EXECUTIVE SUMMERY

The Indus-Ganga-Brahmaputra are the largest river systems in South Asia, which originate in the Himalaya and support a large number of population. The landscape of these river systems evolved due to several phases of aggradation and incision; varying climatic and tectonic perturbations. Therefore, it is important to understand these processes and their forcing factors in both, time and space. Rivers like the Satluj, Yamuna, Bhagirathi, Alaknanda, Gandaki and others that drain orthogonally to the southern front of Himalaya, the factors governing aggradation and incision, and their relationship to climate and tectonics are reasonably well understood. However, the Indus River that flow through the arid and semiarid regions of NW- Himalaya has recieved less attention.

The hydrological budget of the Indus River is determined from glacial melt, precipitation from the westerlies and Indian summer monsoon (ISM). The whole region are controlled by tectonics surrounding the Indus-Tsangpo Suture zone (ITSZ), western syntaxis and Karakoram fault.

The contextual information motivated me to frame the objectives of my Ph D dissertation as: (1) to study the impact of past climate variability and tectonic control on the landform development of Ladakh Himalaya, along the Indus River, in particular, (2) the paleo-discharge estimation and to understand the climatic variability, and (3) late Pleistocene aeolian activity in the area.

Ladakh Himalaya has diverse landforms, which are being explored to understand

the paleoclimate variability and suture zone tectonic. In this region, the landforms are related to glacial – interglacial events and intense orogenic movements throughout the Quaternary time. With time, the variable erosional processes e.g. glacial, fluvial and hill slope, developed the landforms and topography of the Ladakh Himalaya. Extensive study on moraine deposits suggest ten glacial stages in Leh and Nubra valleys.

In fieldwork, the detail sedimentological and geomorphological analysis has been done. On the basis of field data, lithofacies have been established in all studied section. In lab, the chronology has been established using OSL dating technique. The sand ramps sediments were analyzed for grain size using sieve shaker, clay minerals using X-ray Diffraction (XRD), environmental magnetic parameters such as magnetic susceptibility (MS), natural remanence of magnetism (NRM), anhysteretic remanence of magnetism (ARM) etc. and grain morphology on few magnetic grains has been done using Scanning Electron Microscope (SEM).

Based on the longitudinal river profile and stream length gradient index (SL index), ~ 350 km stretch, the Indus River is divided into four segments. Each segment has its own geomorphological and sedimentological setup. The valley cross-section enable us to understand the landscape related to aggradation and incision along the trunk channel. There are valley fill terraces in Segment I to III and one to two levels of strath terraces (T-2) with one cut-filled terrace (T-1) in Segment IV, which were used to calculate the aggradation and incision rates respectively. The geomorphological analysis on the sand ramps include the slope, area covered, and aspect, were done on twenty one sand ramps located in Leh valley.

Sedimentation pattern and aggradation in a river valley depend upon the relative proportions of water and sediment in the channel network. A channel aggrades when the sediment load exceeds its carrying capacity *i.e.* the sediment-to-water ratio increases and incises if vice-versa (Ray and Srivastava, 2010; Blum and Törnqvist, 2000). Most of the stretch of the Indus River from Mahe to Dah Hanu exhibits of widespread valley fill in form of terrace T-1 and fan aggradation. The stratigraphy of terrace T-1, suggests that the channel bound processes controlled the valley aggradation.

The chronology of the channel bound and fan aggradation in Segment I to III, suggest that there are three pulses of wet phases at ~ 16 ka, ~ 28 ka and ~ 52 ka, which facilitated fluvial aggradation. Hence aggradation was climatically controlled that occurred place during the wetter phases in MIS-1 and MIS-3.

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, where, the Indus flows through the Indus Molasse, the SL index is low, whereas in Segment-II, between Kiari and Tirido, it attains higher values with batholith as bedrock. Again in the Segment-III, where channel follows the molasse-batholith contact, the SL values are again low. In Segment-IV, downstream of Spituk to

Skyurbuchan, river cuts through the Indus Molasse, where the SL index increases and attains high values where the channel cutting into the Ladakh Batholith.

SL index in Segment-IV exhibits an overall increasing trend. K_s for the Indus also shows similar trend (Munack et al., 2014), which imply that the channel steepness is controlled by the active tectonic uplift and not by the bedrock erodibility. This is similar to studies in SE Tibet plateau front where no relationship between the bedrock erodibility and steepness index of rivers was observed. 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*).

Putting together the height and chronology data of terraces helped in reconstructing the levels of paleo-riverbed profiles of Indus. 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*).

Sand ramps of Ladakh provide composite records of wet and dry climate, e.g., the aeolian facies are represent relatively arid conditions while the fluvial facies and sedimentary hiatus (hard crust) and intra-dunal lakes facies are indicative of wetter climatic conditions. The deposition of hillslope debris also suggests the dominance of wetter conditions in the region. The records at Shey-3, Choglamsar, Saboo and Spituk show two major phases of aeolian accretion, the phase-I, between 25-15 ka and the phase-II between 12-8 ka. The sand ramp at Shey-2 records an additional older phase of aeolian accretion at ~ 44±3 ka. Phase-I represents aridity around the Last Glacial Maximum (LGM). Several studies from Ladakh Himalaya incorporating OSL and cosmogenic radionuclide chronologies (CRN) on glacial moraines suggest aridity and glacial expansion during the LGM.

The major output from this study are:

(a) Landscape along 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.