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Sediment storage and release from Himalayan piggyback basins and implications for downstream river morphology and evolution

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Abstract

Piggyback basins developed at the mountain fronts of collisional orogens can act as important, and transient, sediment stores along major river systems. It is not clear, however, how the storage and release of sediment in piggyback basins affects the sediment flux and evolution of downstream river reaches. Here we investigate the timing and volumes of sediment storage and release in the Dehra Dun, a piggyback basin developed along the Himalayan mountain front in northwestern India. Based on OSL dating, we show evidence for three major phases of aggradation in the dun, bracketed at ~41-33 ka, 34-21 ka, and 23-10 ka, each accompanied by progradation of sediment fans into the dun. Each of these phases was followed by backfilling and (apparently) rapid fan-head incision, leading to abandonment of the depositional unit and a basinward shift of the active depocentre. Excavation of dun sediment after the second and third phases of aggradation produced time-averaged sediment discharges that were ~1-2% of the modern suspended-sediment discharges of the Ganga and Yamuna rivers that traverse the margins of the dun; this sediment is derived from catchment areas that together comprise 1.5% of the drainage area of these rivers. Comparison of the timing of dun storage and release with upstream and downstream records of incision and aggradation in the Ganga show that sediment storage in the dun generally coincides with periods of widespread hinterland aggradation but that late stages of dun aggradation, and especially times of dun sediment excavation, coincide with major periods of sediment export to the Ganga Basin. The dun thus acts

to amplify temporal variations in hinterland sediment supply or transport capacity. This conceptual model appears to explain morphological features of other major river systems along the Himalayan front, including the Gandak and Kosi Rivers, and may be important for understanding sediment flux variations in other collisional mountain belts.

Keywords

Himalayas, Ganga River basin, sediment transport, sediment storage, erosion, intermontane valley

Introduction

Piggyback basins are ubiquitous features of foreland basin systems (Ori and Friend, 1984; DeCelles and Giles, 1996), and serve as links between hinterland areas of sediment production and foreland depocentres. While such basins may be essentially passive features that fill with sediment and then are buried as the fold and thrust belt migrates into the foreland (e.g., DeCelles and Horton, 2003), several studies have shown that piggyback basins may be highly dynamic environments on shorter time scales (10^3 – 10^4 years), with repeated cycles of aggradation and incision (e.g., DeCelles et al., 1991; Hilley and Strecker, 2005). Temporary trapping and release of sediment in piggyback basins or other intermediate sediment stores is thus a critical control on long-term sediment efflux, not least because such storage can buffer the system against changes in external forcing conditions (Castelltort and van den Driessche, 2003).

It has long been known that intermediate storage can account for a large proportion of the sediment produced in upstream parts of a catchment (e.g., Meade, 1982; Walling, 1983; Phillips, 1991; Blum and Törnqvist, 2000; Bloethe and Korup, 2013), but our understanding of the downstream impacts of sediment storage and release remains relatively limited. These impacts have been investigated in analogue experiments (e.g., Kim et al., 2006; Powell et al., 2012) and numerical simulations (Paola, 2000; Allen and Densmore, 2000; Carretier and Lucazeau, 2005), or at relatively small spatial scales (e.g., Lane and Richards, 1997; Malmon et al., 2005; Lancaster and Casebeer, 2007), but field examples in large river systems are comparatively scarce (e.g., Clift, 2006).

Here, we begin to address this problem by focusing on sediment storage and release along the Himalayan mountain front, portions of which are characterized by frontal piggyback basins or 'duns' along individual segments of the mountain front (Nakata, 1972; Raiverman, 1997; Powers et al., 1998; Thakur and Pandey, 2004; Thakur et al., 2007). These duns are formed in response to marked along-strike variations in the geometry and distribution of slip on the Himalayan Frontal Thrust (HFT) system (Nakata, 1989; Yeats et al., 1992; Wesnousky et al., 1999; Thakur, 2013). Some of the main Himalayan river systems – including the Yamuna, Ganga, and Gandak – flow across these duns before debouching into the foreland basin, whereas others – including the Ghaghra, Karnali, and Kosi – flow directly into the foreland (Fig. 1). This region thus provides an opportunity to assess the rates and timing of sediment storage and evacuation from the duns, the role of duns in setting sediment supply to the foreland, and the effects of the presence or absence of a dun on the geomorphology of large Himalayan river systems.

We focus initially on the Dehra Dun in northwestern India, which is traversed by two of the largest rivers of the Ganga Basin, the Yamuna and Ganga rivers. We use this example to examine the degree to which proximal piggyback basins can influence the timing and magnitude of sediment discharge in a large river system. Ray and Srivastava (2010) provided a comprehensive review of the evidence for aggradation and incision in the mountain hinterland of the Ganga Basin upstream of the Dehra dun, and linked this with downstream records of sediment accumulation and incision in the Ganga plain. Our work fills the gap between these regions, and allows us to evaluate the role of the dun in the Ganga sediment routing system. We combine new and published data on the geometry and age of sedimentary deposits in the dun into a conceptual model of dun evolution since ~40 ka. We use this model to estimate the volumes of sediment that have been stored and released over this time period, and to compare events in the dun with episodes of aggradation and incision that have been documented for the Ganga and Yamuna rivers in the hinterland (Ray and Srivastava, 2010) and foreland (e.g., Gibling et al., 2011; Roy et al., 2012). Finally, we evaluate the conceptual model against observations from the Gandak and Kosi Rivers, and show that fundamental differences in the foreland morphology and evolution of foreland rivers can be linked to the presence or absence of a dun sediment store.

Study area

Setting

The development of duns along some, but not all, segments of the Himalayan mountain front (Fig. 1) has been linked to a number of different factors, including structures on the underlying Indian lithosphere (Yeats and Lillie, 1991; Raiverman et al., 1993) or lateral variations in orogenic wedge properties (Mugnier et al., 1999a, 1999b), leading to differences in the extent to which strands of the HFT have propagated into the foreland. For example, Mugnier et al. (1999b) showed that thicker Siwalik deposits and a slightly steeper (2°) dip of the basal detachment would produce early propagation of the thrust front and thus large stable wedge-top or piggyback basins. They suggested that the Dehra and Chitwan duns might form via a similar mechanism. More generally, Leturmy et al. (2000) argued that erosion or deposition of the wedge could promote or suppress piggyback basin development, by controlling the timing and propagation of faulting into the foreland. Simpson (2010), in contrast, demonstrated that the strength of the basal detachment, and to a lesser extent the strength of the cover sequence, controls the sequence and propagation of deformation. A frictional (high-viscosity) detachment leads to regular propagation of the wedge and localization of deformation at the thrust front. A weak detachment, in contrast, leads to rapid propagation of slip into the foreland and formation of wedge-top basins, but activity on individual faults is episodic and deformation shifts frequently from the thrust front to structures in the hinterland. What is important for our purposes is that dun development is spatially limited along the Himalayan front, and affects only some of the major Himalayan rivers (Fig. 1).

The Dehra Dun

The Dehra Dun (Fig. 2), in Uttarakhand state, northern India, has developed in response to folding of the Mohand anticline over a ramp in the HFT, which has remained active into the Holocene (Wesnousky et al., 1999). The anticline is an upright, asymmetric fold composed of Middle and Upper Siwalik sandstones and conglomerates of Miocene to Pleistocene age; the onset of folding and dun formation is constrained to after ~500 ka but before 220 ka (Thakur et al., 2007; Barnes et al., 2011). Accommodation generation in the dun is controlled by slip on both the HFT and the Main Boundary Thrust (MBT) (Fig. 2).

The Yamuna and Ganga rivers traverse the lateral margins of the dun before entering the foreland, and set base level for the channels that drain the dun. Thus, any storage or erosion of sediments in the dun has a direct impact on the sediment discharge of the Yamuna and Ganga rivers at the HFT. A complex late-Quaternary history of aggradation and erosion within the dun is recorded by sequences of fill terraces along both the Yamuna (Dutta et al., 2012) and Ganga (Sinha et al., 2010). The Yamuna terraces in the footwall of the MBT (Fig. 2) record major phases of aggradation from >37 to 24 ka and >15 to 12 ka, each followed by incision and terrace abandonment, along with several minor aggradation and incision cycles within the Holocene (Dutta et al., 2012). The Ganga terraces span a shorter time period, but also record aggradation to ~11 ka followed by incision from 11-9.7 ka (Sinha et al., 2010). These records are matched by evidence from fill terraces at a number of upstream sites in the Ganga Basin, which broadly indicate phases of aggradation from ~49-25 ka and ~18-11 ka, with incision beginning soon after 11 ka (Srivastava et al., 2008; Ray and Srivastava, 2010).

Sediment supply from the Ganga and Yamuna rivers at the Himalayan mountain front, or alternatively the hinterland erosion rates of these basins, has been quantified over several different time scales. Jha et al. (1988) used measurements of suspended sediment for a single year to estimate a present-day suspended sediment discharge for the Yamuna of 18 Mt/yr at Tajewala, just downstream of the HFT; assuming a solid grain density of 2650 kg/m^3, this corresponds to a volumetric discharge of 6.8 Mm^3/yr. Lupker et al. (2012) used cosmogenic radionuclide analysis of a bed sample from Paonta, within the dun, to estimate a total sediment discharge of 13±5 Mt/yr or 5.3 Mm^3/yr. Values for the Ganga vary more widely. Reported present-day discharge estimates from suspended sediment measurements at Rishikesh or Haridwar are 13-14 Mt/yr (Abbas and Subramian, 1984; Sinha et al., 2005; Chakrapani and Saini, 2009), and Wasson (2003) cited a value of 33 Mt/yr on the basis of Galy and France-Lanord (2001), but further supporting analysis is not available for this estimate. These correspond to volumetric discharges of ~5 Mm^3/yr. In contrast, Vance et al. (2003) and Lupker et al. (2012) used cosmogenic radionuclides to derive longer-term Ganga sediment discharge estimates of 20-30 Mm^3/yr (or 65-67 Mt/yr) and 52 Mm^3/yr (or 139±37 Mt/yr), respectively.

Sediment is also supplied to the dun, and thus to the Yamuna and Ganga rivers, by a set of catchments that drain the hanging wall of the MBT (Fig. 2), with a total area of about 503 km^2 upstream of the MBT; this represents about 1.5% of the total catchment area of the Yamuna and Ganga upstream of the HFT (34,300 km^2). These dun catchments feed a set of coalescing stream-flow and debris-flow fans that have deposited a thick sequence of sediment, ranging from silts to cobble conglomerates, atop Upper Siwalik bedrock

(Singh et al., 2001). At the northern edge of the dun, Middle Siwalik rocks are folded and thrust over the fan deposits (Thakur et al., 2007), while the youngest generation of fan deposits have backfilled paleovalleys eroded into the hanging walls of the Santaugarh fault and the MBT (Fig 2). Nossin (1971) and Nakata (1972) mapped the sedimentary fill of the Dehra Dun, and classified it into several discrete fan and terrace units. Singh et al. (2001) extended this classification and identified three main depositional fans within the dun; from west to east, these are the Donga, Dehradun, and Bhogpur fans (Fig. 2) and we adopt this nomenclature here.

Methods

To assess sediment volumes and storage in the dun, we prepared geomorphic maps of the central Dehra Dun showing the major fan surfaces and fill terraces, using LISS-3 satellite images (23.5 m spatial resolution) from 2004 and the CGIAR-CSI Shuttle Radar Topography Mission version 4 digital elevation model (DEM), with a cell size of 90 m. False-colour composite images were prepared from the LISS-3 data, using near-infrared, red, and green bands. Identification and correlation of different fan and terrace surfaces was done on the basis of the false-colour composite images, a Normal Difference Vegetation Index (NDVI) image created from the LISS-3 data, the DEM, and a gradient raster created from the DEM. We also obtained a total of 118 borehole logs from Uttar Pradesh Jal Nigam for locations within the dun in order to map the major lithological transitions and establish minimum fan deposit thicknesses. In addition, field data on elevations of the Quaternary surfaces and exposed Siwalik bedrock were collected using handheld GPS and 1:50,000 Survey of India topographic maps. Stratigraphic logs were prepared to characterise the sub-surface deposits of most of the mapped geomorphic surfaces. We collected six samples for optically-stimulated luminescence (OSL) dating from beds of fine to very fine sand and coarse silt within the fan deposits (see Supplementary Material for methods and analytical procedures). These data were integrated with the geomorphic maps and with existing OSL dates (Singh et al., 2001; Thakur et al., 2007) to constrain the timing and geometry of major aggradational episodes in the dun.

To assess the contribution of dun sediment storage and evacuation to the Yamuna and Ganga Rivers, we estimated the volumes of the major depositional units, and of the material that was removed from each unit by incision. To do this, we correlated remnant depositional surfaces across the fans using elevation, surface morphology and image texture, vegetation, and available OSL age constraints. We then interpolated smooth surfaces across the correlated remnants using polynomial functions in ArcGIS. These surfaces were constrained to include the mapped remnants, and were truncated where they dipped below older, higher topography (either bedrock or older depositional units); we also ensured that the interpolated surfaces were bounded by the MBT and by the present-day boundaries of the fans. By subtracting the interpolated surfaces from the present-day topography, we estimated the depth and spatial pattern of post-abandonment incision into each surface, which can be summed to yield the volume of sediment that was removed during abandonment. We compared the results of interpolations using third, fourth, and fifth-order polynomials, and found that the estimated volumes differed by $\leq 5\%$, so only results using fourth-order polynomial interpolations are reported below. We also checked our incision patterns against minimum sediment fill thicknesses from the borehole logs, to ensure that the estimates were geologically reasonable and did not exceed the present-day sediment thicknesses along the valley floors. The volume estimates assume that previous episodes of incision did not lower thalweg elevations in the dun below present-day elevations, and are thus minima; however, we lack any evidence of the depth of incision or clear subsurface distinctions between different depositional units, so at present this limitation cannot be addressed. Finally, we combined our volumes of sediment removal with the time constraints provided by the OSL dates to estimate average sediment discharges out of the dun.

Results

Geometry and timing of depositional units

Because the detailed stratigraphy of the sedimentary fill in the Dehra Dun has been described by Singh et al. (2001), we focus here on the geometry and ages of the deposits. We concentrate on the most volumetrically important depositional units that comprise the Donga, Dehradun, and Bhogpur fans, and ignore both the younger, more spatially-restricted fill terrace deposits along streams in the dun (Nakata,

1972) and the older deposits in the hanging wall of the Santaugarh fault (the 'Dissected Siwalik Hills' of Singh et al., 2001), which clearly pre-date the formation of the present-day dun. From oldest to youngest, these key depositional units (Fig. 2) are here termed (1) the 'isolated hills' unit, which corresponds to the 'Pedimented Siwalik Hills' geomorphic unit and depositional unit GD-I of Singh et al. (2001), and unit A of Thakur et al. (2007); (2) the 'proximal fan' unit, which corresponds to the Piedmont geomorphic unit and depositional unit GD-II of Singh et al. (2001), and unit B of Thakur et al. (2007); and (3) the 'distal fan' unit, which corresponds to depositional units GD-III and GD-IV of Singh et al. (2001), and unit C of Thakur et al. (2007).

The isolated hills unit is composed of massive, clast- or matrix-supported pebble to boulder conglomerates (Singh et al., 2001). These deposits form rounded hills that reach elevations of 620-880 m that flank the major dun rivers (Sitla Rao, the Suarna River, and the Asan River) in the western and central parts of the dun (Fig. 2, 3). Exposure of this unit is limited to a narrow belt, 2-4 km wide, in the immediate footwall of the Santaugarh fault. The exposed thickness is at least 90 m, but the actual thickness of this unit is unknown. Singh et al. (2001) inferred a basal age of ~50 ka based on OSL ages of 40.3±3.9 and 38.3±9.4 ka near the base of this unit on the Dehradun fan, and also reported an age of 29.5±5.0 ka from the Donga fan, although its position is not certain. Thakur et al. (2007) reported OSL ages of 35.40±7.30 and 33.57±4.73 ka from this unit, both from proximal parts of the Donga fan. Our sample IH/2 yields an age of 41.3±1.2 ka from 2.8 m below the top of an exposure of isolated hills sediment on the east flank of the Suarna River valley (Fig. 2, Table 1).

The proximal fan unit consists of massive, clast- or matrix-supported pebble to boulder conglomerates with some interbedded sand layers (Singh et al., 2001; Thakur et al., 2007). The unit underlies smooth, south-dipping near-planar fan surfaces (Fig. 3A) that cover most of the proximal areas of the Donga, Dehradun, and Bhogpur fans (Fig. 2), and extend 5-10 km downstream of the Santaugarh fault (for the Donga and Dehradun fans) or the MBT (for the Bhogpur fan). These fan surfaces have typical surface slopes (averaged over 270 m windows) of 2-4 degrees, and appear to onlap onto deposits of the underlying isolated hills in the footwall of the Santaugarh fault. Importantly, the surfaces and their underlying deposits can be traced continuously up to 1.5 km upstream of the Santaugarh fault along several of the major dun drainages, including the Koti Nadi (Fig. 3A) and the Suarna River. In the Santaugarh fault hanging wall, deposits of the proximal fan unit lie unconformably atop steeply-dipping to overturned Middle Siwalik sandstones (Thakur et al., 2007) and the isolated hills unit, but our observations show that there is no evidence of offset or deformation across the Santaugarh fault. Exposures along both the Koti Nadi and Suarna River indicate that proximal fan sediments were deposited in steep-walled paleovalleys that were incised at least 70-75 m into the underlying deposits of the isolated hills (Fig. 3B). The axes and orientations of these paleovalleys are slightly offset from those of the modern river drainage system, which means that their width cannot be observed directly.

Thakur et al. (2007) obtained an OSL age of 20.5±1.8 ka from their unit B, and correlated this unit with an age of 29.4±1.7 ka from the west flank of the Suarna River valley (Singh et al., 2001), although the basis for this correlation is not clear. We obtained an OSL age of 21.2±1.3 ka from sample FS3.1 10 m below the fan surface near the Santaugarh fault, on the east flank of the Suarna River valley (Fig. 2, Table 1).

The distal fan unit consists of well-bedded pebble to cobble conglomerates, with some discontinuous layers of sand and silt (Singh et al., 2001; Thakur et al., 2007). The unit underlies widespread, smooth, near-planar fan surfaces that occur south of, and appear to onlap against, surfaces of the proximal fan and isolated hills units. These surfaces form the southern, distal expanses of the Donga and Dehradun fans, with typical surface slopes (averaged over 270 m windows) of 0.2 to 1.1 degrees. Singh et al. (2001) reported OSL ages of 22.8±2.3 and 20.3±7.5 ka from near the base of this unit, and ages of 9.4±0.6 and 10.7±2.4 ka near the top, while Thakur et al. (2007) reported ages of 13.2±1.1 and 17.1±2.0 ka from the distal Donga fan. Likewise, we obtained an OSL age of 14.4±0.6 ka from sample FS2.2 on the west flank of the Sitla Rao, 5 m below the distal fan surface (Fig. 2, Table 1). Two other samples, collected from east of the Suarna River (Fig. 2), yielded OSL ages of 16.2±1.4 ka (sample LIS-TOP) and 13.8±0.9 ka (sample FS2.1) (Table 1). A final sample (FS1.1) yielded an OSL age of 33.8±3.2 ka from 3 m below the fan surface (Fig. 2, Table 1), which is substantially older than any other reported age for the distal fan unit. Given its position near the southern limit of the dun depositional units, and the lack of a clear textural difference between the different units, it is possible that this sample was collected from an isolated distal exposure of the proximal fan unit, but at present we cannot resolve this apparent discrepancy.

Erosional volume estimates

Because the original depositional surface of the isolated hills unit is not preserved, we cannot estimate the volume of material that has been removed due to post-depositional incision. We therefore focus only on incision of the proximal and distal fan units. Incision of the proximal fan unit on the Donga fan (Fig. 4) has yielded 1900 Mm^3 of sediment since abandonment of the surface, while incision on the Dehradun (Fig. 4) and Bhogpur fans has yielded 750 Mm^3 and 720 Mm^3, respectively. In total, these add up to 3300 Mm^3 of sediment that has been evacuated from the dun by incision of the proximal fan unit. The distal fan unit is not exposed on the Bhogpur fan, but incision of the distal unit on the Donga and Dehradun fans has yielded 1800 Mm^3 since abandonment of the distal fan surface. Error estimates on these volumes are due largely to uncertainties in mapping the fan surface remnants, and are conservatively estimated at ±20% through exploration of different possible remnant configurations with various levels of certainty.

Discussion

Evolution of the dun fill

We interpret the sedimentary units that were deposited in the Dehra Dun since ~41 ka in terms of a sequence of repeated episodes of fan deposition, backfilling, fan head incision, and basinward migration of the depocenter. Such an evolutionary sequence has been widely documented for experimental fans and fan deltas (Kim et al., 2006; Reitz and Jerolmack 2012; Powell et al., 2012), and may be triggered by both autogenic (e.g., Kim and Muto, 2007; Kim and Jerolmack, 2008; Clarke et al., 2010; Pepin et al., 2010) and allogenic (e.g., Davies and Korup, 2007; Duehnforth et al., 2008) mechanisms. In this model, the isolated hills unit represents the first phase of deposition, filling accommodation that was produced by slip on the Santaugarh fault and MBT and starting by at least 41 ka. The morphological expression of this unit indicates that it has undergone widespread post-emplacement erosion, such that the original fan surface topography is not preserved. It is thus impossible to use dates on the isolated hills material to identify the precise time at which this depositional unit was abandoned and incised. Based on dates from the next-youngest unit, however, abandonment of the isolated hills depositional regime appears to have taken place by 29-30 ka, and occurred by incision of the isolated hills deposits near the sediment entry points into the basin and by a major basinward shift of the active locus of deposition. This shift was followed by widespread deposition of the proximal fan unit, which filled much of the available accommodation within the dun. As deposition progressed, the unit began to backfill toward, and eventually across, the Santaugarh fault, eventually leading to the deposition of >100 m of sediment in the hanging wall of the fault (Figs. 3B, 4).

Abandonment of the proximal fan deposit appears to have occurred by incision at the fan heads and a second basinward shift of the depositional locus, leading to deposition of the distal fan unit. This shift took place between about 23 ka (the oldest age in the distal fan unit) and 20.5 ka (the youngest age in the proximal fan unit). Deposition of the distal fan unit may have eventually led to backfilling, but if so this did not extend as far north as during the deposition of the proximal fan unit, and no distal fan sediments were deposited in the Santaugarh fault hanging wall. The distal fan unit, in turn, was abandoned by about 10 ka, when the river network entered a major phase of incision that has carved the present-day topography and valley network. After 10 ka, there have been several minor episodes of aggradation and incision, leading to sequences of low Holocene fill terraces along some of the major dun rivers (Nakata, 1972; Singh et al., 2001). These terraces, while well-developed along the Suarna and Sitla Rao, have treads that are within 5-10 m of the modern river bed levels, and are thus likely to be volumetrically insignificant in comparison with the three major depositional units.

Sediment fluxes

Abandonment of the proximal fan unit led to evacuation of 3300 Mm^3 of sediment, primarily via incision along the major dun rivers. This evacuation must have started at 20.5-23 ka. The duration of this incision episode is not known, but it must have been concluded well before the abandonment of the later distal fan surface at 10 ka. We therefore take, as a conservative estimate, an incision duration of 13 kyr, noting that the true value may be several times shorter than that. This assumption yields a time-averaged sediment discharge from the proximal fan unit of 0.26 Mm^3/yr. This discharge must have been added to the sediment loads of the Ganga and Yamuna rivers as they traversed the dun during this time period, because there is only limited accommodation available for sediment storage along the river corridors within the dun. Likewise, abandonment of the distal fan unit led to evacuation of 1820 Mm^3 of sediment since 10 ka, directed into the Yamuna River only. This corresponds to a time-averaged sediment discharge of 0.18 Mm^3/yr over that time period.

For comparison, these time-averaged sediment discharges from the dun represent 1-2% of the summed present-day suspended sediment discharge of the Ganga and Yamuna rivers, derived from 1.5% of the combined Ganga and Yamuna drainage area. Dun excavation thus represents an important sediment source for the Ganga and Yamuna rivers, with sediment yields comparable to the overall catchment-averaged values. We stress that the time-averaged discharge values reported here almost certainly underestimate the true sediment discharge from the dun, because our depositional ages provide only maximum bounds on the duration of incision during abandonment of each depositional unit. For example, if incision and sediment evacuation were focused in the first few thousands of years following abandonment, then the 'true' time-averaged sediment discharge values could be many times higher than our conservative estimates. Also, our comparison with available present-day suspended sediment discharge values is made simply to provide some context for the time-averaged discharge values, and we do not know either (1) the corresponding total sediment discharge, including both bedload and suspended-load components, or (2) how that discharge has varied through the late Quaternary.

Comparisons to hinterland and foreland sedimentary records

The short time scale over which the major depositional units in the Dehra Dun were emplaced, and our observation that there does not appear to be substantial slip on the Santaugarh fault during or after deposition of the proximal fan unit, both appear to rule out major changes in fault slip rate and accommodation generation as the underlying mechanism behind the abandonment of one unit and the onset of deposition of the next. It seems more likely that temporal variability in sediment storage and evacuation in the dun has been driven by some combination of autogenic processes and regional-scale climatic variability; the latter control has been argued convincingly for the Ganga basin hinterland (e.g., Juyal et al., 2009; Ray and Srivastava, 2010) and foreland (e.g., Gibling et al., 2005; Sinha and Sarkar, 2009; Roy et al., 2012). To understand the wider context of our results, we therefore compare and contrast our depositional unit chronology to the timing of valley filling and incision episodes in the Ganga basin, both upstream and downstream of the study area.

Upstream of the dun, Ray and Srivastava (2010) compiled a number of published studies, along with new OSL dating, and argued for major phases of valley aggradation at 49-25 ka and 18-11 ka based on clustering of OSL ages in terrace fill deposits. They attributed these aggradational episodes to high sediment supply due to glacial-deglacial transitions. Widespread incision after 11 ka was linked by Ray and Srivastava (2010) to increased monsoon precipitation after 15 ka, peaking at 9 ka, combined with post-LGM sediment exhaustion. This inference was based on a number of lines of evidence for increasing monsoonal strength, and thus river discharge, after 15 ka, including sedimentary (Juyal et al., 2009) and geochemical (Galy et al., 2008) records. Our results from the Dehra Dun, with aggradation at ~41-33, 34-21, and 23-10 ka, agree closely with this framework, indicating that the controls on sediment aggradation and incision in the hinterland of the Ganga catchment also set the response of the dun. Unsurprisingly, the dun thus forms an integral part of the Ganga catchment and responds near-synchronously with the hinterland, within the uncertainties of the age constraints, to large-scale climatic variations. Our results also broadly agree with the summary and interpretation of Pandey et al. (2014), who argued for multiple phases of alluvial aggradation in the dun between >40 and 10 ka. We disagree, however, with the conclusion by Pandey et al.

(2014) that fan aggradation had been continuous over this period, because of the clear geometrical distinction between different depositional units (Singh et al., 2001) – and we note that Pandey et al. (2014) also raised the possibility of intervening erosional episodes. Thus, while the age ranges of our aggradational episodes overlap in time, they represent spatially distinct aggradational events that have given rise to discrete depositional units.

Downstream of the dun, Ray and Srivastava (2010) argued for two main pulses of sediment delivery to the foreland: one before 26 ka (seen also by Sinha et al., 2007), and a second at 13-6 ka. The second pulse was followed by incision to form the present-day Ganga channel, with the onset of incision varying from 13 to 7 ka at different locations between the HFT and Kanpur. More recently, Roy et al. (2012) combined new stratigraphic observations in the central Ganga plains, about 300 km downstream of the HFT, with results from a number of existing studies, and suggested major accumulation phases at 30-23 ka and 16-11 ka, separated by episodes of incision. We compare these observations with our chronology below.

The isolated hills depositional phase that began by 41 ka in the dun coincides with lowering of the floodplain in the Ganga plains (Roy et al., 2012) and declining precipitation around ~40 ka as modelled by Prell and Kutzbach (1987), but there is limited, if any, evidence for aggradation within the Ganga valley. Minor channel fills dated to 37 ka and levee deposits dated to 34 ka have been recorded (Roy et al., 2012), but these are volumetrically small. It may be that relatively weak flow through the river systems during 41-33 ka, perhaps combined with high hinterland sediment supply (Ray and Srivastava, 2010), led to widespread deposition of sediment upstream of the HFT and in the dun, but was insufficient to transport large sediment volumes into the plains, leading to only minor and local aggradation during this period. This hypothesis would need to be tested with careful sedimentological analyses of transects extending from the dun into the northern foreland. We also note that Singh et al. (2001) interpreted many of the deposits in this phase as the result of debris-flow or other mass-flow processes, which would not require high water discharges in the river systems.

The second phase of major aggradation in the dun (34-21 ka) is represented by the development of the proximal fan unit, and overlaps with a period of widespread fluvial aggradation recorded downstream of the dun in the Ganga plains (Goodbred, 2003; Tandon et al., 2006; Sinha and Sarkar, 2009; Ray and Srivastava, 2010; Roy et al., 2012). Several of these studies have inferred the occurrence of high-intensity floods in the foreland (Goodbred, 2003), while others have interpreted high sediment flux from the Himalaya at this time (Taylor and Mitchell, 2000; Sharma and Owen, 1996). Given the wide extent of the proximal fan unit on the floor of the dun, it is possible that the dun at this stage was essentially full, leading to bypass of dun accommodation by the rivers that supply it and to high rates of sediment supply directly into the foreland.

During the period from 28 to 16 ka, including the Last Glacial Maximum (LGM), deposition is recorded in the dun by emplacement of the lower part of the distal fan unit. Aggradation in the hinterland was limited during this period (Ray and Srivastava, 2010), perhaps due to limited sediment supply and glacial cover at high elevations (e.g., Rahaman et al., 2009); we do not know what fraction of the distal fan unit was emplaced during this time, but it may be that deposition occurred in the dun during this period because the dun catchment area drains only lower-elevation Lesser Himalayan areas and was never glaciated. LGM-age sediments are not found in the central Ganga plains upstream of Kanpur (Gibling et al., 2005; Sinha et al., 2007); indeed, Roy et al. (2012) found no evidence for channel deposition in the Ganga valley between 25 and 15 ka. This hiatus has been interpreted as resulting from relatively cold, arid LGM conditions (Goodbred, 2003), and it is possible that some combination of low rates of supply and low LGM river discharges may have led to relatively limited sediment transport into the foreland. In the early post-glacial period (16-11 ka), there is evidence for widespread deposition of the distal fan unit, perhaps driven by high rates of hinterland supply (Ray and Srivastava, 2010) along with extensive slope failures and hillslope sediment transport (Pratt et al., 2002). In the Ganga plains, major channel aggradation has been recorded between 15.1 to 11.7 ka (Srivastava et al., 2003; Gibling et al., 2005; Tandon et al., 2006; Roy et al., 2012), and has again been interpreted as being due to high rates of supply (Roy et al. 2012). We infer from this, and from the wide extent of the distal fan unit, that the dun may have been filled by the later stages of deposition of the distal fan unit and was certainly bypassed during this period, again allowing high sediment discharge to the foreland.

In sum, the dun may act to modulate climate-driven variations in sediment flux from the hinterland to the Ganga plains. Sediment appears to be sequestered during periods of low transport capacity and perhaps when the dun is underfilled, but dun aggradation is somewhat independent of hinterland sediment supply. In contrast, sediment is exported duinrg periods of high transport capacity and incision of the dun fill, and also during periods of high hinterland supply when the dun is filled and bypassed. Several of the times of widespread aggradation within the dun (~41-33 ka, 23-16 ka) coincide with periods of limited downstream deposition, and we infer that during these periods the dun may have acted as a partial, transient sediment trap, perhaps due to some combination of low river discharges or low rates of hinterland supply. Later, however, due to some combination of rising discharge and increasing hinterland supply, we infer that the dun 'filled and spilled', in concert with widespread downstream aggradation at 34-21 ka and 15-12 ka.

Comparison to the Gandak River

Our results from the Dehra Dun help to place constraints on the timing and magnitude of its contribution to sediment flux in the Ganga and Yamuna rivers. To what extent is this model applicable to other duns along the Himalayan front? To answer this question, we compare our results with observations from several other large Himalayan river systems, the Gandak and Kosi rivers. The Gandak River (also referred to as the Narayani River in southern Nepal) flows through the Chitwan Dun (Fig. 1), which has developed between strands of the MBT and Main Dun Thrust to the north and the HFT system to the south (Fig. 5). As in the Dehra Dun, the Chitwan Dun is impounded behind anticlinal ridges of Siwalik sediments developed above strands of the HFT (Lavé and Avouac, 2000, 2001). Estimates of the present-day suspended sediment discharge of the Gandak near Narayangarh, at the upstream entrance to the Chitwan Dun, are 105-110 Mt/yr (Lavé and Avouac, 2001; Garzanti et al., 2007), while Lupker et al. (2012) used cosmogenic radionuclides to estimate total sediment discharge of 110-184 Mt/yr. At Tribeni, near the downstream end of the dun, Sinha and Friend (1994) estimated a suspended sediment discharge of 79 Mt/yr. These values are equivalent to volumetric discharges of ~30-70 Mm^3/yr. Note that the much larger sediment discharge estimates of 450-510 Mt/yr by Singh et al. (2008) are based on a mixing model, and may not be directly comparable. At present, the river occupies a wide, low-gradient meander belt across the Chitwan Dun and is not substantially incised into the dun floor, perhaps indicating that accommodation in the dun is nearly full.

Within the Chitwan Dun, sediment from the Gandak and Rapti Rivers, and from smaller basins that drain the Main Dun Thrust hangingwall, has been deposited in a series of interfingering fans and fill terraces (Fig. 5), which form extensive low-gradient depositional surfaces similar to those of the Dehra Dun (Kimura, 1995, 1999). Kimura (1995) identified three main depositional units that could be correlated across multiple catchment-fan systems. While interpretation of his assignments is somewhat complicated by uncertainty in correlation between different lithostratigraphic units, the two youngest units broadly comprise (1) an older set of fan remnants (the Barakot and Belani deposits) with quasi-planar to slightly convex-up surfaces that range from ~180 to 300 m above the modern river beds, (2) a more extensive, younger set of planar fan remnants (the Bishannagar and Kirtipur deposits) that are clearly inset into, and onlap, the older remnants, and form widespread near-planar surfaces, 10-70 m above the modern river beds (Fig. 5).

No absolute ages are available for the Chitwan Dun fill deposits, although Kimura (1995) suggested ages of 26-16 ka and <10 ka for the two youngest depositional units. On the basis of surface morphology, deposit geometry, and cross-cutting relationships between units, we tentatively correlate the older fan remnants (Barakot and Belani deposits) with the proximal fan unit in the Dehra Dun, and the younger fan remnants (Bishannagar and Kirtipur deposits) with the Dehra Dun distal fan unit. This does not, of course, imply that the depositional ages are similar in these two settings, only that the deposits occupy similar spatial settings and have similar geometrical relationships. This correlation must be tested with more careful mapping and dating of the Chitwan Dun fill.

If we accept the correlations of Kimura (1995) and apply the same techniques to determine incision depths and erosional volumes as we used in the Dehra Dun, then we find that incision of the older fan remnants has removed a volume of 6300 Mm^3, while incision of the younger fan remnants has removed 2400 Mm^3 from the dun (Fig. 5). If we further assume that incision of the younger fan remnants began at around 10 ka, as with the correlative deposits in the Dehra Dun, then this evacuation would imply a time-averaged sediment discharge of ~0.2 Mm^3/yr, about 1% of the modern Gandak suspended sediment discharge. We stress, however, that the timing of deposition and incision in the Chitwan Dun remains unconstrained, and so such estimates must remain indicative.

Downstream of the HFT, the Gandak has built a highly avulsive fan system in the foreland (Gupta, 1997). Sinha et al. (2014a) used resistivity surveys and limited borehole data to document two lithological units within the upper 100 m of the fan: a lower unit characterized by narrow but thick (>40 m) channel fills set into thick muds, and an upper unit that comprises thinner, laterally-stacked sand bodies separated by mud layers. Importantly, channel fills are discontinuous in both units, perhaps due to depositional hiatuses caused by episodic trapping of sediment in the dun (Sinha et al., 2014a). The observation that the dun appears to be nearly full at the present day may explain the high modern sediment discharge of the Gandak (e.g., Singh et al., 2008), and may be analogous to the bypass conditions inferred for the Dehra Dun at 34-21 or 16-11 ka.

Comparison to the Kosi River

In contrast to the Yamuna, Ganga, and Gandak, the Kosi River debouches directly into the Ganga plain in eastern Nepal (Fig. 1, Fig. 6). Late Quaternary deformation appears to be focused on the HFT system at the mountain front (Lave and Avouac, 2001), and the lack of propagation into the foreland has resulted in an abrupt mountain front and a relatively short distance (as little as 5-8 km) between the HFT and MBT systems (Schelling, 1992; Lave and Avouac, 2001). The thrust sheet between the HFT and MBT is composed of relatively weak Middle and Lower Siwalik foreland basin rocks in the HFT hangingwall (Fig. 6), with local relief (measured over a 1 km radius to reflect typical hillslope lengths) of up to 1 km. Estimates of the present-day suspended sediment discharge of the Kosi range from 95 Mt/yr and 43 Mt/yr at Barakhshetra and Baltara, respectively (Sinha and Friend, 1994; Sinha et al., 2005) to 175 Mt/yr (Lave and Avouac, 2001), while Gohain and Parkash (1990) reported a much higher value of 345 Mt/yr. Lupker et al. (2012) used cosmogenic radionuclides to estimate a longer-term total sediment discharge of 69-141 Mt/yr. Apart from the high estimate of Gohain and Parkash (1990), these values are equivalent to volumetric discharges of ~30-70 Mm^3/yr, broadly comparable to those of the Gandak (although derived from approximately twice the drainage area).

Downstream of the HFT, the Kosi River has constructed a large, highly avulsive fan system (Chakraborty et al., 2010; Sinha et al., 2013), with evidence for rapid historical aggradation (Desai, 1982; Sinha et al., 2014b). Subsurface investigation of the top ~100 m by Sinha et al. (2014a) reveals widespread multi-story sand bodies, 20-30 m thick, with thick gravel deposits in the proximal fan. Sinha et al. (2014a) interpreted this depositional architecture, along with the short avulsion timescale of the Kosi River (approx. 24 years), as being due to the lack of intermediate sediment storage upstream of the fan. This contrasts with the Gandak River, which, despite comparable present-day (Sinha et al., 2005) and late Holocene (Lupker et al., 2012) sediment discharge and a higher suspended sediment yield, has built a fan with finer overall grain sizes and much more isolated channel bodies within the subsurface (Sinha et al., 2014a). These observations agree with our interpretation from the Dehra Dun and Chitwan Dun that proximal dun storage can 'filter' hinterland sediment supply, amplifying high discharge values but also acting as a transient sediment store during periods of low sediment discharge to the foreland.

Conceptual model

We summarise our results from all river systems in a conceptual model of temporal variations in sediment supply to the foreland in both the presence, and absence, of a dun (Fig. 7). Our key inference from the field observations is that intermediate dun sediment storage and release will act to modulate and amplify the sediment supply to the foreland. This may occur through changes in hinterland sediment supply, changes in transport capacity, or both. Sediment is sequestered in the dun during periods of low transport capacity and either high or low hinterland supply, leading to underfilled conditions (Fig. 7A). Sediment is evacuated from the dun when either (1) transport capacity is high, resulting in incision of the dun fill, or (2) both hinterland supply and transport capacity are high, leading to filling of the dun and spilling of sediment into the foreland (Fig. 7B). In contrast, rivers without proximal storage are likely to be characterised by a more continuous, less temporally-variable sediment flux (Fig. 7C), leading perhaps to enhanced likelihood of ‘stacking’ of channel units in the foreland. Rivers without duns may also be more prone to bed aggradation and subsequent avulsion, as in the modern Kosi River (Sinha, 2009; Chakraborty et al., 2010), although it is important to note that avulsion frequency is dependent on a number of other variables as well (e.g., Bryant et al., 1995; Mohrig et al., 2000; Wickert et al., 2013; Sinha et al., 2014b). It is also important to recall that large-scale behaviour and evolution of the major Himalayan river systems depends on a range of factors (e.g., Sinha et al., 2005), of which transient storage in a dun is but one example. Unravelling the relative importance of these factors will require enhanced understanding of sediment fluxes over different time scales, and careful study of the links between proximal and distal sediment stores along these rivers.

This model highlights the importance of understanding the tectonic ‘template’, or spatial distribution and rates of rock uplift. This template is critical, not just because it helps to set erosion rates in the hinterland of the major river systems (e.g., Sinha et al., 2005; Scherler et al., 2014), but because the distribution of rock uplift at the mountain front dictates whether or not piggyback basins or other local depocentres are likely to form at the mountain front. Distributed tectonic activity also implies more spatially-distributed foreland subsidence, such that the rate of accommodation generation immediately adjacent to the mountain front is likely to be lower in the presence of a dun bounded by multiple active faults. While there has been some effort to understand Holocene rates of slip on structures associated with the HFT (e.g., Wesnousky et al., 1999; Kumar et al., 2006; Sapkota et al., 2013), our results point to the need for better assessment of the full pattern of rock uplift along faults bounding the Himalayan duns.

We have inferred the link between upstream sediment supply and downstream fluvial response using available stratigraphic and age data from the Ganga Basin. It would be useful to explore the possible implications of episodic storage and release for spatial variations in specific sediment characteristics. For example, Granet et al. (2007, 2010) used U-Th disequilibria to estimate transfer times of both suspended and bedload sediment in the Ganga and Gandak rivers. A natural question is whether river systems without a dun, such as the Kosi or Karnali, show evidence for more rapid transfer than those systems with abundant upstream storage. A more systematic study of these variations could help improve our large-scale understanding of sediment movement through the entire Ganga sediment routing system (e.g., Bloethe and Korup, 2013).

Conclusions

We investigate the timing and magnitude of sediment storage and evacuation from the Dehra Dun, a piggyback basin in northwestern India, in order to understand the effects of this time-varying sediment source on the downstream morphology of the major river systems that drain through the dun. The dun shows evidence for at least three phases of late Quaternary sedimentation, at ~41-33, 34-21, and 23-10 ka. During each of these phases, sediment fans built out into the dun, accompanied in at least the later stages by fill terrace deposition along the Ganga and Yamuna rivers. Each progradation phase was followed by fan-head incision, abandonment of the active depositional lobes, and a basinward shift of the depocentre. The volumes of sediment released during these incision phases, when divided by the maximum time span available for incision, yield estimates of palaeo-sediment discharge that are 1-2% of the modern suspended-sediment loads of the Ganga and Yamuna rivers, from about 1.5% of the combined catchment areas of these rivers. Our results show that the dun fill is highly dynamic, with major changes in both volume and depocentre location on ~10^4 yr time scales.

The early stages of at least two episodes of sediment storage in the dun appear to coincide with periods of upstream aggradation in the hinterland and partial depositional hiatuses in the Ganga plains, indicating that the dun may act as a partial, transient sediment trap. Later phases of dun aggradation, and subsequent excavation and evacuation of dun sediment, correspond to periods of widespread downstream aggradation. The dun may thus amplify climate-induced variations in sediment supply to the major river systems. This model appears to explain some contrasting features of the Gandak and Kosi river systems in central Nepal; the presence of a dun along the Gandak has led to episodic storage and release of sediment upstream of the Himalayan mountain front and construction of a mud-rich fan in the Ganga plains. In contrast, the Kosi River debouches directly into the foreland, and the lack of upstream storage means that a more continuous supply of sediment has built a coarse-grained, highly avulsive fan characterised by stacked multi-story channel bodies. We infer from these examples that the tectonic framework at the mountain front – specifically, the way in which shortening is distributed across different faults – plays a critical role in determining downstream river morphology, stratigraphy, and evolution.

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Figure Captions

1. Location map showing major rivers (white) and duns along the Himalayan mountain front, India and Nepal. Heavy black lines show simplified trace of the Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT) fault systems, while light shaded areas highlight the region between the MBT and HFT where the major duns are developed. Barbs on faults mark the upthrown block. Faults simplified from Yeats et al. (1992) and Taylor and Yin (2009). White boxes show the locations of the three regions discussed here.

2. A, Overview and geomorphic map of the Dehra Dun area, overlain on a hillshade image of the SRTM DEM. MBT, Main Boundary Thrust system; HFT, Himalayan Frontal Thrust system. Heavy white lines show the Ganga and Yamuna catchments, while white shaded areas indicate the Catchments that flow into the dun. Holocene terrace deposits are shown in pale yellow; those along the Yamuna River are taken from Dutta et al. (2012), while those along the Ganga River are taken from Sinha et al. (2010). DO, DD, and BP mark the Donga, Dehradun, and Bhogpur fans of Singh et al. (2001). B, Depositional units on the Donga and Dehradun fans. Our analysis is focused on the isolated hills, proximal fan, and distal fan units. SF, Santaugarh fault. White circles mark OSL ages determined in this study, while grey circles mark ages published by Singh et al. (2001); sample positions, ages, and depths below surface are given in Table 1. Red dots mark locations of boreholes used to establish minimum fan deposit thicknesses. Eye symbols in hangingwall of Santaugarh fault show viewpoints of photos in Fig. 3.

3. Relationships between depositional units near the headwaters of the Koti Nadi, in the hangingwall of the Santaugarh fault. See Fig. 2 for locations. A, Deposits of the isolated hills unit unconformably overlie Middle Siwalik rocks in the fault hangingwall; in turn, both of these units are unconformably draped by the proximal fan unit. View is to the west-southwest. The near-planar surface of the proximal fan unit is clearly visible, and can be traced continuously across the Santaugarh fault (out of the photo to the left) on the south bank of the Koti Nadi. B, spatial changes in sediment transport direction recorded in the walls of the Koti Nadi. View is to the east. Deposits of the proximal fan unit are separated from the underlying isolated hills unit by an angular uniformity that marks the margin of a paleovalley incised into the isolated hills unit.

Subsequently, the proximal fan unit was abandoned and incised, and the new valley trends more westerly (toward the camera).

4. Estimated depth of incision into the proximal fan unit on the Donga (DO) and Dehradun (DD) fans. Orange areas show the mapped extents of the proximal fan unit that were used to interpolate the likely original depositional extent. Shading indicates the depth of incision, which reaches ~180 m near the headwaters of the major valleys, particularly the Suarna and Asan rivers, and tapers to 0 downstream. This is equivalent to the removal of 1900 Mm^3 of sediment from the Donga fan and 750 Mm^3 from the Dehradun fan since abandonment of the proximal fan unit.

5. Overview of the Chitwan Dun area, overlain on a hillshade image of the SRTM DEM. The dun is formed between strands of the Main Boundary Thrust (MBT) and Main Dun Thrust (MDT) fault systems to the north, and the Himalayan Frontal Thrust (HFT) system to the south. Faults are simplified from Lave and Avouac (2001). The Gandak River enters the dun at Narayangarh and flows west-southwest across the dun, eventually crossing the HFT at Tribeni and flowing into the foreland. The Bishannagar-Kirtipur (yellow) and Barakot-Belani (orange) depositional units of Kimura (1995) are preserved along the northern margin of the dun, in the footwall of the MDT. Shading indicates the depth of incision into the more widespread Bishannagar-Kirtipur unit, which reaches ~70 m in the immediate fault footwall and tapers to the south.

6. Overview of the Kosi River exit. Background is Landsat 7 ETM+ image with band combination 732. Faults are simplified from Lave and Avouac (2000, 2001). The Kosi flows across strands of the MBT and HFT and enters the foreland at Chatra. High sediment supply and frequent avulsions by the Kosi have constructed a broad sediment fan in the foreland; several south-draining palaeochannels are visible in the image.

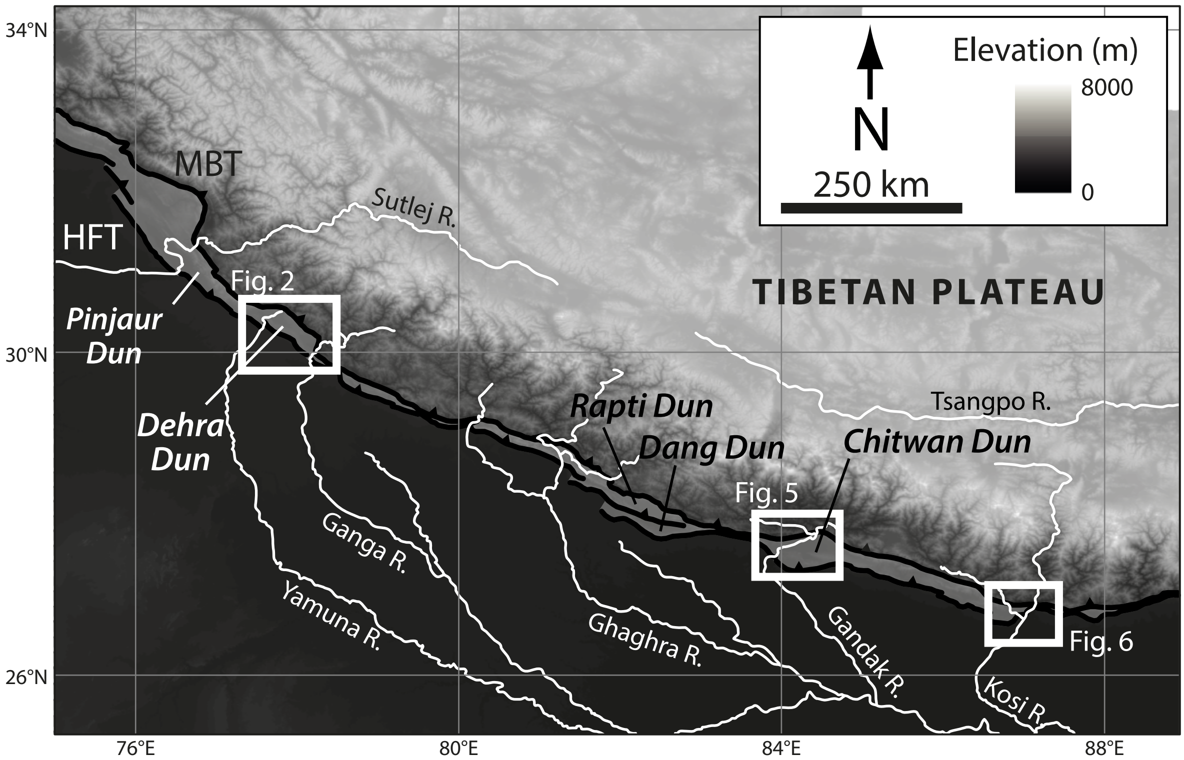
7. Conceptual model of sediment supply to the foreland in the presence (A, B) and absence (C) of a dun. Insets show hypothetical evolution of sediment discharge into ($Q_{s\ in}$) and out of ($Q_{s\ out}$) the dun in the face of

externally-imposed variations in climate and sediment supply. A, Mountain front evolution during times of sediment accumulation within the dun, such that $Q_{s\ in} > Q_{s\ out}$. This mismatch could arise due to some combination of low or increasing sediment supply from the hinterland, low transport capacity in the system, or both. Deformation is distributed between active faults on the upstream and downstream margins of the dun, leading to moderate rates of rock uplift and incision above individual structures. The dun provides accommodation for sediment from both local river systems and large-scale hinterland rivers. Fan deposition in the dun acts as a partial, transient sediment trap until the dun fills, at which point the dun can be bypassed and sediment discharge to the foreland $Q_{s\ out}$ may rise (inset). This phase represents aggradation in the dun observed during 41-33 and 23-16 ka. B, Mountain front evolution during times of sediment evacuation from the dun, such that $Q_{s\ in} < Q_{s\ out}$. The mismatch could arise due to some combination of high sediment supply from the hinterland, high or increasing transport capacity, or both. Fan incision and sediment evacuation from the dun is likely to cause an increase in $Q_{s\ out}$ (inset). This phase represents incision in the dun observed since 10 ka. C, Mountain front evolution in the absence of a dun. Deformation is concentrated at the thrust front, leading to rapid rock uplift of recycled, easily-erodible foreland basin deposits and high rates of sediment supply from the immediate fault hangingwall. The addition of this eroded material means that the sediment discharge to the foreland $Q_{s\ out}$ is greater than the sediment discharge delivered to the immediate hangingwall $Q_{s\ in}$. The lack of intermediate storage leads to efficient export of sediment to the foreland, so that $Q_{s\ out}$ tracks $Q_{s\ in}$ closely (inset).

Table 1. OSL samples and analytical results

Sample (Lab code)	Depo. unit	Position	Elev. (m)	Depth (m)[a]	U (ppm)	Th (ppm)	K (%)	Moist. cont. (%)	Equivalent dose De (Gy)		Dose rate (Gy/ka)	Age (ka)	
									Weighted mean	Least		Weighted mean	Least
FS2.1 (LD1040)	Distal fan	30° 24′ 20.4" 77° 56′ 55.5"	790	4	2.23±0.02	15.3±0.15	2.91±0.03	3.44	59.68±3.96	45.26±3.41	4.33±0.05	13.8±0.9	10.5±0.8
FS2.2 (LD1041)	Distal fan	30° 26′ 41.9" 77° 51′ 35.5"	618	5	2.43±0.02	16±0.16	2.46±0.02	13.53	51.46±1.87	44.36±5.44	3.58±0.06	14.4±0.6	12.4±1.5
LIS-TOP (LD1147)	Distal fan	30° 24′ 18.9” 77° 56′ 56.8"	789	2.8	3.3±0.03	18.1±0.18	3.02±0.03	1.27	80.72±6.82	72.23±7.62	4.99±0.06	16.2±1.4	14.5±1.5
FS3.1 (LD1042)	Proximal fan	30° 24′ 46.7” 77° 57′ 35.3"	855	10	1.89±0.02	16.4±0.16	2.21±0.02	18.16	65.71±3.62	66.36±3.8	3.10±0.06	21.2±1.3	21.4±1.3
FS1.1 (LD1039)	Proximal fan	30˚ 21′ 39.6" 77˚ 56′ 28.6"	606	3	4.56±0.05	21.4±0.21	2.65±0.03	14.38	150.87±14.2	128.9±15.4	4.47±0.08	33.8±3.2	28.8±3.5
IH/2 (LD1148)	Isolated hills	30° 24′ 46.2” 77° 57′ 29.7"	843	2.8	3.1±0.03	18.4±0.18	3.08±0.03	1.36	207.20±5.47	208.6±6.2	5.02±0.06	41.3±1.2	41.6±1.3

[a] Depth below surface of depositional unit, in m



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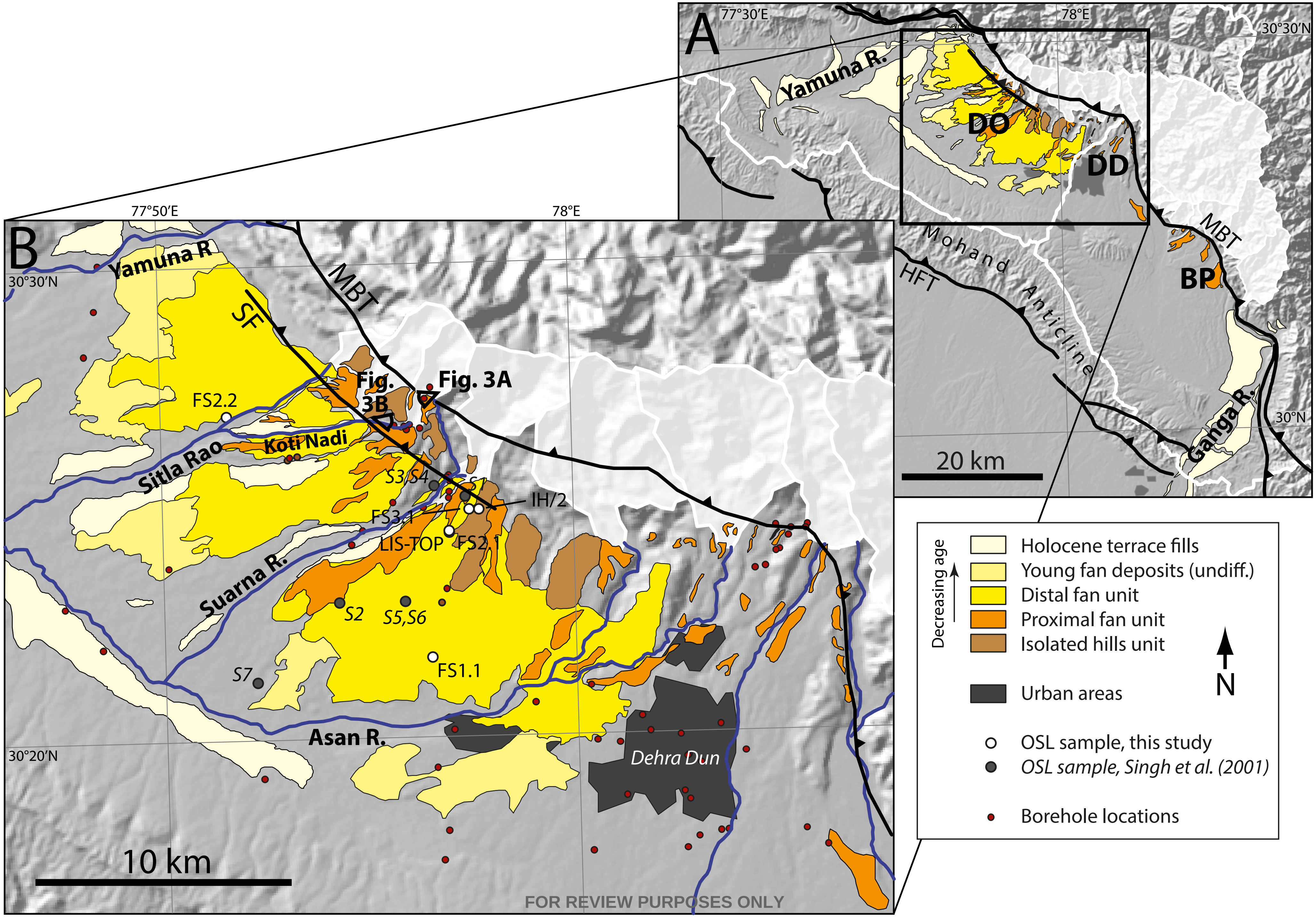
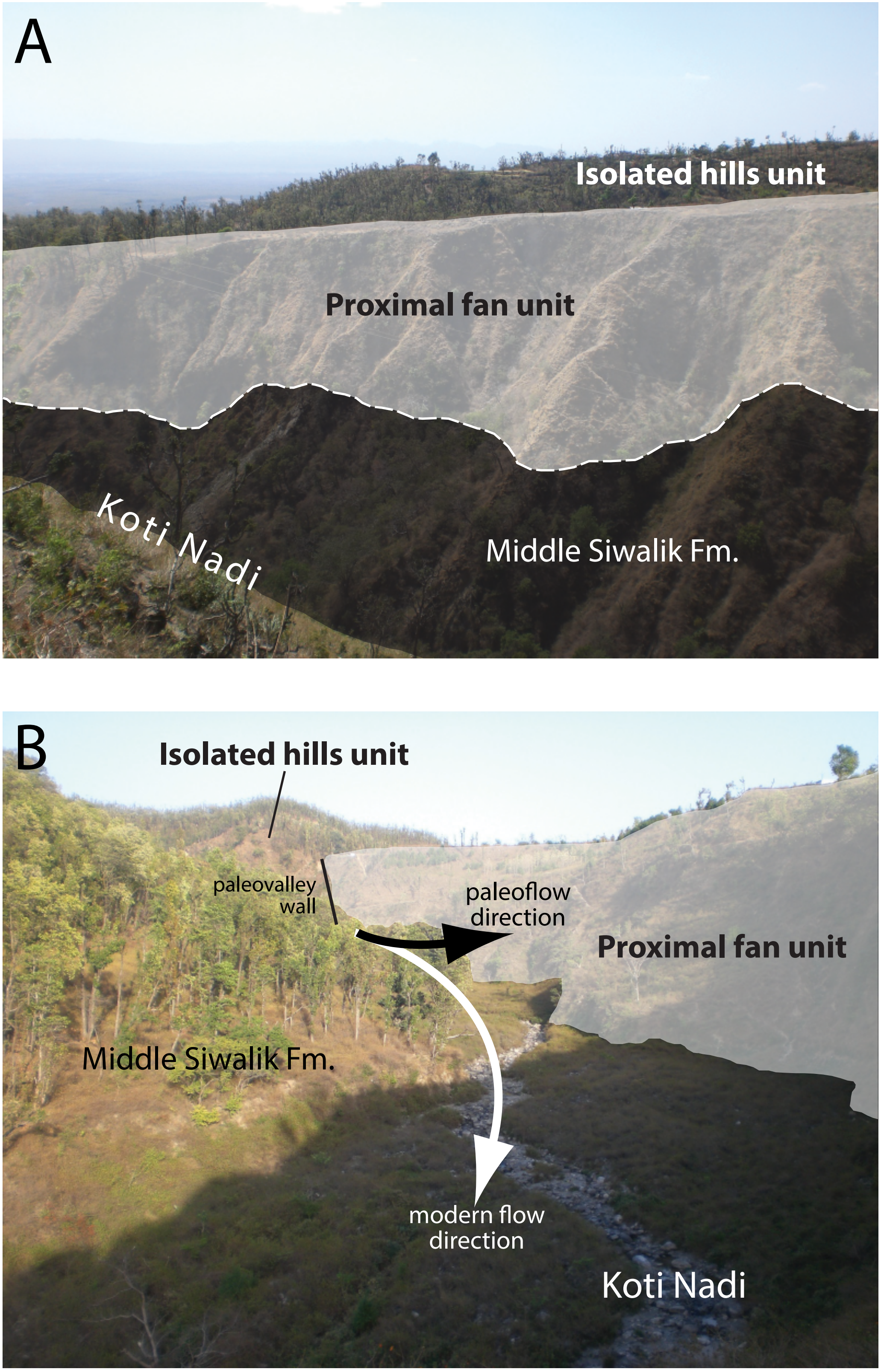

A
77°30′E
78°E
30°30′N
30°N
Yamuna R.
DO
DD
BP
MBT
Mohand Anticline
HFT
Ganga R.
20 km
B
77°50′E
78°E
30°30′N
30°20′N
Yamuna R
SF
MBT
Fig. 3B
Fig. 3A
FS2.2
Koti Nadi
Sitla Rao
S3/S4
S1
IH/2
FS3.1
LIS-TOP
FS2.1
Suarna R.
S2
S5,S6
FS1.1
S7
Asan R.
Dehra Dun
10 km
Decreasing age
Holocene terrace fills
Young fan deposits (undiff.)
Distal fan unit
Proximal fan unit
Isolated hills unit
Urban areas
N
OSL sample, this study
OSL sample, Singh et al. (2001)
Borehole locations



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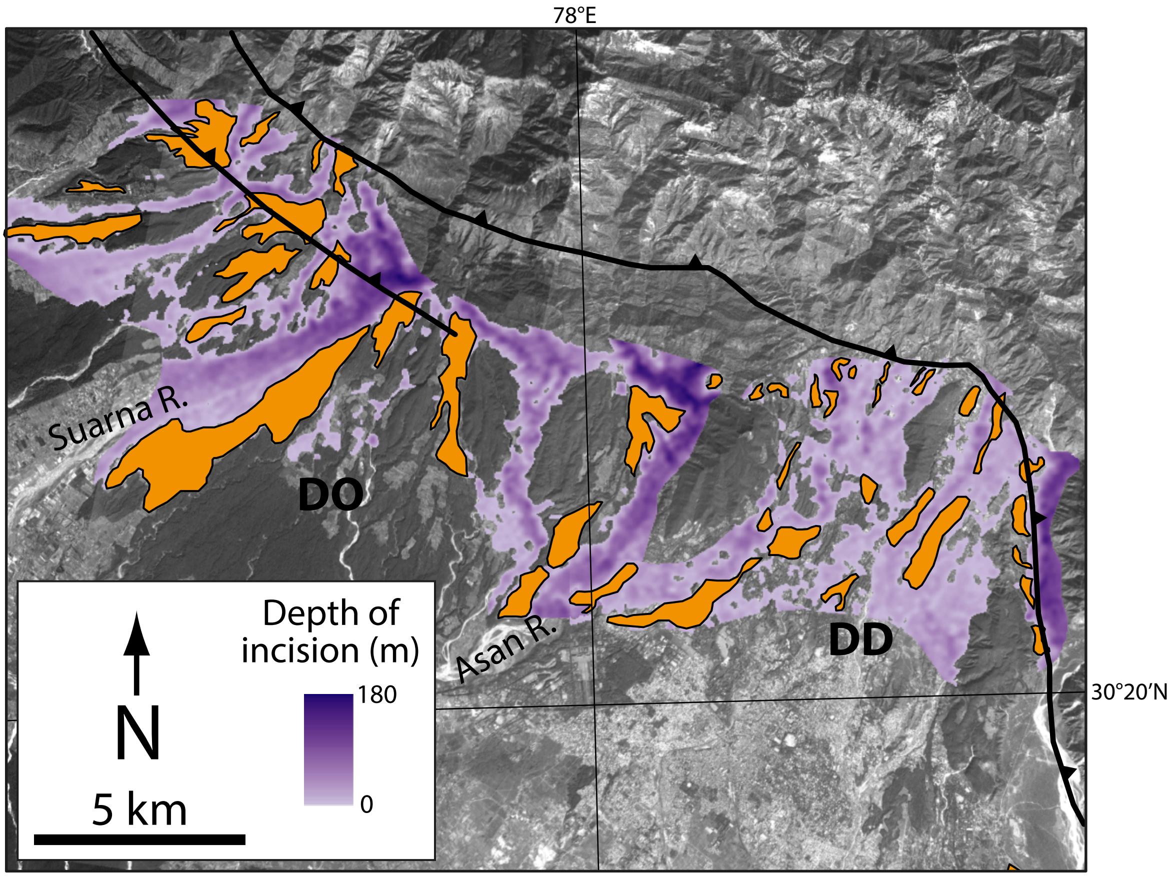

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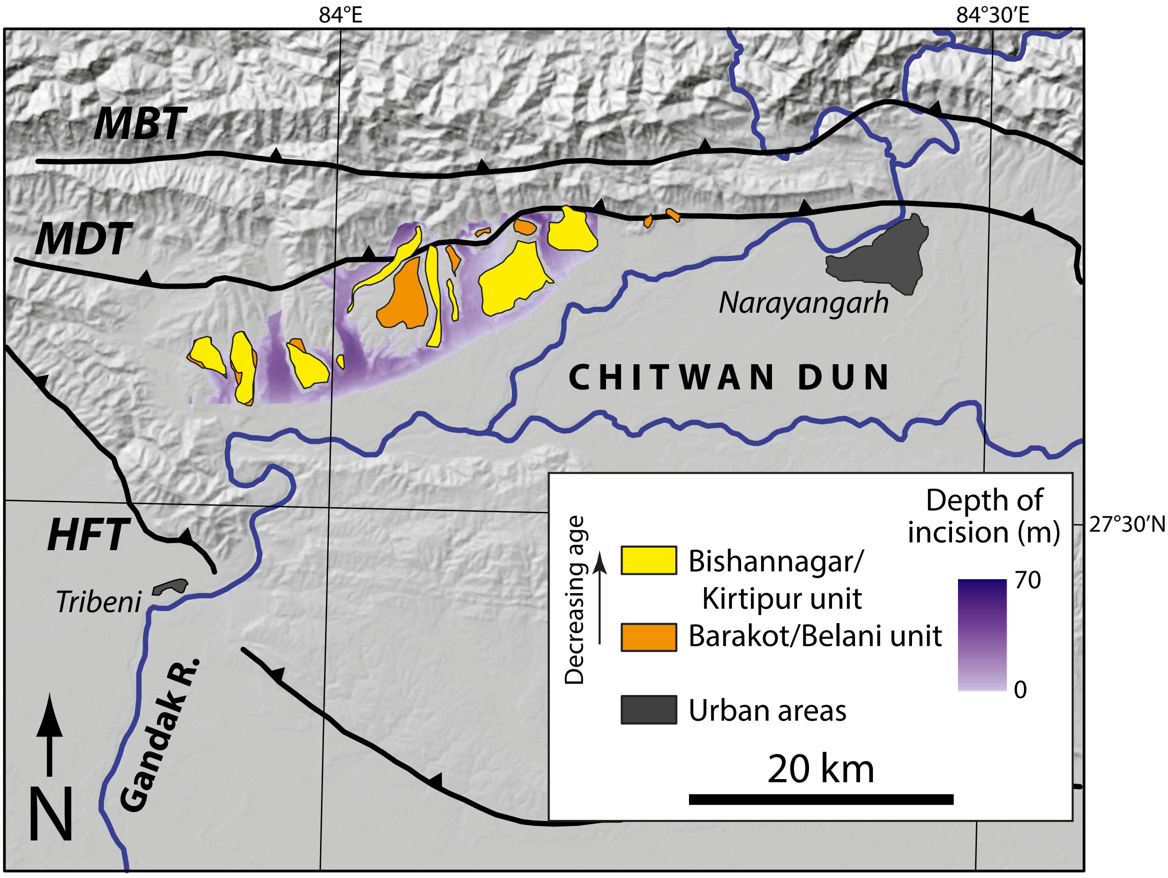

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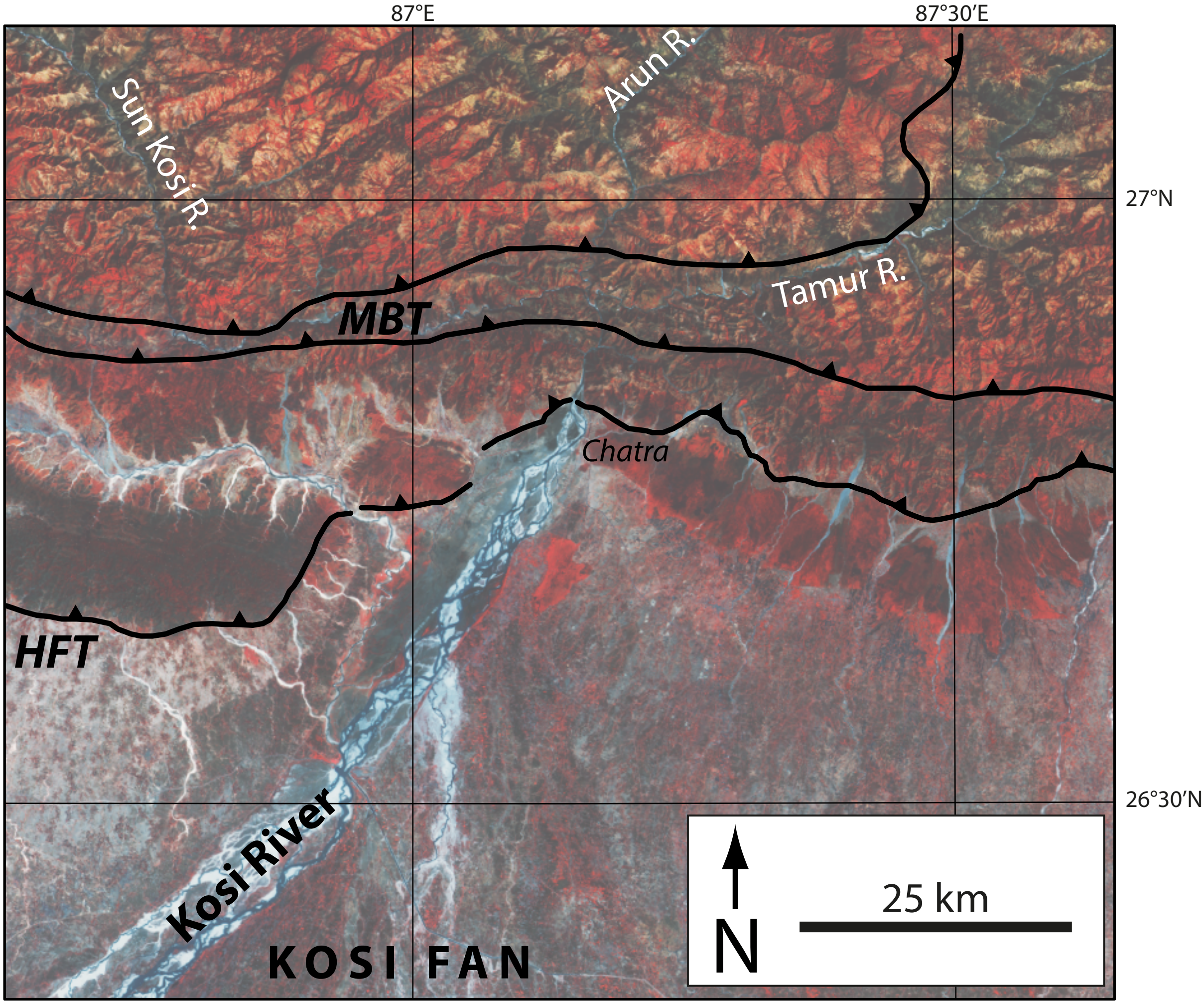

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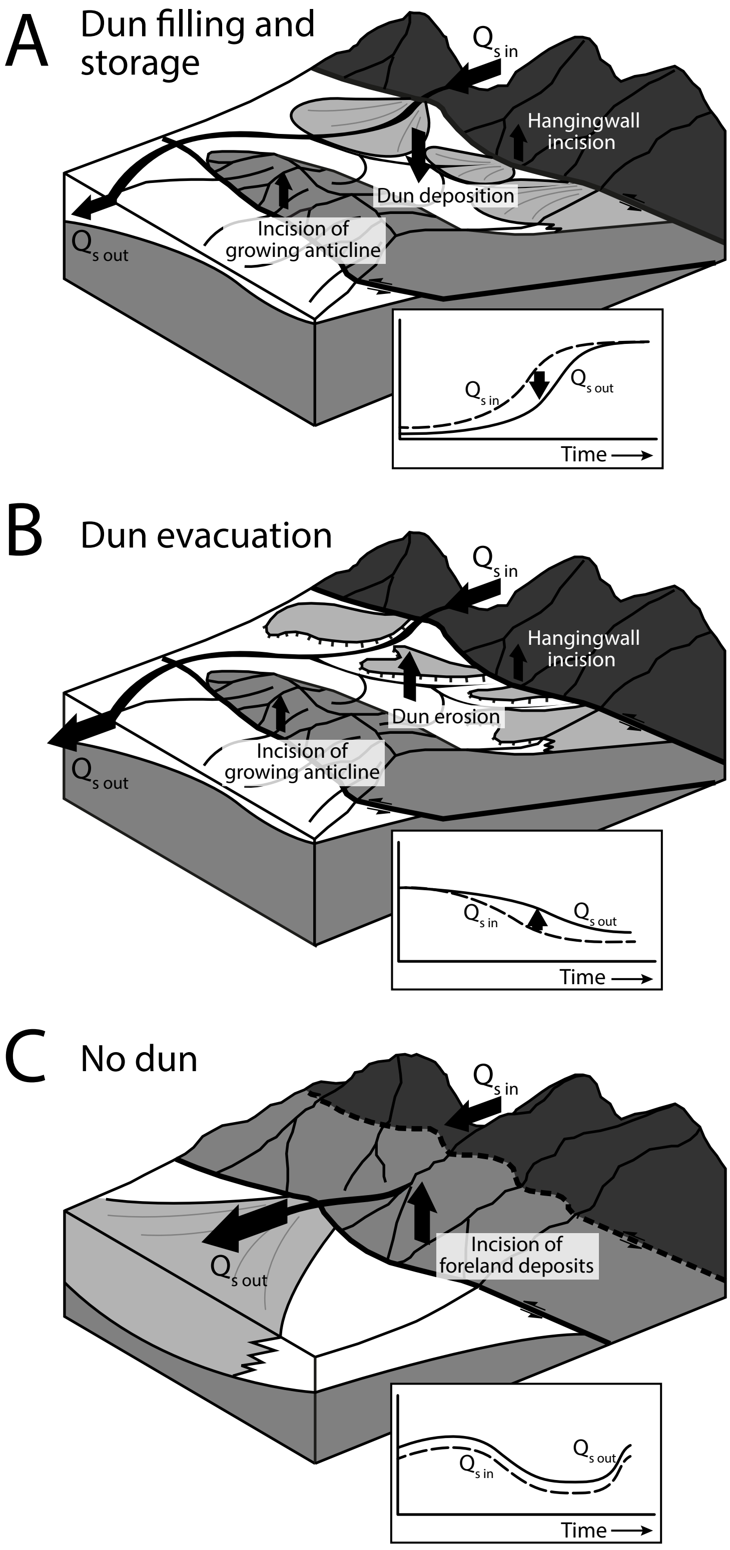

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Sediment storage and release from Himalayan piggyback basins and implications for downstream river morphology and evolution

<u>Supplementary Material</u>

Optically-stimulated luminescence dating: sampling and analytical details

The sediment samples collected from depositional units in the Dehra Dun were dated using luminescence dating techniques. Samples were collected in plastic pipes and immediately sealed in black, lightproof plastic bags to prevent exposure to light.

In the laboratory, under subdued red light conditions, sample material from the middle part of the pipe was transferred to a beaker and treated with 1N HCl and 30% H_2O_2 to remove carbonate and organic matter, respectively. After treatment, the material was sieved to obtain the 90-125 μm size fraction (Aitken, 1985). Quartz grains (with an assumed density of 2.65 g/cm^3) were extracted from this size fraction by density separation using sodium polytungstate solution. The extracted quartz grains were etched for 80 minutes in 40% hydrofluoric acid (HF) to remove the outer layer from each grain, treated with HCl and washed in distilled water, and then re-sieved using a 200 mesh (75 μm)vsieve. The HF treatment also served to remove any feldspar contamination. The purity of the etched quartz and the lack of feldspar contamination was verified by infra-red stimulated luminescence (IRSL). The values obtained were low for all samples, suggesting negligible feldspar contamination (Suppl. Fig. S1).

The etched quartz grains were then fixed into the centre of 10 mm diameter stainless steel discs to form a 3 mm diameter monolayer, using silicon oil as the adhesive agent. Between 35 and 39 aliquots were prepared per sample, and the Single Aliquot Regeneration (SAR) protocol (Murray and Wintle, 2000) was used to determine the radiation energy received by the sample after its burial, also known as the equivalent dose (De). Optically Stimulated Luminescence (OSL) measurements were carried out on an automated Risø TL/DA 20 reader (Risø Laboratories, Denmark) equipped with a blue LED light source for stimulation, using the following measurement settings: pre-heat 240°C, cut-heat 160°C, test dose ~15% of expected De, blue light stimulation 40 s and Hoya U-340 detection filters.

In the SAR protocol, the same aliquot is subjected to a series of cycles of measurements and the resulting sensitivity changes (due to repeated heating during measurement cycles) were normalized by a test dose signal. We first measured the natural luminescence (Ln) using 240°C pre-heat and 40 s blue light stimulation at 125°C, followed by the test dose luminescence signal (Tn) using 160°C cut heat and 40 sec blue light stimulation at 125°C for sensitivity correction. Subsequently, the regenerated luminescence signals were generated by applying different irradiation doses (Lβ1, Lβ2, Lβ3, Lβ0 and Lβ1), along with the corresponding test dose signals. Estimates of De were achieved by comparing the natural luminescence signal with those induced by laboratory irradiation, and the regenerated growth curve for each sample was constructed using Duller's Analyst software, using an exponential fit for De calculation. This was done using the test dose value normalized fast component of the OSL (initial integral of 0.8 s) and the regenerated signals. The shine down curves (OSL intensity plotted as a function of light stimulation) and representative regenerated growth curves for samples LD1039-LD1042, LD1147, and LD1148 are shown in Suppl. Fig. S2. The disc-to-disc scatter (5–10%) is typical of that observed in quartz OSL measurement (Smith et al., 1990). The quartz shine down curve shows how the luminescence emitted by the mineral grains evolves as the electrons in the traps are emptied, rapidly for the first few seconds and then at a decaying rate. The growth curve is used to determine the laboratory dose that regenerates a luminescence signal that matches the intensity of the natural luminescence signal in the sample.

Additional aliquots were prepared for sample LD1039 to conduct a dose recovery test. The aliquots were first bleached (similar to natural bleaching) for 100 sec by blue LED stimulation and a known quantity (133.33 Gy) of dose was applied using the calibrated beta source (Sr/Yr^{90}) in the instrument. The given dose was recovered using the SAR protocol. The dose recovery test was carried out at various pre-heat temperatures (200, 220, 240 and 260°C), showing that the recovered value is always within error limits and does not show any systematic changes with pre-heat temperatures, and hence documenting the thermal stability of the quartz signal (pre-heat plateau). The results of the dose recovery test for this sample are shown in Suppl. Fig. S3.

Our samples show a wide distribution of De values, perhaps due to partial bleaching during transportation. Thus, the abnormally high De values were omitted from subsequent calculations, and the De value was obtained from between 8 and 20 aliquots (out of 35-39 per sample). For the annual dose rate estimation, the concentrations of uranium, thorium and potassium in the samples were measured by XRF and the water content was determined by heating at 100^{o}C. No measurements for cosmic ray contribution were carried out. The ages were calculated using AGE (Grun, 2009), which uses the depth of the sample below the surface to determine the cosmic dose rate, assuming a sediment density of 2000 kg/m^3 using a standard value of 150 µ Gy. The ages were calculated using the weighted mean of De divided by the dose rate value. We argue that the weighted mean is a better estimate of age as it will depend upon the actual distribution of De values. However, we have provided the least De values and associated ages in Table 1.

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Supplementary Figures

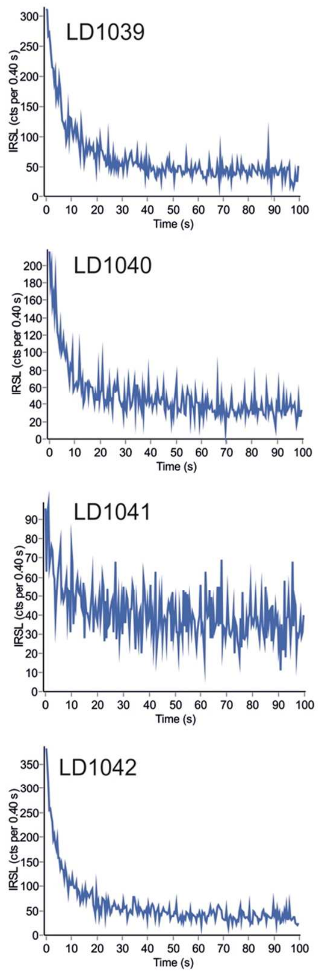

Fig. S1. IRSL signal for samples LD1039 to LD1042. Low values of the IRSL signal suggest that feldspar contamination in the samples is negligible.

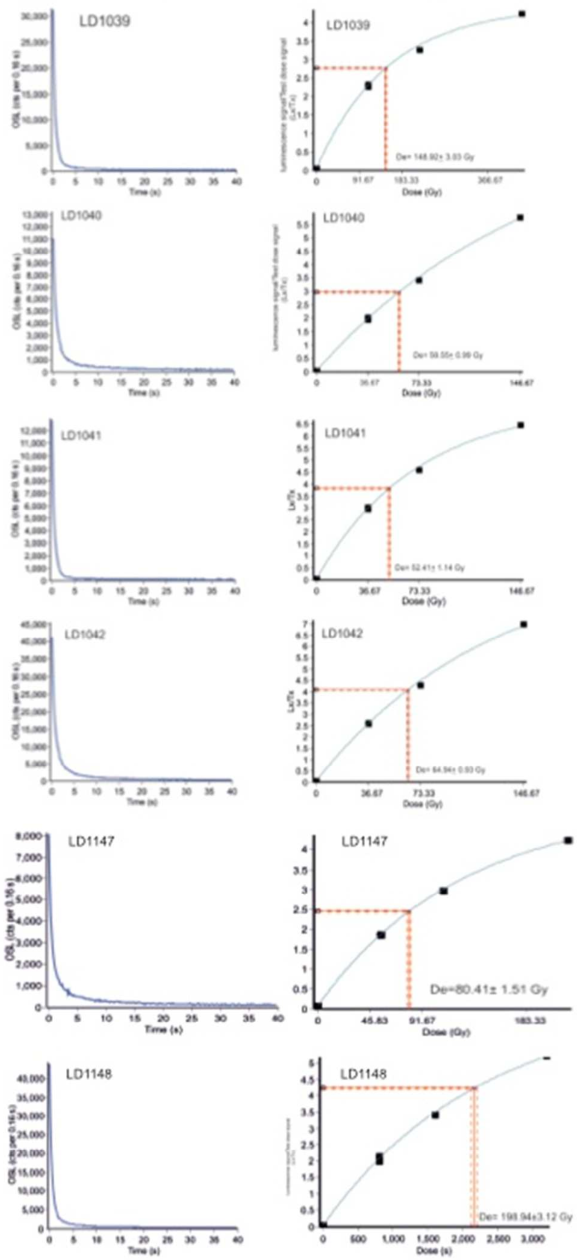

Fig. S2. Shine down curves (equivalent dose versus stimulation time, left panels) and regenerated growth curves (test dose normalized luminescence intensity versus laboratory beta dose, right panels) for equivalent dose determinations for samples LD1039 to LD1042, LD1147, and LD1148.

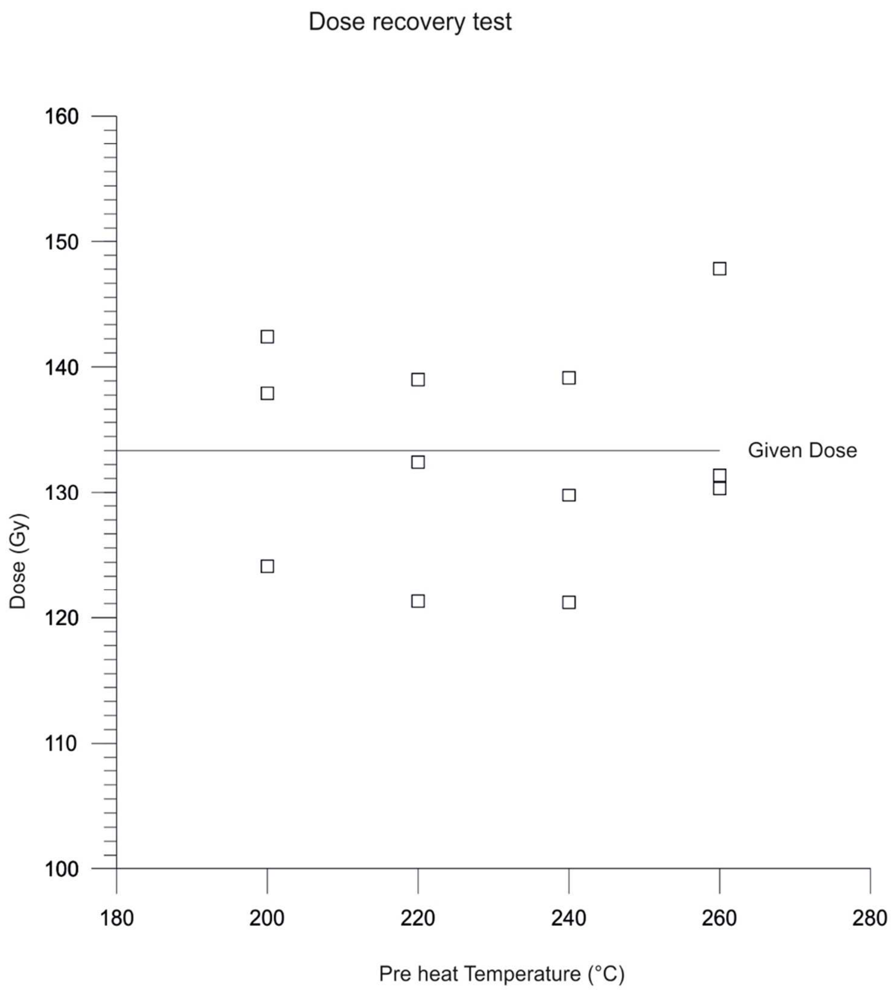

Fig. S3. Results of dose recovery test for sample LD1039. The applied beta dose (133.33 Gy) was successfully recovered using quartz SAR protocol. The test was carried out at various pre-heat temperatures (200, 220, 240, and 260°C), which shows the thermal stability of the quartz OSL signal and the suitability of the material for OSL dating.