Post-glacial landform evolution in the middle Satluj River valley, India: Implications towards understanding the climate tectonic interactions

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Late Quaternary landform evolution in monsoon-dominated middle Satluj valley is reconstructed using the fragmentary records of fluvial terraces, alluvial fans, debris flows, paleo-flood deposits, and epigenetic gorges. Based on detailed field mapping, alluvial stratigraphy, sedimentology and optical chronology, two phases of fluvial aggradations are identified. The older aggradation event dated between ~13 and 11 ka (early-Holocene), occurred in the pre-existing topography carved by multiple events of erosion and incision. Climatically, the event corresponds to the post-glacial strengthened Indian summer monsoon (ISM). The younger aggradation event dated between ~5 and 0.4 ka (mid- to late-Holocene), was during the declining phase of ISM. The terrain witnessed high magnitude floods during transitional climate (~6.5–7 ka). The fluvial sedimentation was punctuated by short-lived debris flows and alluvial fans during the LGM (weak ISM), early to mid-Holocene transition climate and mid- to late-Holocene declining ISM. Based on the terrace morphology, an event of relatively enhanced surface uplift is inferred after late Holocene. The present study suggests that post-glacial landforms in the middle Satluj valley owe their genesis to the interplay between the climate variability and local/regional tectonic interactions.

1. Introduction

The Indian summer monsoon (ISM) is considered to have profound control on earth surface processes and landscape development in monsoon-dominated Southern Mountain Front (SMF), located to the south of Main Central Thrust (MCT) in the Himalaya. The terrain experiences accelerated erosion due to a combination of focussed high intensity rainfall and seismicity (Hancock and Anderson 2002; Thiede *et al.* 2004; Bookhagen *et al.* 2005; Wobus *et al.* 2005; Clift *et al.* 2012). Himalayan fluvial systems show a strong relationship between ISM and fluvial dynamics as ~80% of the annual flow is discharged during ISM along with most of the

sediment production and transportation (Goodbred 2003; Wulf *et al.* 2012). The monsoon intensity controls erosive potential and carrying capacity of the fluvial systems by influencing the discharge and hence, the stream power.

Though not unanimously, it is suggested that fluvial aggradation occurs during wetter climate due to enhanced sediment flux whereas, incision is facilitated during reduced sediment supply in drier climate (Bogaart and Balen 2000; Pratt *et al.* 2002; Juyal *et al.* 2010; Chaudhary *et al.* 2015). Increased monsoonal precipitation also heightens the pore pressure causing slope failures and activates processes like landslides, debris flows, and/or alluvial fans (Schmidt and Montgomery 1995;

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Vandenbergh 1995; Pratt *et al.* 2002; Attal and Lave 2006) along with the mobilization of glaciogenic sediments eventually causing valley floor aggradation (Blöthe and Korup 2013). Whereas, incision begins once the sediment flux decreases and stream power increases due to continued bedrock uplift in the Himalaya (Pratt-Sitaula *et al.* 2004; Bookhagen *et al.* 2006). Contrary to this, evidence from upper Ganga valley suggests that phases of valley-fills were associated with periods of weak monsoons such as the Last Glacial Maximum (LGM) and the Younger Dryas (YD) whereas, incision occurred during the strengthened monsoon (Srivastava *et al.* 2008; Ray and Srivastava 2010). Glaciers, being potent erosive agents, control sediment supply in the Himalaya. A recent study demonstrates that compared to western and eastern Himalaya, aggressive fluvial erosion in central Himalaya, limits the amount of glaciogenic sediments sequestered in relict glaciated valleys (Blöthe and Korup 2013). Implying that in the central Himalaya, appreciable mobilization and hence contribution towards the valley-fill aggradation would have occurred during periods of deglaciation (Benn and Owen 1998; Juyal *et al.* 2010). Extreme events like debris flows, landslides, and floods in the Himalaya are known to limit the relief (Barnard *et al.* 2001; Korup *et al.* 2010). Being potent erosive agents, in a non-glaciated terrain like middle Satluj valley extreme events shape the landscape besides augmenting sediment supply into river valleys (Pearce and Watson 1983; Griffiths and Webb 2004; Lancaster and Grant McKoy 2006; Anderson *et al.* 2015). The sediment supply is often in surges and is enhanced especially during catastrophic flash floods which causes incision and erosion of the landforms besides modifying the channel morphology (Eaton and Lapointe 2001; Baker 2002; Waitt 2002; Kale 2003, 2007).

Evidences from the Indian subcontinent suggest considerable variability in ISM during the last 20 ka (Juyal *et al.* 2004, 2009; Sharma *et al.* 2004; Sinha *et al.* 2005). Fluvial landforms in the Himalaya have been widely investigated to understand relationship between monsoon variability and fluvial dynamics (Pratt *et al.* 2002; Pratt-Sitaula *et al.* 2004; Bookhagen *et al.* 2006; Srivastava *et al.* 2008; Juyal *et al.* 2010; Ray and Srivastava 2010). There are some studies on the genesis and climatic significance of debris flows, alluvial fans, landslides, epigenetic gorges, and paleo-flood deposits (Scheidegger 1998; Viseras *et al.* 2003; Barnard *et al.* 2004; Malamuda *et al.* 2004; Bookhagen *et al.* 2005; Suresh *et al.* 2007; Ouimet *et al.* 2008; Wasson *et al.* 2008, 2013; Zygmunt 2009, 2012; Kothyari and Juyal 2013). However, integrating the variegated landforms and providing an understanding of the response of earth surface processes to spatial

and temporal changes in climate and tectonics are scanty.

The present study is therefore, an attempt to (i) understand the causes of spatial and temporal variability in the late Quaternary landforms, (ii) to generate a preliminary model of landform evolution in the middle Satluj valley and (iii) to ascertain the role of climate and tectonics in evolution of landforms.

2. Study area

Satluj river is the largest tributary of Indus River and drains third largest catchment area in Himalaya with >80% of the river catchment located in rain shadow zone with scanty vegetation (>4000 m). In the lower reaches (<4000 m), particularly in the SMF, ISM is the major contributor to river discharge with peak flow during monsoons. The rainfall is concentrated near two orographic barriers, viz., the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT) (Bookhagen *et al.* 2006).

The present study area lies in the lesser Himalayan domain of the middle Satluj valley (31°14' 57.08"–31°14'58.82"N; 77°4'55.33"–77°7'21.87"E) with elevation ranging between 600 and 900 m (figure 1). The valley morphology alternates between wide and narrow segments between the MCT (Rampur) and Shalighat Thrust (Tattapani). Mean rainfall varies between 813 and 1280 mm of which the maximum precipitation occurs during the summer monsoon. Rampur and Sunni areas are the zones of high precipitation (Luhri Project Report 2010).

The terrain is traversed by Suketi Thrust (Jutogh Thrust) near Behna and Shalighat thrust near Tattapani. The Suketi Thrust separates phyllites from limestone and dolomite whereas, the Shalighat thrust demarcates the limestone and dolomite from shale and silt-stone (GSI 1976; Srikantia and Bhargava 1988; Thakur and Rawat 1992) (figure 1).

3. Methodology

Landform mapping is carried out using the satellite imageries followed by detailed field investigation. The imageries with datum WGS84 were geo-referenced and digitized using ArcGIS 10.2 software. In a bedrock river, valley morphology plays an important role in aggradation and incision (Grant and Swanson 1995). The spatial changes in valley morphology is ascertained using valley width (W) to depth ratio (D) which is expressed as $\alpha = WD$ (Finnegan *et al.* 2005). Tributary cross-section profiles and slope of the catchments were calculated by using ASTER GDEM–level 1B

Figure 1. Regional geological map of the middle Satluj valley (modified after GSI memoirs 1976 and Thakur and Rawat 1992). (a) Inset showing major earthquakes in the valley (modified after Wulf *et al.* 2012) and (b) recent events of Landslide Lake Outburst (LLOFs) (source: DDMA, Kinnaur; Gupta and Shah 2008; Wulf *et al.* 2012).

(Advanced Space borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (spatial resolution 30 m) in ArcGIS 10.2 software.

The spatial and lateral variability of the sedimentary sequences is documented in the field using conventional sedimentological techniques. In order to ascertain the sediment provenance, lithoclast analyses using 1×1 m grid overlays is employed on the exposed fluvial terraces.

Chronology of the sediment is obtained using Optically Stimulated Luminescence (OSL) dating technique. OSL provides the deposition age of the sediment and relies upon the premise that geological luminescence is reset to zero by daylight exposure during sediment transportation (Aitken 1998). The ages are obtained using the modified single aliquot regeneration (SAR) protocol of Murray and Wintle (2000), where contribution from feldspar is reduced by IR simulation before measuring OSL signal from quartz (Banerjee *et al.* 1999; Roberts and Wintle 2001; Zhang and Zhou 2007). Quartz is extracted through sequential pre-treatment using 10% HCl and 30% H_2O_2 to remove the carbonates

and organic carbon respectively and sieved to obtain 90–125 μm size fraction. Quartz and feldspar minerals were separated using Na-polytungstate ($\rho = 2.58 \text{ g/cm}^3$) and magnetic separation, which are etched for 80 min in 40% HF followed by 10 N HCl for 30 min to remove the outer alpha irradiated skin. The equivalent doses (D_e) were measured using modified single aliquot regeneration (double SAR) (Murray and Wintle 2000; Banerjee *et al.* 1999) protocol with preheat of 240°C for 10 sec and cut heat of 200°C . The OSL were measured at 125°C for 40 sec and prior to every OSL measurement, infrared stimulated luminescence (IRSL) were measured at 50°C for 100 sec to remove any contribution from feldspar.

4. Results

Based on morphology and sediment assemblages, five major landforms are identified. These are:

- (i) the fluvial terraces (valley-fill and strath),
- (ii) paleo-flood deposits,

- (iii) debris flows/landslide deposits,
- (iv) alluvial fans, and
- (v) relict valleys and epigenetic gorges (figure 2a and b).

Detailed description of each landform is given below.

4.1 Fluvial terraces

Fluvial terraces and landforms have been used to reconstruct the history of Quaternary climate oscillations and tectonic uplift (Starkel 2003; Bridgland and Westaway 2008; Vandenberghe 1995). In actively uplifting orogen like Himalaya, rivers are dominantly involved in incising the underlying resistant bedrock (Whipple 2004). As a result, the fluvial sequences are discontinuous and patchy (Howard et al. 1994).

In the middle Satluj valley, two phases of aggradations in the form of asymmetrically paired terraces are identified in the wider valley segments (figure 3). The flat topped topography of the fluvially aggraded surfaces is differentiated with distinct vertical offsets of ~ 80 m between older aggradation surface (terrace T2) and younger aggradation surface (terrace T1) and 5–10 m between younger aggradation surface and present day river channel. The terrace sediments overlie bevelled bedrock strath surfaces of variable thickness (figures 2b and 3). Following the definition of Bull (1991), the bevelled bedrock with alluvial thickness < 10 m are termed as strath terraces whereas, surfaces with alluvial thickness > 10 m are termed as fill terrace. Thus, older aggradation surface (T2) is classified as valley-fill terrace, whereas, the younger aggradation surface (T1) is identified as strath terrace.

Figure 2(a). Inset at the top marks the geomorphic maps (A–D) of the study area between Tattapani and Rampur showing various landforms. In maps (A–D), T2 and T1 are aggradation surfaces, DF3, DF2, and DF1 are debris flows and AF2 and AF1 are alluvial fans. The insets marked as (1–7) give the location of field photographs of various landforms (as shown in figure 2b on the next page).

Figure 2(b). Field photographs in (1a and 1b) represent older aggradation surface (T2) at Shakra with inset in (1a) showing the contact with debris flow deposits. (2) Paleo-flood deposits at Sunni overlying the younger aggradation surface (T1). Seasonal tributary stream (marked with red arrow). (3) (a and b) Bevelled bedrock at Shakra and at Tattapani respectively. (4) Epigenetic gorge at Ogli associated with younger aggradation surface (T1). (5) Undulating surface of *Ghanghar* composed of multiple debris flows (marked as (B)), with landslide deposits on the surface (marked as (A)). The distal end of the *Ghanghar* is modified into three levels of terraces (marked i, ii and iii). (6) Red dotted line marks the alluvial fan incised by Satluj River which appear as triangular facets opposite Sunni. (7) Fining upward sedimentary units of alluvial fan at Shakra.

4.1.1 Older aggradation phase (T2)

In the wider segment of the river valley, older aggradation phase with distinct tabletop topography lies at elevation ranging from 10 to 90 m above the present river channel. Terrace gravels are weak-to-moderately lithified, and at places contain landslides and debris flow/alluvial fan deposits, particularly near MCT zone (below Rampur and Sainj). Although the surface is preserved at multiple locations, below the sediment successions preserved at Shakra and Rampur are discussed (figure 4).

Shakra (31°13'56.8"N; 77°09'21.6"E): Older aggradation surface is preserved at an elevation of ~90 m from the present day river bed and can be traced laterally for ~2 km upstream. A NE–SW draining seasonal stream has incised ~34 m thick sediment succession on the right bank of Satluj River. Based on broad textural variability, six sedimentary units have been identified.

Stratigraphy: From bottom upwards (base unexposed), 10-m thick, matrix-supported, rounded and imbricated gravel grades into subrounded gravel along with decrease in clast size and increase in matrix proportion towards the upper part (unit-I). This is overlain by ~5 m thick, clast supported and moderately imbricated rounded to subrounded gravel (unit-II), which is succeeded by ~4 m thick, matrix supported, rounded to subrounded gravel, interspersed with sand lenses (unit-III). This is followed by ~4 m thick matrix supported, rounded to subrounded gravel containing impersistent sand lenses (unit-IV). Unit-V is ~4 m thick, subrounded, poorly organised, matrix supported gravel, capped by ~2 m thick moderately weathered coarse to medium sand containing discrete slope wash and gravel deposit (unit-VI). Lithoclast analysis of randomly selected 300 gravel samples indicates dominance of quartzite (57%), followed by granite (25%), slate and phyllite (17%).

Figure 3. Panoramic view of the Satluj valley around Shakra with two aggradation surfaces (valley-fills T2 and T1). A prominent bevelled strath surface overlain by debris flow towards the downstream segment is inferred as an expression of the differential movement along the inferred NW–SE trending fault (shown in red dotted line) and sense of movement is marked by the black arrows.

Depositional environment: The sedimentary architecture of older aggradation surface suggests change in sediment–water ratio caused due to fluctuating hydrological discharge during the deposition of various units. For example, the flow regime changed from steady water flows with reduced sediment–water ratio to low flow velocities and low water depths with decreased stream competency, as indicated by the imbricated and moderately sorted gravel changing to matrix dominated, crudely fining-upward lithoclast, with random orientation (Miall 1996; Reading 2009). Evidence of the increase in flow velocity with variable hydrological discharge can be inferred based on the presence of moderately imbricated clast-supported gravels of variant clast size (Smith 1986; Miall 1996; Reading 2009). The impersistent sand lenses (point bars) indicate change in the hydrological condition with short-lived high magnitude discharge followed by a prolonged low flow regime (Miall 1996; Reading 2009; Dutta *et al.* 2012); whereas, the matrix-supported gravel suggests irregular and flashy discharge with dominance of hyper-concentrated flood events (Smith 1986; Juyal *et al.* 2010). Persistent angular boulder layer

indicate activation of slope activity for a short time during the aggradation event. Lithoclasts show dominance of quartzite, granite and gneisses implying sediment contribution from the Higher Himalayan catchment.

Duttnagar ($31^{\circ}23'41.8''\text{N}$; $77^{\circ}35'03.3''\text{E}$): This section is exposed along the road upstream near Rampur and lies ~ 50 m above the river bed.

Stratigraphy: A total of six units can be distinguished. At the bottom is ~ 2.15 m thick, assorted, matrix supported, rounded to subrounded gravel (unit-I) followed by ~ 0.5 m thick, coarse to medium sand lens (unit-II). Unit-III is ~ 1.5 m thick, matrix supported, largely assorted, rounded to subrounded gravel and is succeeded by ~ 0.3 m thick, medium to fine sand layer (unit-IV). Unit-V is ~ 2.15 m thick, moderately sorted, matrix supported, rounded to subrounded gravel followed by ~ 4 m thick, coarse sand layer (unit-VI).

Depositional environment: The textural characteristics indicate fluctuating hydrological conditions which varied between high flow regime (irregular appearance of rounded to subrounded gravels) to low flow regime (point bars) (Singh *et al.* 2007). Presence of uppermost sand lens indicates

Figure 4. Stratigraphy of older aggradation surface (T2) and younger aggradation surface (T1) at different locations in the study area. Optical ages indicate that older aggradation surface (T2) formed during ~ 13 to ~ 11 ka after the Last Glacial Maximum. Note the temporal changes in the facies architecture in Rampur terrace (fluvial, debris flow alteration) signify terrain instability during strengthened ISM in the vicinity of the Main Central Thrust (MCT). The youngest aggradation surface (T1) dated to ~ 5 ka and 0.4 ka suggest deposition under declining ISM.

decline in the hydrological conditions leading to the river experienced lateral channel avulsion (Singh *et al.* 2007).

Bael ($31^{\circ}24'2.772''N$; $77^{\circ}35'41.0274''E$): On the opposite flank, asymmetrical pair of older aggradation surface of Duttanagar is present ~ 50 m above

the river bed. The fluvial succession is terminated by an alluvial fan.

Stratigraphy: Based on the textural variability, five stratigraphic units can be discerned. The low-est unit-I is ~ 2 m thick, matrix supported, assorted, subrounded to subangular gravel and

is overlain by ~ 1 m thick, subrounded boulders (unit-II). Unit-III is ~ 2 m thick, clast supported, subrounded to rounded gravels, followed by ~ 3 m thick, assorted matrix dominated subrounded to rounded gravels (unit-IV). Succeeding unit-V is ~ 1 m thick, medium to coarse sand layer, interspersed with subrounded gravel. The succession is terminated with the deposition of ~ 4 m thick, alluvial fan sequence.

Depositional environment: The temporal changes in the textural attributes suggest that the fluvial discharge fluctuates between cohesive debris flows (matrix supported, assorted, subrounded to subangular gravel) to non-cohesive persistent stream flow (clast supported subrounded to rounded gravel). Towards the upper part, deposition of sand layer indicates decline in the hydrological conditions (Reading 2009).

Rampur ($31^{\circ}26'35.52''\text{N}$; $77^{\circ}37'44.3274''\text{E}$): Around Rampur, older surface is exposed along the road on the left bank of Satluj River at an elevation of ~ 65 m above the present river bed. The ~ 20 m thick sediment succession comprises of alternating fluvial gravel mixed with debris flow/landslide deposits.

Stratigraphy: The sequence begin with deposition of ~ 3 m thick clast-supported, imbricated, subrounded fluvial gravel with discrete angular boulders (unit-I). This is followed by ~ 2 m thick, randomly oriented, angular boulders embedded in gritty matrix containing crudely fining upwards, lensoidal pebbly gritty sand (alluvial fan facies) (unit-II). Overlying this is ~ 1 m thick, rounded to subrounded, moderately sorted, matrix supported gravel (unit-III). This is followed by 0.5 m thick, angular lithoclast embedded in gritty matrix (unit-IV) and is succeeded by ~ 1 m thick, swelling and pinching, moderately sorted, matrix-supported rounded to subrounded gravel (unit-V). This is followed by ~ 0.3 m thick, angular boulders embedded in platy lithoclast dominated matrix (unit-VI). This unit is succeeded by ~ 1 m thick, rounded to subrounded, moderately sorted and imbricated, clast-supported gravel (unit-VII). Overlying this is ~ 0.5 m thick, swelling and pinching, crudely laminated, coarse to medium sand (unit-VIII). A distinct platy lithoclast dominated layer (debris flow facies) of ~ 0.5 m overlies this unit (unit-IX) which is succeeded by a massive ~ 4 m thick, crudely fining upwards, matrix supported, angular to subrounded, crudely imbricated gravel (unit-X). Finally, ~ 2 m thick, assorted, angular lithoclast embedded in gritty and sandy matrix (unit-XI) marks the termination of sedimentation at this location.

Depositional environment: The textural variability and sedimentary architecture indicate mobilization of sediments both from the upper catchment

and the surrounding valley slopes. It has been observed that such sedimentary packages are associated with overall strengthened ISM, during which mobilization of sediment occurs from nearby hill slopes due to increased pore water pressure (Miall 1996; Pratt et al. 2002).

4.1.2 Younger aggradation phase (T1)

Younger aggradation phase is widespread in the middle Satluj valley. Detailed sedimentological observations are made at Tattapani and Duttnagar (figure 4), where the aggradation surfaces appear as wide flat-topped surfaces covered with varying sediment thickness ($0-8$ m). At places, the younger surface is represented by incised bevelled bedrock up to a depth of $\sim 2-5$ m (e.g., between Tattapani and Sunni) and is covered with recent to subrecent flood sediments (figures 2b and 4).

Tattapani ($31^{\circ}14'41.8''\text{N}$; $77^{\circ}05'41.2''\text{E}$): Around Tattapani, the surface is represented by ~ 7 m thick sediment fill overlying the bevelled bedrock, which occur ~ 8 m above the present day river bed. The sediments are unconsolidated, matrix supported, relatively fresh, poorly imbricated and contain admixture of locally driven slope wash (figure 4).

Stratigraphy: A total of five stratigraphic units overlying phyllite bedrock strath can be discerned. From bottom upwards is ~ 1.25 m thick, matrix supported, rounded, imbricated gravel (unit-I), followed by ~ 1.50 m thick, poorly sorted, angular to rounded boulders embedded in gritty sand (unit-II). It is overlain by ~ 1.25 m thick, coarse sand with occasional boulders (unit-III). Overlying it is ~ 1.5 m thick, poorly sorted, angular to subrounded gravel (unit-IV) capped by 1.5 m thick, coarse to medium sand punctuated with locally derived platy phyllite lithoclast (unit-V). Lithoclast analyses show dominance of slate (30%), followed by quartzite (29%), dolomite (23%), crystalline (16%) and granite (2%).

Depositional environment: Bevelled bedrock strath underlying the fill sediment suggests lateral erosion dominated over vertical incision implying a phase of relative tectonic stability. Conceptually, strath formation requires changes in the ratio of vertical incision to lateral planation (Hancock and Anderson 2002). Further, due to the limited sediment supply from upper catchment and adjoining valley slopes, fluvial energy was utilized for the bedrock incision (Pratt et al. 2002). The hydrological conditions were fluctuating as the river environment changed from point bar to mid-channel bar as indicated by the deposition of alternating sand and sandy gravel (Singh et al. 2007).

Duttnagar ($31^{\circ}23'41.8''\text{N}$; $77^{\circ}35'03.3''\text{E}$): The ~ 8 m thick sediment succession is preserved above

the present river bed and overlies the bevelled bedrock.

Stratigraphy: The lowermost unit-I is ~1.5 m thick, matrix supported, moderately sorted gravel, followed by ~0.5 m thick, coarse to fine sand with granules (unit-II). Unit-III is ~1.5 m thick, matrix supported, moderately sorted, gravel and is overlain by ~0.5 m thick, coarse sand lens (unit-IV). This is succeeded by ~0.5 m thick, matrix supported, rounded to subrounded gravel (unit-V). This is followed by ~0.5 m thick, gritty-coarse sand lens (unit-VI). The uppermost unit-VII is ~1.5 m thick, matrix supported, moderately sorted, subrounded to rounded gravel.

Depositional environment: The facies architecture indicates fluctuating hydrological discharge with alternating mid-channel and point bar deposits. The water depth and sediment to water ratio was fluctuating as indicated by the variability in lithoclast size and intervening matrix (Miall 1996; Singh *et al.* 2007).

4.2 Debris flows (DF)

Debris flows are gravity-driven, highly concentrated mixtures of sediment and water, commonly composed of poorly sorted lithoclast, matrix supported sediment ranging in size from clay to cobbles and boulders (Jahns 1949; Fisher 1971; Pierson 1980; Major 1997; Lavigne and Suwa 2004; Leeder 2009). The texture of the lithoclast is governed by sediment provenance, distance of transportation and amount of water involved during transportation (Major 1997). In mountain areas, the deposits are usually associated with rainfall induced runoff causing failure of debris-laden slopes/landslides (Iverson *et al.* 1997). In order to generate debris flow, there should be enough weathered bedrock or colluvium wedges in catchment (Iverson *et al.* 1997; Griffiths and Webb 2004). These are usually associated with smaller catchments which receive proportionally greater amount of water during rainstorms and have steeper slopes (Costa and Fleisher 1984).

In the study area, debris flows are associated with first or second order tributary streams having catchment area <3 km² and an average slope of 0.82. The profiles of debris flow catchments show a drastic drop in gradient as it opens into the trunk stream. The lithoclasts are dominated by local lithology, comprising of dolomite and slate with subordinate quartzite. On the basis of degree of lithification/cementation and various textural properties, three major generations of debris flows are identified, and are named as DF3 (oldest) to DF1 (youngest).

4.2.1 Debris flow DF3

Oldest debris flow deposits are lithified, sub-angular to angular, crudely sorted, clast supported, with corroded edges, coated with precipitated carbonate and give a metallic sound on striking with a hammer. These are preserved around Shakra (31°14'22.60"N, 77°8'54.70"E; elevation 846 m) and Tattapani (31°14'30.1"N, 77°05'28.0"E; elevation 672 m). DF3 shows a cross-cutting relationship with older aggradation surface.

4.2.2 Debris flow DF2

Dominated by non-lithified, poorly organized, matrix supported, angular to sub-angular lithoclast, the surface of the debris flow is gullied. The DF2 either overlie older aggradation surface or show a cross-cutting relationship with it.

4.2.3 Debris flow DF1

The youngest matrix supported debris flows are non-lithified and consists of platy angular lithoclasts of phyllite, slate and dolomite. The DF1 are inset within the older DF2 and incise through older aggradation surface.

Ghanghar: 'Ghanghar' in local parlance means irregular surface topography dominated by unorganized distribution of boulders. These occur between Shakra and Sunni (figure 2b) (31°14'22.60"N, 77°8'54.70"E; elevation 846 m), as triangular-shaped debris flow deposits corresponding to DF1 and DF2, which taper out radially in the distal part. Maximum thickness of the deposit (~50 m) is observed in the central segment (figure 2b). According to a local folklore, large angular boulders on surface were transported during a historical landslide that emanated from the southern flank of Satluj River. Stratigraphically, 'Ghanghar' overlies older aggradation surface with its distal end bevelled into three terrace surfaces.

4.3 Alluvial fans (AF)

Alluvial fans are associated with second and higher order tributary streams having catchment area >3 km² and the average slope of 0.25. Morphologically, the deposits appear as fans (cones) radiating downslope from tributary valleys due to the sediment mobilization during episodic rainfall events (Blair and McPherson 1994). The fan shape morphology develops due to frequent shifting of radial channels (braiding) from the nodal point of entry to depositional basin (Bull 1997; Leeder 2009). According to Blair (1999), alluvial fans facies occur as rhythmic, gravelly coarse to

very coarse pebble layer and coarse gravelly sand couplets, with sharp bedding plain having occasional scouring at the base which is attributed to sediment laden flood events.

Deposits either show a cross-cutting relationship with older aggradation surface, or are truncated at the distal end, and thus, at places appear as vertical scars, for example, around *Randhol* (31°14'2.5" N, 77°06'33.3"E; elevation 660 m) (figure 2b). At few places such as near *Behna* (31°21'39.9"N, 77°22' 28.1"E; elevation 787 m), these extend down to the river bed. Based on morpho-stratigraphic position, sedimentary architecture and degree of weathering/lithification, two generations of alluvial fan are identified.

4.3.1 Older alluvial fan (AF2)

The AF2 deposits are matrix supported, moderately lithified, and sorted. Texturally, a crudely fining upward succession can be observed in sub-angular platy gravel interspersed with swelling and pinching silty-sand layers. The sedimentological details at Shakra are discussed below.

Shakra (31°14'13.3"N; 77°08'50.4"E; elevation 739 m): The alluvial fan is preserved on the right flank showing a cross-cutting relationship with older aggradation surface and can be traced in the upstream of a small tributary valley (~3 km²) having a slope of 0.39.

Stratigraphy: Sediments are moderately compact and facies architecture show crudely fining upward succession with imbricated sub-angular gravel layers (0.3–1 m thick) interspersed with pinching and swelling silty-sand layers (0.2–0.5 m thick). A total of six such units can be identified in a 6-m thick succession (figure 2b). The bottom-most horizon is ~0.4 m thick, silty-sand with gritty granules (unit-I). It is overlain by ~0.3 m thick, clast dominated, fining upwards, coarse, subrounded pebble layer (unit-II). Following this a ~0.5 m thick, matrix dominated, sub-angular pebble and granule layer interspersed with silty-sand lenses (unit-III). It is overlain by ~0.3 m thick, silty-sand lens with gritty granules (unit-IV). Unit-V is ~0.2 m thick, matrix supported, angular to sub-angular pebble layer. Finally, ~2 m thick, silty-sand lens with intervening angular pebble layers of ~0.2 m thick, tops the fan sequence (unit-VI).

4.3.2 Younger alluvial fan (AF1)

The sediment associated with AF1 are non-lithified, poorly sorted, clast dominated, sub-angular lithoclasts with occasional boulders embedded in silty-sand matrix. Detailed stratigraphy of the

alluvial fan exposed at Luan village is discussed below.

Luan (31°20'21.3"N, 77°26'31.6"E; elevation 888 m): Located ~40 km upstream of Shakra village, the section is exposed by a tributary stream emanating from a ~42 km² catchment area having a slope of 0.19.

Stratigraphy: The lowermost horizon contains ~0.3 m thick, gritty sand (unit-I). This is overlain by ~0.4 m thick, platy and angular lithoclast (unit-II) and is overlain by ~0.3 m thick gritty coarse sand (unit-III). Overlying this is ~0.75 m thick, angular to sub-angular pebble layer (unit-IV) which is succeeded by ~0.75 m thick, platy angular gravels (unit-V). Finally, sequence terminates with the deposition of ~4 m thick angular gravels (unit-VI).

Considering small catchment areas, both debris flows and alluvial fan sediments owe their genesis to the presence of fractured and fissile catchment lithology which is a pre-requisite for alluvial fan sedimentation (Blair and McPherson 1994; Leeder 2009). The study area is traversed with regional and local faults (MCT, Shalighat thrust, and Suketi thrust) (figure 1), as a result the local lithology is sheared. Alluvial fans which are intermediate deposits between normal stream flow and debris flow deposits (Bull 1972, 1964) resulting from hyper-concentrated flood/flow in region are spasmodically introduced into a fluvial system. However, the sedimentary facies of alluvial fan show alternate upward fining packages where, each package represents a complete cycle of high discharge coupled with its weaning phase. Usually, hiatuses in alluvial fan sedimentation are represented by pedogenized and/or weathered horizons (Tablot 1979). Absence of incipient paedogenesis in alluvial fan sediments suggest that there were insignificant breaks during alluvial fan sedimentation (Kochel 1990). This in turn may also be interpreted as deposition under short-lived episodic high precipitation events and probably associated with transient climates (McDonald *et al.* 2003).

4.4 Paleo-flood deposits

Paleo-flood deposits are used to infer the past flood magnitude, frequency, and discharge along with periods of extreme climates (Ely *et al.* 1992; Thorndycraft *et al.* 2005). Such deposits in Himalaya (from upper Ganga valley), have been used to reconstruct the past flood history spanning the last 1000 years. The studies implicated breaching of the landslide dam during intensified ISM (Srivastava *et al.* 2008; Wasson *et al.* 2008, 2013).

Paleo-flood deposits are observed either (i) proximal to the trunk river or (ii) are deposited in the tributary valleys (sheltered locations). Deposits

proximal to the trunk river channel are frequently modified by subsequent floods and thus, seldom preserve a longer flood history. Comparatively, in sheltered locations the sequences are continuous and provide a longer history of high magnitude past floods (Kochel and Baker 1982; Baker 1987, 2008). Paleo-flood sequences are built by vertical accretion successive large floods, where the stratigraphically higher flood units indicate higher associated discharges (Baker 1987). Presence of pedogenised/weathered horizons within the flood couplet indicates hiatuses between the succeeding flood events (Thomas *et al.* 2007).

Paleo-flood deposits are observed at multiple locations overlying older aggradation surface and younger aggradation surface between Rampur and Tattapani (figure 5). At *Bithal* (31°21'05.8"N; 77°28'55.7"E), *Gharyana* (31°14'39.6"N; 77°05'59.2"E), *Randhol* (31°14'59.4"N; 77°06'21.7"E) and *Sunni1* (31°14'43.6"N; 77°07'04.8"E), the deposits are associated with older aggradation surface. At *Duttnagar* (31°23'41.8"N; 77°35'03.3"E), *Tattapani* (31°14'41.8"N; 77°05'41.2"E and 31°14'48.8"N; 77°05'28.7"E), and *Sunni-2* (31°14'44.9"N; 77°07'01.0"E) flood deposits are located on younger aggradation surface.

Duttnagar: Located ~10 km downstream from Rampur (left bank of Satluj river), the deposits occur ~25 m above the river bed. The deposits overlie younger aggradation surface and laterally extend towards the valley flank. In the absence of grain size data, interpretation is based on visual observations in the field which allow identification of six flood units. The lowermost horizon is ~100 cm thick which contain 80 cm thick, planar laminated coarse sand and is overlain by 20 cm thick, sandy-clay (unit-I). This is overlain by 30 cm thick, planar cross-stratified coarse to medium sand containing dispersed calcrete and is capped by 10 cm thick, silty-sand (unit-II). The overlying 200 cm thick unit-III is dominantly coarse, planar laminated sand and is succeeded by 100 cm thick, gritty channel sand (unit-IV). A 600 cm thick, coarse to medium planar laminated sand which at places is massive and contains both nodular and bedded calcretes, is capped by a moderately rich sandy-silt dominated humus layer (unit-V). The topmost horizon is 300 cm thick, planar to massive, coarse gritty sand which eventually grades into silty-sand (unit-VI). The horizon is overlain by matrix dominated alluvial fan facies (figure 5).

Bithal: The flood deposits occur as a distal flood plain facies along the left flank of Satluj River at an elevation of ~60 m above the river bed and laterally merges with older aggradation surface. Based on sediment texture, seven sedimentary units are identified. The micaceous sand dominated succession overlies ~1 m thick, planar to cross-stratified

sand. Unit-I is divided into the lower 25 cm thick horizon, dominated by fine sand with occasional calcretes and upper 15 cm thick horizon containing dark brown silty-clay. Succeeding 35 cm thick unit-II is divided into lower 25 cm thick horizon containing massive fine sand followed by upper 10 cm thick horizon dominated by dark brown silt and clay. This is succeeded by 40 cm thick, buff coloured unit-III dominated by fine to very fine sand. Succeeding this is 115 cm thick, chocolate brown coloured unit-IV, divided into lower 80 cm thick, coarse to medium sand and upper 35 cm thick, silty-clay. This unit is incised by a local channel which is represented by assorted fluvial gravel admixed with the local angular lithoclast. The overlying unit-V is 15 cm thick, buff coloured, crudely laminated fine sand with dispersed nodular calcrete and is capped by 3 cm thick, buff coloured clay. This is succeeded by 400 cm thick, parallel laminated (rhythmic) coarse to medium sand capped by 10 cm thick dark sandy-silt (unit-VI). Overlying this is a 100 cm thick, crudely laminated coarse to medium sand capped by anthropogenically modified silty-clay (unit-VII) (figure 5).

Sunni-1: The flood deposits are preserved along the course of a northerly draining seasonal stream around ~35 m above the Satluj river bed. The mica rich sediment succession overlies cross and planar stratified angular pebbles. Based on the sediment texture and degree of weathering/pedogenesis, seven flood units are identified. The lowermost unit-I is 215 cm thick, which is differentiated into a lower 150 cm thick, coarse to medium grey sand with dispersed rhizolith, a middle 55 cm thick, fine sand and an upper 10 cm thick, fine sand with dispersed humus. The overlying 50 cm thick, unit-II is moderately weathered. In the field though no obvious fining upward gradation is observed, however, presence of bedded calcretes indicates that the sediments were exposed (during hiatus) before the onset of the subsequent flood events. This is succeeded by 70 cm thick unit-III, in which the lower 60 cm thick horizon is dominated by coarse to medium sand. The upper 10 cm thick horizon is dominated by fine sand. Overlying this is 35 cm thick unit-IV, which has a lower 30 cm thick fine sand overlain by 5 cm thick, weathered, humus rich layer. The overlying 310 cm thick unit-V is differentiated into lower 280 cm thick fine sand capped by a 30 cm thick, humus rich silty-sand. Overlying this is a 30 cm thick unit-VI, of which the lower 20 cm thick is dominated by fine sand, overlain by a 10 cm thick, humus rich silty-sand. The unit-VII is a 140 cm thick, containing dispersed calcareous nodules in the lower 50 cm and is succeeded by 150 cm thick dark to light grey massive coarse to medium sand (unit-VIII). The uppermost unit-IX is 150 cm thick massive medium to fine sand (figure 6).

Figure 5. Locations and stratigraphy of the paleo-flood deposits (inset) investigated at multiple sites in the study area. Flood unit-V dated ~ 6.5 – 6.9 ka at Duttnagar suggests that the floods in the valley pre-dated mid-Holocene and continued till late Holocene. Each flood couplet has been differentiated by pedogenised humus rich weathered horizon, except for few units at Sunni-1 (unit-II and unit-VII), Sunni-2 (unit-III), Bithal (unit-III), and Duttnagar (unit-IV), where the flood couplets are differentiated by the occurrence of bedded calcrete layer, and abrupt change in grain size from fine to coarse and/or higher concentration of calcareous nodules.

Figure 6. Field photograph and the close-ups of Sunni-1 paleo-flood deposits located at Sunni.

Sunni-2: The paleo-flood deposits of Sunni-2 are located ~100 m downstream of Sunni-1, where three micaceous rich fining upward sequences are differentiated. The lowermost unit-I is 55 cm thick, which is differentiated into 50 cm thick lower micaceous fine sand, overlain by 5 cm thick desiccated sandy-clay. The overlying 60 cm thick unit-II has lower 40 cm thick fine sand, a middle 15 cm thick, rubified weathered horizon and an upper 5 cm thick humus rich horizon. The uppermost unit-III is 160 cm thick, where lower 140 cm is dominated by faintly laminated fine sand containing dispersed calcrete nodules and rhizo-concretions (figure 5).

Interpretation: Field observations demonstrate that the deposition occurred under relatively low energy environment and each flood unit show a gradation in the grain size with uppermost flood couplet invariably dominated by relatively finer size fractions. Presence of either weathered humus rich horizons or bedded calcrete layers in the flood sequences indicate reasonable time hiatuses between the succeeding flood events. Combining the laterally distributed flood sequences in the study area, it can be suggested that Satluj River experienced at least nine major floods of increasing magnitude in the past.

4.5 Epigenetic gorges

Epigenetic gorges and associated fossil valleys are common features in a tectonically active orogen. The term 'epigenetic' refers to the secondary nature of bedrock gorges, formed due to lateral shifting of a channel by accelerated sedimentation either from landslide debris, alluvial fans or widespread fluvial aggradation (Pant 1975;

Kothyari and Juyal 2013). Formation of epigenetic gorges and associated fossil valleys relies upon the bedrock geometry and original valley configuration. Bedrock geometry affects the location and lateral mobility of incising channel, whereas original valley shape determines rates of bedrock incision (Ouimet *et al.* 2008). The morphology and sediment characteristics of epigenetic gorges can be used to ascertain the processes (climate) responsible for accelerated sedimentation, and structural (tectonics) and lithological control (if any) in their evolution (Kothyari and Juyal 2013).

Two generations of fossil valleys and associated epigenetic gorges are observed in the study area near *Ogli* village ($31^{\circ}15'45.6''\text{N}$, $77^{\circ}16'40.5''\text{E}$; elevation 751 m) (figure 2b). Fossil valleys also exist near *Tattapani* ($31^{\circ}15'15.5''\text{N}$, $77^{\circ}04'37.2''\text{E}$), *Luhri* ($31^{\circ}20'51.8''\text{N}$, $77^{\circ}27'19.2''\text{E}$), and *Behna* ($31^{\circ}20'38.6''\text{N}$, $77^{\circ}21'10.7''\text{E}$). The older fossil valley contains moderate to well sorted gravels punctuated by multiple sand bodies and texturally correspond to the major valley-fill sequences observed near Shakra (older aggradation surface). The younger fossil valley lying proximal to the present day river bed is stratigraphically equivalent to younger aggradation surface. Plugged with assorted boulders and sand with an upstream slope and separated from the present day channel by a prominent rock spur (figure 2b), it suggests that the older channel was abandoned as a result of increased sediment flux. Consequently, active channel laterally migrated in the upper reaches into the pre-existing subsidiary channel. Therefore, in accordance with the earlier observations (Kothyari and Juyal 2013; Chaudhary *et al.* 2015), the evolution of the fossil valleys and associated gorges can be

ascribed to the events of climatically induced high sediment flux.

Ages based on the weighed mean of the equivalent dose (Juyal *et al.* 2006) indicate that the older aggradation phase (T2) is dated to 13.0 ± 1 ka (Duttanagar) and 10.8 ± 1 ka (Shakra). The sediment corresponding to the younger aggradation phase (T1) at Duttanagar and Tattapani are dated between 5.2 ± 0.4 and 0.4 ± 0.0 ka, respectively. The flood plain sediments (palaeo-flood deposits) at Duttanagar are dated to 6.9 ± 0.6 and 6.5 ± 0.5 ka. Table 1 gives the radioactivity values, equivalent dose and the ages obtained.

5. Discussion

5.1 Climate variability

Fluvial dynamics is widely recognized as the primary control on style and pace of landscape evolution in areas outside the realm of glaciers. As observed in actively deforming mountain belts, rivers flowing within few meters of bedrock (Tinkler and Wohl 1998) are continuously incising with insignificant sediment storage (similar to present day Satluj River). However, considering the discontinuous records of valley-fills, alluvial fans and debris flow deposits, it can be suggested that incision was punctuated by climatically driven pulses of aggradation (Pratt-Sitaula *et al.* 2004). Based on field stratigraphy and limited optical ages, two distinct phases of aggradations are observed. The older phase of aggradation (T2), constitute a major landform in the study area. This event is dated between ~ 13 and ~ 11 ka and suggests deposition during the post-glacial revival of ISM (Sirocko *et al.* 1993; Schulz *et al.* 1998) and accords well with the textural data discussed earlier. For example, the clast-supported angular to subrounded gravel is interpreted as deposition under flashy hydrological discharge with sudden mobilisation of sediment from the upper catchment. Such abrupt sediment flux is usually associated with a shift from dry to wetter conditions (transient climate) (Moscariello *et al.* 2002, 2009 and references therein). Similar observation was also made by Suresh *et al.* (2007) from the lower Satluj valley. Following this, the sediments are represented by moderate to well rounded, imbricated gravels separated by impersistent lensoidal sand horizons (point bars) suggesting that sediment supply outpaced the fluvial transport capacity. This can either happen by the decrease in river gradient or an increase in sediment flux (Pratt-Sitaula *et al.* 2004). We tend to suggest that high sediment flux associated with the strengthening of post-glacial ISM was responsible for the older aggradation

Table 1. Details of radioactivity, dose rate (DR), equivalent dose (De) and ages obtained using the Double-SAR (single aliquot regeneration) method, where aliquots with $< 20\%$ error in De are considered. Water content is assumed as $10 \pm 5\%$ for all samples. Cosmic ray dose (CR) is calculated from Prescott and Stephan, (1982).

Sl. no.	Sample no.	Sample type and location	U (ppm)	Th (ppm)	K (%)	CR ($\mu\text{Gy/a}$)	De (Gy)	DR (Gy/ka)	Age (ka)
1.	D20S35	Paleo-flood (Duttanagar), $31^{\circ}23'42.576''\text{N}$, $77^{\circ}35'6.144''\text{E}$	2.2 ± 0.1	13.1 ± 0.7	2.1 ± 0.1	228 ± 68	23.4 ± 0.8	3.4 ± 0.2	6.9 ± 0.6
2.	D20S36	Paleo-flood (Duttanagar), $31^{\circ}23'42.576''\text{N}$, $77^{\circ}35'6.144''\text{E}$	3.4 ± 0.2	17.7 ± 0.9	2.3 ± 0.1	228 ± 68	26.7 ± 0.7	4.1 ± 0.3	6.5 ± 0.5
3.	D20S37	T1 (Duttanagar), $31^{\circ}24'11.36''\text{N}$, $77^{\circ}35'53.9''\text{E}$	2.0 ± 0.1	13.0 ± 0.7	2.1 ± 0.1	228 ± 68	17.4 ± 0.4	3.4 ± 0.2	5.2 ± 0.4
4.	D20S38	T2 (Duttanagar), $31^{\circ}24'11.36''\text{N}$, $77^{\circ}35'53.9''\text{E}$	3.8 ± 0.2	22.0 ± 1.1	1.9 ± 0.1	228 ± 68	53.8 ± 1.4	4.1 ± 0.3	13.0 ± 1
5.	S2S105	T2 (Shakra), $31^{\circ}13'55.2''\text{N}$, $77^{\circ}09'08.9''\text{E}$	0.6 ± 0.0	17.9 ± 0.9	2.9 ± 0.2	222 ± 66	44.1 ± 1.7	4.1 ± 0.3	10.8 ± 1
6.	TT1011/15	T1 (Tattapani), $31^{\circ}14'46.7''\text{N}$, $77^{\circ}05'31.9''\text{E}$	7.1 ± 0.1	23.2 ± 0.6	2.3 ± 0.0	219 ± 65	2 ± 0.04	5.2 ± 0.4	0.4 ± 0.0

phase in the middle Satluj valley. Corroborative evidences of post-glacial strengthened monsoons are well represented in various records from central Himalaya. For example, Sinha *et al.* (2005) observed consistent depleted oxygen isotope values in speleothem record from the western Himalaya during 15–13 ka. Similarly, Beukema *et al.* (2011), Juyal *et al.* (2009), and Srivastava *et al.* (2013), using major geochemical and isotopic proxies in relict lake sediments from central Himalaya suggest a gradual improvement of the ISM after LGM.

In the absence of uppermost ages for the older valley-fill, it is difficult to infer the longevity of the aggradation event. However, considering that the terraces are incised to various depths, studies suggest incision was facilitated during periods of reduced sediment flux in weak ISM (Pratt *et al.* 2002; Bookhagen *et al.* 2006; Juyal *et al.* 2010; Chaudhary *et al.* 2015). We speculate that the second aggradation phase continued beyond ~11 ka probably till early mid-Holocene (~6 ka). This seems logical considering that the palaeoflood deposits which are laterally comparable with the upper part of the older aggradation phase (discussed below) are dated to ~6.5 ka. Thereafter the ISM began to decline in Satluj valley as suggested by Bookhagen *et al.* (2006).

The middle Satluj valley experienced at least nine high magnitude floods. Presence of pedogenised/ weathered horizons associated with each flood couplet suggests variable hiatuses in the flood recurrence frequencies. Presence of mica in the flood couplets suggests that floods were triggered by the landslide dam outburst in the Higher Himalaya Crystalline zone. This accords well with the observations made by Bookhagen *et al.* (2005) that exceptionally large mass movements occurred during middle Holocene in the upper catchment of Satluj valley. Similar evidences accrued from the monsoon dominated Alaknanda valley where landslide dam bursts are implicated for multiple high magnitude floods during last 1 ka (Wasson *et al.* 2008, 2013, 2008). Optical ages of 6.9 and 6.5 ka on the flood unit-V at Duttanagar (figure 5) suggest that Satluj valley responded to unusual weather events during the early to mid-Holocene. Most importantly successive increase in flood magnitude probably indicates increase in severity of extreme weather events in the study area. However, definitive answers would await more detailed analysis of the flood sequences in the middle Satluj valley which is in progress.

The youngest aggradation phase is represented dominantly by a strath surface and suggests reduced sediment supply from the catchment area. At places local debris flows have been fluvially modified to form younger fluvial surface, while at places, older aggradation surface has been scoured

to deposit the sediments. Importantly, there is an appreciable bedrock incision (2–4 m) associated with the strath terrace which perhaps indicates relatively higher bedrock uplift after younger aggradation which is dated between ~5 and ~0.4 ka. The facies assemblages dominated by channel and point bar thus suggest frequent lateral avulsion (within the confines) of Satluj River during fluctuating hydrological conditions (Singh *et al.* 2007). The youngest debris flows and the alluvial fans overlying younger aggradation phase (<0.4 ka) can be interpreted as local slope instability caused during short-lived intensified rainfall events. The fossil valleys and associated epigenetic gorges further support till mid-Holocene, the middle Satluj valley witnessed episodic high sediment fluxes which exceeded the transport capacity of Satluj River.

The sporadic and extreme events like debris flows, floods, epigenetic gorges and alluvial fans are the sedimentological expressions and responses of the terrain to the variability in the ISM (Wasson *et al.* 2008, 2013). The sediment mobilization occur in surges both during enhanced and transient climatic conditions (Dorn 1994; McDonald *et al.* 2003; Bookhagen *et al.* 2005; Juyal *et al.* 2010). An appreciable contribution of debris flows, alluvial fans and landslides is observed in the older fluvial aggradation phase particularly around the Main Central Thrust (MCT). The landslides in upper Satluj valley are ascribed to the abnormal monsoon events (Bookhagen *et al.* 2005). However, our study indicates that the debris flows and alluvial fans are also triggered by the same mechanism. Compared to this, in the middle Satluj valley (south of MCT), these events are associated with transitional climatic conditions.

5.2 Tectonics

In a tectonically active orogen like Himalaya, crustal deformation is a continuous process. On a regional scale, crustal shortening/uplift can be assumed to be constant for different segments in Himalaya (Vance *et al.* 2003). Study in the foothills of Nepal Himalaya suggests that during the last 10 ka crustal shortening was fairly constant (Lavé and Avouac 2001). At a local scale, however, abnormal uplift in the proximity of major and minor structures can modify the river profile (Tyagi *et al.* 2009). The fluvial sediment associated with the older aggradation phase required large accommodation space. Was the accommodation space created immediately prior to the aggradation under low sediment water ratio along with tectonics (Pratt-Sitaula *et al.* 2004)? Or, alternatively, did the deposition occur in the pre-existing valley topography? Morphology of the

Figure 7. Summary diagram plotted against the (a) Guliya ice core ($\delta^{18}\text{O}$): a surrogate for the Indian summer monsoon variability (Thompson *et al.* 1997). The enriched oxygen isotopic values suggest strengthened ISM and *vice-versa*. Also shown is the temporal changes in the hydrological condition (b) Inferred Indian Summer Monsoon and (c) The geomorphic response. Accommodation space for older aggradation (~ 13 – 6.5 ka) was available in pre-existing topography. During this period shallow landslides and oldest debris flows were also generated. The major flood events, second major debris flow (DF2) and the first major alluvial fan (AF2) sedimentation occurred under fluctuating ISM after early Holocene and continued till mid-Holocene. Relatively enhanced bedrock uplift after mid-Holocene during overall declining ISM was accompanied by youngest generation of debris flows (DF1) and alluvial fans (AF1) caused due to sporadic rainfall events under transition climate. The phase continued until around the late Holocene (~ 0.4 ka).

older aggradation phase at multiple locations, viz., *Chebdi* ($31^{\circ}14'28.7''\text{N}$, $77^{\circ}12'16.5''\text{E}$); *Jaishi* ($31^{\circ}15'08.3''\text{N}$; $77^{\circ}14'57.9''\text{E}$); *Kot* ($31^{\circ}20'54.8''\text{N}$; $77^{\circ}24'58.2''\text{E}$); *Nirath* ($31^{\circ}23'15.47''\text{N}$, $77^{\circ}34'03.9''\text{E}$); and *Nainj* ($31^{\circ}20'14.5''\text{N}$, $77^{\circ}20'33.3''\text{E}$) show that the deposits are confined by the vertically incised valley flanks representing relict channel topography. Thus, in the central part of the relict aggraded channel there is no bedrock incision, instead the river flowed through the older aggraded sediments. The lateral correlation of the sediments corresponding to the older aggradation phase indicates existence of a broad sinuous course. In view of this, we speculate that the pre-existing valley topography that existed much before the older aggradation phase and probably created by multiple events of incision/uplift, provided the accommodation space for the older aggradation phase. Following the aggradation, the incision seems to occur during the weakened ISM, thus, can be attributed to the reduced sediment supply. An expression of relative displacement (differential uplift?) is

observed near Shakra village where the older aggradation (T2) is juxtaposed by a laterally persistent strath terrace and associated gorge in downstream (figure 3). Such channel morphology is ascribed to when a river crosses a fault (Whittaker *et al.* 2007). This could be a localized expression of tectonic instability after the older aggradation phase in the study area. Nevertheless, the morphology of the younger aggradation phase (T1) which is dominated by the strath surface can be interpreted as evidence of relatively enhanced bedrock uplift after ~ 0.4 ka (figure 7).

6. Conclusions

This study based on detailed field mapping, stratigraphy, sedimentology and limited optical chronology allows us to draw the following broad inferences.

The monsoon dominated middle Satluj valley responded to a combination of ISM variability and

tectonics during the post-Last Glacial Maximum (LGM). The older aggradation phase is ascribed to the post-LGM strengthening of ISM.

Although preliminarily in nature, our observations suggest that the older aggradation was accommodated in the pre-existing valley topography that was carved by multiple events of incision and uplift.

The valley experienced major floods caused due to breaching of landslide dams in upper catchment (Higher Himalayan Crystalline). As suggested by Bookhagen *et al.* (2005), we ascribe the formation of landslide dams to the abnormal monsoon events during the early to middle Holocene period. Successive higher magnitude flood events are ascribed to increased severity of extreme rainfall events and associated landslide dam outbursts.

To the south of MCT, incision of valley-fill sediments (T2) and the reactivation of tributary valleys and hillslope processes causing debris flow and alluvial fan sedimentation occurred during the weakened ISM (post-LGM and ~6.5 ka) which is in contrast to the upper Satluj valley where these processes were activated during abnormal monsoon years (Bookhagen *et al.* 2005). Younger aggradation surface (dated between ~5 and ~0.4 ka) development is ascribed to the weak and fluctuating ISM, with considerable contribution from locally mobilised sediments. It appears that the terrain experienced relatively enhanced bedrock uplift (incision) after ~0.4 ka.

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