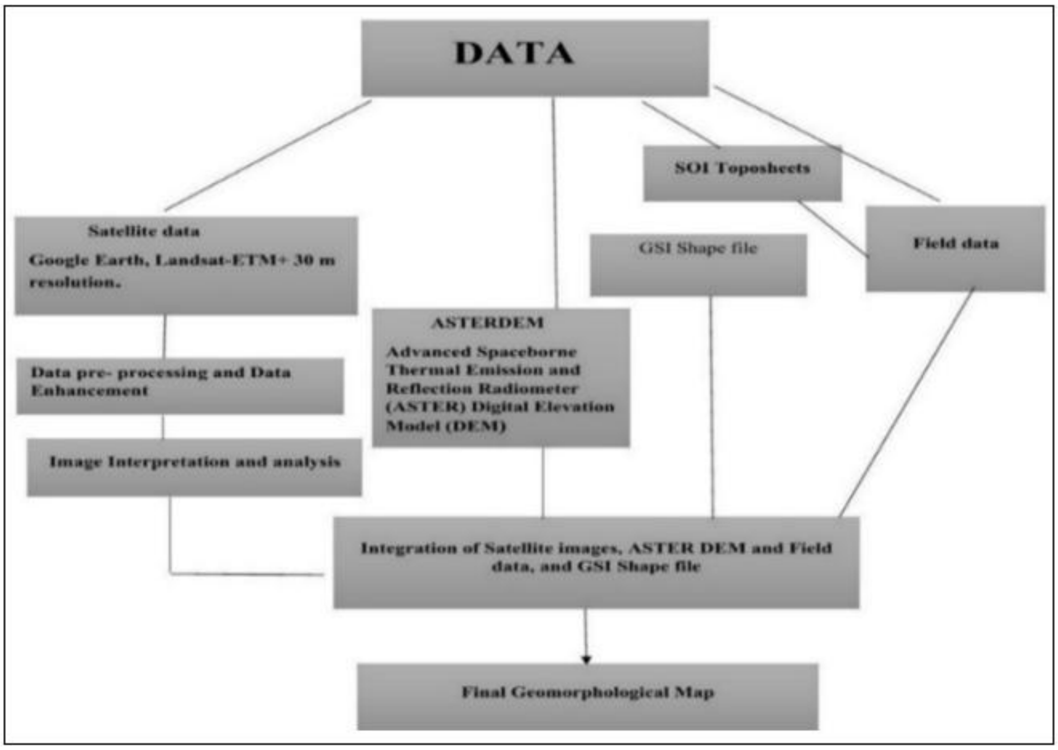


Figure 2: Flow chart for geomorphological map

4. Result and Discussion

The geomorphological landscapes between Hemiya to Khalsi in Ladakh is a spectacular showcase of processes shaped by a cold desert environment, tectonics, and the mighty Indus River. This area is located within the Indus Suture Zone (ISZ), a crucial geological border where the Eurasian and Indian plates met. This collision has provided the fundamental framework for the landscape, which is then sculpted by a combination of fluvial (river), glacial, mass wasting and aeolian (wind) processes.

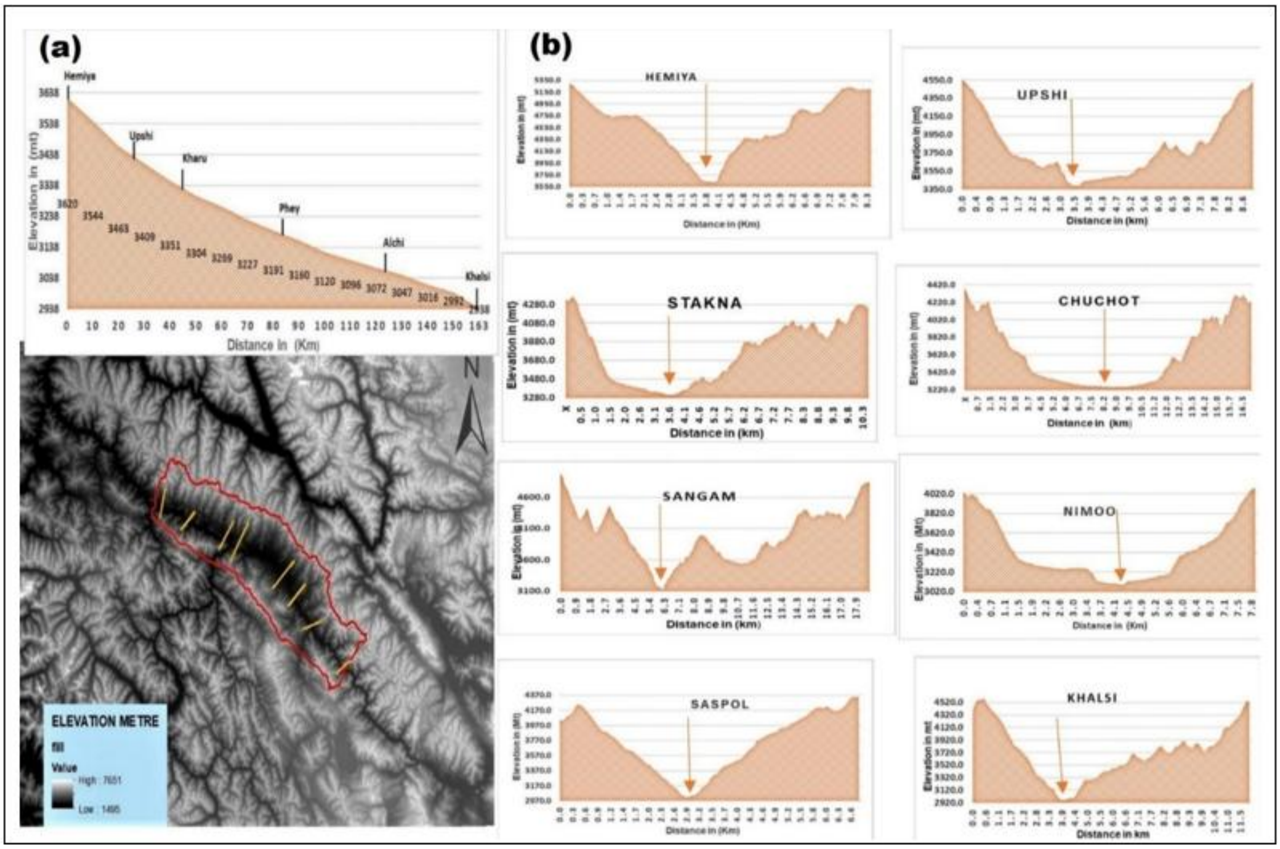
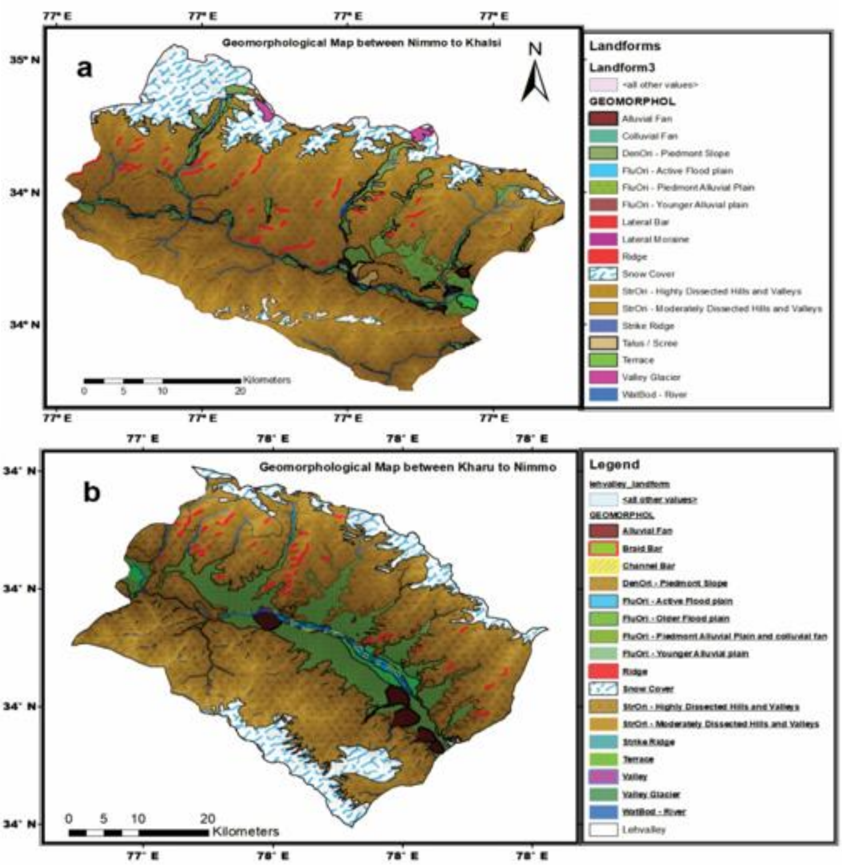


Figure 3: Geomorphological landforms map in the Indus Valley between Hemiya to Khalsi.



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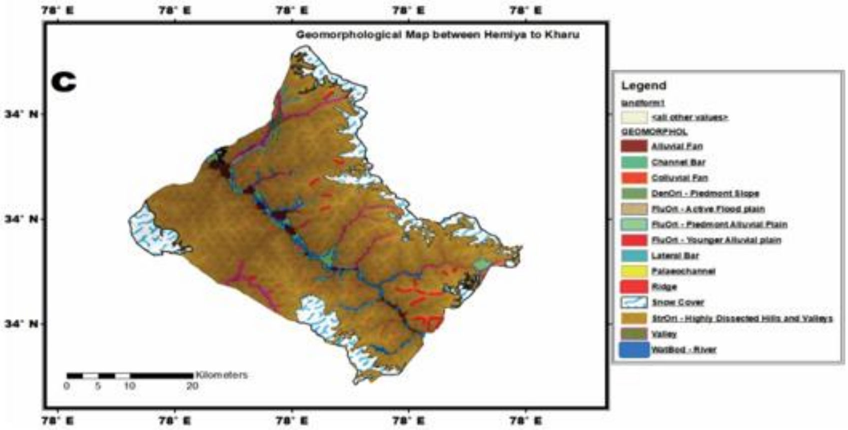

Figure 4: (a) Longitudinal profile of the Indus River valley between Hemiya to Khalsi generated using Google earth b) Eight Cross-sectional River valley profiles of the Indus valley between Hemiya to Khalsi using ASTER DEM

Landforms description

Fluvial processes and their associated

Landforms:
Based on the channel width, channel pattern, and the long stretch of the river valley, the area is divided into three segments. Segment 1 from Hemiya to Kharu, segment 2 from Kharu to Nimmo, and segment 3 from Nimmo to Khalsi.

Segment 1 Hemiya to Kharu: One of the most obvious landforms created by streams is the channel in which they flow. The river width from Hemiya to Kharu ranges between 47m to 124m. At Hemiya, it is 47.5m; at Shara, 72.56 m; at Upshi, 121.4m; and near Kharu, 123.3 m. The upper river course from Hemiya to Upshi, owing to its narrow valley and high channel gradient, deepened the stream channel by removing material from the riverbed. The river cross-sectional profile shows that at Hemiya, the valley and channel are narrow and deep, resulting from significant vertical erosion (Fig. 3b). From Upshi, the channel gradually broadens towards Kharu, and vertical erosion is slowly replaced with lateral erosion. Downstream from Hemiya, the channel is bordered on either side by steeply sloping alluvial fans that emerge from the Zanskar range in the south, Amphitheatres' valleys, in the north, and valley-fill terraces. Sixteen asymmetrical small alluvial fans and Amphitheatre valleys were identified in this segment. Fluvial terraces with one to two levels have been observed on the side of the mainstream. They represent the level of the older floodplains.

Segment 2 From Kharu to Nimmo: From Kharu, the river loses its gradient, and the narrow valley is replaced by an open, wider valley. The river exhibits a sudden drop in its gradient in the wider, open valley, from 7.2 to 1.8 m/km (Kumar & Srivastava, 2018). The water volume increases, and the river's slope gradient decreases due to the wide-open valley, resulting in lateral erosion (Fig. 4(b). Downstream from Stakna, the channel pattern changes from incised meandering to braided channels. Braided channels occur in river courses, forming a mixture of distinct channel bars and river islands of varying dimensions. The braided channel in the river course at Chuchot village is 650 m wide at an altitude of 3264 m, while at Spituk it is 421 m wide and at an altitude of 3197 m. Wide Indus valley basin between the villages of Stakna in the southeast and Phey in the northwest, where the river Indus flows over a large flood plain covering a length of 26.5 km at an altitude between 3282 and 3100 m. Large Fans emerge from the left and right banks of the Indus River in the form of alluvial fans and Amphitheatre valleys, respectively. From Phey village, the river flows through a narrow gorge, and the broad braided channel valley now transforms into a V-shaped valley. Fig. 4 (d) shows the incised V-shaped valley near the Sangam (river confluence of Indus and Zanskar) at Nimmo. Along the riverside, seven terraces have been identified in this segment, three of them are valley-fill terraces, one toe-cut, and two strath terraces at Karu, Stakna, Spituk, Phey, and Nimmo. Figure 4(a) displays the river terraces at Kharu Nimmo and Igoo, respectively.

Segment 3 From Nimmo to Khalsi: Downstream from Nimmo the river width is gradually narrowing Towards Khalsi. The width of the river at Nimmo is 133.32m, at Saspol 78.32 m, and at Khalasi 66.25 m. Every tributary comes in the Indus River constructed an alluvial fan out into the main valley. Several Fluvial terraces and patches of fluvial-lacustrine are seen on the side of the mainstream channel and in the valley. The river channel is deepened by removing material from the stream bed because of the narrow valley and high channel gradient. In this segment, Channel bars are rarely seen on the inside bend of a stream.

Figure 5: Field Photograph displays various Fluvial landforms in the study area a) cut-infill, strath, and two-level cut terraces **b)** Lateral erosion c) active flood plain d) V-shaped valley e) Alluvial fan f) mid sand bar g) fluvial-lacustrine deposits.

Table 1: Classification of landforms according to the geomorphological process type.

S. No	Processes type	Land Forms (Erosional and Depositional)
1)	Fluvial	River Terraces, Channel Bar, Braided Channel, Lateral bar Alluvial Fan, Bajada, Fluvial Lacustrine, Flood Plain, V Shape Valley, George
2	Glacial	Cirques, Glacier Valleys, Arêtes, Horn, Lateral and terminal moraines, and Striation
3)	Gravitational	Scree, Talus, Rockfall
4)	Mass movement	Debris flow and Landslides

Glacial processes and associated Landforms:

Five glacial advances were detected and dated in the Ladakh range by (Owen et al; 2006) and for the Zanskar Range, three major glacier stages and a minor advance have been identified (Taylor and Mitchell, 2000). The relative dryness with the cold arid climate and high elevation of both the Ladakh range and Zanskar range several small glaciers are still present.

i) Cirque: Cirques are the prominent glacial landforms in the Ladakh and Zanskar ranges. They are bowl-shaped depressions with steep headwalls and a relatively flat base, carved by the erosive power of glaciers. In the Zanskar range, they are observed at altitudes between 5,400 and 6,000 meters, and in the Ladakh range, they are observed at altitudes above 4,500 meters. Figure 5 (d) displays the cirque landform of the Stok glacier near the summit facing toward the north. The width of the cirque landforms in the Zanskar range varies between 600 m and 1500 m, whereas in the Ladakh range, it ranges between 350 m and 130m.

Aretes and horns: The formation of valleys and cirques, caused by glacial erosion, significantly modifies the natural shape of mountainous areas. These glacial excavations continue to expand, aided by mechanical disintegration, which leads to the creation of some peculiar forms, such as an Arête and a horn. Several Arête and horns are identified in the study area. Fig. 5(c) Google satellite image displays a series of arêtes and horns on the Stok glacier of the Zanskar range.

Lateral and terminal Moraines: From the edge of the glacier onto the valley walls long-Elongated ridges of lateral moraines debris composites of loose sediments and rock, debris are deposited on both ranges. These elongated ridges of debris range between 300m to 1800m in length. A series of parallel lateral moraines below the cirque glacier in the Stok glacier valleys is shown in fig 5(c). Moreover, several crescent-shaped ridges-like accumulations of terminal moraines debris with widths ranging between 200 to 500m are deposited on both Ladakh and Zanskar ranges.

Glacial valley: A valley that has been sculpted and altered by the erosive action of a moving glacier is called a glacial valley, also referred to as a glacial trough (Lone, 2016). Glacial valleys are mainly found in the Ladakh range, related to the Zanskar range. In the Ladakh range, the valleys are Long, narrow, and steep-sided, whereas in the Zanskar range, the valley floors are wide and short in length, with low-height, steep-sided walls. The reason for the short valleys in the Zanskar range may be due to the steep slopes compared to those in the Ladakh range. In their lower reaches, the Glacier valleys are transformed into fluvial valleys. The glacier melts form water streams (locally called Tokpo) (Fig. 5(b)), which flow toward the Indus River after irrigating the agricultural fields and meeting the water requirements of the settlement.

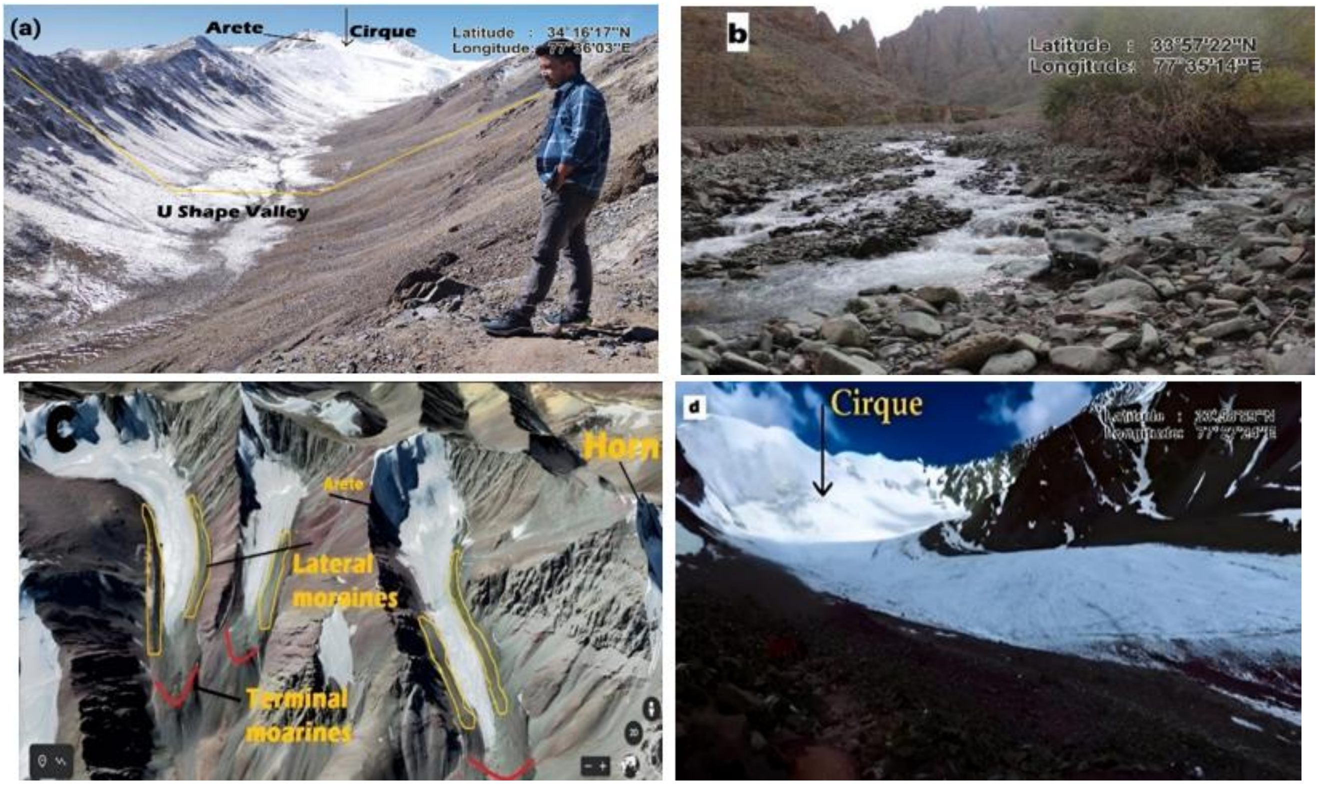

Figure 6: Field evidence and satellite images show the different glacial landforms in the study region. a) U-shaped valley, cirque, and talus cone in Ladakh range near Khardong la b) Glacial stream in the Matho valley c) Google image shows the Horn, arete, lateral and terminal moraines of Stok Glacier d) Cirque glacier of Stok glacier near the summit.

Gravity and associated Landforms

Mass movement:
The Himalayas in Northern India is characterized by widespread mass movement, ranging from minor soil creep to massive landslides that deposit more than a million m cubes of debris (Owen 2014). In the Ladakh mountain range, weathering of the hillslopes has created loose regolith and sediment that is prone to landslides.

Rockfall: Mechanical weathering, catastrophic climatic events, and undercut slopes by streams, as well as road construction, are the major causes of rockfall in the study area. Mechanical weathering on the Ladakh batholith and Zanskar metasediments has resulted in the formation of unconsolidated clasts, which make up the hill slopes more sensitive to mass wasting (Sant et al., 2011). Rockfalls in the study area are primarily associated with the sepration of rocks from a rocky erosional scarp; however, in most cases, the rocks originate from previous deposits, such as tills, alluvial fans, or terraces. Rockfall in areas below snow cover is mainly associated with mechanical weathering, and these rockfalls have been creating a talus cone on the foothills. Furthermore, many rockfalls in the study areas are associated with road construction. Fig. 6(b) displays a recent rockfall on the Leh-Srinagar national highway near Ule tokpo in the Indus Valley. A large block of rock that had separated from the undercut hill slope blocked the Leh -Srinagar National Highway.

Debris Flow: These are a mixture of water, mud, and rock that can transport big stones and other debris. In the tributary valleys of Ladakh, this is now common during the rainy season and frequently brought on by heavy, short-term rainfall events, such as cloudbursts, which are occurring more frequently. The most devastating cloud burst event in Leh on 6 August 2010 resulted in intense rainfall that produced a series of Mud and Debris flows in a very short period. That incident had a significant impact on the Leh main valley and Saboo (Sharma et al., 2022). Debris flows were clearly passing the settlements and existing infrastructure in this area. In the Arzu valley, a recent debris mixture of large boulders, sand, gravel, and mud occurred due to heavy rainfall on the unconsolidated clast slope of the Ladakh batholith (Fig. 6c). During the field survey, two different locations of mud flows were also identified in the Matho valley. The first one is on the unconsolidated clasts slope on the foothill of the Zanskar range, and the other is along the glacier streams. Debris flow on the Zanskar range creates a gulley or narrow channel on the slope before depositing it in the valley (Fig. 6a). This debris resulted from intense rainfall on the steep slopes, primarily consisting of a composite of sand, gravel, and mud.

Scree: Scree deposits have been identified on both hill slopes and throughout the valley. These are formed by the accumulation of rock debris that falls from weathered and fractured bedrock walls and is deposited at the foothills of slopes. The soil layer of a scree slope is primarily gravelly and comes in a range of coarser, bigger, and finer sizes. On top of this soil layer are massive boulders and cobbles. Fig. 6(c) 1 shows the scree slope near Saspol village on the right bank of the River Indus, and the second one shows the scree slope on the foothills of the Zanskar range near Khalsi

Figure 7: (a) Picture displays the debris deposit in the upper Matho valley near the Glacial stream. (b) Recent rock falls on the Leh-Srinagar national highway near the Ulletokpo in the Indus valley (c) (1) Scree deposits on the right bank of the Indus River near Saspol village and on the foothill of the Zanskar range near Khalsi (c) a large boulder along with a mixture of sand, gravel, and mudflow in the Arzu valley

5. Conclusion

The geomorphological map, prepared from a detailed field survey and using Google Earth images, LANDSAT data, and ASTER DEM data, demonstrates the various landforms and processes responsible for shaping the Landscapes in the Indus Valley between Hemiya and Khalsi villages of Leh District, Ladakh, India. Mass-wasting, fluvial, glacial, and gravitational processes are recognised as playing a major role in shaping the landscape of the study area. Twenty-one different types of landforms, related to glacial, fluvial, and gravitational origins, are well-distributed along 163 long stretches of the northern and southern slopes, with distinct geological structures exposed in some places. The geomorphological map, prepared based on field surveys, field observations, and satellite data, serves the purpose of the study by providing a detailed and synoptic picture of current and past geological processes, paleo-landforms, and vulnerable spots of geological risk and geomorphic hazards. Furthermore, it will provide valuable insights and basic information to researchers, planners, governmental and non-governmental agencies, as well as geographers.

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