Chapter 1

Introduction

Man needs his difficulties because they are necessary to enjoy success.

-Dr. A.P.J. Abdul Kalam

CHAPTER 1 INTRODUCTION

1.1 Research Problem

The Indus – Ganga – Brahmaputra river systems, hydrologically controlled by Indian summer monsoon (ISM) and support more than 20% of the global population. The geomorphic configuration of headwater of these rivers is largely controlled by ongoing and past tectonic developments in Himalaya. Consequently the landscape evolution of Himalaya and that of these rivers is closely linked. Therefore, fluvial landforms associated with these river systems, can provide clues to terrain responses to tectonics of Himalaya and variations in ISM. Variations in precipitation, glacial cover, sediment accommodation space, tectonic activities in time and space affect the erosion and depositional activities in the thrust-fold belt of Himalaya. The landscape's sensitivity towards these forcing factors can however introduce chronological lead and lag in responses. Ladakh, drained by the Indus River, lies in the most hinterland part of Himalaya. The area, as per the critical taper wedge model should experience the least tectonic deformation. Also it lies in the rain shadow zone of ISM and the westerlies driven rainfall plays an important role. Therefore the landscape along the Indus River has potential to unravel fluvial responses to (i) neotectonics of the Himalayan hinterland, and (ii) past hydrological changes.

The Quaternary period witnessed a number of glacial and inter-glacial cycles that might have strong control on sediment generation and buildup of fluvial landscape of Ladakh Himalaya. It is largely understood that phases of excess sediment generation and weaker monsoon can lead to valley filling, high water to sediment ratio during subsequent wetter phases can lead to incision of fills and formation of terraces. During the incision phase, river cut its own deposited sediment, followed by incising of the bedrock. The amount of bedrock cut often equals to tectonic uplift. This tectonic instability leads to lower the residence time of the river and more frequent incision into the bedrock and the formation of strath terraces. Rivers like Sutlej, Beas, Bhagirathi, Alaknanda, Gandaki, Yamuna and others that drain the wetter southern front of Himalaya receive ~ 40 % of their annual discharge from glacial melt water and ~ 60 % from ISM. These rivers cut orthogonally through the major litho-tectonic and structural discontinuities of Himalaya from north to south, the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT). The aggradation and incision phases of Himalayan rivers, geomorphic evolution and their linkages to the foreland and delta are well studied and their relation with climate and tectonic movements along MCT, MBT and HFT are reasonably understood (Goodbred, 2003; Theide et al., 2004; Bookhagen et al., 2005; Wobus et al., 2005; Srivastava et al., 2008; Ray and Srivastava, 2010; Juyal et al., 2010). However the rivers draining through the drier hinterland of Himalaya have received less attention and their phases of aggradations and incision, and forcing factors are less understood.

1.1.1 Study area

The Indus River, which constitutes a major part of this study, after descending from the SW margin of Tibet flows northeastward and traverses through the Indus Suture Zone in Ladakh before incising into the canyons of NW syntaxis of Himalaya. This studied segment makes a ~ 350 km of the middle Indus River catchment and lies between the SW edge of Tibet, Nyoma and Dah located, ~250 km upstream of SW Syntaxis. It ranges in east from E 79° to E 77° 30' and in north, from N 33° to N 34° 38' (Fig 1.1). This segment of the river displays a range of landforms like, steep gradient narrow channel making deep gorges, wide valley of Leh flanked by large alluvial fans, and fill and strath type of terraces. The valley walls are often mantled with semi-consolidated aeolian sand ramps. Besides depositional and geomorphic setup of fans, and terraces, sand ramps located at Shey, Saboo, Choglamsar and Spituk were also studied for their sedimentological structure and chronology. The Saboo sand ramp was studied in detail for clay mineralogy, grain size and magnetic susceptibility.

1.1.2 Objectives

The objectives of the present study are as follows.

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.

3) Late Pleistocene aeolian activity in Leh and surrounding area.

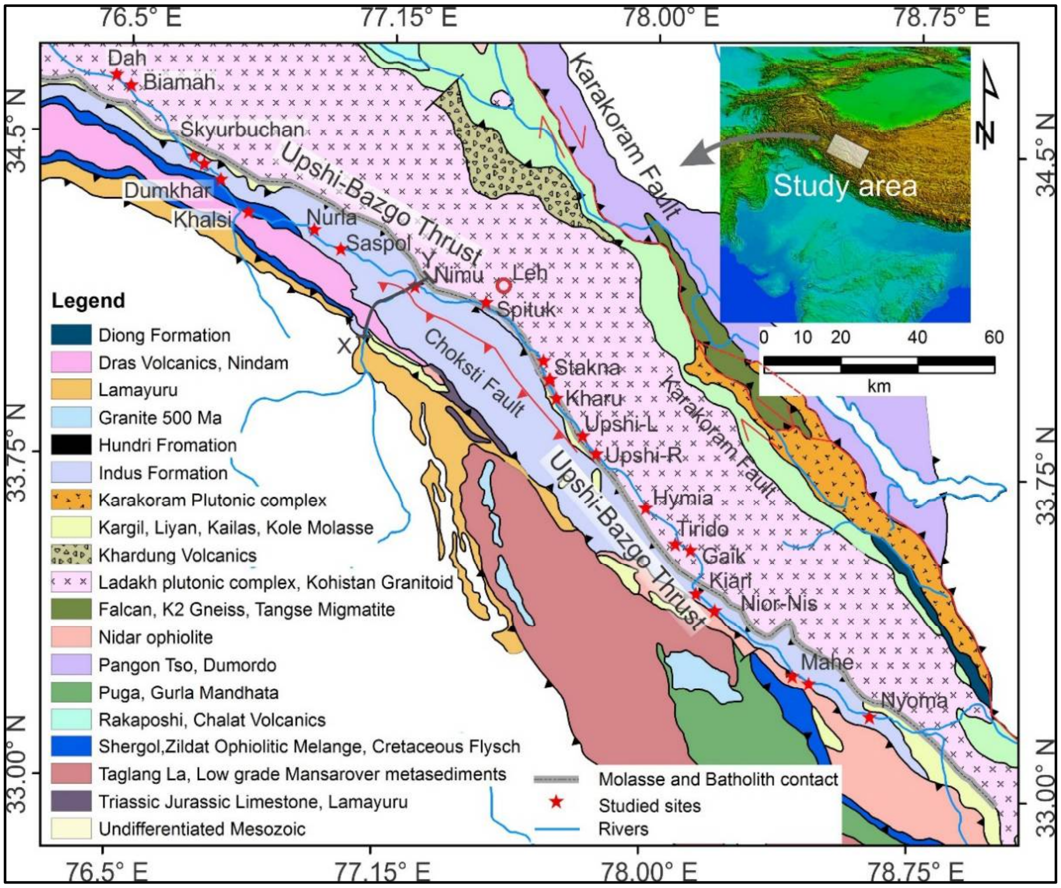

Figure 1.1 Geological map of the northwestern Ladakh Himalaya (after Thakur and Rawat, 1992). The grey line shows the boundary between the Indus Molasse and Ladakh Batholoth, red line with teeth show the faults and stars indicate the study sites.

1.2 Geology of Himalaya

The 2400 km long mountain range of Himalaya is a result of continent- continent collision between the Indian and Eurasian plates and makes the highest topography and relief on the planet Earth. The *Himalaya* word comes from Sanskrit words *him* (snow) + *alaya* (abode). 100,000 km^2 area of Himalaya is covered by glaciers so scientist referred Himalaya as "the Third pole" (Yao et al., 2012). The average topographic height of the Himalaya is ~ 3500 m msl (mean sea level).

The two major structural syntaxes lie on northeast and northwest Himalaya named as Namcha Barwa (7782 m) and Nanga Parbat (8125 m) respectively. The geomorphological and regional variation subdivided whole Himalaya into western (66° – 81°), central (81° – 89°) and eastern Himalaya (89° – 98°; Yin, 2006). The Himalaya can be divided into five major litho-tectonic divisions from south to north: (1) Sub Himalaya, (2) Lesser Himalaya, (3) High Himalaya, (4) Tethys Himalaya and (5) Trans Himalaya (Ganssar, 1964; Le fort, 1975). These litho – tectonic divisions are separated by major structure discontinuities, from south to north, termed as Himalayan Frontal Thrust (HFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT), South Tibetan Detachment system (STDS) and Indus Tsangpo Suture Zone (ITSZ). At southern margin, the Cenozoic sediment of Indo-Ganga plain known as active Himalayan foreland basin, is separated from Neogene sandstone, mudstone and conglomerates sequence of Siwalik Supergroup (Sub Himalaya) through north dipping HFT. Toward north, the Siwalik rocks are separated from Proterozoic – Cambrian Lesser Himalayan Sequence (LHS) through MBT. The LHS is composed of meta – sedimentary to unfossiliferous low grade metamorphic rocks, carbonates, meta basic volcanics and granites. These low grade metamorphic rocks of LHS have a thrust contact through MCT with the High

Himalayan Crystalline Complex (HHC) or the Great Himalayan Crystalline Complex (GHC). The continuous belt of HHC consists of high grade metamorphic rocks (Neoproterozoic to Ordovician), where the metamorphic grade first increases from lower to middle part and then decreases till the upper part toward the STDS (DeCelles et al., 2002; LeFort, 1996). The isolated patches of HHC rocks occur as basement rocks in Tethys Himalayan sediments and in the Lesser Himalayan segment as Nappes. The HHC and Tethys Himalayan Sequences (THS) are separated by STDS. In the Zanskar region, the THS composed of shelf and shelf edge facies sediments (Cambrian to Eocene). Further north, the Indus Tsangpo Suture Zone (ITSZ) separates Trans Himalaya and THS. The whole Himalaya from north (MCT), having sequence of north dipping thrusts younging toward the south (HFT) and considered splays of Main Himalayan Thrust (MHT) is considered as the basal detachment fault (Zhao et al., 1993). Tectonically, all these thrust sheets except the THS lies under compressional regime where southward younging series of thrusts and few out-of-sequence thrusts played important role in accommodating the shortening. The Tethys Himalaya bound by STDS in the south and the Zanskar counter thrust in the north forms a pop-up structure and shows signature of extensional tectonics in the form of large scale normal faults.

1.2.1 Geology of Indus Tsangpo Suture Zone, Ladakh Himalaya

Indus Tsangpo Suture Zone (ITSZ) is made up of ophiolite sequence that marks a boundary between Indian and Eurasian plates. The Kohistan-Ladakh island arc, Khardung volcanics and Lhasa- Karakoram block are present north of the ITSZ whereas the Zanskar ranges, Tethyan sediments and High Himalayan Crystalline complex are toward south (Fig 1.1; Brookfield and Andrews-Speed, 1984; Henderson et al., 2010 a, b, 2011; Searle, 1986; Searle et al., 1990; Thakur, 1983; Thakur and Misra, 1984, Wu et al., 2007). The Trans- Himalaya, Lhasa- Karakoram block represent the southern margin of Eurasian plate and are assemblages of low grade metamorphosed Paleozoic – Mesozoic sedimentary rocks (Henderson et al., 2011). The Karakoram fault (~ 800 km long) extends through Pamir in the north (Pakistan) to Shyok Suture Zone (SSZ) and to Gar Basin in southwest Tibet. The SSZ had developed parallel to the ITSZ by the collision of Kohistan- Ladakh island arc with the southern margin of the Eurasian plate during late Cretaceous time (Clift et al., 2000). The calc- alkaline granitic intrusion and volcanism occurred by continuous subduction of Indian oceanic crust below the Eurasian plate. This magmatic arc is represented in the form of Ladakh Batholith, which is an assemblage of granite, granodiorite and tonalite suites of rocks (Thakur and Misra, 1984). The Ladakh plutonic complex has multiphase intrusive geological history in between 103 to 20 Ma (Thakur and Misra, 1984; Wu et al., 2007).

The Tethyan sedimentary sequence, south to the ITSZ, consists of meta-sedimentary and sedimentary rocks deposited at the passive margin of the Indian plate representing shelf and shelf edge facies of Cambrian to Eocene time. The granitic bodies of Precambrian to Cambrian are also emplaced within the Tethyan sediments (Wu et al., 2007). The ITSZ sedimentary rocks (carbonate and siliciclastic) are separated from the Tethyan sedimentary succession by Zanskar

Back Thrust in the south and Upshi- Bazgo thrust from the Ladakh Batholith towards the north (Brookfield and Andrews-Speed, 1984). The principal units of ITSZ are Indus Molasse consisting marine and terrestrial sediments and granitic batholith (Thakur, 1983; Brookfield and Andrews-Speed, 1984; Thakur and Misra, 1984; Searle, 1986; Searle et al., 1990; Wu et al., 2007; Henderson et al., 2010 a, b, 2011). These molasses are onlap on to the Ladakh Batholith via Upshi-Bazgo thrust (Garzanti and Van Haver, 1988).

The Indus Molasse is exposed in the Ladakh, India, although equivalent rocks also found along the strike of ITSZ in Pakistan and Tibet (Wu et al., 2007). Stratigraphically, the Indus Molasse are sandwiched between the Tethyan sedimentary rocks and the Ladakh Batholith. The Lamayuru turbidities, which situated extreme south to the ITSZ, are made up of Indian shelf margin deposits. The Cretaceous volcanogenic clastic sandstones and shales of Nindam Formation and Dras volcanic arc, lies unconformably over the Lamayuru Complex in the western Ladakh (Thakur and Misra, 1984; Searle, 1986; Sinclair and Jaffey, 2001; Henderson et al., 2010 a, b, 2011). The mid Cretaceous Khalsi Limestone contains abundant foraminifera and overlies ophiolitic mélange, which represents the base of Indus Molasse in the SW. The rock is exposed near Khalsi village (Garzanti and Van Haver, 1988). The Indus Molasse is mainly divided in two groups: 1) Tar Group, and 2) Indus Group. The Tar Group is comprised of marine to fluvio-deltaic sequences (mid Cretaceous to early Eocene) corresponding to the closer of the Neo-Tethys (Garzanti and Van Haver, 1988; Clift et al., 2002; Henderson et al., 2010 b). The Indus Group (mid Eocene to Miocene) lies conformably above the Tar Group and onlaps on the Ladakh Plutonic Complex toward north. The Indus Group comprised of continental deposits from deltaic to alluvial and fluvial deposits (Henderson et al., 2010 b, 2011).

Tar Group

Tar Group is subdivided into four Formations (Fm) *1) Jurutze Formation, 2) Sumda Formation 3) Chogdo Formation and 4) Nummulitic Limestone*. The oldest sedimentary unit in the Indus basin sedimentary rocks, mid Cretaceous to early Eocene, is *Jurutze Fm*, which lies unconformably over the *Nindam Fm*. This formation consists of primarily black shale, siltstone and grey phyllites with fine grained sandstones. The carbonates are present at the upper level of *Jurutze Fm* near Sumda-Do village (Clift et al., 2002; Henderson et al., 2010 b). This sedimentary unit is interpreted as shallow marine outer shelf / slope deposits. The *Sumda Fm* follows the *Jurutze Fm* conformably, where the fossiliferous limestone of early Eocene marks the base. The rocks of this formation consist of Nummulitic limestones, wackestones, brownish phyllites, and fine to coarse grained sandstones lithologies. This is overlain by fining upward units of *Chogdo Fm*, which is composed of terrestrial green gritstone or conglomerates with fining upward units of green sandstone and maroon shales (Searle et al., 1990; Henderson et al., 2010 a). The *Chogdo Fm* dated 51- 50.8 Ma, contain conglomerate clasts of both the Indian and Eurasian province, hence the deposition of the *Chogdo Fm* occurred during or before the Indian- Eurasian collision (Clift et al., 2002; Henderson et al., 2010 b). The *Nummulitic Limestone* overlies this with a conformable contact. The transition of these two formations is characterized by interfingering of conglomerates and carbonates. The dating of benthic nummulitid foraminifera in the *Nummulitic Limestone* that suggest the depositional age is early Eocene. The *Nummulitic Limestones* represents the marine transgression condition which is interpreted as Indian shelf or slope deposition (Sinclair and Jaffey, 2001; Henderson et al., 2010 b). Further towards the top a coarse grained rippled sandstone and mudstone sedimentary units replaces the carbonates that marks the cessation of marine sedimentation and the closer of Neo-Tethys Ocean (Searle et al., 1990; Henderson et al., 2010 a, b) and signifies the collision of Indo- Eurasian plates.

Indus Group

Thakur and Misra (1984), Garzanti and Van Haver (1988), Searle et al. (1990), Clift et al. (2002), Henderson et al. (2010 a, b), and various workers interpret the Indus Molasse as a result of post collision sedimentation. The Indus Molasse is subdivided into three major formations *1) Nurla Formation, 2) Choksti Formation, and 3) Nimu Formation* (Henderson et al., 2010 b, 2011). The *Nurla Fm* has been exposed in the Zanskar, Shang and Martselang valleys. Folding and thrusting of the *Nurla Fm*, stratigraphically, follows the *Choksti Fm* and is dated as 51 Ma (Henderson et al., 2010 b). The fining upward sequence of sandstone, mudstone and locally interbedded conglomerates, vary in colour from red to green, comprise the *Nurla Fm* (Sinclair and Jaffey, 2001; Henderson et al., 2010 b). The *Choksti Fm* has four subdivisions: (i) *Basal Conglomerates,* (ii) *Red Shale Member,* (iii) *Middle Sandstone Member* and (iv) *Upper Sandstone Member*. The *Basal Conglomerates* of *Choksti Fm* are packed in between *Nurla Fm* at the base and *Red Shale Member* towards the top (Henderson et al., 2010 b). The *Basal Conglomerates* are made up clasts of mixed lithologies like red and green meta-sediments of volcanic and granodioritic origin with dominance of clasts derived from the Ladakh Batholith (Searle et al., 1990; Sinclair and Jaffey, 2001). This *Red Shale Member* is dominantly made up of red shale and greenish-yellowish sandstone (Sinclair and Jaffey, 2001; Henderson et al., 2010 b). The *Middle Sandstone Member* is composed of normally graded grey-green and yellow sandstones and greyish-blackish shale. The *Upper Sandstone Member* has similar lithology and sedimentary structures, but differentiated by conglomerate bed in *Upper Sandstone Member* (Henderson et al., 2010 b). The whole *Choksti Fm* is interpreted as deposited by ephemeral braided fluvial systems (Sinclair and Jaffey, 2001). The *Nimu Fm* is having SW dipping faulted contact with the *Choksti Fm* and is sub-divided into two members *Lower Nimu* and *Upper Nimu*. These two members have similar lithology of sandstone, shale and conglomerates. The *Lower Nimu* and *Upper Nimu* are distinguished by SW dipping and NE propagating thrust.

These mid Eocene- Miocene sedimentary rocks are interpreted as axial river deposits evidenced by NW palaeo- flow direction of palaeo- Indus. The detrital mica age of *Upshi Fm* of Indus Group suggests deposition occurred until ~ 24.2± 0.2 Ma (Sinclair and Jaffey, 2001; Henderson et al., 2010 b, 2011).

1.2.3 Structural setting

The Indus basin has evolved into an intermontane depression between the Ladakh Batholith and the Zanskar ranges, due to northward movement of Indian plate during the early Eocene. This basin later suffered compressive deformation persistently and shortening progressively as a result continuing collision between India and Eurasia (Garzanti and Van Haver, 1988). Structurally, ~ 20 km wide Indus Group is bounded by highly deformed Zanskar Supergroup, Indian shelf/slope deposits of Lamayuru turbidities, Nindam forearc deposits, volcanic arc rocks of Dras Unit and ophiolitic mélange, from SSW (Fig 1.2). The NNE margin of Indus Group onlapped onto the Ladakh Plutonic Complex. (Searle et al., 1990; Sinclair and Jaffey, 2001). The Zanskar Supergroup and Indian passive margin *Lamayuru Fm* are separated by a NW verging Zanskar Back Thrust (ZBT). The calcareous flysch of *Lamayuru Fm* 13ccurs as a thrust slice, sandwiched between Zanskar Supergroup in the south and *Nindam Fm* in the north. The volcaniclastic sandstones and shales of *Nindam Fm* are folded and thrusted. The Tar Group and Indus Group are demarked by marine to continent facies changes and high angled, SSW dipping reverse fault known as Choksti fault, which can be observed near Choksti village. The Choksti fault transports *Chogdo Fm* over *Nurla Fm* (Searle et al., 1990; Sinclair and Jaffey, 2001). The *Jurutze Fm* and *Sumda Fm* occurred as a core member of polyharmonic anticline, whereas the intensely folded and thrusted *Chogdo Fm* and *Nummulitic Limestone* are limbs of this anticline fold (Searle et al., 1990). The *Nurla Fm*, north to the Choksti fault, is highly deformed. Several

SSW dipped thrusts were documented in very short distance in *Nurla, Chokski* and *Nimu Fm*. The folds found north to the Chokski thrust that verges in NNE direction (Sinclair and Jaffey, 2001). At the confluence of Indus and Zankar rivers, the Indus River exhibits entrenched meanders with successively increasing sinuosity that indicates the presence of tectonic structure, which may be the continuity of SSW dipping Upshi-Bazgo thrust marked by Searle et al. (1990).

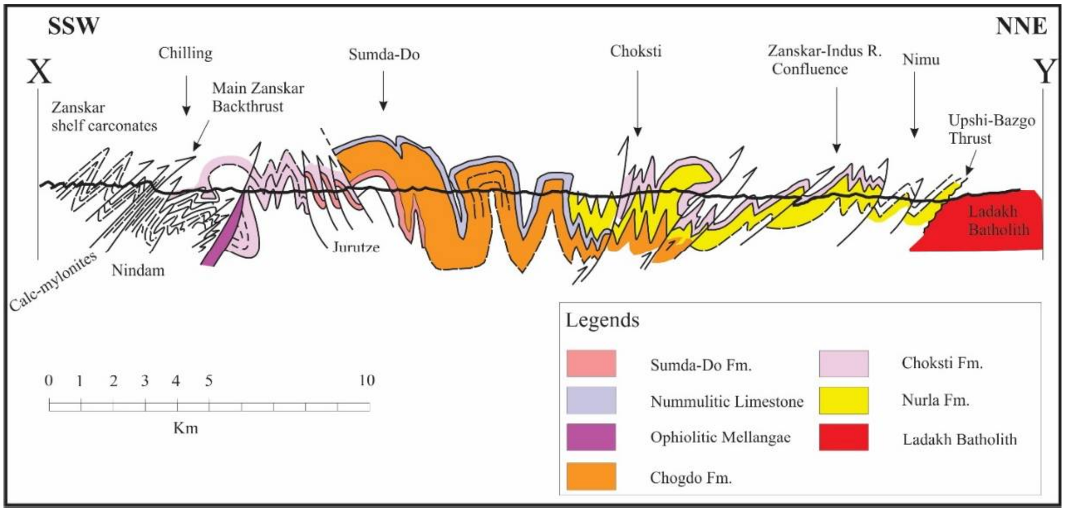

Figure 1.2 The structural cross-section along X-Y (shown in Fig 1.1), showing deformation of Indus basin sedimentary rocks (after Brookfield and Andrews-Speed, 1984). This small area (~35 km) has several north verging trusts and high angled reverse faults; Zanskar Back Thrust, Chokski thrust, and Upshi-Bazgo thrust.

1.3 Quaternary Geology of Indus Tsangpo Suture Zone

Ladakh Himalaya has diverse bared paleo-landforms, which are being explored to understand the paleoclimate variability and suture zone tectonic. In this region, the landforms are allied 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 and chronology (Fort, 1983; Burbank and Fort, 1985; Brown et al., 2002; Damm, 2006; Owen et al., 2006; Dortch et al., 2010, 2013) suggest ten glacial stages in Leh and Nubra valleys. The Indus valley glacial stage is one of the oldest glacial stage dated ~ 430 ka (Owen et al., 2006). The moraine of Leh valley glacial stage are dated to ~ 311 ka. Dishkit-3 stage in Shyok valley, Kar glacial stage and Skardu glacial stage in Skardu valley (157±13 ka; Seong et al., 2008) has synchronous extension and dated to ~ 146 ka (Owen et al., 2006; Dortch et al., 2010). Ladakh-4, Dishkit-2, and Pangong-2 glacial stages were advances ~ 80 ka; Bazgo glacial stages advances ~ 61 ka; Dishkit-1 and Pangong-1 glacial stages advances ~ 46 ka; Ladakh-2 glacial stage during MIS-2 (~ 20 ka); Ladakh-1 advances ~ 13.9 ka; Ladakh cirque and Pangong cirque advances ~ 1.7 and ~ 0.4 ka, respectively (Owen et al., 2006; Dortch et al., 2010, 2013). These glacial events generated enormous sediments which further carried by the rivers to aggrade the valleys in this region. During late Quaternary time, the valley filling and incision are reported in the upper and lower reaches of both Indus and Zanskar rivers (Blöthe et al., 2014; Burbank et al., 1996; Leland et al., 1998; Phartiyal et al., 2013). Phartiyal et al. (2013) dated a valley filling phase at 13±1 ka along the Indus River, near Kiari (~ 100 km upstream from Leh). The staircase terraces in the Indus (at Indus – Zanskar confluence) and Zanskar valleys, suggest the valley filling initiated before ~ 200 ka and 50 – 20 ka, which were evidenced by relict strath at ~ 150 m and 30 – 40 m above the river level respectively (Blöthe et al., 2014). These valleys were incised at the rate of 1.5±0.2 mm/a during late Quaternary (Blöthe et al., 2014). Chronology and morphology of straths of the Indus River, at Nanga Parbat Haramosh Massif (NPHM), northwestern Himalayan syntaxis, divided into two groups: low strath (< 7 ka) and high strath (> 7 ka). The low strath has fast incision rates, 9 – 12 mm/a, whereas, the high strath incise the bedrock at lower rates, 1 – 6 mm/a (Burbank et al., 1996; Leland et al., 1998). The exposure dates at NPHM mimic that the incision rates have not varied much in the last 65 ka to 15 ka and then rapidly increased due to moment in Raikot fault (< 7 ka, Burbank et al., 1996; Leland et al., 1998).

The large numbers of lacustrine deposits were studied in this region to understand the paleoclimate and tectonic conditions. The reactivation of faults, protrude the fans into the rivers, which causes the river damming and formation of lakes (Phartiyal et al., 2005), but the Blöthe et al. (2014) considered the Ladakh Himalaya as tectonically quiescent, the river dammed lakes generated due to landslides, alluvial fans and glaciers extensions into the rivers. The lacustrine deposits at Spituk, and Lamayuru were dated as 50 – 30 ka, and > 35 ka (Kotlia et al., 1997; Phartiyal et al., 2005), respectively. The several paleo-lacustrine deposits were also studied along the lower reaches of Indus River (~ 136 km) from Nimu to

Batalik at Saspol, Rizong, Khalsi, Achinathang and Biamah. These were dated as ~ 11 ka, 17 – 14 ka, 15 – 5 ka, ~ 11 ka and 14 – 6 ka, respectively, indicating rise in lake level from 35 ka to 5 ka, which further attribute to inconsistent increase in temperature and monsoon influence in the Ladakh Himalaya (Nag and Phartiyal, 2015)