JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.77, June 2011, pp.499-510

Morphostratigraphy and Palaeoclimate Appraisal of the Leh Valley, Ladakh Himalayas, India

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Abstract: In the present paper we study morphology, occurrence and mutual interrelationship of erosional (amphitheaters) and depositional landforms belonging to glacial (moraines), fluvio-glacial (glacial out wash), mass wasting (alluvial fans), aeolian (obstacle dune and sand sheets) and lacustrine (palaeo-lake sediments) processes within the Leh valley. These landforms are the geomorphic expression of past deglaciation grouped into five Formative Stages of Landform (FSL 1 to FSL 5) development in the Leh valley. The broad age bracket for the formative stages are based on the empirical relationship of the landforms, available chronology and their correlation with comparable climate phases. The retreat of glaciers in the Leh valley, along the southern slopes of Ladakh hill range and their retention over the northern slopes and Karakoram is further explained.

Keywords: Leh Valley, Ladakh Himalayas, Geomorphology, Climate change, Snow Accumulation Zone, Westerlies.

INTRODUCTION

The Leh valley is developed as an arcuate depression along the interface of undeformed Ladakh batholith to its north and folded, thrusted Zanskar meta-sedimentaries to its south (Fig. 1). It forms an integral part of the Ladakh Himalayas, the western central sector of the Himalayan mountain range that accumulates the largest body of ice outside the Polar Ice Cap in the mid-latitudes. The Leh valley preserves plethora of paraglacial landforms viz. moraines, dunes, sand-sheets, alluvial fans, and palaeo-lakes. It gives an opportunity to study the inter-relationship within these paraglacial landforms and understanding of denudational processes in the valley.

The Leh valley lies in the rain shadow of the Great Himalayas (towards south) with Karakoram range (towards north) and Tibetan plateau (towards east) serve as an orographic barrier that controls the continental wind system and consequently, the climate of the region. It receives scanty and infrequent rainfall /snowfall under the influence of both Southwest Indian Monsoon and Westerlies (Owen and Benn, 2005; Fowler and Archer, 2006; Bhutiyani, et al. 2007). The wind interface locates itself along the Karakoram and its variation is controlled by the mid-troposphere thermal anomaly (Vernekar and Ji, 1999). Historical records from weather monitoring station at Leh indicate that the average summer temperature goes up to 20ºC by July, while the average winter temperature dips down to -13ºC by January. It receives rainfall twice a year during June to September (Southwest Monsoon: average precipitation is 41 mm) and October to May (Westerlies: average precipitation is 53 mm); whereas above 5000 m. a. s. l. the precipitation is in the form of snowfall. Glacier melted water is a major contributor to the Indus drainage system than the rainfall. High altitude and reduced amount of rainfall in the valley portions of the Ladakh Himalaya elucidate prolonged cold and arid climate assigning a status of High Altitude Cold Desert.

Numerous glaciological, palaeo-climatological and chronological studies indicate that glaciers in lower Himalayas (Thompson et al. 2006; Owen, 2009; Seong et al. 2009), southern Ladakh range (Owen et al. 2006) the Zanskar range (Burbank and Fort, 1985; Osmaston, 1994; Mitchell et al. 1999) and Tibetan plateau (Thompson et al. 2006; Heyman et al. 2009) shows sign of overall recession over Himalayas, while the glaciers over Karakoram sector (Hewitt, 2005) and western Tibet (Damm, 2006) show signs of advancement in recent times. Most studies carried out

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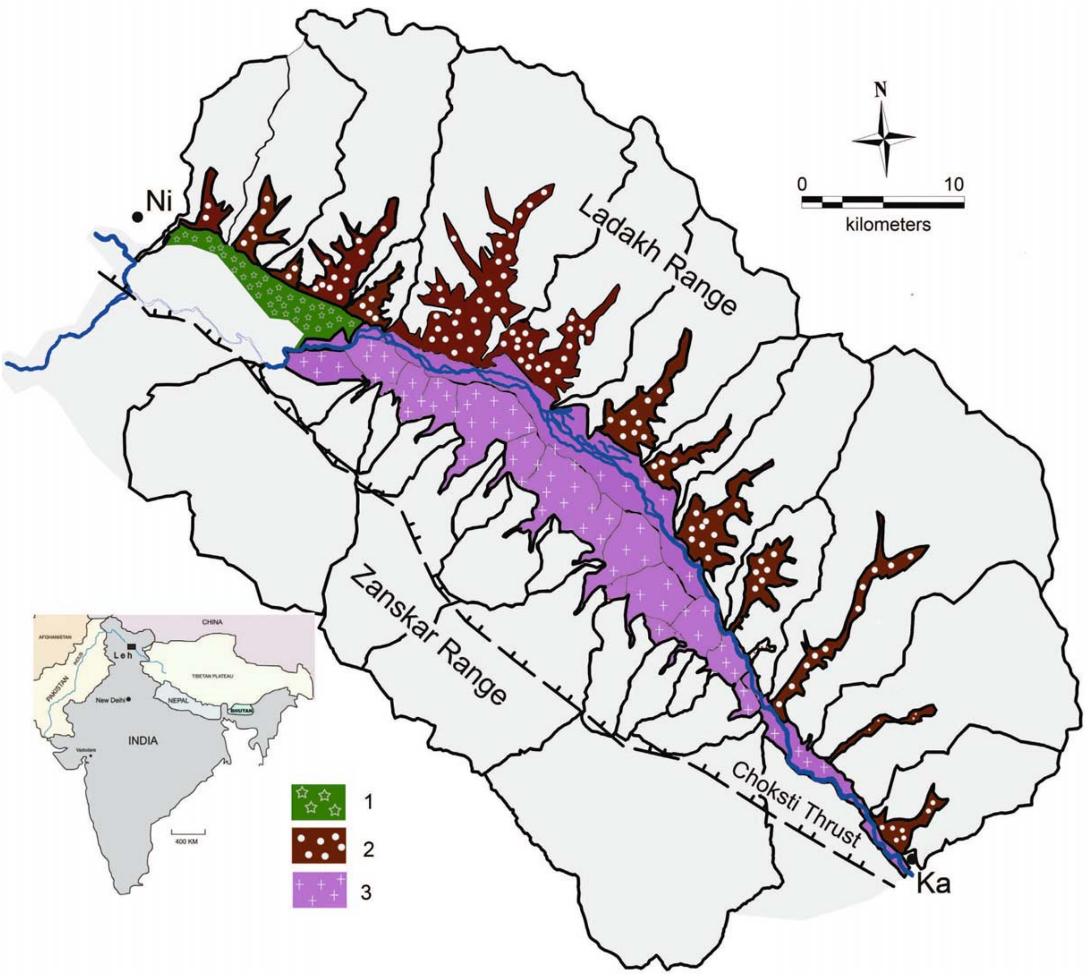

Fig.1. Location map and broad geomorphic units within the Leh valley. **1** - Shri Pather Sahib Gurudwara surface; **2** - Amphitheater valleys; **3** - Gumpuk–Leh–Shey-Karu surface; Ka - Karu hill; Ni - Nimu Hill.

by earlier workers have focused on a definite landform or on a particular aspect viz., studies on moraines (Drew, 1873; Fort, 1978; Dainelli, 1922 referred in Owen et al. 2006; Fort, 1983; Burbank and Fort, 1985; Fort et al. 1989; Osmaston, 1994), lacustrine deposits (Burgisser et al. 1982; Fort et al. 1989; Bagati and Thakur, 1993; Bagati et al. 1996; Kotlia et al. 1998; Shukla et al. 2002; Phartiyal et al. 2005, Phartiyal and Sharma, 2009) chronology - using the magnetic method (Fort et al. 1989), radiocarbon method (Bagati et al. 1996; Phartiyal et al. 2005) and surface dating of moraines using terrestrial cosmogenic nuclides (^{10}Be isotope: Brown et al. 2002; Owen et al. 2006; Heyman et al. 2009). The present study, in contrast looks into the assemblage of landforms available for inspection in the Leh valley detailing their morphology, occurrences and mutual interrelationship. The study on establishing this interrelationship within the landforms is as important as the chronological models and models based on the study of independent landform; since inferences derived from such studies are based on studying more than one landform belonging to different processes occurring simultaneously or one after another.

GEOLOGY OF LADAKH HIMALAYA

Geology of the Leh valley has been discussed by several researchers (Searle et al. 1990; Searle et al. 1997; Sinclair and Jaffey, 2001; Jamieson et al. 2004). The northeastern margin of the Leh valley is bounded by Ladakh hill range exposing undeformed Ladakh batholith and Kardungla volcanics, an igneous rock complex belonging to Miocene age, whereas the north eastern margin is bounded by Zanskar hill range exposing meta-sedimentaries belonging to early Miocene to late Palaeocene age (Indus Formation) followed by Palaeocene to Palaeozoic age (Zanskar Formation) (Figs. 1 and 2). The contact between Indus and Zanskar Formation is manifested by Choksti thrust along the northeastern fringe of the Zanskar hill range. Choksti thrust has a substantial role in the development of gorges

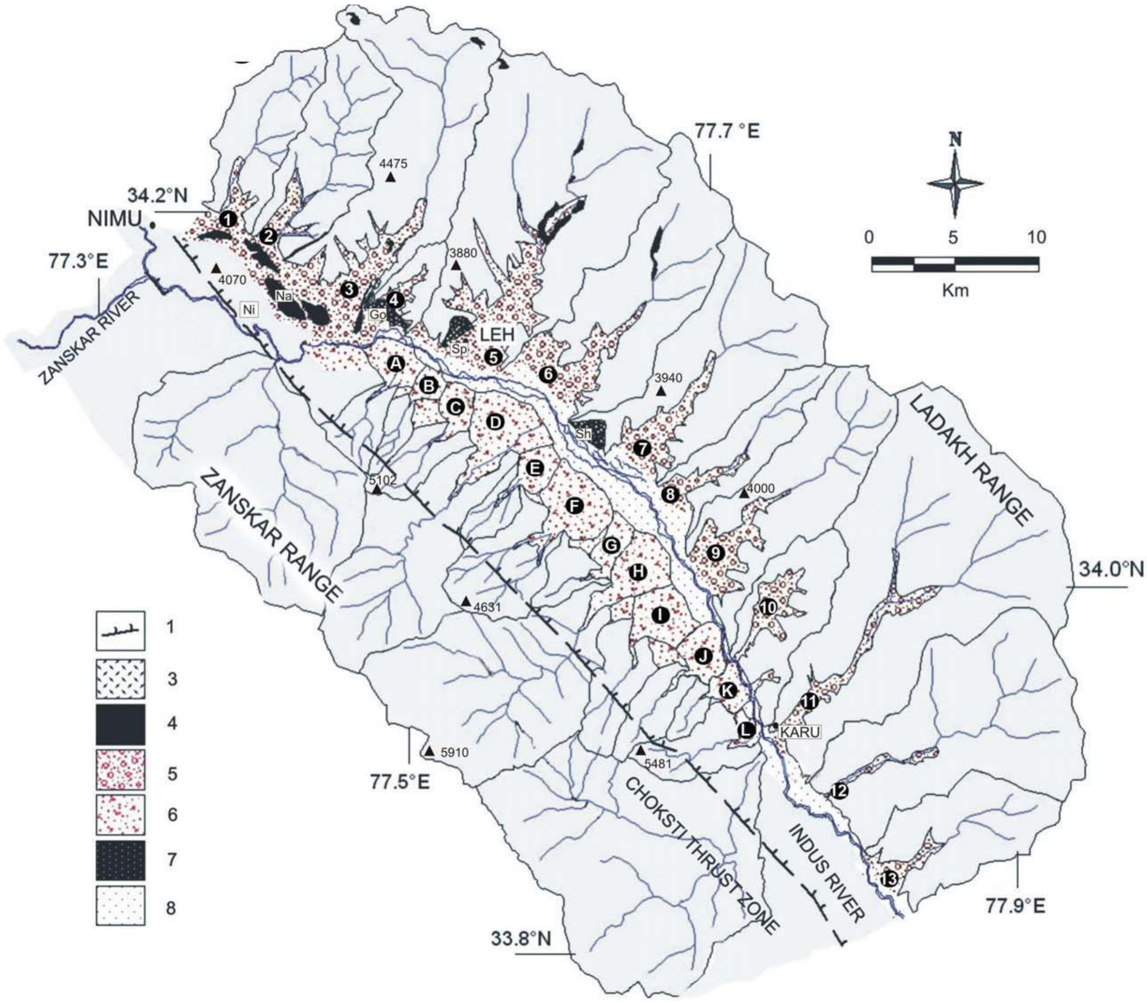

Fig.2. Geomorphology of the Leh valley. **1.** Thrust, **2.** Rock fall, **3.** Glaciers, **4.** Moraines, **5.** Glacial out wash, **6.** Alluvial fans, **7.** Ponding, **8.** Indus flood plain; The encircled numbers from 1 to 13 represents names of amphitheater valleys namely, Umlah, Taru, Pyang, Gupugas, Leh, Choklamsur, She, Thekse, Rabinpura, Kildyrmala, Karu, Changa, Upshi respectively; The encircled letters from A to L identifies various alluvial fans Ni – Nimu hill; Na – Shri Nanak moraine; Go – Gumpuk; Sp – Spituk; Sh – Shey.

(northwestern portion: gorge connecting Leh valley and Nimu valley; southeastern extremes: gorge SE of Karu) (Figs. 1 and 2). Presence of ophiolites and related complex rocks (Tso Morari crystalline complex) help tracing the Choksti thrust further southwest in the Leh valley through Zanskar range following the trend of the Indus - Tsangpo Suture Zone. Initiation of continental collision is marked by termination of early Eocene marine sequence (Searle et al. 1997) that are overlain unconformably by intermountain fill deposits identified as Indus Formation (Eocene - early Miocene age: Garzanti and van Haver, 1988; Searle et al. 1990). Upliftment of Zanskar and Indus Formations was along Choksti thrust during Miocene, when Himalaya underwent a major upliftment attaining the present height (Thakur, 1981; Coleman and Hudges, 1995; Sinclair and Jaffey, 2001). Uplift in Ladakh Himalayas (Clift et al. 2004), studies on plate movement (Jade et al. 2004) and records of seismites in sedimentary sequence (Shyok valley, Upadhyay, 2001, 2003; Spituk and Shyok, Phartiyal and Sharma, 2009) have emphasized for continued deformation in Quaternary.

GEOMORPHOLOGY OF THE LEH VALLEY

The arcuate Leh valley bordered by snow covered cragged Ladakh and Zanskar hill ranges is unique in terms of its status near to a closed geomorphic system between two narrow gorges near Karu and Nimu (Figs.1 and 2).

Geomorphologically the Leh valley is grouped into three broad geomorphic units (Fig.1). Unit 1: Shri Pather Sahib Gurudwara (SPSG) surface, Unit 2: Amphitheater valleys, and Unit 3: Gumpuk –Leh –Shey -Karu surface; retaining imprints of paraglacial processes. They together show a plethora both erosional (amphitheaters) and depositional landforms belonging to glacial (moraines), fluvio-glacial (glacial out wash), mass wasting (alluvial fans), aeolian (obstacle dune and sand sheets) and lacustrine (palaeo-lakes sediments) origin (Fig. 2).

Shri Pather Sahib Gurudwara surface (Geomorphic Unit 1) forms a high ground, in the northwestern portion of the Leh valley sloping southeasterly, between Umlah Fu and Pyang Fu (Fig. 1). SPSG surface composed of boulders and cobbles of moraine sediments with sand and gravel of fluvio-glacial origin derived from Ladakh range.

Amphitheater valleys (Geomorphic Unit 2) are the triangular, gently sloping surface bounded by hill range on three sides (Figs. 1 and 2). The gradual slope merges with the steeply rising Ladakh hills on its margins. They occur discordant to the Leh valley and are deeply incised within the Ladakh granites suggesting prolonged erosion. Assorted rounded cobble, boulder, pebbles and gravels with sand lenses characterize the floor of the amphitheater valley. The Leh valley features eight such large, moderate and minor amphitheater valleys identified after their tributaries or villages (Fig. 2). In upstream of the amphitheater, the deglaciated valleys preserve both lateral and end moraines.

Gumpuk-Leh-Shey-Karu geomorphic unit is a significant portion of the Leh valley that lies along a depression (Figs. 1 and 2). The large scale mass wasting process results into the development of bajada along the foot hills of steeply sloping Zanskar hill range in the Leh valley. Large and small lobes of alluvial fans emerging from Zanskar range have enveloped the valley reaching the distal edge of the amphitheater valleys (Fig. 2). The aeolian and lacustrine deposits are well preserved at the steep hill slopes and their fringes in amphitheaters. The morphological details of landforms recorded from the field were supplemented using topographic maps and satellite imageries.

GLACIAL LANDFORMS

Transverse Mountain Valleys

The transverse mountain valleys along undeformed Ladakh hill range (granite batholith) and thrusted Zanskar hill range (meta-sedimentaries) shows a different response to the similar processes acting in the Leh valley. The mountain valleys transverse to Ladakh hill range are a result of past glacial processes, whereas the mountain valleys transverse to Zanskar are formed by mass wasting processes.

The hill range show cragged rocky peaks, steep slopes, and small cirques at an elevation of 5626 m. a. s. l and above. The longitudinal profiles of the transverse glacial valley give an understanding of the valley formative process (MacGregor, et al., 2000; Jaimieson, et al., 2004). The longitudinal profile of the Leh valley show flattening with a convexity in the intermediate portion where as Phyang valley shows gentle concavity followed by linear slope (Fig. 3a). Similarly other mountain valleys flowing along southern slopes of Ladakh hill range show gentle profile with a flattened amphitheater in their front. The longitudinal profile of Leh and Phyang valleys further suggests that they do not have enough snow accumulation zones for the formation of glacier in its present settings. However, the northern slopes of Ladakh hill range has a well developed snow accumulation zone that allows glaciers flow north (Jaimiesion et al. 2004). Similarly, the Karakoram mountain range also has well developed glaciers that flow south.

The steep slopes of Zanskar hill range along Choksti thrust controls the morphology of the transverse valley in Zanskar hill range. The glaciers from Zanskar range flow further south away from the Leh valley, however, the steep narrow mountain valleys with sharp hill crests along the Zanskar range source the melt water triggered mass wasting leading to the development of alluvial fans at the mouth of each valley resulting in the formation of bajada all along steep Zanakar hill slope towards the Leh valley.

Amphitheater Valleys

The amphitheater valleys are triangular funnel shaped deglaciated valley bounded by steep rocky slopes on three sides within Ladakh hill range comprising glacial out wash and lag deposits all along the valley floor (Figs. 4a and 4b). They are narrow at the apex and merge with mountain valley at the upstream, while the wide distal edge merges with floor of the Leh valley. The amphitheaters (Fig. 2: 1 to 13) are identified and named after either the tributary or the villages. The amphitheaters are classified into three distinct group based on the plot of amphitheater area and drainage basin area (Fig. 3b) viz. small (Umlah, Taru, Gupugus, Thekse, Kildyrma La), moderate (Pyang, Choklamsur, She, Ranbirpura) and large (Leh). The plot show that the size of amphitheater area increases with the increase in drainage basin area suggesting glacial and fluvio-glacial processes as the valley formative processes. The amphitheater surface hosts varied landforms viz., moraine (end moraine: Leh amphitheater; lateral moraine: Phyang); the valley floor features glacial out wash and lag deposit, aeolian and lacustrine deposits from the peel of the steep hill slopes in the distal edge of the amphitheaters.

We suggest that the pass between Nimu and Leh on SPSG surface as a past defunct amphitheater (Fig. 2), The strong head ward erosion by the past glaciers is evidenced by lateral moraine opposite Shri Pather Sahib Gurudwara and moraine next to Nimu hill trending N100°.

Moraines

The moraines are mappable landforms well preserved over both SPSG surface (Unit 1) and within the amphitheater valleys (Unit 2). They occur at four different elevations, namely, 3380 m to 3790 m a.s.l; 3900 m to 4360 m a.s.l; 4690 m to 4790 ma.s.l; and 5150 m a.s.l and above. A total number of thirteen moraines were identified (Fig. 2). Majority of moraine ridges occurred between elevations, 3380 m to 3790 m. The number of moraines decreases at higher elevations. The palaeo-glaciers trend is inferred based on concordant nature of moraine to the valley and its morphology. The SPSG surface exposes moraine ridges trending in two directions namely; N 90° (Fig. 4c), adjacent to Shri Pather Sahib Gurudwara and N 100° (Fig. 4d), along Nimu hill towards the south eastern edge of SPSG surface. The moraines are about 100 m to 150 m in width. They occur as discontinuous ridges that run for few kilometers. Commonly, these ridges expose unconsolidated rounded cobbles and boulders are embedded within pebbles and gravels. The moraine sediments showing consolidated rounded cobbles, boulders and pebbles with yellowish-brownish coatings are observed along Nimu hill and at the mouth of Phyang amphitheater suggesting them to be older. The moraines are identified along Shri Pather Sahib, Umlah, Taru, Pyang, Leh and Choklamsur amphitheaters (Fig. 2).

The longitudinal profile of the Leh and Phyang valley show different segments with varied slopes (Fig. 3a: six in Leh and seven in Phyang), however, overall slope for both the profile is 5° and 6° respectively. The present study suggests that the slope breaks are the prospective zones for locating a lateral or end moraine. In Leh valley, the end

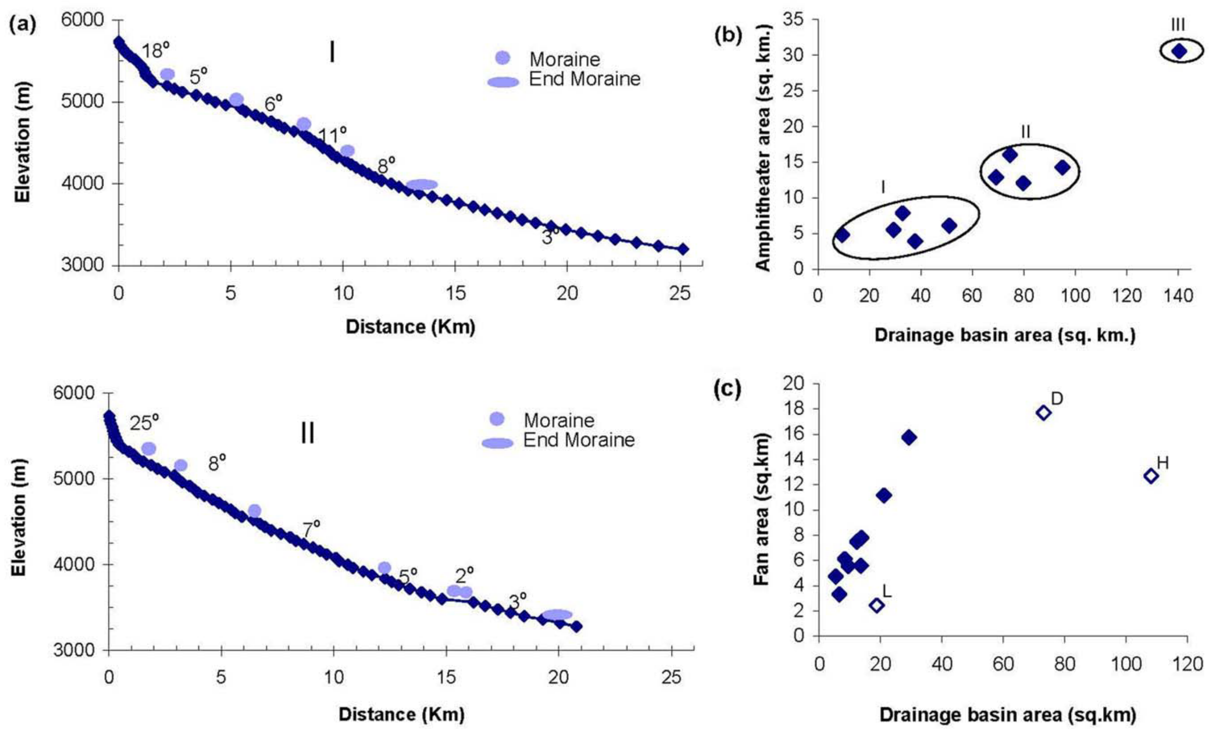

Fig.3. **(a)** Longitudinal profiles (I) Leh valley and (II) Phyang valley. The moraines (filled circle) and end moraines (ellipse) are observed to be preserved at the slope breaks along the profiles. **(b)** Plot of Drainage basin area (transverse to the Leh valley over Ladakh hill range) against amphitheater area developed at lower reaches in respective drainage basins is used to classify amphitheaters I small (Umlah, Taru, Gupugus, Thekse, Kildyrma La), II. Moderate (Pyang, Choklamsur, She, Ranbirpura) and III large (Leh). The plot further show that size of amphitheater area increases with increase in drainage basin area suggesting role of glacial and fluvio-glaical processes in valley formative process. **(c)** Plot of drainage basin area against fan area developed across Zanskar hill range shows a linear relationship with the exception in fan D, H and L. These fans have the small fan area in comparison to drainage basin area. The plot implies that the morphology of the Leh valley (near to close basin) restricts the extension of the alluvial fan where fans in the central portion of the Leh valley are larger in area whereas on towards gorge are restricted to smaller sizes.

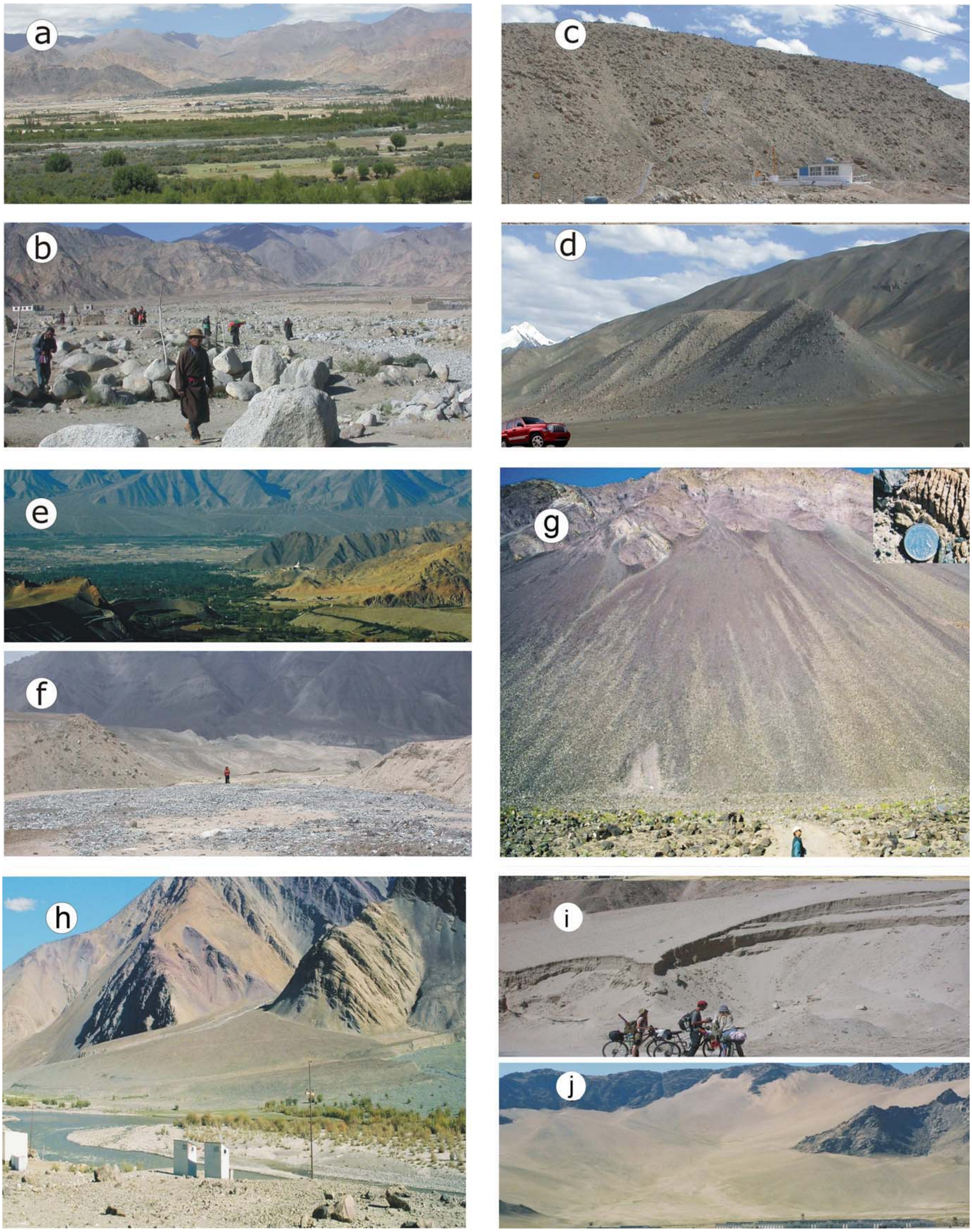

Fig.4. Field photographs. **(a)** Leh amphitheater valleys, **(b)** Lag deposits in amphitheater, **(c)** Older moraine in front of Shri Pather Sahib Gurudwara (N 90°), **(d)** Older moraine extending along Nimu hill (N 100°), **(e)** Leh end Moraines with a breach, **(f)** Phyang end moraine with a breach, **(g)** Scree slopes, (inset) Mechanical breaking of granites, **(h)** Alluvial fan from Zanskar range, **(i)** Obstacle dune developed along Ladakh hill range, **(j)** Sand and silt-clay aeolian sheet deposited over Ladakh hill range at Leh.

moraine occurs within the amphitheater at 3700 m. a. s. l., whereas that of Phyang valley end moraine is developed 4 km away from the mouth of Phyang amphitheater at 3200 m. a. s. l. along the eastern edge of SPSG surface unit (Figs. 4e and 4f). Based on the field observations the amphitheaters pre dates the moraines in the Leh valley.

MASS WASTING

The Ladakh batholith and Zanskar metasediments experience large temperature variation, which results in mechanical breaking of rocks that gives rise to unconsolidated clast material over the hill range and along hill slopes. Pebbly-gravely material creeps down along the unstable slopes or is carried down by the glacier or glacier melt water. The scree slopes form a common feature in the Leh valley all along the face walls in the gorges near Karu and Nimu hill (Fig. 4g).

Bajada

The coalescing alluvial fans are the most conspicuous geomorphologic expression in the Leh valley (Figs. 2: A to L) is documented as geomorphic Unit III (Fig. 1-II). The plot of drainage basin area against fan area shows a linear relationship with the exception in fan D, H and L (Fig. 3c). These fans have the small fan area in comparison to drainage basin area. It further suggests that the morphology of the Leh valley restricts the extension of the alluvial fan. In the central portion, the alluvial fans are larger in the area, whereas towards the gorge alluvial fan size decreases. The thick colluvial deposited along foot hills of steeply sloping Zanskar hill range is the result of prolonged mass-wasting (Fig. 4h). The sedimentary sequence belonging to alluvial fans are exposed in cliff section (25 m to 30 m) along the southern bank of River Indus. The fan sedimentary facies shows a wide variation in grain size; ranging from boulder, cobble, pebble, gravel, sand to clay both in lateral and vertical accretion. The field based sedimentological study ascertains four major aggradation phases in alluvial fan. Fan Event -1, Angular cobble-bounder fans: The exposures of alluvial fan (Fan B and C) opposite Kali hill expose thick pile of angular cobble and boulders. The random pile of angular cobbles and boulders has large interspaces, which were later filled by gravel, sand and clay. Fan Event-2, Pebbly Fans: The fans dominate by pebbles are observed in Fan D and further southeast. The massive unstratified thick sequence of pebbles and coarse sand suggest a major event of mass movement. Fan Event -3, Gravel Fans: These fans are exposed on the present day fan surface towards northwest (Fan A) of Leh valley. Intercalation of mud flows and gravel sheets are observed in the fan sequence as well as in lacustrine sediments. The relicts of fan lobes (Fan A and B) are traced based on correlation of angular, imbricated gravels exposed on the fan surface and across River Indus intercalated with silty clayey-sandy sequence next to Ladakh range (Spituk area). Lobes of active fans, reworking of fan surface (gravel sheets) along glacial melt are further traced in recent Indus River channel.

Aeolian and Lacustrine Landforms

The high altitude dry land environment at Leh valley also preserves classical obstacle dune and sand sheets (Figs. 4i and 4j). The dunes are observed well developed along the foot hills. A distinct depression developed between an obstacle dune and periphery of hill range forms a glacial melt water lake. Remnants of such lacustrine deposits are identified at three localities viz., Gumpuk, Spituk and Shey within the Leh valley. Sedimentologically the sediment profiles show intercalated sequence between gravel, sand and silty clay. The imbricated gravels present within the Spituk section shows metasediments of Zanskar range; the bluff sand corresponds to local wind blown deposits; the silty clay (10YR8/1 and 10YR7/2) and coloured bluff clay showing concoidal fracture extending long hill slopes for short distance are mudflow caused by glacial melt water over deglaciated granite surfaces. The laminated, carbonate rich and fissile silty clay (10YR7/1, 10YR7/2 and 10YR8/2) lacking swelling property are reworked sediments derived from mountain slopes and deposited in a lacustrine environment. They indicate seasonal drying and filling up of lake by glacial melt water.

The silty clay facies intercalated with sand facies are encountered over different landforms on steep and gentle slopes up to 3900 m. a. s. l. The uppermost sediment sequence in Spituk section (sand with thin lamellae of clay) spreads over hill slopes exemplifies recent aeolian activity and slope wash process by occasional rain splash (Fig. 4j).

FORMATIVE STAGES OF LANDFORMS IN THE LEH VALLEY

The Leh valley is partially a close geomorphic system. The landforms suggest a significant time gap between valley formative processes (Mio-Pliocene) and presently recorded glacio-fluvial–lacustrine–aeolian landforms within the valley. The scree on hill tops and slopes produced by the *insitu* mechanical breaking is transported along the steep valley slopes by glacio-fluvial processes irrespective of the clast size and energy conditions. The clast size of moraine, therefore, does not represent widespread or local nature of glaciers. It is similar to the rounded boulder and cobbles formed in the arid environment due to spheroidal weathering and not representative of long distance transportation. It implies that large amount of sediments within the Leh valley is derived from mass wasting, transported by glaciers, glacial melt water and aeolian from adjoining hill slopes rather than the contribution by main Indus river.

We use terrestrial cosmogenic nuclide ages (^{10}Be) and data on sample location (latitude, longitude and altitude) published by Owen et al. (2006). The plot of age of moraine and their altitude suggest four broad groups of moraines spanning between >385 ka to 130 ka; 130 ka to 75 ka; 75 ka to 30 ka; and 30 ka to present (Fig. 5).

Based on the empirical relationship of landform assemblage, available chronological data (Fort et al. 1989; Bagati et al. 1996; Phartiyal et al. 2005; Brown et al. 2002, Owen et al. 2006), and climatic phases (Guliya ice core: Thompson et al. 1997; GRIP ice core records: Dansgaard et al. 1993; GRIP Members, 1993; Johnson et al. 1997; Rangarajan and Sant, 2000) the formation of the Leh valley may be described under five broad Formative Stages of Landforms (FSL) in order of emergence (Fig.6) namely, FSL -1: Formation of amphitheater and the Leh valley is certainly >385 ka; FSL -2: Rock fall and moraine stage 1 can be bracketed between 385 ka to 130 ka (MIS 12 to MIS 6); FSL-3: Moraine phase II, pebbly fans and glacial out wash between 130 ka to 75 ka (MIS 5); FSL-4: Moraine phase III aeolian activity, glacial melt water lakes, glacial out wash, and gravel fan lobes between 75 ka to 30 ka (MIS 4,3, 2); FSL -5: fluvio-glacial phase, formation of Indus across the Leh valley, braiding of Indus River can be bracketed between 30 ka to present (MIS 2 and MIS1).

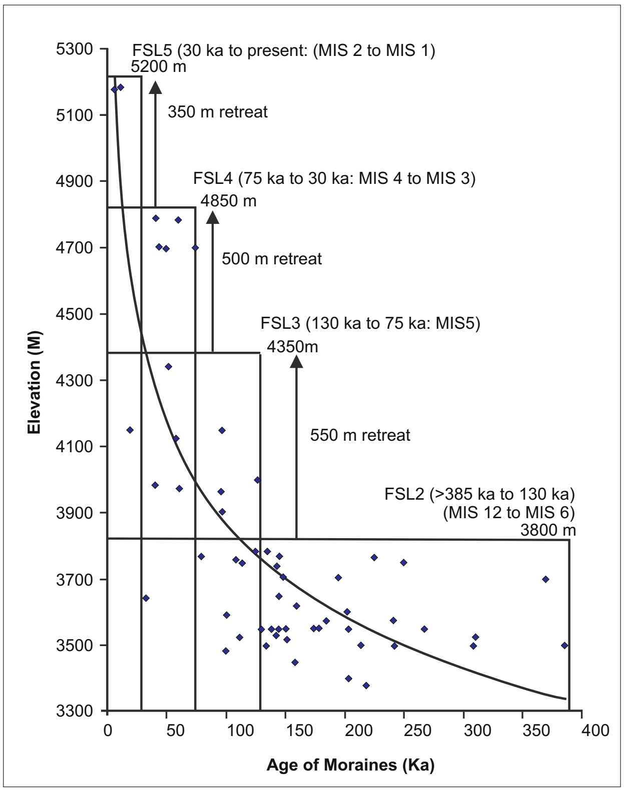

Fig.5. Plot of elevation verses moraine ages (Data on minimum ^{10}Be chronology (in ka) and samples latitude, longitude and altitude are taken from Owen et al. 2006); in present case the ages are used to define broad bracket of formative stages. Recalculation of terrestrial cosmogenic nuclide ages using the latest scaling models and considering their production rates is not applied. The Plot suggests four distinct glacial phases in the Leh valley: FSL 2, >385 ka to 130 ka – MIS12 to MIS 6; FSL 3, 130 ka to 75 ka – MIS 5; FSL 4, 75 ka to 30 ka – MIS 4 to MIS 3; and FSL 5, 30 ka to present MIS 2 to MIS 1. The plot further suggests the older moraines at lower elevation continued to influence by younger glacial phases. Glacial retreat between FSL 2 and FSL 3 is 550 m; FSL 3 and FSL 4 is 500 m; FSL 4 and FSL 5 is 350 m.

FSL-1: Formation of Amphitheater and Leh Valley

Gravity and glacio–fluvio activities were the key processes that played a leading role in eroding the mighty Himalayas along the weaker segments and transporting sediments on the lower slopes. Absence of Plio-Pleistocene sediments in the valley suggests glacio -fluvial process had played a significant role in eradicating Plio-Pleistocene sediments from the inter-mountain depressions. The Leh valley is one of the several such local depressions that were developed along a thrusted contact of steeply deepening metasediment and Ladakh granites. Ladakh granites under changing climatic phase spur weathering of granites resulting in the removal of large quantity of sediments from the region leading to the formation of amphitheater valleys, which got interlinked head ward over a time span (till Plio-Pleistocene) had modified the Leh valley by removing older sediments.

FSL -2: Moraine Phase I and Rock Fall (MIS 12 to MIS 6)

During FSL -2 new depocenters were defined over the erosional surfaces in the Leh valley and the amphitheaters. Initiation of glaciation and mass wasting in the Leh valley is evidenced by identifying the moraine stage 1 (earliest evidence of glaciation) and rock fall events (initial phase of alluvial fan activity) in the Leh valley. The evidence of early glaciations in the Leh valley is preserved in Unit-1,

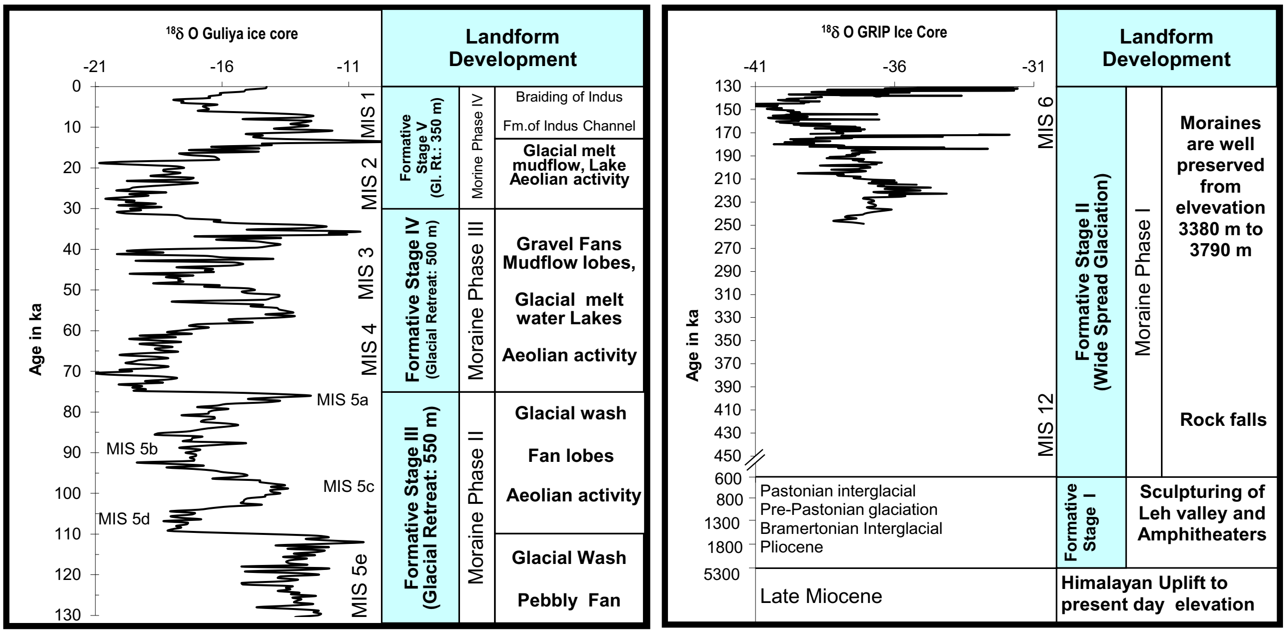

Fig.6. Comparison between Formative Stages of Landform with climatic phases recorded in Guliya ice core (Thompson et al. 1997; Rangarajan and Sant, 2000) and GRIP ice core (Dansgaard et al. 1993; GRIP Members, 1993; Johnson et al. 1997) records.

SPSG surface at the elevation of 3380 m. The SPSG lateral moraine suggests east to southeasterly movement of the glacier during MIS12 to MIS 6. The pass between Ladakh hill and Nimu hill forms a relict, defunct amphitheater due to strong head ward erosion. An alluvial fan (3.305 sq km) opposite Kali hill has large angular fragments of cobbles and boulders as clasts with gravel-sand matrix. This sequence is identified as an earliest rock fall event that forms the core of the alluvial fans.

FSL-3: Moraine Phase II, Glacial Out wash and Pebbly Fans and (MIS 5)

Moraines, glacial out wash and pebbly fans dominate during FSL- 3. Developments of moraines (lateral and end) within the amphitheaters suggest that the glaciers during Moraine stage II were restricted within amphitheaters. The glacial retreat inferred between FSL -2 and FSL -3 on the Ladakh range is of about 550 m (from 3800 m to 4350 m: Fig. 5). The moraines high up in the valleys are the youngest, with exceptions, where moraine dammed lake continues to accrete along the inner convex wall until a breach, causing a glacial out wash. This explains the younger dates of few moraines (Fig. 5). The accretion of end moraine in Leh amphitheater continued from 225 ka to 33 ka, whereas, accretion of the Phyang end moraine continued from 222 ka to 1ka (Owen et al. 2006).

The pebbly fans emerged from northern steep slopes of Zanskar hill range during the MIS 5e to MIS 5a. This major landform building event is well preserved in the southeastern portion of the Leh valley.

FSL-4: Moraine Phase III, Glacial Melt Water Lakes, Glacial Out wash, Aeolian Activity, Gravelly Fans (MIS 4 and MIS 3)

At the onset of Last Glacial stage, the glaciers in the amphitheaters further retreated by about 500 m (from 4350 m to 4850 m: Fig. 5). This is contemporaneous with the moraine accretions and aggradations of valley floor. Local mobilization of sand (glacial out wash) under strong winds operated simultaneously in the Leh valley. Several obstacle dunes and sand sheets developed within the Leh valley along the slopes of Ladakh hill range. The alluvial fans and obstacle dunes obstructed the glacial melt water channels that led to the development of numerous isolated lakes within the Leh valley. Fine golden yellow silty clay locally derived from the weathered granites (feldspars) blanketed the ambient landscape. The reworked silty clay caused surges of mudflows over the alluvial fans and aeolian – lacustrine depocenters. The clays intercalated with sand deposited in the lacustrine environment preserved variety of structures (structures due to entrapped ice block within mudflows and gravity or load structures). These structures indicate a rapid influx of glacial melt water bearing sediment and blocks of ice (Moretti et al. 2001). The glacial out wash sediments belonging to geomorphic Unit -1 preserve the herringbone structure suggesting an oscillating lacustrine environment in local pondings upstream of end moraines. Glacial melt water flowing down the Zanskar range into the Leh valley initiated surges of gravel and coarse sand as fan lobes. Occurrence of gravel lobes intercalated with aeolian - lacustrine at Spituk and Gumpuk suggest fan lobes extended northerly abutting Ladakh hill.

FSL -5: Moraine Phase IV, Formation of Indus across Leh Valley and Braiding of Indus River (MIS 2 and MIS 1)

The studies on the sedimentary sequence at Spituk and Gumpuk sectors show intercalated gravels comprising of metasediments derived from the Zanskar range along with aeolian-lacustrine sediments. It suggests an aggradational phase in the Leh valley, where by the gravel lobes emerged from Zanskar could extend up to foothills of Ladakh range across present Indus. The occurrence of River Indus during this phase must be an interesting topic to be addressed. It is the glacial melt water and flash floods (Juyal, 2010) in the Leh valley that lead to erosion and incision at the interface of fine clay, sand and gravel intercalated sequences and pebble- cobble -boulder sequence of the alluvial fans. Between FSL -4 and FSL -5 glaciers retreated about 350 m (from 4850 m to 5200 m: Fig. 5). Decrease in accumulation of snow along the slopes of Ladakh Hill range in late Holocene caused braiding in the Indus River. The present Indus channel preserves evidence of gravel, coarse sand and surges of fanning events belonging to recent times at many sites within the Leh valley. The lobes of the younger fan could erode Indus banks and prograde further into the channel.

DISCUSSION

The Leh valley provides a unique, geographical and geological set up to carry out a study on landform assemblage that belongs to different processes and understand their interrelationships and formative processes both contemporaneously and stages wise in the Trans Himalayan region. In present scenario, there are no active glaciers in the Leh valley. The northern slope of Ladakh Hill range exhibits well developed glaciers supported with glacier expansion along the Karakoram range (Hewitt, 2005) and western Tibet (Damm, 2006). The present understanding on the geomorphology of Ladakh hill ranges suggested formation and expansion of glaciers would depend on the percentage of the snow accumulation zone at a certain elevation and valley slopes. Underdeveloped snow accumulation zone with unfavorable slope hinders snow accumulation and growth of glacier showing overall retreat. This is best exemplified by the hill ranges of lower central and Ladakh Himalayas. The Karakoram hill range on the other side has a vast area above 5000 m elevation acting as snow accumulation zone and demonstrates the expansion of glaciers.

On the regional perspective, the Indus catchment over Zanskar, Ladakh and Karakoram hill ranges are influenced by Westerlies. The isotope analysis of Indus River water collected from various sectors allude towards the source of water precipitating in the Indus basin originating (80%) from the Mediterranean or other inland sea (Lambs et al. 2005). The influence of Westerlies is regulated by Mid Tropospheric Thermal Anomaly. In the prevailing conditions (interglacial), it is the northward shift of the wind interface that leads to increase in the snowfall over Karakoram range and decrease in snowfall over central and lower Himalayas (Hewitt, 2005; Vernekar and Ji, 1999), whereas during glacial phase, the mid tropospheric thermal anomaly shifts southwards, influencing the interface to shift further south. Consequently, snowfall over the central and lower Himalayas increases.

Geomorphology, field relationship among the landforms and their sediment characters together suggest formative stages of landform. The landforms stage is further comparable to global climatic signature GRIP and Guliya ice core records (Fig. 6). The moraine ridges exposed adjacent to Shri Pather Sahib Gurudwara over SPSG surface is the only moraine concordant with the Leh valley suggesting a peak in glaciation between MIS 12 to MIS 6. The onset of glacial retreat in the Leh valley could be during MIS 5 (130 ka to 80 ka) that continued until the recent time (Fig. 5). Moraines remained significant landform thereafter in the amphitheater valleys discordant to the Leh valley. The discordant relation of the majority of the moraines within the Leh valley, therefore, suggests that moraines belong to subsequent glacial-interglacial phases (MIS 12 to MIS 6) and did not participate into the valley formation process. There has been variety of paraglacial landforms developed during deglaciation such as debris flow, mudflow, obstacle dune, aeolian sheet deposits and local ponds developed along the margins of the amphitheater and form the significant landforms in the landscape of the Leh valley emerging from Zanskar hill range. The interrelationships between the processes are well exemplified at the sequences exposed at Spituk, Gumpuk and She (Sant et al. *communicated*). The Leh valley is comparable with the glacial record from Tibetan Plateau, where major phase of glaciation pre dates the global Last Glacial Maxima offering opportunity to study glaciations significantly older than is normally found in the northern hemisphere (Heyman et al. 2009).

The present study raises three important observations and queries, (1) the present course of River Indus in the Leh valley (between Karu and Nimu) appeared only during early Holocene. In that case, it would be interesting to decipher the course of palaeo-Indus during MIS 12 to MIS 2. We envisage that the present Shyok River, a tributary of Indus River, that has Karakoram range as catchment played an active role contributing large influx of melt water compared to its present Indus course between Ladakh and Zanskar hill ranges. (2) The study shows availability of loose sediment ready for transport (derived under gravity, glacio-fluvial and strong winds) within Indus catchment. In that case, the high rate of sediment flux in the Indus delta during Last Glacial, Last Glacial – Holocene transition and Holocene are related to transporting of available unconsolidated sediment (Rangarajan and Sant, 2000) rather inferring high sedimentation rate in terms of tectonic uplift of Himalayas (Clift et al. 2004). (3) Absence of deformation in the Quaternary sediments other than sedimentary structures, seismites or structures due to sudden loading of sediments / ice rafts demands judicial investigations.

CONCLUSIONS

1. The Leh valley is formed as a result of erosive process at an interphase of Ladakh batholith and Zanskar metasediments.
2. There is intricate morphostratigraphic relationship between glacial, glacio-fluvio, aeolian and lacustrine landforms in the Leh valley.
3. The Leh valley preserve evidence of four moraine phases during FSL -2, >385 ka to 130 ka - MIS 12-MIS 6; FSL -3, 130 ka to 75 ka – MIS 5; FSL -4, 75 ka to 30 ka MIS 4, 3 and FSL -5, 30 ka to Recent – MIS 2 and MIS 1.
4. The glaciers in the Leh valley remained prominent and widespread during MIS 12 to MIS 6
5. Significant retreat of glaciers in the Leh valley is recorded between FSL -2 and FSL -3 (550 m: from 3800 m to 4350 m) and FSL -3 and FSL -4 (500 m: from 4350 m to 4850 m) and FSL -4 and FSL -5 (350 m: 4850 m to 5200 m).

Acknowledgements: We thank Geological Survey of India for conducting UNESCO - IGCP 500 workshop in Leh during September 2006. We thank Col. Pankaj Sethi and Major Kamlesh Devchakke for providing logistic support during field season July 2007. This work forms part of Indian contribution towards IGCP-500 (DAS, SKW and RKG). We thank the reviewer for the valuable suggestions which helped to improve the manuscript.

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(Received: 12 August 2010; Revised form accepted: 21 December 2010)