Chapter 4

Sedimentology

To succeed in your mission, you must have a single minded devotion to your goal.

- Dr. A.P.J. Abdul Kalam

CHAPTER 4 SEDIMENTOLOGY

4.1 Introduction

The lithofacies analysis is the most widely and successfully field based research used in sedimentology to decipher its depositional environment. The physical and chemical characteristics of any sedimentary entity is termed as Lithofacies (Nichols, 2009). This includes physical structures, grain size, color, bioturbation, vertical and lateral geometry and type of upper and lower contacts of the sedimentary units. The sum total of these observations is termed as lithofacies. Subsequently group of genetically related lithofacies is called as lithofacies association. Lithofacies analysis of terrace sediments of Indus River helped to understand its sedimentary record and palaeo- depositional environment. Based lithofacies characters the Indus deposits were divided into six major lithofacies (sum of both gravel and sand facies) and based on their genetic relationships, the identified lithofacies were classified into two lithofacies associations after Miall (2006). The gravel lithofacies has three Subfacies. Subfacies A, where the constituent clasts are granitic and derived from northern Ladakh Batholith. Subfacies B, comprised clasts from the Indus Molasse and Subfacies C, is of mixed source and represents deposition in the trunk channel of the Indus.

4.2 Sedimentary architecture of Indus River and associated sediments

4.2.1 Gravel Facies

4.2.1.1 Gh (Clast supported horizontal stratified imbricated gravels)

This lithofacies comprises well-rounded, moderately-well sorted and imbricated clasts (Fig 4.1). The clast size ranges from 4 to 50 cm. The individual facies make 0.5 m to few meters thick multistoried, vertically fining upward sequences. Laterally, these units are sheet to lensoid in shape, with lateral extent of ~50 m. The matrix ranges between 10 and 30%. This facies is common in all the studied sections along the Indus River. This facies has three subfacies, out of which, ~ 70 % of Gh facies is deposited as Subfacies C.

The Gh lithofacies represents deposition as channel bars (Reineck and Singh, 1973). The vertical aggradation of this facies suggests high sediment load and that the deposition occurred during the high sediment to water ratio conditions. In general, the upper and lower contacts of this facies are found with Sh and Sp (sand facies) and Gcm and Gp facies, respectively. The Gcm and Gp facies can be converted to Gh facies if the threshold discharge for gravel lifting meets. The waning phase of the flood, settled the fine suspended sediment and deposited in the form of Sh and Sp facies.

4.2.1.2 Gcm (Clast supported massive gravels)

This lithofacies is 1-10 m thick and made up of thick well rounded, moderately to well sorted, clast supported massive gravels (Fig 4.2). The clast size ranges from 3 to 80 cm and clasts often show imbrication. This facies is observed as laterally coalescing lensoidal units of Gcm that often laterally extend for ~30 m. Often the units are found vertically stacked more than one depositional event, where individual events are seen separated by lenses of fine sand. The matrix is grey to dark grey in colour, texturally fine to coarse sand with granules that constitute 10-20% of the bulk volume. This lithofacies also has three Subfacies, where ~ 59 % is covered by Subfacies B.

The amalgamation of channel bar during riverbed accretion developed the Gcm facies. This facies suggests a low strength laminar to turbulent flow. Commonly this lithofacies is deposited with an erosional base and is bounded by Gp and Gh facies. The successive flood events erode upper few cm of previously deposited fluvial unit and deposit new sediment in the form of Gcm facies (Miall, 2006).

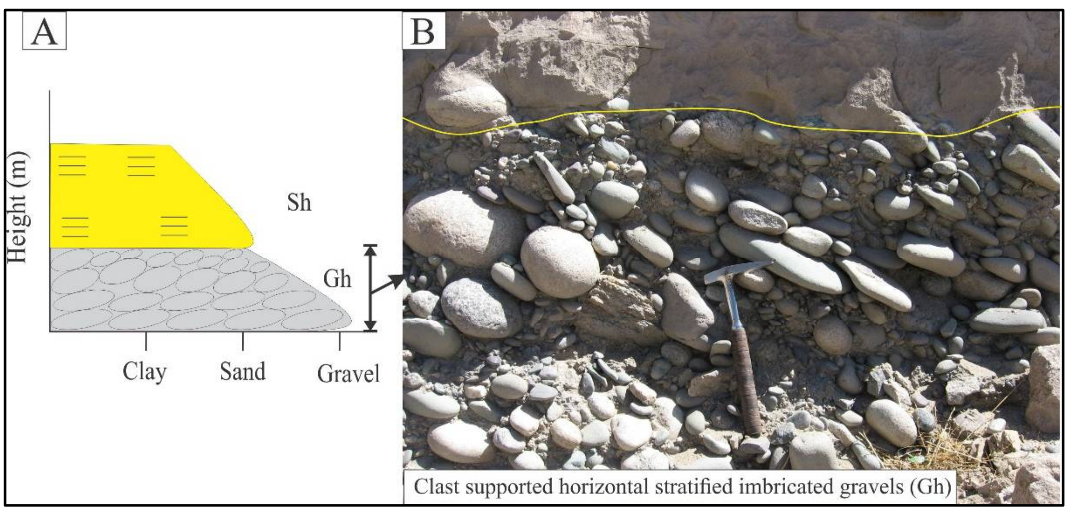

Figure 4.1 (A) Litholog showing clast supported horizontally stratified imbricated gravels (Gh) facies. The longer axis of discoid gravels are dipped to upstream direction, due to high energy of Indus River. (B) A photograph giving a view of the Gh facies at Stakna-1 section.

4.2.1.3 Gmg (matrix supported graded gravels)

This facies is comprised of 0.35-3 m thick units of sub- angular to poorly rounded, moderately to poorly sorted, matrix supported graded gravels (Fig 4.3). The gravel size ranges from 5 to 55 cm. The matrix contribution to this facies is up to 40% of the volume, and it is medium to gritty sand. The individual unit often grades upward into sand units which indicate termination of a flood event. The beds of this facies have sharp erosional relationship with the underlying units. This facies is also divisible into three Subfacies, where Subfacies A is found widely spread (~69 %).

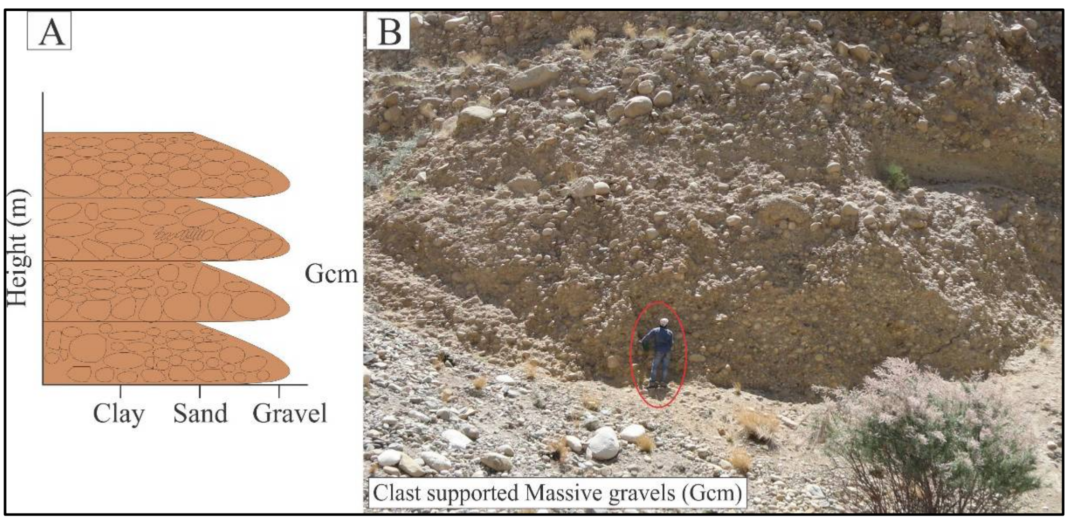

Figure 4.2 (A) Litholog showing a thick succession of clast supported massive gravels (Gcm) facies. (B) The photograph showing accretion of this facies at Upshi-L section due to amalgamation of channel bars.

The Gmg was deposited by high energy plastic debris flow where the clasts are suspended in the plastic silty- sand medium with low water concentration (Miall, 2006) and represent episodic flood events.

4.2.1.4 Gmm (matrix supported massive gravels)

This facies includes sub-angular to poorly rounded, poorly sorted, matrix supported massive gravels. Clasts size is 5 to 100 cm and the unit ranges in thickness from 2 to 6 m. Matrix is medium to gritty sand, contribute ~ 40-50 % of the total volume. This unit is massive and has erosional contacts with the lower as well as the upper unit.

This unit indicates a high energy plastic debris flow (Ray and Srivastava, 2010).

4.2.1.5 Gp (clast supported planar cross bedded gravels)

This facies comprises 1- 3 m thick well rounded, moderate to well sorted, planar cross bedded gravels and is divisible into Subfacies A, B and C (Fig 4.4). All the subfacies have almost equal contribution to the Gp lithofacies. The gravels of 5 to 10 cm diameter have cross beds with a toe angle of 10-15°. The matrix is ~10% medium and pebbly sand. Internally it makes co-sets of fining upward units capped by sandy lenses and invariably has a basal erosional contact.

The Gp lithofacies is formed by migration of high relief 2D bedforms in a channelized flow with a velocity of 2-3 m/s forming channel bars (Shukla, 2009). Generally, this facies has lower and upper contact with Gh and Gcm lithofacies, respectively. The channel bar aggradation and amalgamation in peak discharge condition can lift the bedload and form a hump like structure. The next erosional or deposition events (Gh or Gcm facies) removes the upper few centimeters and makes an erosional contact.

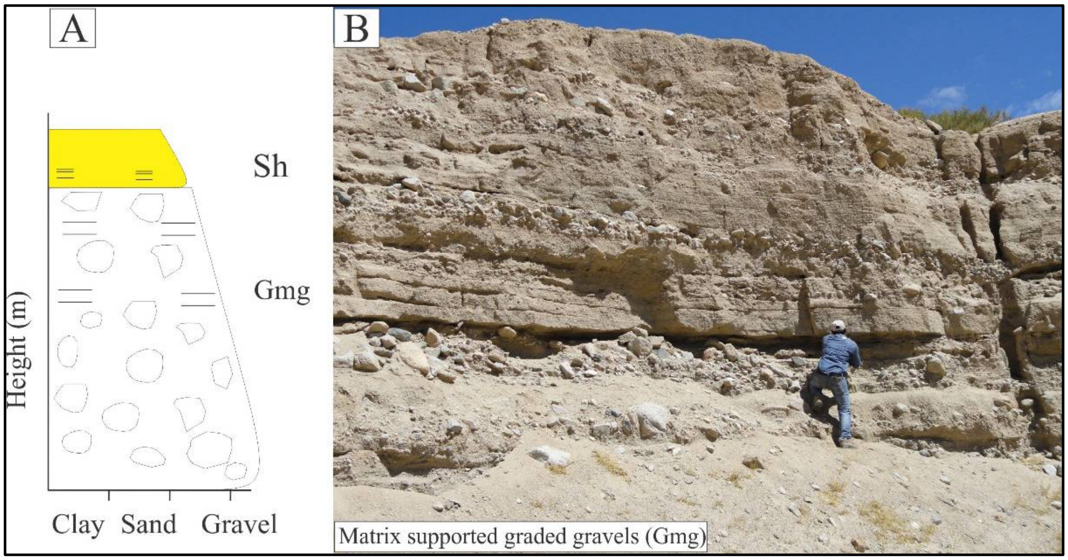

Figure 4.3 (A) The matrix supported graded gravels consist of sub-angular to poorly rounded, moderately to poorly sorted gravels. This facies is often capped by a sand facies. (B) Panoramic view of fan bound sequence showing the Gmg facies.

4.2.2 Sand Facies

4.2.2.1 Sh (Horizontally laminated sand)

This lithofacies comprises 0.25-3 m thick horizontally bedded, parallel laminated units of coarse to fine sand (Fig 4.5 A, B). The individual lamina is 1-2 mm thick. This unit is common in all studied sections and occurs in sheet or lensoid geometry laterally extending up to 20 m. This facies occurs in association with the gravel facies.

The Sh lithofacies is deposited on the top of the channel bars under waning flood conditions and generally represents the termination of a flood event or deposition in a shallow back bar channel (Miall, 2006).

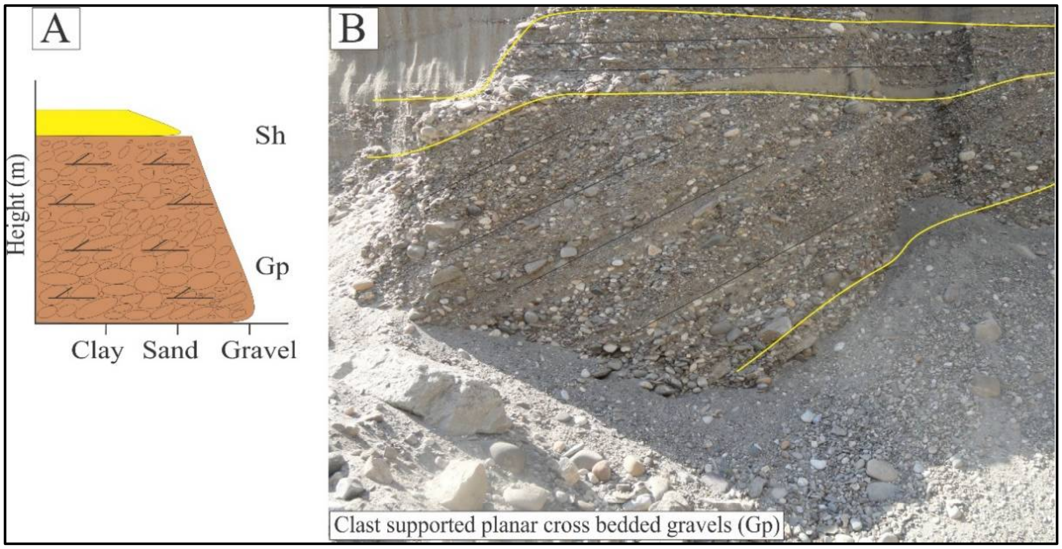

Figure 4.4 (A) The well rounded, moderately to well sorted gravels of clast supported planar cross-bedded gravels (Gp). (B) The photograph showing Gp lithofacies exposed at Nurla section.

4.2.2.2 Sp (planar cross bedded sand)

This facies comprises 0.30 m to 4 m thick greyish coloured planar cross bedded medium to coarse sand (Fig 4.5C, D). Individual bed is about 10 to 15 cm thick. The cross laminations are ~2 mm thick and make foreset angle of ~15° and often occur as co-sets. This unit is observed as a lenticular heap that laterally extends from 2 to 10 m.

The planar cross bedded sand facies is formed by the movement of 2D bedforms on a channel bar (Miall, 2006).

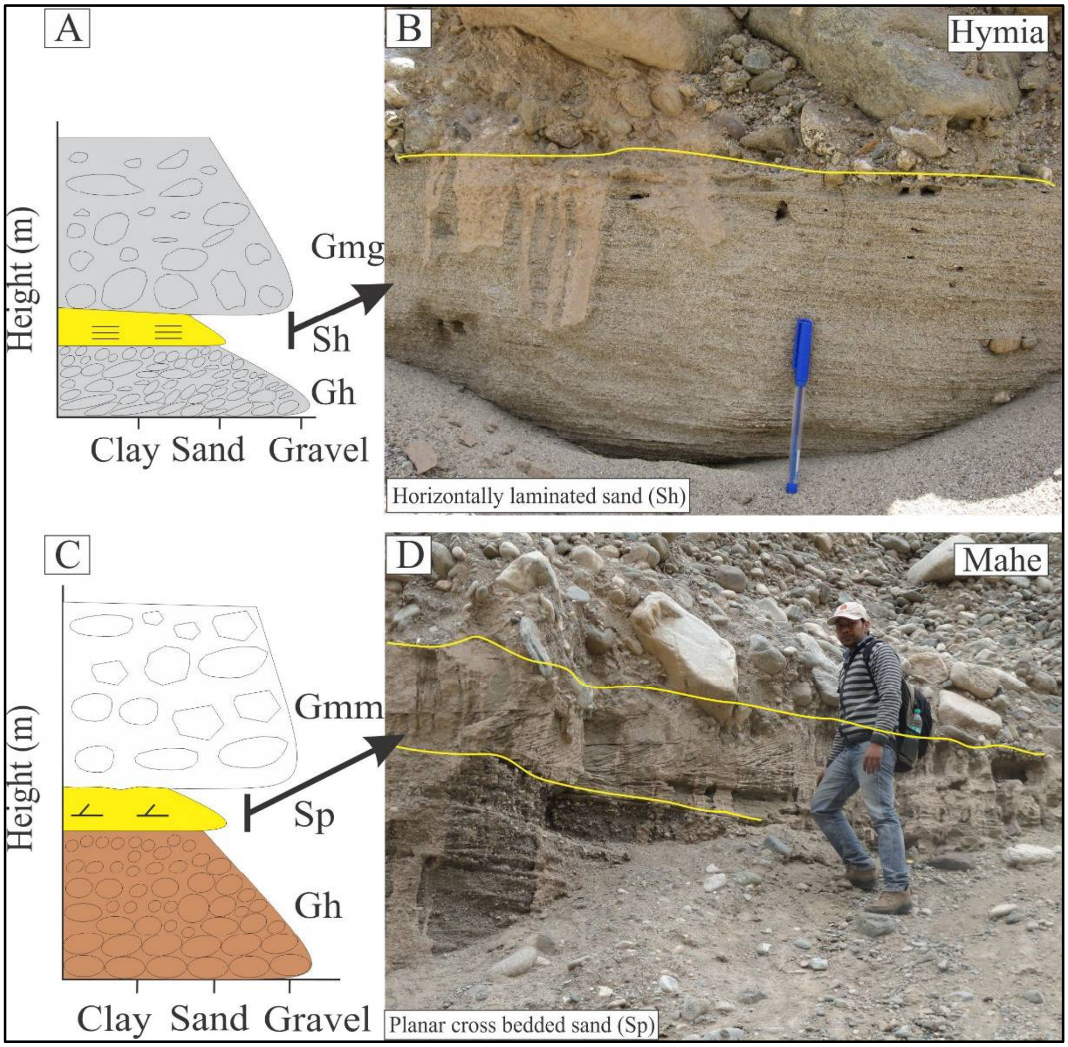

Figure 4.5 (A) and (B) showing the litholog and photograph of horizontally laminated sand (Sh) lithofacies from Hymia section. The Sh facies is generally preceded by the gravel facies. (C) Showing a planar cross bedded sand facies (Sp), having sharp and erosional contacts with lower channel bound gravelly unit and upper fan bound unit, respectively at the Mahe section. (D) Photograph showing the same section showing Sp facies.

4.3 Lithofacies Associations

Genetically related lithofacies were clubbed as Lithofacies Associations (LA) and accordingly in terrace deposits two lithofacies associations were identified *viz.* Channel bound LA and fan bound LA.

4.3.1 Channel bound lithofacies association

The channel bounded LA is 2.5 – 27 m thick with up to ~50 m wide multistoried units comprising Gh, Gcm, Gp, Sh and Sp lithofacies. Internally, the units are fining upwards and thickness of individual gravel body is ~ 5 m. The units are stacked with erosional base and are often separated by lenses of planar laminated sand facies. They can be unconformably overlain or underlain by Gmg lithofacies. The ideal 2-5 m thick sequence will be made up of Gcm at the base followed by Gh or Gp overlain by Sh. Sp often occurs as lenses that mark the top of fining upward individual depositional event (Fig 4.6).

Thick vertical aggradation and facies association indicate braided channels with high sediment flux (Ray and Srivastava, 2010). Sandy units capping these indicate waning phase of flood deposited in regular floods with broad hydrograph, suggestive of warm and wet climatic phase with established rainfall season. The intervening units of Gmg suggest debris flows of a storm event.

4.3.2 Fan bound lithofacies association

This LA comprises unsorted, angular to sub-rounded gravels with high matrix concentration consisting of Gmg, Sh, and Sp facies. Individual units that are internally fining upwards often show tabular bedded nature that can run laterally for several tens to hundred meters. These units are sometimes capped by a horizontal or planar cross bedded sandy unit and can be multistoried. Gravel composition of this association is generally from single provenance (Ladakh Batholith or Indus Molasse) and represents tributary or outwash fan aggradation via sheet floods originating from the glaciers (Srivastava et al., 2013). Ideal sequence that can range up to 15 m in thickness comprises Gmg at the base followed by Sp and Sh (Fig 4.6). The fine grained facies demarcate the termination of an individual event. The associated sandy units with the Gmg facies represent waning flash floods (Sundriyal et al., 2007).

4.4 Sedimentary architecture of Sand ramps

Sand ramps are deposits accreted on the hill slope and follow the geomorphic slope of the valley walls. The sedimentary architecture is a composite of hill slope, aeolian, fluvial and lacustrine processes. Based on physical structures, colour, matrix, gravel size & their composition, four lithofacies were identified. Five sand ramps between Spituk and Shey near Leh city were studied in detail. The major lithofacies identified and the stratigraphy of the sections is discussed below:

4.4.1 Parallel laminated medium sand

This facies is made up of 1.0-8.0 m thick, grey to reddish grey, moderately to well sorted, moderately bioturbated, parallel laminated medium sand unit. Internally, 1-

2 mm thick parallel laminations are seen that gently follow the dip of the hill slope (Fig 4.7).

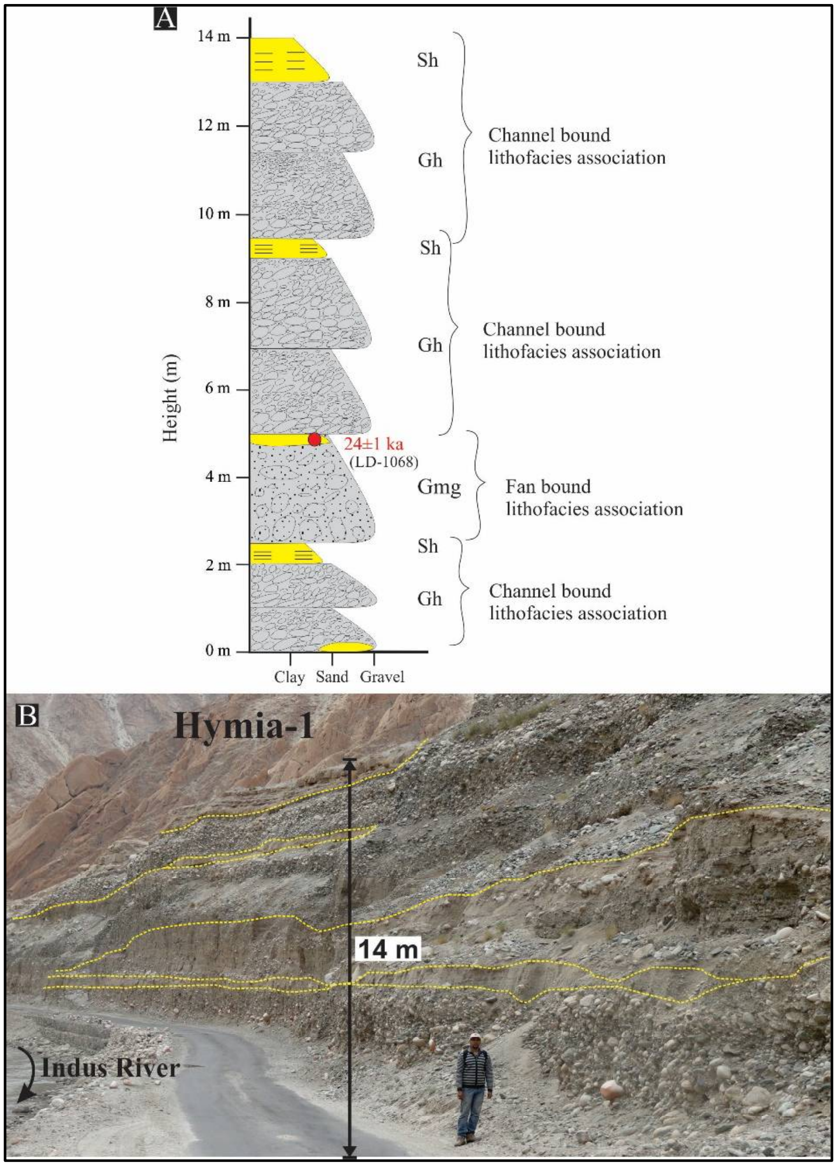

Figure 4.6 Hymia-1 section having both channel bound and fan bound lithofacies associations. (A) Litholog of Hymia-1 section representing the association of Gh-Sh as a channel bound, and Gmg-Sh as a fan bound lithofacies association. (B) A picture of Hymia-1.

This facies is thicker towards the toe and makes relatively thin units in steeper and head ward segments of the ramp. This makes an apron all over that may extend from the toe to head of the sand ramp. At places, in vertical stratigraphy, it shows development of hard crust. The beds of hard crust are yellow- brownish in colour, 3-5 cm thick and made up of poorly sorted granules to pebble size locally sourced granitic particles and follows the geometry of the hill slope.

This facies represents active accretion of windblown sand on the hill slopes. The thickness of this facies is dependent upon the gradient of the substrate and thus is not suggestive of duration or intensity of arid phase. In relatively wetter conditions when aeolian deposition diminishes, the hill slope debris covers the ramp surface. The available moisture and fine sand aided by algae, bind the hill slope debris, which make the hard crust and thus represent a sort of hiatus in aeolian sedimentation. Such hard crusts on the aeolian bound surfaces are also known as dune bounding surface representing relatively wetter climatic phase (Talbot, 1985; Lancaster and Thakerien, 1996).

4.4.2 Poorly sorted coarse sand

A 1.0-4.0 m thick, poorly sorted, grey coloured coarse sand makes this facies. Generally, this facies is massive, at places showing cross beds with a scoured base and pebbly channel lag. The laminae of cross beds are lined by clay curls (Fig 4.7). It occurs at the distal part of the sand ramp.

This facies is deposited by a channel or gullying activities on the distal slope of the sand ramp (Lancaster and Thakerien, 1996). The presence of scouring structures, coarse grained sand and clay curls along the laminae suggests higher erosive event that might take place in an ephemeral stream during sporadic high rainfall (Krapf et al., 2003; Brook et al., 2006). This indicates fluvial interaction in the sand ramp building process.

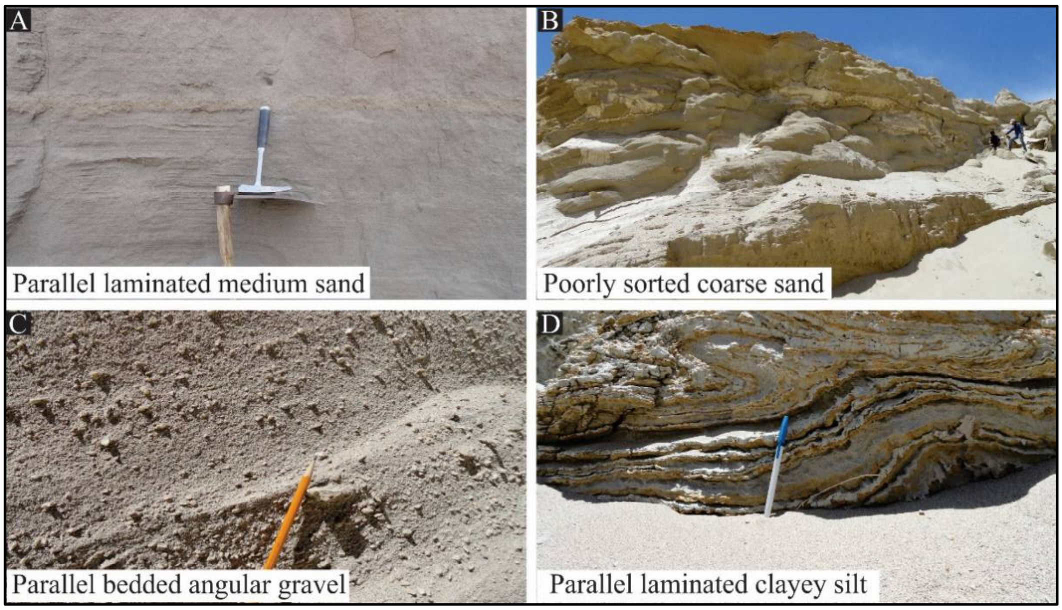

Figure 4.7 A photograph of identified sand ramp facies: (A) Parallel laminated medium sand at Saboo, (B) Poorly sorted coarse sand, (C) Parallel bedded angular gravel, and (D) Parallel laminated clayey silt at Shey.

Parallel bedded angular gravel

This facies consists of 1.5-8.0 m thick, parallel bedded angular gravels. Individual beds are inclined at 5-7° with the ramp slope and are 5-10 cm thick. Within each bed, there are 2-5 cm thick angular gravels incorporating 10-20% of reworked aeolian sand as matrix. The gravels are of granitic composition and are a result of the erosional event from the adjacent hill slope due to episodic rainfall. This unit occurs above or below the parallel laminated medium sand (Fig 4.7 C).

The parallel bedded angular gravel facies represents the talus deposited under sheet flow conditions on the hill slope or over the previously deposited aeolian sediment. The angular granitic clasts produced due to freezing and thawing of the exposed bedrock and strewn on the hill slope are reworked and deposited as sheet. The aeolian sand acts as matrix. This may represent an onset of wetter conditions or a break in aeolian sedimentation (Lancaster and Thakerien, 1996; Clarke and Rendell, 1998).

4.4.4 Parallel laminated clayey silt

A 0.5-7.0 m thick, parallel laminated clayey silt facies is found laterally associated with parallel laminated medium sand facies and is often superimposed on parallel bedded angular gravel facies. Internally, the clayey silt unit frequently exhibits pene-contemporaneous deformation (PCD) structures in the form of convolute beddings (Fig 4.7D), where, the deformed clayey silt lamination are oxidized. This facies is interpreted as intra-dunal playa lake deposits and may suggest reduction in aeolian activity and expansion of intra-dunal lake during climatically wet phases (Clarke and Rendell, 1998). Deformation structures are uniform in geometry and thus may be the result of cryoturbation.

4.4.5 Grain size characterization

A total of 4.5 m thick sedimentary sequence of Saboo sand ramp is a composite record having aeolian, fluvial and talus units. The bottommost unit is composed of aeolian sand with a ~5 cm thick layer of hard crust 3.3 m above the base. Above this, a scour filled fluvial sand bed is seated.

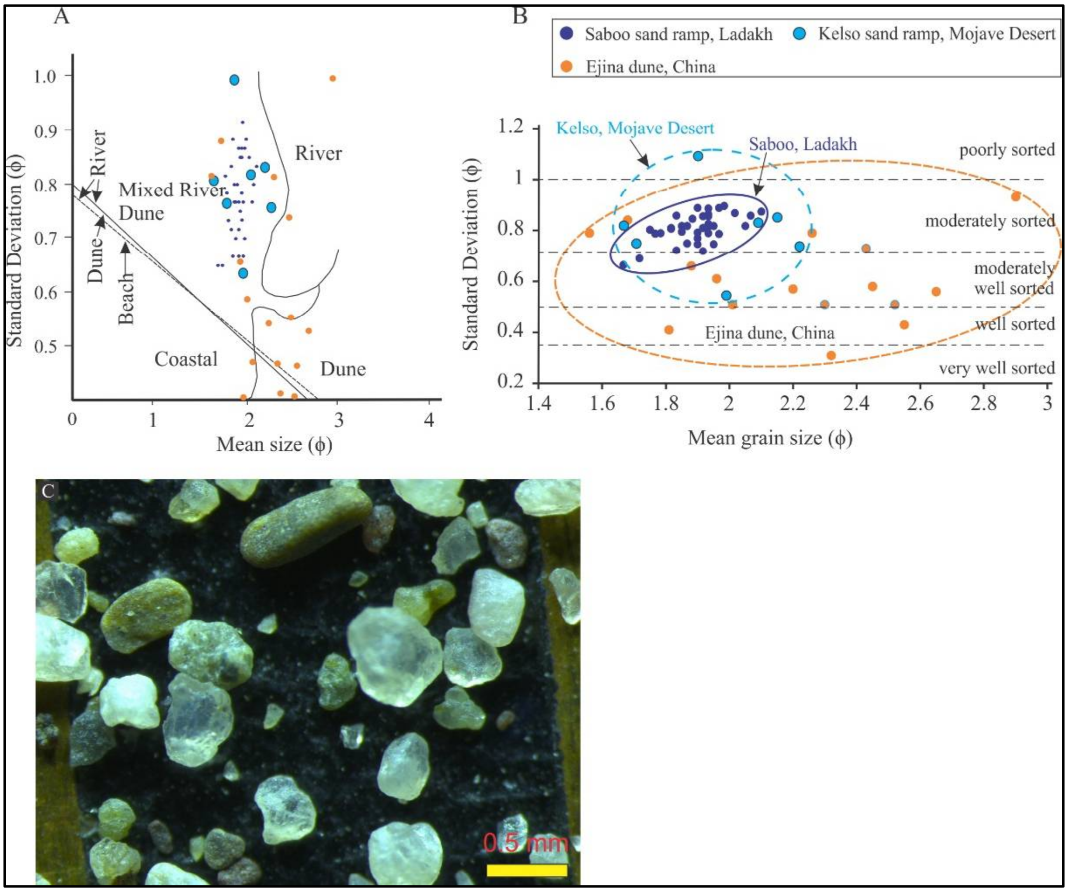

Figure 4.8 (A) Bivariate plot between mean size and standard deviation of Saboo, Kelso (Mojave Desert) and Ejina dunes (Chinese Desert) in Passega's curve (1964, 1977). (B) Comparison of mean size and standard deviation of these sand ramps. The narrow scattering characterizes the aeolian sand of Saboo and Leh valley. (C) The stereographic image of aeolian sand unit showing the angularity of quartz grains.

The whole sequence is again blanketed by an 8 cm thick hard crust at the top which also forms the modern surface of the ramp. The grain size characterization as performed on the whole Saboo sand ramp stratigraphy at 10 cm resolution.

Mean size and standard deviation (SD) of Saboo sand ramp plotted in Passega's curve (1964, 1977) to discriminate the source of the aeolian sediment was compared with that of Kelso sand ramp, Mojave Desert, (USA) and Ejina sand dune, China (Zhu et al., 2014). The bivariate plot between the mean size and the SD, suggest that both Saboo and Kelso sand ramps lie in the fluvial zone, whereas Ejina falls in both fluvial and dune zones (Fig 4.8 A) implying fluvial plains to be the provenance. A plot between the SD and the mean size of Saboo, Kelso and Ejina dunes suggests that cold desert sand ramps or dunes have a wide range of SD and mean size, whereas the Saboo sand ramp (Ladakh area sand ramps) forms a narrow cluster (Fig 4.8 B).

4.4.6 Environmental magnetism, SEM and RAMAN spectroscopy

Environmental magnetic parameters are also being used to identify the type of magnetic minerals, and their concentrations that can serve as a strong tool to understand the climate variability (Evans and Heller, 2003; Maher et al., 2003; Maher, 2011; Bateman et al., 2012; Srivastava et al., 2013).

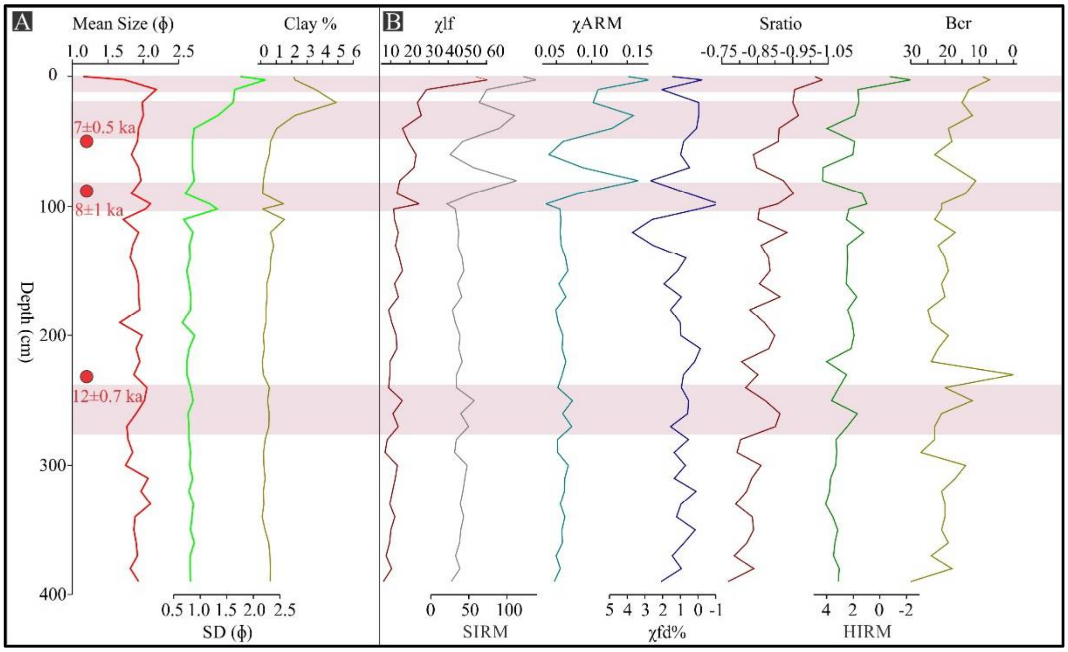

Figure 4.9 (A) Mean grain size, SD and clay % of Saboo sand ramp section (43 samples). (B) The environmental magnetic parameters of Saboo section. Top and middle crust showing sharp bulge in both grain size and environmental magnetic parameters. The shaded bars provide information regarding changes in depositional processes and climatic fluctuations.

The various magnetic parameters respond differently with the concentration of ferrimagnetic or ferromagnetic minerals. The proportional increase in the concentration of magnetic minerals increases the values of χlf (susceptibility) and SIRM (Verosub and Roberts, 1995; Evans and Heller, 2003). The parameters like frequency dependent susceptibility (χfd%) indicate the occurrence of superparamagnetic grains (SP) and anhysteretic susceptibility (χARM), indicate the presence of magnetic grains that belong to stable single domain (SSD). The various environmental magnetic parameters along with mean grain sixe, standard devivation and clay % are ploted in figure 4.9

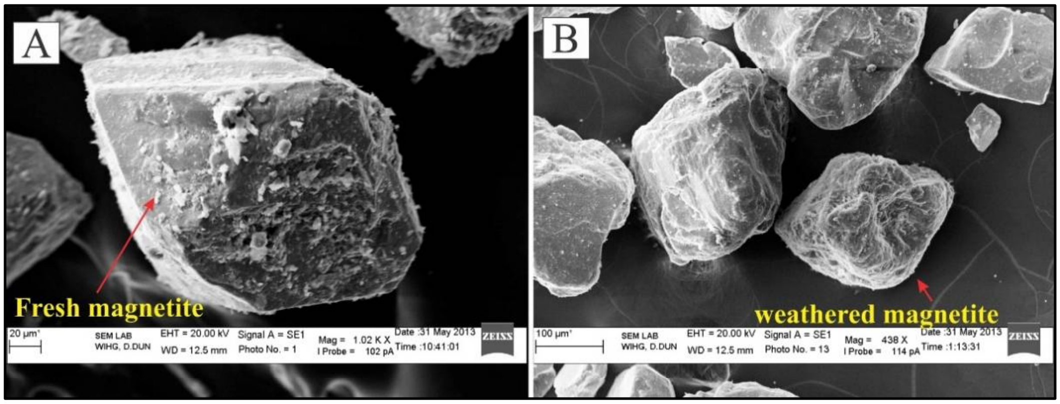

Figure 4.10 SEM images: (A) un-weathered, perfect crystalline magnetite in the hard crust. (B) Weathered magnetite grain in the aeolian unit.

The scanning electron microscopic (SEM) images from the hard crusts horizon and parallel laminated aeolian sand show euhedral fresh and weathered magnetite grains, respectively (Fig 4.10). The RAMAN spectroscopy on top and middle hard crust along with aeolian unit was performed on separated magnetic grains using bar magnet (Fig 4.11).

4.4.7 Clay minerals and weathering patterns

In general the presence of smectite and kaolinite indicates weathering under humid climatic conditions, while illite and chlorite signify physical weathering in arid climate. The dominancy of illite and chlorite throughout the vertical profile of Saboo sand ramp were notice (Fig 4.12).

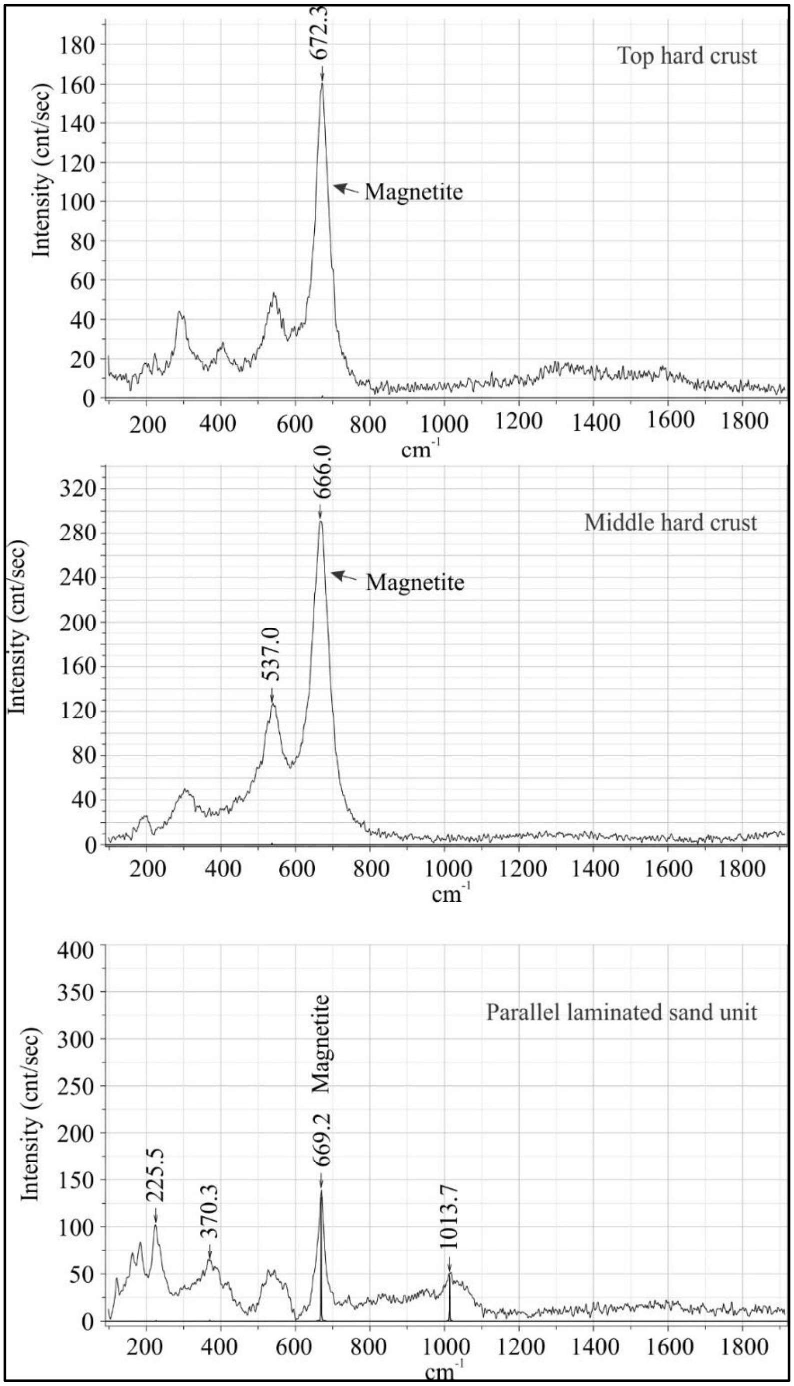

Figure 4.11 Raman spectrum of top and middle hard crust along with parallel laminated sand unit showing presence of magnetite throughout the Saboo sand profile.

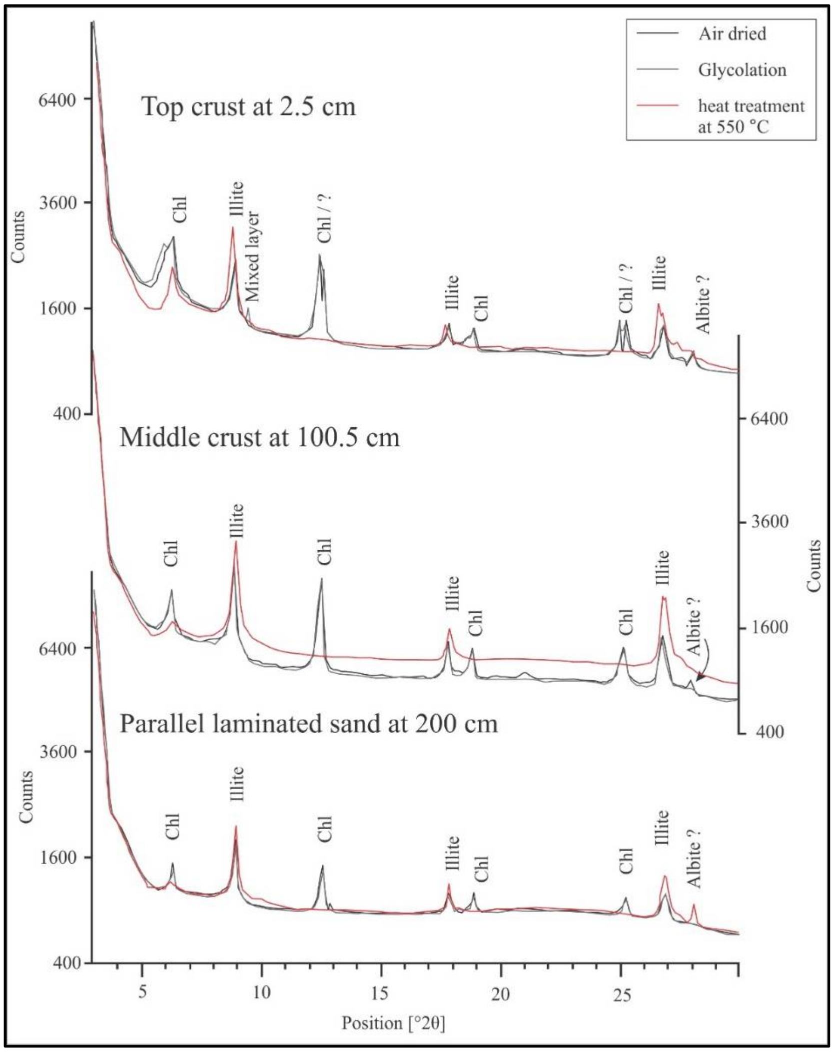

Figure 4.12 X-ray diffraction patterns of representative samples from top and middle hard crust along with parallel laminated sand unit showing dominancy of illite and chlorite clay minerals throughout the Saboo sand profile.

4.5 Sedimentary style and depositional patterns of Indus River system

The relict sediments as preserved in different sections and their lithofacies association throw light on the sedimentary style of the Indus River during the past.

The morphostratigraphy of valley fills and strath-terraces is described in Chapter 3. The section wise sedimentary details with chronology are given below:

4.5.1 Segment I

Nyoma (N 33°10'22.27" E 78°44'51.62")

Nyoma is situated in the extreme NE part of the Ladakh Himalaya. In this section, the valley is very broad and filled with multiple mid channel bars. The large number of multiple threads of the main stream formed these mid channel bars.

4.5.2 Segment II

Mahe (N 33°17'3.8" E 78°25'16.6")

Two sections are studied here, one at the left bank and other at the right bank of the Indus River. The left bank section is situated near the Mahe Bridge and is comprised of 11.76 m thick channel and fan facies. At the bottom, 2 m well rounded, well sorted, horizontally bedded clast supported gravels classified as Gh facies are present as Channel bound Lithofacies association. The maximum clast size is 25 – 35 cm. These gravels are normally graded and ~ 80 % of them are sourced from the Indus Molasse. This facies is overlain by 1.2 m thick Gmg unit having moderately sorted, rounded to sub-rounded matrix supported pebbles termed as fan bound LA. The fining upwards sedimentary structure and six depositional cycles are well marked in this unit. This is followed by a 36 cm channel bound LA, composed of moderately sorted, moderately rounded, and horizontally bedded imbricated clasts. This, in turn, is overlain by a 6 m thick fan bound LA composed of moderately to well rounded, poorly sorted, matrix supported pebbly sediments with an erosional base. This facies has a maximum clast size of 5 – 10 cm and up to 70 % clasts are sourced from the Indus Molasse. The matrix is composed of 65 – 70 % grits in this unit. This is overlain by 1 m thick moderately sorted, rounded, clast supported massive gravels classified as Gcm facies, where the clast size range from 15 to 25 cm and the matrix is sandy that ranges up to 25 % by volume. 75 – 80 % of clasts are sourced from the Indus Molasse. Above this facies, lies a 1.2 m thick unit of well sorted, well rounded, clast supported massive pebbly channel bound LA where matrix is 10% by volume and out of the total clasts, 90% are sourced from the molasse and rest are from Ladakh Batholith. This unit is dated to 14±2 ka (LD-1433; Fig 4.13 A).

At the right bank, 10.5 m thick fluvial deposits at the base show a ~5 m thick channel bound LA composed of well rounded, horizontally bedded, 50 – 10 cm diameter imbricated gravels with gritty matrix, classified as Gh facies. Internally, in this facies three fluvial cycles are identifiable where 90 % of constituent clasts were sourced from the Indus Molasse. Above this, lies a 50 cm thick alternating clay and planar cross bedded grey sand of the Sp facies. With an erosional base, a 3 m thick batholith-sourced, poorly sorted, matrix supported angular boulders of fan bound Gmm facies overlie the Sp facies. Above this, lies the 2 m thick Gcm facies with moderately sorted, rounded to sub-rounded gravels (Fig 4.13 B).

Both Gh and Sp facies make channel bound LFA where Sp indicates a waning phase of flood in the Indus River. The sand unit associated with channel bound LFA yielded an OSL age of 41±2 ka (LD-1047).

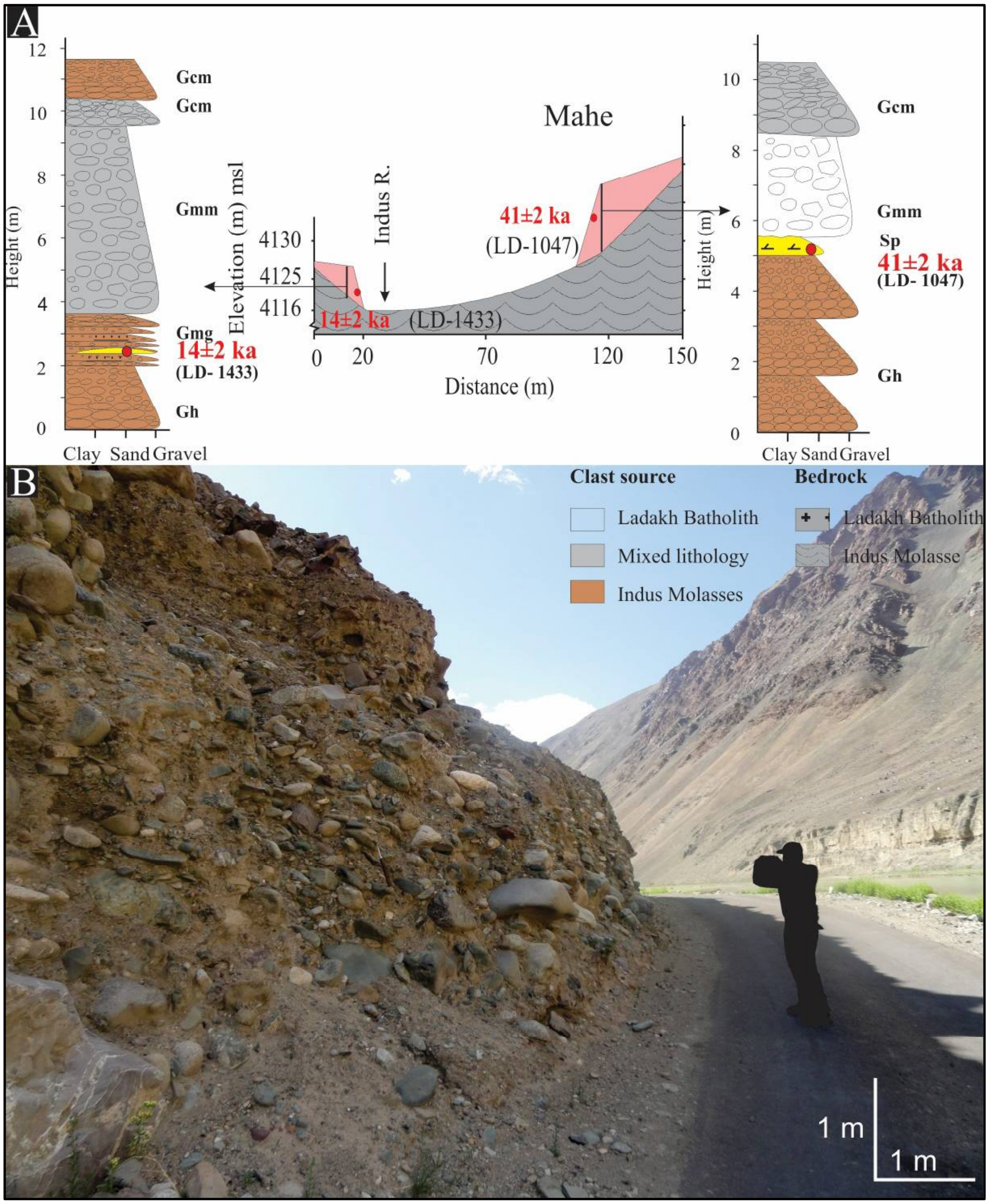

Figure 4.13 (A) Both banks of the Indus River at Mahe showing valley fill in valley cross-section. The Mahe-L and Mahe-R, lithologs shown on the left and right banks of the valley cross-section, suggest that both channel and fan bound processes filled the valley. (B) A photograph of Mahe-R.

Kesar (N 33°24'45.6" E 78°13'57.3")

This 5.25 m thick section located on the left bank of the trunk channel, where the bottom 2.75 m thick unit is composed of moderately sorted, well rounded, horizontally bedded, imbricated gravels of Gh facies in which the matrix is ~20 % by volume and ~ 90 % clasts are grano-dioritic sourced from the batholith. The maximum size of the clasts is up to 1 m. This unit is overlain by 2.5 m thick unit composed of well sorted, well rounded, horizontally bedded, imbricated clast supported gravels (Gh). In this unit, the maximum gravel size ranges from 25 – 30 cm and ~ 70 % of them are derived from the Ladakh Batholith (Fig 4.14).

Niornis (N 33°25'57.2" E 78°11'56.3")

This section is exposed near the confluence of a minor stream with the Indus from the north (Ladakh Batholith) where ~ 70 m thick sequence is made up of channel bound sedimentary deposits (Fig 4.15 A). The sequence from the base starts with a ~ 5 m thick unit made up of moderately sorted, moderately rounded, disorganized horizontally bedded clast supported gravels having 25-30 % matrix (Gh). The gravel size ranges from 5 to 20 cm and a majority of these are derived from the Ladakh Batholith. Above this lies a 4 m thick unit having similar facies elements with matrix reduced to ~15% and this, in turn, is overlain by two depositional units of 20 m and 3 m thickness, having clasts derived from the Ladakh Batholith with 15 – 20 % gritty matrix. This is followed by a 40 m thick, moderately rounded, moderately sorted, massive, clast supported gravelly unit. Internally, this unit is divisible into 20 cycles of deposition that are often separated by lensoid units of coarse sand.

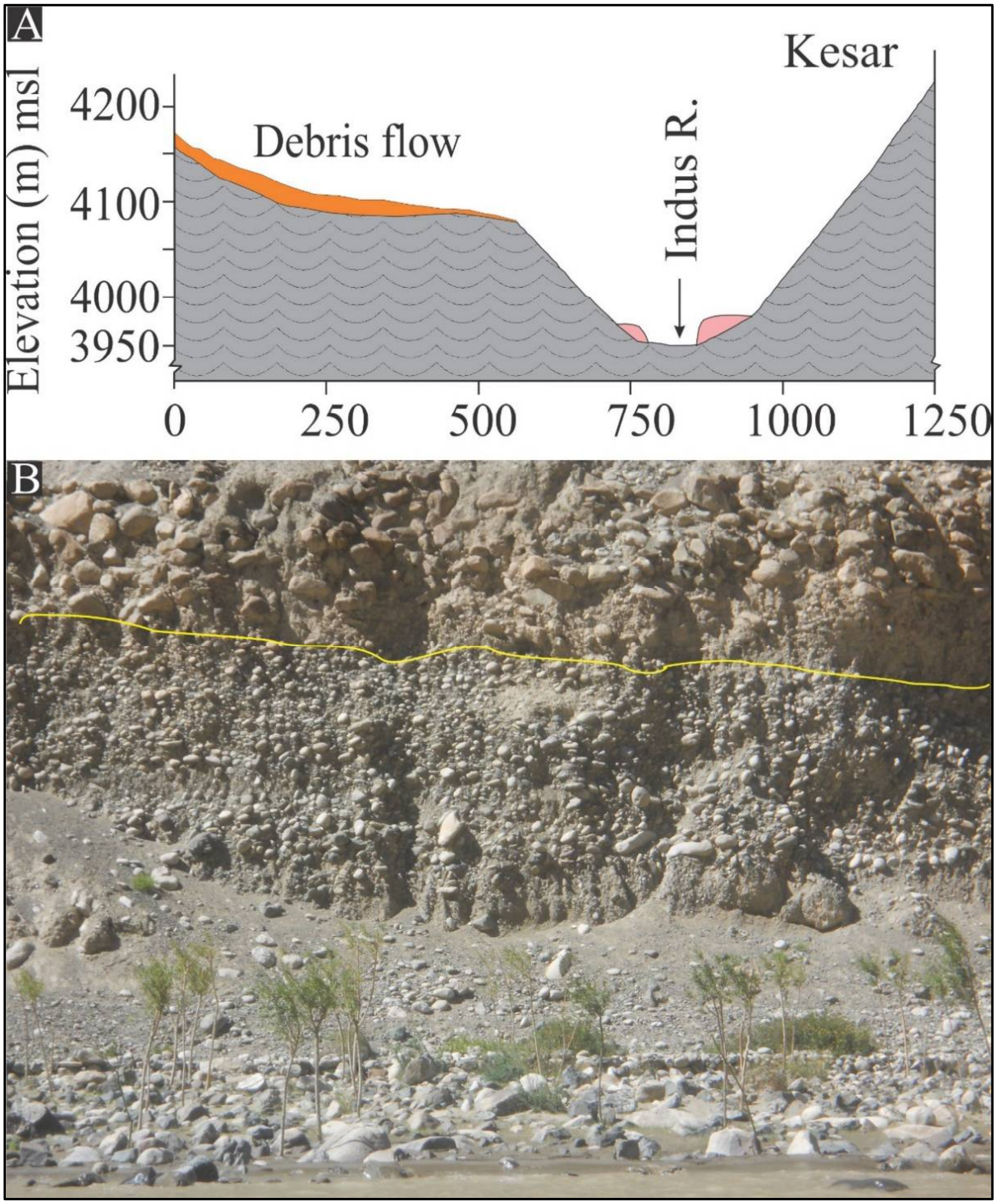

Figure 4.14 (A) The valley cross-section of Kesar section. (B) A picture of fill terrace at Kesar showing, a sharp erosional contact between the lower and upper Gh facies.

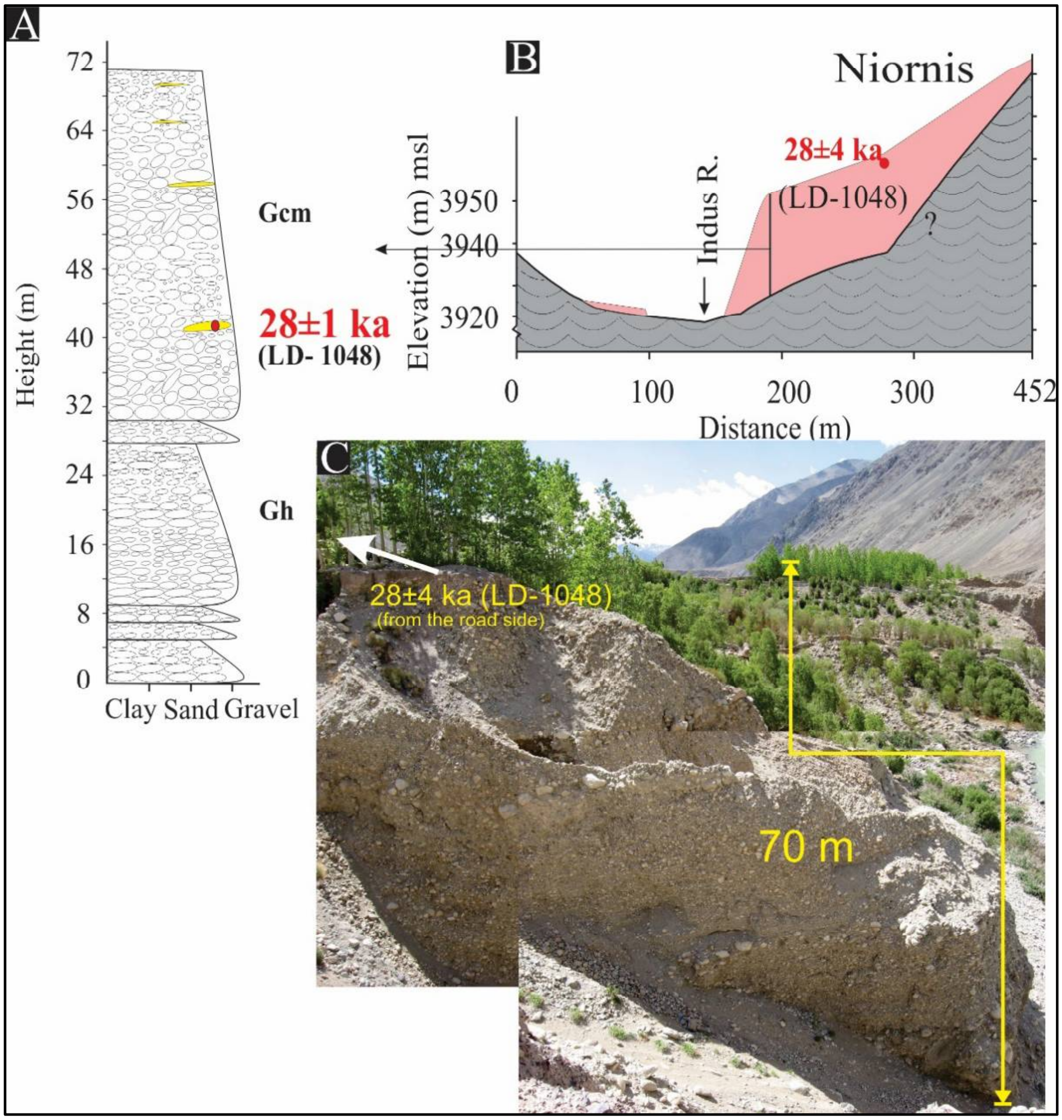

Figure 4.15 (A) Litholog and (B) valley cross-section showing the valley fill. (C) Photograph showing the channel bound facies association at Niornis.

Here the clast size ranges from 5 to 70 m and sourced from granitic rock. This is facies is recognized as Gcm facies. The sample from 30 m below the top of the Niornis section yielded an OSL age of 28±4 ka (LD-1048; Fig 4.15 B, C).

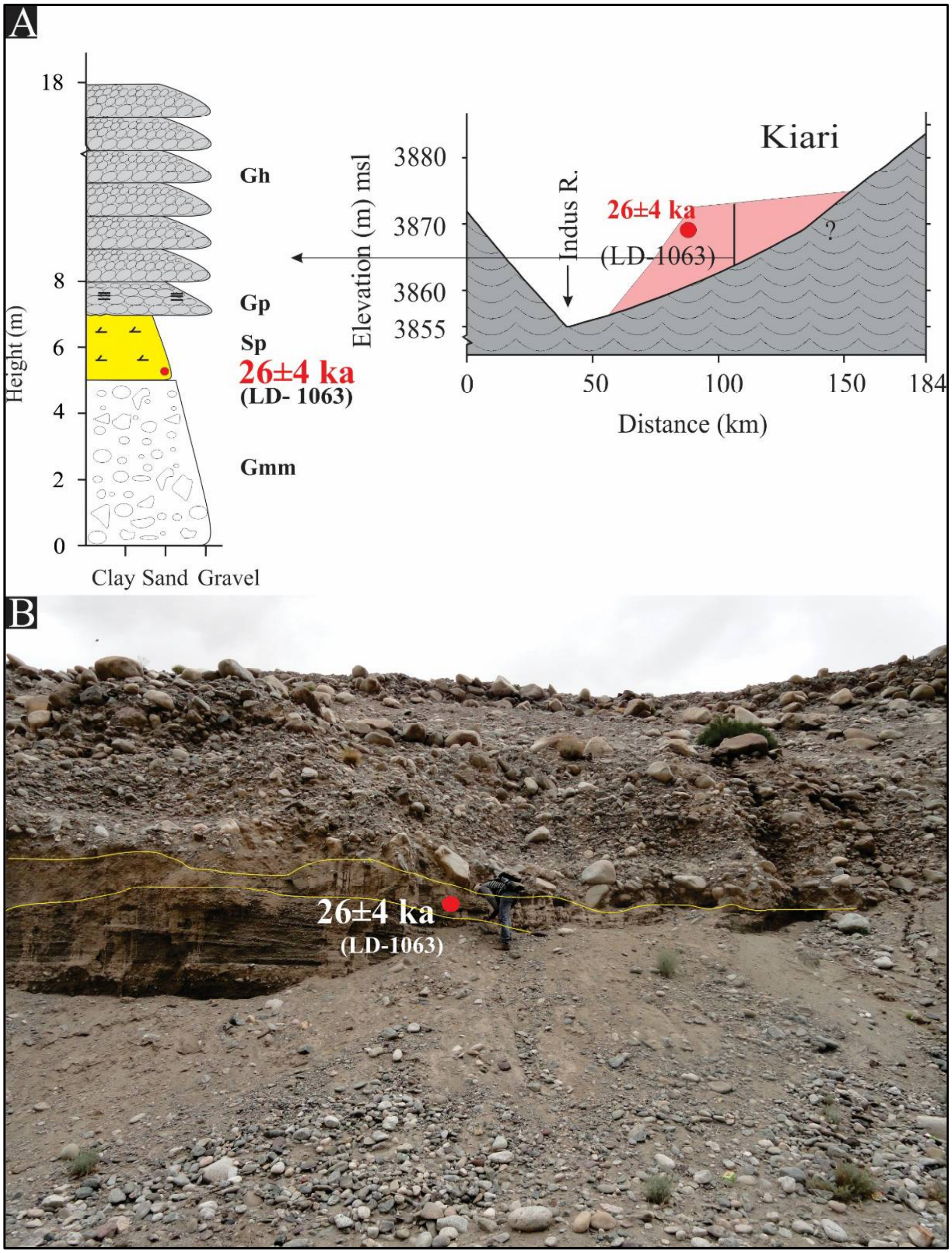

Figure 4.16 (A) The litholog and valley cross-section of the Kiari section. The litholog shows both fan and channel bound facies. (B) Photograph showing the OSL age from Sp facies.

Kiari (N 33°28'11.5" E 78°08'40.2")

The right bank of the Indus River here shows a 18 m thick well developed section which is largely composed of channel and fan bound facies. Basal 5 m fan bound part is made up of poorly sorted, sub-rounded to sub-angular, disorganized, massive, matrix supported clasts (Gmm facies). The gravels of grano–dioritic lithology range in size from 30 to 50 cm. This unit is overlain by 2 m thick cross-bedded coarse sand capped by a lenses of fine sand (Sp facies).

The cross-beds are directed westward conforming to modern flow direction. Above this lies 1 m thick, trough cross bedded Gt lithofacies, having rounded and well sorted gravel. The sequence is capped by a 10 m thick, well rounded and sorted, horizontally bedded, clast supported gravels with 6 fining upward cycles (Gh lithofacies). The gravels of this unit are derived equally from Indus Molasse and the Ladakh Batholith (Fig 4.16 A, B).

The basal Gmm and Sp facies showing the fan bound LFA indicate a debris flow event. Chronology of the base of the Sp facies suggest that the debris flow event occurred at 26±4 ka (LD-1063) BP.

Gaik (N 33°34'17" E 78°07'31.8")

Exposed on the right bank of the Indus River, this section from base onwards shows, a 20 m thick horizontally bedded, sorted, well rounded, imbricated, clast supported gravels (Gh facies). This is followed by a 2 m thick horizontally bedded, fine to medium sand (Sh facies) which in turn is overlain by 2 m thick unit of the Gh facies. The clasts of both units of the Gh facies are of mixed source. This unit, with an erosional base, is overlain by 11 m thick unit composed of sub-rounded, matrix supported graded gravels classified as Gmg facies.

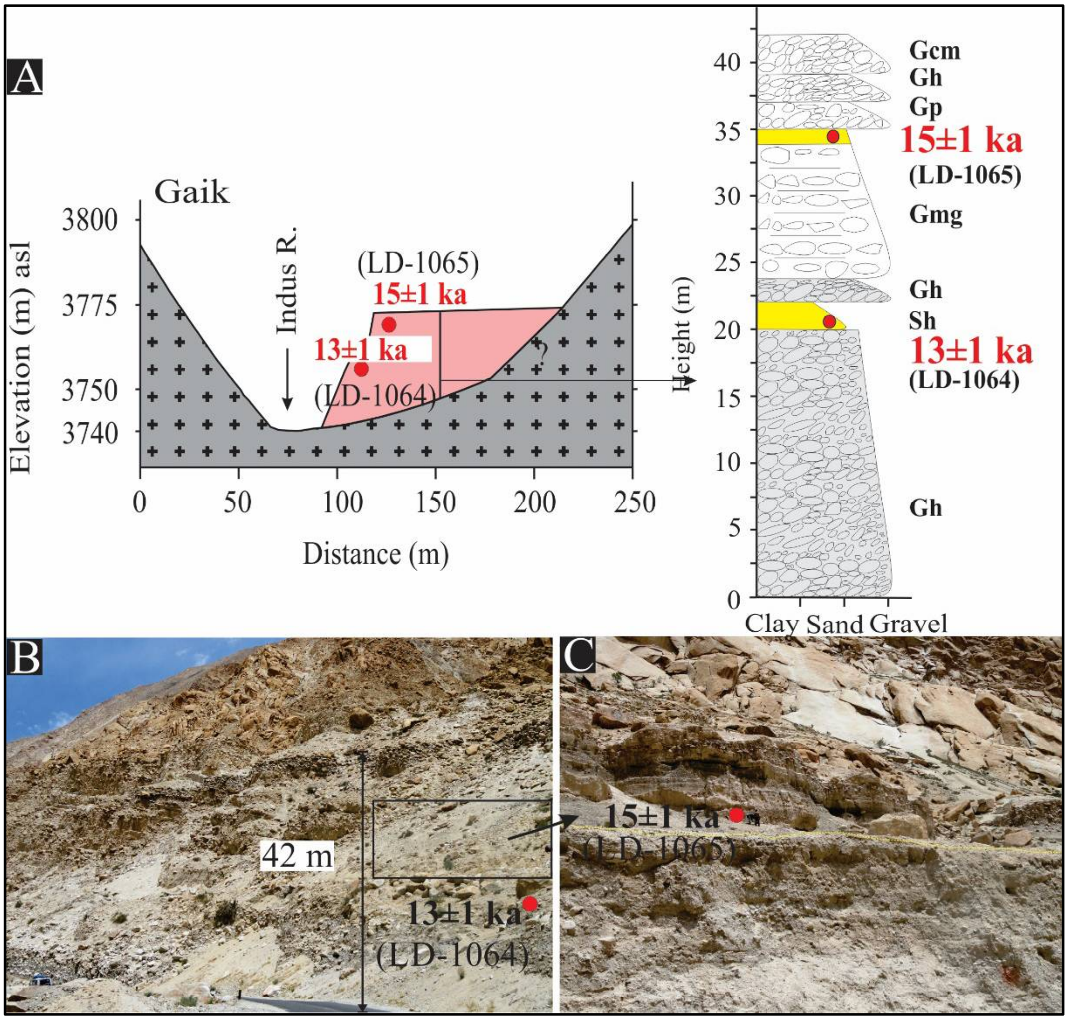

Figure 4.17 (A) Gaik section: litholog, valley cross-section (V-shaped). The litholog showing mixed and batholithic sourced clast. (B) and (C) suggest that the valley fill has been influenced by both channel and fan bound processes

This unit internally can be divided into 6 depositional cycles, and generally a lense of fine sand tops each cycle. This is followed by a 2 m thick unit made up of round, cross-bedded gravel (Gp facies). Laterally, this unit runs for 40 m. This is overlain by a 2 m thick unit composed of well rounded, sorted, horizontally bedded, imbricated, clast supported facies (Gh facies) which, in turn, is followed by a 3 m thick unit of sub-rounded, moderately to poorly sorted, clast supported massive gravel (Gcm facies). The clasts of the Gmg, Gp, Gh, and Gcm facies, all are having Ladakh Batholith affinity (Fig 4.17 A).

From the base, Gh and Sh facies form channel bound LFA and suggest deposition as a channel bar. The Sh facies that occurs towards the top represents the waning phase of flood. Above this, there is a unit consisting of fan bound LFA which internally is made up several units of Gmg facies showing the normal grading. Each unit is seen capped by a thin sand lense. The ages of the basal channel bound unit (13±1 ka; LD-1064; Fig 4.17 B) and upper fan bound unit (15±1 ka; LD-1065; Fig 4.12 C) LFAs within the error limits are overlapping and suggest that the two events happened so quickly that the OSL technique is not able to provide temporal resolution.

Tirido (N 33º35'3.8" E 78º04'54.3")

This section is exposed on the right bank of the Indus River where the basal 4 m is covered with scree. The following 3 m unit is composed of well rounded, poorly sorted, matrix supported gravels. This unit is classified as Gmm facies having gravels of mixed lithology. Above the Gmm facies, is a 1.5 m thick massive coarse to medium sand unit classified as Sm facies. This is overlain by 2 m thick unit composed of well rounded, sorted, horizontally bedded, imbricated, clast supported gravels having about 20 % matrix and classified as Gh facies. Above this, a ~ 2 m thick unit of rounded, poorly sorted, matrix supported massive gravels, classified as Gmm facies. The gravels are 10 to 75 cm in size.

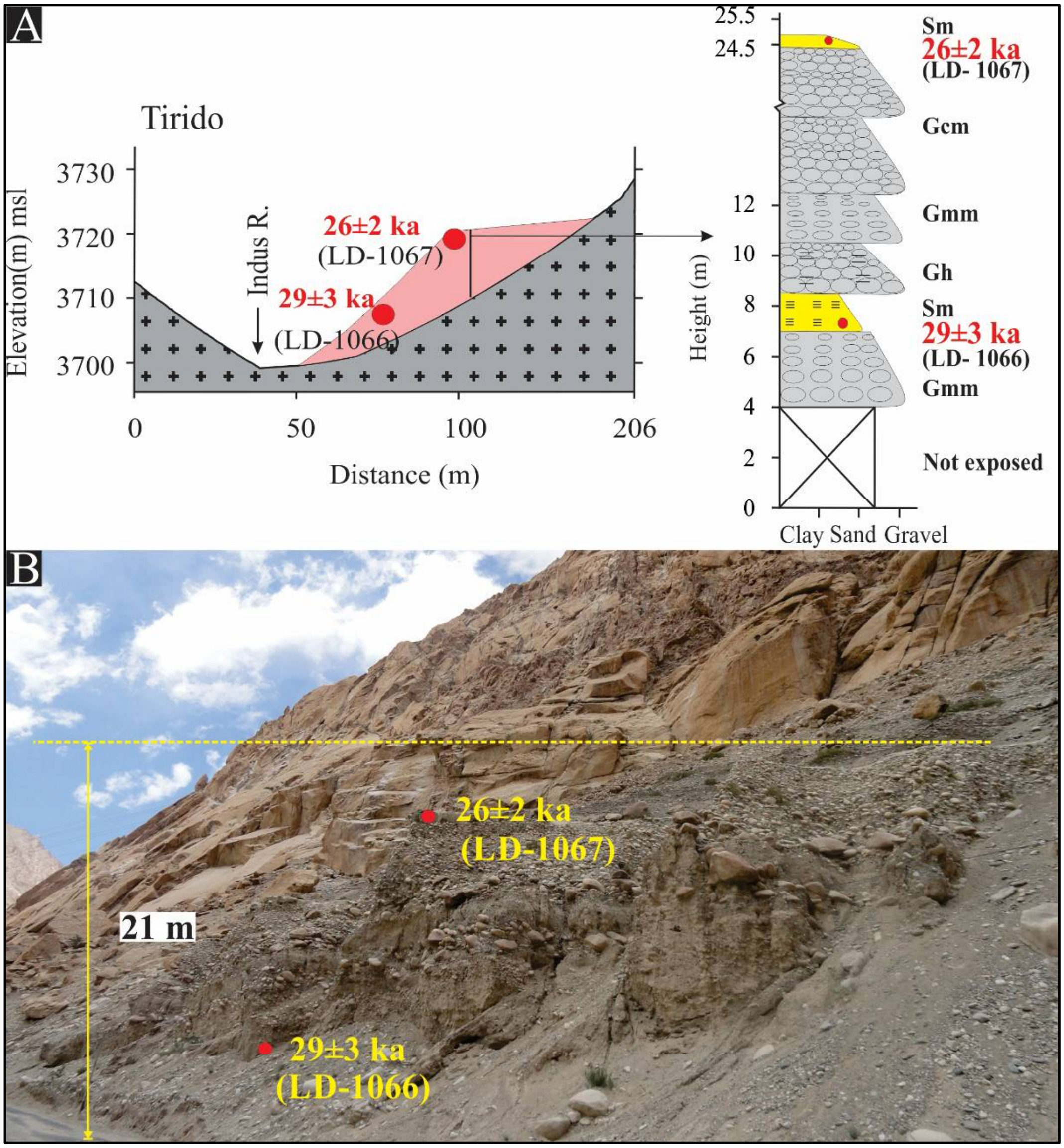

Figure 4.18 (A) Litholog of Tirido section showing the aggradation of the narrow valley by both channel and fan bound activities in a narrow valley. (B) Photograph showing sedimentary fill in the Tirido.

Following this, there is a 12 m thick unit of moderately sorted, well rounded, clast supported massive gravels. This unit is internally divided into two fining upward depositional cycles and is capped by a 0.5 m thick massive, coarse to gritty sand (Sm facies). All the gravelly units are of mixed source rock (Fig 4.18 A).

The bottom Gmm and the upper Gcm facies show association with Sm facies. The Gmm facies is having fan bound LFA, whereas the top most Gcm has channel bound LFA. The Gmm, representing a debris flow and is dated to 29±3 ka (LD-1066; Fig 4.18 B), whereas, the Gcm representing the amalgamation of channel bar and a phase of river aggradation is dated to 26±2 ka (LD-1067; Fig 4.18 B).

Hymia-1 (N 33º39'58.6" E 77º59'44.7")

This section is exposed on the left bank of the Indus River. At the base, 2 m is made up of well rounded, well sorted, horizontally bedded, imbricated, clast supported gravels. The gravel size ranges from 5 to 20 cm. This unit is internally divided into two depositional cycles and is classified as Gh facies. A 50 cm parallel laminated, coarse to medium sand of Sm facies caps this unit. This is overlain by a 2.5 m thick unit of poorly sorted, sub-rounded to sub-angular, matrix supported gravels. The size range of these gravels is 2 to 10 cm. The matrix is coarse to gritty sand. This unit is internally divided into several laterally coalescing lensoid bodies and has a sharp contact with the basal Sh facies. The unit is capped by a unit of parallel, medium sand. This is classified as Gmg facies.

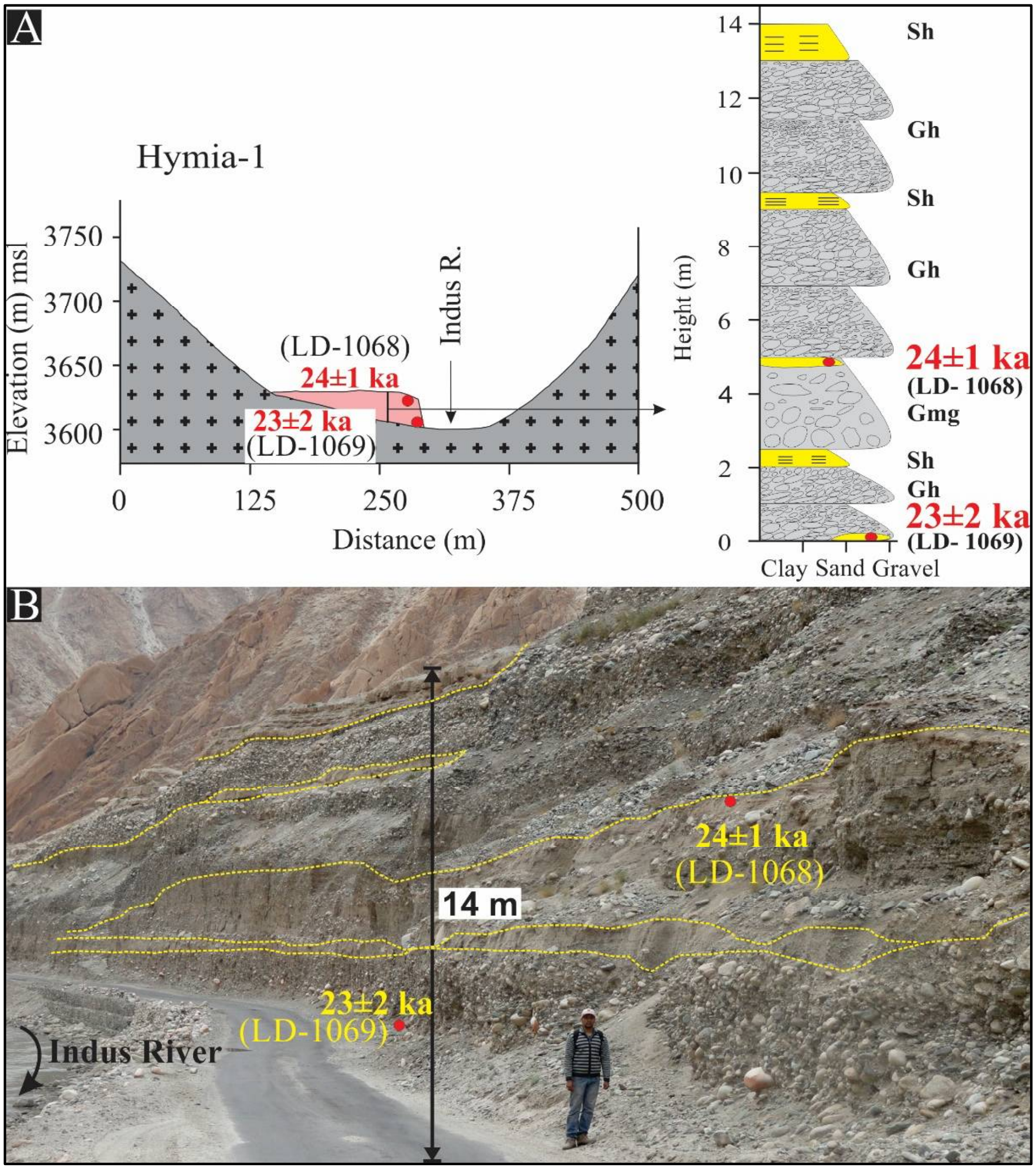

Figure 4.19 (A) The valley at Hymia-1 is narrow and V-shaped, where the valley fill sequence lies on the left bank. The litholog showing mixed clasts and aggradation is followed by channel bound processes. (B) Photograph showing Hymia-1 section.

This is overlain by a 4 m thick well rounded and sorted clast supported gravels, internally divided into two fining upward cycles where the lower is composed of small sized clasts (~ 5 cm diameter) and the upper of coarser clasts (5 to 15 cm). This unit is capped by a parallel, fine to medium sand body. These units are classified as Gh and Sh lithofacies. This is followed by a 3.5 m thick unit of Gh facies gravels which internally is divisible into two depositional events. The clast size ranges from 5 to 40 cm. The sequence is capped by a 1 to 2 m thick unit of parallel laminated, gritty sand unit (Fig 4.19 A). The whole section is composed of clasts of mixed lithology of Indus Molasse and Ladakh Batholith.

The two units at the bottom make channel bound LFA deposited by channel bar aggradation where the sandy unit represents the waning condition of the flood. This is dated to 23±2 ka (LD-1069; Fig 4.19 B). Following this, the Gmg facies with high matrix content is inferred as the high energy plastic debris flow which is dated to 24±1 ka (LD-1068; Fig 4.19 B) overlapped the age of lower Gh facies.

Hymia-2 (N 33º40'45.19" E 77º59'16.88")

The Hymia-2 section is exposed on the right bank of the Indus River, ~ 1.5 km downstream from the Hymia Bridge-1 section. ~ 7.5 m thick, at the bottom, section is covered with the scree. Above this, a 2.4 m thick unit is composed of well rounded, moderately sorted, horizontally bedded, imbricated, clast supported gravels of the Gh facies. The clasts are of mixed lithology and the grit sized matrix ranges upto 30 %. This is followed by a ~ 1 m thick unit of poorly sorted, sub-rounded to sub-angular, matrix supported massive gravels having an erosional base.

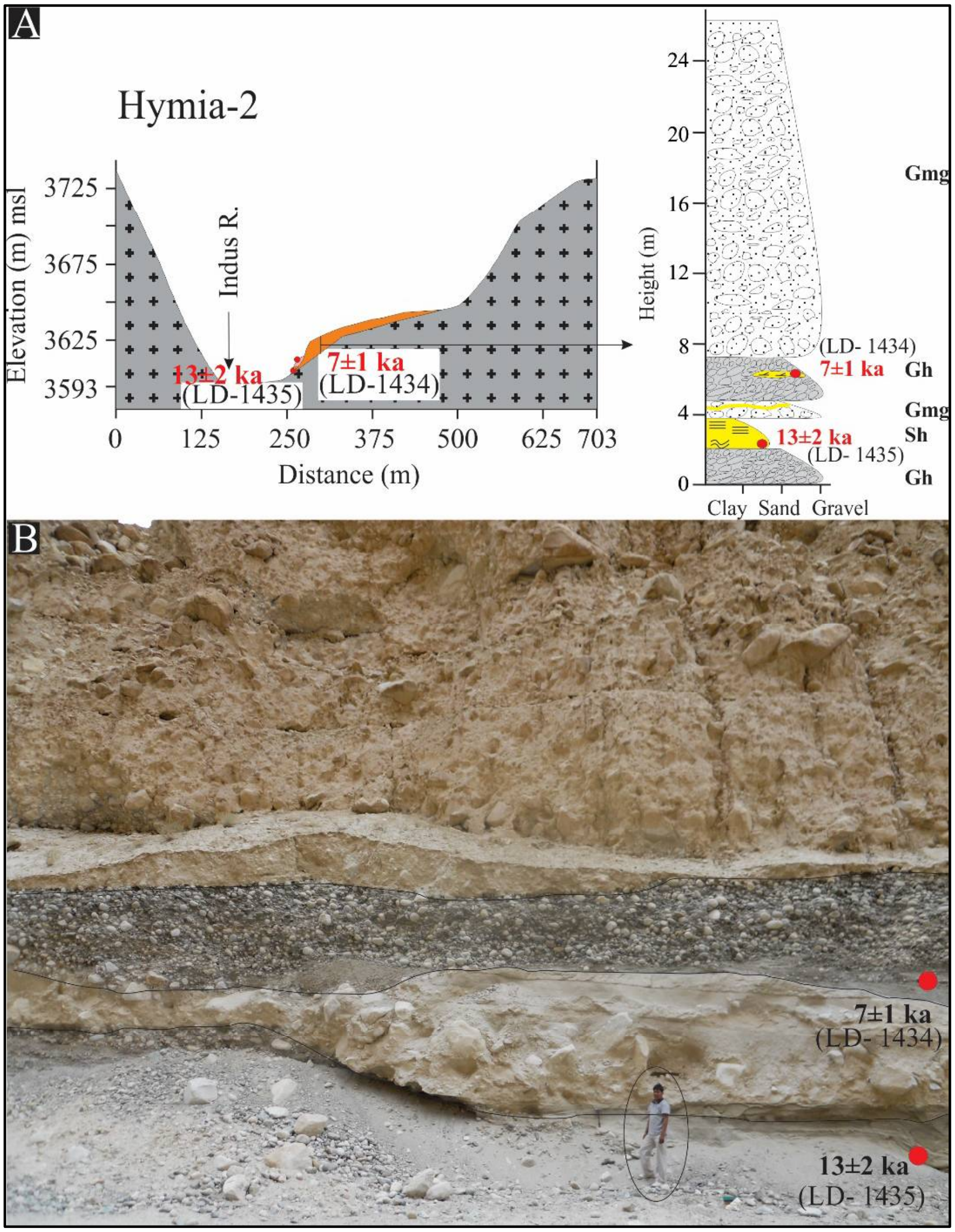

Figure 4.20 (A) The valley cross-section and litholog suggest that fan bound process was very active at 13±2 ka, where the channel was very active during 7±1 ka. (B) Photograph showing channel bound facies in between the successive fan bound processes at Hymia-2, located near to second bridge (person for scale is encircled).

The clasts size ranges up to 1 m. The unit is classified as Gmm having matrix of about 60 – 70 %. This unit has an erosional basal contact with the Gh facies. Above this lies a 1.7 m thick unit comprising of parallel laminated fine sand with clay and internally made up of seven fining upward cycles of deposition. The bottommost part of this unit exhibit trough-cross stratification (St facies). The St facies is overlain by a 2.5 m thick unit of well sorted, rounded, cross-stratified clast supported gravels. Internally, it makes six fining upwards depositional cycles. Each cycle is capped by thin lenses of gritty sand. The matrix is gritty to medium sand and makes 25 – 30 % of this unit. This unit laterally extends up to 50 m and is classified as Gp facies. At the top, lies a 20 m thick unit of poorly sorted, sub-angular, matrix supported gravels where, matrix ranges up to 70%. The gravels size ranges from 5 cm to ~ 1 m (Fig 4.20 A, B).

The section starts from deposits of channel bar aggradation to fan bound LFA, which is followed by a high energy debris flow of plastic nature. The basal channel event is dated at 13±2 ka (LD-1435) and the upper unit to 7±1 ka (LD-1434).

4.5.3 Segment III

Upshi-R (N 33º47'22.1" E 77º51'8.3")

This section is exposed 6 km upstream from the Upshi town on the right bank of the Indus River. The section starts with a 30 m thick unit of rounded, horizontally bedded, imbricated, clast supported gravels making the Gh facies. Internally, the unit is identifiable into four depositional cycles, where the clasts are composed of mixed lithology and each cycle is separated by thin sand lense. A sand body exposed towards the top of this section has yielded an OSL age of 37±3 ka (LD-1070). This unit, with an erosional basal contact, is overlain by an 8 m thick poorly sorted, sub-rounded to sub-angular, matrix supported gravel unit. This unit, internally, is made up of several depositional cycles of massive nature. All clasts of this unit are sourced exclusively from the Ladakh Batholith (Fig 4.21 A, B). This unit is classified as Gmm facies. Laterally, the whole section extends for ~ 100 m.

The section has evolved due to channel bar aggradation in the Indus River followed by a Ladakh Batholith sourced massive debris flow. The chronology indicates that channel aggradation took place at 37±3 ka (Fig 4.21 E).

Upshi-L (N 33º49'49" E 77º48'4535")

This section lies on the left bank of the Indus River, near the Upshi Bridge, and starts with a 15 m thick unit of rounded, well sorted, horizontally bedded, clast supported imbricated gravels. Matrix makes up to 20 – 25 % and is composed of gritty sand. The framework clast size ranges from 4 to 15 cm where, the larger clasts are derived from the Ladakh Batholith and small pebbles are from the Indus Molasse. The Indus Molasse clasts contribute only 30 – 40 % of total clasts. This unit is identified as Gh facies. Internally, this unit is made up of three cycles and each cycle is separated by a sand lense. This is followed by a ~ 1 m planar cross-bedded sand (Sp facies). This, in turn, is followed by a 7 m thick unit of poorly sorted, rounded, clast supported massive gravels that internally is made up of four depositional episodes (Gcm facies). The clast size of this unit ranges from 5 to 100 cm and are derived from the molasse.

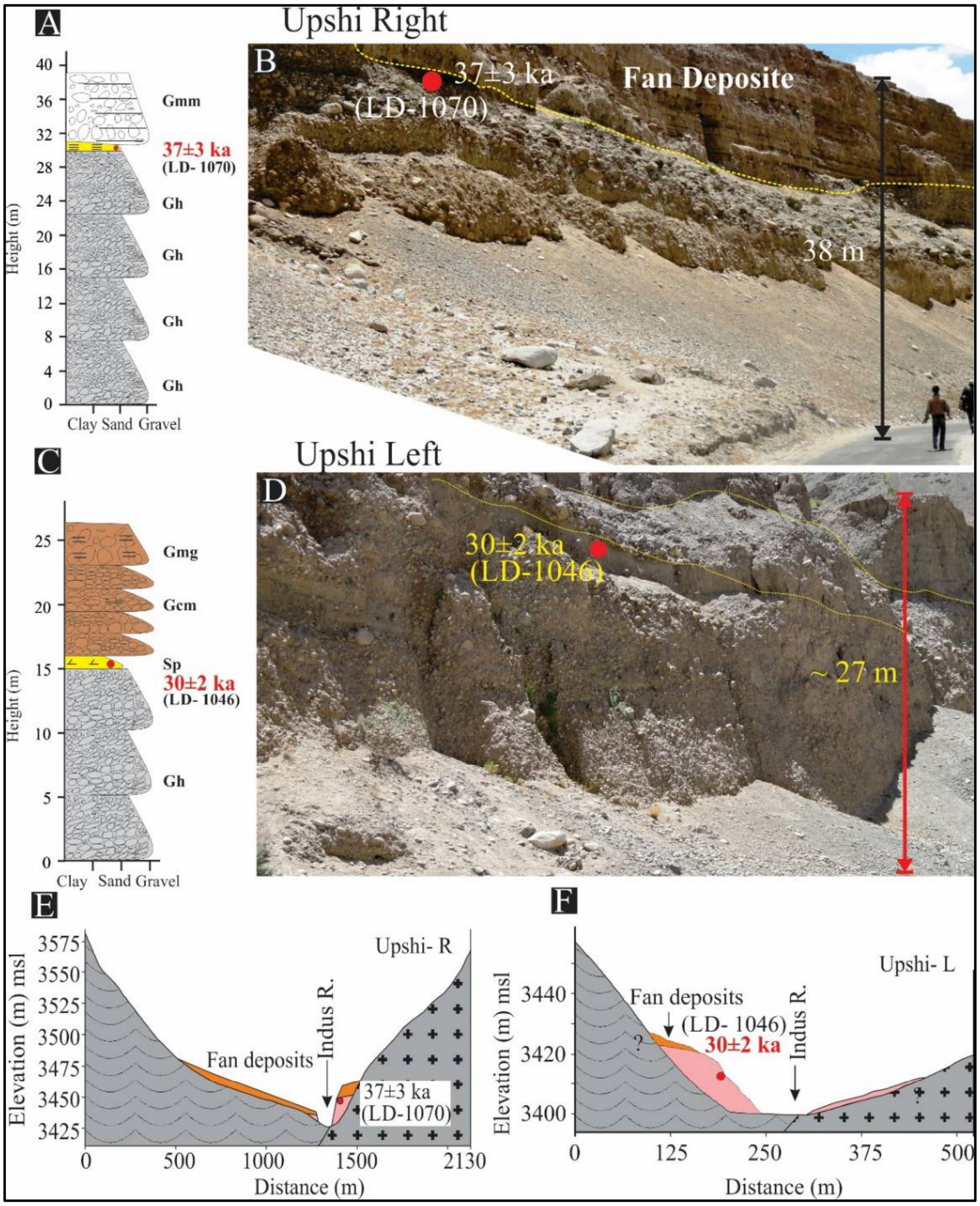

Figure 4.21 (A) and (B) Represent the litholog and panoramic view of Upshi-R section. A 38 m Upshi-R section is a fill terrace made up of both channel and fan activities. (C) and (D) Showing channel and fan bound activities at Upshi-L section as shown in litholog and photograph. (E) and (F) The valley cross-sections of both Upshi-R and Upshi-L.

This unit represents deposits of a fan of a river draining the Indus Molasse in the south. Towards the top of this, there is a 3 m thick unit of very poorly sorted, angular, matrix supported gravels that are sourced from the Indus Molasse. The matrix is composed of gritty sand and contributes about ~ 70 % to this facies. The normal grading is also marked as sedimentary structure, therefore, this unit is classified as Gmg facies (Fig 4.21 C, D).

The basal 15 m of this section represents aggradation in the Indus River (its top of which is dated to 30±0.2 ka; LD-1046; Fig 4.21 F) followed by a fan event of a molasse sourced river. The section terminates with a debris flow event which again is sourced from the Indus Molasse.

Kharu (N 33°54'56.9" E 77°44'04")

This section is located on the left bank of the Indus River near the Kharu Power House. It is composed of 30 m thick unit of well rounded, moderately sorted, clast supported massive gravels. It has several depositional cycles and separated from each other either by sand lenses or by fine clasts. The gravel size ranges from 5 to 10 cm and 80 % of which are derived from molasse. This whole section is classified as Gcm facies, and inferred as deposits of amalgamated channel bars (Fig 4.22 A, B).

The OSL sample from 5 m below the top yielded an OSL age of 33±0.3 ka (LD-1045). This makes a fan sequence of the stream draining the Indus Molasse in the south.

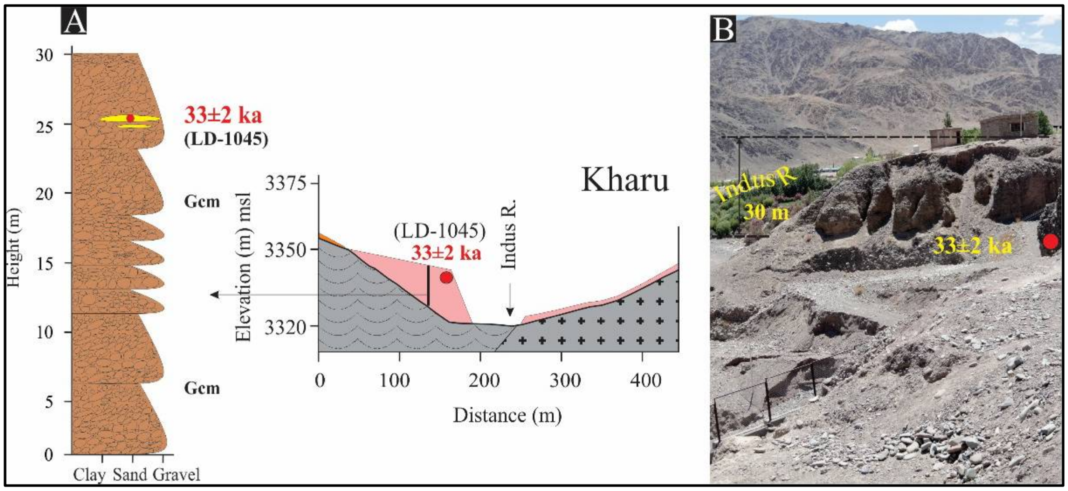

Figure 4.22 (A) Litholog showing the 30 m thick section made up of channel bound processes, where the clasts are sourced from the fans coming from the Indus Molasse. The valley cross-section representing the width of the valley is mainly filled with fan sediment. (B) A photograph of Kharu.

Stakna (N 33º57'30.7" E 77º42'46.5")

Three sections were studied at this location. Stakna section is 12 m thick and lies on the left bank of the Indus River. The bottom 4 m unit comprises well rounded, well sorted, horizontally bedded, clast supported imbricated gravels (Gh facies) of Indus Molasse affinity. This unit shows two depositional fining upward cycles. Laterally, individual units extend up to 50 m. The clast size ranges from 2 to 10 cm. With an erosional basal contact, this unit is overlain by a 3 m thick unit composed of Gh facies, where, the clast, that are source from Indus Molasse, vary from 3 to 50 cm in size. This unit, internally, also shows two depositional cycles separated by sand lenses. Above this, with an erosional base, occurs a 5 m thick unit of Gh facies with clasts being moderately sorted and well rounded. Lithologically, 90 % of clasts are derived from the Ladakh Batholith and are 5 to 100 cm in size. Thus this 12 m thick section is made up of channel bound LFA (Fig 4.23 A, B). Two lower units are contributed by the fan sediment coming from the south and the top most facies is deposit of a debris flow originating in amphitheater valley coming from the north (from the batholith). The chronology of this section suggests that the bottom two units of aggradation of fans from the molasse and then debris flow from the Ladakh Batholith occurred at 47±1 ka (LD-1015), 28±1 ka (LD-1016) and 25±1 ka (LD-1044), respectively.

Stakna-1 (N 33°57'35.5" E 77°42'52.6")

This section is 11.55 m thick and situated on the right bank of the Indus River. Its lower part is composed of (Fig 4.23 C) a 100 cm unit of well round, well sorted, imbricated clast supported gravels with mixed lithology (Gh facies). The gravel size is ranging from 2 to 20 cm. This, in turn, is overlain by a 1 m thick unit of parallel laminated, rippled and normally graded fine sand (Sh facies) that makes a sharp contact with the underlying unit. Above this, lies a 5 m thick unit, of poorly sorted, matrix supported angular to sub-angular gravels, where the gravels are granitic and range in size from 20 to 50 cm and the matrix is gritty and of granitic composition. This unit is classified as Gmg facies and has an erosional contact with the underlying the Sh facies. Internally, these units are 10-25 cm thick, run parallel to each other and following sheet like geometry and extend laterally up to 50 m. Above this lies a ~ 1 m thick unit of massive, coarse sand that transforms upward into parallel laminated fine sand (Sh facies). Above this is a ~ 50 cm thick unit of poorly sorted, matrix supported sub-angular gravels (Gmg facies) where the gravel size ranges from 5 to 15 cm and the unit extends for ~ 25 m laterally. This unit is overlain by a 1.25 m thick, lensoidal body of parallel laminated coarse sand, where the laminations show discordances at places (Sh facies). This, in turn, is followed by a 2 m thick unit consisting of poorly sorted, matrix supported sub-angular gravels with clast size of 5 to 15 cm (Gmg facies).

The section has evolved from a channel aggradation and terminated with a debris flow event. Luminescence ages of the sequence indicate that aggradation of the Indus River took place at 29±1 ka (LD-1017), whereas the debris flow event preserved towards the top of the section occurred at around the same time at 30±1 ka (LD-1043). Both, channel activity and debris flow show overlapping ages indicate that the temporal space between the two events is too less to be resolved by the luminescence technique.

Stakna-2 (N 34º00'1.1" E 77º41'44.5")

The third section at Stakna is situated in between the Stakna and Ranbirpura villages on the right to the trunk channel (Fig 4.23 D). This is ~ 49 m thick section, where the lower ~ 35 m thick unit is composed of rounded, moderately sorted clast supported massive gravels. The matrix is yellow coloured gritty sand. The clast are weathered and of 100 % granitic composition. The gravel size is ranging from 10 to 110 cm. This unit is classified as Gcm facies. Above this lies a 1 m thick unit of parallel laminated compact fine sand. This is considered as a part of the Gcm facies. Following this is a 13 m thick unit of rounded, moderately sorted, clast supported massive gravel. The clasts are highly weathered, showing yellow stain on the surface of the clast. The matrix is white, coarse sand - gritty and of granitic composition. The clasts are having similar composition (granitic clast) as the bottom unit and this unit is also categorized as Gcm facies (Fig 4.23 E).

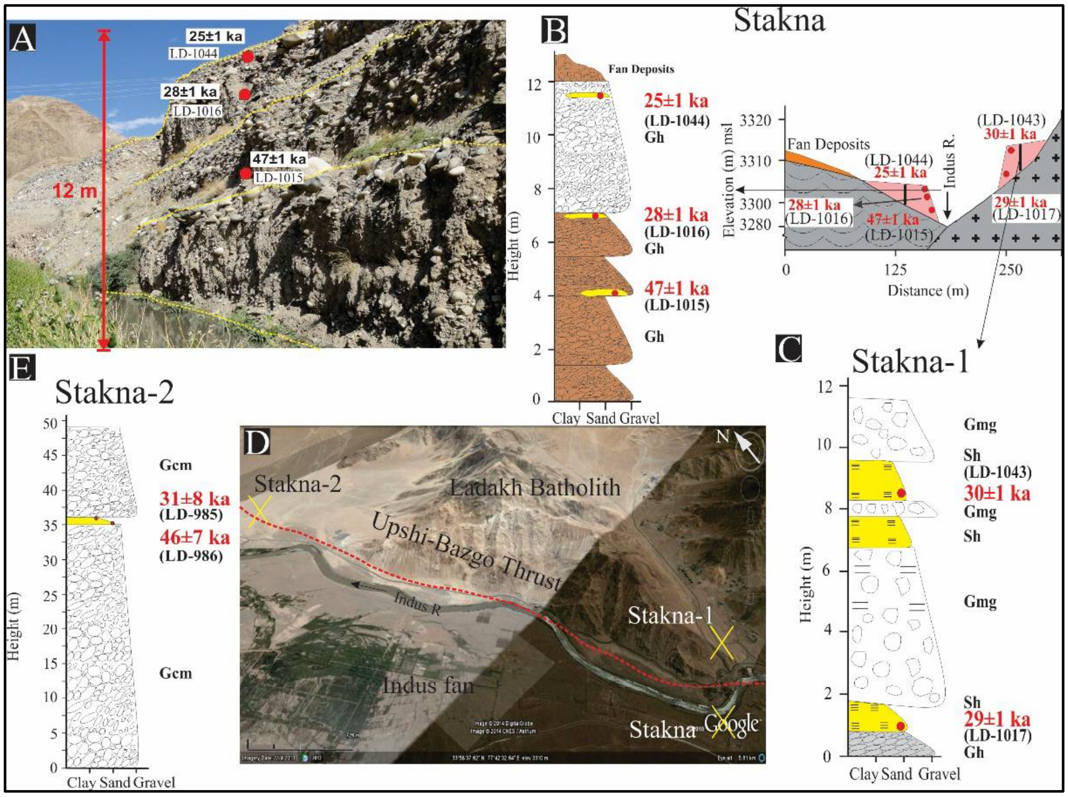

Figure 4.23 (A) A picture of Stakna. (B) Litholog and valley cross-section. (C) The litholog of Stakna-1 lies on right bank of the river just in front of the Stakna. (D) The google earth view of all three sections at Stakna. (E) The litholog of Stakna-2 section showing that fan bound processes were dominant at ~ 30 ka.

Both the units have similar compositional and structural characteristics. By field observations, it is anticipated that these units were deposited by a fan coming from Batholith side through a small channel via an amphitheater valley. The OSL samples from the lower and the upper unit have yielded ages of 46±7 ka (LD-986) and 31±8 ka (LD-985), respectively.

Spituk (N 34º07'50.69" E 77º31'30.9")

This section is situated on Leh – Nimu road in front of the Leh Airport. The total thickness of the section is ~ 43 m which is an assemblage of channel, fan, lake, and aeolian sediments (Fig 4.24 A). At the base, lies a 77 cm thick fining upward unit of greyish, cross-bedded medium to fine sand. The basal 65 cm is medium and the top 12 cm is fine sand, categorized as Sr facies. This is overlain by a 36.5 cm thick unit of normally graded coarse to very fine sand that exhibit deformed laminae are marked as seismites by previous workers (Phartiyal and Sharma, 2009). Above this, there is a 1.8 m thick, yellowish coloured parallel laminated, sand unit, in which the thickness of individual lamina ranges between 1 to 3 mm (Sm facies). This is overlain by a 3.69 m thick unit of horizontally bedded, whitish coloured clay unit, where, thickness of each bed ranges from 10 to 60 cm. This clay unit is classified as Chb (h: horizontally; b: bedded; C: clay). The clay unit is overlain by ~ 83 cm thick parallel laminated pebbles with intervening the clayey lenses. The pebbles are angular and are composed of maroon to brownish shale (Indus Molasse). The matrix is coarse to gritty sand of dark brown. This unit is termed as distal fan bound lithofacies and classified as Gmg. Above this, lies a 2.5 m thick, greyish coloured, medium to fine sand. The sand unit is normally graded and has pene-contemporaneous deformation sedimentary structures. The pene-contemporaneous deformed structures are associated with clay and sand and form ball and pillow structures towards the top of the unit. This unit is classified as Sm facies and is overlain by 4.9 m thick, parallel bedded, whitish clay. This unit is has similar characteristics as the Chb facies described above. Above this unit, lies a 3.33 m parallel laminated clay having alternate light and dark bands termed as varves. Each laminae is 1 to 10 mm thick. This unit is classified as Chl facies (h: horizontally; l: laminated; C: clay). This is overlain by a 37 cm thick unit of parallel laminated, greyish, coarse - fine sand (Sm facies). The sand unit is normally graded and has an erosional contact with the base. Above this lies a 5.43 m thick Chl facies is encountered again, which in turn, is overlain by a 2.83 m thick unit of parallel laminated clay of Chl facies that exhibits sandy lenses with symmetrical ripples. This is overlain by a 72 cm thick, greyish coloured trough cross bedded coarse – medium sand (St facies). This again is overlain by a 15.5 m thick clay unit of Chb facies that shows development of iron nodules towards the top. This unit is capped by ~ 8 m thick medium to coarse aeolian sand (Fig 4.24 A, C).

The sequence at the ~8.3 m is by the Indus River system which is capped by a fan of northerly flowing stream. Following this is a lacustrine sequence with intermittent channel activity. The sandy units within the lacustrine units indicate shallowing events of the lake. The upper part of the lake showing development of iron nodules indicates reducing aquatic conditions. This is followed by aeolian sedimentation. The bottommost unit of the section is dated as 52±2 ka (LD-1003). A fan bound LFA directed from the south, overrides the channel bound LFA.

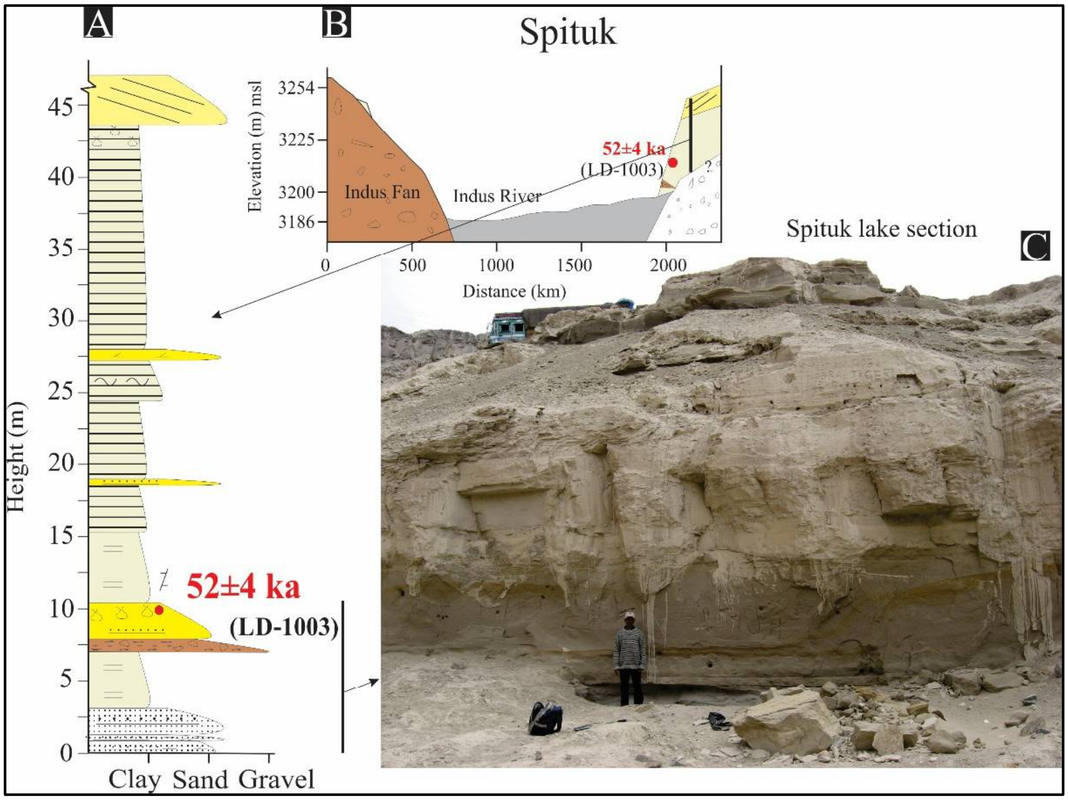

Figure 4.24 (A) and (B) The litholog and valley cross-section of the Spituk lake section. (C) A picture showing the bottommost part of the Spituk section.

4.5.4 Segment-IV

Nimu (N 34º09'58.82" E 77º19'27.88")

This section is located near the Indus – Zanskar confluence, as downstream from here the Indus flows into a gorge and exhibits two types of terraces. The lower level of terrace, T-1, is fill type and situated at ~ 12 m from above the river level (arl), whereas the strath terrace, T-2, has ~ 124 m thick bedrock bench and the overlying ~ 12.5 m thick debris flow facies. ~ 3 m alluvial cover at the base is composed of well rounded, poorly sorted, matrix supported massive indurated gravel.

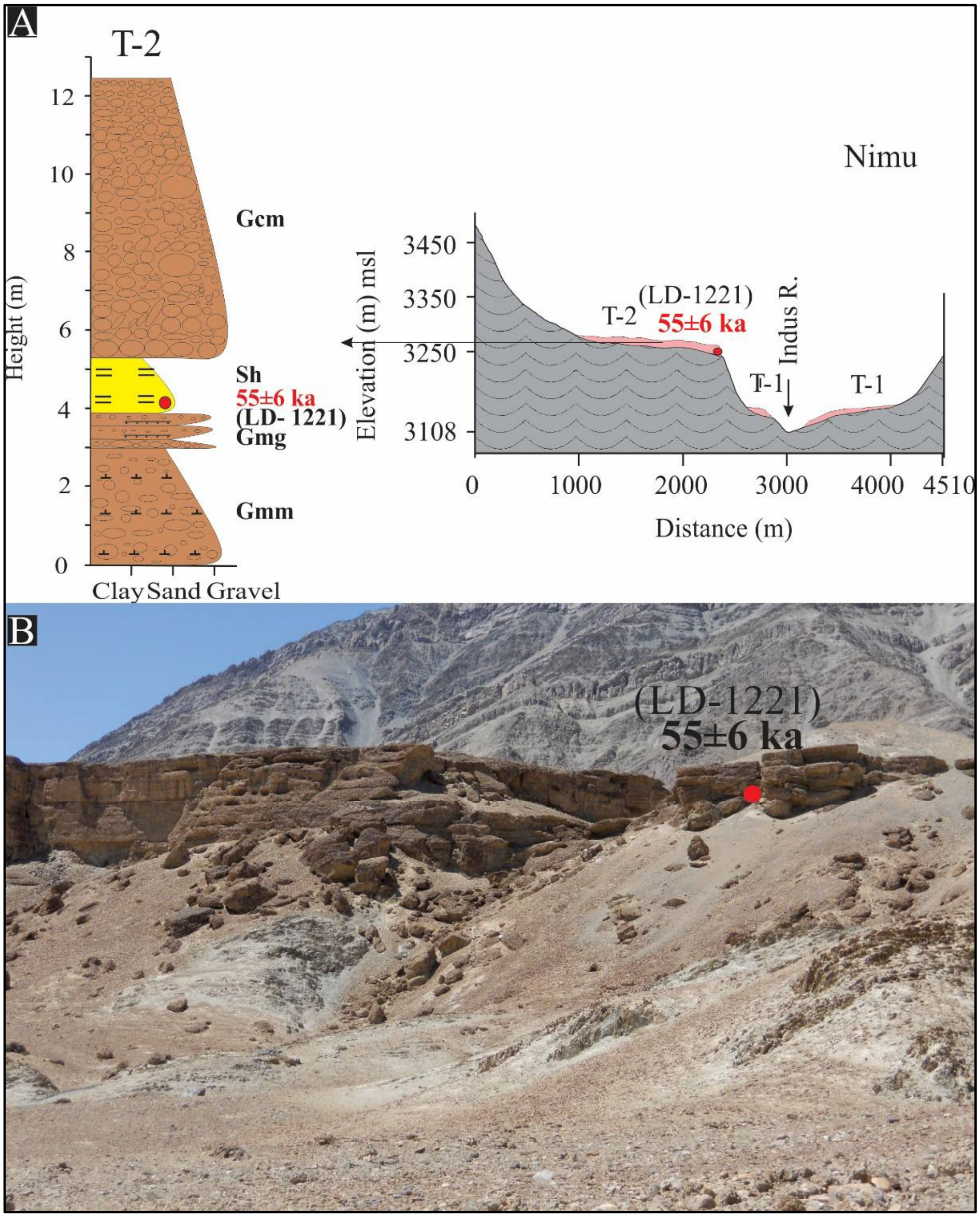

Figure 4.25 (A) Cross-section showing the configuration of T-1 and T-2; the litholog of T-2 sequence showing a more prominent channel bound deposit at the Nimu gorge. (B) Panoramic view of Nimu section near the confluence of Indus and Zanskar rivers with fill and strath terraces T-1 and T-2, respectively.

The clasts are sourced from molasse, and are in 5 to 30 cm size range. The matrix is fine sand to gritty and forms 50 – 55 % of volume. This unit is classified as Gmm facies. This is overlain by a 15 cm thick unit of well rounded, poorly sorted, clast supported gravels. Above this lies a ~ 60 cm thick unit of well rounded, poorly sorted, matrix supported gravels of the Gmg facies. The clasts and matrix both are derived from rocks of the Indus Molasse, where the matrix is 60 -70 % by volume. Internally this unit is divisible into two depositional episodes. This unit is overlain by a 1.4 m thick unit comprising horizontally bedded, medium to coarse sand lens of 15 m width (Sh facies). At the top, ~ 7.35 m thick, well rounded, poorly sorted, clast supported massive gravels of Gcm facies is marked. In this facies ~ 90 % clasts are sourced from molasse with matrix being 30 – 40 %.

The bottommost Gmm, Gmg and Sh facies were developed by the debris flow. The top Gcm facies may be modified by overcoming the threshold of incipient motion of gravels from the bottom facies and may be developed by the amalgamation of bar and debris flow unit. The Sh facies is dated as 55±6 ka (LD-1221; Fig 4.25).

Saspol (N34º14'50.3" E77º06'40.6")

This section is located ~ 6 km downstream from the Saspol village. Two levels of terraces are noticed here. Lower terrace T-1 shows a 19 m thick fill sequence and the T-2 above the bedrock shows ~ 17 m thick fluvial cover. The sequence of T-1 from the base onwards shows a 3 m thick unit of well rounded, sorted, cross-bedded, clast supported gravels (Gp facies). The clasts of this unit are of mixed lithology and range from 2 to 5 cm in diameter. This unit, with a sharp contact, is overlain by a ~ 4 m thick unit comprising horizontally bedded, well rounded, moderately sorted, imbricated, clast supported gravels. The clasts size ranges from 5 to 20 cm and they are composed of mixed lithology (Gh facies). This is followed by a ~ 2 m thick unit with clast size of 2 to 5 cm while other features remain the same as in the underlying unit. This is overlain by a ~ 3 m thick unit composed of poorly sorted, sub-angular to sub-rounded, matrix supported gravels (Gmg facies). This unit internally shows four depositional cycles with each being separated by lensoidal sand units. The clasts that show better rounding towards the top are sourced equally from the Indus Molasse and the Ladakh Batholith. The clasts of 5 to 70 cm diameter, show imbrication toward the modern flow direction of the river. The following unit towards the top of the section is made up of ~ 7 m thick, horizontally bedded, well rounded, sorted, imbricated, clast supported gravels of mixed lithology (Gh facies), where the clasts size is 2 to 5 cm. A 17 m thick section of the terrace T-2, from the bottom, has 5.5 m thick Gh facies unit with clasts of 4 to 35 cm diameter that are sourced both from the Indus Molasse and the Ladakh Batholith. Matrix is made up of sand and granules. This unit is overlain by a ~ 40 cm thick unit of cross-bedded medium sand (Sp facies), which is followed by a 1.25 m thick cross-bedded gravelly unit (Gp facies) where the clasts size is 4 to 15 cm. The clasts show mixed source 60% from the Indus Molasse and 40% from the Ladakh Batholith. The unit of Gp facies is overlain by a ~ 2 m thick Gmg facies with an erosional basal contact where the clast range from 7 to 55 cm in diameter, and are dominantly derived from the Ladakh Batholith clasts (70%). The topmost unit is composed of ~ 8 m thick Gh facies made up of 3 -15 cm mixed clasts and sand – granules matrix. Matrix makes up to ~ 25 – 30 % of the unit.

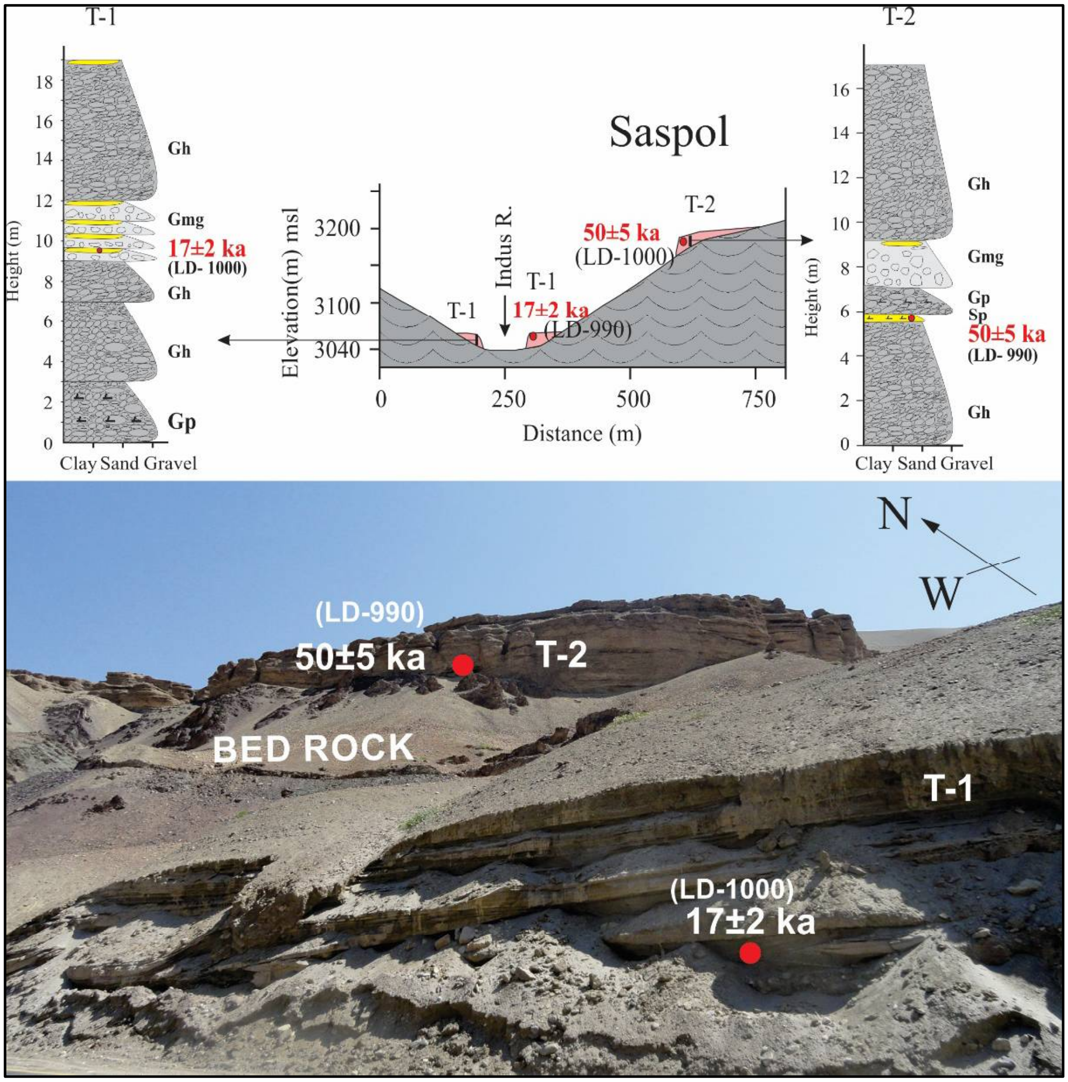

Figure 4.26 (A) The cross-section showing T-1 and T-2; the litholog shows channel bound deposit in both T-1 and T-2. (B) Panoramic view of the Saspol section.

T-1 terrace mainly has channel bound LFA with one event in the middle as debris flow (fan bound LFA). The channel bound units are mainly the results of deposition on a channel bar and the Gmg facies deposited by the locally sourced debris flow event. This event is dated to 17±2 ka (LD-1000). Similarly, fill of the T-2 terrace largely shows channel bound sedimentation with one event of debris flow of the fan bound LFA. The Sp facies of the channel bound LFA is dated to 50±5 ka (LD-990; Fig 4.26).

Nurla (N34º17'24.3" E77º02'3.4")

At this section, two levels of terraces are noted. The lower T-1 terrace exhibits 12.5 m thick channel bound lithofacies LFA, at the base exists a 3 m thick unit comprising well rounded, well sorted, cross-bedded, clast supported gravels of Gp facies, where, clasts that are derived from molasse vary from 2 to 7 cm in size and matrix is gritty sand 25 – 30 % in total volume. This is followed by a 3 m thick unit of horizontally bedded, clayey silt (Sh facies). This in turn is overlain by a 3 m thick unit of well rounded, sorted, massive Gcm facies which is capped by a 50 cm horizon of Sh facies. Towards the top of the section lies a 3 m thick unit of Gcm facies. The alluvial cover of the terrace T-2 is made up of ~ 21 m thick channel bound lithofacies. At the base lies a 2 m thick unit of horizontally bedded, coarse – gritty sand lens (Sh facies) that laterally extends upto ~ 20 m. This is overlain by a 6 m thick unit which is made up of well rounded, sorted, cross-bedded, clast supported gravels (Gp facies). This is followed by a 1 m thick horizontally bedded sand unit of Sh facies. This in turn is overlain by ~ 12 m thick unit of horizontally bedded, well rounded, moderately sorted, clast supported imbricated gravels (Gh facies). This unit is internally divided into two cycles of deposition. The constituent clasts of all the units are derived from the Indus Molasse.

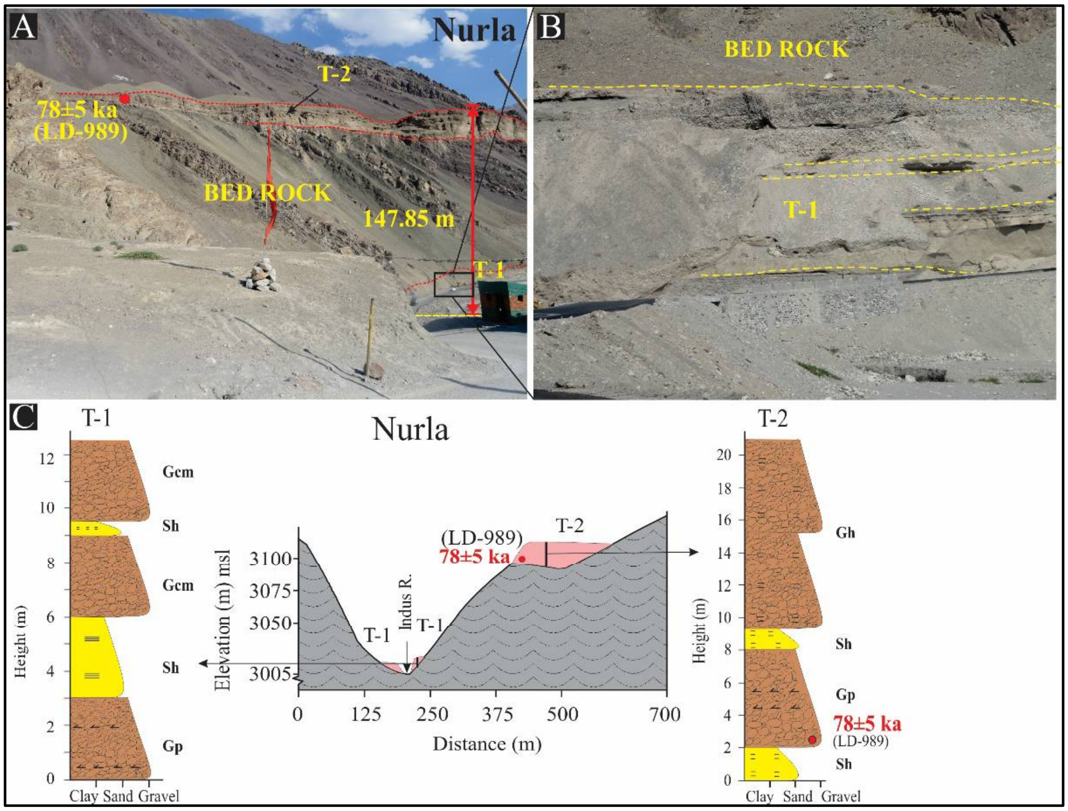

Figure 4.27 (A) A photograph of the Nurla section showing one fill (T-1) and one strath (T-2) terrace. (B) A closer view of T-1. (C) The lithologs of T-1 and T-2 showing that both terraces have aggraded via channel bound processes. The valley cross-section signifies the reduced valley width and deep and narrow gorge.

Sedimentation and aggradation on both T-1 and T-2 terraces are dominated by channel bounded LFA. The sequence of Gcm – Sh – Gcm makes bar events deposited by an individual flood event and the two flood events are separated by waning phase deposition of Sh facies.

The sequence of T-2 terrace alluviation is also a result of channel bound sedimentation, very similar to that of the T-1 terrace. This is dated to 78±5 ka (LD-989; Fig 4.27).

Khalsi (N34°19'33.6" E77°50'45.0")

There are three terraces, two older ones are strath and the youngest one is a fill terrace. The fill of T-1 terrace is made up of 31 m channel bound lithofacies association. Sequence from the base starts with a 1.5 m thick unit of well rounded, well, horizontally bedded, poorly imbricated, clast supported gravels (Gh facies). The clasts are 5 to 15 cm in diameter and are dominantly (70 – 75 %) sourced from batholith. The top 40 cm of this unit is made up of poorly sorted, sub-angular to sub-rounded, matrix supported massive batholith derived gravels of Gmm facies. This is overlain by 1 m thick unit comprising well rounded, moderately sorted, clast supported massive gravels with gritty matrix, classified as Gcm facies. This is capped by a 25 cm thick unit of parallel laminated sand. Above this, lies a 1.5 m thick unit of well rounded, moderately sorted, clast supported imbricated gravels of Gh facies. This is followed by another Gh facies unit, ~ 26.5 m thick, having mixed source.

A 7 m thick sequence of T-1' of well rounded, moderately sorted, clast supported imbricated gravels of Gh facies, which internally is composed of three depositional units. Each unit is separated by parallel medium to fine sand lenses. The constituent clasts are 3 to 15 cm in size and are derived from mixed lithology of the Indus Molasse and the Ladakh Batholith. T-2 bears a 19.8 m thick alluvial cover which is deposited by channel bound processes. The sequence from the base starts with a 2 m thick unit of well rounded, moderately sorted, clast supported massive gravels of Gcm facies where the clasts are 3 to 12 cm.

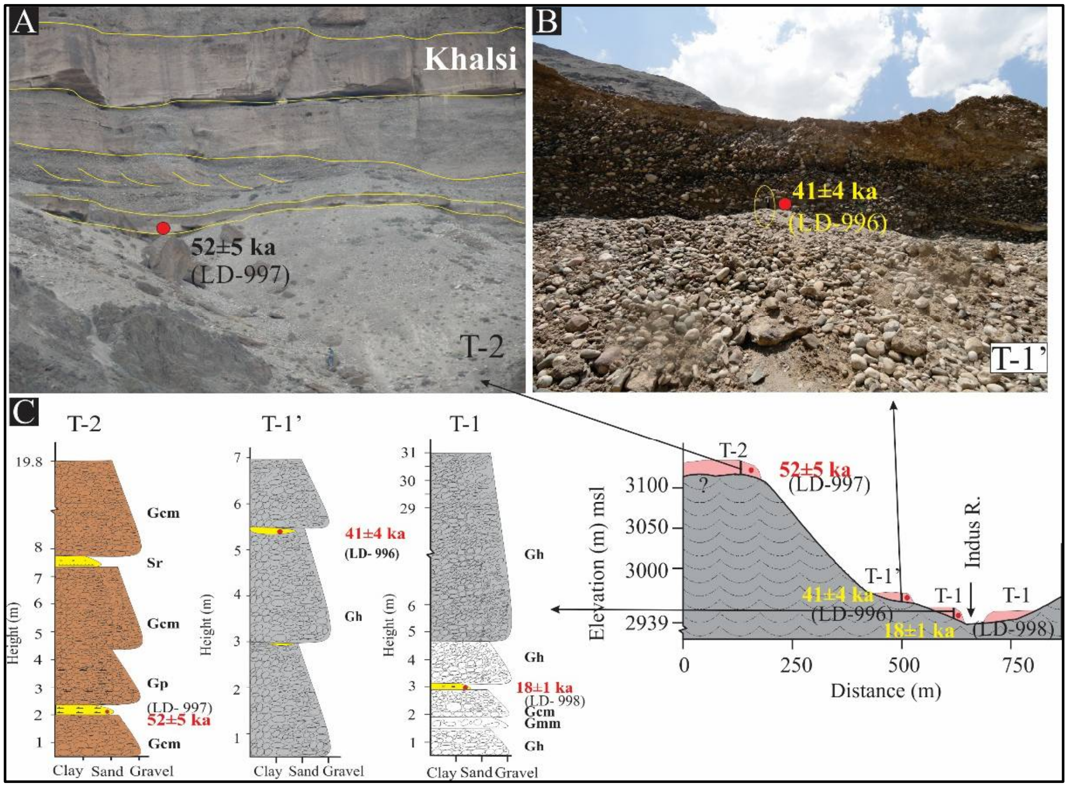

Figure 4.28 (A) and (B) Showing closer view of strath terraces T-2 and T-1' indicating the channel bound LFA. (C) The lithologs of T-1, T-1' and T-2 representing aggradation via fluvial processes. The valley cross-section showing the arrangement of three levels of terraces in the wide valley.

This is followed by a 35 cm thick unit of cross-bedded coarse sand. Above this, there is a 2 m thick unit of rounded, moderately sorted, cross-bedded gravels of Gp facies. This is overlain by a 3 m thick unit of well rounded, clast supported massive gravels of Gcm facies where the matrix is medium sand to granule size and makes 20 – 25 % by volume. This is followed by a 40 cm thick unit of parallel laminated, normally graded sand unit which towards the top shows development of ripples with wavelength of 7 to 10 cm (Sr facies). The topmost unit is 12 m thick, well rounded, moderately sorted, clast supported massive gravels of Gcm facies. The matrix is gritty to granules and contributes 20 – 30 % to total volume. The sediments of the whole section are derived from the Indus Molasse.

The sedimentary sequences of the T-1, T-1' and T-2 are all largely deposited by channel bound processes (Fig 4.28 A, B, C). The sequence of T-1, besides channel bound units also preserves a debris flow event. The sand unit that represented waning phase of bar event in this sequence is dated to 18±1 ka (LD-998). Likewise the sandy unit in T-1' is dated to 41±4 ka (LD-996; Fig 4.28 B). Similarly, the sequence of T-2 is dated to 52±5 ka (LD-997; Fig 4.28 A). This indicates that the Indus River was actively aggrading at 52 ka, 41 ka and 18 ka and that the process of aggradation was punctuated by two phases of incision (Fig 4.28 C).

Dumkhar (N 34º23'58" E 76º45'49.8")

The Dumkhar section has two levels of terraces. T-1 is composed of 31 m thick, horizontally bedded, well rounded, moderately sorted, clast supported imbricated gravels of Gh facies. The bottom 7.5 m is not exposed and is covered by scree. This sequence internally shows eight depositional cycles, where ~ 90 % constituent clasts are derived from the Ladakh Batholith (Fig 4.29 A). The alluvial cover of T-2, from the bottom, shows a 3 m thick unit of well round, moderately sorted, clast supported massive gravels of Gcm facies having matrix of coarse sand. The clasts size ranges from 7 to 45 cm. This is followed by a 1.25 m thick unit of parallel laminated, fining upward, gritty sand unit. This unit extends laterally for 30 m and is classified as Sh facies. This is overlain by a 2.5 m thick unit of well rounded, moderately sorted, clast supported massive gravels of Gcm facies with an erosional contact. The matrix is composed of coarse sand to granules and makes 20 – 30 % of total volume. This is followed by a 90 cm thick unit of massive, coarse sand bed of Sm facies. Above this, with an erosional base, lies a 5 m thick unit of sub-angular to sub-rounded, poorly sorted, matrix supported massive gravels of Gmm facies. The matrix is gritty to granules. This in turn is overlain by a 5 m thick unit of well rounded, moderately sorted, clast supported massive gravels of Gcm facies with sharp basal contact where, the clast size ranges from 7 to 80 cm and 80 – 90 % them are the Batholith rocks (Fig 4.29 A).

Aggradation of T-1 took place by channel bound processes (Fig 4.29 B) where eight depositional cycles are identified. The sequence overlying the strath of T-2 again shows facies association with Gcm - Sh and Gcm - Sm suggesting aggradation due to bar migration during the floods and waning phase. The Sm facies representing the waning phase of one such unit is dated to 57±3 ka (LD-995; Fig 4.29 C). The sequence also preserves a unit indicating a debris flow in a fan bound LFA.

Skyurbuchan Gompa (N 34°26'0.6" E 76°42'54.3")

Like the Dumkhar section, Skyubuchan Gompa section has two levels of terraces. T-1 is composed of 31 m thick, well rounded, moderately sorted clast supported gravels of Gh facies which internally show four depositional cycles.

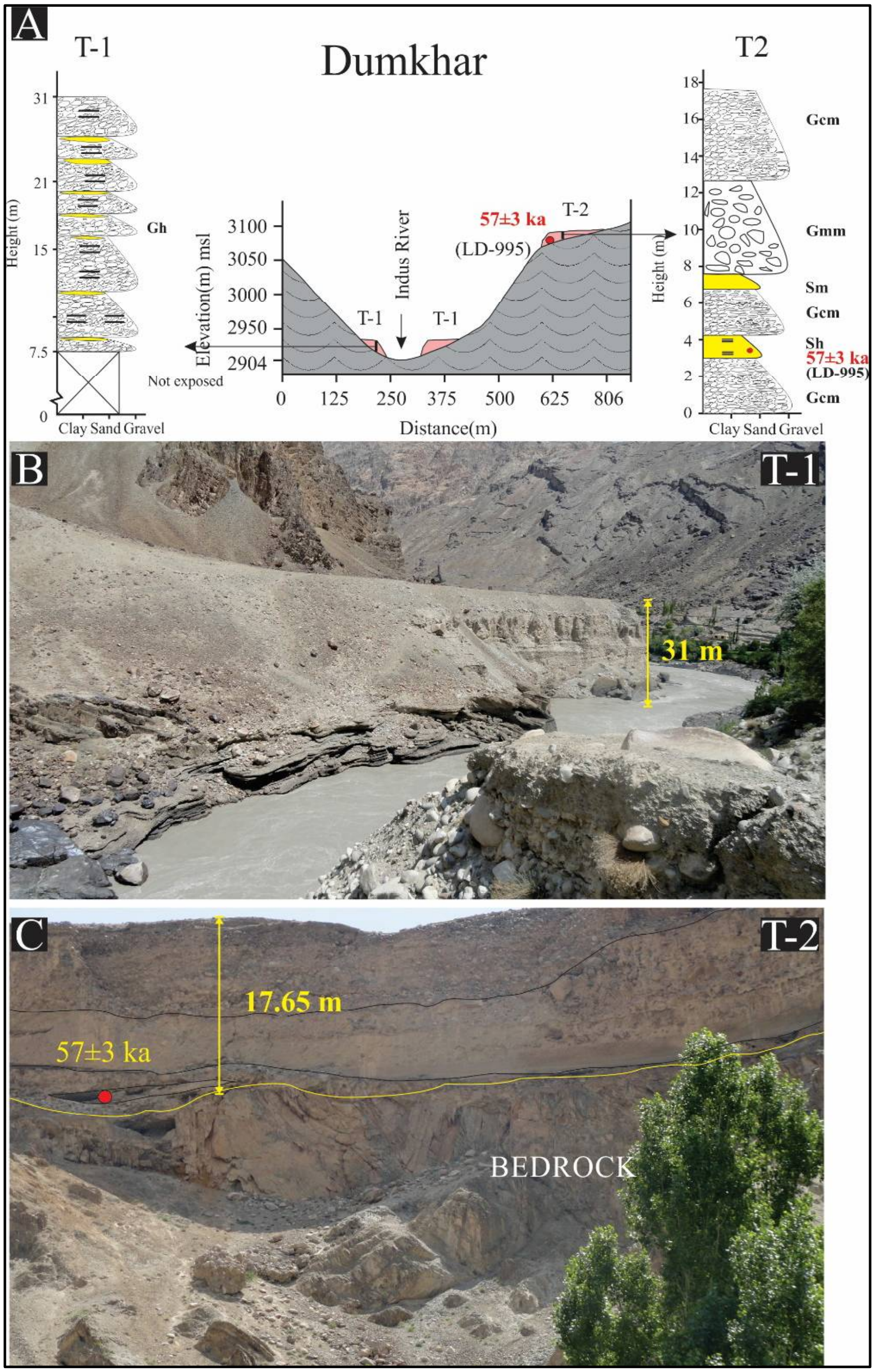

Figure 4.29 (A) The litholog of fill terrace T-1, showing the channel bound deposits T-2 is associated with both channel and fan bound deposits at Dumkhar. (B) and (C) Showing T-1 and T-2.

Each cycle is capped by a thin sand lens. The constituent clasts are of mixed lithology (Fig 4.30 A). The alluvial cover of T-2 is made up of ~ 15 m thick, horizontally bedded, well rounded, well sorted, clast supported imbricated gravels. The imbrication of gravels follows the present day river flow direction. The clasts are dominantly granitic in composition with size range of 3 to 20 cm and have 25 – 30 % medium to coarse sandy matrix. This unit is classified as Gh facies (Fig 4.30 A).

Alluviation of both the terraces took place due to channel driven processes depositing channel bound LFA, mainly Gh facies. The sand layer, which caps the gravelly unit in this facies represents the waning phase of flood (Miall, 2006). The momentary changes in the upstream propagated continuous bar migration at low channel gradient conditions and thick multi-story gravel facies is deposited. The sand lens towards the bottom of sequence T-2 is dated 56±7 ka (LD-988; Fig 4.30 B and C).

Skyurbuchan Downstream (N 34°27'0.6" E 76°41'5.7")

This section has two levels of terraces. T-1 is composed of 40 m thick channel bound deposits. Bottom ~ 28 m is covered by the scree deposits and only intermittently exposed. Therefore, the facies classification is done on the exposed section only (Fig 4.30 D). From the road level, a ~ 1.4 m thick unit has well rounded, sorted, horizontally bedded, clast supported imbricated gravels capped by ~ 30 cm planar cross-bedded sand unit. The gravel unit is classified as Gh facies, whereas the sand unit as Sp facies. The clasts of Gh facies are sourced from mixed lithology. This facies is overlain by 2.3 m gravel unit of similar structural and textural properties and therefore, classified as Gh facies. This unit is capped by 30 cm horizontally laminated sand and classified as Sh facies.

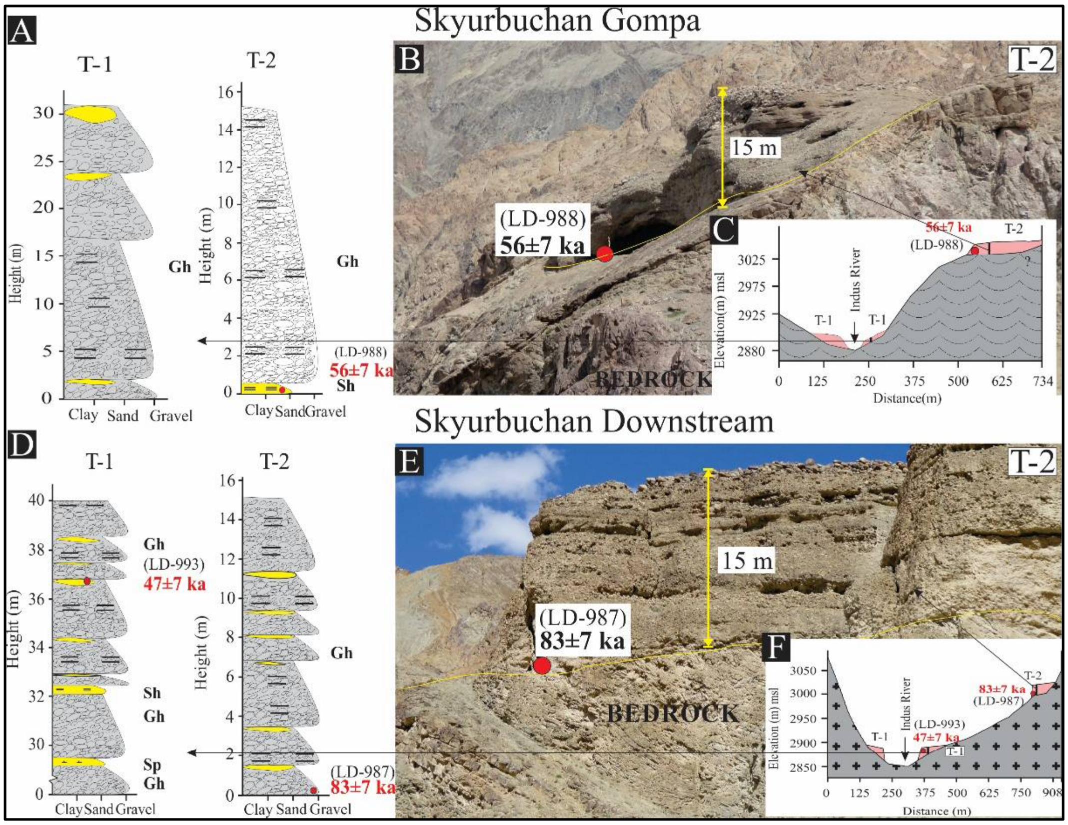

Figure 4.30 (A) Lithologs of two terraces at the Skyurbuchan Gompa section suggest that the river aggraded via channel bound processes. (B) A photograph of T-2 terrace. (C) The valley cross-section showing wide valley at the time of T-2 aggradation and narrow at present day (T-1). (D) The litholog of T-1 and T-2 of the Skyurbuchan Downstream section. (E) A photograph of T-2 of the Skyurbuchan Downstream section. (F) V – shaped valley can easily be seen in the valley cross-section.

This is followed by a 6.7 m thick unit with Gh facies, which is divisible into six depositional cycles. Each cycle is capped by small sand lens.

T-2, is covered by ~ 15 m thick channel deposits (Fig 4.30 D and E). The whole unit is deposited by multistoried lensoidal bodies of well rounded, moderately sorted, horizontally bedded, clast supported gravels. Each story is capped by a sand lens at the top. Clasts of the entire unit are sourced from mixed lithology of the Indus Molasse and granites of the Ladakh Batholith. The structure and texture of this multistory unit classifies it as Gh facies.

The facies associations of both the terraces show that these are composed of channel bound LFA. Luminescence chronology on the sand lenses from the top of T-1 terrace and from the base of T-2 has yielded depositional ages of 47±7 ka (LD-993) and 83±7 ka (LD-987), respectively (Fig 4.30 F).

Biamah (N 34º36'34.9" E 76º29'58.4")

In this section only one level of fill terrace is noticed. A 17 m thick section is deposited by both channel as well as fan bound processes. The bottommost unit is made up of 2 m thick, well rounded, moderately sorted, clast supported planar cross-bedded gravels (Gp facies). The clasts of this unit are 5 -10 cm in diameter. This is overlain by an 8 m thick unit, which is composed of sub-angular, poorly sorted, matrix supported graded gravels of Gmg facies. The clasts size is ranging from 5 to 50 cm and has an erosional contact with the basal unit. Above this is a 4 m thick unit with rippled fine sand of Sr facies. The ripples are climbing in nature.

Towards the top, a unit of well rounded, moderately sorted, clast supported imbricated gravels of Gh facies is deposited. The clasts and matrix has granitic composition in all the facies.

The Gp facies of channel bound LFA was deposited when river had high channel gradient and traction current. The Gmg facies represents the fan bound LFA and suggests that this facies was deposited by large plastic debris flow event. In both cases aggradation took place because sediment to water ratio was very high in the channel. The Sr facies with climbing ripples also indicates towards excess sediment load even during the waning phase of the flood. The sample from this unit (Sr facies) yielded an OSL age of 7±1 ka (LA-991; Fig 4.31).

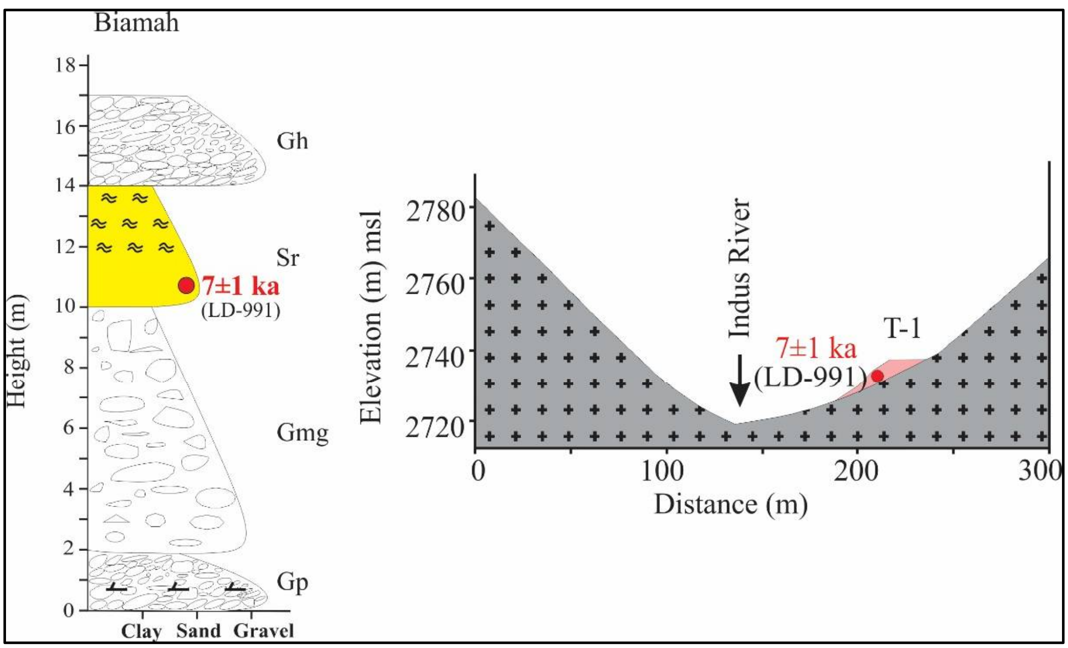

Figure 4.31 Litholog of Biamah section. The valley is V – shaped and sediment lies on right bank of the river.

4.6 Sedimentary style and depositional patterns of Sand Ramps in Leh valley

Spituk sand ramp (N 34° 8'2.4" E77° 31'39.9")

This section is located in front of the Leh Airport, on the right bank of the Indus River. The Spituk sand ramp caps a paleolake deposit. It is made up of 8 m thick, yellowish, moderately sorted, parallel laminated medium to coarse sand, characterized as *parallel laminated medium sand* facies. This facies is overlain by, 7 m thick, greyish coloured, well sorted, parallel laminated, clayey sand. The individual lamina is 1-2 mm thick and shows deformation structure.

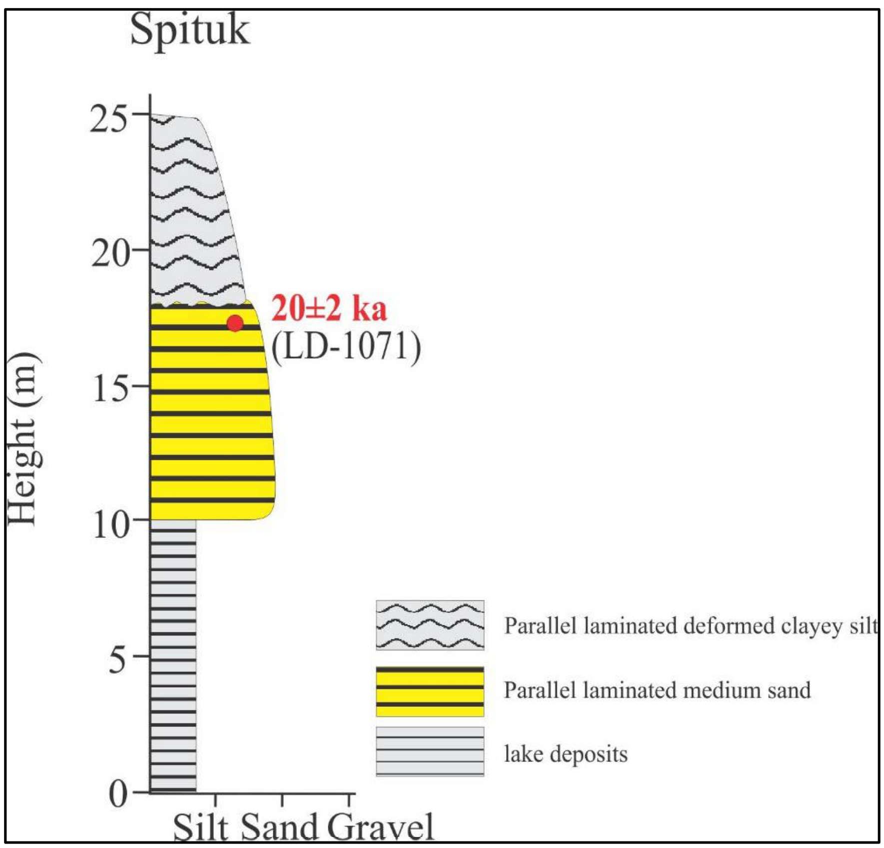

Figure 4.32 Litholog of Spituk sand ramp showing the facies distribution.

Therefore, it is classified as parallel laminated deformed clayey sand. Laterally, the unit pinches out over the distance of ~30 m (Fig 4.32).

The sand facies is an aeolian deposit, whereas the clayey unit is intra-dunal lake deposit, which internally deformed due to cryoturbation. The aeolian sand from the top yielded an OSL age of 20±2 ka (LD-1071).

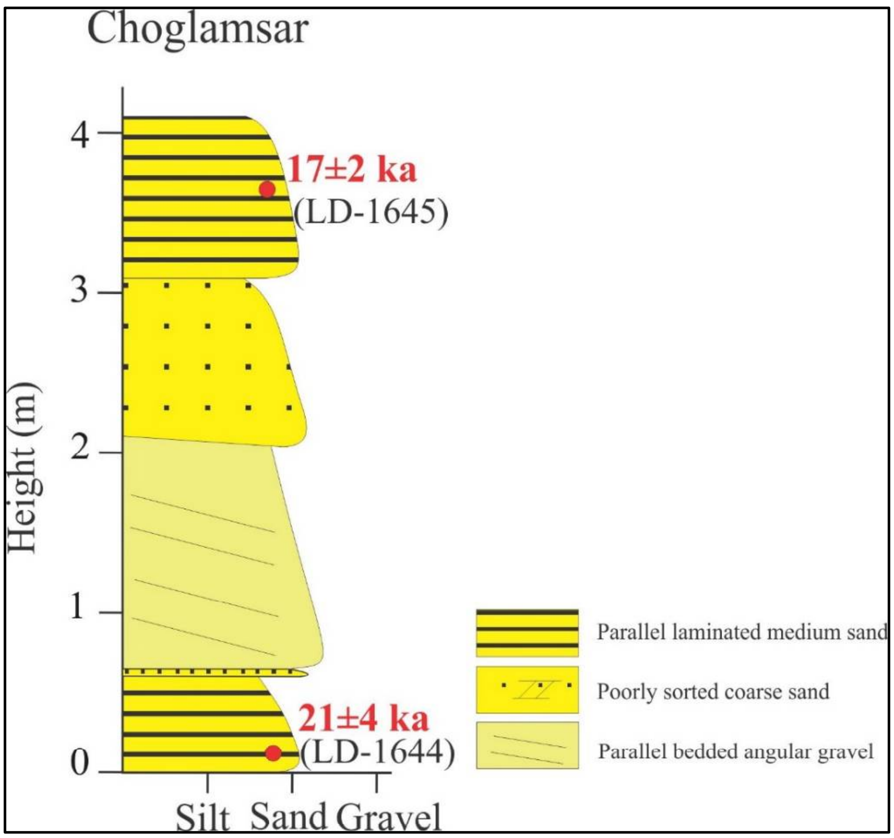

Figure 4.33 The litholog of Choglamsar sand ramp section showing the distribution of aeolian, fluvial and talus facies.

Choglamsar sand ramp (N 34° 7'44.5" E77° 36'3.6")

This section is located on the Leh - Saboo road, where 4.1 m thick sequence of sand ramp (Ch-3 in table 1) accreted on the Ladakh Batholith (south facing slope). This is made up of aeolian, fluvial and talus related facies. Basal 0.6 m unit comprises well sorted, parallel laminated, medium to coarse sand characterized as *parallel laminated medium sand* facies. This unit is capped by 8 cm thick layer of hard crust that bears a gradational contact with the aeolian unit. Hard crust internally is made up of indurated poorly sorted granules floating in sandy matrix. This is overlain by a 1.5 m thick, poorly sorted, massive medium to coarse sand. This is a lensoidal channelized unit with angular gravels at the base exposed as channel lag. This represents gulling event and that can be seen in this unit frequently. This unit is classified as *parallel bedded angular gravels* facies. Overlying this, is a 1 m thick, poorly sorted, grayish to yellowish coarse sand unit with sporadic granule size particles, characterized as *poorly sorted coarse sand* facies. At the top, a 1 m thick, parallel laminated, moderately sorted, medium sand occurs as *parallel laminated medium sand* facies (Fig 4.33).

The *parallel laminated medium sand* facies is interpreted as deposited by aeolian processes, the *parallel bedded angular gravel* as talus deposits and *poorly sorted coarse sand* with channel lag as the gully fills. Two samples one each from basal and top aeolian units have yielded OSL ages of 21±4 ka (LD-1644) and 17±2 ka (LD-1645), respectively.

Saboo sand ramp (N 34° 08'3.6" E77° 37'21.7")

Saboo sand ramp accreted on the SE facing hill slope of the Ladakh Batholith and is exposed along a small stream at Saboo village. A total of ~ 4.5 m thick sequence has a composite record of aeolian, fluvial and talus processes. The basal 3.5 m thick unit is parallel laminated, medium to fine sand. The whole sand unit follows the topographic slope and dips at an angle of 9°45'. This unit is characterized as *parallel laminated medium sand* facies. This facies is overlain by a ~5 cm thick layer of hard crust, composed of matrix supported granitic angular gravels at 3.3 m level above the base. The matrix is very fine silt to clay. The gravel size ranges from 2 to 5 cm. This unit is identified as *parallel bedded angular gravel* facies. This facies has a sharp contact with the parallel laminated sand facies. Overlying this, a 90 cm thick, poorly sorted, gritty to coarse sand unit, sandwiched between two hiatus. This unit has clay curls and angular gravels as channel lag and is termed as *poorly sorted coarse sand* facies. This facies is capped by 8 cm thick hard crust of *parallel bedded angular gravel* facies (Fig 4.34).

The section evolves with an active sedimentation of aeolian sand, which, after a hiatus as represented by a thin hard crust, is gullied by the activity of small rill that operated on the surface. This was again followed by a phase of aeolian sedimentation that terminated with the formation of another hard crust present towards the top of the section. The samples from the basal aeolian unit represent the activity from 12±0.7 ka (LD-1072) to 8±1 ka (LD-1073) and one sample from the gully fill unit yielded an age of 7±0.5 ka (LD-1074).

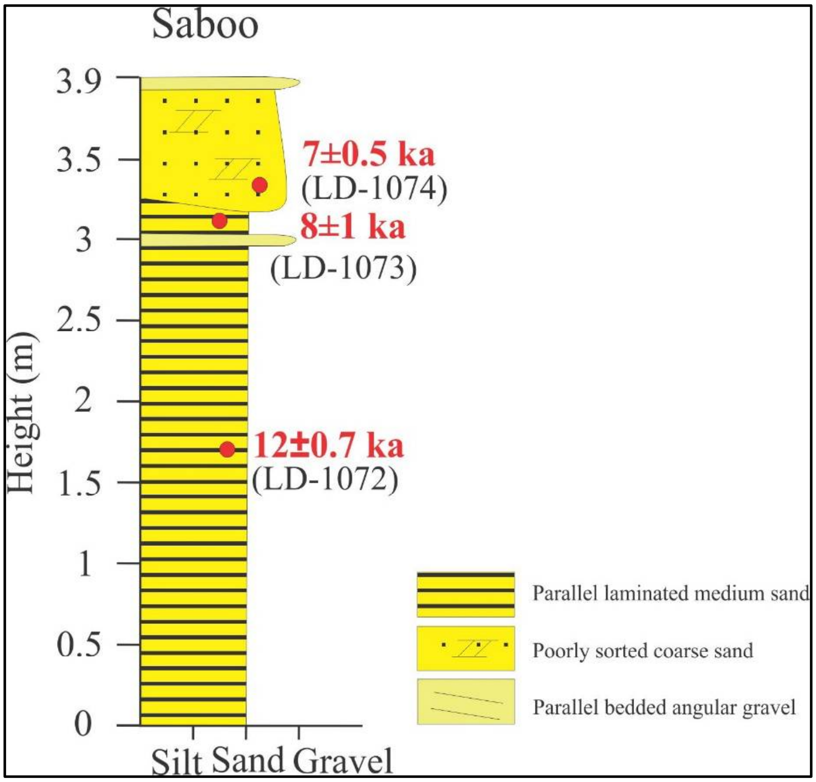

Figure 4.34 Parallel laminated medium sand, poorly sorted coarse sand and parallel bedded angular gravel facies that characterize the Saboo sand ramp.

Shey Sand ramp -2 (N 34° 04'56.13" E77° 37'53.3")

A 14.5 m thick section is exposed at Shey and from the base onwards it shows a 6 m thick unit of parallel laminated, well sorted, grey coloured aeolian sand. Each laminae is 1 to 2 mm thick and follows the gentle slope of topography. This unit is classified as *parallel laminated medium sand* facies. This, with an erosional base, is overlain by a 4 m thick unit comprising poorly sorted *parallel bedded angular gravel* facies. The gravels are 2 to 5 cm in size, granitic and derived from rocks exposed along the hill slope. Above this, lies a 2 m thick, parallel laminated greyish clay rich silt. This unit is internally deformed by pene-contemporaneous deformation structure and *parallel laminated clayey silt* facies. This is followed by a 1.5 m thick unit of parallel laminated, grey coloured, moderately sorted, medium sand of *parallel laminated medium sand* facies. At the top, a 1 m thick parallel bedded, poorly sorted, grey coloured sand with granitic grits of *parallel bedded angular gravel* facies is deposited.

This section starts accretion with an aeolian facies followed by a quiescence and deposition of hill slope debris. This is further operated by gully erosion and filling. Subsequent to this, there is a phase of active aeolian sedimentation with the coexistence of an intra-dunal lake. The deformational features exhibited in the lacustrine unit seem to be a result of cryogenic deformation. OSL samples from the base of the aeolian and the upper hill slope deposits have yielded 44±3 ka (LD-1647) and 26±1 ka (LD-1646, Fig. 3.26), respectively.

Shey Sand ramp -3 (N 34° 04'36.4" E77° 38'10.3")

This section is located near Shey palace and is well exposed due to sand mining. The basal 8 m of this section is composed of poorly sorted, yellowish – greyish coloured, inclined *parallel bedded angular gravels*. The gravels are sourced from the adjacent granitic hill. This unit is followed by a ~ 5 m thick unit consisting of grey coloured, poorly sorted sand unit with pebbly channel lag. The channel lag contains 1 to 5 cm wide channel curls and 1 to 2 cm angular gravels. This facies is classified as *poorly sorted coarse sand* lithofacies. This is overlain by two units comprising *parallel laminated medium sand* facies, each ~2 m thick, reddish coloured, parallel laminated medium sand. At the top, 1 to 1.5 m thick, parallel laminated grey, deformed clayey – silt is deposited that shows pene-contemporaneous deformation. The deformed lamina shows oxidation and exhibits dark yellow layer lining. This unit is classified as *parallel laminated clayey silt* facies (Fig 4.35).

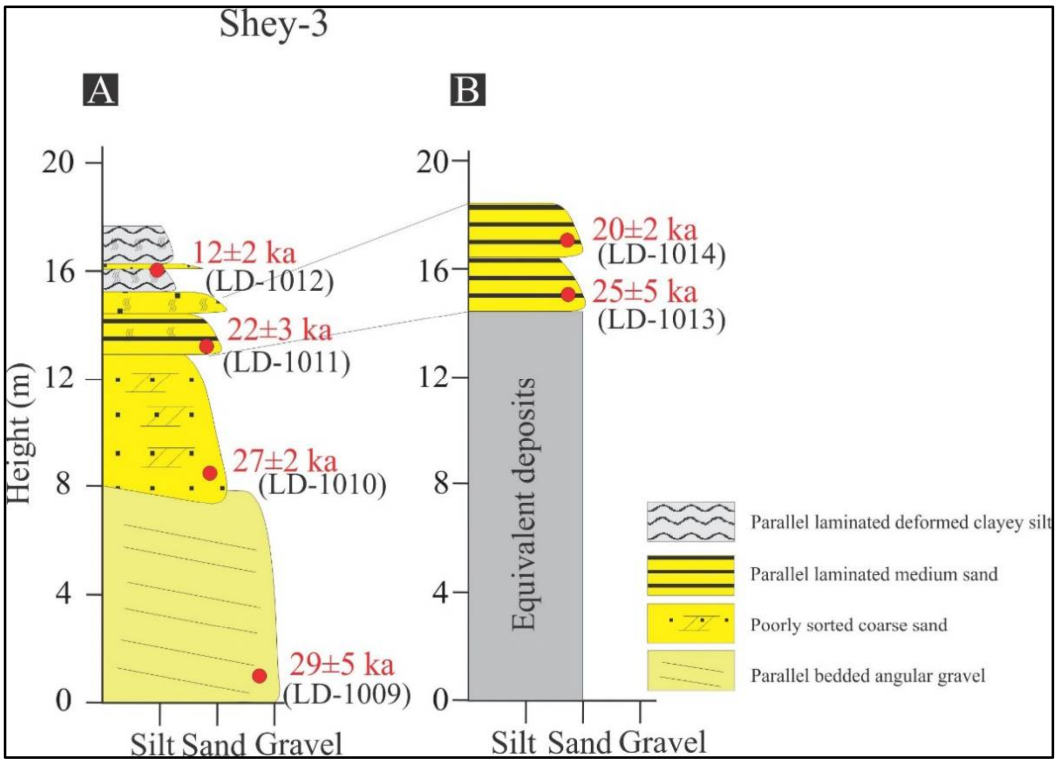

Figure 4.35 The two lithologs of Shey-3 sand ramp showing the distribution of different facies. The lateral extension of these facies is quite similar as shown in (A) and (B). The litholog (A) is located ~ 50 m towards the river side from (B). This indicate that the intra-ramp-lake had limited lateral extension (~ 20 m).

The *poorly sorted coarse sand* facies with channel lag is deposited by the fluvial process. The presence of clay curls indicates strong erosive power of the flood. The *parallel bedded angular gravels* facies follows the hill slope (11°) and was deposited by sheet wash occurring along the hill slope and depositing hill slope debris. The *parallel laminated clayey silt* facies represents the formation of 1 to 1.5 m deep intra-dunal lake, which later got deformed by cryoturbation as shown by the PCD structure. The OSL chronology suggests that the talus was deposited at ~29±5 ka (LD-1009) and the fluvial aggradation took place at 27±2 ka (LD-1010). Three samples from the upper aeolian units and one from the intra-dunal lake have yielded ages of 22±3 ka (LD-1011), 25±5 ka (LD-1013), and 20±2 ka (LD-1014) and 12±2 ka (LD-1012), respectively.

4.7 Sediment generation, aggradation and deposition

The sediment generation and aggradation pattern in any river depend upon various factors; (1) available sediment in the valley, (2) annual water budget of the stream, (3) the relative sediment to water ratio and (4) valley configuration. Large values for sediment to water ratio, will produce fill terraces (Ray and Srivastava, 2010; Blum and Törnqvist, 2000), whereas the formation of strath terraces depends upon the valley configuration and local / regional tectonics of the area (Wegmann and Pazzaglia, 2009). The Indus River system is located in the Trans-Himalaya; the water budget of Indus is influenced mainly by the glacial-melting and abnormal rainfall in summer, and westerly's solid precipitation in winters (Bookhagen et al., 2005). The sediment supply is mainly controlled by glaciation – de-glaciation processes, debris flow, landslide and flash flood events. In this region, the sediment is generated by glaciation – de-glaciation processes, valley wall erosion, and debris flow from narrow and amphitheater valleys. There is little or no vegetation cover, which support more denudation and eventually more sediment supply leads to valley aggradation. The aggraded sequences have the signatures of debris flow, flash flood, and channel bar formation.

The stratigraphy of fill and strath terraces has been studied on best exposed sections in the field. The lithofacies analysis and mode of deposition were characterized by detailed study on different depositional units. The clast size, roundness, sorting, matrix and its percentage were used to classify the lithofacies. The clast lithology and clast count data have been used for provenance. In the upper reaches of the Indus near Mahe section, sandstone, siltstone and grano-dioritic clasts suggest that these were derived from the Indus Molasse or the Ladakh Batholith (Sub-facies-C). In stratigraphy of fill terrace, the fluvial unit has been interrupted by the debris flow unit, therefore, the channel and fan bound LFA are marked simultaneously. The significance of this association points toward the climatically warmer phase. From Upshi downstream, the valley dominates the alluvial fans, hence, the molassic clasts increased in the stratigraphy. The Leh valley is very wide and has a lot of accommodation space of other geomorphological landforms like palaeolake deposits, sand ramps, glacial moraines, etc. The aeolian lithofacies (Sand ramps), in this valley, has intermingling of talus and intra-dunal lake deposits. Such interfingering of lithofacies suggests different climatic phases. The stratigraphy of strath terraces has dominantly channel bound LFA associated with Sub-facies-C (mixed clasts), and at some places, Sub-facies-A (Ladakh Batholith clasts). This has spatial and temporal importance for strath aggradation. The high stream gradient, high sediment supply, and high annual water budget of the Indus River suggest that there is very less lag time to carry the sediments from the upstream and deposit in the downstream of the valley. Thus, these fluvial records preserve the history of exogenic (climatic variability), endogenic (regional and local tectonics) as well as the coupling of these two processes.