Chapter 6

Discussion and Conclusion

The best brains of the nation may found on the last benches of the classroom.

- Dr. A.P.J. Abdul Kalam

CHAPTER 6 DISCUSSION AND CONCLUSION

6.1 Indus River System

Indus River is one of the largest rivers in the world, originating in the Mount Kailas (5182 m asl) in the Gangdese range of southern Tibet. It drains through various tectonically active zones, including the Karakoram fault zone in Tibet, Ladakh Himalaya (Indus Tsangpo Suture Zone), and Nanga Parbat in the western syntaxis of Himalaya (Fig 6.1; Brookfield and Andrews Speed, 1984; Thakur and Misra, 1984; Garzanti and Van Haver, 1988; Searle et al 1990; Wu et al., 2007; Henderson et al 2010 a, b, 2011). Geological and geophysical investigations on sediments of the Indus Molasse, Ladakh and Indus fan suggested that predecessor of modern Indus basin was a centripetal drainage that filled the basin in the Ladakh Himalaya until ~45 Ma and then due to regional tectonic uplift during early Miocene (<26 Ma), present south-west flowing the Indus River came into (Clift et al., 2001; Sinclair and Jaffey, 2001). Approximately 3200 km length and 1.12×10^6 km^2 catchment area of Indus River, from source to sink, place it on 12^{th} position among the world's largest rivers. The major tributaries that contribute water and sediments to the Indus significantly are Sengge and Gar in Tibet, Zanskar, Suru, Shyok, Shigar, Gilgit, and Kabul in the Higher Himalaya and Gomal, Kurram, Jhelum, Chenab, Ravi, Beas and Satluj in the Punjab plain of Pakistan. The Indus valley civilization, one of the ancient known civilizations, existed along the Indus during ~ 6000 BP.

In Ladakh region, from Mahe to Dah Hanu, the total length of the Indus is ~470 km that shows a phase of widespread valley fill in the form of 10-40 m thick terrace T-1 and fan aggradation. The lithofacies and stratigraphy of terrace T-1 suggest that mainly channel bound processes, in the form of channel bars, controlled the valley aggradation. Development of a channel bar takes place during a flood cycle that in Ladakh commences between June and August (SW monsoon). Gravel imbrications and fining upward cycles in the depositional units suggest that the sedimentation occurred during a wetter climate, high sediment availability and a broader flood hydrograph (Ray and Srivastava, 2010). Sedimentation pattern and aggradation in a river valley depends upon the relative availability of water and sediment in the channel network and the rainfall event. Likewise, large outwash fans emanating from the Ladakh Batholith and Zanskar ranges (Indus Molasse) in Leh valley, where debris flows are common, were formed during episodic rainfall events and glacial melting after a major glacial advancement. Downstream from Nimu, the Indus River cuts through the Indus Molasse then makes a deep gorge into the Nanga Parbat Harmosh Massif (NPHM) and flows south-westward thereafter. This segment is characterized by the presence of strath terraces indicating active role of tectonics. Besides the aggradation and incision history I attempted to estimate the paleohydrology of the Indus River by utilizing gravel geometry and studied the sedimentological record of sand ramps (obstacle dunes).

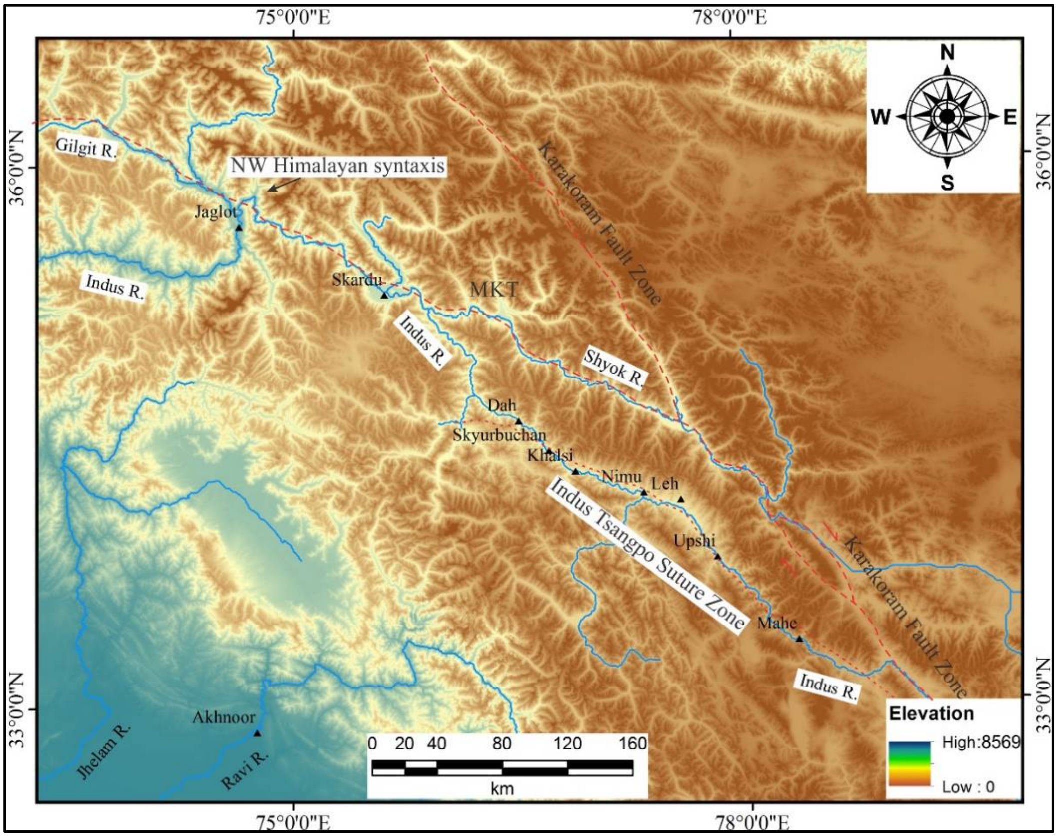

Figure 6.1 The Indus River flowing SE to NW direction and draining various tectonic zones; the Karakoram fault zone in the north, the Indus Tsangpo Suture Zone, the northwestern Himalayan syntaxis and the major tributaries of Indus River.

6.2 Role of Climate and Tectonics

6.2.1 Indus river sedimentation and palaeoclimate

Before understanding the aggradation record in terms of climate, a brief account of paleoclimatic history of the studied area is presented here. Ladakh region is associated with two precipitation systems, first, SW Indian Summer Monsoon (ISM), which contributes ~ 50% and the second is Westerlies that mainly are responsible for the snowfall during winters and add the remaining ~ 50% to the hydrological budget of the river (Bookhagen and Burbank, 2010). Abnormally wet monsoon years potentially tilt the water budget towards the ISM significantly when Indus experiences massive flash floods and events of cloud bursts (Bookhagen et al., 2005).

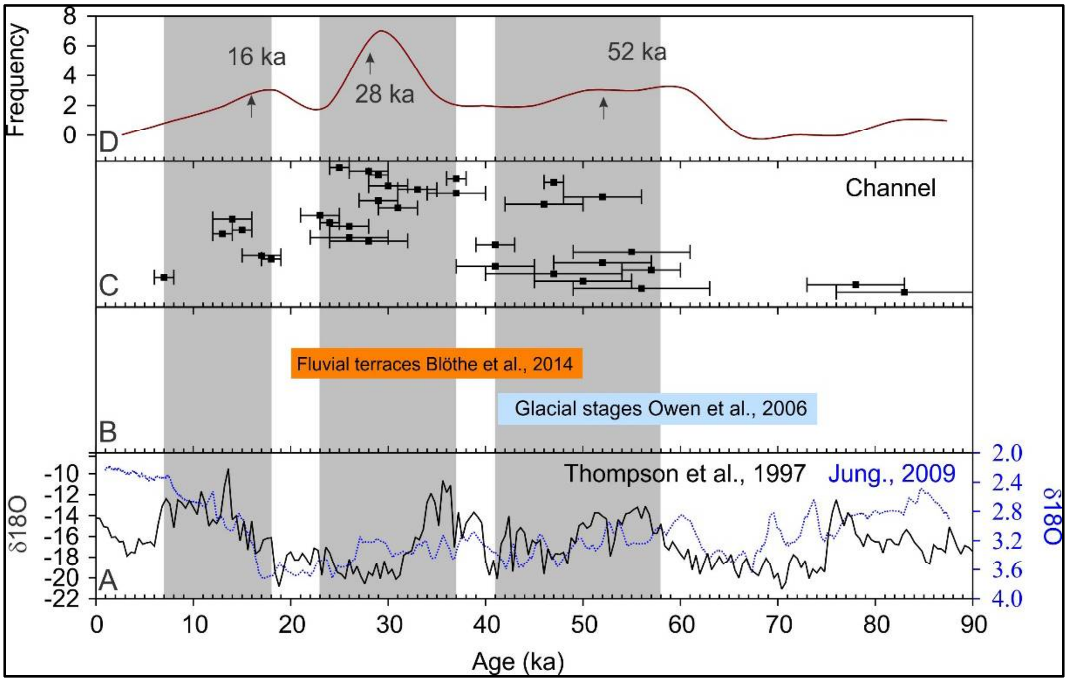

Figure 6.2 Aggradation in the Indus River vis-à-vis paleoclimate record. (A) Climate record from the Guliya Ice Core (after Thompson et al. 1997) and Benthic Stable Isotope Data from Arabian Sea sediment core NIOP905 87KYr (Jung et al., 2009). (B) Glacial record of Ladakh Himalaya, (C) OSL ages of the Channel and outwash fan sediments along the Indus River, (D) Frequency distribution curve of all the ages. Here it can be noted that the major aggradation has occurred during the warm MIS-1 and MIS-3.

Guliya Ice Core records, from ~ 400 km NE of the study area, suggests that MIS-1 (post LGM) and MIS-3 (60-30 ka) had stronger ISM than the MIS-2 (Marine isotope Stage-2; 25-18 ka; Thompson et al., 1997; Fig 6.2 A). Lake record from Ladakh and speleothem records from Mawmluh cave, NE India indicated post glacial warming because of Bølling-Allerød, leading to Early Holocene optimum (Wünnemann et al., 2010; Dutt et al., 2015).

A cold and drier spell between 13 and 11.6 ka (Younger Dryas) with subsequent warm phase from 11.6 to 8.8 ka has been reconstructed using peat-lake deposits from the Chandra Tal (Rawat et al., 2015). The palaeo-lake (Rizong, Saspol and Spituk-Gupuk paleo-lakes) and glacial moraine sediments (Nimu) from the Ladakh Himalaya suggest phase of deglaciation from 17.5 to 14 ka, intensified ISM during 14 to 5 ka (Nag and Phartiyal, 2015), and cold arid climate during 23 – 21 ka (Phartiyal et al., 2013). Glacial records suggest expansion during cool wetter phases. Therefore, MIS-3 witnessed glacial advance in Tibet and Ladakh when the Equilibrium Line Altitude (ELA) descended by 1000 m from its present value (Figure 6.2 B; Owen et al., 2005, 2006 a, 2008; Damm, 2006; Ali and Juyal, 2013; Dortch et al., 2013; Owen and Dortch, 2014). The studies on fluvial terraces and lake records from China and the NW Himalaya (Pangong Tso) also showed climatically wetter conditions between 44 and 34 ka (Shi et al., 2001). Fang (1991) suggested an increase in lake level during 43-33 ka, 27-24 ka, and 11-4 ka.

A regional glacial expansion in the Ladakh Himalaya has been noticed by studying the glacial moraine during MIS 5a (SWHTS 5A glacial stage; 81±20 ka) and MIS 4/5a transition (SWHTS 5A; 72±8 ka; monsoon recession phase) (Dortch et al., 2009, 2013), which suggest an arid climate phase in the NW Himalaya in MIS 5a and transition phase of MIS 4/5a (72 – 81 ka).

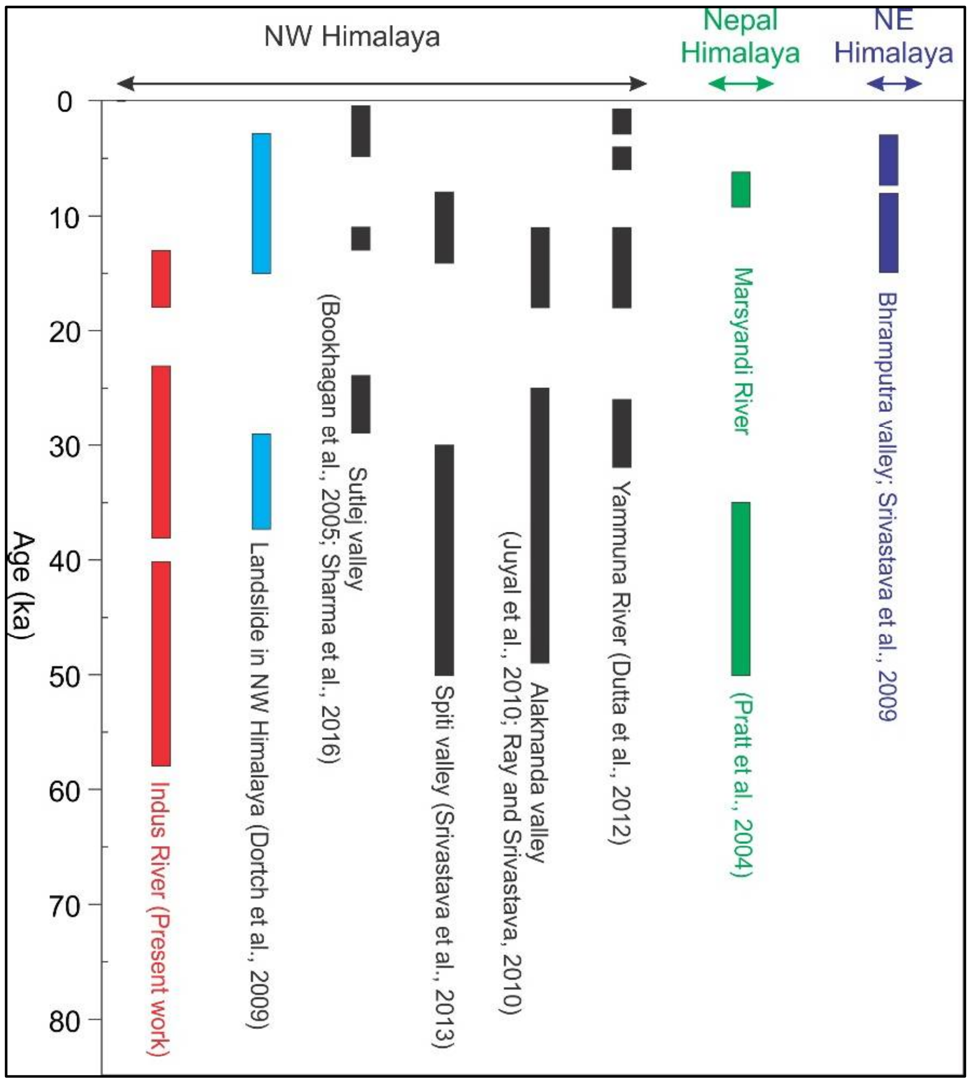

Figure 6.3 Major aggradation phases in the NE Himalayan to Nepal and the NW Himalayan Rivers.

The records from the Zanskar valley also suggest that the valley aggraded intermittently between 50 and 20 ka (Fig 6.2 B; Blöthe et al., 2014). OSL ages of fluvial fills (T-1 and T-2 terraces of Indus River), debris flows, and outwash fans from the Ladakh Himalaya are plotted and compared with regional climatic as well as glacial variability (Fig 6.2 C). This broadly suggests that the aggradation related to channel and fan bound processes occurred in three pulses centered at ~ 16 ka, ~ 28 ka and ~ 52 ka (Fig 6.2 D). The intervening periods may correspond to phases of channel incision. The fans prograded and aggraded from ~ 47 to 29 ka, whereas three debris flow events occurred at ~27 ka (MIS-3). The progradation of fans and aggradation in river valley took place during climatically wet phases of MIS-3 and MIS-1 just after the major glaciation in the region.

Other rivers in Himalaya from Brahmaputra in the NE to Indus and Spiti in the NW experienced extensive aggradation during MIS-1 and MIS-3 (Fig 6.3). The Spiti River aggraded during 50-30 ka and 14-8 ka (Srivastava et al., 2013). River Sutlej, shows intensified monsoon during MIS-3 (29 – 24 ka; Bookhagan et al., 2005), also incorporated two phases of aggradation during the late Pleistocene (13 – 11 ka) and mid – late Holocene (5 – 0.4 ka) punctuated with one intensified ISM event during 6.5 – 7 ka (Sharma et al., 2016). Likewise, Alaknanda (NW Himalaya) and Brahmaputra (NE Himalaya) also aggraded during 49 - 25 ka and 18 - 11 ka due to the strong ISM (Srivastava et al., 2009; Juyal et al., 2010; Ray and Srivastava, 2010; Chaudhary et al., 2015; Kothiyari et al., 2016). In the central Nepal Himalaya, the aggradation in Marsyandi River during 50-35 ka and 9-6 ka suggested intensification of ISM during MIS-3 and MIS-1 (Fig 6.3; Pratt-Sitaula et al., 2004).

From the present study, it can be the concluded that rivers flowing in the arid to semi – arid Himalaya aggraded during the wetter phases (MIS-3 and MIS-1). During these climatic phases, the aggradation of valley took place only when the sediment to water ratio was higher (transient climate, Scherler et al., 2015).

6.2.2 Morphometric indices, channel incision and their possible causes

The terrace configuration of any river is a consequence of the phases of aggradation and incision that a particular stretch of channel has undergone. The thickness of aggraded sequences and underlying bedrock potentially indicate the residence time of the channel, accommodation space, sediment and water availability, and climate and . Analysis of the longitudinal river profile and some specific geomorphic indices, such as Ksn and SL index, has a potential to unravel the stream power, erodibility of channel due to lithology change and / or tectonics, and knickpoints. SL index quantifies the variation in the bedrock erosion along a channel and any changes in this index indicate, (1) lithological contacts with varied erodibility, and/or (2) differential uplift along an active fault (Troiani et al., 2014).

In Segment-I, near Nyoma, the river flows in a wide U-shape valley with 0.75 m/km channel gradient. The longitudinal profile of the Indus River shows change from flat to concave downward suggesting a knickpoint at Mahe. The channel gradient at Mahe suddenly increases ten times (from 0.75 to 7.2 m/km). The geomorphic changes in the channel decide the beginning of Segment-II (Mahe to Hymia). From Upshi the valley becomes very wide (~ 1200 m at Leh), the channel gradient decreases to 1.8 m/km, and the river profile become saddle. This zone is Segment-III (Upshi to Spituk). Downstream from Spituk, the Indus River profile again shows an increase in the channel gradient (4 – 7.5 m/km), where the valley shrinks to 100 – 500 m. The Segment-IV has been divided based on the knickpoint marked just upstream to Indus – Zanskar confluence and the channel geomorphology (terrace configuration). The lithology varies throughout the channel stretch, from Nyoma to Dah Hanu. The Indus River from Mahe to Kiari flows through the Indus Molasse and then into the Ladakh Batholith up to a little upstream of the Upshi. In the Leh valley it largely follows the contact of the two lithotectonic units; from Spituk downstream it flows into Indus Molasse up to Skyurbuchan and then again into the Ladakh Batholith (Fig 6.4 A). Based on erodibility, higher value of SL should fall into the zone of molasse (sandstone and shale). In the Segment-I, where Indus flows through the Indus Molasse, the SL index is low. In the Segment-II, between Kiari and Tirido, it attains higher values with the Batholith as the bedrock. Similarly, in the Segment-III, where channel follows the contact of the two lithotectonic units, the SL values are again low. In the Segment-IV, downstream of Spituk to Skyurbuchan, river cuts through the Indus Molasse and the SL index increases and attains higher values where the channel cuts into the Ladakh Batholith.

The SL index in the Segment-IV exhibits an overall increasing trend (Figure 6.4 B). In K_s, the ratio of channel gradient and drainage basin area can quantify the knickpoints and their possible causes. The K_s for the Indus River also shows similar trend like SL (Munack et al., 2014), which implying that the channel steepness is controlled by the active tectonic uplift and not by the bedrock erodibility.

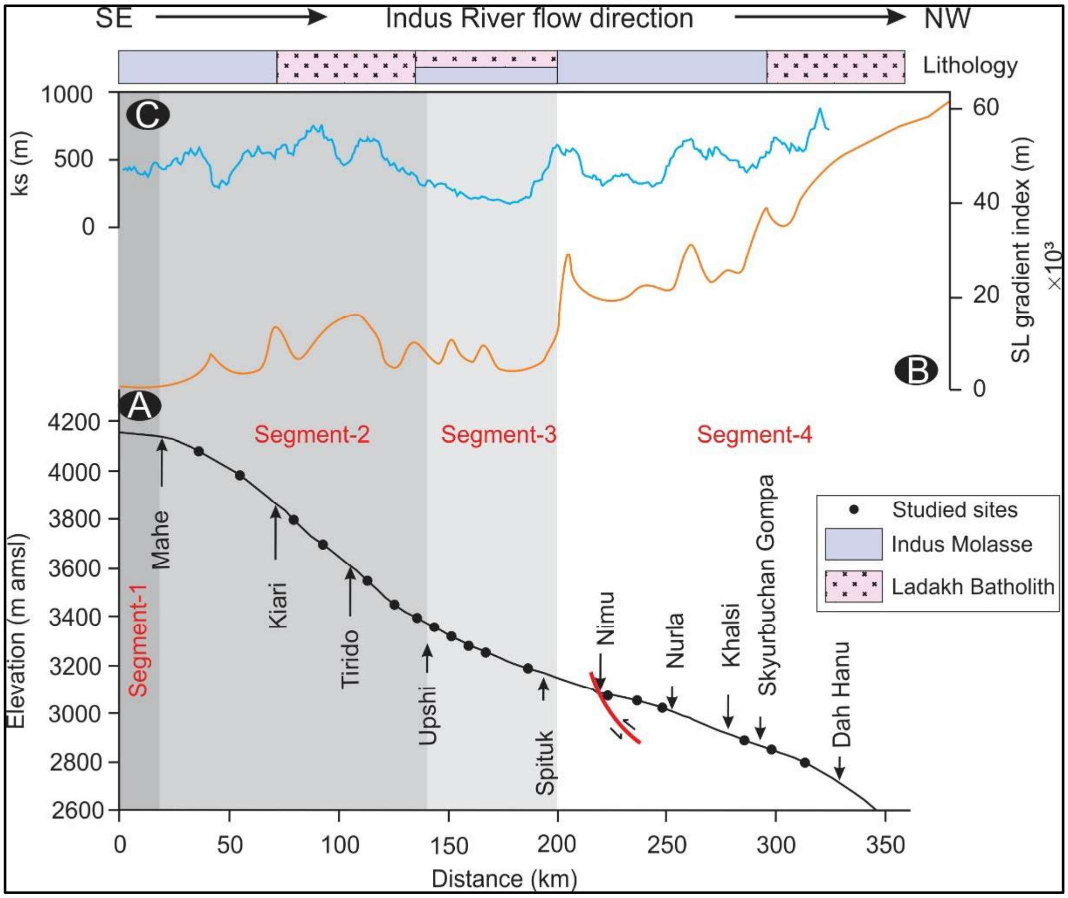

Figure 6.4 (A) Longitudinal river profile of Indus River, (B) SL index plotted along the Indus from upstream Nyoma to Dah Hanu section. (C) Concavity Index (K_s) showing the variations (after Munack et al., 2014) in the SL index. A panel showing the lithology from the Indus River draining through its course. Based on longitudinal profile, SL and K_s indices, two major knickpoint have been observed (1) Mahe and (2) upstream Nimu section.

This is similar to studies in the SE Tibet plateau front where no relationship between the bedrock erodibility and steepness index of rivers was observed and the rivers were proposed to be adjusting to uplift of the plateau (Kirby et al., 2003). In Tibet and adjoining areas, long term tectonic uplift of plateau facilitates river incision and erosion. Here phases of valley alluviation protect bedrock, impedes incision and helps in stabilizing the plateau and the surrounding regions (Korup et al., 2010). In the Indus, Segment-I exhibits the lowest channel gradient and steepness index but its flood plain geomorphology shows changes in channel platform from meandering to braided-anastomosing type implying changes in channel gradient. This segment on the SW edge of Tibet (Munack et al., 2014) is affected by an active Karakoram strike slip fault and this probably explains the low relief and channel pattern changes. A N-S trending seismogenic (earthquake of January 19, 1975) normal fault, visible from Nyoma, and passing southwards into the Indus Molasse could have played a role in changing the channel -gradient and its channel pattern (Ni and York, 1978). The Segment-II shows steep channel gradient and high SL index due to river's adjustment to active tectonics and uplift in its headwater region (Fig 6.4). In the SE Tibet also, channel steepness index of longitudinal river profiles suggest that rivers draining through the edge of plateau are over steepened and are adjusting to differential uplift between the Tibetan plateau and its surrounding (Kirby et al., 2003). Ample evidences based on sedimentology, geomorphology and structure suggest more recent uplift in the southern Tibet (Liu, 1981; Li and Zhou, 2001) leading to vertical incision.

In the Segment-III, from Upshi to upstream of Nimu, where valley is broad and is flanked by large outwash fans, the river loses its gradient and the SL index decreases (Fig 6.4). The braided nature of channel in this segment suggests that the river is aggrading and the riverbed is protected from incision. Chronology of this segment indicates that the fan aggradation and river valley filling continued during 47 - 29 ka. Most of these fans emanate from the Zanskar ranges and therefore, excess sediment delivery from the Zanskar ranges, which has also pushed the river northward is responsible for the lower SL index. It is to be noted that outwash fans emerging from the Zanskar ranges are larger and have steeper surface slope as compared to those emanating from the batholith (Ladakh ranges) and this indicates higher relief in the Zanskar zone. Denudation rates based on ^{10}Be along the Indus River also indicate a steep increase in relative sediment supply from Zanskar ranges in the Leh valley (Munack et al., 2014). Upshi-Bazgo and Choksti thrusts located along and south of the Indus River, respectively have been active resulting in high relief of Zanskar ranges and excess sediment supply (Sinclair and Jaffey, 2001; Searle et al., 1990).

In the Segment-IV, SL index is high and further increases westwards. The chronology of the alluvial cover preserved over the strath terraces indicates incision of the order of 1.1 – 2.8 mm/yr. The average incision rate from Nimu to Nurla is 1.8 mm/a and it increases downstream to 2.3 mm/a (Kumar and Srivastava, *in communication*).

6.3 Spatial variations bedrock incision rates

The Indus River in the Segment-IV shows development of two levels of strath terraces and one level of fill. The thickness of the bedrock strath divided by the age of its alluvial cover yielded the maximum incision rates.

Towards this nine sections were studied between Nimu and Dah Hanu (Fig 6.5 A). Putting together the height and chronology data of terraces helped in reconstructing the levels of paleo-riverbed profiles of Indus (Fig. 6.5 B). The upper profile running at an average elevation of 134±24 m arl has a central age of 62±15 ka and an average incision rate of 2.2±0.6 mm/a, whereas the lower profile at 45±5 m arl has an age of 44±8 ka and average erosion rate of 1.0±0.2 mm/a (Kumar and Srivastava, *in communication*). If we interpolate these reconstructed profiles upstream in the present river profile, then (i) the lower profile truncates upstream into the fill sequences preserved in the Segment-III (Leh valley) as both the bear same ages, (ii) the upper profile is older and the sediment of equivalent age might be present in the subsurface in Segment-III and upstream. This suggests that both lower and upper profiles are divergent downstream implying a base level fall in the downstream region (Pazzaglia et al., 1998; Kumar and Srivastava, *in communication*).

In the Nanga Parbat Harmosh Massif (NPHM) of the NW syntaxis (~350 km downstream from Dah Hanu), where two sets of strath terraces along the Indus are dated ~7 ka and between 67-27 ka (^{10}Be and ^{26}Al), the inferred bedrock incision rates are 9-12 mm/a during the Holocene and 1-6 mm/a during pre-LGM (Burbank et al., 1996; Leland et al., 1998).

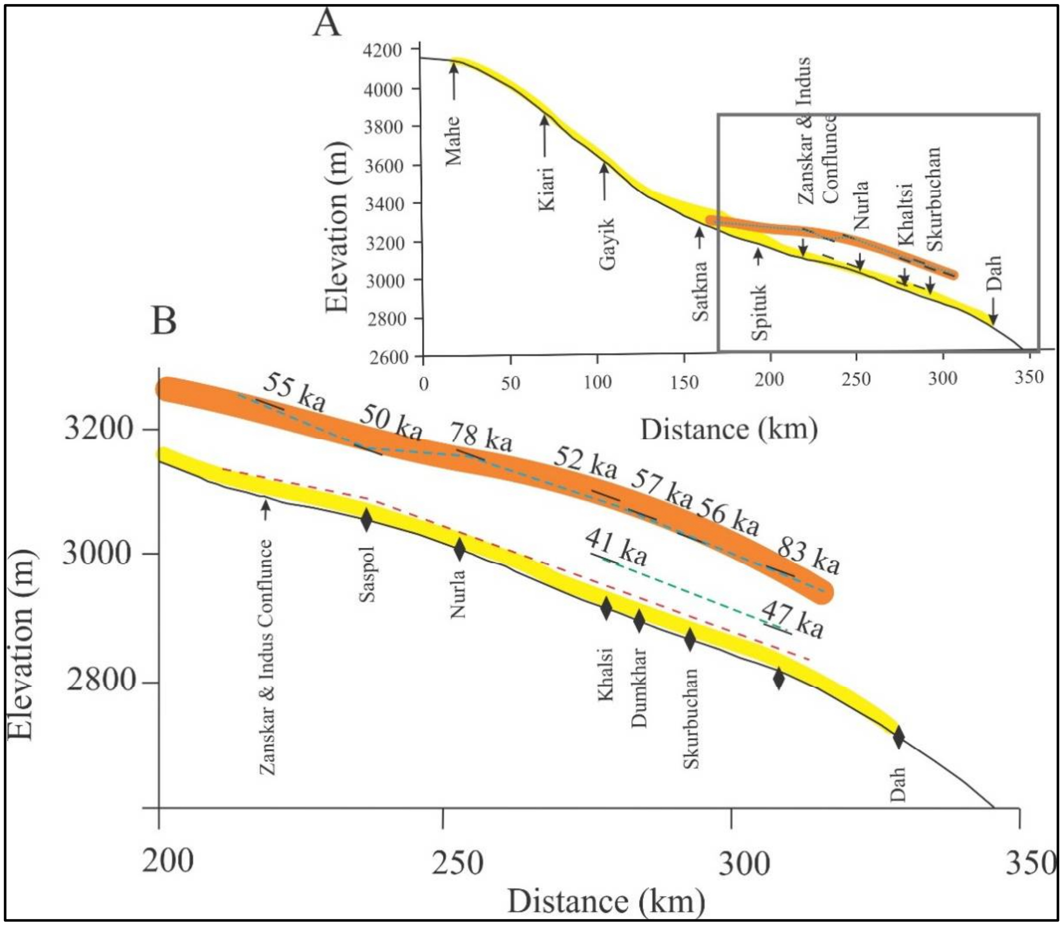

Figure 6.5 (A) Longitudinal River profile showing valley fill and strath terraces in yellow and orange colours, respectively. (B) Longitudinal profile of Indus (Segment-IV) showing reconstructed two levels of paleo-river bed and ages of the strath terraces.

Modern incision rates of Indus in the NPHM are ~12 mm/a which ~50 km upstream at Skardu reduces to 3-6 mm/a. Post glacial incision rates of the Baraldu

River that meets Indus near Skardu are 2-29 mm/a (Seong et al., 2008). The present study and the previously published data suggest that the incision rates along the Indus River, as it flows from Nimu to NPHM in NW syntaxis, increase sharply from 1.1 to 2.8 mm/a to ~12 mm/a (Fig 6.6).

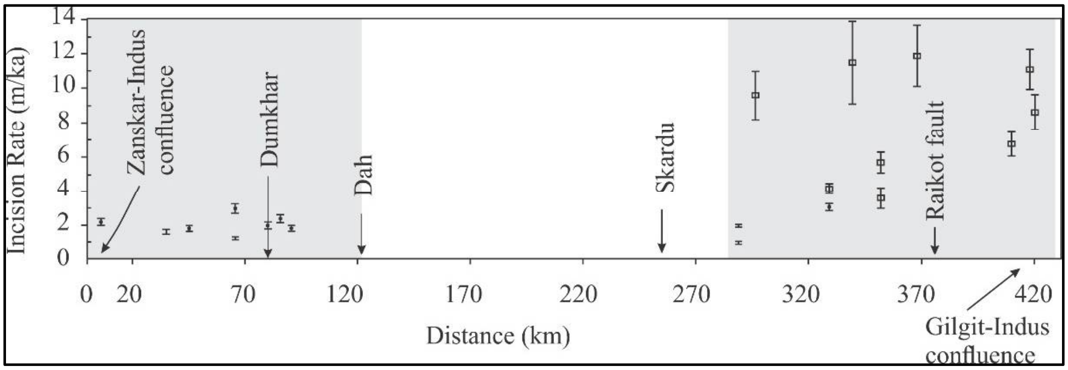

Figure 6.6 Panel showing the bedrock incision rates in the Nanga Parbat Harmosh Massif (NPHM) region of the NW Himalayan Syntaxis (after Leland et al., 1998) and the incision rates deduced in this study. The distance zero represents the Indus – Zanskar confluence. Note the systematic downstream increase in the incision rates.

The incision rates deduced in this study and by earlier studies thus allow an understanding of the regional response of tectonics of Himalaya in shaping up the landscape. Increase in the channel slope and bedrock incision rates in the downstream reaches can produce an upstream moving knickpoint that in long term can induce incision as far as 300 km upstream (Gardner, 1983). Based on structural and geomorphic analysis it is already suggested that incision and aggradation in the

Skardu basin are controlled by far field effect of rapid uplift in the NPHM zone and N-S compression along the Himalayan arc (Cronin, 1989). Therefore, there can be a proposition that the formation of strath terraces in the Segment-IV are also aided by the far field effect of the rapid incision and exhumation in the NPHM of the NW Himalayan syntaxis. A systematic distribution of the strath terrace T-2 along the long profile shows its initiation in the most downstream part at ~83 ka (Skyurbuchan downstream section) and in the upstream, the same level of terrace gives younger ages (50 ka) suggesting upstream moving incision wave. The older age (78 ka) of the strath terrace T-2 in Nurla section is an exception which at present we are unable to explain and a detailed structural mapping of the area might help in future. Further, the terrace profile is divergent to the present longitudinal profile indicating that the bedrock incision is controlled by the riverbed lowering in the downstream region (Crosby and Whipple, 2006; Wobus et al., 2006). Hence, the formation of strath terraces and the magnitude of incision might be controlled by the knickpoint migration in the upstream direction.

Another possibility is that between Nimu and upstream of Dah Hanu, the Indus River carves its valley in the Indus Molasse and the geomorphology along the river in this stretch is controlled by the intra-basinal geology of the Indus Molasse. The following evidences imply that strath terraces in this segment might be the result of neotectonic activity as well:

(i) Molasse sequence is highly deformed and comprises of several north vergent thrusts like the Choksti and Upshi – Bazgo, and large steep angled fans emerging from the Zanskar ranges in Leh valley may suggest ongoing tectonic activity along these thrusts (Brookfield and Andrews-Speed, 1984; Sinclair and Jaffey, 2001).

(ii) The strath terraces are located on the hanging block of the Upshi - Bazgo thrust and any movement along this thrust will lead to river incision and formation of such strath surfaces, e.g., at Nurla, the down cutting and shifting of the channel and formation of the strath terrace (shown in Fig 3.17 B) pointing some tectonic activity along this thrust during the late Pleistocene (~78 ka).

(iii) At Nimu, the channel is increasing its sinuosity with phases of river down cutting in the form of entrenched meanders that can be formed in response to tectonic uplift (Gardner, 1975; Schumm et al., 1987; Rogers et al., 2002).

(v) Based on basin morphometry and hypsometric indices of tributaries draining into rivers Indus and Shyok between Leh and Khalsi (Zone B of Jamieson et al., 2004), it is suggested that long term shortening in the Indus Molasse. Thrusting has caused the lateral migration of channels and depozones northeastward into the Ladakh Batholith (Jamieson et al., 2004)

(vi) Although molasse belt of Ladakh is considered to be largely aseismic but there are records of occurrence of seismites in the Quaternary sequences along the Indus at Spituk, Saspol and Lamayuru and other surrounding areas that point towards past seismic activity (Bagati et al., 1996; Singh and Jain, 2007; Phartiyal and Sharma, 2009).

Geodetic surveys do not show any significant relative movement between the Indus Molasse zone and the Ladakh Batholith (Jade et al., 2011) and seismic monitoring records suggest it to be largely aseismic. But global strain assessment based on 3000 geodetic data implies higher strain along the Indus Suture Zone (Kreemer et al., 2003). Therefore, our field observations provide an assessment of the role of neotectonic deformation of sequences in the Indus Suture Zone. This raises the need to map the active faults in the region.

6.4 Sand ramps

Sand ramp is an obstacle dune that preserves a composite records of aeolian, hill slope and fluvial processes and thus can be used as a potential archive to understand past environmental conditions. Five sand ramps from the Leh valley based on their geomorphology, sedimentology and Optically Stimulated Luminescence (OSL) chronology, were studied. One sand ramp, at Saboo, is studied in detail using grain size analysis, mineral susceptibility and clay mineralogy to understand the paleo-environmental conditions.

The chronology of Saboo sand ramp shows that the aeolian sedimentation was dominant during >12-8 ka. This phase is disrupted by the occurrence of the hard crust and indicating a phase of stability, followed by gullying and gully filling events at ~7 ka.

Conditions for sand ramp accretion

The combination of physical as well climatic conditions which are responsible for the accretion and expansion of sand dunes or sand ramps occur in a narrow *'window of opportunity'*, which includes 1) ample sediment availability, 2) strong winds, and 3) low vegetation cover. The vegetation cover is very important factor which reduces the erosional activities and helps in trapping the sand and development of stratigraphy. In Ladakh, there are longer winters and shorter summers that regulate the development of the sand ramps. In summers (June – September), the Indus and its tributaries flow with huge water flux and cover the flood plain areas. Therefore, the sand availability is limited. In winters (October – February), due to the frozen condition, the sediment supply reduces drastically and flood plains are obscured due to snow cover. Nonetheless, in pre-monsoon months, (March – June), the snow starts melting and the river beds (flood plains) get exposed to the open system, with narrow channel thread, surface is moist with blooming thin vegetation to trap the sand. The rivers flood plains and fan surfaces in Leh valley are also open to erosion due to strong pre-monsoon winds. Therefore, the '*window of opportunity'* for the accretion and development of sand ramps in the Leh valley seem to be the physical and climatic conditions in course of pre-monsoon time. In pre-monsoon time, the wind direction in this area is NE to SW. Geomorphologically, the aspects of the sand ramps are attesting that the SW winds (Fig 6.7) are responsible for their accumulation. But in mountains the wind directions are controlled mainly by the valley orientation, therefore, the buildup of these sand ramps cannot directly be connected with strengthening of SW winds.

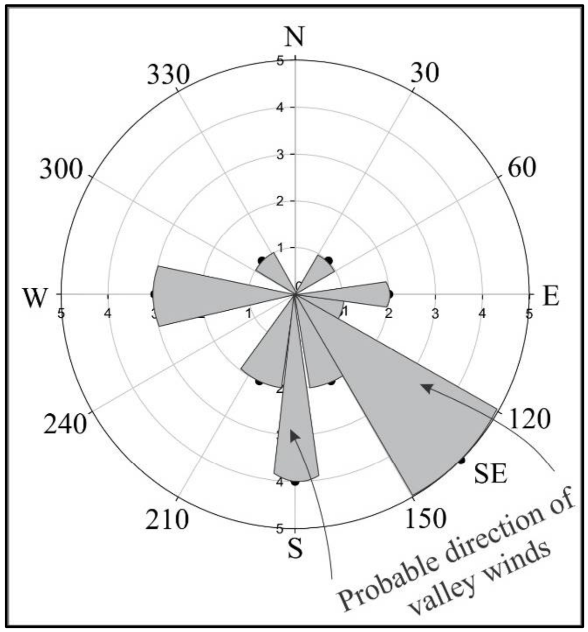

Figure 6.7 Radial frequency plot of aspect of all 21 studied sand ramps in Leh valley.

Grain size, Environmental magnetic parameters and clay mineral variations

Grain size and its distribution pattern has the ability to tell the pathway of grains including mode of transportation and weathering conditions in the source area. The bivariate plot between SD and mean grain size indicated constant strong wind which in this case will be from 12 to 8 ka. The stereo-zoom images from aeolian units and the hard crust advocates that this sand ramp was sourced from flood plains of the Indus River.

In the Saboo sand ramp, χlf increased in hard crusts, where clay is also increased, hence, an increase of fine grained ferromagnetic minerals is suggested. Similarly, the SIRM showed similar trend as χlf in the Saboo profile. The magnetic enhancement has also been noticed in χARM and χfd% trends due to authigenic mineralization in units dated at 8±1 ka to 7±0.5 ka. The HIRM and S-ratio trend, when compared with other environmental magnetic parameters at the same depth (8±1 ka to 7±0.5 ka.), the occurrence of ultrafine magnetite/meghemite were observed (Fig 4.9). The scanning electron microscopic (SEM) images (Fig 4.10) suggest the euhedral ultrafine magnetite together with hematite can be precipitated by increase in moisture and change in redox conditions and implies the formation of hard crust. The dominance of hematite in the hard crusts, and less abundance in gritty sand (talus unit) and absence in the aeolian sand unit is noticed by the RAMAN spectroscopy (Fig 4.11) on separated magnetic grains using bar magnet. The precipitation of ultrafine magnetite and variation in hematite concentration through the sedimentary column of Saboo sand ramp shows that iron minerals respond to small climate change. The magnetic enhancement also indicate climatically warm and humid phase at 8±1 ka and 7±0.5 ka (Evans and Heller, 2003; Maher et al., 2003; Meena et al., 2008, 2011; Maher, 2011; Kumar et al., 2016, in press).

The weathering conditions under certain climatic environments can be understood by studying the clay mineralogy (Bhattacharyya et al., 1993; Srivastava et al., 1998). The presence of illite and chlorite minerals indicated the physical weathering throughout the accretion of Saboo sand ramp.

Sand ramp accumulation and palaeoclimate

Sand ramps of Leh valley formed as result of varying climate from warm and wet to dry spells. The parallel laminated sand facies are indicative of active accretion of sand against the hillslope suggesting comparatively arid environment. Poorly sorted coarse sand with scours indicate deposition by fluvial activity suggesting wetter climatic phase. Parallel laminated angular gravels represents hard crusts (sedimentary hiatus) and are indicative of increased precipitation. The parallel laminated clayey silt (pene-contemporaneous deformed silty clay) suggests the intra-dunal lakes deposits and wetter phase. The hill slope debris also accumulated as a result of wetter climate. The study shows two major aeolian accretion phases as unraveled from the stratigraphy of Shey-3, Choglamsar, Saboo and Spituk ramps. Phase-I occurs between 25 and 15 ka and phase-II from 12 to 8 ka (Fig 6.8). There is one older aeolian phase observed at ~ 44±3 ka in Shey-2 stratigraphic records. The phase-I (25 – 15 ka) may include several short term relatively wetter spells punctuating the overall semi-arid to arid dry phase, i.e., peak Last Glacial Maxima (LGM), which increased the threshold moisture and enhanced the vegetation cover for sand accumulation. The studies on glacial moraines from the Ladakh Himalaya indicate glacial advances in the phase-I (Demske et al., 2009; Dortch et al., 2010, 2013; Owen et al., 2006, 2008; Phartiyal et al., 2013; Owen and Dortch, 2014). This phase of sand accumulation between 26 and 15 ka, has also been observed in the Chinese loess records (Porter, 2001). The occurrence of gully and channel borne sediments and formation of intra-dunal lake indicate relatively wetter climate during the phase-II (12 – 8 ka). The glacial and lake records from

Tso Kar suggest glacial expansion at 10.6±0.7 ka and 8.3±0.5 ka (Owen et al., 2006; Dortch et al., 2013) and arid phase between 13.5 – 11.5 ka and 8.5 – 7 ka, respectively (Demske et al., 2009; Wünnemann et al., 2010). Chinese loess shows extensive aeolian activities from 11.2 to 10.6 ka and 9.5 to 5.5 ka (Porter, 2001). Thar Desert, India also experienced dune expansion during the same time (Singhvi and Kar, 2004; Juyal et al., 2006; Singhvi and Porat, 2008). In the early Holocene which is known to be relatively wetter phase, the accretion of aeolian deposits indicated: (1) decline in effective moisture, which can be related to high solar insolation and, therefore, reduction in vegetation cover (Stauch et al., 2012; Qiang et al., 2013, 2014, 2016); this reduced vegetation still has potential to subdue the erosional processes and assist in further accumulation in sand, (2) the other possibility is the dry spells in Holocene that may lead to aeolian accretion and formation of sand ramps in Ladakh. The older aeolian event dated ~44±3 ka at Shey-2, can be understood as a regional drier phase as indicated by (i) a coeval glacial advance in Ladakh (Owen et al., 2006), and (ii) the enhancement of Chinese loess sedimentation at 43.5 ka (Porter, 2001). The sedimentary facies analysis on each studied sand ramps suggest that during the wetter climate the aggradation of sand ramps took place via hill slope erosion (30-25 ka), fluvial gullying and infilling, formation of hard crust (~7 ka at Saboo), and development of intra-dunal lakes (~12 ka at Shey-3). This was the time when the Indus River system, the Ganga Plain and the Thar desert were undergoing vigorous fluvial aggradation (Srivastava et al., 2003; Singhvi and Kar, 2004; Juyal et al., 2006; Ray and Srivastava, 2010; Kumar and Srivastava, *in communication*). Coevally, lakes from Ladakh and Tibet were experiencing high water level due to higher rainfall (Fang, 1991; Van Campo et al., 1996; Demske et al., 2009; Wünnemann et al., 2010).

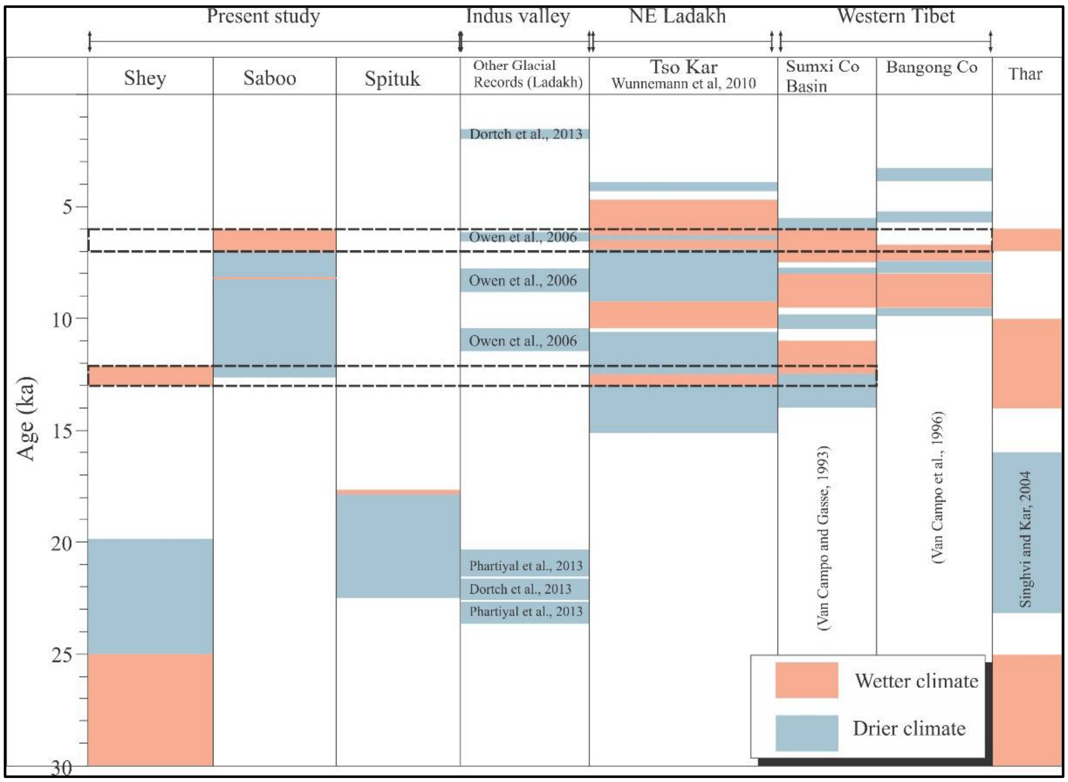

Figure 6.8 Shey-2, Shey-3, Choglamsar, Saboo and Spituk sections are correlated with major cold and warm events marked by various workers by studying moraines of Leh valley, and pollen, spores and diatoms of Tso Kar of NE Ladakh, Sumxi Co, Bangong Co basin of western Tibet and Thar Desert.

The sedimentology of sand ramps of Leh valley along with the chronology and published climatic records suggest that the climate factors are the significant factors for the accumulation of sand ramps in the Ladakh region. The improved vegetation (moisture in the atmosphere) helped to reduce the erosional activities and further facilitated the aggradation process (Kumar et al., 2016).

6.5 Conclusions

(a) Conclusions made from aggradation and incision history of the Indus River

i. Indus River, between Nyoma and Dah Hanu (~350 km stretch), based on geomorphology and channel steepness index (SL index), is divided into four segments. Segment-I from Nyoma to Mahe, is characterized by the lowest channel gradient and low steepness index where the river has a braided channel pattern. The imagery data of the flood plain in this segment indicates recent changes in channel pattern from highly meandering to braiding. Segment-II from Mahe to upstream Upshi, is marked by a sharp increase in gradient to 7.2 m/km where river flows into a narrow gorge that alternates into the Indus Molasse and the Ladakh Batholith, and is characterized by the fill terraces. Segment-III from Upshi to downstream Spituk is characterized by a wide, low gradient valley with braided river conditions. The SL index is lower in this segment. The channel in this segment is flanked by outwash fans and fill river valley terrace. Segment-IV from downstream Spituk to Dah Hanu is characterized by channel gradient of ~4 m/km and a narrow valley. This shows the development of a lower fill terrace and 1-2 levels of strath terraces.

ii. Sedimentological analysis of fill and alluvial covers of strath terraces suggests that the valley filling is largely controlled by bar aggradation within the channel and fan building. OSL chronology of the fill and strath terraces indicates that the channel bound aggradation took place in three pulses centered at ~52 ka, 28 ka (MIS-3), and ~16 ka (MIS-1); aggradation on fans took place from ~47 to 29 ka (MIS-3). Hence aggradation is climatically controlled and took place during the wetter phases.

iii. The palaeodischarge of aggraded sequences from Mahe to Spituk varies from 834 to 5003 m^3s^{-1}, which suggest the enhanced sediment supply during 47 – 23 ka.

iv. Comparing the modern discharge (130 – 250 m^3s^{-1}), modelled palaeodischarge during aggradation (834 – 5003 m^3s^{-1}) at 47 – 23 ka (MIS 3), and incision discharge 30,300 – 40,000 m^3s^{-1} estimated from the slack water deposits of the Nimu section during 13 to 9 ka, an important conclusion emerges that the aggradation in the Himalayan rivers occurred in transient climatic condition, when the sediment budget in the rivers increased just after the glacial events. A subsequent incision event occurs during the climatically wet conditions.

v. The SL index of the channel seems independent of lithology.

vi. Our study on the strath terraces of Segment-IV suggests that these can be identified into two levels and can help in the reconstruction of palaeo river profiles of the Indus. The upper profile that runs at an elevation of 134±24 m arl has a central age of 62±15 ka indicating an average erosion rate of 2.2±0.6 mm/a, whereas the lower profile at 45±5 m arl having age of 44±8 ka indicates an average erosion rate of 1.0±0.2 mm/a. Based on a comparison of our results from previously published incision rates from

Nanga Parbat Harmosh Massif in the NW syntaxis (Burbank et al., 1996; Leland et al., 1998 and Seong et al., 2008), we propose that the strath development in Segment-IV occurred due to far field effect of uplift and rapid incision in the NW syntaxis. There are also compelling evidences that point towards a local neotectonic deformation of the Indus Molasse, which may have amplified the total amount of incision of the river.

(b) **Sand ramp studies**

vii. Sand ramps of Ladakh show a composite record of aeolian, hill slope and fluvial activity.

viii. The OSL chronology on the studied sand ramps suggests that the ramp accumulation started prior to ~ 44 ka and continued till ~8 ka. The period between 25–17 ka and <12-8 ka was dominated by the aeolian activities in the Leh valley. At ~12 ka, the formation of intra-dunal lake and at 7 ka fluvial gullying suggest wetter climate. These subsequent dry and wet phases can be linked to variations in the ISM.

ix. The grain size along with environmental magnetic data from the Saboo sand ramp show substantial enhancement of magnetic susceptibility at ~ 12 ka and ~ 7 ka, which suggest warm and wet conditions. A piercing positive jump at hiatuses (hard crust) suggest its formation during warm and wet phases. Occurrence of perfectly octahedral neo-formed magnitite in this horizon also validates this statement.

x. The grain texture of the Saboo sand ramp indicates that the sand supplied to accrete the sand ramps in the Leh valley are recycled sediments of the Indus River and its tributaries.

xi. The clay mineralogy from the Saboo sand ramp shows illite and chlorite throughout the profile, which supports physical weathering. Here one important inference is made that although climate fluctuated between wet and dry, a signal captured by iron mineralogy, the climatic fluctuations were limited to the threshold of alteration of clay mineralogy during the late Pleistocene in the Leh valley.