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Linkage of Paraglacial Processes from Last Glacial to Recent Inferred from Spituk Sequence, Leh Valley, Ladakh Himalaya

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Abstract: The paraglacial sequence in the Leh valley, Ladakh Himalaya preserves imprints of various processes active during deglaciation in the late phase of Last Glacial. In present work, a high resolution sedimentological record generated for Spituk is presented identifying aeolian episodes, mudflow events from Ladakh Range and debris flows extending from Zanskar Range across present Indus River. Two temporal phases of water ponding within Spituk Sequence are also identified. The seismites recorded at various stratigraphic depths and their association with the sediment facies signifies gravity induced process besides possible seismic activity as an added phenomena. Linkage between paraglacial processes since Last Glacial to Recent is tracked and evaluated.

Keywords: Paraglacial, Soft-sediment deformation structures, Leh, Spituk, Ladakh Himalaya.

INTRODUCTION

The sedimentary sequences in the Leh valley, Ladakh Himalaya provide a window to study the paraglacial processes that were active during deglaciation ever since Last Glacial. The term 'Paraglacial', coined by Ryder (1971a, b), and later, Church and Ryder (1972) describes non-glacial processes (mass movement and fluvial) that are directly conditioned under glacial environment. The term is also extended to cluster of non-glacial landforms that capture the response of high altitude mountains to changing environmental conditions in terms of denudational history (Ballantyne, 2002a, b). In the present paper, we discuss aggradation of Spituk sequence under the influence of three paraglacial processes namely, mass movement (mudflows, debris flow and sheet wash); fluvio-glacial (glacial wash); aeolian (dunes and sand sheets) and local isolated lakes within the Leh valley. The Leh valley has been investigated by various workers on several aspects namely, moraines (Drew, 1873; Dainelli, 1922; Fort, 1978, 1983; Burbank and Fort, 1985; Fort et al. 1989; Osmaston, 1994); glacial influence over transverse valleys (Jamieson et al. 2004); influence of glacial and fluvial processes over high mountain landscape (Hobley et al. 2010); lacustrine deposits (Burgisser et al. 1982; Fort et al. 1989; Bagati and Thakur, 1993; Sangode and Bagati 1995; Bagati et al. 1996; Kotlia et al. 1998; Shukla et al. 2002; Phartiyal et al. 2005; Phartiyal and Sharma, 2009) and on chronology using magnetic method (Fort et al. 1989), radiocarbon method (Bagati et al. 1996; Phartiyal et al. 2005) and surface dating of moraines using ^{10}Be isotope (Brown et al. 2002; Owen et al. 2006).

The present paper focuses on the detailed study of the known sedimentary sequence exposed at Spituk (34°07' 50.25" N; 77° 31' 28.30" E; 3213 m). The radiocarbon dates along the sequence (~40 ka: Phartiyal et al. 2005) places the sequence in a time frame of Late phase of Last Glacial (LLG). The study records sedimentary facies, nature of transition, and sedimentary structures at high resolution so as to resolve paraglacial processes that operated during the aggradation of Spituk sequence. The present findings are significant for they establish the linkage of paraglacial processes operative during LLG to Recent time. Further the paper brings out a comprehensive understanding on recent catastrophe that occurred in Leh (Juyal, 2010) where a cloud burst triggered mud flows swept over the Leh town destroying civil infrastructure and buried several persons within the flow.

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GEOLOGY

The Leh valley is bounded by Ladakh hill range (undeformed Ladakh batholith and Khardung volcanics, an igneous rock complex) to its north east and Zanskar hill Range (meta-sedimentaries: Paleozoic to Palaeocene age – Zanskar Formation and latest Palaeocene to early Miocene – Indus Formation) to its southwest (Brookfield and Andrews-Speed, 1984; Garzanti and Van Haver, 1988; Searle et al. 1990; Searle et al. 1997; Sinclair and Jaffey, 2001; Jamieson et al. 2004; Wu et al. 2007; Bhutani et al. 2009). The contact between Indus Formation and Zanskar Formation is manifested by Choksti thrust along the northeastern fringe of the Zanskar hill Range. The upliftment of Zanskar hill Range occurred along Choksti thrust during Miocene, when Himalaya underwent a major upliftment attaining the present height (Thakur, 1981; Coleman and Hodges, 1995; Sinclair and Jaffey, 2001). Choksti thrust has a substantial role in the development of gorges (northwestern portion: gorge connecting Leh valley and Nimu valley; southeastern extremes: gorge SE of Karu). The uplift in Ladakh Himalaya (Clift et al. 2004), studies on plate movement (between Leh and Bayi, 17.8±1 mm/yr, Jade et al. 2004) and records of liquefaction structures / seismites from sedimentary sequence (Shyok valley, Upadhyay, 2001 and 2003; Spituk and Shyok, Phartiyal and Sharma, 2009) have emphasized on neotectonics. However, earlier observation by Sinclair and Jaffey (Sinclair and Jaffey, 2001, Fig.10, p.158) and our present investigations, across a variety of landforms, highlight primary trends of Quaternary sediments in Leh valley are not disrupted/ deformed.

GEOMORPHOLOGY

Geomorphologically the Leh valley is divided into three broad geomorphic units namely, the high elevated terrain of Shri Pather Sahib Gurudwara (Unit-1), the deglaciated amphitheater valley (Unit-2) and low lying terminal alluvial fans (Unit-3) (Fig.1). The divisions of the units are based

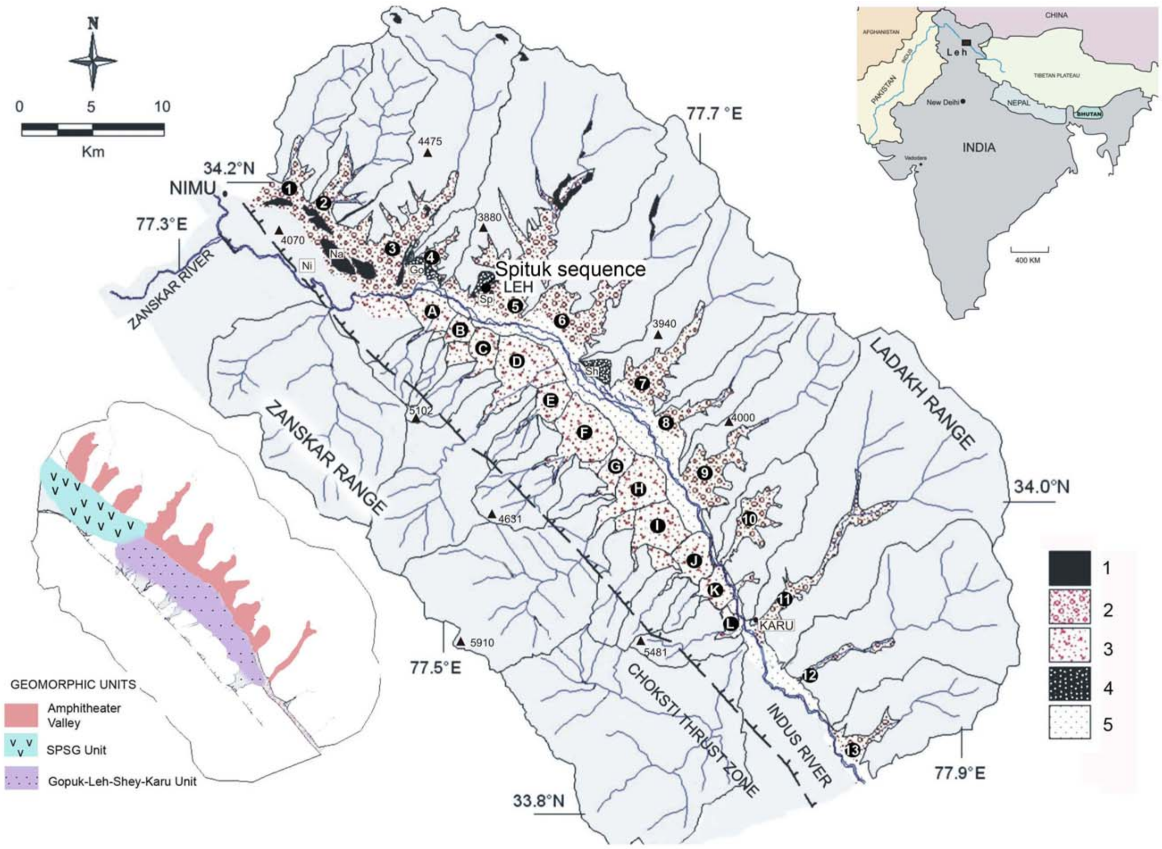

Fig.1. Location and Geomorphology of the Leh valley, Ladakh Himalayas (*after* Sant et al. 2011). **1** - Moraines, **2** - Glacial wash, **3** - Alluvial fans, **4** - Paraglacial sequences at Gumpuk, Leh and She, **5** - Indus flood plain; The encircled numbers from 1 to 13 represent names of amphitheater valleys namely, Umlah, Taru, Pyang, Gupugas, Leh, Choklamsur, She, Thekse, Rabinpura, Kildyrmala, Karu, Changa, Upshi respectively; The encircled letters from A to L identify various alluvial fans Ni – Nimu hill; Na – Shri Nanak moraine; Go – Gumpuk; Sp – Spituk; Sh – She.

on assemblage of geomorphic features and sediment characteristics (Sant et al. 2011).

Unit-1 forms a high ground, to the northwest of the Leh valley sloping southeast, between the rivers Umlah Fu and Phyang Fu. The surface is mainly composed of moraine ridges (~100 m high) and glacial wash sediments (~10 m thick) derived from granites exposed along Ladakh Range.

Unit-2 comprises thirteen triangular shaped and deglaciated valleys developed transverse to Ladakh hill range (Fig.1; 1 to 13). The valleys show head ward erosion towards cirques, whereas downstream the valley forms a wide sloping floor merging with the transverse floor of Leh valley. The upper reaches of these valleys have well preserved repository of lateral and terminal moraines. The glaciers melt/rain water drains the lower reaches, gently sloping valleys show moderate incision exposing ~1 m thick sediments. Presence of rounded to sub-rounded gravels with intervening sand lenses manifest role of glacial and paraglacial processes.

Unit-3 constitutes a geomorphic depression between Unit-2 and Zanskar Range filled up by thick sediments brought by mass movement. The most significant geomorphic feature of the Unit-3 is alluvial fans. The alluvial fans are composed of three independent sediment facies namely angular cobble-boulder facies, pebble facies and gravel facies. The intercalated clay facies and sand facies in the lower part of Sputik sequence is capped by gravel facies, which is also identified as uppermost lobe of alluvial fans emerged from Zanskar valley in the Leh valley. The lobes of fan with gravel facies are laterally mappable across present day Indus channel into the Spituk sequence, abutting against the Ladakh hill Range.

SEDIMENTARY FACIES

A systematic study was carried out in the cut-open trenches over 12 benches across the 2796 cm vertical profile of Spituk sequence. The younger unconsolidated sandy sequence (1050 cm) accreted over the upper slope of Ladakh hills was also logged.

Three sedimentary facies and five sub facies have been identified based on grain size and primary sedimentary structures along the 2796 cm sedimentary sequence exposed at Spituk (Fig.2; Table 1). The most dominant lithofacies is that of fine grained (clay, 68.36%) followed by sand (26.26%) and gravel (5.38%). The sediment facies, their association and geometry of the litho-unit together are used to identify processes responsible in aggradation of the Spituk sequence. The intercalated fine and sand facies endorse that sediments were deposited by aeolian, mass flow, lacustrine

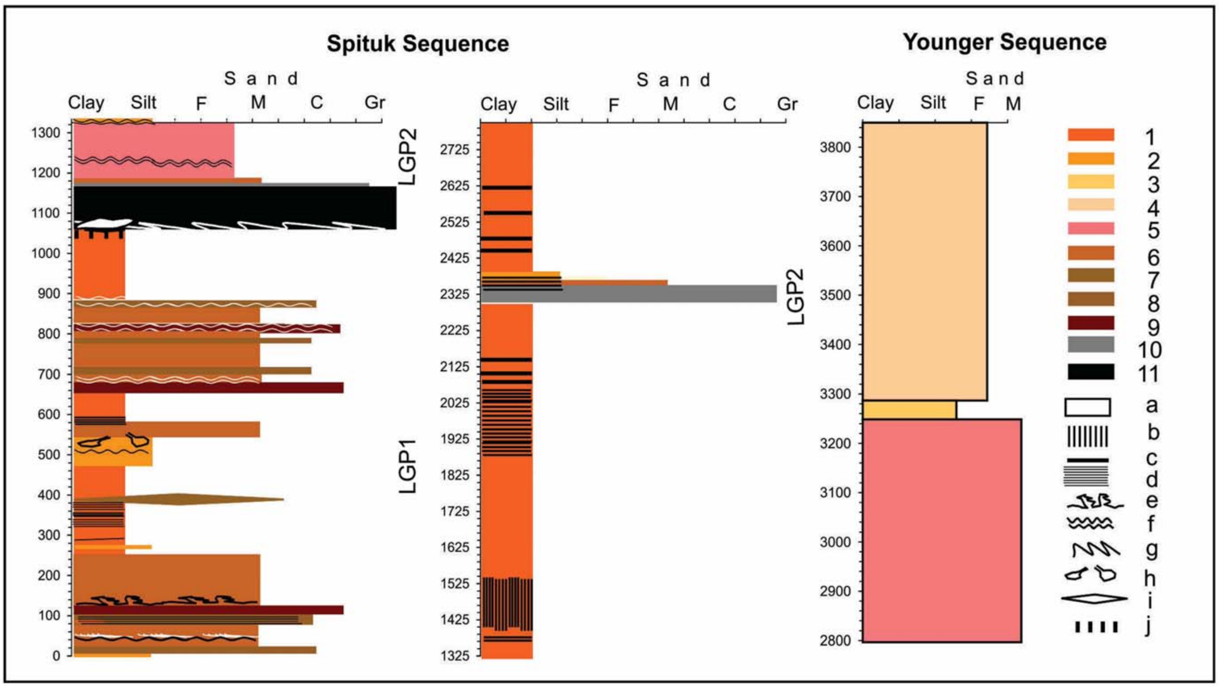

Fig.2. Litholog of Spituk sequence: **1** - clay, **2** - clayey silt, **3** - silt, **4** - silty fine sand, **5** - fine sand, **6** - fine-medium sand, **7** - medium sand, **8** - medium coarse sand, **9** - coarse sand, **10** - coarse sand and gravel, **11** - gravel; **a** - massive, **b** - concoidal fracture, **c** - banded, **d** - laminated, **e** - convolute bedding, **f** - flaser bedding, **g** - flame structure, **h** - pseudo balls, **i** - lens, **j** - discordant clay bands. LGP - Last Glacial Phase.

Table 1. Sedimentary facies recorded along Spituk sequence

Clast grade	Facies code	Description
Clay	F_m F_l	Massive with concoidal fracture Laminated with compositional bands
Sand	S_l S_m	Fine sand with lamination; occasionally show cross bedding / wavy structure. Fine sand bluff, massive occasionally graded
Gravel	G_l	Matrix supported, grading, clast imbricated and unsorted

(shallow numerous local ponds) environment, mixed facies signify interchanging/overlapping sedimentary environment, whereas, the unsorted gravel facies represents debris flow events (Table 2). The contacts along the fine facies are usually sharp. Gradational contact is observed within the sandy facies. The study leads to recode new sediment facies from the sequence (coarse sand and imbricated gravels) at two distinct levels (depths: 1164 cm to 1282 cm and 2356 cm to 2394 cm) occurring within 2796 cm vertical profile at Spituk. The clast composition (metasediments) and grain orientation of this facies give important clues regarding the interplay of influx in sediments from provenance (Zanskar and/or Ladakh Range).

Clay facies (F_m, F_l)

The fine-grain facies is the most abundant facies (68.36%) in the exposed Spituk sequence. The average particle size is that of clay (<2 μm). Based on primary structures, the fine-grain facies are further subdivided into two sub facies namely, bluff and massive clay (F_m), and laminated clay (F_l). The clays are the weathering product derived from Ladakh granites transported through various agencies.

Among the fines, the massive clay sub facies (F_m facies) dominants the Spituk sequence. The massive character in the fine facies is largely due to identical composition and grain size suggesting rapid accumulation, single source and uniform energy conditions during the depositional process. The F_m facies units show distinct geometry of a lobe that follows the dip and trend of the previous litho units (Fig. 3F and 4-II). The lobe laterally terminates at short distance and are site specific. They have sharp lithofacies contact (sand and clay and clay and gravel). The F_m facies are a consequence of mudflow triggered by glacial melt water. In case of Spituk sequence the F_m facies represents a rapid influx of mudflow along the steep slope of Ladakh hills (short distance) that flowed over other litho units accumulated over slopes and foothills (sand sheets / dunes). The oxidation bands (1 cm to 2 cm thick) within the massive clay facies suggest exposure of water laden mud to the atmosphere for a significant period leading to oxidation of upper layer of mudflow.

Table 2. Architectural elements at Spituk

Element	Symbols in Fig.4	Principal Lithofacies Assemblage	Geometry and relationships
Debris flow	D	G_l	Variable lens shape
Mudflows	M	F_m	Restricted lateral extension
Aeolian	A	S_l, S_m, F_{cs},	Sheets, lenses, wedge
Lacustrine mix facies	P	F_l	Thinly laminated

The laminated fine facies (F_l facies) represents a difference in composition or seasonal accumulation. The F_l facies indicates deposition in a seasonal water body, where the thin lamination suggests temporal breaks. However, their occurrences are restricted and are at two levels within Fm facies. Thus the laminated clay (F_l) represents periodic deposition of clay in the local squall in a water body defined by dunes and mud flows/debris flows at the Spituk sequence.

Sand facies (S_l, S_m)

The sand facies is the next dominant facies (26.25%) best exposed in the lower portion (1464 cm from base) of Spituk sequence. The sand facies is moderately well sorted having average particle size varying from 63 μm to 250 μm. The sand facies comprises of two sub-facies namely massive fine sand bluff (S_m) and thin laminated fine sand (S_l).

The massive character within the sand facies reflects homogenous composition and grain size suggesting rapid accumulation, single source and uniform energy conditions of the depositional process. In Spituk sequence, the S_m facies represents the rapid accumulation by strong winds (Fig. 4-III), whereas, the S_l facies is developed by local reworking of aeolian sediments in the presence of seasonal glacial water developing laminations along with thin fining upward units. The S_l facies also suggests seasonal dry and wet phases. The winds contribute thin veneer of sediments followed by local surface reworking along glacial melt water giving rise to laminations. Thus the succession of S_m and S_l facies in the Leh valley are representing seasonal climatic fluctuation in overall arid environment.. The similar processes are observed along present day sand sheets over Ladakh Range in the Leh valley, dune accretions at the Kalli foot hill and on way from Leh to Karu. The muscovite flake concentration along the flaser bedding suggests sands are reworked from local source.

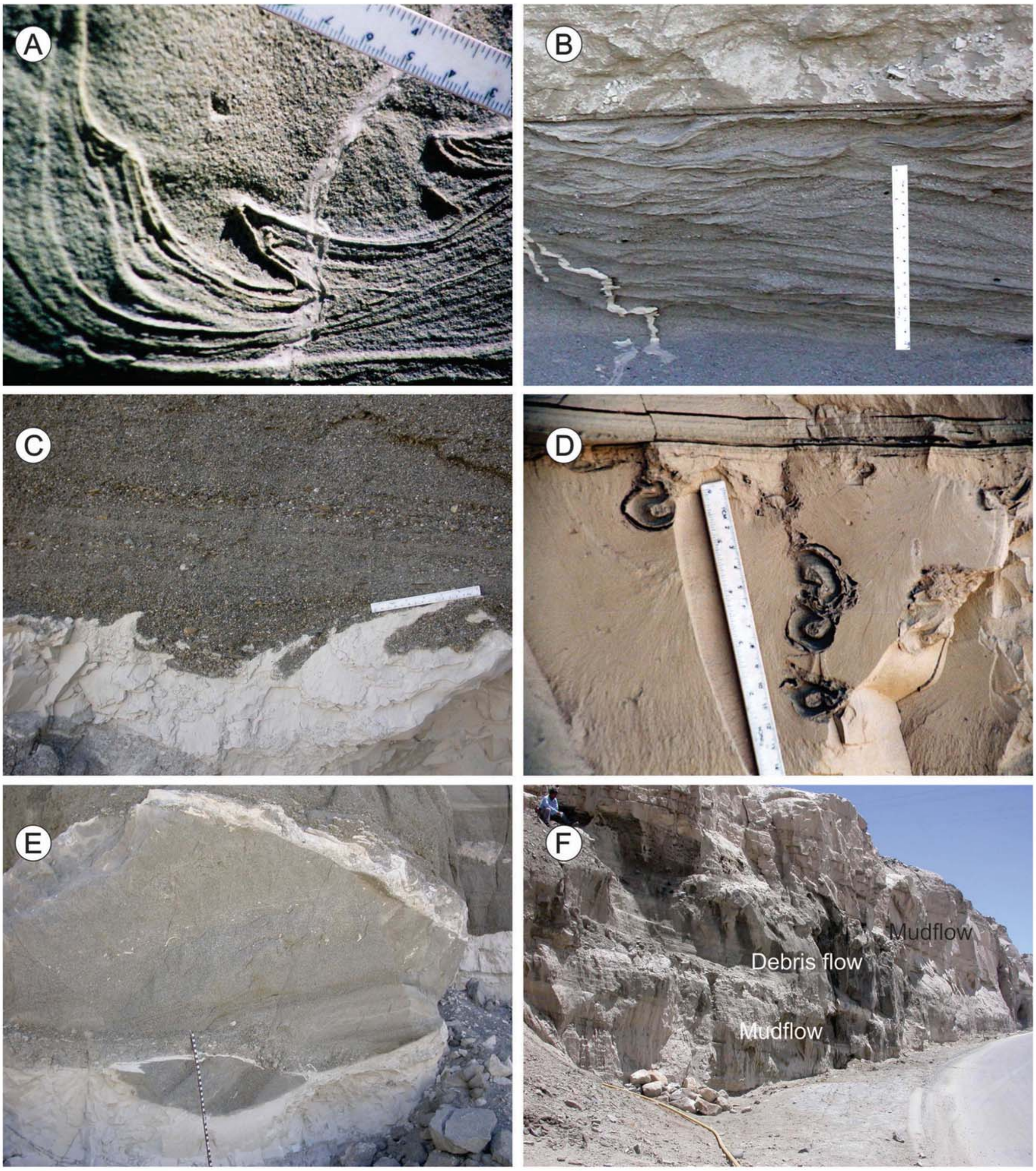

Fig.3. Field photographs of: (**A**) Convolute bedding (**B**) Flaser bedding (**C**) Flame structure (**D**) Pseudo balls (**E**) Debris flow and lens (**F**) Mudflow and Debris flow Relationship.

Gravel facies (G_l)

The gravel facies constitute about 5.38% in the exposed Spituk sequence. The average grain sizes vary from 320 mm to 4 mm. The G_l facies is characterized by elongated, angular, platy and imbricated gravel clast giving lamellar structure (Fig.4-IV). The gravel clasts are composed of meta-sedimentary rock fragments supported with coarse grain sand matrix. The gravel unit follows geometry of a lobe that dip 20° towards the northeast guided along the surface of previous clayey sandy deposits with abrupt termination. The lobate geometry, meta-sedimentary imbricated clasts trending northerly together suggest gravel lobes have emerged from Zanskar Range and are abutting against Ladakh Range. The G_l facies marks an event of debris flow

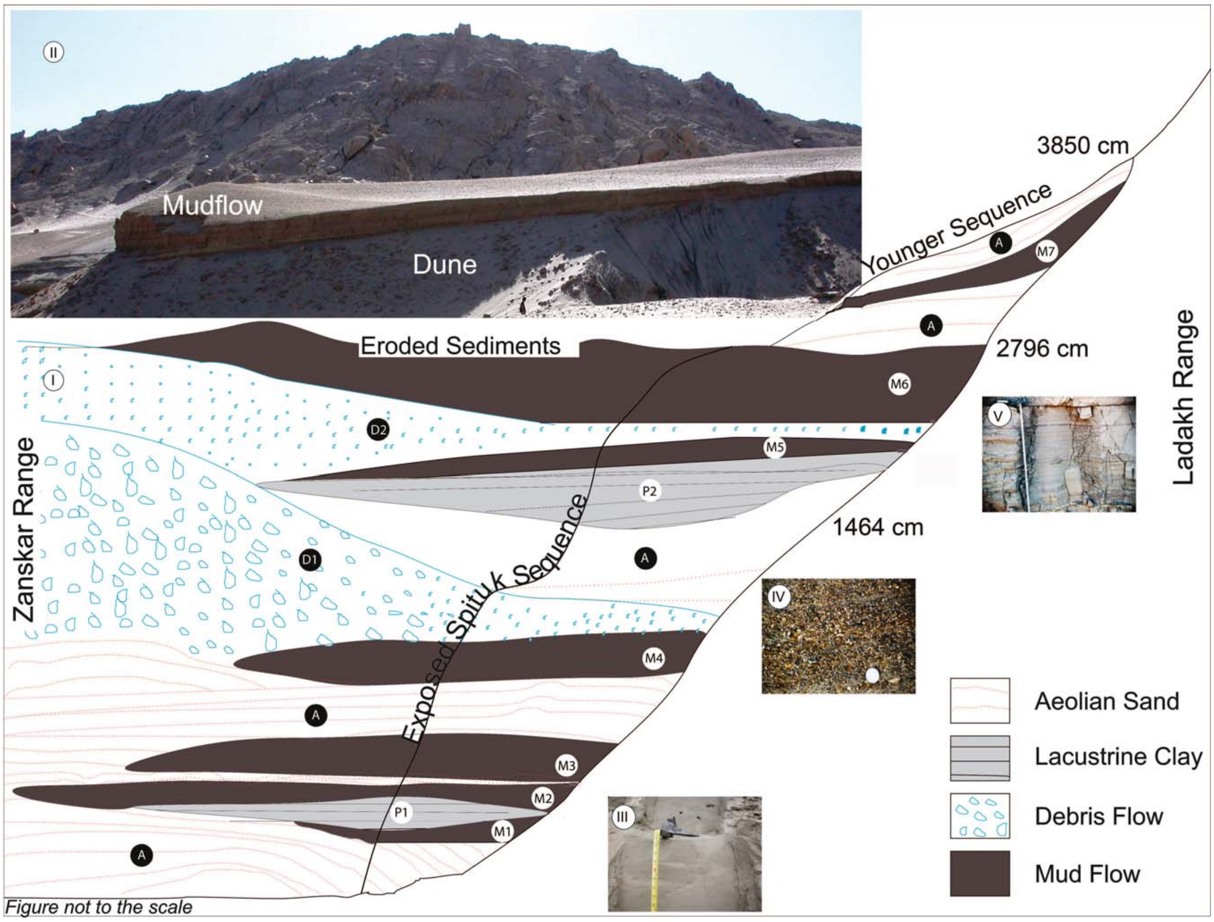

Fig.4. I - Model depicting accretionary phases in the Spituk sequence. **II** - Photograph showing mudflow-dune relationship at She. **III** - Aeolian massive sand. **IV** - Imbricated gravels in debris flow. **V** - Varvites. A - Aeolian deposit. D1 and D2 - Debris flow. M1 to M6 - Mudflows. P1 and P2 - Local Ponding (see Table 2).

supplemented by the glacier melt waters in the high altitude arid deglaciating environment over the Zanskar Range in the Leh valley.

Secondary Sedimentary Structures

Spituk sequence also preserves post depositional concordant and discordant structures such as convolute bedding, flaser bedding, flame structure and pseudo balls (Fig 3A-3D). These structures are commonly observed along the clay-sand and gravel-clay and sand-clay interphase. However, their occurrences within a litho unit are not uncommon.

Convolute bedding occurs within F_1 facies intercalated with clay, and very fine sand from 116 cm to 124 cm from the base of the section. They occur in various sizes and shapes where crest height varies from 1 cm to 15 cm much higher than the wavelengths (2 cm to 10 cm). The thin laminations of clay generate complex and diversified patterns of convolutions within fine sand (Fig. 3A). At most places crest show flattening to give rise to mushroom head shape with wrinkles. Such structures are the consequence of load that acted upon the water bearing laminated sediments. The plastic (clay) and ductile (sand) gives the primary conditions for their formation (Dzuynski and Smith, 1963). The sandy silt sediments readjust as compared to plastic flow of clay. The mechanism involved here is gravity mass flow at a micro level due to mud flows and debris flows.

The flaser bedding is simple open undulations having crest height less than its wavelength (Fig.3B). The clayey sediment occupies the trough portion that pinches out into thin lamellae to form the structure. They stand out distinctly with a sharp contact and are different from ripples. They are usually found in fine sand (incompetent layers) overlain by clay (competent layer). At places, they lie below the convolute bedding.

The flame structures are well preserved at the interphase of clay and gravels (1164 cm from base). The contact shows concordant–discordant relationship (lens and flame Fig.3C and 3E) within clay. Gravel lens, splashing thin clay around, patches of angular fragments and thin clay dykelet and sill all together suggest sudden splash of the gravel lobe over the water saturated clay. High density of G_l facies (Boggs, 2009) could further provide mechanism for inducing emplacement of clay tongue into the overlaying gravels.

Pseudo balls (Fig. 3D) are seen well developed within clay at the interphase of sand and clay (550 cm to 592 cm from the base. The balls are broken into various sizes packed vertically and laterally within the clay. The balls are composed of laminated fine sand of different shapes (pillow hassock, kidney and ball). The sandy balls completely detached from the overlaying sand are identified as pseudo nodules.

These structures are described in literature as liquefaction, a consequence of rapid sedimentation under gravity or by induced tectonics (Sanders, 1956; Sullwold, 1959; Dzulynski, 1965; Sanders, 1965; Ricci Lucchi, 1969; Lowe, 1976; Allen, 1977; Leppard, 1978; Hein, 1982; Stromberg and Bluck, 1998; Moretti et al. 2001). In the Spituk sequence, the described liquefaction structures are observed within a sequence of 1282 cm from the base, below 120 cm thick gravel unit (debris flow). The structures are recorded at both gravel – clay and sand-clay interphase as well as within the sand and clay facies. However, it is remarkabe that such structures are absent above the gravel unit (D1, Fig. 4). The distictive local confinment of structures indicate role of gravity and / or seismic triggers operative during the post depositonal period.

PARAGLACIAL PROCESSES

The Quaternary deposits at the high altitude, cold and arid climate of Ladakh Himalaya has preserved both overall geometry of sediment units as well as primary and secondary structures within the sediment unit at several locations giving an ample opportunity for a field base researcher to resolve paraglacial process acting within the valley in past and establish their linkage to present day processes. In the proposed model for Spituk sequence, we integrate sedimentological records and propose three distinct phases of aggradation namely Last Glacial Phase -1(LGP1), Last Glacial Phase-2 (LGP2) and Younger Unconsolidated Sequence (YUS).

Last Glacial Phase - 1

The sediment sequence of LGP1 occurs below the gravel unit. Overall the sequence comprises of intercalation of fine S_m and F_m facies. The S_m facies had aggraded in three episodic aeolian domain. The lower and upper sediment units are well developed, whereas the intermediate unit is thinner. In the present landscape, the most common feature in the Leh valley is the blanket of fine sediment covering Ladakh hill Range. Such landscape in the Leh valley is a consequence of katabatic winds generated under local dynamics. Further the presence of lamellae of a medium to large flakes of muscovite in the sand at the base of Spituk sequence (0 to 76 cm) suggests that sand is transported for short distance from moraines or glacial wash surface and relocated in the forefront of Ladakh hill Range or over their hill slopes. At the lower part of the sequence S_m facies shows flaser bedding and convolute structures. Intercalation of S_m facies with thin relatively coarser facies (graded at places) is pronounced in upper sediment unit. These units represent slope wash from Ladakh granites over the aeolian sediments.

The F_m facies shows sharp contact with underlying and overlaying S_m facies. F_m facies are the mud flows that were derived from the Ladakh granites along the glacial melt water during the deglaciating phase in LGP1. The mudflows on an average are 120 cm thick showing massive character. Four mudflow phases are recorded in the Spituk sequence during LGP1 of which the earliest is recorded as a lens within sand at 90 cm. A local ponding of glacial melt water is inferred based on F_l facies (350 cm to 450 cm) capped by glacial facies that occurs as lenses. F_m records pseudo balls within the upper portion of F_m facies at interphase of S_m and F_m.

The G_l facies unit shows sharp, irregular contact with underlying F_m facies (depth 1164 cm to 1282 cm) and gradational contact with overlaying S_m facies. The F_m - G_l facies contact preserves mega structures (gravel lens enveloped by clay) and macro structures (flame structure). At places the contact show patches with amalgamation of F_m and G_l facies. The clasts within the gravel facies are elongated, angular, platy and imbricated together giving lamellar structure across 120 cm thick facies. Furthermore, the clasts and matrix composition do not belong to the Ladakh granites, but are comparable with meta-sedimentaries exposed over Zanskar Range. The field mapping over alluvial fans developed in forefront of Zanskar Range, south of Spituk across River Indus in the Leh valley has revealed exposures of G_l facies as residual ridges over the surfaces of alluvial fans. The above records suggest G_l facies exposed within the Spituk section is the extension of a debris flow originated from Zanskar Range extended northerly abutting along Ladakh Range. At Spituk the debris flow along the margins (towards hill range) shows 20° northerly dip that flattens easterly into the section. The debris flow event marks the end of LGP1.

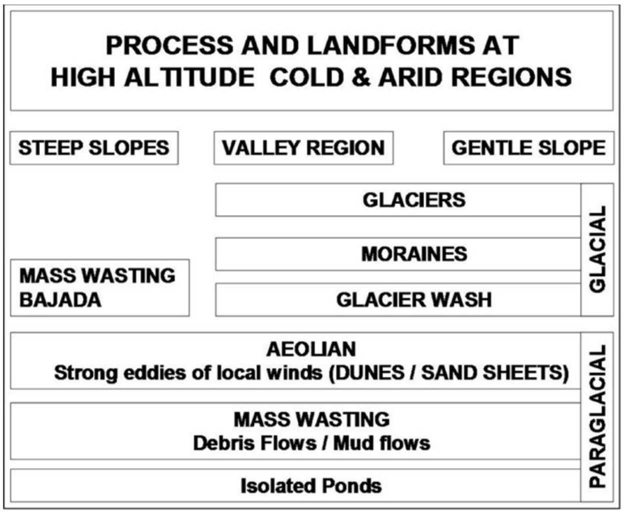

Fig.5. Flow chart explaining Paraglacial Processes in the Leh valley.

Last Glacial Phase - 2

The LGP2 marks the aggradation after the debris flow. A gradational contact between G_l facies and S_m facies signifies slope wash processes. The aeolian activity got reinvigorated followed by mudflow events. The oxidation bands within the F_m suggest time lapse between two mudflows or mudflow phases. We identify about nine bands within 1282 cm and 2796 cm. The mud flow units are on an average 120 cm thick and massive in nature. F_l facies between 1968 cm to 2122 cm represents the second phase of ponding within Spituk sequence. The laminated clay captures seasonal drying up of lake. G_l facies (from depth 2356 cm to 2404 cm) represents a second debris flow event, where the lobe is relatively thinner (48 cm thick).

Younger Unconsolidated Sequence (YUS)

Unconsolidated younger sandy sequence (1050 cm thick) is accreting over the upper slope of Ladakh hills detached from the main Spituk sequence. The sequence shows both S_m and F_m facies. A hard pan of F_m facies (silty-clayey unit; 50 cm thick) sandwich between two aeolian F_m facies namely the fine sand (0-450 cm) and silty fine sand (500 cm - 1050 cm). The S_m facies represents ongoing aggradation of sand dune and sand sheets, whereas F_m facies (silty-clayey facies) reflects the water laden with fine sediment lobe triggered during the out burst of rains (flash floods) in the recent past.

CONCLUSIONS

The sedimentological studies on Spituk sequence show an intricate relationship of paraglacial processes during LLG (Fig.4 and 5). The sequence suggests building up of dunes and sand sheets at foothills and hill slopes of Ladakh hill Range, deglaciation triggered mudflows from Ladakh granites that flowed over the dunal / sand sheet surface, debris flow comprising imbricated gravels comprising of Zanskar meta-sediments belonging to Zanskar Range, and two phases of temporal ponding as evidenced by laminated clay (Fig. 4-I). Further the paraglacial processes during LLG are comparable with YUS accreted over the upper slope of Ladakh hills above the Spituk sequence linking the continuity of paraglacial processes with the difference of rainwater triggered mudflow instead of glacial melt water. Finally, the catastrophic event that took place on 6th August 2010 in the Leh valley in response to cloud burst (Juyal, 2010) where water laden with fine sediment swept into the lower slopes of Ladakh Range at different locations in the Leh valley further suggest processes similar to upper sequence at Spituk in the Leh valley. Our detailed field studies and interpretation of sedimentary facies are at variance with the earlier works that had attributed the presence of thick clayey-silty-sandy sequence in the Leh valley as relict lake deposits that were formed due to tectonic blockage (Phartiyal et al. 2005) and convolution to the paleoseismic activity (Phartiyal and Sharma, 2009).

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