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Late quaternary fluvial incision and aggradation in the Lesser Himalaya, India

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Abstract

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Late Quaternary fluvial incision and aggradation in the Lesser Himalaya, India

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Abstract

Reconstructing how rivers respond to changes in runoff or sediment supply by incising or aggrading has been pivotal in gauging the role of the Indian Summer Monsoon (ISM) as a geomorphic driver in the Himalayas. Here we present new chronological data for fluvial aggradation and incision from the Donga alluvial fan and the upper Alaknanda River, as well as a compilation of previous work. In addition to conventional OSL-SAR (Single-Aliquot Regenerative-Dose) dating method, we have tested and applied pulsed OSL (POSL) dating for quartz samples that include K-rich feldspar inclusions, which is expected to improve the applicability and validity of OSL ages in the Lesser Himalaya. For previously dated deposits, our OSL ages are shown to be systematically older than previously reported ages. These results suggest periods of aggradation in the Alaknanda and Dehradun Valleys mainly between ~25 and 35 ka. This most likely reflects decreased stream power during periods of weakened monsoon. In addition, in-situ cosmogenic beryllium-10 was used to infer bedrock surface exposure ages, which are interpreted as episodes of active fluvial erosion. Resulting exposure ages span from 3 to 6 ka, suggesting that strath terraces were exposed relatively recently, and incision was dominant through most of the Holocene. In combination, our results support precipitation-driven fluvial dynamics, which regulates the balance between stream power and sediment supply. On a larger spatial scale, however, fluvial dynamics are probably not spatially homogeneous as aggradation could have been taking place in adjacent catchments while incision dominated in the study area.

1. Introduction

Earth's surface is shaped by the interaction of tectonic, climatic, and - more recently- anthropogenic processes. A particularly crucial question is how landscapes respond to changing climatic conditions over millennial timescales. For instance, how do rivers respond to a change in rainfall, or air temperature and consequent changes in vegetation cover, sediment yield, or water supply by melting snow or ice? Future global warming has predicted a decreasing return period of extreme rainfall events (Huntingford et al., 2003). This also increases flooding risk (Ashley et al., 2005) and might impact fluvial erosive power and sediment transport capacity. Tucker and Slingerland (1997) showed that river response to changes in runoff is non-linear, possibly explaining the complex relationship between runoff and what we term hereafter *fluvial dynamics*, i.e. how rivers aggrade and incise over a time interval of interest. Some of this complexity arises from the type of forcing signal on the sediment flux (Simpson and Castelltort, 2012): an increase in sediment flux is amplified downstream, when associated with increased discharge; while it is dampened if it occurs without an increase in discharge, such as bank erosion or earthquake-triggered landsliding.

We can learn much about how fluvial dynamics responded to past climatic change by chronologically constraining times of local to regional-scale fluvial erosion and deposition. In this context, sedimentary archives in alluvial plains (e.g. Rahaman et al., 2009) or ocean basins (e.g. Clift, 2006) provide continuous records of fluvial activity, however the information from sediment source to sink regions can be distorted or delayed for several reasons: (1) changes in characteristics (mineralogical, geochemical) of sediments can reflect sediment provenance or hydrodynamic sorting during transport, rather than hillslope and fluvial erosion in the source region; (2) the duration of sediment transport from source to sink can range from a few 1,000's to several 100,000's of years (Dosseto et al., 2006a; Dosseto et al., 2006b; Granet et al., 2007; Granet et al., 2010; Blöthe and Korup, 2013) so there can be a time lag between when information in the source region was produced and when it was recorded in the sedimentary archive; and (3) sediment transport can destroy environmental signals affecting sediment supply in source regions, and the potential for signal shredding increases with river length and depth (Jerolmack and Paola, 2010). For these reasons, sedimentary archives located in source regions are more likely to provide a reliable picture of past environmental changes. This is the case in Himalayan valleys, where thick fluvial terraces have developed and been preserved along the major rivers and alluvial fans, representing a promising but discontinuous sedimentary record for the reconstruction of late Quaternary fluvial dynamics (Srivastava et

al., 2008; Juyal et al., 2010; Ray and Srivastava, 2010). The investigation of these deposits has yielded contrasting interpretations of fluvial dynamics in the Himalayas. Some studies have suggested that rivers aggrade during periods of intensified Indian Summer Monsoon (ISM), in response to increased hillslope erosion and sediment supply (Pratt et al., 2002; Bookhagen et al., 2006; Juyal et al., 2010; Dutta et al., 2012). Conversely, others have proposed that aggradation in Himalayan fluvial systems occurs during periods of weakened monsoon, as a result of reduced stream power (Srivastava et al., 2008; Ray and Srivastava, 2010; Scherler et al., 2015). This debate on what drives fluvial aggradation and incision in the Himalaya is ongoing, and hinges on the ability of obtaining a reliable chronology of aggradation and/or incision. For example, radiocarbon dating provides equivocal chronologies with frequent age inversions (e.g. Scherler et al., 2015). While optically stimulated luminescence (OSL) dating has become a useful tool for dating alluvial deposits, it has proven difficult in the Himalayas (e.g. Juyal et al., 2010), and has been limited by several unsuitable OSL properties of quartz, such as large recuperation and unwanted luminescence signals. Strategies have been proposed to overcome these difficulties; one aim is to be able to differentiate quartz and feldspar signals, which can be challenging for instance when feldspar inclusions are present within the quartz crystal lattice. Ankjærgaard et al. (2010) proposed that pulsed-OSL (POSL) can achieve this efficiently.

To produce a more complete picture of fluvial dynamics over time, one needs to also constrain the fluvial incision history. A common approach is to study strath terraces, which represent phases of lateral bevelling in rivers and can serve as approximate markers for subsequent fluvial incision. In-situ cosmogenic isotopes can be used to date strath terraces, even though the chronology can be equivocal for terraces with a complex burial and exposure history. Clearly, there is the need to combine geochronological techniques that constrain fluvial aggradation and incision (e.g. Scherler et al., 2015).

The Dehradun Valley in the Siwalik Hills and the Alaknanda River in the Lesser Himalaya offer an abundance of fill and strath terraces as well as alluvial fans (Singh et al., 2001; Juyal et al., 2010; Ray and Srivastava, 2010; Scherler et al., 2015). The study of these two valleys allows us to obtain a regional picture of fluvial dynamics, and discuss when localised episodes of aggradation and incision occur. Here, we use in-situ cosmogenic beryllium-10 along the Alaknanda River to infer bedrock exposure on strath terraces, and constrain a chronology of fluvial incision. Considering the challenges presented by quartz OSL dating of Himalayan

sediments, we performed a series of tests on samples derived from alluvial terrace deposits to evaluate the luminescence properties of quartz contained in these sediments (e.g. POSL) and thus devise a strategy to provide sound OSL ages. Following this approach, we identify episodes of aggradation and incision in the study area.

2. Study Area

2.1. Lithology, Regional Structure & Tectonics

The study area encompasses the Donga alluvial fan in the Dehradun Valley, and the Alaknanda River, a major tributary of the Ganga River. The ~230-km studied stretch of the Alaknanda River flows orthogonally across a thrust stack bounded by the Main Boundary Thrust (MBT) to the southwest, and the Main Central Thrust shear zone (MCT) to the northeast (Fig. 1). These two thrust faults also separate the Lesser Himalaya Series (LHS) from the High Himalayan Crystalline Series (HHCS) and Tethyan Sedimentary Series (TSS) to the north, and the Siwalik Hills to the south. The dominant lithology of the LHS is an imbrication of greenschist-amphibolite facies meta-sediments, and carbonates collectively known as the Krol-Chandpur-Berinag nappe system (Valdiya, 1978).

The Dehradun Valley is a crescent-shaped intermontane depression separated from the Lesser Himalayan Series in the north by the MBT, and bounded by the Ganga and the Yamuna Rivers in the east and west, respectively. The Siwalik Group underlying the Dehradun Valley is mid-Miocene to Pleistocene and mainly composed of fluvial sediments. It is thrust over the Himalayan Frontal Thrust in the south (HFT; Fig. 1), resulting in the Dehradun Valley forming as a piggyback basin (Singh et al., 2001). The valley is divided into three alluvial fans: Donga, Dehradun and Bhogpur, from west to east. This study focuses on alluvial sequences in the Donga Fan region.

Figure 1. A) Shaded relief of the Alaknanda River catchment (based on ALOS AW3D30 DSM Ver.1.1 global topography data) with general patterns of the ISM in the Garhwal Himalaya (inset). Rectangles show zoomed-in regions in Fig. 2. B) Map of rainfall data for the study region (in mm/yr) shows two purple bands of high precipitation along the range front. Data from the TRMM (NASA Tropical Rainfall Measuring Mission; Mulligan, 2006). Yellow circles: alluvial deposit sampling locations; red circles: bedrock surface sampling locations. Squares: towns. Dashed curves denote the Alaknanda catchment drainage divide. HFT: Himalayan Frontal Fault; MBT: Main Boundary Trust; MCT: Main Central Thrust.

Figure 2. Shaded relief map for the study areas: (a) the Donga alluvial fan. Samples IND02 and IND03 are from terraces of the Suarna River. (b) and (c) Alaknanda River valley. Blue curve: Alaknanda River. Yellow circles: alluvial deposit sampling locations; red circles: bedrock surface sampling locations.

2.2. Catchment Hydrology & Channel Morphometrics

Warm moisture of the Indian Summer Monsoon (ISM) is dominantly sourced from the Arabian Sea (Gimeno et al., 2010), before being delivered to the intra-montane valleys of North Central India (Hren et al., 2009; and references therein). A two-step adiabatic sequence currently attenuates precipitation to the north before warm monsoonal air masses encounter the impenetrable 6000+ m peaks of the Garhwal Himalaya. The Siwalik Hills receive precipitation of $\sim 2750 \text{ mm yr}^{-1}$, while the Lesser Himalaya receives $\sim 2200 \text{ mm yr}^{-1}$ in an elevation band of 1200-2600 m (Fig. 1B). Penetration of these orographic barriers is likely to have varied through time (Bookhagen et al., 2005), depending on the strength of the ISM. This is illustrated by the variable provenance of detrital sediments within alluvial terraces below the MCT (Srivastava et al., 2008) and alluvial deposits in the Ganga Plain (Rahaman et al., 2009). The annual precipitation during the summer months favours large floods with stream power $> 900 \text{ W.m}^{-2}$; compared to $60\text{--}10 \text{ W.m}^{-2}$ along the Ganges floodplain (Ray and Srivastava, 2010).

The Alaknanda River catchment covers 10,237 km², with 60% of the catchment lying below the limits of late Pleistocene glacial influence at 3850 m.a.s.l. (Nainwal et al., 2007). Flowing from Satopanth and Bhagirath Kharak glaciers, the trunk channel is joined by the Pindar, Mandakini, Nandakini, and Dhualiganga rivers before merging with the Bhagirathi River at Devprayag. The Donga Fan drains 220 km², of which about 52 km² are north of the MBT. The Suarna River drains only 16 km². It incises through the Donga Fan and has formed a set of terraces, previously dated using OSL by Singh et al. (2001).

2.3. Field Sites & Geomorphic Observations

For cosmogenic isotope analysis, 18 samples (<4 cm thick) from fluvially-polished and -sculpted bedrock surfaces were collected from seven sites in the Alaknanda valley (Fig. 2). Geographic latitude and longitude (and projected coordinates in UTM Zone 44N on the World Geodetic System 84 datum) were recorded with a handheld GPS device. Altitude and relative height above the channel bed were also recorded, with an estimated vertical accuracy of $\pm 20\%$. The seven sampling sites have similar morphology characterised by a narrow, incised bedrock channel flanked by remnants of fluvially-polished bedrock surfaces adjacent to large cut and fill terraces (Fig. 3B). Quaternary fill sequences are best preserved below the MCT in V-shaped valleys 100-1000 m wide. The base of most terrace sequences consists of local colluvial sheets or shallow debris flows (Srivastava et al., 2008). Narrow epigenetic gorges (Ouimet et al., 2008) up to 50 m deep occur at some entrenched paleochannel cutoffs and may explain the existence of isolated, mid-valley bedrock ridges. The remnants of fluvially-polished and -sculpted bedrock surfaces, found up to 135 m above the channel, are not continuous and can occur in marginal and mid-valley settings. The strongly fluted surface of the extensive uppermost bedrock strath at Bamoth (Fig. 3C), San and Bairdand, distinguishes these surfaces 50-70m above the channel.

For luminescence dating, alluvial deposits were sampled from two fluvial regions for which some chronology of aggradation exists: (i) the Donga alluvial fan in the Dehradun Valley, and (ii) the Alaknanda River (Fig. 1). Some sampled deposits were previously dated with OSL (Singh et al., 2001; Juyal et al., 2010; Ray and Srivastava, 2010), however they were re-sampled in order to assess the consistency of ages produced. In the Dehradun Valley, several sets of fluvial terraces flank the Suarna River, a tributary of the Yamuna River (Singh et al., 2001) (Fig. 2A). A sample was collected from the terrace termed ST6 in Singh et al. (2001) (~823 m a.s.l.), located ~110 m above the channel (sample ID: IND03); and another from the

203 lowest terrace ST2 (~745 m a.s.l.), ~20 m above the channel (sample ID: IND02). Two samples
204 were also collected from a section on the surface of the Donga alluvial fan, at field section D3
205 in Singh et al. (2001) (Fig. 2B): one was collected near the top of the section (sample ID:
206 IND05), 7.3 m below the surface; and the other one near the bottom, >20 m below the surface
207 (sample ID: IND04). This section is composed of Unit GD-III in Singh et al. (2001), consisting
208 of gravel beds with minor, poorly sorted unorganised pebbles and cobbles. It was interpreted
209 as having been deposited from braided streams (Singh et al., 2001). In the Alaknanda Valley,
210 fluvial terraces near Srinagar and previously described in (Juyal et al., 2010; Ray and
211 Srivastava, 2010) were also sampled: six samples were collected from terraces T6, T5, T4, T3,
212 T2 and T1 (Fig. 2; sample IDs: IND 62, 63, 64, 65, 72 and 73T, respectively).

Figure 3. Field photos of selected sampling sites. A) Fluvial gravels and sand lens at Srinagar (sample IND64). B) Abandoned bedrock channel (dashed arrow showing direction of flow) separated from the main Alaknanda channel by a bedrock ridge (vertical arrow) at Devprayag (note the presence of recent fluvial sediment in the bedrock paleochannel). C) Gholtir site, looking downstream (south), also showing an abandoned bedrock channel (dashed arrow showing direction of flow) and bedrock ridge (vertical arrow). D) Bamoth site, palaeo-bedrock channel, looking downstream (south); a bedrock ridge (vertical arrow) separates the palaeo-channel from the active channel, which lies at a lower elevation than the palaeo-channel. E) Top of the bedrock ridge at Bamoth (looking east); the ridge displays a typical example of a fluvially-sculpted and fluted bedrock surfaces, similar to the surface of San and Bairdand strath

terraces described by Barnard et al. (2001). F) Polished bedrock with fluvial abrasion marks and G) flutes ~1.5 m above dry season river level along the lowermost bedrock ridge at Bamoth.

3. Methods

3.1. Luminescence dating

Luminescence dating was performed at the Korea Basic Science Institute. In the subdued darkroom, the samples were wet sieved to recover the 180-250 μm size fraction which was treated with 10% HCl (1h) and 10% H₂O₂ (1h). This was followed by heavy liquid separation using sodium polytungstate (SPT; $2.62 < \rho < 3.00 \text{ g/cm}^3$) to extract the quartz-rich fraction. This fraction was then etched with 40% HF for 1 hour.

All the OSL measurements were carried out with a standard Risø system (TL/OSL-DA-20), which is equipped with a ⁹⁰Sr/⁹⁰Y beta source delivering $\sim 0.116 \pm 0.003 \text{ Gy/s}$ to the sample position. Blue-LED array ($470 \pm 30 \text{ nm}$) was used as a stimulation light source with a maximum power density of $\sim 80 \text{ mW/cm}^2$. Photon detection was through 7mm of Hoya U-340 filter. Quartz CW (continuous wave)-OSL signals were measured for 40 s at 125 °C with constant stimulation power. The reader is also equipped with a POSL (Pulsed OSL) attachment which was used to measure POSL of the samples. As suggested by Ankjærgaard et al. (2010), the POSL signal is useful to maximize the luminescence signal ratio between quartz and K-rich feldspar by adjusting the *on*- and *off*-time of the stimulation light pulse, particularly when there exists feldspar inclusions within quartz crystal lattice which cannot be chemically or physically eliminated. Because the reader used in this study does not have a photon counter, we could not determine the optimized *on*- and *off*-time combination for each sample. Instead, we applied *on*- and *off*-time combinations of 50 μs each, which is suggested for the best separation of quartz and K-rich feldspar signals in Ankjærgaard et al. (2010). For POSL dating, only *off*-time signal was used.

Equivalent dose (D_e) values were derived using the single-aliquot regenerative-dose protocol (SAR protocol; Murray and Wintle, 2000; Murray and Wintle, 2003). For most samples, the signal intensity was so low that we decided to use multiple-grains for dating (aliquots with the masking size of 8 mm, consisting of several thousands of sand-sized quartz grains); in particular, samples from the Alaknanda Valley (IND62-65) show initial CW-OSL count rates of several hundreds to a few thousand counts per 0.16 s even with large aliquots. The Central Age Model (CAM; Galbraith et al., 1999) was applied to calculate the final D_e values. In addition, where partial bleaching was suspected as reported in Ray and Srivastava (2010), we also tested MAM ages using the numOSL R™ package of Peng et al. (2013). For dose rate

estimation, radionuclide concentrations were measured using a low-level high resolution gamma spectrometer. Conversion to dose rates used the data presented by Olley et al. (1996). Cosmic ray contributions to dose rates were assessed by the method in Prescott and Hutton (1994).

3.2. *In-situ cosmogenic ^{10}Be*

Sample processing was undertaken at the Australian Nuclear Science and Technology Organization (ANSTO). For bedrock samples, quartz was isolated, purified, digested, and chemically isolated to target ^{10}Be for accelerator mass spectrometry on the ANTARES accelerator using an ANSTO protocol modified from Kohl and Nishiizumi (1991). Quartz fractions were also isolated from selected sediments analysed for OSL. They were not processed for ^{10}Be determination but analysed for aluminium (Al) concentrations by single collector ICP-MS at the Wollongong Isotope Geochronology Laboratory (University of Wollongong) using a ThermoFisher iCAP-Q. Samples were introduced in 0.3M HNO_3 using a concentric nebulizer and cyclonic spray chamber. Standard nickel cones were used. Concentrations were calculated using an external calibration curve, established by analysing 13 calibration standards with concentrations ranging from 0 to 250 ppb. A procedure blank was processed with the samples and contributed to the mass of Al from the samples by $<0.3\%$. For ^{10}Be determination, potential boron contamination was accounted for by using full procedural blanks with a $^{10}\text{Be}/^9\text{Be}$ of $3.96 \pm 0.96 \times 10^{-15}$ (Fink, 2007), while drift in the AMS detector was quantified by periodic measurements of the NIST-4325 standard. The exposure ages presented in Table 1 were calculated from measured radionuclide concentrations using a half-life for ^{10}Be of 1.387 ± 0.012 My (Fink, 2007), a sea-level high latitude (SLHL) production rate of $4.60 \text{ at}\cdot\text{g}^{-1}\cdot\text{y}^{-1}$ (including 2.5% surface production for muons) adjusted for latitude, atmospheric pressure, and local topographic shielding. There was no palaeo-geomagnetic correction made to this dataset as calculated SLHL production rates inherently integrate geomagnetic polar wander over their respective exposure timescales (see Balco et al., 2008; and references therein). Exposure ages are considered minimum values because of the potential and uncertain attenuation of cosmic radiation.

4. Results

4.1. *Luminescence dating experiments and inferred ages*

4.1.1. *CW (continuous wave)-OSL signal properties*

To test whether the samples have suitable OSL properties for dating, we first examined their quartz CW-OSL signals. All the natural CW-OSL signals (*i.e.* non-irradiated quartz) were read after preheating at 260 °C for 10 s. CW-OSL signals of all the samples from the Dehradun Valley (IND02-05) and two samples from the Alaknanda Valley (IND 72 and 73T) reached 10% of their initial signal intensities between 2-10 s after the onset of blue stimulation (Fig. 4). However, the remaining samples from the Alaknanda Valley (IND 62-65) showed slowly decaying curves, with OSL signal intensities still significantly above 10% of the initial signal intensity even after 40 s of stimulation. Note that for well-behaving quartz grains, e.g. Risø calibration quartz for instance, the CW-OSL signal intensity reaches less than 10% of its initial counts in less than a few seconds of blue stimulation.

Figure 4. Quartz CW-OSL signals. Signals were measured at 125 °C for 40 s after preheating at 260 °C for 10 s. All the CW-OSL curves were normalised to the initial count rates. In the inset, the curves are displayed with a logarithmic scale for the x-axis.

4.1.2. Dose recovery test

In order to examine the ability of commonly-used SAR procedures to recover the known laboratory dose (Murray and Wintle, 2000; Wintle and Murray, 2006), we performed a dose recovery test, in which three aliquots of each sample were bleached with blue-LED for 2,000

s twice, with an intervening pause of 10,000 s to remove charges in thermally unstable traps. After administering known beta doses to each aliquot (taken as surrogate natural doses), conventional SAR procedure was applied. In this performance test, preheat temperatures of 220 °C and 260 °C (for 10 s for both) were applied for comparison, with a fixed cut-heat (*i.e.* test dose preheat) of 220 °C for 0 s. Aliquots were stimulated with IR-LED at 50°C for 100 s prior to every blue stimulation to reduce any possible contributions from K-rich feldspars. As expected from the slowly decaying CW-OSL properties, some of the samples failed to recover the laboratory doses (Fig. 5). In particular, for samples IND62-65 (all from the Alaknanda Valley) the measured doses showed significant variation when applying preheating of 260 °C. In addition, recuperation levels far exceeded 10% of the natural signal for these samples. The dose recovery results did not show any improvements when a preheat of 220 °C was applied, although there was a clear improvement in recuperation level. Most samples (except IND 04, 72) showed recycling ratios within ± 10 % of unity for both applied preheat temperatures. The measured/given dose ratios for samples from the Dehradun Valley (IND02-05) were all within ± 10 % of unity when preheating at 220 °C was applied (Fig. 5). Dose recovery results and OSL signal indicators (recuperation and recycling ratio) of sample IND72 was not satisfactory for both preheat temperatures, thus this sample was not considered further.

Figure 5. Results from SAR dose recovery test of all OSL samples showing the measured/given dose ratio (top), recuperation levels and recycling ratios (bottom). Red and black symbols are for 220 °C and 260 °C preheats, respectively. In the bottom panel, squares are recycling ratios and circles are recuperation levels.

4.1.3. IRSL (Infrared Stimulated Luminescence) vs OSL

The slowly decaying CW-OSL properties and the failure in dose recovery test, as shown for samples from the Alaknanda Valley (IND 62-65), may be attributed to either K-rich feldspar inclusions within the quartz crystal lattice or significant contributions from slower OSL components (e.g. Choi et al., 2003). To examine this, we treated the quartz fractions with 40%

HF for an additional 4 hrs and compared the IRSL/OSL signal proportions (one aliquot for each sample); here OSL signal means the luminescence signal stimulated by blue LEDs. Even with prolonged HF etching, slowly decaying samples from the Alaknanda Valley showed significant IRSL signal intensities, more than 100% compared with quartz OSL signals (Fig. 6). Thus, the slowly decaying CW-OSL features of these samples (IND62, 63, 64, 65) are presumably attributed to the presence of K-rich feldspar inclusions within quartz crystal lattices. This is supported by Al concentration measurements in quartz aliquots of the same sediment samples, prepared for in-situ ^{10}Be . Although optical analysis using a binocular microscope shows aliquots are almost entirely quartz, Al concentrations show values as high as 5,000 ppm (Table S1). This clearly indicates that quartz grains contain inclusions of aluminosilicates.

Figure 6. Ratio of IRSL to blue OSL (BSL) signal intensities. Here, OSL signal refers to the signal stimulated by blue LEDs. In this experiment, each sample was bleached and β -irradiated, similarly to their natural doses as in the dose recovery test. Then, samples were preheated at 220°C for 10 s (red circles) and 260 °C for 10 s (black circles), followed by IRSL (at 50 °C for 40 s) and OSL (at 125 °C for 40 s) readout. Both IRSL and OSL signals were measured for 40 s at 125°C. The signals measured during the initial 0.8 s were background-corrected and used to calculate the IRSL to BSL ratios. The background was determined using the last 4 s.

4.1.4. Dose recovery test using pulsed OSL (POS�)

It has been recently reported that, in a mixture of quartz and K-rich feldspar, the OSL (from quartz) to IRSL (from K-rich feldspar) signal ratios can be maximised by pulsing the

stimulation light and reading out *off-time* signals only (e.g. Ankjærgaard et al., 2010). Thus, we investigated the applicability of POSL signals to dating through a dose recovery test. Four samples were selected for this experiment; two samples for which IRSL/OSL ratios were less than 20% (IND02 and 73T) and two which showed significant IRSL contributions (>170%) compared with OSL signals (IND62 and 63) (Fig. 6). In this experiment, three aliquots of each sample were bleached and dosed in the same manner as conventional dose recovery tests (see above). Then, after a preheat of 220 °C for 10 s and IR bleaching at 150 °C for 100 s, the aliquots were stimulated by pulsed blue-LEDs at 125 °C for 80 s (equivalent to 40 s of CW stimulation). We adopted the optimised *on- and off-time* combination (or *gating time*) of 50 µs, as suggested by Ankjærgaard et al. (2010). The signal measured during the initial 1.6 s of POSL curves (equivalent to 0.8 s of CW-OSL signal) was used to obtain measured doses.

There was a clear improvement in the dose recovery test, in particular for samples IND 62 and 63, with measured/given dose ratios within 10 % of unity (Fig. 7). Furthermore, the recuperation level and the recycling ratios were much improved. Consequently, for samples from the Alaknanda Valley, OSL ages were derived using pulsed OSL mode applied to the SAR protocol, where a preheat of 220°C (for 10 s) and cut-heat of 220°C (for 0 s) were used. IR bleaching at 150°C for 100 s was also applied before every quartz POSL signal measurements. While the number of aliquots was small for samples IND62-65 (n=8-9) compared to the other samples, tests on a larger number of aliquots for IND62 and IND63 (n=22 and 21, respectively) show no significant difference in D_e values and thus final age estimates (Table 1).

Figure 7. Dose recovery test using POSL (IR stimulation at 150 °C for 100 s prior to every blue stimulation at 125 °C for 80 s; both on- and off-time were set to be 50 μ s with an on-gate delay of 5 μ s).

4.1.5. OSL ages

4.1.5.1. Dehradun Valley and Donga alluvial fan

Our OSL ages for samples IND 02-05 range between 21 and 47 ka (Table 1); conventional SAR protocol using the preheat at 220°C for 10 s and the cut-heat at 220°C (for 10 s) was applied. The representative CW-OSL decay and the growth curves of the samples IND03 and 05 are shown in Fig. 8A-B. For IND 02, we obtained an age of 21 ± 2 ka (1σ standard errors are reported throughout) while ST2, which comes from the same location and stratigraphic context, was dated at 10.7 ± 2.4 ka in Singh et al. (2001). Conversely, there is agreement between OSL dating of ST6 in Singh et al. (2001) (29.4 ± 1.7 ka) and our OSL age of 33 ± 3 ka from sample IND 03. Our results for samples IND04 and 05 give ages of 47 ± 4 ka and 44 ± 3 ka, respectively. Previously, bottom and top parts of the section were dated at 20.3 ± 7.5 ka and 9.4 ± 0.6 ka, respectively (Singh et al., 2001). Again, our OSL ages are significantly older than previous estimates and imply that >20m of sediments were deposited over a short interval at ~45 ka. The causes of the differences in OSL ages between this work and those in Singh et al. (2001) could

not be investigated, because details of OSL dating, particularly the measurement protocol applied and other prerequisite experimental results, were not reported in Singh et al. (2001).

4.1.5.2. Alaknanda Valley

For samples of the Alaknanda Valley, test results for OSL properties were only satisfactory for IND73T and thus while this sample was dated using conventional quartz CW-OSL signals, others were dated using quartz POSL signals (preheat at 220°C for 10 s and cut-heat at 220°C for 0 s) (Fig. 8C-D). At Srinagar, our OSL ages range between ~3.5 and ~47 ka. The lowermost terrace T1 at ~5 m above dry season water level, had not been dated previously and yielded an age of 3.5 ± 0.2 ka. For terraces T2 to T5, we obtained ages ranging from 47 ± 5 to 21 ± 2 ka (Fig. 9). This supports previous suggestions that the sequence T2-T5 represents a single cut-and-fill terrace, but ages calculated here are much older, and span a much wider range than found by Ray and Srivastava (2010) (17 ± 2 to 14 ± 1 ka) and Juyal et al. (2010) (15 ± 1 to 6 ± 1 ka). For terrace T6, we could not calculate an age since the D_e values were much higher than the $2D_0$ (characteristic dose) values (Wintle and Murray, 2006). Ray and Srivastava (2010) showed that sediments could have undergone partial bleaching. In order to assess whether this could significantly affect our samples, we used a Minimum Age Model (MAM) to estimate doses. In multiple-grain single-aliquot scale, the calculated ages were similar to CAM values (Table 1). It is worth noting that the multiple-grain aliquots, our ability to detect incomplete or heterogeneous bleaching is limited. Younger ages previously published may result from incomplete removal of K-rich feldspar contamination from quartz grains, despite the IRSL cleaning step added in the SAR protocol (e.g. Ray and Srivastava, 2010). It should be noted that, because internal K contents in K-rich feldspar inclusions were not considered in the final age calculations, the OSL age estimates presented here may slightly overestimate the depositional ages. However, considering the low K contents in quartz as shown in Table S1, the OSL age overestimation, if any, is limited to less than 2%. Thus, the effect from the internal K contents is not considered further in the discussion.

Figure 8. The decay and growth curves of the conventional OSL signals in quartz from the Dehradun Valley (a: IND03, b: IND05), and those constructed using quartz POSL signals of samples from the Alaknanda Valley (C: IND62, d: IND65).

437

438 Figure 9. Cross-section of alluvial deposits (in yellow) at Srinagar (modified from Ray and
 439 Srivastava, 2010). Dots show samples collected, and values in italics are OSL ages from this
 440 study.

441

442 4.2. Exposure ages

443 Calculated minimum exposure ages are presented for each site in sequence with increasing
 444 distance from the headwaters (Table 2). At Pipalkoti, back-tilted cut-fill terraces dominate the
 445 broad valley, rising more than 100 m above the modern channel (Fig. 3). Two samples were
 446 collected from a bedrock ledge on the southern valley margin at the same elevation (~1120 m
 447 asl) as the top of terrace T2 in Juyal et al. (2010). For these two samples, we calculated
 448 minimum exposure ages of 7.6 ± 0.7 and 8.8 ± 0.8 ka. At Langasu, fluvially-sculpted bedrock
 449 ledges were sampled at ~17 and 9.5 m above the channel. The corresponding calculated
 450 minimum exposure ages are 2.7 ± 0.3 ka and 1.9 ± 0.2 ka, respectively.

451 At Bamoth, a ~40 m wide and 250 m long fluvially-sculpted bedrock ridge stands ~45 m above
 452 the river and separates the active channel from a palaeo-bedrock channel 35 m above the active
 453 channel (Fig. 3B, C). On top of the bedrock ridge, we obtained an exposure age of 0.7 ± 0.1 ka.

In the palaeo-bedrock channel, four exposure ages were determined and range from 0.5 ± 0.1 to 2.7 ± 0.3 ka. One hundred fifty meters upstream, a smaller ~40 m long and ~8 m high bedrock ridge is exposed along the northern margin of active channel, showing abundant evidence of bedrock erosion by polishing, abrasion and fluting (Fig. 3F,G). An 8-m profile taken from this lower ridge (IND93, and IND129-132) returned exposure ages ranging from 0.8 ± 0.1 to 1.9 ± 0.2 ka, increasing with elevation above the channel.

Gholtir displays a similar geomorphic setting to Bamoth and has a bedrock palaeochannel which is separated from the lower, modern channel by a bedrock ridge (Fig. 3C). Three samples were collected. The highest sample (IND85) from the bedrock ridge yielded a minimum exposure age of 5.0 ± 0.5 ka (Fig. 3A). The middle sample (IND86) is from the fluvially-polished bedrock palaeochannel ~15 m below the bedrock ridge and yielded a minimum exposure age of 2.1 ± 0.5 ka. The lowermost sample (IND83) comes from a fluvially-sculpted bedrock outcrop along the modern river and yielded a minimum exposure age of 0.5 ± 0.1 ka.

Nagrasu also features an epigenetic gorge incised ~30 m below an adjacent bedrock palaeochannel. Another bedrock palaeochannel is located 135 m above the active riverbed and was sampled. This yielded a minimum exposure age of 9.4 ± 0.9 ka. At Tilani, the Alaknanda River valley is constricted into a deep gorge. Bedrock is exposed and there is no sign of alluvial deposit, most likely as a result of the lack of accommodation space. A bedrock sample was collected from the top of the 90-m deep bedrock gorge. It returned an exposure age of 27.3 ± 2.5 ka. Finally, Devaprayag, the most downstream site, is near the confluence with the Bhagirathi River and displays a channel morphology similar to Langasu. A single sample was taken from a bedrock ledge in a very confined valley reach devoid of significant alluvial cover, ~15 m above the narrow modern channel. Here an exposure age of 2.4 ± 0.3 ka was obtained.

5. Discussion

Establishing a chronology of fluvial aggradation in the Himalayas has been a challenge, in part because of the poor luminescence properties of Himalayan quartz. Despite acknowledging this difficulty, most studies which have attempted to undertake OSL dating of Himalayan alluvial terraces have used the standard SAR protocol on quartz (Table 3). However, for some samples from this region, this protocol is not suitable as illustrated by failed dose recovery tests. Some studies have used the MAAD (Multiple-Aliquot Additive-Dose) protocol as an alternative (Thakur et al., 2007; Juyal et al., 2010), however this does not address the presence of IRSL

signal as outlined above. Our results show that IRSL signal in quartz is a major complication in this setting, particularly for samples from the Alaknanda Valley, adding to the poor luminescence sensitivity common for quartz from young orogens. While IRSL cleaning has been employed in previous studies to address this issue (e.g. Ray and Srivastava, 2010), our dose recovery results seem to imply that signal separation by pulsing the stimulation light source (after the IR bleaching at 150°C for 100 s) should yield more robust ages than when only IRSL cleaning is used in the SAR protocol. One issue that remains untested is potential partial bleaching of the grains. Ray and Srivastava (2010) showed that grains from an alluvial fill at Seroli exhibited heterogeneous bleaching. The observation of older ages using our protocol compared to previously published values is validated by comparison of sediments from the same alluvial deposits. Partial bleaching would have affected equally previously published OSL ages and our estimates.

Bootstrap resampling of our OSL ages returns a weighted mean age ranging from 24 to 36 ka (5% and 95% quantiles, respectively; Fig. 10). This is significantly older than the ages previously inferred for the same deposits, which ranged between 8 and 15 ka (Singh et al., 2001; Ray and Srivastava, 2010). Singh et al. (2001) did not report any tests, such that it is difficult to assess the validity of ages for the latter study (Table 3). Ray and Srivastava (2010) reported shine-down curves and dose distributions. They subjected samples to an additional HF etching for 20 min and included an IRSL cleaning step (for 100 sec at 60 °C) to remove K-rich feldspar components, however we show here that even with an additional etch of 4 hr the contribution of IRSL to the luminescence signal is still significant. While they used the weighted mean of the lowest 20% paleodose values to calculate ages, which could explain why their ages are younger than ours, ages calculated using their mean paleodose (i.e. similar to our calculation) yield values still significantly lower than ours.

Juyal et al. (2010) showed that their samples displayed recycling ratios between 0.9 and 1.1, and recovered doses within 10% of given doses, suggesting satisfactory OSL properties. Srivastava et al. (2008) retained aliquots with recycling ratios between 0.9 and 1.1, but the shine-down curve reported showed a relatively slow decay. Suresh et al. (2007) reported shine-down curves, which clearly showed slow decay; while Thakur et al. (2007), Sinha et al. (2010) and Dutta et al. (2012) did not report any OSL tests.

There is a broad negative relationship between previously published ages and the degree of quartz OSL age under-estimation (Fig. 11). This is supported by the observation of quartz OSL ages younger than corresponding IRSL ages for Himalayan sediments in the neighbouring Yamuna Valley (Scherler et al., 2015). Assuming this relationship is valid for alluvial deposits

across the Alaknanda and Dehradun Valleys, it can be tentatively used to estimate corrected OSL ages for previously published chronologies (Table 3). Bootstrap resampling of published ages returns a weighted mean age ranging from 14 to 17 ka (5% and 95% quantiles, respectively; Fig. 12), suggesting that aggradation mostly took place during the late Pleistocene. However, bootstrap resampling of tentatively ‘corrected’ ages returns a weighted mean age ranging from 24 to 31 ka (5% and 95% quantiles, respectively; Fig. 11), a range similar to that obtained when considering our OSL ages only. This is consistent with previous studies which place most of the aggradation at pre-Last Glacial Maximum, LGM (Suresh et al., 2007; Dutta et al., 2012; Scherler et al., 2015). Note that if instead of selecting a subset of samples to define the relationship between factor of age under-estimate and previously published ages (squares in Fig. 11), all data are considered; bootstrap resampling of the ‘corrected’ ages returns a weighted mean age ranging from 22 to 26 ka (5% and 95% quantiles).

Figure 10. Bootstrap resampling of the weighted mean of our POSL ages ($n = 9$), using the *boot* package in the R software (number of bootstrap replicates = 10,000).

Figure 11. Relationship between the factor of quartz OSL age under-estimation and previously published ages for the Alaknanda and Dehradun Valleys. For a given deposit, the factor of age under-estimation is calculated as the ratio of the OSL age determined in this study to that inferred in a previous study (Ray et al., 2010; Singh et al., 2001). The linear regression shown applies only to data represented by square symbols (the grey envelope shows the 95% confidence interval on the linear regression; multiple R^2 : 0.9615, p-value: 0.01945). It was used to 'correct' other previously published ages and represents a maximum correction (because considering all the data would result in lower correction factors).

Figure 12. Bootstrap resampling of the weighted mean of OSL ages from valley fills of the western Himalayas, using the *boot* package in the R software (number of bootstrap replicates

= 10,000). Red: previously published ages ($n = 122$); green: tentatively corrected ages for previously published values, using the approach detailed in Fig. 11 ($n = 122$). Source: (Singh et al., 2001; Suresh et al., 2007; Srivastava et al., 2008; Juyal et al., 2010; Ray and Srivastava, 2010; Sinha et al., 2010; Dutta et al., 2012). Data from Scherler et al. (2015) were not included as definite ages could not be defined. Ages from (Juyal et al., 2010; Ray and Srivastava, 2010) were not corrected since they report satisfactory OSL tests. Ages for Srinagar terraces in Ray and Srivastava (2010) were excluded since we used our values instead (although this does not affect the bootstrapped mean age distribution).

Most records of incision are indirect since they are derived from the absence of dated alluvial terraces. Only a few studies have given a chronology of incision, by dating of bedrock straths (Barnard et al., 2001; Pratt et al., 2002; Pratt-Sitaula et al., 2004). However, this approach has its limitations too since it dates exposure of bedrock, which can postdate incision if the bedrock surface was covered with alluvium. Thus, cosmogenic-derived bedrock exposure ages, which analytically already are minimum exposure ages, also provide minimum ages for the onset of fluvial incision.

Bedrock exposure ages range from 0.5 ± 0.1 to 9.4 ± 0.9 ka (Table 2). Barnard et al. (2001) dated two strath terraces in the Alaknanda Valley, yielding ages between 13 and 16 ka ($n=4$). Taken together, bootstrap resampling of our exposure ages returns a weighted mean age between 2.7 and 6.2 ka (5% and 95% quantiles, respectively; Fig. 13). As indicated above, in most cases the river would have had to erode valley fills before exposing bedrock. Thus, incision probably started in the early Holocene, at the latest, in agreement with Scherler et al. (2015), coinciding with peak ISM intensity, as inferred from a range of continental records (Sanyal and Sinha, 2010).

Figure 13. Bootstrap resampling of the weighted mean of compiled exposure ages (in ka), using the *boot* package in the R software (number of bootstrap replicates = 10,000). Data from this study and Barnard et al. (2001).

Our results suggest that aggradation most likely took place between ~25 and 35 ka. A warm and humid climate has been proposed for this period (Lehmkuhl and Haselein, 2000; Shi et al., 2001; Yu et al., 2003; Yang et al., 2004; Yang and Scuderi, 2010), although this has been recently contested (Long et al., 2016) and Sanyal and Sinha (2010) have also shown that the ISM was weaker during that time compared to the Holocene. Previous studies have proposed that aggradation occurred during periods of intensified ISM (Juyal et al., 2010; Dutta et al., 2012). However, OSL ages may have been tainted by under-estimation. Fill terraces were dated at 7 ± 1 ka in the Marsyandi Valley (Nepal) (Pratt et al., 2002) and from 3 to 10 ka in the Sutlej Valley (northwest Himalaya) (Bookhagen et al., 2006). In both cases, alluvial terraces were dated using cosmogenic isotopes and thus these results are not flawed by the potential under-estimation of OSL ages. This discrepancy with the chronology from our study site could indicate spatial differences in fluvial dynamics: in the Holocene, aggradation was operating in the Marsyandi and Sutlej Valleys, while at the same time incision was dominating the Alaknanda Valley.

While also potentially affected by under-estimation of OSL ages, other studies support aggradation during weakened ISM (Srivastava et al., 2008; Ray and Srivastava, 2010). Suresh et al. (2007) showed that aggradation took place in the Pinjaur Dun (west of the Dehradun Valley) at 100-80 ka and 70-25 ka, with minor episodes at 16 and 4 ka. They also proposed

that incision was driven by strong ISM between 80 and 70 ka, and after the LGM, as inferred independently from other continental records (Sanyal and Sinha, 2010). In this case, aggradation between 70-25ka was hypothesized to reflect a response to tectonic quiescence. In the same region, Scherler et al. (2015) argued that aggradation occurred from 50 to 10-15 ka during an arid late Pleistocene, followed by incision during a humid Holocene.

We propose that aggradation was taking place during a period of variable climate and weaker ISM, when sediment supply could have increased as a result of (peri-)glacial processes. Enhanced landslide activity could be another possible driver for enhanced sediment supply, in response to the variable nature of climate at 25-40 ka (despite a weaker ISM). However, this would contrast with studies proposing that landslide activity is increased during periods of strong ISM (e.g. Bookhagen et al., 2005). Incision was taking place in the Holocene, when stream power could have increased in response to intensification of the monsoon. While tectonic activity must play a role on fluvial dynamics, it does not overprint the climatic control and generally operates on longer timescales, although we may lack the resolution in alluvial records to confidently affirm this. Thus, within a given valley, fluvial response is controlled by climatic fluctuations; while variable response at a given point in time in different valleys may reflect differences in intrinsic controls and/or tectonic environment.

Further downstream, Roy et al. (2012) have proposed that aggradation in the Ganga floodplain was taking place between 23 and 30 ka, which is similar to the chronology inferred here and could suggest that sediment supply was feeding alluvial deposits in the Himalayan valleys as well as the Ganga floodplain. Note that luminescence chronology of Ganga floodplain deposits face the same challenges as those presented above, and the OSL ages in Roy et al. (2012) could also be under-estimated, in which case it would be difficult to compare them with our chronology. Clift et al. (2008) investigated sediment provenance in the Indus River and inferred that pulses in sediment supply from Himalaya occurred at 14-20, 11-12 and 8-9 ka. This supports a scenario of incision of Himalayan valley fills and export to oceanic depot centres post-LGM.

6. Conclusions

Investigating the links between climate variability and fluvial dynamics in active orogens like the Himalayas is complicated by the challenging nature of luminescence dating of alluvial deposits in these regions. For instance, tests on alluvial deposits, particularly those from the Alaknanda Valley show that quartz continuous wave-OSL signals yield slowly decaying curves, and SAR procedures result in poor dose recovery. These limitations are overcome by

using POSL signals measured after the IR bleaching at 150°C for 100 s. Resulting POSL ages are up to four times older than previously published OSL ages of the same deposits. Thus, while bootstrap resampling of a compilation of published OSL ages suggests that aggradation took place between 12 and 15 ka, this range is probably at least partially flawed by the poor properties of alluvial quartz. Using the relationship between our OSL ages and previously published values for the same deposits, we tentatively corrected compiled OSL ages. Bootstrap resampling of this corrected set suggests that aggradation would have mostly taken place between 25 and 35 ka.

In-situ cosmogenic dating of bedrock strath terraces places the exposure of these surfaces between 3 and 6 ka. Because straths were covered with alluvial material, this suggests that incision was initiated at least in the early Holocene, if not earlier. Erosion of alluvial material could also explain the gap between proposed chronologies of aggradation (25-35 ka) and bedrock strath exposure (3-6 ka). Overall, the chronology of alluvial features in the Alaknanda and Dehradun Valleys suggests that within a given valley, there is a relatively simple relationship between fluvial dynamics and climate variability.

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Table 1. Dosimetry and OSL ages of alluvial deposits

Site name	Sample ID	Depth ^a (cm)	Water content ^b (wt. %)	²³⁸ U (ppm)	²²⁶ Ra (fg.g ⁻¹)	²³² Th (ppm)	⁴⁰ K (ppm)	Dry beta ^c (Gy·ka ⁻¹)	Dry gamma ^c (Gy·ka ⁻¹)	Cosmic ray ^d (Gy·ka ⁻¹)	Total dose rate ^b (Gy·ka ⁻¹)	n ^e	D _e CAM (Gy)	Age CAM ^{b,f} (ka)	O.D. (%)	D _e MAM ^h (Gy)	Age MAM ^h (ka)
Suarna ST2	IND02	200	0.3 (20.8)	3.03±0.78	903±22	17.48±0.47	3.14±0.07	2.81±0.11	1.76±0.04	0.020±0.002	4.59±0.12 (3.69±0.09)	23	99±9	21±2 (27±3)	43	62±5	14±1
Suarna ST6	IND03	465	1.2 (22.3)	2.79±0.76	1009±22	19.01±0.49	3.46±0.08	3.08±0.12	1.94±0.04	0.11±0.01	5.05±0.12 (4.06±0.10)	21	169±14	33±3 (42±4)	35	112±8	22±2
Section D3 bottom	IND04	>2000	4.7 (19.1)	3.24±0.76	1045±19	17.41±0.42	3.31±0.06	2.97±0.11	1.84±0.04	0.020±0.002	4.57±0.11 (3.93±0.10)	19	216±16	47±4 (55±4)	25	183±15	40±3
Section D3 top	IND05	730	3.3 (20.2)	3.54±0.80	1083±19	16.10±0.44	3.16±0.06	2.87±0.11	1.75±0.04	0.07±0.01	4.52±0.11 (3.79±0.09)	18	198±12	44±3 (52±3)	19	199±11	44±3
Srinagar T4	IND62	2500	0.2 (26.9)	1.79±0.47	654±16	8.31±0.39	1.65±0.05	1.50±0.06	0.93±0.03	0.010±0.001	2.44±0.07 (1.85±0.05)	9	90±7	37±3 (49±4)	18	90±6	37±3
Srinagar T4	IND62											22	91±4	37±2 (49±3)	19		
Srinagar T3	IND63	20	0.2 (18.2)	2.69±0.64	1039±19	13.73±0.37	1.15±0.04	1.44±0.06	1.20±0.04	0.13±0.01	2.76±0.07 (2.30±0.06)	8	85±6	31±2 (37±3)	17	85±5	31±2
Srinagar T3	IND63											21	92±4	33±2 (40±2)	13		
Srinagar T2	IND64	1500	0.2 (31.3)	1.99±0.54	1009±16	11.81±0.35	1.82±0.05	1.79±0.07	1.23±0.04	0.030±0.003	3.04±0.08 (2.22±0.06)	9	141±13	47±5 (64±6)	25	119±12	39±4
Srinagar T5	IND65	1000	0.4 (33.3)	3.22±0.80	1603±22	18.17±0.42	2.50±0.06	2.59±0.10	1.85±0.05	0.05±0.01	4.47±0.12 (3.22±0.08)	9	95±8	21±2 (30±3)	21	93±7	21±1
Srinagar T1	IND73T	380	0.4 (31.8)	4.26±1.05	1346±22	10.50±0.37	2.42±0.06	2.46±0.11	1.43±0.05	0.12±0.01	3.98±0.12 (2.92±0.08)	24	13.9±0.7	3.5±0.2 (4.8±0.3)	22	13.1±0.1	3.3±0.1

^a Depths are below the ground level. ^b Numbers in parentheses are based on saturated water contents. ^c Data from high-resolution low level gamma spectrometry were converted to infinite matrix dose rates using conversion factors given in Olley et al. (1996). ^d Cosmic ray contributions to dose rates were calculated by the equations given in Prescott and Hutton (1988, 1994). D_e: equivalent dose. ^e Number of aliquots. ^f Central age ±1σ standard error. ^g Minimum age ±1σ standard error. O.D. = Overdispersion. n.d. = not detected. ^h MAM D_e and ages were derived using an assumed overdispersion of 20%.

Table 2. In-situ ¹⁰Be data and calculated exposure ages for bedrock straths

Site name	Sample ID	Elevation (m.a.s.l.)	Height above the active channel (m)	Shielding factor	Quartz mass (g)	Carrier mass (mg)	¹⁰ Be concentration (10 ⁶ at·g ⁻¹ quartz)	Exposure age (ka)
Pipalkoti	IND118	1120	90±10	0.970	103.0	0.3932	0.064±0.003	7.6±0.7
Pipalkoti	IND119	1120	90±10	0.987	102.3	0.3961	0.075±0.003	8.8±0.8
Langasu	IND104	893	17±1	0.982	102.3	0.3931	0.018±0.001	2.7±0.3
Langasu	IND105	881	4.5±0.5	0.980	103.7	0.3948	0.013±0.001	1.9±0.2
Bamoth	IND88	771	39±2	0.952	95.01	0.4041	0.007±0.001	1.1±0.2
Bamoth	IND89	781	49±2	0.982	105.8	0.4023	0.005±0.001	0.7±0.1
Bamoth	IND90	767	35±2	0.980	114.0	0.3976	0.017±0.001	2.7±0.3
Bamoth	IND93	751	8.5±0.5	0.957	89.36	0.4160	0.012±0.003	1.9±0.4
Bamoth	IND94	744	2±0.5	0.961	103.3	0.3925	0.015±0.001	2.4±0.2
Bamoth	IND95	750	8±1	0.969	73.57	0.5251	0.003±0.000	0.5±0.1
Bamoth	IND129	748	5.6±0.2	0.932	93.47	0.3831	0.008±0.001	1.2±0.1
Bamoth	IND130	749	7.0±0.2	0.926	107.9	0.3951	0.011±0.001	1.7±0.2
Bamoth	IND131	747	4.8±0.2	0.923	57.44	0.3971	0.008±0.009	1.3±0.1
Bamoth	IND132	744	2.4±0.2	0.934	111.2	0.3949	0.005±0.001	0.8±0.1
Gholtir	IND83	704	8.4±0.5	0.968	103.2	0.4071	0.003±0.000	0.5±0.1
Gholtir	IND85	719	25±5	0.968	102.8	0.4081	0.031±0.002	5.0±0.5
Gholtir	IND86	709	15±5	0.968	103.7	0.3039	0.013±0.003	2.1±0.5
Nagrasu	IND55	816	105±10	0.985	103.1	0.4058	0.067±0.002	9.4±0.9
Tilani	IND53	685	90	0.990	103.8	0.3003	0.170±0.005	27.3±2.5
Devaprayag	IND48	468	20	0.973	112.4	0.3961	0.013±0.001	2.4±0.3

Calculations were conducted using a high latitude sea level production rate of 4.6 atoms·y⁻¹, a ¹⁰Be half-life of 1.38x10⁶ y (Fink, 2007), and a NIST 27900 standard correction. * Data from (Barnard, 2001)

668 Table 3. Compilation of OSL ages from Himalayan alluvial deposits

Reference	Singh et al. (2001)	Srivastava et al. (2008)	Sinha et al. (2010)	Ray and Srivastava (2010)	Juyal et al. (2010)	Dutta et al. (2012)	Thakur et al. (2007)	Scherler et al. (2015)
Location	Donga, Dehradun, Bhogpur Fans	Alaknanda (around Devprayag)	Alaknanda / Ganga Exit	Alaknanda (Nandprayag to Chandi Devi)	Alaknanda (Goting to Devprayag)	Dehradun Valley, Yamuna River	Dehradun Valley	Yamuna Catchment
No. of samples	12	12	12	32 (+1 fault gouge)	24	25	10	6 + 3
Lab	Physical Research Laboratory, Ahmedabad	N.A. (Wadia, Dehradun?)	Wadia, Dehradun	N.A. (Wadia, Dehradun)	N.A.	Wadia, Dehradun	Wadia, Dehradun	Sheffield (Q) Bern (Q + F)
Grain sizes	4-11 μm 90-150 μm	90-150 μm	90-125 μm	90-150 μm	150-210 μm	90-125 μm	90-125 μm	N.A.
Mineral	Q (N.A. for fine-grained?)	Q	Q	Q	Q	Q	Q	Q - 6 samples; K- rich feldspar - 3 samples
Preparation details	N.A.	Sieve 40% HF for 80' HCl 40'	HCl 30% H ₂ O ₂ Sieve Density Separation 80' HF HCl	40% HF for 80' HCl for 40'	10% HCl 30% H ₂ O ₂ Sieved Magnetic Separation Density Separation 40% HF for 80' HCl for 30'	HCl 30% H ₂ O ₂ Density Separation HF for 80' HCl	Chemical treatment (not specified) HF (not specified) Sieve Density separation	N.A. HCl H ₂ O ₂ Na-Oxalate, Density Separation Q 40% HF for 60', IR tests = contamination

								H ₂ SiF ₆ etching for 1 week
Aliquot size	N.A. (10 mm?)	N.A. (7 mm?)	3 mm	N.A. (“small aliquots”)	N.A.	3 mm	N.A.	2 mm
Aliquots per sample	N.A.	N.A.	N.A.	30-40	45-50	N.A.	N.A.	Q – N.A. F - 12
Protocol	N.A.	SAR	SAR incl. IRSL test	SAR incl. IRSL check (>100 cts undergo additional density separation and HF 20 min)	SAR incl. IRSL wash of 100 s at 50°C, For 1 sample IRSL MAAD method on fine- grained	SAR incl. IRSL check	SAR (?) - GLS 5 samples SAR 5 samples MAAD	Q – SAR i) SAR on but poor character (dim, absence of fast comp), then ii) IRSL SAR from Preusser (2003)
Preheats	N.A.	240°/160°C	240°/160°C	220°/160°C	240°/200°C	240°/160°C	N.A.	Q – N.A F - 250°/250°C
Shine down curves	N.A.	Yes: dim, hard to interpret	N.A.	Yes (>400 cts)	N.A.	N.A.	N.A.	Q – N.A. F – Yes, for Q (< 400 cts)
Selection	N.A.	RR 1.1-0.9	N.A.	RR 1.1-0.9	RR 1.1-0.9 DRTs on aliquots for De estimate	N.A.	N.A.	DRTs
Dose rate	...	XRF	XRF	XRF	TSAC for U and Th, gamma ray spectrometry for K	XRF	TSAC for U and Th XRF for K	Q – N.A. F - HRGS
Age model	N.A. (CAM??)	Least 10% (~MAM) for young,	N.A. (CAM?)	Weighted mean of lowest 20%	Minimum value + 2*err	N.A.	N.A.	Q – CAM(?) or FFM (>20% od)

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Comments and considered problems	Stratigraphic consistency Workable luminescence chronology until further confirmation	mean for old				F - CAM
		Low sensitivity -	Partial bleaching	All info in appendix	-	
		Partial bleaching in De	Low luminescence sensitivity Feldspar contamination			Green-light stimulated luminescence
						Caution with Q due to medium component
						Caution with F due to fading
						Thermal transfer problems 270 and 290°C
						Feldspar good characteristics
						No fading tests - ages min. ages

Q: quartz, F: feldspar. SAR: single-aliquot regeneration, MAAD: multiple aliquot additive dose. DRT: dose recovery test, De: dose. XRF: x-ray fluorescence, TSAC: thick source alpha counting, HRGC: high resolution gamma spectrometry. CAM: Central age model, MAM: Minimum age model, FMM: Finite mixture model.

671 Table S1. Element concentrations in quartz aliquots of sediments prepared for in-situ ^{10}Be

Sample ID	Al	Na	Mg	K	Ca	Ti	Fe
IND64	1980	101	26	604	1600	79	84
IND65	206	25	23	76	91	37	57
IND72	5470	169	218	1790	1530	399	793
IND73	2230	93	93	410	1270	332	866

672 All concentrations are given in ppm. Quartz aliquots were prepared following the same method as presented for bedrock
673 samples destined to in-situ ^{10}Be analysis described in the Methods section.
674

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