Chapter 3

Geomorphology

If you want to shine like a sun. First burn like a sun.

- Dr. A.P.J. Abdul Kalam

CHAPTER 3 GEOMORPHOLOGY

3.1 Geomorphology

The valley and terrace configuration of any river is a result of phases of aggradation and incision that a particular stretch of channel has undergone. The thickness of aggraded sequences and underlying bedrock potentially indicate towards the residence time of the channel and accommodation space, sediment and water availability, and tectono-climate conditions. River will aggrade and make thick valley fills when sediment supply is higher than its carrying capacity and will incise as soon as the supply diminishes and water increases relatively. During a terrain uplift, the river will incise while cutting through the sediment fill and the underlying bedrock. The thickness of the underlying bedrock cut often corresponds to the amount of uplift (Srivastava and Misra, 2008). Based on the thickness of fluvial cover and height of bedrock, the terrace configuration has been divided into three categories that imply towards the climatic and tectonic state of the area. According to Starkel (2003), these divisions are, (1) a thick alluvial cover over thin bedrock bench suggests that the area is tectonically stable and has high accommodation space to aggrade the fill terrace and the channel had enough residence time, (2) the moderate tectonic activities create almost equal thickness of alluvial and bedrock strath, and (3) The tectonically active regions are distinguished by thin alluvial cover over the thick bedrock strath. The river flowing through these intensely active regions experiences frequent uplifts and therefore lesser residence time to aggrade and the unremitting incision along the river develops a sequence of strath terraces. The study of these terraces thus has potential to unravel the history of the climatic driven aggradation and tectonic uplift driven incision. The longitudinal profile has potential to display these regional topographical changes. The morphometric indices such as stream length gradient (SL) index, is also sensitive to sudden drop in the river's gradient (knick points). This study provided us an opportunity to understand the aggradation and incision along the longitudinal river profile of the Indus River during the Late Pleistocene to Holocene.

3.2 River valley profile and geomorphic index

The channel gradient profile, is influenced by the imbalance between bedrock uplift and channel incision. The variations in bedrock lithology, sediment flux, precipitation etc, can influence the spatial distribution of bedrock incision and evolutionary history of longitudinal river profile (Kirby et al., 2003). The quantitative analysis of channel gradient, landscape and characterization of size, slope and elevation measures the influence of exo- and endogenic processes.

The Indus River flows northwesterly in a valley along the ITSZ and that represents the first order geomorphological feature of Ladakh Himalaya. It originates from Mount Kailas, 5182 m above sea level (asl) and drains through Karakoram zone, Ladakh Batholith and tectonic units of ITSZ and empties into Arabian Sea via plains of Punjab (Pakistan). The Indus valley has a catchment area of 1×10^6 km^2, which positioned at 12th rank in the list of world largest rivers. A ~ 350 km stretch of Indus River that cuts through Ladakh, from Nyoma to Dah, exhibits different configurations of valley cross sections from wide U- shape to deeply incised V- shape gorges. Based on the valley configuration and channel gradient this study divides the Indus into four segments (Fig. 3.1 A).

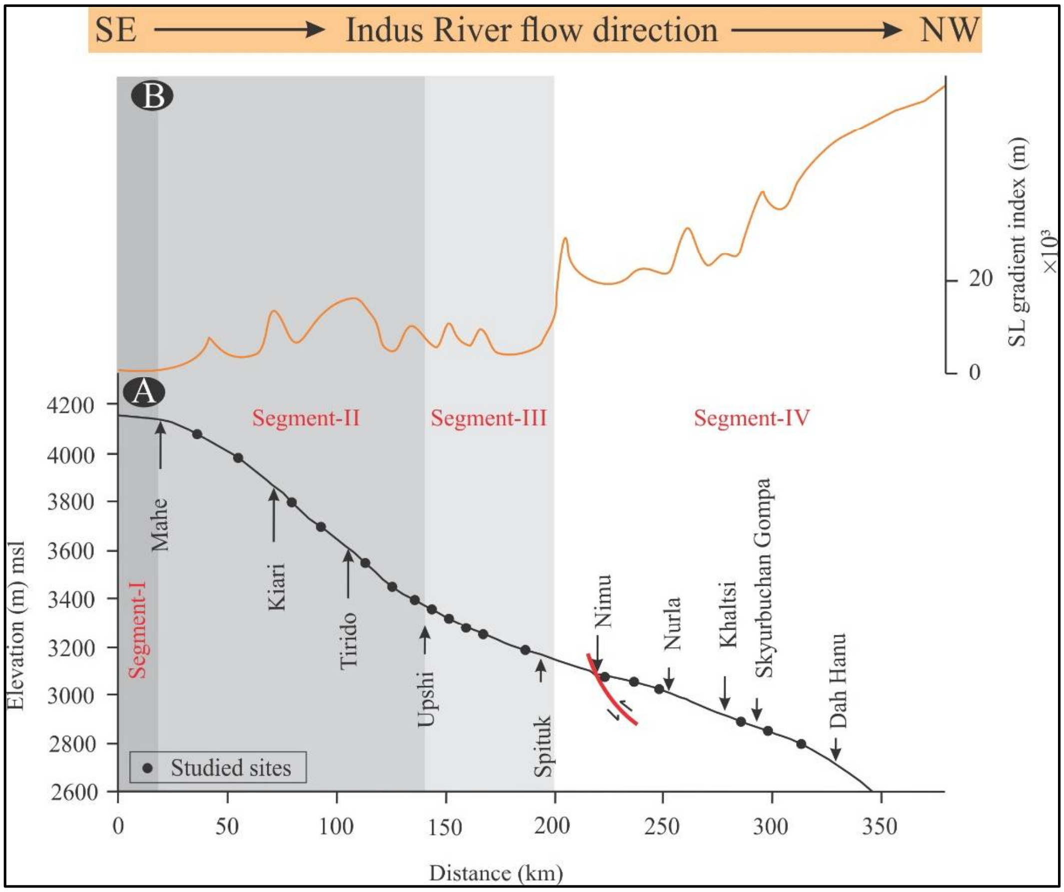

Figure 3.1 (A) Longitudinal river profile of the Indus River, showing studied sites. (B) Stream length gradient (SL) index variation with the downstream distance. The analysis of these two geomorphic tools identifies the whole reach into four segments.

Segment-I (U – shaped valley), it extends from Nyoma to Mahe, where the valley is very wide (~ 4 km) with braided pattern and very gentle river slope, i.e. 0.75 m/km. The older tight meander of the river can be seen in the flood plain that are flanked with sediment fill terraces of few meter thickness. In the upstream area, the river flows along the Karakoram fault zone (KFZ) in the southwest Tibet margin. River migrated its course in the vicinity of two fault (F1 and F2) emerged from the Indus Molasse, south of the Indus River (Fig 3.2).

Segment-II (V–shaped valley), it extends from Mahe – Upshi (~ 107 km), where the valley becomes narrower, where the average valley width reduces to ~ 192 m and slope increases to ~ 7.2 m/km. In this segment, the river flows in a deep gorge and enters from the Indus Molasse to the Ladakh Batholith. The topographic slope of the river reduce from 4116 m to 3397 m asl. This segment shows the development of thick fill terraces that range in thickness from 10.5 m to 70 m.

Segment-III, it extends from Upshi to Spituk (~ 60 km), with a large valley width (~ 1200 m) and low channel gradient (1.8 m/km). In this segment Indus is flowing on Molasse – Batholith contact zone, which is known as Upshi-Bazgo thrust (Brookfield and Andrews-Speed, 1984). The meanders of Indus is transformed to braid in the middle of this segment. The valley is covered by alluvial fans on both, south and north of the trunk channel. Eleven fans are coming from de-glaciated amphitheater valleys, bounded by the Ladakh Batholith from three sides. The continuous sedimentation from north and south fans, rises the local base level that leads to decrease the local slope and results expansion of aggradation into the tributaries coming from the north.

Segment-IV, it extends from Nimu to Dah-Hanu (~ 120 km). Strath terraces, deep gorge and steep gradient characterizes this segment. The Indus River entered into the gorge by drifting its course from Segment-III (Batholith-Molasse contact zone) to Segment-IV (Molassic bedrock). In the beginning of the Segment-IV, the bedrock of the Indus River is deformed in the vicinity of north verging Choskti and Upshi-Bazgo thrusts. The valley again has V–shaped configuration and shows 1-2 levels of strath terraces at places and one level of fill terrace. The valley width and channel gradient ranges from 100 to 500 m and 4 to 7.5 m/km, respectively.

Stream length gradient (SL) index

The variation in the SL gradient index has often shows good correlation with lithology and tectonic discontinuities. It estimates the stream power of the basin at a given point that further can be correlated with the erodibility and sediment transport capacity. The SL index has high values if (1) out crop lithology changes from hard to soft more erodible rock, (2) sudden change in the slope of the river and (3) the landscape is tectonically active and the channel traverses an active fault. Sharp changes in SL gradient index must be noticed if any one of the above occurs (Keller and Pinter, 1996; Troiani, F., et al., 2014).

Table 3.1 Type of terraces and bedrock incision rates along the Indus River

S No.	Location	Elevation (m)	Type of terrace	Thickness arl (m)	Chronology (ka)	Minimum Incision rates (mm/a)
Segment-I						
Wide valley no terraces are preserved						
Segment-II						
1	Mahe	4116	Fill terrace	T-1: 10.5	14 - 41	--
2	Niornis	3920	Fill terrace	T-1: 70	28±4	--
3	Kiari	3855	Fill terrace	T-1: 18	26±4	--
4	Gaik	3746	Fill terrace	T-1: 42	13 - 15	--
5	Tirido	3705	Fill terrace	T-1: 24.5	26 - 29	--
6	Hymia-1	3605	Fill terrace	T-1: 14	23 - 25	--
7	Hymia-2	3602	Fill terrace	T-1: 28	7-13	--
Segment-III						
7	Upshi R	3429	Fill terrace	T-1: 38	37±3	--
	Upshi L	3397	Fill terrace	T-1: 26	30±2	--
8	Kharu	3327	Fill terrace	T-1: 30	33±2	--
9	Stakna-1	3305	Fill terrace	T-1: 13	25 – 47	--
	Stakna-2	3305	Fill terrace	T-1: 12	29 - 30	--
	Stakna-3	3280	Fill terrace	T-1: 49	31 - 46	--
10	Spituk	3185	Fill terrace	T-1: 45	52±4	--
Segment-IV						
11	Nimu	3108	Strath terrace Fill terrace	T-2 : 124 T-1: 12	T-2 : 55±6	2.2
12	Saspol	3040	Strath terrace Fill terrace	T-2 : 81.2 T-1 : 1	T-2 : 50±5 T-1: 17±2	1.6
13	Nurla	3005	Strath terrace Fill terrace	T-2 : 148 T-1 : 0.5	T-2: 78±5	1.9
14	Khalsi	2939	Strath terrace Strath terrace Fill terrace	T-2 : 158.8 T-1' : 50.2 T-1 : 31.2	T-2 : 52±5 T-1' : 41±4 T-1: 18±1	3 1.2
15	Dumkhar	2904	Strath terrace Fill terrace	T-2 : 132.5 T-1 : 31	T-2: 57±3	2.3
16	Skyurbuchan Gompa	2880	Strath terrace Fill terrace	T-2 : 142.5 T-1: 31	T-2: 56±7	2.4
17	Skyurbuchan Downstream	2850	Strath terrace Strath terrace Fill terrace	T-2 : 150 T-1': 15 T-1 : 25	T-2 : 83±7 T-1': 47±7	1.8
18	Biamah	2720	Fill terrace	T-1: 17	7±1	--
19	Dah	2650	Fill terrace	T-1: 15	--	--

The average SL index value for Indus River is considerably higher and ranges from 0.16 to 15826 (Fig. 3.1 B). Segment I, has lowest values compared to other three. A sudden change in the SL index is observed as river enters into Segment II, where lithology remained same i.e. Indus Molasse. In this segment the values are highest between, Kiari to Tirido and ranges up to 10872, where river cuts through the granites of the Ladakh Batholith, which has rather low erodibility as compared to sedimentary rocks of the Indus Molasse.

In Segment III, from Upshi to Leh, the SL index has consistently low values, where the stream flows along the contact of Ladakh Batholith and Indus Molasse. The SL index sharply rises from the Spituk downstream. The highest value of the Segment-III noticed from the Spituk downstream, where Indus again entered in the highly deformed Indus Molasse. Downstream from Skyurbuchan, where Indus enters into granitic country rock, the SL index increases abnormally to 15826.

3.3 Landforms

The geomorphology of Ladakh Himalaya is marked by steep sedimentary cones made up of frost shattered rocks, glacial moraines, sand ramps, alluvial fills, alluvial fans, alluvial fan dammed palaeo- lake deposits, debris flows and strath terraces (Jamieson et al., 2004). The headwaters of all major tributaries of Indus River have large and medium sized glaciers that are often flanked by moraines of past glacial advances. These tributaries contribute enormously to the sediment budget of Indus and phases of high sediment generation and transportation helped in making wide and thick valley fills that were subsequently transformed into terraces due to river incision. In the present study, the river terraces are mapped and their sediment characteristics were studied and chronostratigraphy was established. The terraces are studied in terms of the thickness of fluvial cover and height of the underlain bedrock step. On the basis of fluvial cover and bedrock step, two types of terrace configurations are identified: (1) cut-fill type, which incorporates thick alluvial cover over a thin bedrock bench, (2) strath terraces type, which includes, thin alluvial cover underlain by thick bedrock bench.

The incision rates were calculated from the dated strath terraces. The incision rate is a ratio of height of the bedrock step from the present day river level or successive younger step, Δh (in meters) to time elapsed to incise the bedrock step, ΔT. The incision rate can directly be correlated with regional or local tectonic uplift (Bull, 1990; Burbank et al., 1996; Pazzaglia et al., 1998; Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2002; Srivastava and Misra, 2008; Ray and Srivastava, 2010). The mean and minimum incision rates are given in Table 3.1.

Sand ramps are another major landform in this semi – arid Ladakh Himalaya, which is studied for their geomorphology, sedimentary architecture and chronology. An attempt was also made to understand magnetic mineralogy and clay mineral variation through the stratigraphy of one such sand ramp.

3.4 Morphostratigraphy of terraces

Morphostratigraphy of the studied sections can be described in terms of strath or fill type terraces and explained from upstream to downstream (NE to NW).

In the following, the configuration of terraces and their OSL chronology in each segment is described. The riverbed is termed as T-0, the youngest and the lowermost terrace T-1 and successively older terraces are termed as T-2 and T-3.

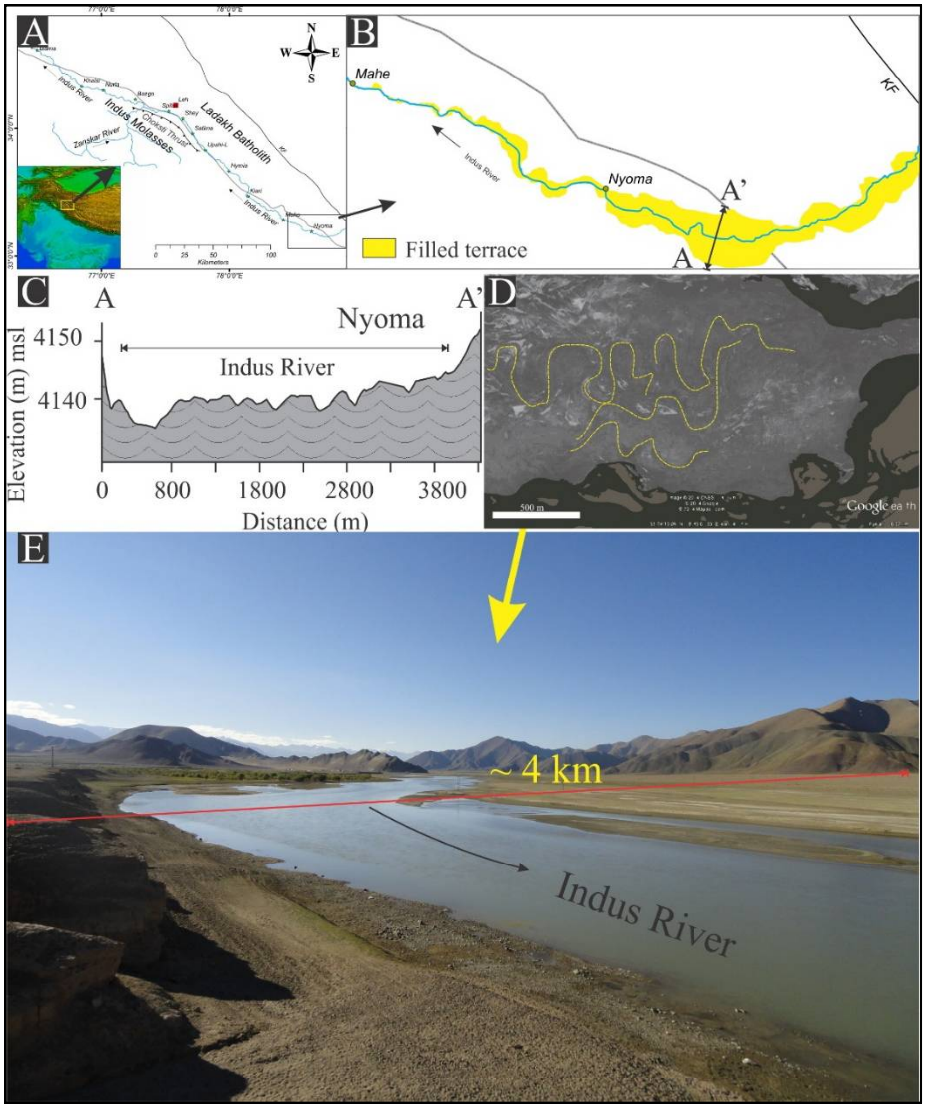

Figure 3.2 (A) Location map of Indus River. Small rectangle showing the Segment I. (B) Terrace map for Segment I. The yellow area shows the extension of fill terrace. (C) Valley cross section at Nyoma showing braided Indus River. (D) The google earth image showing the valley of the Indus at Nyoma is ~ 4 km wide.

The closely spaced paleo-meander is also visible, implying increased channel gradient. (E) A panoramic view of the Indus at Nyoma, showing braided nature of the trunk channel Segment-I.

Nyoma Section

Indus River in this segment has the lowest gradient (Fig 3.1 A). An older tight meander pattern, suggests increase in channel gradient during the recent past (Fig 3.2 C, D). The trunk channel shows large number of lenticular bars separated by multi- threads of the main stream. The wide valley (~ 4 km) around this section accommodated huge amount of sediments in its wide flood plains and shows developments of thin (1-2 m) terraces of fill nature on its banks (Fig 3.2 E). The upstream to Nyoma, at Thangra village, the braided Indus River aligns along NW –SE trending the dextral strike – slip Karakoram Fault (KF) where the fans made by its transverse tributaries are skewed along the KF. This twisting of fans toward the dextral strand of KF is due to Quaternary activity along KF.

3.4.2 Segment-II

Eight sections are studied in this segment, which show one level of fill terrace, indicating, this reach of the Indus River experienced a phase of valley filling.

Mahe section

At Mahe, the valley width reduced up to ~180 m, the valley is still U- shaped (Fig 3.3). The slope of the river increases to 9.5 m/km where the river bed lies at 4116 m asl and bedrock is Indus Molasse. At right bank, a 10.5 m and left bank 11.75 m thick fluvial deposits were studied. The OSL ages of these fill – terraces suggest that the aggradation started from 41±2 ka (LD-1047) and ceased at 14±2 ka (LD-1433).

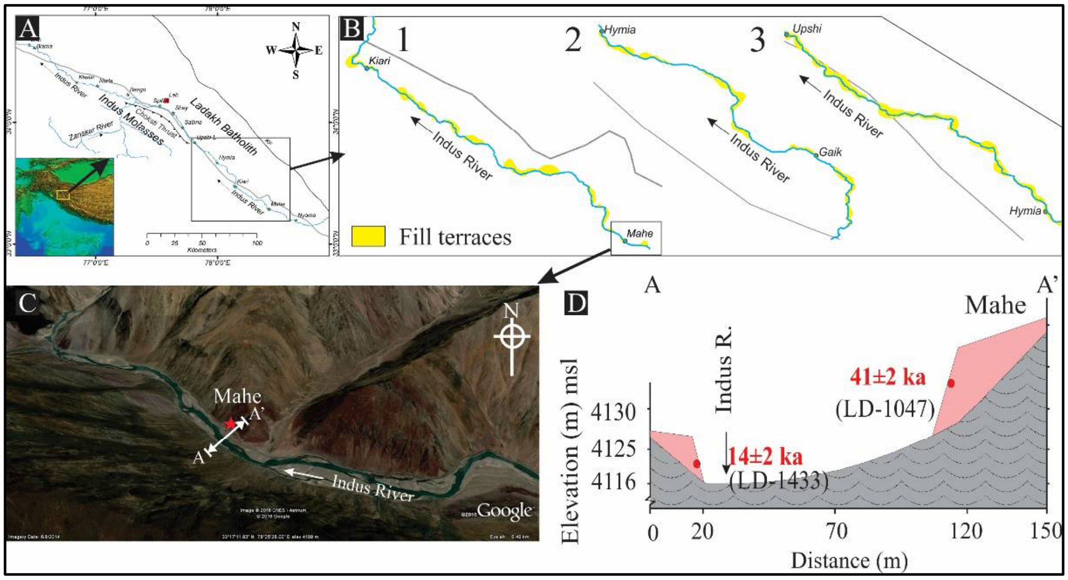

Figure 3.3 (A) Location map of Indus River and Segment-II. (B) A filled terrace has been marked throughout the segment. (C) The google earth image showing Indus Molasse as a bedrock at Mahe section. (D) Here, two filled terraces, one at left and the other at right bank have been located, shown in valley cross-section.

Kesar section

At this section, the Indus River flows in ~210 m wide, V- shaped valley as a braided channel. A 2.75 m thick sediment terrace flanks the riverbed. Here the river continues to flow into mechanically weak rocks of Indus Molasse. The slope of the Indus River is 6.95 m/km where the river bed is noted at 3959 m asl (Fig 3.4).

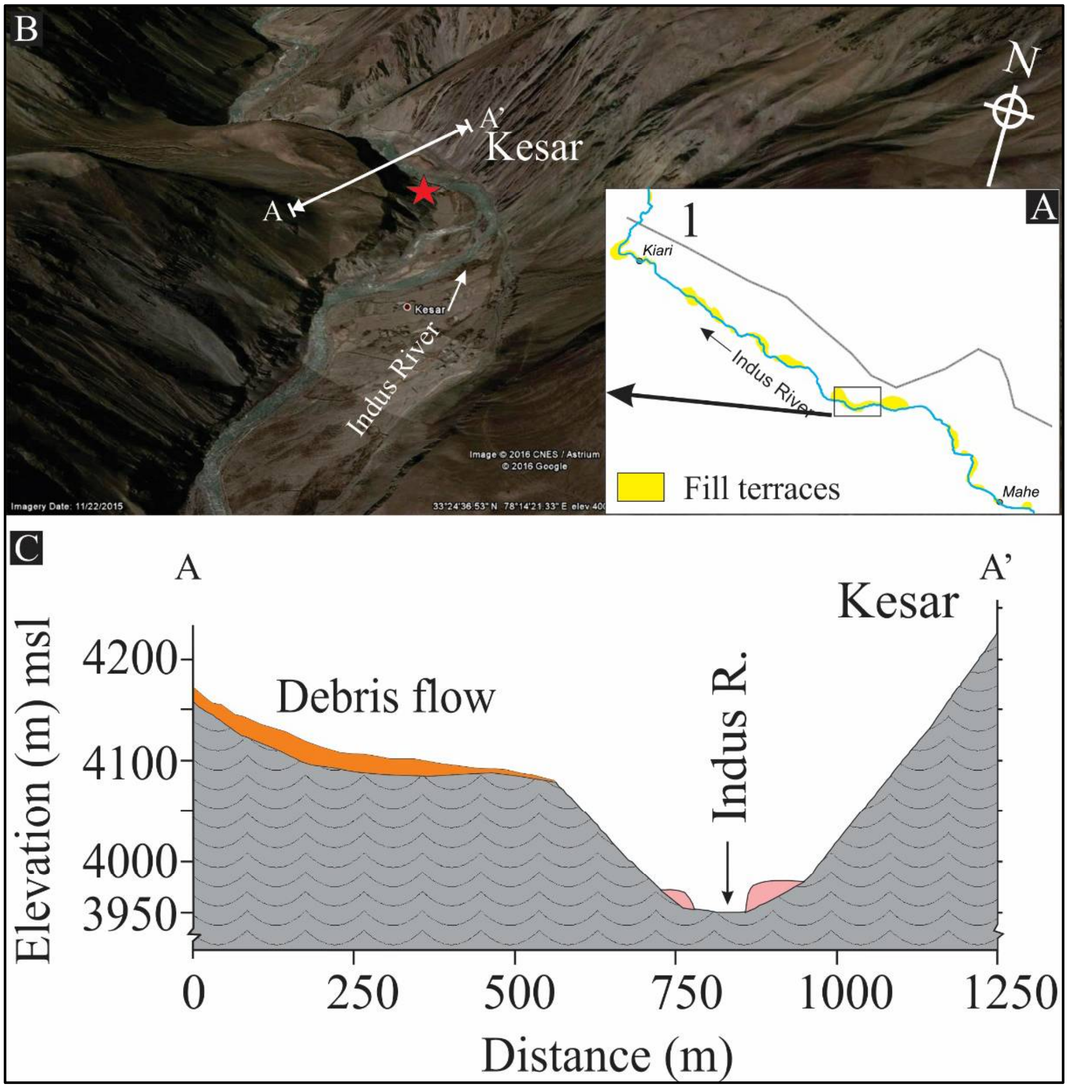

Figure 3.4 (A) Location map. (B) The goole earth showing the location of Kesar section along the Indus River. (C) A fill terrace has been marked in V-shaped valley. However, a debris flow has also been marked on the valley wall.

Niornis section

The Niornis section is situated near the confluence of small tributary that drains the batholith and joins the Indus River at its right bank where a 70 m thick valley fill makes a terrace. OSL age of the sample taken from ~ 40 m from the river base yielded 28±4 ka (LD-1048). The slope of the river at this section has been calculated as 8 m/km. The Indus River flows as a meandering channel in ~ 385 m wide V-shaped valley where riverbed is situated at 3920 m asl (Fig 3.5). The surrounding mountains have ~ 800 m topographical relief from the valley floor.

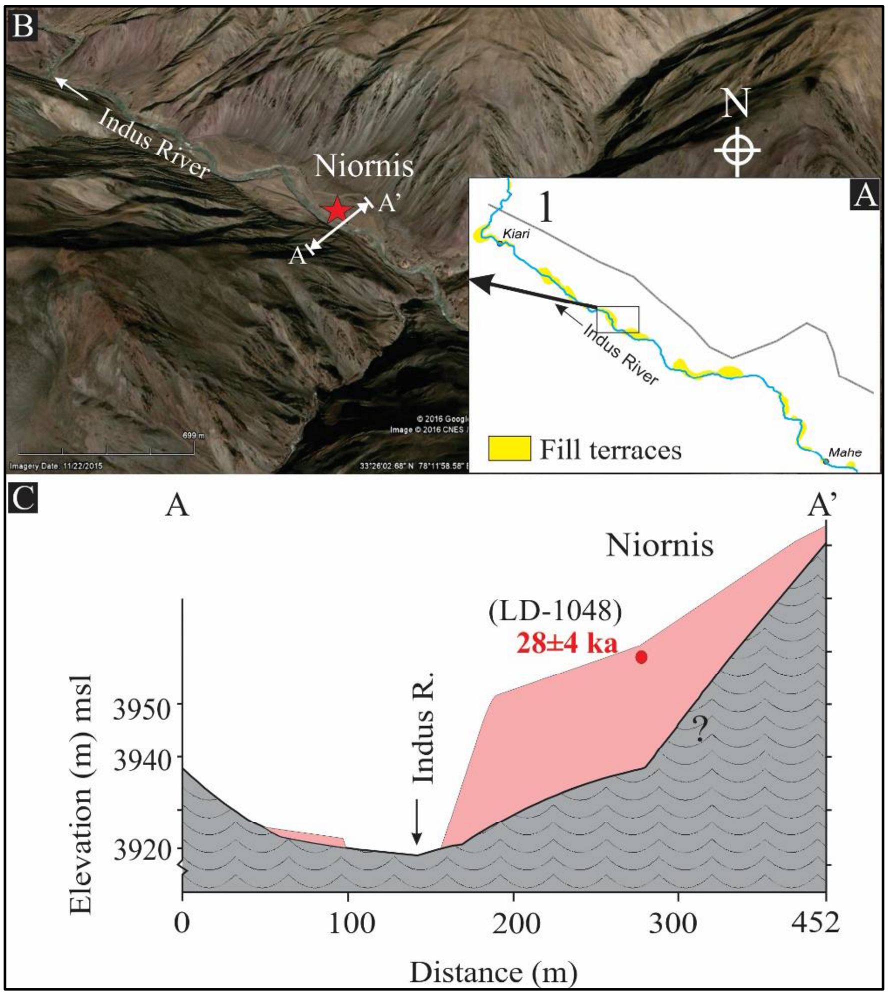

Figure 3.5 (A) Location map. (B) A panoramic view of Niornis section showing the geomorphological setup. (C) A valley cross-section (A-A') showing a V-shaped valley and a fill terrace along the Indus River.

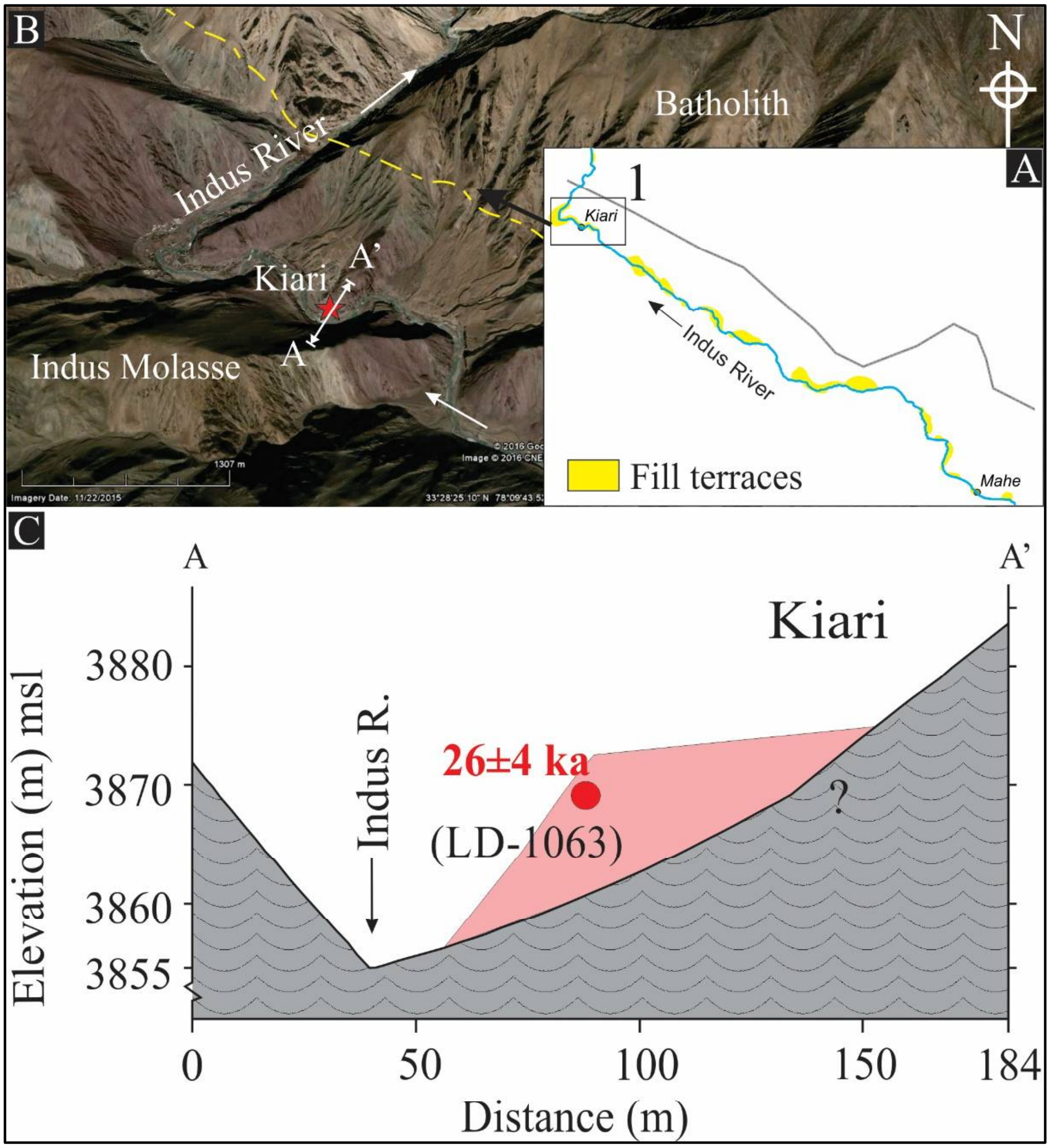

Figure 3.6 (A) Location map. (B) At Kiari, the Indus River makes a sharp diversion in its path from the Indus Molasse to the batholith. The yellow line showing the contact of Indus Molasse and Ladakh Batholith. (C) Fill terrace in the V-shaped valley.

Kiari section

At this section, ~ 18 m thick fill terraces is exposed. The river is flowing in ~ 175 m wide, V- shaped valley (Fig 3.6). An OSL sample 13 m from the top yielded 26±4 ka (LD-1063). The river here continues to flow through the Indus Molasse. At Kiari village, the river takes an abrupt turn at 90^{o}, and makes ~500 m wide valley. The channel slope at this section has been measured as 7.7 m/km whereas the riverbed is located at 3855 m asl. Kiari to Hymia, the Indus River flows in the Ladakh Batholith.

Gaik section

At Gaik, river flows in a narrow gorge, carved out in the Ladakh Batholith, where the width of an active channel is 50 m. The river gradient as measured in this stretch is 12.5 m/km. One level of fill terrace is exposed on the right bank and makes a 42 m thick valley fill sequence (Fig 3.7). This section has overlapping ages of fluvial and debris flow events, signifying rapid aggradation during 13±1 ka (LD-1064) and 15±1 ka (LD-1065), respectively. This also indicates that the river incision and terrace formation took place at ~13 ka.

Tirido section

A 24.5 m thick fill terrace is exposed in ~110 m wide, V-shaped valley. The width of an active channel is 62 m and gradient is 10.4 m/km (Fig 3.8). The valley has > 600 m topographical relief from valley floor. The average river velocity 2.1 m/s is calculated by floating rubber cork method. The OSL chronology indicate that this section preserves records of valley aggradation that took place between 26±2 ka (LD-1067) to 29±3 ka (LD-1066).

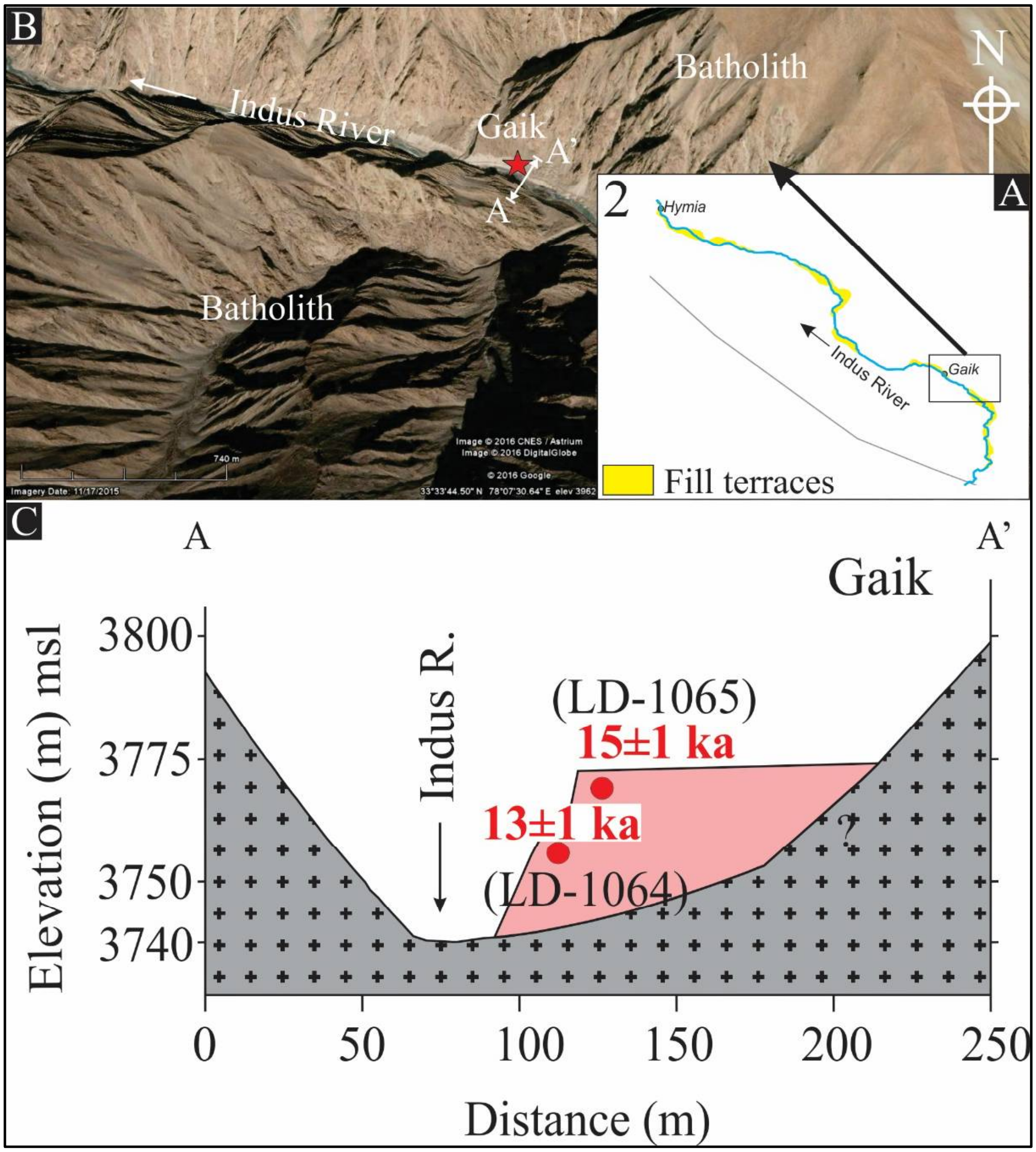

Figure 3.7 (A) Location map of the Gaik section. (B) Google earth image showing, in a narrow deep gorge. A-A' is a valley cross-section at this section. (C) A valley fill terrace has been located in V-shaped valley.

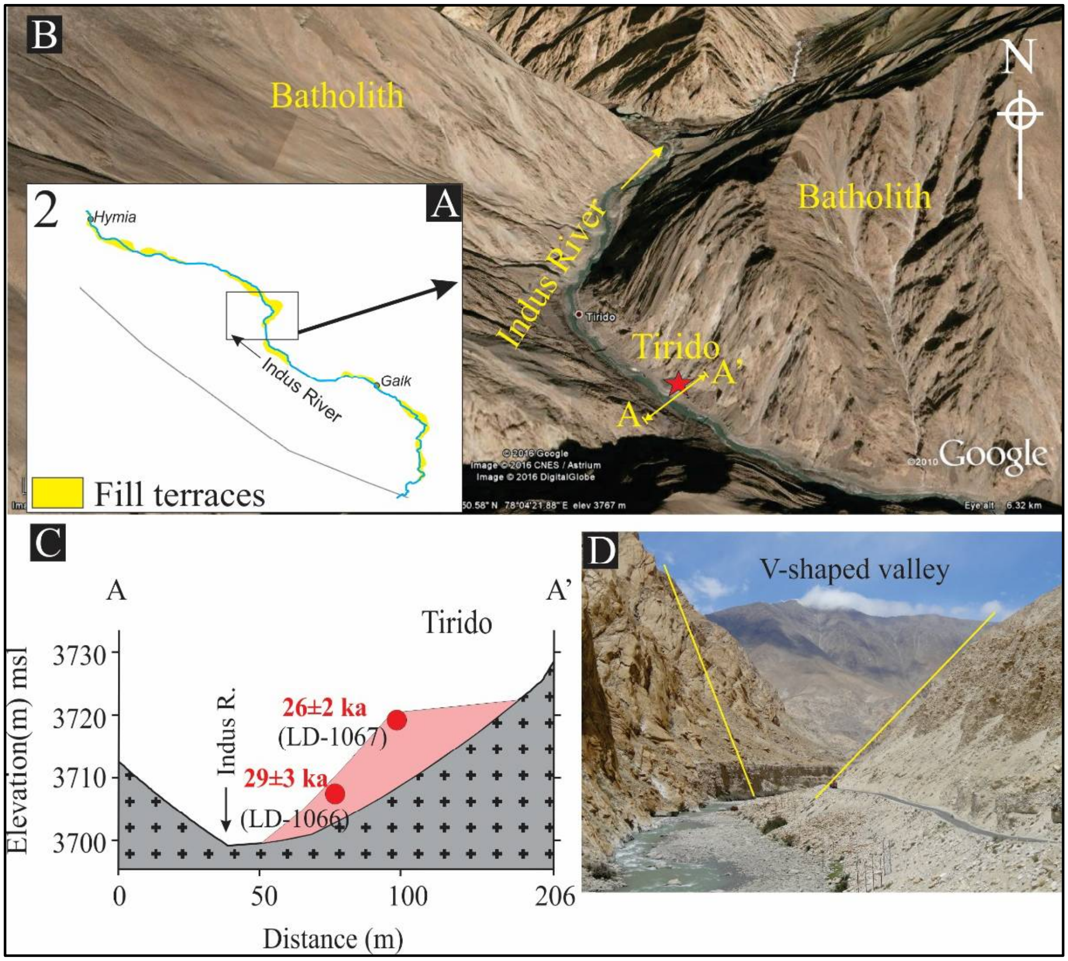

Figure 3.8 (A) Terrace map around Tirido section. (B) Google earth image, locating the studied section, valley cross-section (A-A') and Batholith as bedrock. (C) A valley cross-section A-A' indicates a V-shaped valley and a fill terrace on the left bank of the river. (D) A panoramic view of the Tirido section. The bedrock is grano-dioritic, where the river is flowing in a deep gorge.

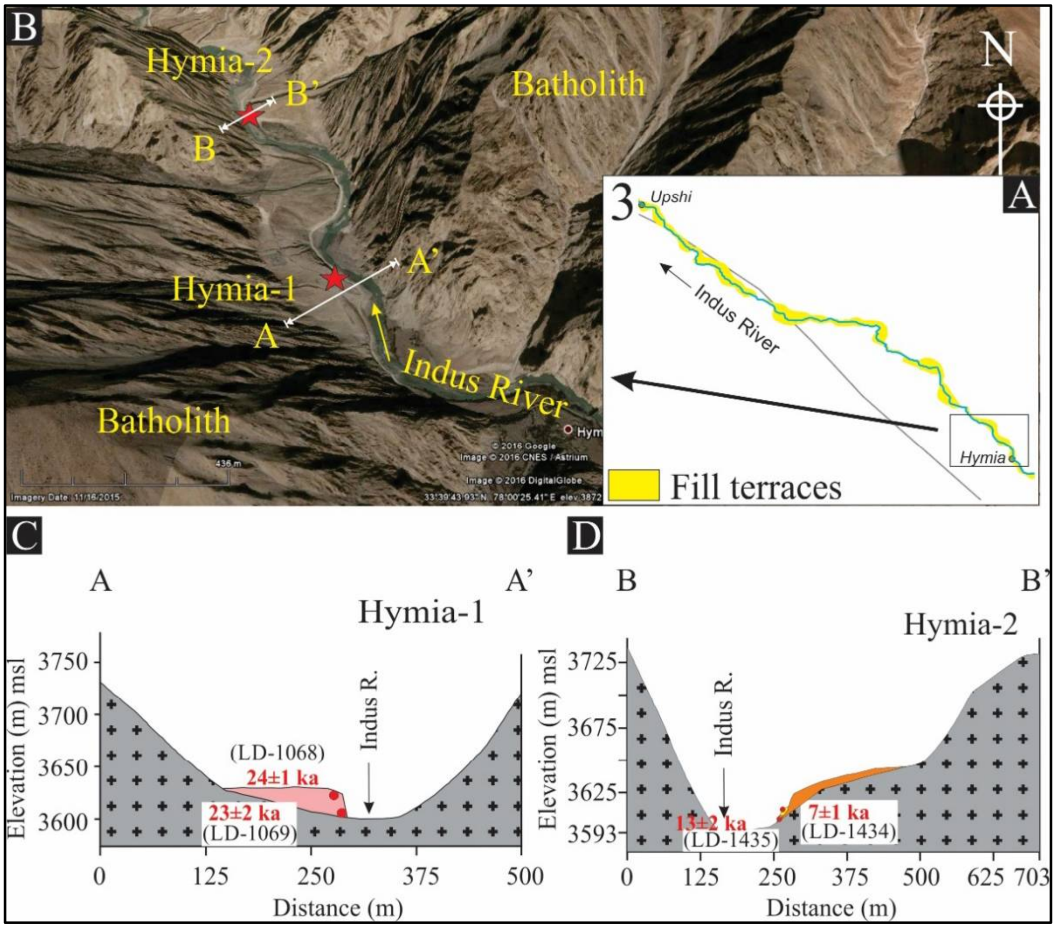

Figure 3.9 (A) Location and terrace map for Hymia sections. (B) Google earth image showing Hymia-1 and Hymia-2. At these sections, the valley become slightly wider. The valley is mainly covered by large fans coming from both banks of the river. (C) and (D) Vally cross-sections for Hymia-1 and Hymia-2.

Hymia-1 section

One level of fill terrace is located on the left bank of the trunk channel that incorporates a 14 m thick sedimentary sequence of valley fill. At this section the valley is widens up to 250 m, where the topographical relief (Fig 3.9) decreases to

~ 600 m. The gradient of the channel also reduces to 9 m/km. The vertical sequence beneath the terrace indicates that a fluvial fan that emerges from the Zanskar ranges, sits on to the Indus river sediments.

The OSL chronology of the section provides overlapping ages of 23±2 ka (LD-1069) and 24±1 ka (LD-1068) from different depths indicated rapid aggradation bank.

Hymia-2 Section

Hymia-2 section was studied on the right bank, where a level of fill terrace is located as well. At this section, the riverbed is at 3602 m asl. The valley has V-shaped configuration with ~ 320 m valley width and ~ 130 m channel width (Fig 3.9 D).

The terrace is made up of ~ 28 m thick vertical aggradation, which, in turn, composed of fan sequence exclusively sourced from the Ladakh Batholith and is dated to 13 – 7 ka.

3.4.3 Segment-III

After crossing Hymia, the Indus River takes almost a straight course for a short distance and then follows the meandering channel pattern. In this Segment, the trunk river drains through the contact zone of Indus Molasse and Ladakh Batholith. The segment is characterized by wide valley, low gradient and large fans emerging from the Indus Molasse and Ladakh Batholith, both. There are total twenty three

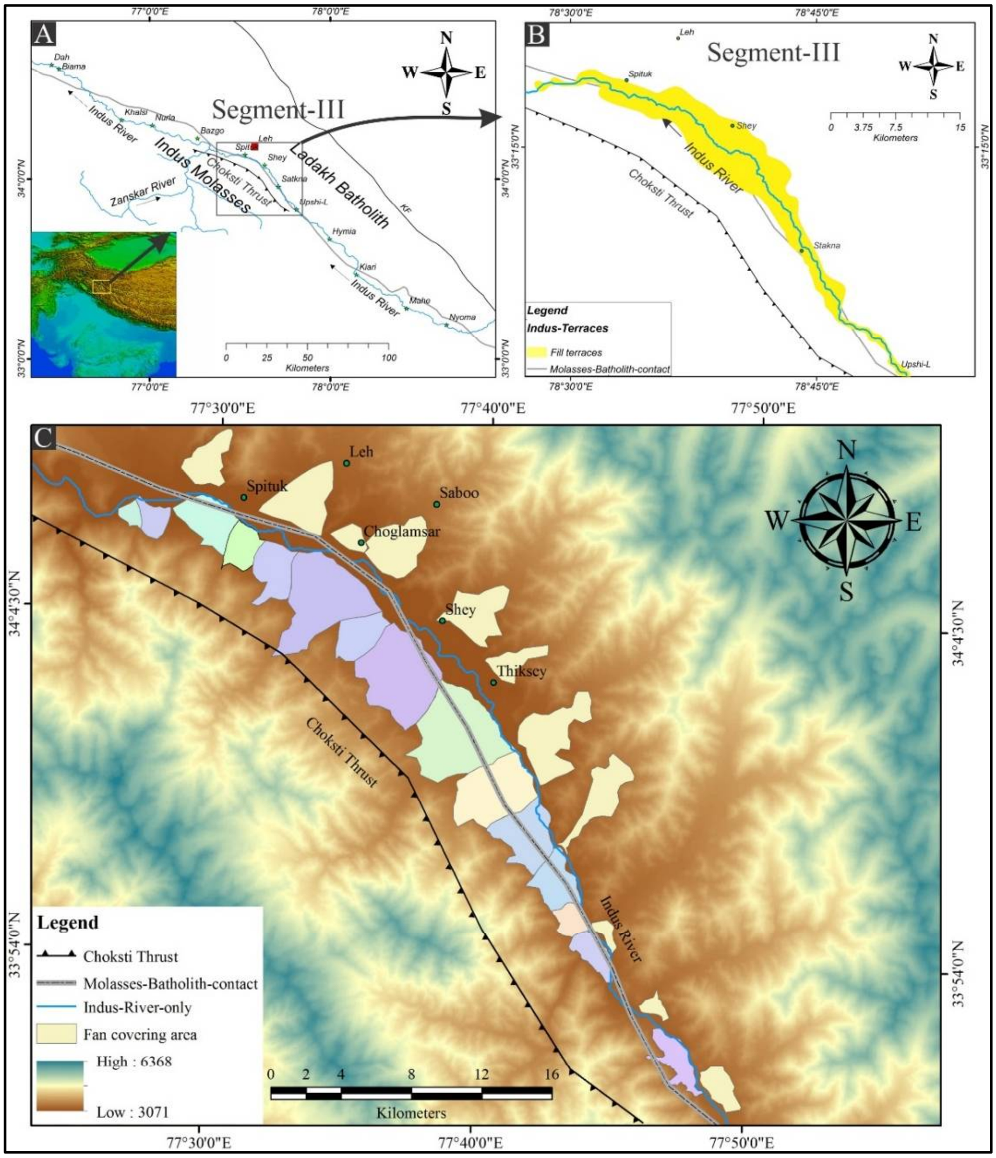

Figure 3.10 (A) Regional map showing the Indus River and major localities in Ladakh. A box locating the Segment-III. (B) A terrace map of the Segment-III. The grey line is the molasse-batholith contact line, black line with teeth is Choksti thrust dipping south. (C) A topographic map of Segment-III, indicates the fans emerging from south are related to the activity along the Choksti thrust. The fans emerging from north, are belong to amphitheater valleys.

number of fans, fourteen are from the Indus Molasse and nine from the batholith (Fig 3.10). Area wise, the fans from molasse are bigger than the batholith. The fans that emerging from the molasse have steeper geomorphic gradient (~12 degrees) than those joining the Indus from the Ladakh Batholith (Sant et al., 2011a).

Upshi-R Section

This section shows a 38 m thick fill terrace composed of basal 30 m of Indus channel deposits followed by 8 m thick fan sediments. The section extends laterally for ~100 m. The actual valley width bounded by valley walls, is wider, however, the fans joining the valley, restrict the channel up to ~ 200 m in width (Fig 3.11). The OSL date from the top of channel deposits of the section suggests that this fan is younger than 37±3 ka (LD-1070).

Upshi-L Section

A 26 m thick section making one level of fill terrace exposed on the left bank of the river at Upshi (Fig 3.11). The modern channel depth near the Upshi Bridge is ~2±0.1 m. At this section, the reworked sediments, derived from distal part of the fans formed a flatter T-1 terrace, which yielded the OSL age 30±2 ka (LD-1046).

Kharu section

At Kharu, the valley retains its width to ~ 410 m (Fig 3.12) and shows low topographical relief. One level of terrace made up of a 30 m thick sedimentary sequence present on the left bank of the river and dated to 33±2 ka (LD-1045).

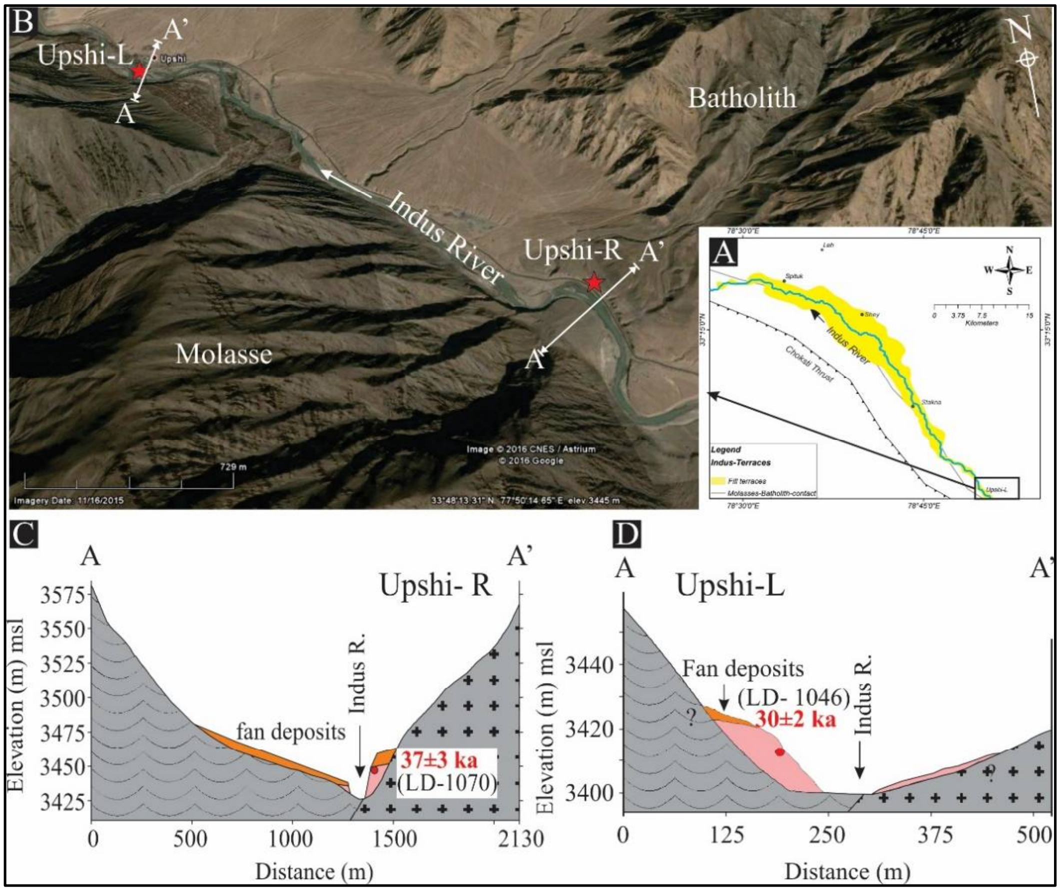

Figure 3.11 (A) Terrace map locating the Upshi section. (B) The google earth image showing the topographic view around Upshi-R and Upshi-L sections. Here the Indus River is flowing on the contact of Indus Molasse and Ladakh Batholith, which is known as Upshi-Bazgo thrust. (C) The valley cross-section of both the sections indicating wider V-shaped valley, which is covered by alluvial fans.

Stakna section

At Stakna, three sections were studied. Stakna and Stakna-1 are located on left and right bank of the river respectively, whereas the Stakna-2 is located ~ 5 km downstream on the right bank of the river (Fig 3.13). Large fans that join the river reduced the actual width of active channel to ~ 240 m. The Stakna section makes a 12 m terrace which is made up of fan sediments dated 47 to 25 ka.

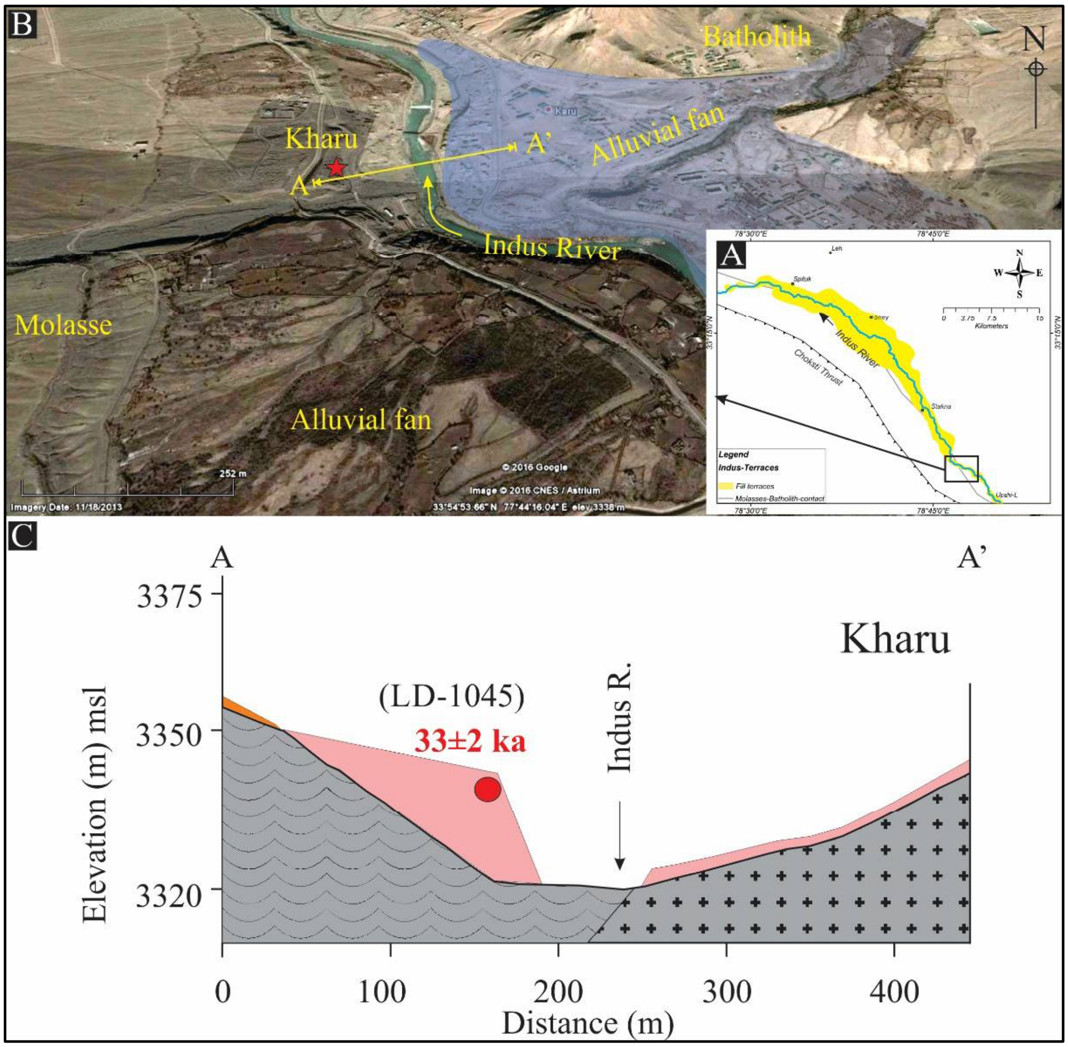

Figure 3.12 (A) Terrace map of Kharu section. (B) The google earth image shows that the river is flowing along the Upshi-Bazgo thrust. Alluvial fans emerges from the batholith and molasse side and unload the sediment into the trunk channel. (C) The valley cross-section of this section indicating that a wider V-shaped valley, where the topographic relief is low.

Stakna-1 section is made up of 12 m thick debris flow deposits derived from fan emerges from north (Ladakh Batholith) and show overlapping ages 29 and 30 ka. The Stakna-2 section preserves a 49 m thick relict fan terrace originated from the batholith. This sequence is dated to 46 – 31 ka.

Spituk Section

Here the valley is ~ 1200 m wide and the river attains a braided pattern (Fig 3.14). The topographic gradient toward the north (Ladakh Batholith) is 24° to 33°, whereas toward the south (Indus Molasse) it increases to 40° to 55°. At southern margin, there are large number of steep fans that emanate from the Indus Molasse and make a lobate structure with a radius of 2 to 5 km. The Spituk section has a composite record of fluvial, glacial lake and aeolian deposits. At the bottom, a 10 m fluvial sand is overlain by the fan deposits of Molassaic affinity. Overlying this, a glacial fed ~ 33 m thick massive paleo-lake unit, at the top, is capped by aeolian sand dated to ~20 ka. The OSL sample from the bottommost fluvial sand yielded 52±4 ka (LD-1003).

The fanglomerate units in this segment are dated from 47 – 29 ka at Kharo, Stakna, Stakna-1 and Stakna-2 sections. This suggest that in Leh valley, the fan building activity was prominent during 47 – 29 ka. The lake deposits which could only be possible when the Indus was blocked by the fans (coming from south) and the glacial melt water continuously fed Spituk paleo-lake (which could be noticed by varve deposition). The top aeolian sand, which lies in the stratigraphic order dated 20±2 ka (LD-1071).

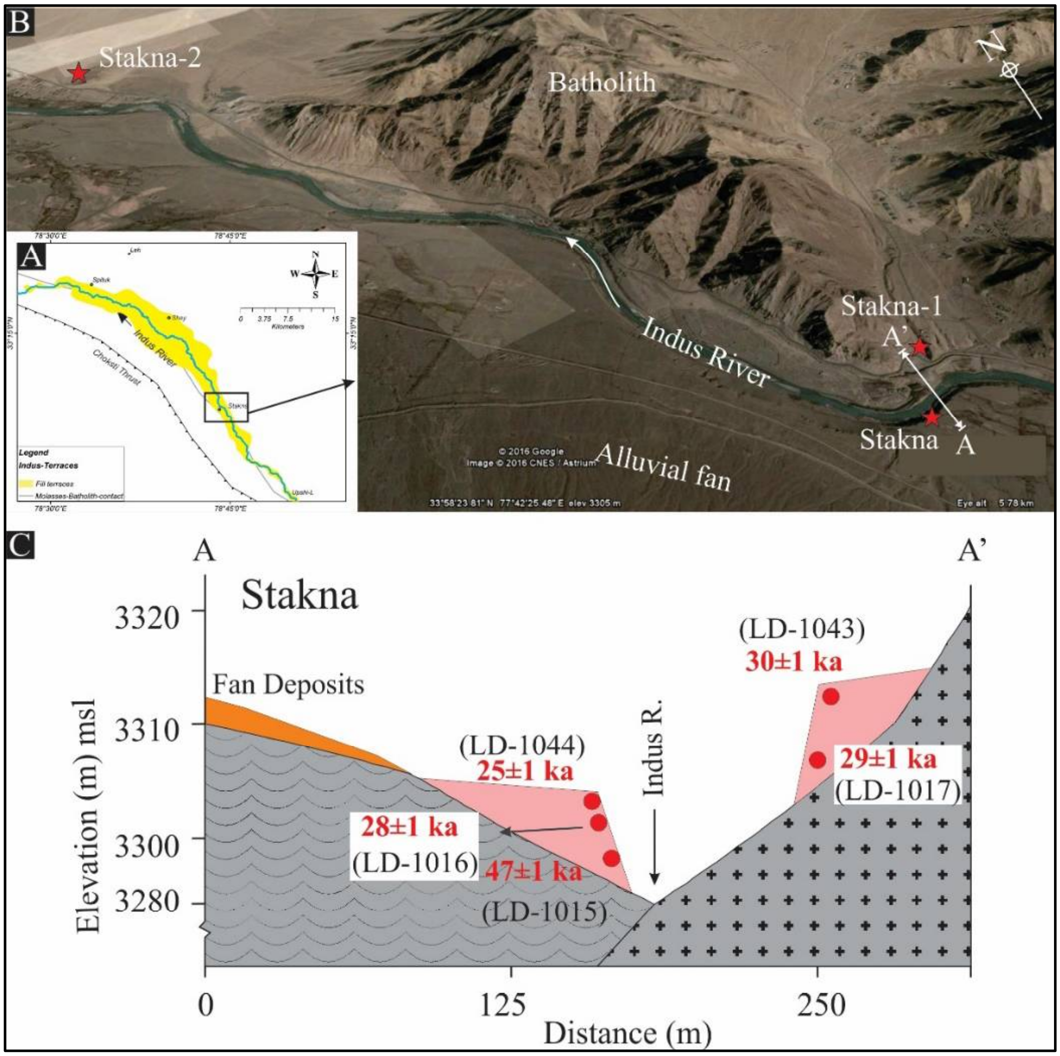

Figure 3.13 (A) Terrace map. (B) A google earth image locating the Stakna, Stakna-1 and Stakna-2 sections and a topographic view around these sections. Stakna-1 section located just opposite bank on Stakna section. Stakna-2 is further downstream, where valley is covered by alluvial fans from both sides of the river. (C) The valley cross-section at this section indicating the V-shaped valley become narrower due to alluvial fans.

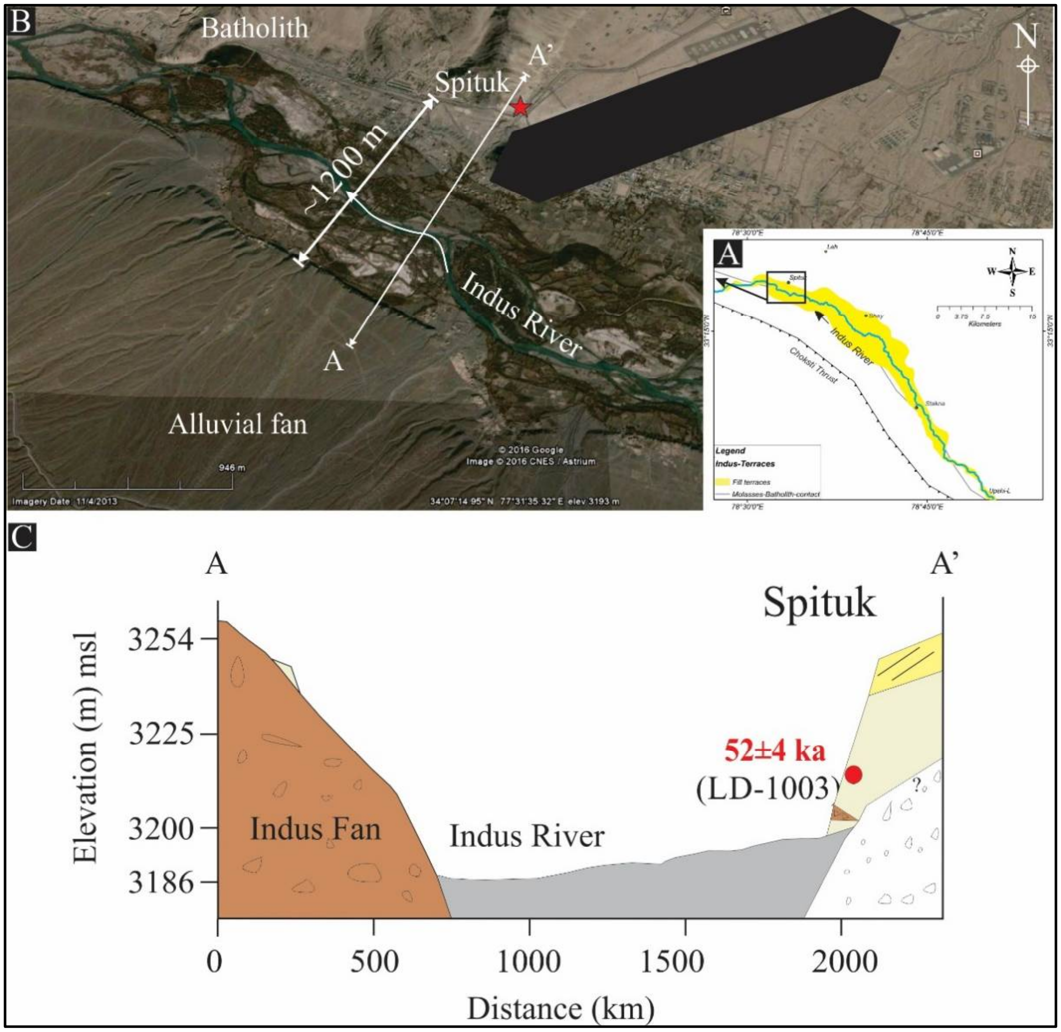

Figure 3.14 (A) Terrace map locating the Spituk section. (B) The google earth image shows a wide valley (~ 1200 m). The river follows a braided pattern. The banks of the trunk channel are not stable and bounded by fan in the south and bedrock in the north. (C) The valley cross-section at Spituk (Leh), indicates that the south bank of Indus is flanked by fanglomerate and north bank has Spituk paleolake deposits lying on fluvial sand.

3.4.4 Segment-IV

This Segment lies from Nimu to Dah Hanu, where the river flows through the gorge and shows the development of older strath and one level of younger fill terraces (Fig 3.15). The strath terraces were mapped and dated to calculate the bedrock incision rates of the region.

Nimu Section

This section is situated at the confluence of Indus and Zanskar Rivers. Two levels of terraces; terrace T-1, a cut – fill type having thick fluvial cover of type – 1 and terrace T-2, a strath type with thick bed rock step overlain by a thin fluvial cover of type – 3 (Fig 3.16). A 124 m thick intensely folded and thrusted bedrock (shale) of Nimu Formation, is overlain by a thin 12 m alluvial cover (T-2). The top surface of T-2 is flat and gullied, extends laterally ~ 2 km. T-1 is a paired terrace, situated ~12 m above the riverbed. The riverbed is present at 3108 m asl. The OSL age from the base of the T-2 is 55±6 ka (LD-1221) and the T-1 is dated to the late Holocene (Clift and Giosan, 2013).

The river in the section meanders and successive terraces make incised meanders with progressively increasing sinuosity. The continuous shifting of the paleo- Indus course is marked above the T-2 can be well seen in Google image (Fig 3.16 B). This fluvio-glacial melt water above the T-2, formed dendritic drainage pattern, which moderately incised the T-2 and merged into a main thread of paleo-Indus course after taking a half circular trajectory from confluence zone.

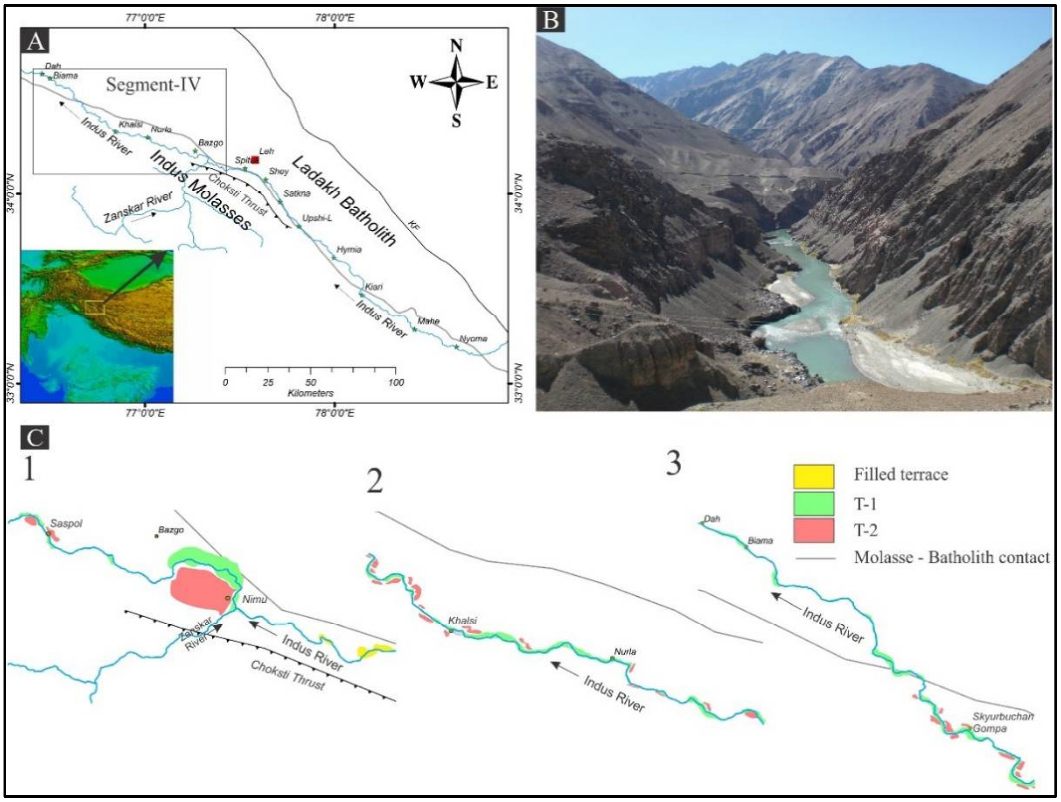

Figure 3.15 (A) A regional map for Segment-IV. (B) A panoramic view of this segment, where Indus is flowing in a deep gorge. (C) The terrace map of Segment-IV, which is divided into three parts; 1) Nimu to Saspol, 2) Saspol to Dumkhar, and 3) Dumkhar to Dah. The yellow, green and red fill along the Indus are filled, strath level – 1 and strath level – 2 respectively. The grey line shows the molasse-batholith contact.

Saspol Section

One level of strath terrace (T-2) and one cut-fill terrace (T-1) marks this section (Fig 3.16 D). A 19 m thick T-1 is situated on 1 m bedrock bench. The T-1 terrace is located on both sides of the river and designated as type – 1. The T-2 is a strath

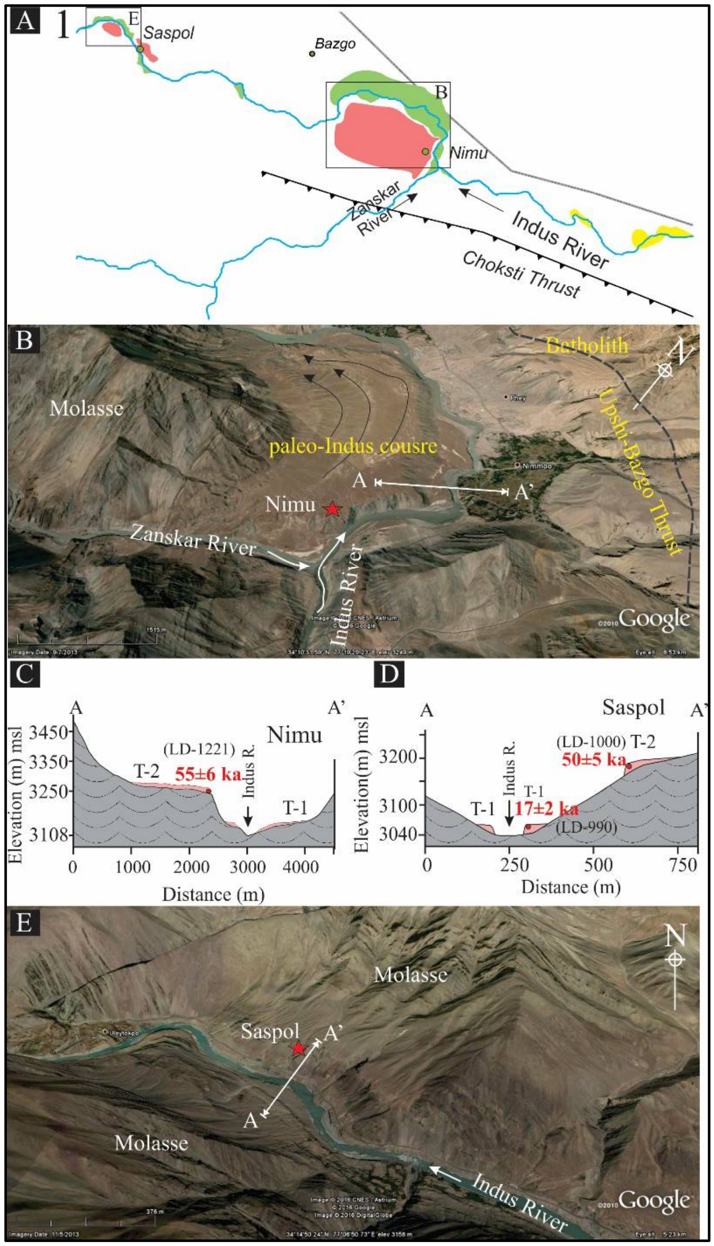

Figure 3.16 (A) Terrace map showing the location of the Nimu and the Saspol sections. (B) The google earth image locating the valley cross-section at Nimu, Upshi-Bazgo thrust and paleo-Indus courses. (C) and (D) The valley cross-section of Nimu and Saspol, indicates V-shaped valley with two levels of terraces. (E) The google earth image shows the Saspol section.

terrace (type – 3), located 110 m above the river level, and comprised of 17 m thick fluvial sediments that are underlain by 81.2 m bedrock step. This strath terrace is traceable downstream to >1 km. The alluvial cover of the T-2 is dated to 50±5 ka (LD-990), whereas, T-1 yielded an age of 17±2 ka (LD-1000). The river here makes deep and narrow V-shaped valley which is carved into molassic rock (Fig 3.16 E). The riverbed is at 3040 m asl.

Nurla Section

This section is also marked with two levels of terraces; one cut-fill (type – 1) and one strath (type – 3). A 12.5 m thick cut-fill type T-1 terrace, seated on 0.5 m bedrock step lies on both banks of trunk channel. The strath terrace T-2, is made up of 20 m thick alluvial cover, situated ~148 m above the riverbed (Fig 3. 17). The T-2 strath of this section is oldest terrace and dated to 78±5 ka (LD-989). The riverbed lies at 3005 m asl. At this section, the arc shaped depressed valley is also located, which is a paleo-meander of the Indus River (Fig 3.17 B). This paleo-valley was filled by a fan emanating from the north. The paleo-channel suggests that the Indus has moved southward.

Dumkhar Section

Two levels of terraces characterize this section. The lower T-1, is made up of 31 m thick fluvial fill and an underlying 2.5 m bedrock. The riverbed here is at an altitude of 2904 m asl. The terrace T-1 is paired in nature. T-2 is composed 18 m thick fluvial cover and 132.5 m bedrock step (Fig 3.19 B, C). The bedrock is intensely folded red shale of Khalsi Flysch.

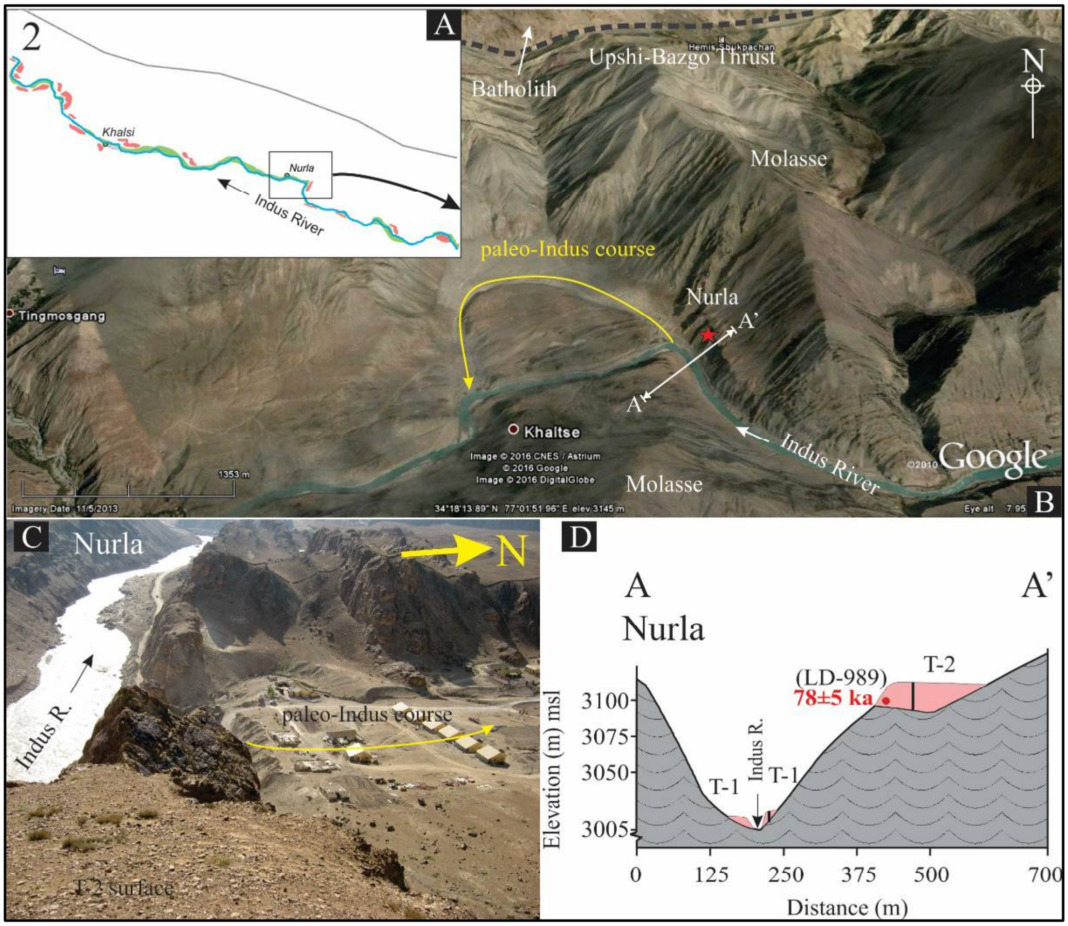

Figure 3.17 (A) The terrace map of Segment-IV, from Saspol to Dumkhar, locating the fill (T-1) and strath (T-2) terraces in green and red colours, respectively. (B) The google image shows that the river flows in the molassic bedrock. The contact of molasse and batholith is shown by bold grey dotted line. At Nurla section, an arc shaped depressed valley indicates the paleo-Indus course. (C) A panoramic view of the Indus gorge at the Nurla section, where T-2 is situated at 142 m arl. (D) A valley cross-section shows a deep V-shaped valley.

The sample for OSL from T-2 yielded an age of 57±3 ka (LD-995). The T-2 has 1 to 1.5 km lateral extension.

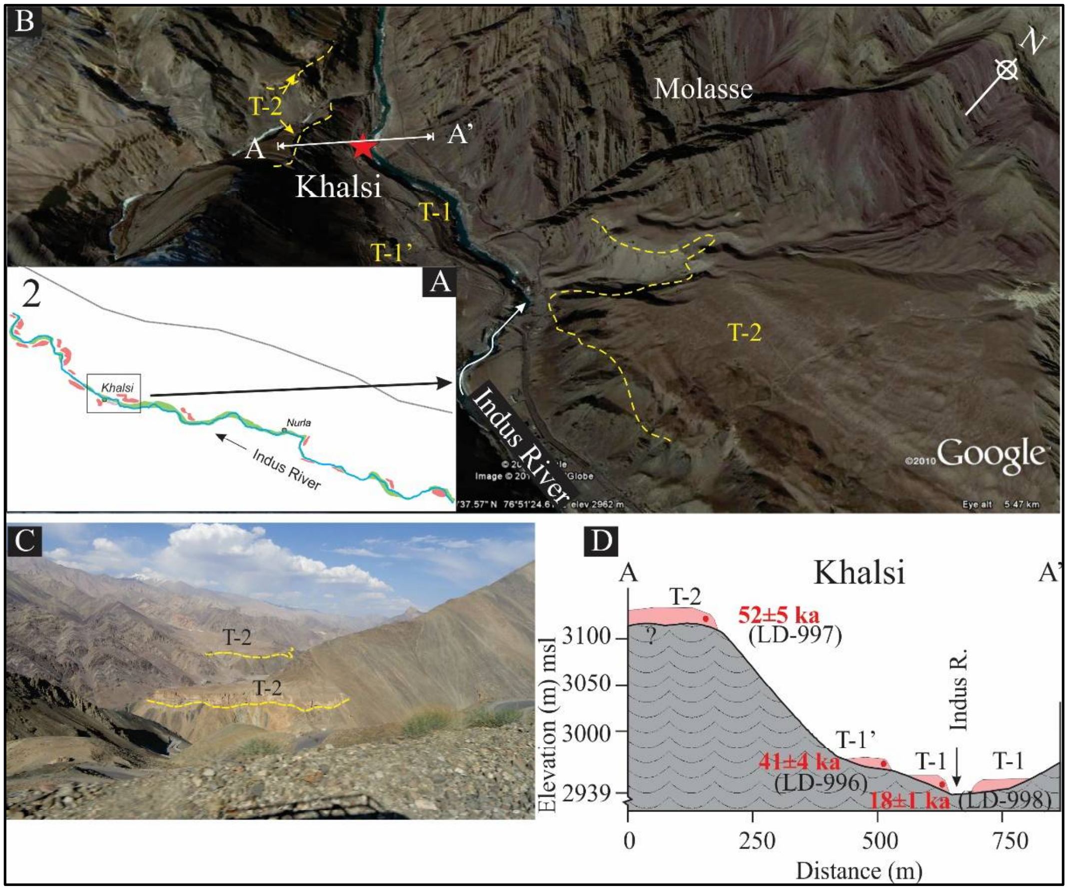

Figure 3.18 (A) Terrace map locates Khalsi section. (B) The google earth image shows that the Indus is flowing over the molassic bedrock and formed a deep gorge. There are two level of strath terraces (T-1' and T-2) and one level of fill terrace (T-1). T-2 can be traceable on both banks of the Indus River at this section. (C) A panoramic view of T-2 terrace. (D) The valley cross-section shows T-2 is lying at ~ 179 m arl.

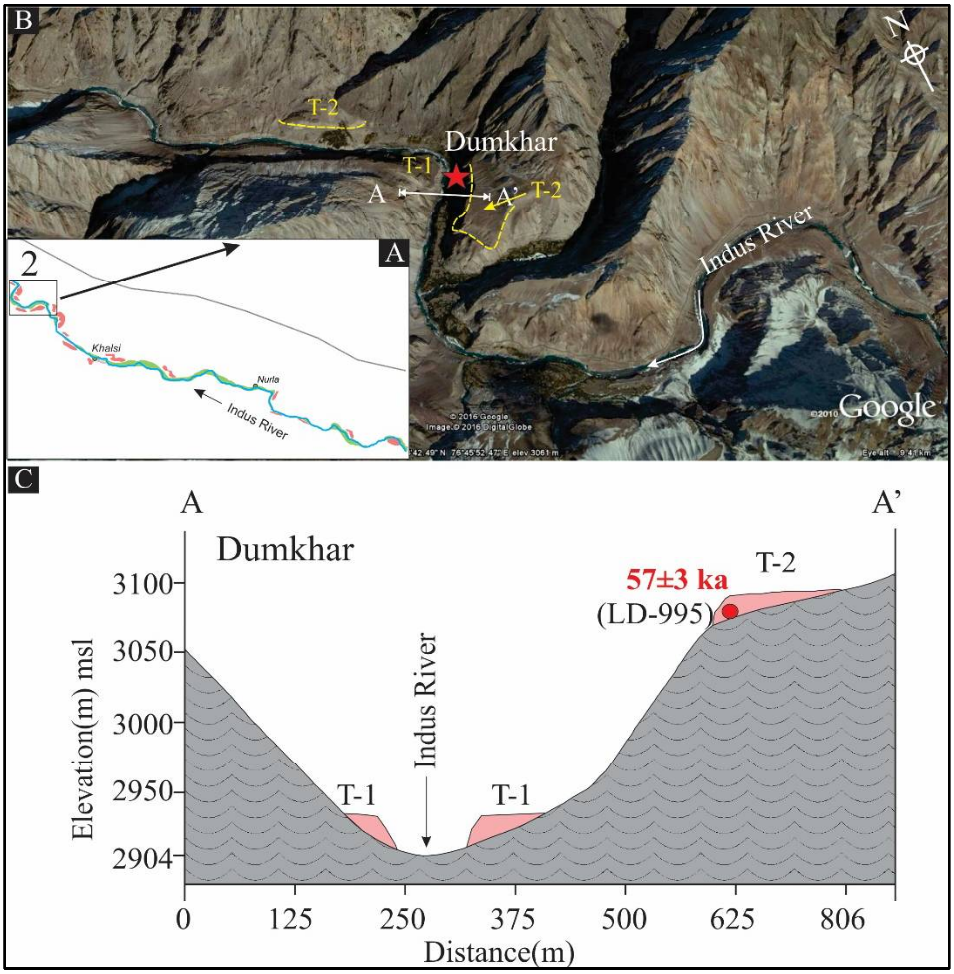

Figure 3.19 ((A) Terrace map locates Dumkhar section. (B) The google earth image shows that the Indus River follows a meandering pattern. At this section, the strath terrace (T-2) can be traceable downstream. (C) The V-shaped valley shows a deep gorge.

Skyurbuchan Gompa section

Two levels of terraces were located at Skyurbuchan Gompa section where the river flows along the tectonic contact of Indus Molasse and Ladakh Batholith (Fig 3.20 B). The cut-fill, T-1 terrace makes a 31 m thick fluvial fill, which rises from the riverbed. This terrace is a paired one and exist on both the banks. The older terrace T-2, is a strath type and made up of a 15.5 m thick alluvial cover with 142.5 m thick underlying bedrock bench. The alluvial cover of this terrace is dated to 56±7 ka. The V-shaped valley formed a deep gorge (Fig 3.20 C), where the topographic relief is ranges up from 850 to 1100 m. The riverbed is located at 2880 m asl.

Skyurbuchan Downstream section

Further 5 km downstream from the Skyurbuchan Gompa section, two levels of strath and one level of fill terrace were observed (Fig 3.20 B, D). The terrace T-1 is a paired and cut-fill type, whereas T-1' and T-2 is unpaired strath terraces. The stratigraphy of T-1 terrace is covered with a scree debris, so not exposed, however, the thickness indicates that it makes ~25 m of fluvial fill (below the scree apron). A strath T-1' lies over the T-1 and composed of a 15 m thick fluvial deposits. The second level of strath T-2, underlain by a 150 m bedrock bench, is composed of a 15 m highly indurated and cemented fluvial cover. The riverbed is located at the altitude of 2850 m asl. The first (T-1'; 40 m from the riverbed), and second strath (T-2) terraces are dated to 47±7 ka (LD-993) and 83±7 ka (LD-987), respectively.

Downstream from this section, the river flows through a deep and narrow gorge of the Ladakh Batholith.

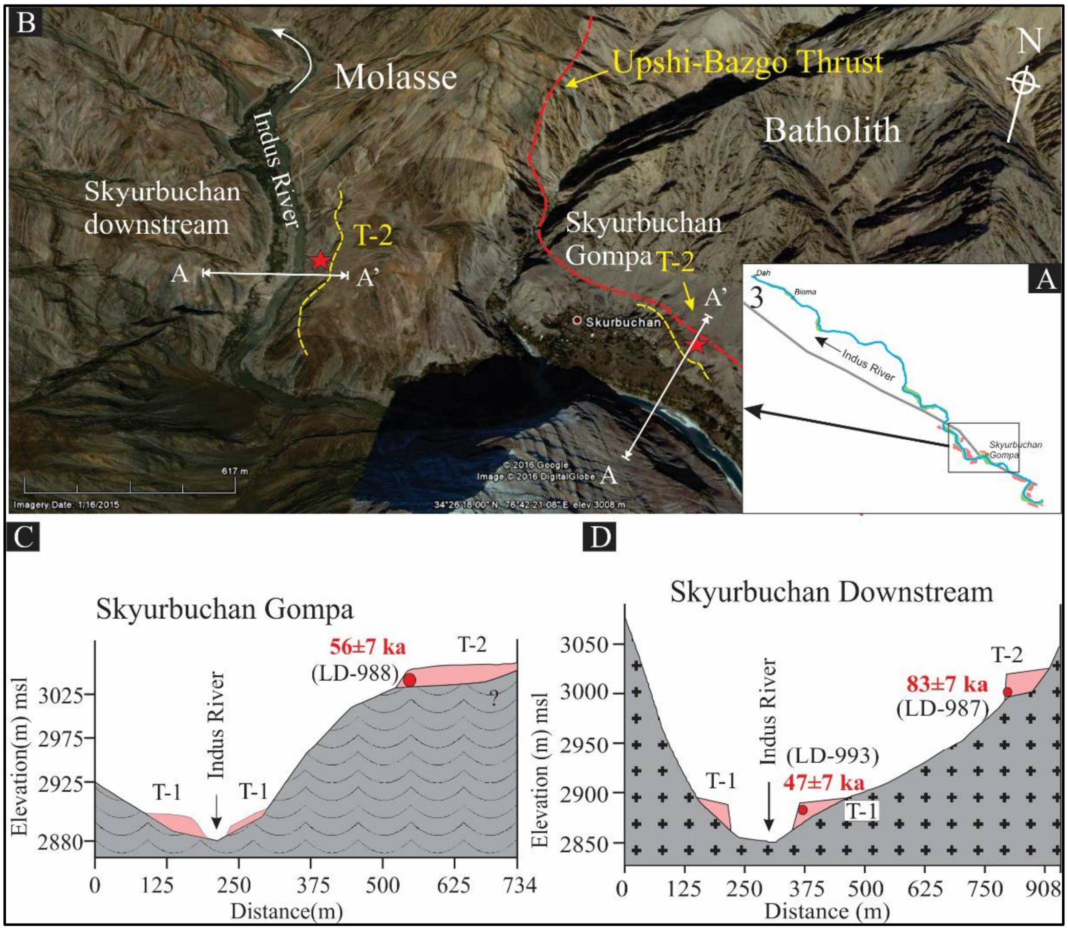

Figure 3.20 (A) A terrace map along the Indus River, shows the studied sections Skyurbuchan Gompa and Skyurbuchan downstream. (B) In google earth image shows Skyurbuchan Gompa section, which lies in the molassic bedrock, whereas the Skyurbuchan downstream section lies in the batholith bedrock. (C) and (D) The valley cross-section of Skyurbuchan Gompa, and Skyurbuchan downstream sections respectively.

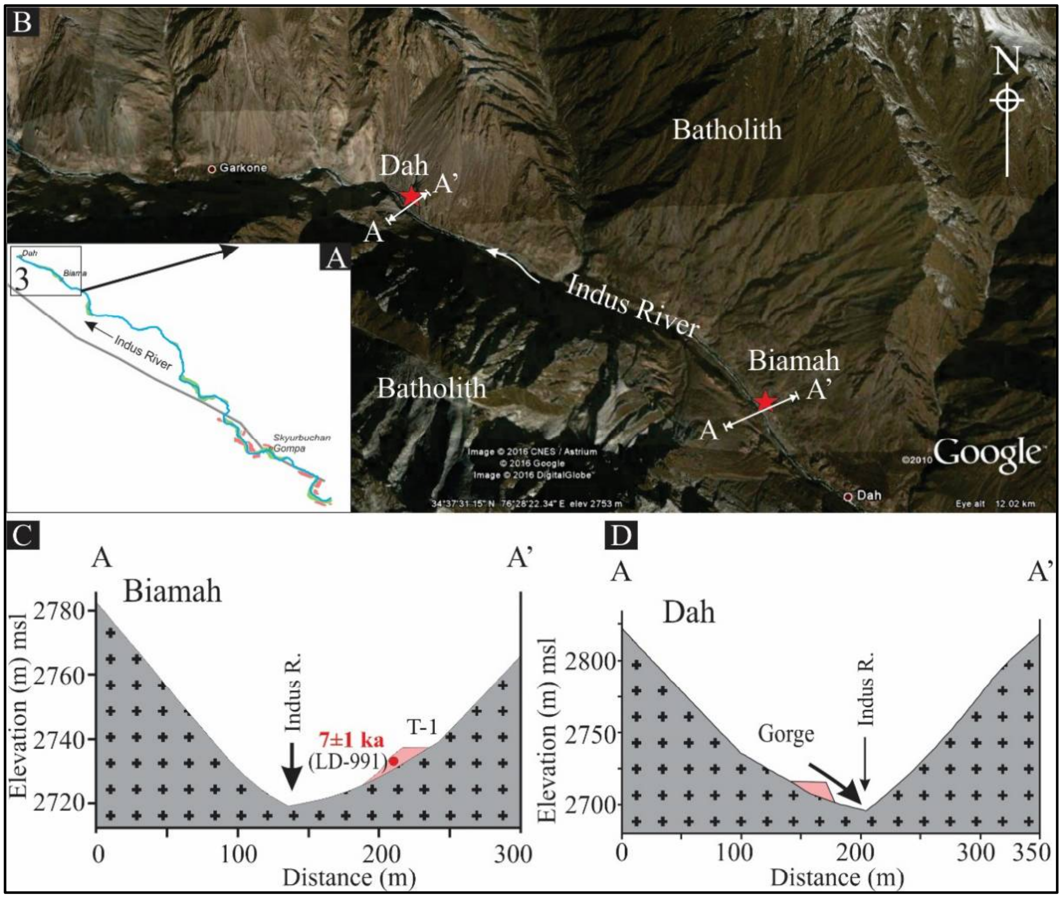

Figure 3.21 (A) A terrace map shows the studied sections Biamah and Dah. (B) The google earth image shows straight channel of the Indus River, here the bedrock is Ladakh Batholith. (C) and (D) The valley cross-sections at Biamah and Dah, respectively. The strath level truncated near Biamah, because Indus entered into the batholith. The V-shaped valley with deep gorge indicating high erosion.

Biamah Section

One level of cut-fill terrace T-1 that rises from the riverbed was observed on the right bank, at this location (Fig 3.21 B). The terrace is made up of a 17 m thick, fluvial sediments. The channel is straight and flows in a narrow V-shaped valley and makes a deep gorge (Fig 3.21 C), where the topographic relief increases to ~ 2000 m. The riverbed is located at 2720 m asl. The OSL age from the top of the T-1 is 7±1 ka (LD-991), which is youngest age, found in all studied sections.

Dha Section

The river flows in a narrow and deep gorge with its ~40 m maximum width, at this section. The interlocking spurs and presence of several rapids indicates the high gradient of the river. The river is flanked by a 15 m thick fill terrace T-1 (Fig 3.21 D). This terrace is composed of fluvial sediment. The bedrock is granites of the Ladakh Batholith.

3.5 Sand ramps

The sand ramps in the Ladakh Himalaya are very common geomorphological features and represents a composite record of hill slope erosion, aeolian and fluvial activity in the region. These sand ramps are very vulnerable to climate change and a minor change in climate can alter the sediment deposition pattern. The physical weathering make loose sediment available for strong winds, which deposit a parallel sheets of sand against the mountain front (Lancaster and Tchakerian, 1996). Globally, the sand ramps of Mojave Desert (Lancaster and Tchakerian, 1996; Rendell and Sheffer, 1996; Pease and Tchakerian, 2003; Bateman et al., 2012), deserts of central Iran (Thomas et al., 1997), central Sahara (Bertram, 2003), southern Namib (Bertram, 2003), Jordan (Turner and Makhlouf, 2002), Mallorca (Clemmensen et al., 1997) and South Africa (Telfer et al., 2012) are published hitherto. This was the first study from the cold desert areas of Himalaya. Spituk, Saboo, Shey, Stakna and Nyoma are major sand ramps located along Indus valley. Largely, these sand ramps were traced near the trunk channel. This reveals that the trunk channel and its tributaries provide sediments for development of these sand ramps.

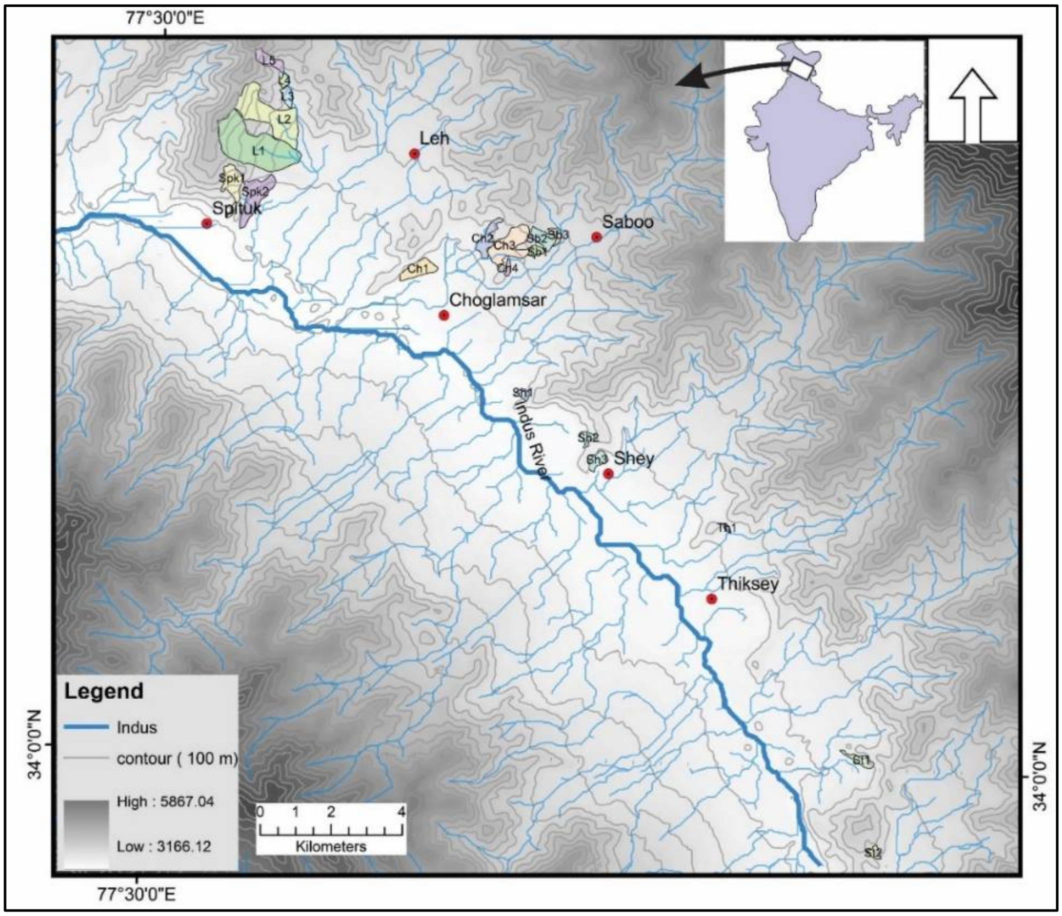

Figure 3.22 Location map shows 21 sand ramp sections in the Leh valley. Blue bold line represents the Indus River, where thin blue lines its tributaries, light grey are elevation contours. The ASTER DEM is used as the base map.

In the Leh valley, twenty one numbers of sand ramps were identified and studied (Fig. 3.22), where the area, slope and aspect define their geomorphology. This study suggests that majority of the sand ramps (14 Nos.) occupy the area < 0.25 km^2, where the geomorphic aspect fall into SE quadrant. From head to toe, these ramps have variable slopes, most of the ramp area falls under the slopes of 11° to 20°. The sand ramp at Leh sand ramp (L 5), is however steeper, ~58% of the ramp area has slope >25°. The sand ramps near Choglamsar, Saboo and Shey are low angled (2° to 10°). Two ramps L 1 and L 2 (near Leh) situated on hill slopes of the northern bank of the Indus River, where river width is maximum, have larger area 1.42 and 2.06 km^2, respectively. The geomorphic data of all studied sand ramps is listed in Table 3.2.

Table 3.2 The studied sites, slope, area covered by a range of slope (%), aspect, probable wind direction and total area covered (km^2) by each sand ramp in Leh valley is listed.

S No.	Studied site name	Lat. / Long.	Slope	Area covered (%)	Aspect	Probable wind from	Total Area (km^2)
Spituk							
1	Spk1	34° 8'29.74" N 77°31'35.91" E	2°-10°	14	S	N	0.45
			11°-20°	55			
			20°-25°	19			
			>25°	12			
2	Spk2	34° 8'8.09" N 77°31'21.64" E	2°-10°	45	SE	NW	0.63
			11°-20°	29			
			20°-25°	7			
			>25°	19			
Leh							
3	L1	34° 9'36.81" N 77°32'45.28" E	2°-10°	38	E	W	2.06
			11°-20°	40			
			20°-25°	12			
			>25°	10			
4	L2		2°-10°	37	SE	NW	1.42

		34° 9'36.81" N 77°32'45.28" E	11°-20°	31			
			20°-25°	12			
			>25°	20			
5	L3	34° 9'36.81" N 77°32'45.28" E	2°-10°	35	EES	WWN	0.14
			11°-20°	59			
			20°-25°	6			
			>25°	0			
6	L4	34° 9'36.81" N 77°32'45.28" E	2°-10°	26	E	W	0.07
			11°-20°	47			
			20°-25°	14			
			>25°	13			
7	L5	34° 9'36.81" N 77°32'45.28" E	2°-10°	5	SE	NW	0.24
			11°-20°	18			
			20°-25°	19			
			>25°	58			
Choglamsar							
8	Ch1	34° 7'24.44" N 77°34'48.74" E	2°-10°	75	SSE	NNW	0.04
			11°-20°	17			
			20°-25°	3			
			>25°	5			
9	Ch2	34° 7'29.06" N 77°36'24.21" E	2°-10°	76	W	E	0.30
			11°-20°	18			
			20°-25°	5			
			>25°	1			
10	Ch3	34° 7'29.06" N 77°36'24.21" E	2°-10°	53	SW	NE	0.74
			11°-20°	42			
			20°-25°	5			
			>25°	0			
11	Ch4	34° 7'29.06" N 77°36'24.21" E	2°-10°	42	NE	SW	0.06
			11°-20°	42			
			20°-25°	11			
			>25°	5			
Saboo							
12	Sb1	34° 5'40.24" N 77°36'45.62" E	2°-10°	58	S	N	0.08
			11°-20°	39			
			20°-25°	3			
			>25°	0			
13	Sb2	34° 5'34.05" N 77°36'45.09" E	2°-10°	64	S	N	0.26
			11°-20°	33			
			20°-25°	3			
			>25°	0			
14	Sb3	34° 7'57.93" N 77°37'15.09" E	2°-10°	93	SE	NW	0.09
			11°-20°	7			
			20°-25°	0			
			>25°	0			
Shey							
15	Sh1	34° 5'33.60" N	2°-10°	47	NW	SE	0.08
			11°-20°	13			
			20°-25°	14			

		77°36'45.03" E	>25°	26			
16	Sh2	34° 4'34.98" N 77°38'10.19" E	2°-10°	7	W	E	0.10
			11°-20°	49			
			20°-25°	27			
			>25°	17			
17	Sh3	34° 7'45.60" N 77°37'18.44" E	2°-10°	39	SE	NW	0.19
			11°-20°	43			
			20°-25°	12			
			>25°	6			
Thiksey							
18	Th1	34° 3'37.96" N 77°40'34.54" E	2°-10°	37	S	N	0.03
			11°-20°	30			
			20°-25°	16			
			>25°	17			
19	Th2	34° 2'4.69" N 77°41'23.43" E	2°-10°	29	W	E	0.12
			11°-20°	62			
			20°-25°	9			
			>25°	0			
Stakna							
20	St1	34° 0'10.94" N 77°43'4.48" E	2°-10°	34	SW	NE	0.17
			11°-20°	42			
			20°-25°	12			
			>25°	12			
21	St2	33°58'42.81" N77°43'27.05 " E	2°-10°	15	SE	NW	0.09
			11°-20°	55			
			20°-25°	26			
			>25°	4			

Spituk sand ramp

Spituk sand ramp overlies a paleo-lake deposit and flanked on S-SE face of the Ladakh Batholith (Fig. 3.23). The 15 m thick section has 8 m aeolian sand. Geomorphologically, two aeolian units have a deformed intervening unit of intra-dunal lake deposits. The aeolian sediments, yielded an age 20±2 ka (LD-1071).

Saboo sand ramp

Saboo sand ramp also accumulated on SE facing hill slope of the Ladakh Batholith (Fig. 3.24). A small stream, called Saboo nala, flowing NE to SW, also interacts with this sand ramp. A 4.5 m thick section is a combination of aeolian, fluvial and ramp slope stability sediments.

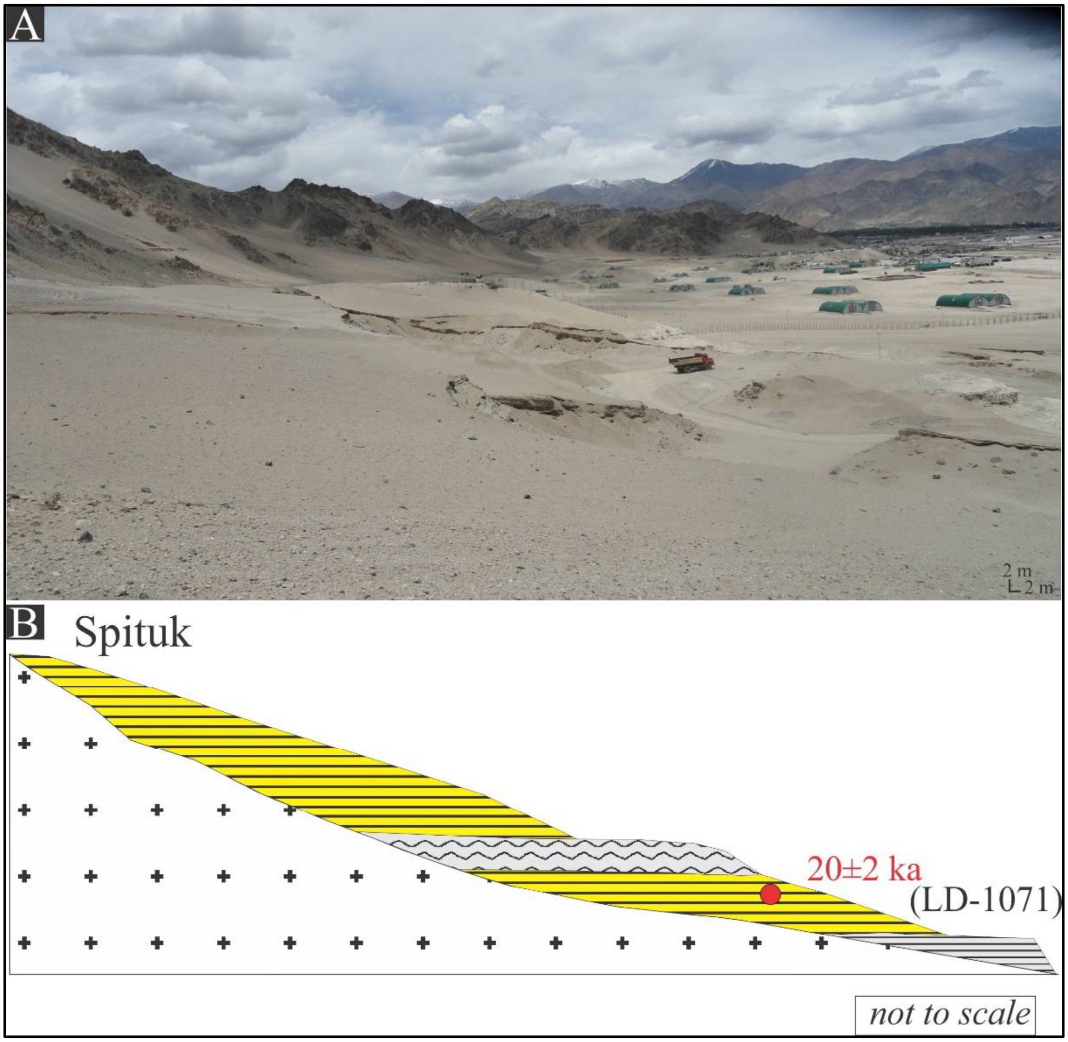

Figure 3.23 (A) A picture showing Spituk sand ramp section. (B) The ramp profile where bedrock is batholith; horizontal line with yellow base are aeolian sand; grey wavy beds are intra-dunal lacustrine deposits and horizontal parallel grey line are Spituk paleo-lake deposits.

The basal aeolian unit is overlain by fluvial and talus deposits. Two samples from aeolian sand and one from overlying fluvial unit yielded 12±0.7 ka (LD-1072), 8±1 ka (LD-1073) and 7±0.5 ka (LD-1074, fluvial), respectively.

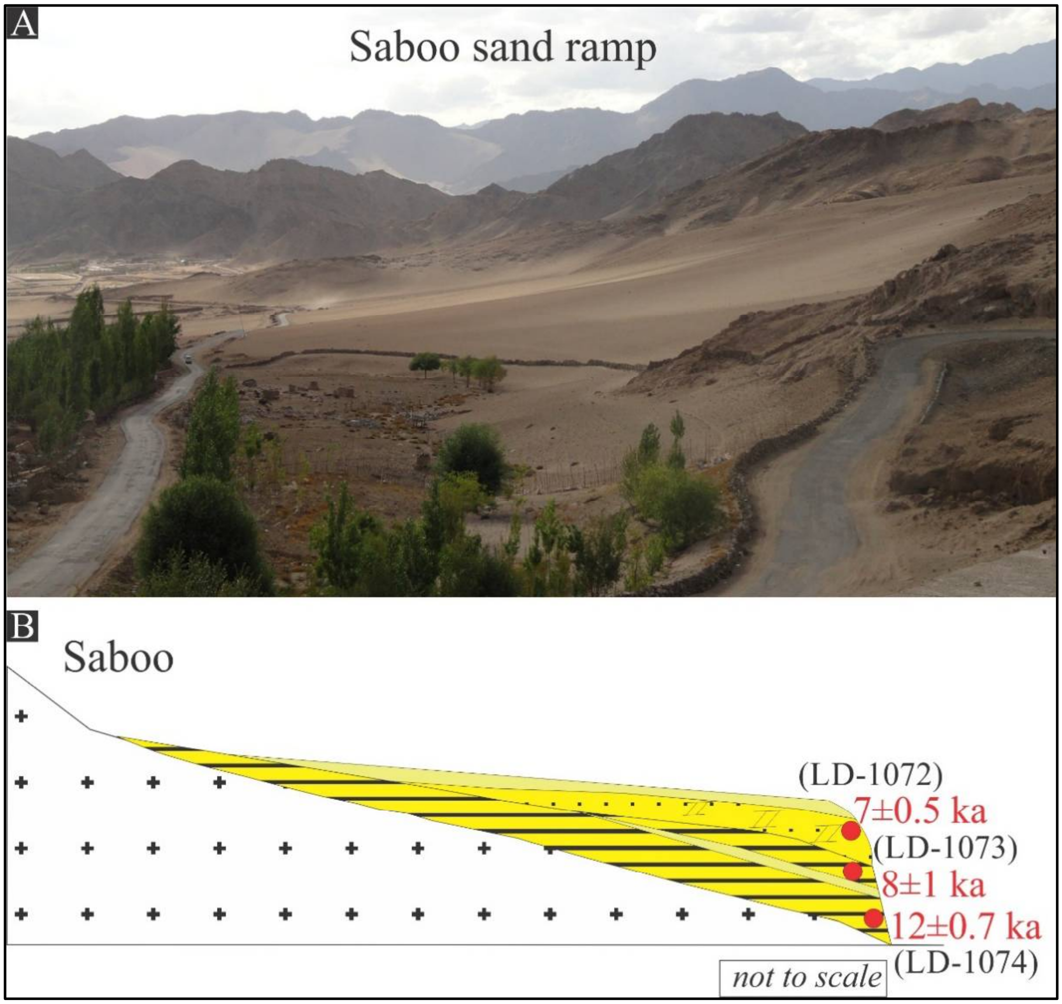

Figure 3.24 (A) A photograph showing the Saboo and ramp. (B) The Saboo ramp profile shows a composite deposits of aeolian, fluvial and talus environment.

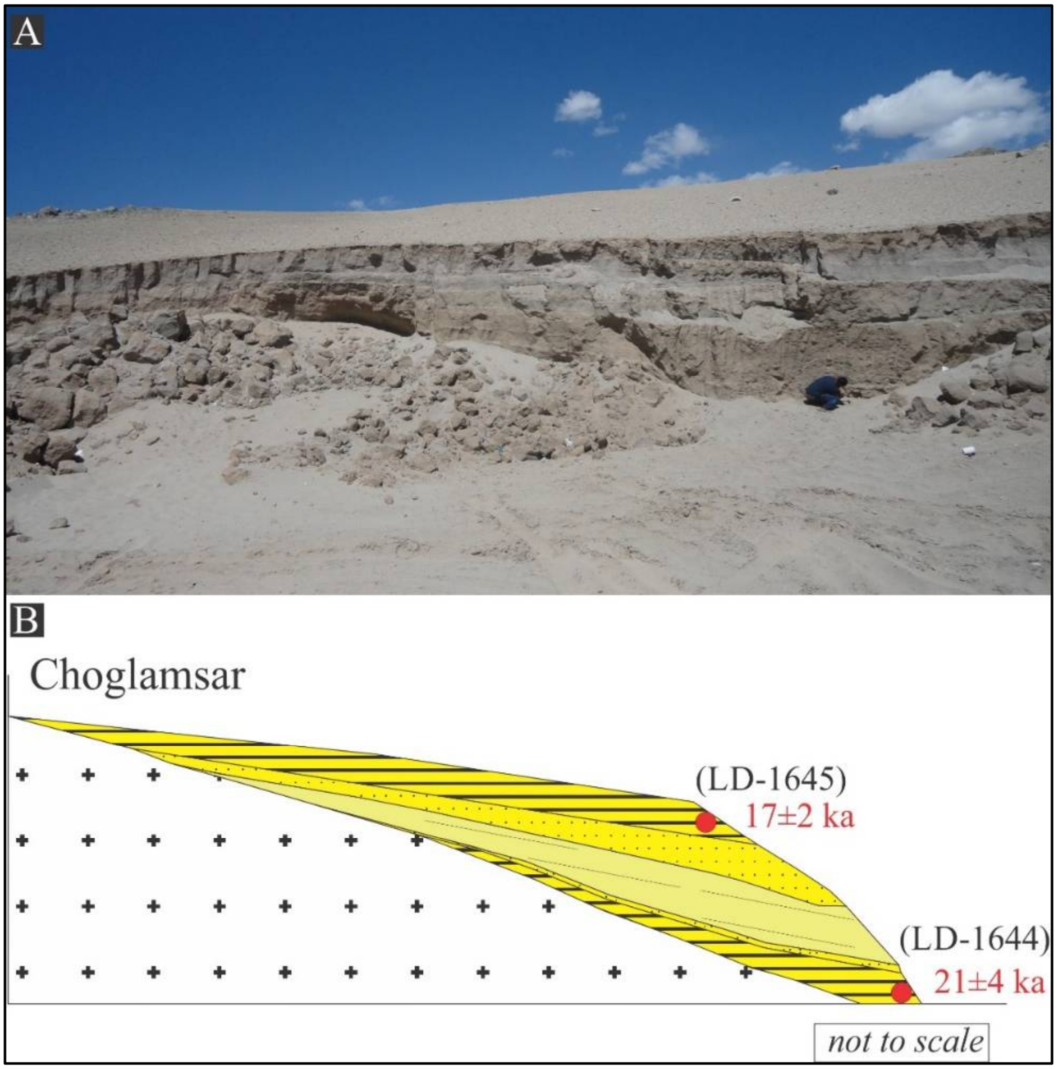

Figure 3.25 (A) A photograph of Choglamsar sand ramp. (B) The ramp profile shows a composite deposits of aeolian, fluvial and talus sediment.

Choglamsar sand ramp

A 4.1 m thick ramp sequence (Ch-3 in Table 1; Fig. 3.25), accumulated on a south facing Ladakh Batholith, includes aeolian, fluvial and talus deposits. The top and basal aeolian sand units yielded OSL ages 17±2 ka (LD-1645) and 21±4 ka (LD-1644), respectively.

Shey sand ramp -2

A 14.5 m thick section exposed at Shey, shows a 6 m thick aeolian sand at base, with an erosional contact, overlain by a 4 m thick hill slope talus deposits. Further, a 2 m intra-dunal lake deposits followed by a 1.5 m aeolian sand overlies this. The section is capped a 1 m thick parallel bedded hill slope deposits (Fig. 3.26). The basal aeolian unit and upper hill slope deposit yielded 44±3 ka (LD-1647) and 26±1 ka (LD-1646), respectively.

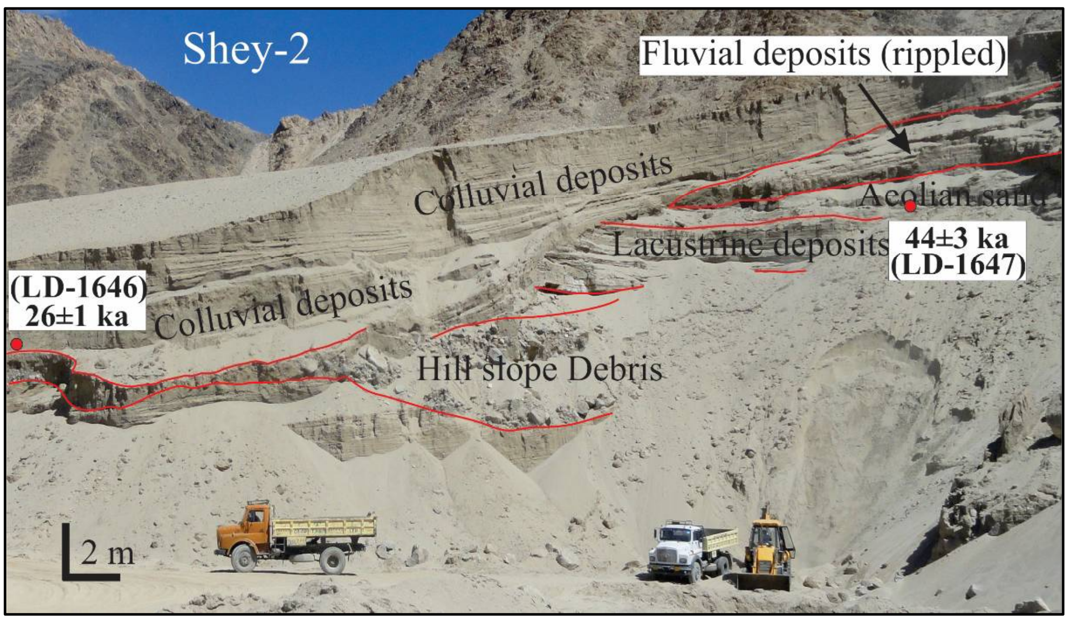

Figure 3.26 A photograph of Shey-2 sand ramp section. This section also has composite sediments of various depositional environment.

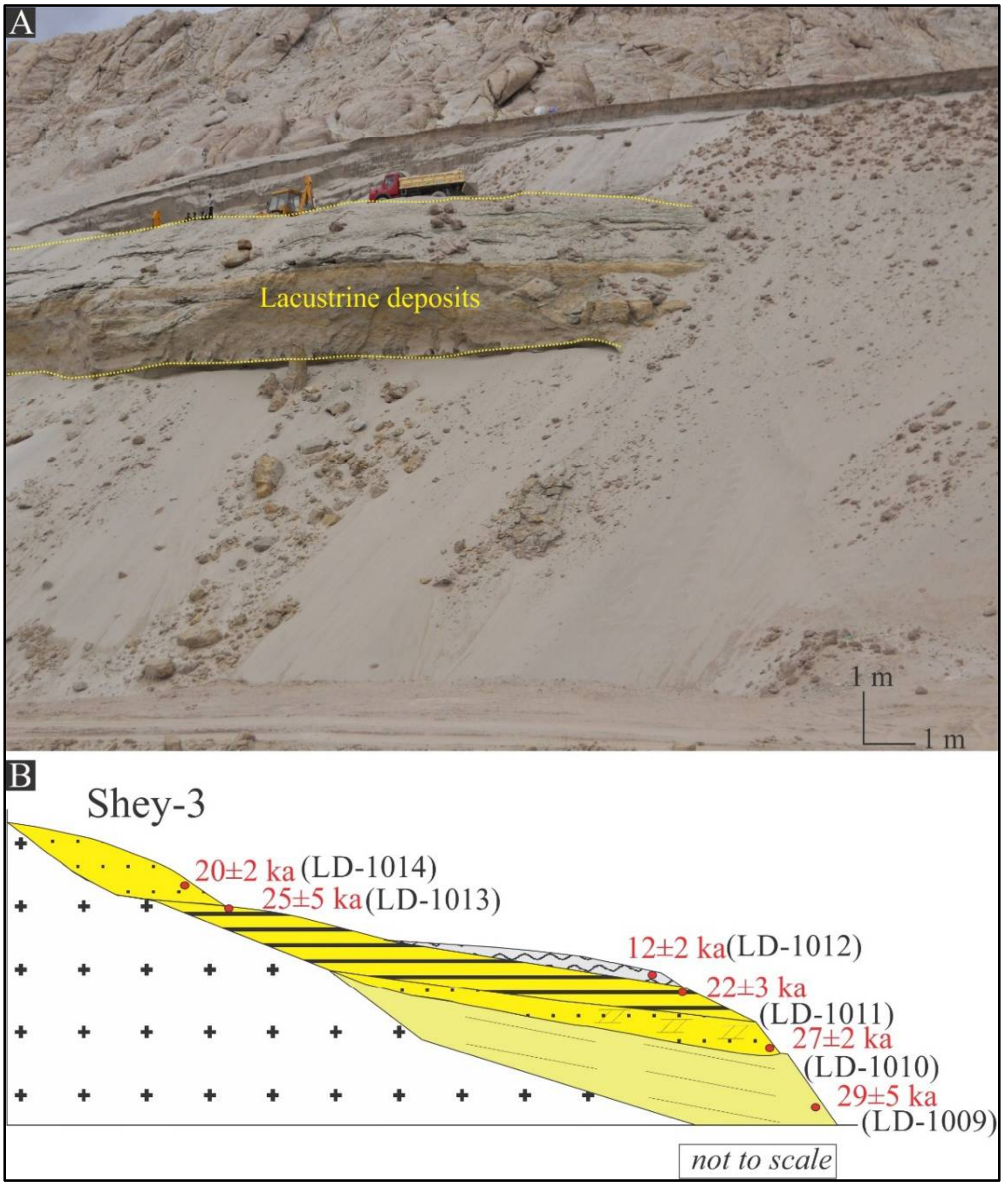

Figure 3.27 (A) A panoramic view of Shey-3 sand ramp section, shows talus, lacustrine and aeolian sediments. (B) The ramp profile, demarking the extension of different sedimentary environment in one composite section.

Shey Sand ramp -3

An 18 m thick section, exposed due to sand mining, was studied. At the base an 8 m hill slope talus deposit is exposed, followed by a ~ 5 m thick channel deposits. This is overlain by two aeolian sand units, each has ~ 2 m thickness. A 1 to 1.5 m thick intra-dunal paleolake deposits is seen preserved in the depression located between these two aeolian units (Fig. 3.27).

The talus was deposited at 29±5 ka (LD-1009), and the fluvial unit was aggraded at 27±2 ka (LD-1010). Three OSL samples from upper aeolian units yielded 22±3 ka (LD-1011), 25±5 ka (LD-1013), and 20±2 ka (LD-1014). The intra-dunal lake formed at 12±2 ka (LD-1012).