Rates of rockwall slope erosion in the upper Bhagirathi catchment, Garhwali Himalaya

Elizabeth N. Orr,1,2* Lewis A. Owen,1,3 Sourav Saha1,4 and Marc W. Caffee5,6

1 Department of Geology, University of Cincinnati, Cincinnati, OH 45221, USA
2 GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
3 Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA
4 Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90095, USA
5 Department of Physics, Purdue University, West Lafayette, IN 47907, USA
6 Department of Earth, Atmospheric and Planetary Sciences, Purdue University, West Lafayette, IN 47907, USA

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*Correspondence to: Elizabeth N. Orr, Department of Geology, University of Cincinnati, Cincinnati, OH 45221, USA.
E-mail: elizabeth.orr@gfz-potsdam.de, orreh@mail.uc.edu

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ABSTRACT: Rockwall slope erosion is defined for the upper Bhagirathi catchment using cosmogenic Beryllium-10 (10Be) concentrations in sediment from medial moraines on Gangotri glacier. Beryllium-10 concentrations range from 1.1 ± 0.2 to 2.7 ± 0.3 × 10⁴ at/g SiO₂, yielding rockwall slope erosion rates from 2.4 ± 0.4 to 6.9 ± 1.9 mm/a. Slope erosion rates are likely to have varied over space and time and responded to shifts in climate, geomorphic and/or tectonic regime throughout the late Quaternary. Geomorphic and sedimentological analyses confirm that the moraines are predominately composed of rockfall and avalanche debris mobilized from steep relief rockwall slopes via periglacial weathering processes. The glacial rockwall slope erosion affects sediment flux and storage of snow and ice at the catchment head on diurnal to millennial timescales, and more broadly influences catchment configuration and relief, glacier dynamics and microclimates. The slope erosion rates exceed the averaged catchment-wide and exhumation rates of Bhagirathi and the Garhwal region on geomorphic timescales (10³–10⁵ years), supporting the view that erosion at the headwaters can outpace the wider Himalaya. The 10Be concentrations of medial moraine sediment for the upper Bhagirathi catchment and the catchments of Chhota Shigri in Lahul, northern India and Baltoro glacier in Central Karakoram, Pakistan show a tentative relationship between 10Be concentration and precipitation. As such there is more rapid glacial rockwall slope erosion in the monsoon-influenced Lesser and Greater Himalaya compared to the semi-arid interior of the orogen. Rockwall slope erosion in the three study areas, and more broadly across the northwest Himalaya is likely governed by individual catchment dynamics that vary across space and time. © 2019 The Authors. Earth Surface Processes and Landforms Published by John Wiley & Sons, Ltd.

KEYWORDS: supraglacial processes; sediment flux; glacier; climate; cosmogenic isotopes

Introduction

Glaciation and erosion are central to the topographic evolution of high-altitude mountain belts such as the Himalayan-Tibetan orogen, by influencing rates of sedimentation and localized incision, limiting relief production and elevation, and offsets tectonic uplift (Brozović et al., 1997; Whipple et al., 1999; Mitchell and Montgomery, 2006; Wulf et al., 2010, 2011; Scherler et al., 2014). The contributions of periglacial erosion at the catchment head to the denudation budgets of Himalayan glacierized catchments have been largely overlooked, with the exception of studies by Heimsath and McGlynn (2008) in the Nepal High Himalaya and Seong et al. (2009) in the Central Karakoram of Pakistan. This is surprising given that lateral slope erosion via periglacial processes are shown to exceed rates of glacial incision in other alpine settings (Brocklehurst and Whipple, 2006; Foster et al., 2008).

Periglacial weathering processes including freeze–thaw, frost cracking and ice wedging deliver large volumes of rockfall and avalanche debris to the mountain glacier sedimentary system from catchment slopes (Schröder et al., 2000; Matsuoka, 2001; Owen et al., 2003; Hales and Roering, 2005; Sanders et al., 2012; Gibson et al., 2017). The strength of coupling between rockwall slopes and glaciers affect glacier dynamics, catchment sediment flux and can dictate the relief and topographic configuration of catchment divides over time (Montgomery, 2002; Thiede et al., 2005; Moore et al., 2009). Erosion of rockwall slopes in the Himalayan-Tibetan orogen therefore has broad implications for its morphological development and the distribution of precipitation (Burbank et al., 2003; Gabet et al., 2004; Anders et al., 2006; Bookhagen and Burbank, 2006).

The distribution and rates of erosion for the Himalayan-Tibetan orogen scale with tectonics (Burbank et al., 2003;
Thiede et al., 2005; Scherler et al., 2014) precipitation (Thiede et al., 2004; Grujic et al., 2006; Biswas et al., 2007; Craddock et al., 2007; Gabet et al., 2008; Wulf et al., 2010; Deeken et al., 2011; Portenga et al., 2015) and/or topography (Vance et al., 2003; Scherler et al., 2011a, 2014). Erosion at the catchment head is shown to outpace catchment-wide and regional landscape denudation rates, and exhibit greater or different sensitivities to local and/or regional external forcing such as shifts in climate, tectonic activity or geomorphic regime (Heimsath and McGlynn, 2008; Scherler et al., 2011a). We aim to assess the importance of periglacial processes in the Himalayan-Tibetan orogen; an essential first step is the quantification of rockwall slope erosion rates. We chose the upper Bhagirathi catchment of the Garhwal Himalaya, northern India, for this initial investigation. This region is the source area for the Ganges and it contains some of the largest glaciers in the monsoon-influenced Himalaya, including Gangotri glacier. This catchment has a well-defined glacial chronostratigraphy, comprehensive records of past and modern glacier behavior and is relatively accessible. We apply geomorphic and sedimentological methods and measure cosmogenic beryllium-10 (10Be) concentrations in medial moraine sediment to calculate rockwall slope erosion rates. Moreover by comparing 10Be concentrations along the length of the medial moraines and examining the sedimentology of the supraglacial sediment, we are able assess the feasibility of using 10Be to determine rates of rockwall slope erosion. We compare our erosion rates to local catchment-wide erosion and exhumation records to assess the difference between rockwall slope erosion and regional landscape denudation in Garhwal. We compare slope erosion rates for upper Bhagirathi, Chhota Shigri in the Lahul Himalaya, northern India and Baltoro in the Central Karakoram of Pakistan with catchment parameters and regional climate records to help identify the factors that may be affecting slope erosion in the northwest (NW) Himalaya.

**Regional Setting**

The Bhagirathi catchment is located in the Uttarkashi district of Uttarakhand, in the Garhwal Himalaya of northern India (Figure 1). Three major lithotectonic units characterize the geology of the Garhwal Himalaya: (1) Tethyan Himalaya sedimentary series; (2) the high Himalaya crystalline sequence (HHS); and (3) the lesser Himalaya sequence (LHS; Searle et al., 1997, 1999; Vannay et al., 2004). Despite the absence of a clear shear zone, Garhwal is bounded in the north by the Tethyan Himalaya low-grade metasedimentary rocks and the south Tibetan detachment (STD) zone (Kumar et al., 2009; Srivastava, 2012). The main central thrust zone defines the southern margin of the region; the boundary between high-grade gneiss, migmatite and granite of the HHS and low-grade metasedimentary rocks of the LHS. The Jhala normal fault trends through central Garhwal and the Bhagirathi catchment, separating quartzofeldspathic sillimanite gneiss from Harsil metasedimentary rocks (Searle et al., 1999). Maximum regional uplift rates range between 4 and 5.7 mm/a (Barnard et al., 2004a, 2004b; Scherler et al., 2014). Neotectonics, which include persistent microseismicity and stochastic earthquakes, greatly influence the geomorphic evolution of the region (Searle et al., 1987; Valdiya, 1991; Rajendran et al., 2000; Barnard et al., 2001; Bali et al., 2003). Detailed summaries of the geologic setting and histories of transient erosion, unroofing and exhumation for Garhwal are provided by Scaille et al. (1995), Searle et al. (1993, 1999), Sorkhabi et al. (1996) and Scherler et al. (2014).

**Figure 1.** Location of Gangotri glacier and tributary glaciers overlying a simplified geologic map of the upper Bhagirathi basin of Uttarkashi, northern India (adapted from Searle et al., 1999). Inset map illustrates the location of the state of Uttarakhand within the Himalayan-Tibetan orogen (base map from geomapapp.org). [Colour figure can be viewed at wileyonlinelibrary.com]
The climate of the western Himalaya is influenced by two major climatic systems, the southwest Indian monsoon and the northern hemispheric mid-latitude westerlies (Finkel et al., 2003; Bookhagen et al., 2005; Owen, 2009). The majority of annual precipitation (1000–2500 mm/a) in Garwhal occurs between July and September; during this time the humid air masses of the Indian monsoon penetrate the high-altitude ranges of the Greater Himalaya (Burbank et al., 2003; Scherler et al., 2010; Thayyen and Gergan, 2010; Wulf et al., 2010). Rainfall magnitudes vary significantly both seasonally and across short distances (101 to 102 km) throughout the region, creating localized microclimates that are affected by the variability in terrain and geomorphic regime (Sharma and Owen, 1996; Barros et al., 2006; Singh et al., 2007; Srivastava, 2012).

Due to the restricted number of meteorological stations located above ~5000 m above sea level (a.s.l.) in the Himalaya (Benn et al., 2012; Srivastava, 2012), climate and weather records for the upper Bhami glacier catchment are traditionally based on data from a single weather station (Mukhim, 30.6°N, 78.3°E, ~1900 m a.s.l.). Mukhim station (1971–2000) records mean annual precipitation of 1648 mm and temperature of 15.5°C. An additional weather station has been established at Bhojbasa (~3780 m a.s.l., 30.9°N, 79.0°E), ~4 km from the snout of Gangotri glacier. Temperatures range between 2.3 and 11°C (2001–2009) each year. The station has documented a mean annual winter snowfall of ~546 mm (Bhambli et al., 2011).

The upper Bhami glacier catchment (3400–7200 m a.s.l.) covers an area of ~550 km2, of which ~50% is glaciated (Tangri et al., 2004; Haritashya et al., 2006; Singh et al., 2006). This transverse catchment is delineated by steep relief peaks (> 45° (averaged over ~770 km2)) that exceed 6000 m a.s.l., including Shiving (6543 m a.s.l.), Meru (6600 m a.s.l.) and the Chaukhambo Massif (7138 m a.s.l.; Bhambli et al., 2011; Satyabala, 2016). Snow-fed meadows with alpine shrubs and grasses with some sandy-gravel soil development are sparsely distributed or absent above elevations of ~3000 m a.s.l. Below Gaumukh (~4000 m a.s.l., 30.9°N, 79.1°E), the catchment is unglaciated and becomes wider and deeper as a result of the calving of a large lateral moraine (~4000 m a.s.l., 30.9°N, 79.1°E; Sharma and Owen, 1996; Haritashya et al., 2006; Ranhotra and Bhattacharya, 2013).

Seven glacial stages have been defined within the upper Bhami catchment and include the: Bhami (60–23 ka), Sudarshan (21–16 ka), Shiving (~5.2 ka), Gangotri (~2.4–1.9 ka), Bhujbasa (~1.7–0.5 ka), Meru (~0.3–0.1 ka) and Gaumukh (~0.3–0.2 ka; Sharma and Owen, 1996; Barnard et al., 2004a, 2004b; Puri et al., 2004; Srivastava, 2012; Singh et al., 2017). The low erosion rates measured within the drainage basin (<1 mm/a; Vance et al., 2003) and wider region (0.15–5.4 mm/a; Haritashya et al., 2006; Scherler et al., 2014) aid in the preservation of glacial landforms across several glacial cycles. The moraine of the Bhami stage (60–23 ka) is located ~30 km downstream from the present glacier snout and records the oldest and most extensive glaciation of the drainage basin. Gangotri glacier has retreated between 6 and 27 m/a over the past 50 years, but since 2007 has ceased retreat. Tangri (2002), Tangri et al. (2004), Bhambli et al. (2012, 2017) provide detailed summaries of the glacier stages and retreat.

### Methodology

#### Background

Past studies have quantified rockfall slope erosion by dating and estimating the volume of slope deposits such as talus (Andre, 1997; Curry and Morris, 2004; Hinchliffe and Ballantine, 2009; Siewert et al., 2012), or modeling supraglacial debris flux (Heimsath and McGlynn, 2008; Gibson et al., 2009; Reeh and Ballantyne, 2009). More recently, rockfall slope erosion has been measured using cosmogenic 10Be in medial moraine sediment (Heimsath and McGlynn, 2008; Gibson et al., 2009; Reeh and Ballantyne, 2009). The terrestrial cosmogenic nuclide (TCN) concentration of a substrate scales with fast erosion; concentrations are higher in boulders compared to coarse-fine sediment (Placzek et al., 2014). TCN-derived erosion rates from amalgamated sediments are considered to best reflect the average rate of erosion for an applicable area, and are treated as maximum estimates. Medial moraines form when rockfall and avalanche debris mobilized from the catchment slopes is exhumed to the ablation zone surface after being buried and transported glacially through the accumulation zone (Matsuoka and Sakai, 1999; Goodsell et al., 2003; MacGregor et al., 2009; Mitchell and Montgomery, 2006; Dunning et al., 2015). The 10Be concentrations in medial moraine sediment reflect the mean surface concentrations of the source area (Ward and Anderson, 2011). For a given medial moraine sediment package, the shorter the duration of exposure of the source rockfall slopes to cosmic rays, the lower the accumulation of 10Be, and the faster the inferred slope erosion rate. On sub-millennial timescales the 10Be concentrations are likely to reflect slope erosion via periglacial weathering processes, whereas over geomorphic timescales (103–105 years) the input is more likely affected by local or regional erosion rates (Gibson et al., 2017). We combine TCN methods with geomorphic and sedimentological analyses of Gangotri glacier.
medial moraines to constrain rates of rockwall slope erosion for the upper Bhagirathi catchment.

Field methods

A detailed geomorphic map of the upper Bhagirathi catchment was constructed in the field and then refined using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global digital elevation models (GDEMs; 30-m-resolution), Landsat Enhanced Thematic Mapper Plus (ETM+; 15-m-resolution) imagery, Google Earth Imagery and published topographic and geologic maps. Geomorphic and sedimentological techniques described by Benn and Owen (2002) were applied to identify and differentiate between landforms and sediment deposits.

Six major medial moraines were identified on the surface of Gangotri glacier system. Each landform originates from an area of glacier convergence and extends to a confluence with, and/or snout of Gangotri glacier (Figure 2). The debris of each medial moraine is sourced from the rockwalls that encompass the glacier(s) above this area of convergence. Ward and Anderson (2011) argue that the trajectory of the englacial transport of rockwall debris is deeper than for debris that has been transferred onto the glacier surface at lower elevations in the catchment. The rockwall debris is entombed within the glacier ice during this transport and therefore does not mix with other sources.

The name of each moraine includes the initial term SD (for supraglacial debris moraine) and a subscript letter from A–F. The moraine sourced from the Kirti tributary catchment is referred to as SD_A, for example. The SD_{A-C} moraines are the focus of this study as they are the largest and most accessible moraines on the glacier, and extend throughout the ablation zones of Gangotri and Kirti glaciers, making them most likely to reflect rockwall slope erosion rates of the upper Bhagirathi catchment. The traditional moraine nomenclature, e.g. M_{1-x}, was not used to avoid confusion with Gangotri terminal and lateral moraines.

Sediment samples from each moraine were collected where possible at intervals from the snout of Gangotri to ~3 km up-glacier. The moraines were inaccessible beyond this point due to major instabilities in both hillslopes and the glacier surface. The samples were taken from high relief, stable and well-defined moraine ridges, to avoid input from external sources of sediment, including lateral moraines and hillslope deposits (Supporting Information Item 1). To ensure the sampling of ≥ 10 rockwall events per sample, the sampling locations were ≥ 200 m² in area and sediment was collected systematically along the moraine crest every 5–10 paces. Approximately 3 kg of amalgamated sediment was collected for each sample, with a grain size range of < 3 cm (clay-coarse gravels) applying bulk sediment sampling methods of Gale and Hoare (1991). Detailed sedimentological and geomorphic descriptions of the moraine were made at each sampling location.

Two samples were collected from the SD_A moraine, three from SD_B and one from SD_C. The samples were numbered in ascending order for each moraine, from the furthest up-glacier to the closest to the snout of Gangotri glacier. The G_{sup1} sample (subscript sup1), e.g., was collected at 4315 m a.s.l., ~3 km from the snout. The location of each sample was recorded using a handheld Garmin Etrex 30 global positioning system (GPS) unit and then photographed.
Medial moraine sediment analysis

To elucidate the characteristics and transport histories of the medial moraine sediment and to assist with interpreting the \(^{10}\)Be inventories of our samples, analyses were conducted at the University of Cincinnati (OH, USA) in the Sedimentology and X-ray Laboratories in the Department of Geology and the Advanced Material Characterization Centre (AMCC). These analyses included grain size distribution (e.g., Wentworth, 1922; Allen, 1981), shape (e.g., Hambrey and Glasser, 2003; Hambrey et al., 2008; Lukas et al., 2013), roundness (e.g., Sneed and Folk, 1958; Ballantyne and Benn, 1994), surface weathering (e.g., Sheridan and Marshall, 1987; Owen et al., 2003) and sample clay mineralogy (e.g., Chen, 1977; Moore and Reynolds, 1997). Further details of the methodologies used are provided in Supporting Information Item 2.

Beryllium-10 production rates and geochemical analysis

Beryllium-10 production rates for the upper Bhagirathi catchment were calculated from an ASTER GDEM (30-m-resolution) with a revised sea-level high-latitude spallogenic production rate of 4.08 ± 0.23 Be atoms/g SiO\(_2\)/a (Martin et al., 2017; http://calibration.ice-d.org/) and \(^{10}\)Be half-life of 1.36 Ma (Nishizumi et al., 2007), using methods of Dortch et al. (2011) in MATLAB R2017.a. The production rate for each pixel was corrected for topographic shielding and then averaged to derive the mean \(^{10}\)Be production rate for the catchment. The mean production rates account for \(^{10}\)Be production on the glacier surface.

Following the initial sedimentological analyses, the sediment fractions of each sample were combined, crushed, and resieved; the 250–500 μm fraction was selected for \(^{10}\)Be analysis. This process minimizes the possibility of bias in the contribution of any one grain size to the geochemical analysis of the sample. Quartz isolation, dissolution, chromatography, isolation of Be and the preparation of beryllium oxide (BeO) were undertaken in the Geochronology Laboratories at the University of Cincinnati using the standards and chemical procedures described by Kohl and Nishizumi (1992), Nishizumi et al. (1994), and Dortch et al. (2009). The \(^{10}\)Be/Be of each sample were measured using accelerator mass spectrometry (AMS) at the Purdue Rare Isotope Measurement (PRIME) Laboratory at Purdue University, West Lafayette, IN, USA (Sharma et al., 2000).

Portenga et al. (2015) have demonstrated that when native \(^{9}\)Be is factored into \(^{10}\)Be/Be ratios, irrespective of geologic setting, the resultant \(^{10}\)Be concentrations and inferred erosion rates can be significantly altered (20–400%). The native \(^{9}\)Be measured in ~5 g fractions of clean quartz for each sample are < 1 ppm, so no adjustment to the \(^{10}\)Be/Be ratios was necessary. A procedural blank \(^{10}\)Be/Be ratio correction of \(3 \times 10^{-15}\) was made for each sample. Muongenic production is negligible for the timescales of the processes characterized for this study (Brown et al., 1995; Braucher et al., 2003).

The accumulation of \(^{10}\)Be between the rockwall and medial moraines (during burial, englacial transport and exhumation of sediment to the glacier surface) was calculated using the Ward and Anderson (2011) analytical model and then subtracted from the total \(^{10}\)Be concentrations. Beryllium-10 accumulation during transport along the length of the medial moraine was found to be negligible. This conclusion is discussed further in the Results and Discussion sections. Rockwall slope erosion rates were calculated using the \(^{10}\)Be concentrations and catchment-wide production rates by applying methods described in detail by Lal (1991), Granger et al. (1996), Balco et al. (2008) and Dorch et al. (2011). A procedural blank\(^{10}\)Be/9Be ratio correction of 3 ± 1 ppm, so no adjustment to the \(^{10}\)Be/9Be ratios was necessary for the timescales of the processes characterized for this study (Braucher et al., 2003).

Topographic and geomorphic analyses

ASTER DEMs and Landsat ETM+ data were used in conjunction with geographic information system (GIS) Spatial Analyst tools for additional topographic analyses including catchment and rockwall slope, 3-km-radius relief, hypsometry and aspect. These parameters are defined for the glacial-periglacial realms of the upper Bhagirathi catchment only, as this is the area that pertains to the focus of our study. Topographic analyses of Chhota Shigri catchment in Lahul, northern India and Baltoro catchment in the Central Karakoram, Pakistan was also conducted to enable comparisons between slope erosion and catchment characteristics throughout the NW Himalaya.

An adiabatic environmental lapse rate (\(\Delta T/\Delta Z\)) of 7°C/km, a product of both an approximate median for the orogen (Derbyshire et al., 1991; De Scally, 1997; Thayyen et al., 2005; Siddiqui and Maruthi, 2007; Bashir and Rasul, 2010; Prapat et al., 2013; Kattel et al., 2013, 2015), and a lapse rate derived from the local weather stations of Mukhim (~1900 m a.s.l.) and Bhojbasa (~3780 m a.s.l.; Bhambri et al., 2011) was used to estimate the summer and winter surface temperatures throughout the upper Bhagirathi catchment. The optimum frost cracking envelope defined by Hales and Roering (2005) falls between mean annual temperatures of -8 and -3°C. Bhagirathi catchment elevations that have surface temperatures within this range were determined using the chosen lapse rate and ASTER DEM. The frost-cracking envelope and distribution of permafrost (0°C; Brown, 1970) was also calculated with respect to depth by modeling the thermal structure of the near surface of the catchment using methods outlined in detail by Anderson and Anderson (2010). A thermal diffusivity of 1.15 mm\(^2\)/s was used as it reflects an approximate midpoint in diffusivity values for the following substrates that characterize the catchment: regolith, landforms and deposits, and bedrock. This provides an estimate for the rate of heat transfer from the surface. Despite offering a reasonable assessment of the frost cracking and permafrost distribution, these simplified methodologies involve a series of assumptions about the physics, temperature data and geologic setting (Anderson and Anderson,
Surface temperatures of upper Bhagirathi will have varied over space and time, a condition that must be accounted for when interpreting this data. These analyses aim to determine whether slope failure in the upper Bhagirathi catchment can be influenced by surface temperature and the associated periglacial weathering processes.

ELA and snowline altitude (SA) reconstructions

ELAs and ELA depressions (ΔELA) were calculated for the contemporary and past glacial stages within the upper Bhagirathi catchment using methods described by Osmaston (2005), Benn et al. (2005), Heyman (2014) and Sharma et al. (2000). To reduce the uncertainties inherent within these reconstructions, a mean ELA was calculated for each glacial stage from reconstructions derived from each of the following methods: area-altitude (AA); area accumulation ratio (AAR) with ratios of 0.4, 0.5 and 0.6; and toe-headwall accumulation ratio (THAR) with ratios of 0.4 and 0.5; Benn et al. 2005). This approach has been successfully applied in Ladakh, northern India (Dortch et al., 2010; Orr et al., 2017, 2018; Saha et al., 2018) and the Karakoram (Seong et al., 2007), reflecting accurate estimates of the ELAs. Our study adopts methods strongly recommended by Porter (2000), whereby the mean ELA of a glacial stage also provides an estimation of the snowline altitude (SA). The aim of reconstructing ELA and SAs is to evaluate the effect of the timing and nature of glaciation on the rates of rockwall slope erosion throughout the last glacial.

Medial Moraine Descriptions

Gangotri glacier system has six major medial moraines on its surface; the three investigated moraines of this study (SDA–C) extend over 50% of the length of the glaciers’ ablation zones (Figures 2 and 3; Table I). The medial moraines are composed of supraglacial diamict, and like many alpine glaciers, the debris thickness is heterogeneous over space and time (10^3 to 10^5 years), ranging from a few millimeters to several meters thick (Owen and Derbyshire, 1989; Schroder et al., 2000; Benn et al., 2012; Srivastava, 2012). The widths of the moraines range from 50 to 650 m, widening towards the snout of Gangotri glacier (Figure 3; Supporting Information Item 1). The moraine morphologies are characterized by irregular surface topographies, the result of variable diamict thicknesses, and distribution and orientation of steep relief ridges, depressions and ice cliffs. This heterogeneity contributes to variations in the surface morphology, mass balance and flow velocities of the glacier (Benn and Owen, 2002; Rowan et al., 2015; Swift et al., 2005; Haritashya et al., 2006; Hambrey et al., 2008; Gibson et al., 2017), in addition to affecting the glaciers’ sensitivity to climatic and environmental change (Scherler et al., 2011a, 2011b).

These supraglacial diamicts are composed of massive sandy boulder gravels with a finer sandy-silt matrix containing interstitial ice (Supporting Information Item 2). The diamicts are composed of biotite granite, tourmaline leucogranite, with some gneiss, mica schist and quartzite, reflecting the local bedrock (Searle et al., 1999; Srivastava, 2012). The subangular to very angular boulder gravels have surfaces that range from unweathered to moderately weathered. Striations or chattermarks are not present on any particle size. Large boulders (> 2–0.25 m) are located on or slightly offset from the moraine ridges with some evidence of varnish and previous toppling. The sediment samples are composed of granites and schists, with the exception of the SDA samples that include some gneiss clasts.

Finer sediment increases with proximity to the debris–ice interface, likely as a result of sorting through rainfall and meltwater flows (Hasnain and Thayyen, 1996). These fine sediments, and evidence of frost action on pebbles–boulders, indicate active periglacial weathering processes and continued sediment...

Figure 3. Views of moraines in the study area. (A) Gangotri glacier medial moraines. White and orange dashed lines highlight boundaries between moraines and moraine ridges, respectively. (B) SDA medial moraine. (C) SDB medial moraine. (D) SDC medial moraine. [Colour figure can be viewed at wileyonlinelibrary.com]
Table I. Catchment and glacier characteristics of the upper Bhagirathi catchment (uncertainties are expressed to 1σ)

| Catchment characteristics | Glacier characteristics |
|--------------------------|-------------------------|
| Area (~km²)              | Glacier area (~km²)     |
| Relative reliefa         | Glacier head (m)        |
| Maximum slopeb           | Glacier aspect (deg)    |
| Mean slopeb              |                         |
| Mean rockwall slopec     |                         |
| HI indexd                |                         |
| ¹⁰Be Production ratee    |                         |
| Catchment                | (-km²)                  |
| Head                     | (m.a.s.l)                |
| Aspect                   | (deg)                   |
| (°N, °E)                 |                         |
| Gangotri (trunk)         | 772.7                   |
| Raktavarren             | 139.0                   |
| Chaturangri             | 214.8                   |
| Swachhandh              | 39.3                    |
| Mainiandi               | 19.5                    |
| Sumeru                  | 12.3                    |
| Ganohim                 | 35.1                    |
| Kirti                   | 79.5                    |
| Meru                    | 23.6                    |

aA 3 km radius relative relief.
bSlope calculated from 0.001 km² catchment grid cells (map provided in Supporting Information Item 3).
cSlope for rockwall only, calculated from 0.001 km² catchment grid cells.
dHypsometric Index (mean elevation – minimum elevation/relief) of Strahler (1952).

dDetails of ¹⁰Be production rates for catchments is provided in Supporting Information Item 3.

production and/or clast modification by interclast attrition and abrasion across the glacier surface (Owen et al., 2003; Benn and Evans, 2014; Benn et al., 2012). No clear glacial sediment horizons were identified in the field, despite some evidence of englacial silts and sands at the glacier surface. The exhumation of subglacial sediment to the englacial or supraglacial environments is therefore likely to be very localized (Owen et al., 2003). Discontinuous soil development and tundra vegetation are restricted to the stable medial moraine ridges.

SDA moraine

The SDA medial moraine extends ~12 km from the Kirti tributary catchment to within ~500 m of the snout of the Gangotri glacier. A medial moraine from a Kirti sub-catchment coalesces with the main tributary moraine at 4670 m a.s.l. SDA narrows in width at the confluence (~600–300 m) between Kirti and Gangotri glaciers, as a result ice deformation and shearing (Hubbard et al., 2004; Gibson et al., 2017). The SDA diamict has a unique rusty brown color, likely the result of the weathering of the local Augen gneiss or Vaikrita group gneiss bedrock slopes (Figure 3B; Supporting Information Item 1). Sharing the same source outcrops, the medial moraine (SDb) of Ganohim glacier also has this coloration. The Gsup1 (30.9°N, 79.08°E) was collected at 4280 m a.s.l., ~3 km from the glacier snout. The Gsup2 (30.9°N, 79.08°E) was collected from each moraine.

SDC moraine

SDC also extends ~15 km from the modern ELA to the glacier snout. The diamict has a slightly darker gray coloration to the SDa moraine (Figure 3D; Supporting Information Item 1). Due to access, only one sample could be retrieved from this moraine, ~500 m from the glacier snout. The Gsup3 (30.9°N, 79.08°E) was collected at 4130 m a.s.l., slightly upstream from the confluence between the Raktavarren tributary catchment and Gangotri trunk glacier.

Results

Medial moraine sediment analysis

Gangotri and Kirti glacier medial moraine samples consist of medium-coarse sands and fine gravels; these fractions together account for 71 to 73% by weight of each sample (Figure 4). The variability in grain size distributions in the samples is insufficient to draw any conclusions about the transport and sorting of medial moraine sediment in upper Bhagirathi. No significant relationship is observed between grain size distribution and proximity of the sample to the glacier snout or margin (Supporting Information Item 2). Caution must be exercised however when interpreting shifts in grain size, or lack of, with distance down-glacier, as only three or fewer samples are collected from each moraine.

The medial moraine samples are largely made up of angular (32–48%) and subangular (19–46%) grains, with ≤1% of grains considered either rounded or well rounded (Supporting Information Item 2). Grains of low sphericity constitute between 71 and 82% of each sample. The bladed (14–23%) and very bladed (30–40%) grain shape classes are the most prevalent samples, where over 50% of grains per sample have c:a and β:α ratios < 0.3 (Figure 5). No significant relationship can be identified between grain size and grain roundness or sphericity for any one moraine or sediment sample (Supporting Information Item 2).
The covariance of clast shape and roundness indices are presented in RA-C_{40} (angular, very angular) and RWR-C_{40} (rounded, well rounded) plots for Gangotri glacier and previous studies in Figure 5. Distinguishing between transport pathways must be approached with care due to the pronounced overlap in facies indices, an important consideration when working in complex alpine settings (Lukas et al., 2013). The RA (85–94%) and C_{40} (75–96%) indices and large proportion of bladed and extremely bladed grains suggest that the medial moraines of this study share a supraglacial transport history (Benn and Owen, 2002; Hubbard, 2004; Lukas et al., 2013). Some extraglacial and moraine control samples also record RA values greater than 80%. The RWR indices for the medial moraines range between 6 and 15%, higher than the 0% values typical for supraglacial samples. The more rounded component of the samples may reflect the input of sediment from other realms of the glacial system, clast rounding by englacial and/or supraglacial transport, or the effects of meltwater on the glacier surface.

Percentage surface weathering estimates of quartz grains range from 30 to 100%, with mean surface weathering for the samples ranging between 66 ± 22 to 78 ± 17%. A slight, yet negligible increase in surface weathering can be identified down glacier for the SDA and SDB moraines, and the glacier as a whole. Further detail of these earlier-mentioned analyses and further sediment analyses that proved less significant to the conclusions of this study are provided in Supporting Information Item 2.

Rockwall slope erosion rates of the upper Bhagirathi catchment

The modeled accumulation of ^{10}Be during the transport of sediment between the source rockwall and medial moraine ranged between 0.02 × 10^4 and 0.025 × 10^4 at/g SiO\textsubscript{2} (Table II; Supporting Information Item 3). The subtraction of this ^{10}Be from the total measured ^{10}Be concentrations increases the calculated erosion rates by ~8.7 to 30.2% relative to uncorrected values.

The accumulation of ^{10}Be during transport along the moraine length is also a concern due to the high production rates (87.0 ± 11.3 to 107.3 ± 13.9 at/g/a) of upper Bhagirathi. If ^{10}Be were to accrue during this transport, G\textsubscript{sup3} would theoretically record a concentration at least 0.4 × 10^4 at/g greater than G\textsubscript{sup2}, which is located 2.5 km up-glacier. Instead a difference of ~0.1 × 10^4 at/g is measured, which shows that the sampled sediment was transported down-glacier at depth in the medial moraine, permitting limited-no ^{10}Be accumulation. In order to test this assumption, the maximum accumulation of ^{10}Be along the SDA and SDB moraines was estimated used methods outlined by Seong et al. (2009; Supporting Information Item 3). The estimates exceed the total sample concentrations measured, therefore indicating little ^{10}Be production during transport along the medial moraines. This suggests that the supraglacial sediment samples were not exposed at the surface for the entire length of each landform. The collection of multiple samples per medial moraine with a known source area is therefore recommended in order to help identify samples that do not reflect the mean surface concentrations of the catchment rockwall. To reduce the potential accumulation of ^{10}Be during this transport, and its affect upon the erosion rates, this approach is perhaps best applied in catchments with medial moraines < 5 km in length, particularly in areas with high annual ^{10}Be production.

Furthermore, G\textsubscript{sup3} and G\textsubscript{sup2} from the SDA moraine have ^{10}Be concentrations of 1.1 ± 0.2 and 1.6 ± 0.3 × 10^4 at/g SiO\textsubscript{2}, respectively. These concentrations infer rockwall slope erosion rates of 6.9 ± 1.9 mm/a for the G\textsubscript{sup3} sample, and 4.3 ± 1.1 mm/a for G\textsubscript{sup2} (Table II). The G\textsubscript{sup2}, G\textsubscript{sup3}, and G\textsubscript{sup5} samples from the SDB moraine have ^{10}Be concentrations of 2.7 ± 0.3, 2.5 ± 0.3 and 2.6 ± 0.3 × 10^4 at/g SiO\textsubscript{2} respectively.

An inferred erosion rate of 2.4 ± 0.4 mm/a is derived from G\textsubscript{sup3}, 2.5 ± 0.5 mm/a from G\textsubscript{sup4}, and 2.4 ± 0.4 mm/a from G\textsubscript{sup5}. The SDC, G\textsubscript{sup5}, sample has a ^{10}Be concentration of 1.5 ± 0.4 × 10^4 at/g SiO\textsubscript{2} and an inferred slope erosion rate of 4.3 ± 1.4 mm/a.

Topographic and geomorphic analyses

The detailed geomorphic mapping of upper Bhagirathi revealed that the identification of discrete geomorphic zones within the catchment is not possible owing to the absence of the vertical stratification of landforms (Figure 2; Supporting Information Item 4). River terraces and fans occupy elevations < 5000 m a.s.l., whereas the remaining landforms extend the full extent of the catchment.

The slopes of upper Bhagirathi catchment range from 0° to 75°, gentle (< 30°), moderate (31°–45°) and steep (46°) slopes occupying 38, 25 and 37% of the total catchment, respectively. The mean tributary catchment slopes of the study area range between 29.6 ± 15.7 and 40.7 ± 18.4° (Table I). Between 10 and 53% of the catchment areas are occupied by glaciers; the glacier surface slopes are included within this catchment slope analysis, which introduces a degree of uncertainty to these mean slope values. Catchment 3-km-radius relief ranges from 1.4 ± 0.4 to 2.2 ± 0.3 km.

Steepest slopes that exceed 35° are largely unable to support regolith, snow or ice (Gruber and Haerberli, 2007; Nagai et al., 2013). The mean slopes of the rockwalls range between 32.8° ± 12.8° and 47.2° ± 14.3° (Table I). Srivastava (2012) maintains that ~50% of the catchment’s rockwall slopes have angles > 60°. The steep topography of the catchment therefore means that it is susceptible to both rockfall and avalanching (Hewitt, 1988; Bookhagen et al., 2005; Dunning et al., 2007; Gruber and Haerberli, 2007; Mitchell et al., 2007), which likely provides the primary source of supraglacial sediment to Gangotri and Kirti glaciers (Srivastava, 2012).

Ideal conditions for periglacial weathering processes including frost-shattering, cryostructureing, and frost heave are present throughout the upper Bhagirathi catchment. Optimum frost cracking conditions (~3 to ~8°C) within the catchment migrate from elevations of ~5680–6380 m a.s.l. during the summer, to ~3780–4480 m a.s.l. during the winter (Figure 6A). This is consistent with the frost-cracking envelope between 4000–6000 m a.s.l. devised by Brozović et al. (1997) for the NW Himalaya. These temperatures extend to a maximum depth of ~2.3 m into the near-surface, between 3780 and 4430 m a.s.l. (Figure 6B).

Peaks which exceed ~6380 m a.s.l. (including Shivling, Meru and the Chaukhamba Massif) have surface temperatures < ~8°C, which theoretically reduces the efficiency of periglacial weathering processes. The distribution and magnitude of these processes are affected by diurnal and seasonal cycles and climatic and microclimatic variations. Optimum frost cracking conditions over the last few glacial cycles are likely to have extended to lower and higher elevations within the catchment than the present.

Transient or seasonal permafrost can occur at elevations between 3380 and 5280 m a.s.l. within upper Bhagirathi; at higher elevations the permafrost can be permanent. Transient permafrost, which exacerbates slope instabilities and mass wasting (Fischer et al., 2006), may extend from the catchment...
slopes to the proglacial zone of Gangotri glacier and catchment floor. Permafrost penetrates the near surface between 3080 and 3380 m a.s.l., to a maximum depth of ~0.8 m (Figure 6B).

**ELA and SA reconstructions**

The ELAs of contemporary glaciers range from 4880 to 5665 m a.s.l. (Table III), falling within the uncertainties of, and marginally above past estimates of 4510 to 5390 m a.s.l. (Owen and Sharma, 1998; Naithani et al., 2001; Ahmad et al., 2004, Burbank et al., 2003; Srivastava, 2012; Singh et al., 2017). Gangotri glacier has retreated ~30 km upstream over the past ~60 ka (Owen and Sharma, 1998; Burbank et al., 2003), the ELA rising in elevation from 4095 ± 295 to 5160 ± 160 m a.s.l., providing an ΔELA of 1065 ± 295 m. Glacial studies across the Tethyan Himalaya of northern India (Dortch et al., 2011; Orr et al., 2017, 2018) and the Tibetan plateau (Heyman, 2014) document maximum ΔELAs between 240–290 and 280–494 m, respectively; the magnitude of Gangotri glacier retreat over this timescale stands in stark contrast to these. This rate of recession has yet to be determined in Garhwal, where local glacial stages record ΔELAs < 100 m within the past 1 ka, compared to an ΔELA of 465 ± 100 m for Gangotri glacier. A net loss in glacier volume since 1.6 ka is indicated by the heights of the ice-contact Gangotri glacial stage moraines relative to the glacier surface. Approximately 50% of the total catchment is above the modern snowline altitude (5160 ± 160 m a.s.l.).

**Discussion**

Bhagirathi rockwall slope erosion

Medial moraine sediment characteristics for the lower ~3 km of the ablation zone of Gangotri glacier are broadly similar, despite the discrete origins of each landform. Grain shape analysis indicates a predominantly supraglacial transport history with possible contributions from other landscape realms, i.e. moraine, extraglacial sources (hillslope deposits). Grain roundness and surface weathering is attributed to periglacial weathering processes including freeze–thaw, frost cracking and ice wedging, which dislodge angular rock fragments from the bedrock and/or regolith slopes (Benn and Lehmkuhl, 2000; Schroder et al., 2000; Benn et al., 2003; Hambrey et al., 2008; Lukas et al., 2012).

Moisture availability, surface temperature (Hales and Roering, 2007; Humphreys and Wilkinson, 2007; Moores et al., 2008; Dühnforth et al., 2010; Fischer et al., 2010, 2012; West et al., 2014; Eppe and Keanini, 2017) and rock mass strength (Augustinus, 1995; Wegmann et al., 1998; Murton et al., 2006; Eppe and McFadden, 2008) are likely to moderate the rockwall debris flux and influence the derived slope erosion rates of this study. In summary, the steep relief topography of the upper Bhagirathi catchment in conjunction with optimal surface temperatures for periglacial erosion promotes slope–glacier coupling through mass wasting events including rockfalls and avalanching (Brozović et al., 1997; Anderson, 2005; Matsuoka and Murton, 2008; Foster et al., 2010; Scherler et al., 2011b). Rockfalls therefore play a significant, if not principal role in rockwall slope erosion, which is consistent with the observation that mass movements are a dominant mechanism for Himalayan landscape denudation (Gabet et al., 2004; Dortch et al., 2009; Lupker et al., 2012). The frequency and magnitude of rockfall events over 10^3–10^5 year timescales are likely controlled by regional erosion rates, which are moderated by climate and/or tectonism (Molnar et al., 2007; Scherler et al., 2014; Gibson et al., 2017).

The 10Be concentrations vary between the samples of each moraine of Gangotri glacier and between individual landforms, despite sharing similar sediment characteristics (Figure 7; Table II). No relationship is evident between 10Be concentration and distance down-glacier or proximity to the glacier margin. The range in 10Be concentrations of our dataset (1.1 ± 0.2 × 10^4 to 2.7 ± 0.3 × 10^4 at/g SiO₂) may be due to variability in the timing and magnitude of mass wasting events, the insufficient mixing of sediment, the prior or punctuated exposure to cosmic rays, and shielding by snow, ice or regolith (Seong et al., 2009; Ward and Anderson, 2011; Heyman et al., 2011).

The SDA moraine records the lowest 10Be concentrations (1.1 ± 0.2 × 10^4 to 1.6 ± 0.3 × 10^4 at/g SiO₂), corresponding to the highest inferred slope erosion rates of this study (4.3 ± 1.1 to 6.9 ± 1.9 mm/a). The close proximity of SDA to rockwall slopes and external sediment sources along the length of the landform, and the possible greater sensitivity of smaller catchments to external forcing, are two possible explanations for these lower TCN concentrations. The concentration disparity between the SDA samples may due to the sampling of isolated rockfall event(s) rather than amalgamated moraine sediment. Similarly, the sedimentology and low 10Be concentrations of SDÉ suggest that the result of sediment input from proximal rockwall slopes at the snout of Gangotri glacier or contributions from Raktavaran and/or Chaturangi tributary glaciers.

The SDÉ samples have the highest 10Be concentrations of this study (2.5 ± 0.3 × 10^4 to 2.7 ± 0.3 × 10^4 at/g SiO₂), which each fall within uncertainty of each other, and record the lowest inferred slope erosion rates (2.4 ± 0.4 to 2.5 ± 0.5 mm/a). The SDÉ moraine extends the full length of the ablation zone of Gangotri glacier with no direct contact with the catchment slopes. Accordingly, the SDÉ rates are considered to be the most representative of upper Bhagirathi rockwall slope erosion, and likely captures the background erosion rates of the periglacial realms of the catchment due to mass wasting. The SDÉ erosion rates are therefore likely to be largely dictated by high frequency, low magnitude mass wasting events, while the SDA and SDÉ signals are controlled by large stochastic events. These SDÉ rates affirm that ~2.5 m of lateral slope erosion through periglacial processes can be achieved across a
have fluctuated throughout the last glacial. The ELA reconstructions for the local glacial stages show that the size of the glacier and the spatial extent of the periglacial realms has decreased over the last 60 ka (Table III). This means that the slope area contributing debris directly to the accumulation zones of the glaciers have reduced, alongside the contribution of periglacial weathering processes, but also as a result of climate-driven glaciation affecting the extent of slope–glacier coupling. Accordingly, rates of rockwall slope erosion and the contribution of the periglacial realms to the denudation budget of the catchment is likely to have fluctuated throughout the last glacial.

Comparisons between \(^{10}\)Be concentrations in medial moraine samples from high altitude alpine catchments. Batal (Benn and Owen, 2002), Khumbu (Hambrey et al., 2008), d’Arolla (Goodsell et al., 2005) and Findelen, Pastorze, Estelette, Tasman, Pasterze, and Fox glaciers (Lukas et al., 2013). (A) Plot of \(\text{RA–C}_{\text{Be}}\) index, (B) \(\text{RWR–C}_{\text{Be}}\) index. [Colour figure can be viewed at wileyonlinelibrary.com]

The ELA reconstructions for the local glacial stages show that the size of the glacier and the spatial extent of the periglacial realms has decreased over the last 60 ka (Table III). This means that the slope area contributing debris directly to the accumulation zones of the glaciers have reduced, alongside the contribution of periglacial erosion to the debutressing of slopes.

Studies suggest that the timing and nature of glaciation and the associated geomorphic change for the upper Bhagirathi catchment is primarily governed by climate (Barnard et al., 2004a, 2004b; Srivastava, 2012; Singh et al., 2017). The magnitude and rates of rockwall slope erosion are therefore not only intrinsically linked to climate through periglacial weathering processes, but also as a result of climate-driven glaciation affecting the extent of slope–glacier coupling. Accordingly, rates of rockwall slope erosion and the contribution of the periglacial realms to the denudation budget of the catchment is likely to have fluctuated throughout the last glacial.

Garhwal landscape denudation

Scherler et al. (2015) have shown that rates of fluvial incision in Garhwal during the late Pleistocene was greater than the present by a factor of ~2 to 4. Whether periglacial erosion has remained constant or varied across these timescales, the influence of rockwall slope erosion on the topographic evolution of upper Bhagirathi is likely to have been maintained over time. The magnitude of this erosion is likely to affect sediment flux and the storage of snow and ice from diurnal to millennial timescales in this setting, and then more broadly influence catchment configuration and margin migration, microclimates (Bhambri et al., 2011; Srivastava, 2012), and be sufficient to limit relief and affect the architectural organization of the local fault systems (Valdiya, 1991; Sorkhabi et al., 1996; Bali et al., 2003). The frequency and magnitude of rockfall events in Bhagirathi is therefore likely to be affected, in part, by catchment-specific conditions such as geologic setting and geomorphic regime, and then external forcing such as shifts in climate or tectonism. The global intensification of late Pleistocene glaciation, for example, caused extensive mass redistribution and localized incision throughout the Himalayan-Tibetan orogen (Zeitler et al., 2001; Brozović et al., 1997; Bookhagen et al., 2005; Hewitt, 2009; Whipple, 2009). This is likely to be similar in the Bhagirathi catchment where landscape denudation can be attributed to a changing glacier mass balance over time.

Comparing lateral slope erosion with other records of landscape change is a challenge as they invariably reflect erosion or denudation through a variety of mechanisms and across different temporal and spatial scales. Moreover, TCN derived catchment-wide erosion rates reflect the net surface lowering of a catchment, which accounts for both vertical and lateral erosion. Similarly, rates of exhumation defined using low temperature thermochronology describe the ascension of rock through modeled isotherms. To better compare our dataset with these records, we calculate an approximate vertical component to our slope erosion data (Table II). Overall the rates of rockwall slope erosion largely exceed the averaged catchment-wide erosion and exhumation rates of upper Bhagirathi and the Garhwal region (Figure 7). Our erosion dataset supports the view that slope erosion of alpine headwaters can outpace the wider drainage basin (Oskin and Burbank, 2005; Naylor and Gabet, 2007), and that the distribution and magnitude of erosion can vary significantly over short distances downstream (Scherler et al., 2014). The difference in the rates of erosion and landscape denudation between these various records may be because our slope erosion dataset offers a higher resolution record of erosion (\(10^3–10^4\) years) than those on the catchment or mountain range scale (\(10^4–10^5\) years) and/or that these latter records eliminate the ‘noise’ in sediment flux data over time, such as single mass wasting events initiated by large and/or stochastic seismic events (Sadler and Jerolmack, 2014; Willenbring et al., 2013). The slope erosion rates of this study remain largely lower than the regional uplift rates of 4 to 5.7 mm/a (Barnard et al., 2004a, 2004b; Scherler et al., 2014), which may explain the preservation of high relief slopes within the study area.

Rockwall slope erosion of the NW Himalaya

Comparisons between \(^{10}\)Be concentrations in medial moraine sediment of the Bhagirathi glacier with similar datasets from Chhota Shigri in Lahul (Scherler and Egholm, 2017) and Baltoro glacier in the Central Karakoram (Seong et al., 2009) show that the \(^{10}\)Be concentrations at these other localities exceed those in our study (Figure 8). The SD\(_{5}\) samples that are considered to
Table II. Medial moraine sample AMS ratios, $^{10}$Be concentrations and inferred slope erosion rates for the upper Bhagirathi catchment

| Location | Sample | Moraine | Latitude (°N) | Longitude (°E) | Elevation (m a.s.l.) | $^{10}$Be production rate$^{a}$ (at/g SiO$_2$/a) | Quartz mass (g) | $^{9}$Be carrier mass, conc. (g, mg/g) | AMS $^{10}$Be/$^{9}$Be ratio$^{b}$ | $^{10}$Be concentration (10$^{-15}$ at/g) | $^{10}$Be accum. transport$^{c}$ (10$^{4}$ at/g) | Erosion rate$^{d}$ (mm/a) | Adjusted erosion rate$^{e}$ (mm/a) | Applicable time range$^{f}$ (ka) | Inferred erosion rate$^{g}$ (~mm/a) |
|----------|--------|---------|---------------|----------------|---------------------|-----------------------------------------------|----------------|----------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Kirti    | $^{G}$$^{A}$$_{sup1}$ | SDA     | 30.90         | 79.09         | 4315                | 93.1±12.1                | 18.7000                       | 0.2631, 1.041                      | 13.7±2.5                          | 1.1±0.2                          | 0.025                          | 5.3±1.2                          | 6.9±1.9                          | 0.09                          | 5.0                          |
|         | $^{G}$$^{A}$$_{sup2}$ | SDA     | 30.90         | 79.08         | 4280                | 93.1±12.1                | 18.7000                       | 0.2563, 1.041                      | 19.2±3.4                          | 1.6±0.3                          | 0.025                          | 3.6±0.8                          | 4.3±1.1                          | 0.14                          | 3.1                          |
| Gangotri | $^{G}$$^{A}$$_{sup3}$ | SDB     | 30.89         | 79.09         | 4325                | 95.4±12.2                | 18.6000                       | 0.2586, 1.041                      | 30.2±3.5                          | 2.7±0.3                          | 0.020                          | 2.1±0.4                          | 2.4±0.4                          | 0.25                          | 1.7                          |
|         | $^{G}$$^{A}$$_{sup4}$ | SDB     | 30.90         | 79.09         | 4285                | 95.4±12.2                | 14.6000                       | 0.2652, 1.041                      | 22.6±2.8                          | 2.5±0.3                          | 0.020                          | 2.3±0.4                          | 2.5±0.5                          | 0.24                          | 1.8                          |
|         | $^{G}$$^{A}$$_{sup5}$ | SDB     | 30.92         | 79.08         | 4130                | 95.4±12.2                | 16.4000                       | 0.2634, 1.041                      | 25.8±3.1                          | 2.6±0.3                          | 0.020                          | 2.2±0.4                          | 2.4±0.4                          | 0.25                          | 1.7                          |
|         | $^{G}$$^{A}$$_{sup6}$ | SDC     | 30.92         | 79.08         | 4130                | 95.4±12.2                | 19.9000                       | 0.2550, 1.041                      | 19.8±5.3                          | 1.5±0.4                          | 0.020                          | 3.8±1.1                          | 4.3±1.4                          | 0.14                          | 3.1                          |

$^{a}$Mean catchment production rates calculated using methods described in Dortch et al. (2011).

$^{b}$$^{10}$Be/$^{9}$Be ratios are corrected for background $^{10}$Be detected in procedural blank (0.3 ± 0.1 × 10$^{-14}$). Negligible (< 1 ppm) $^{9}$Be was detected in each sample.

$^{c}$Accumulation of $^{10}$Be during burial, englacial transport and exhumation is calculated using methods detailed in Ward and Anderson (2011; see Supporting Information Item 3).

$^{d}$Erosion rate which does not include $^{10}$Be accumulation during transport from source bedrock slope to medial moraine. $^{10}$Be decay constant of 5.1 ± 0.3 × 10$^{-7}$, and a $^{10}$Be half-life of 1.36 Ma.

$^{e}$Erosion rate which has been adjusted for $^{10}$Be accumulation during transport from source bedrock slope to medial moraine.

$^{f}$Applicable time range follows Lal (1991).

$^{g}$Inferred vertical erosion: cos (mean rockwall slope) × lateral slope erosion (Heimsath and McGlynn, 2008). Mean rockwall slope: 43.3° ± 13.9°.
best reflect upper Bhagirathi slope erosion measure $^{10}$Be concentrations $> 1 \times 10^3$ a/g SiO$_2$ lower than Chhota Shigri or Baltoro, and record erosion rates twice as fast. The $^{10}$Be concentrations of the three study areas are compared with catchment parameters and regional climate records to decipher the possible drivers of rockwall slope erosion in the NW Himalaya.

No significant relationship is evident between catchment area and $^{10}$Be concentration. The catchment area does not account for the total surface area of the source rockwall slopes, a parameter that may influence these concentrations to a greater extent. Approximately 80, 50 and 53% of the total catchment area of Bhagirathi, Chhota Shigri and Baltoro respectively, are above the ELA/SA altitudes and nourish the glaciers through snow and ice avalanching. Changes to the SA over time are likely to affect the relative abundance of exposed bedrock and regolith-covered slopes and will help to moderate the slope debris flux. Similarly, there is no correlation between $^{10}$Be and glacier area, and by association, size of medial moraine.

No relationship is apparent between mean catchment or rockwall slope and $^{10}$Be concentration, despite other studies being able to link these variables on a catchment scale and show that greater slope angles promote a larger debris flux (Finlayson et al., 2002; Burbank et al., 2003; Ouimet et al., 2009; Sche rer et al., 2011a, 2014). Although the slopes will broadly facilitate rockfall and avalanching (Luckman, 1977; Gruber and Haerberli, 2007; Bernhardt and Schulz, 2010; Nagai et al., 2013) and the eventual evacuation of sediment from the catchment, each of the investigated catchments is also able to store extensive volumes of sediment in the form of landforms and sediment deposits (Figure 2; Seong et al., 2009). These landforms typically have gentler slopes, which transfer sediment to the glacier surface via diffusive creep processes (Carson and Kirkby, 1972). Not only will these stores of sediment have implications for the sediment flux of the catchments, but also they may influence the $^{10}$Be concentrations measured within medial moraine sediment.

Table III. Reconstructed ELAs for the upper Bhagirathi catchment

| Time | Area-altitude | Area-accumulation ratio | Toe-Headwall altitude ratio | Mean ELA | $\Delta$ELA |
|------|---------------|--------------------------|----------------------------|----------|--------------|
|      |               |                          |                            |          |              |
| Contemporary glaciers | | | | | |
| Gangotri | — | 5100 | 5210 | 5080 | 4960 | 5165 | 5440 | 5160±160 | — |
| Raktavaran | — | 5630 | 5790 | 5680 | 5560 | 5720 | 5620 | 5665±80 | — |
| Chaturangi | — | 3500 | 3650 | 3550 | 3430 | 3385 | 3465 | 5350±175 | — |
| Swachhand | — | 5290 | 5360 | 5280 | 5180 | 5325 | 5440 | 5310±85 | — |
| Maiandi | — | 5625 | 5730 | 5530 | 5400 | 5735 | 5885 | 5650±170 | — |
| Sumeru | — | 5155 | 5170 | 5130 | 5090 | 5170 | 5235 | 5160±50 | — |
| Ganohim | — | 5115 | 5200 | 5060 | 4920 | 5240 | 5305 | 5150±160 | — |
| Kirti | — | 4940 | 4920 | 4850 | 4770 | 5175 | 5350 | 5000±220 | — |
| Meru | — | 4875 | 5010 | 4870 | 4760 | 4830 | 4950 | 4880±90 | — |
| Glacial stages | | | | | |
| Bhujbasa | 1.7–0.5 | 4770 | 4540 | 4760 | 4680 | 4615 | 4795 | 4695±100 | 465±100 |
| Gangotri | ~2.4–1.9 | 4750 | 4530 | 4750 | 4670 | 4605 | 4745 | 4675±90 | 485±90 |
| Shivling | ~5.2 | 4730 | 4530 | 4740 | 4650 | 4520 | 4710 | 4645±100 | 515±100 |
| Sudarshan | 21.0–16.0 | 4425 | 4700 | 4570 | 4450 | 4275 | 4360 | 4425±215 | 735±210 |
| Bhagirathi | 60.0–23.0 | 4025 | 4550 | 4290 | 3810 | 3770 | 4110 | 4095±295 | 1065±295 |

$^a$ELAs rounded to the nearest multiple of five.

$^b$± standard deviation.

$^c$± standard deviation (of $\Delta$ELAs from all reconstructions).

Figure 6. Optimum frost-cracking for the upper Bhagirathi catchment. (A) Simplified map showing the regional distribution of the optimum frost shattering elevations during the summer and winter (temperature data from Bhamari et al. [2011] and CRU 2.0). Gray shading refers to the optimal frost-cracking zone during the summer/winter transition. (B) Optimum frost cracking (blue shading) and permafrost boundaries with respect to depth and projected surface temperatures for the summer and winter within the basin elevations. Textured pattern represents elevations devoid of permafrost with depth. [Colour figure can be viewed at wileyonlinelibrary.com]
The 3-km-radius relief of the study areas exceed ~1.6 km, the steeper relief catchments measuring the highest \(^{10}\)Be concentrations, and therefore the lowest inferred rockwall slope erosion rates. This suggests that rates of rockwall slope erosion can in some cases be insufficient to limit catchment relief in the NW Himalaya. A more likely explanation is that the 3-km-radius relief is largely dictated by the local uplift of the study areas.

A possible lithological control to slope erosion is expressed in upper Bhagirathi. The highest rates of erosion are defined by the SD\(_{\alpha}\) and SD\(_{\gamma}\) moraines, which are sourced from rockwalls composed of, in part, augen gneiss and schist respectively. Lower rates of erosion from SDB may be due to the granite source rockwalls that have a greater rock mass strength than those of SD\(_{\alpha}\) and SD\(_{\gamma}\), and are therefore more broadly resistant to erosion (Bhattarai and Tamrakar, 2017). However, a lithological control to erosion is less clear for the NW Himalaya, where we measure a large range of \(^{10}\)Be-derived slope erosion rates within an area argued to have a relatively uniform rock mass strength (Burbank et al., 2003; Scherler et al., 2014). Investigating the jointing, structure and moisture content of the catchment walls would help to evaluate the susceptibility of the rock to failure and the ongoing damage of frost action (Hallet et al., 1991; Murton et al., 2006; Hales and Roering, 2007).

The temperature data is recovered from weather stations outlining the study areas and therefore does not accurately reflect catchment temperatures. The ranges in annual recorded temperatures prevent any correlations being made between this climatic parameter and the derived slope erosion. The high altitude setting of each study area with mean catchment elevations > 4000 m a.s.l. (Figure 8D) does however mean that the rockwall slopes of each catchment lie within the Brozović et al. (1997) 4000–6000 m a.s.l. frost cracking window for the NW Himalaya.

A tentative relationship lies between mean annual rainfall and \(^{10}\)Be concentration, where higher rainfall coincides with higher rockwall slope erosion rates. This supports the extensive work on the coupling between precipitation and erosion in the Himalaya, where enhanced moisture in the monsoon-influenced Lesser and Greater Himalaya is thought to drive more rapid landscape denudation, compared to the semi-arid interior of the orogen (Benn and Owen, 1998, 2002; Harper and Humphrey, 2003; Bookhagen et al., 2005; Anders et al., 2006; Bookhagen and Burbank, 2007; Gabert et al., 2004; Owen, 2009). This relationship is not completely straightforward for our study areas however, as \(^{10}\)Be concentrations shared by samples from Baltoro glacier (4.4 ± 0.3 × 10\(^4\) to 11.7 ± 2.2 × 10\(^4\) at/g SiO\(_2\)) and Chhota Shigri (3 to 6 × 10\(^4\) at/g SiO\(_2\)) receive contrasting annual rainfall of < 500 and > 900 mm, respectively. The complex climate-topography interactions of each study area prevent a conclusive relationship between erosion and this climatic parameter from being identified. This association does suggest however that rockwall slope erosion is sensitive to precipitation and therefore the glacial-periglacial realms of Himalayan catchments are likely to respond to major climatic events and/or environmental change over time.

Studies across the Himalayan-Tibetan orogen have drawn links between erosion, climate and topography (Scherler et al., 2011a, 2011b, 2014; Bookhagen et al., 2005; Bookhagen and Burbank, 2006; Gruber and Haeberli, 2007; Dortch et al., 2011). Our regional assessment of the NW Himalaya demonstrates that no single discussed parameter provides a dominant control for rockwall slope erosion. We must therefore consider what other variables may be influencing landscape change in these high-altitude settings.

Although glacial erosion is considered secondary to periglacial erosion; glacier dynamics may affect the rates of rockwall slope erosion. Temperate glaciers, which occupy the monsoon-influenced Himalaya, erode the glacier bed through quarrying and abrasion, which exploit fractures at the base of the catchment slopes, and also generate subglacial debris which may later be incorporated into the medial moraines (Benn and Evans, 2014; Benn and Owen, 2003). Glacier retreat and changes to mass balance can therefore lead to the debuttressing of these slopes and release glacially derived sediment. These processes can affect the rockwall debris flux and either contribute to, or trigger mass wasting (Church and Slamyaker, 1989; Watanabe et al., 1998; Ballantyne, 2002a, 2002b). In the semi-arid Himalaya, sub-polar glaciers frozen to the bed are unlikely to further slope denudation processes and therefore would maintain low erosion rates. The velocity of Gangotri (< 5–120 m/a; Gantayat et al., 2014; Bhattacharya et al., 2016), Chhota Shigri (~20–50 m/a; Wagnon et al., 2007; Azam et al., 2012) and Baltoro (~30–160 m/a; Copland et al., 2009) may also affect the efficiency of glacial erosion and/or influence the \(^{10}\)Be concentrations by largely dictating the residence time of sediment on the glacier surface. Glacial hydrology and snow blow may also affect the rates of slope erosion over time (Matsuoka and Sakai, 1999; Mitchell and Montgomery, 2006; MacGregor et al., 2009; Scherler et al., 2011b; Barr and Spagnolo, 2015).

Studies throughout Garhwal and the NW Himalaya have underpinned a tectonic control within the distribution and

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**Figure 7.** Beryllium-10 concentrations (10\(^{17}\) at/g SiO\(_2\)) of upper Bhagirathi medial moraine samples and rates of erosion for the Garhwal Himalaya. Gray points indicate the unadjusted slope erosion rates. 1: Erosional exhumation rates using thermochronometric methods from Sorkhabi et al. (1996), Searle et al. (1999), Thiede et al. (2009), Thiede and Ehlers (2013). [Colour figure can be viewed at wileyonlinelibrary.com]
magnitude of denudation, where landscape change is strongly influenced by the Indo-Asian convergence and rock uplift patterns dictated by the geometry and shortening of the Main Himalayan Thrust (Burbank et al., 2003; Thiede et al., 2005; Scherler et al., 2014). Although contributing to this work is beyond the scope of this study, persistent seismicity throughout the Punjab, Himachal Pradesh and Uttarakhand districts of northern India may introduce a neotectonic control to landscape evolution (Bali et al., 2003; Scherler et al., 2014). In Garhwal, e.g., the 1991 Uttarkashi (M 6.1; Valdiya, 1991; Owen et al., 1996; Bali et al., 2003) and 1999 Chamoli (M 6.6; Rajendran et al., 2000) earthquakes occurred during the applicable timescales of the Bhagirathi slope erosion record and may have therefore triggered mass redistribution on a sufficient scale to affect the erosion rates of our study.

The mobilization and transfer of sediment from the catchment walls to the glacier surface is an example of one of the primary stages in the evacuation of sediment from a glaciated catchment. Models of sediment transfer on the catchment scale argue that a shift in sediment flux requires a set of preconditioning factors and one or more forcing factors (Ballantyne, 2002a, 2002b; McColl, 2012; Orr et al., In press). This is true of the upper Bhagirathi catchment, where the pre-existing landscape dynamics, which include catchment parameters, and transitions in climate, tectonic or geomorphic regime, are necessary to explain the nature and rates of rockwall slope erosion over time. Understanding the topographic evolution and configuration of upper Bhagirathi and glaciated catchments throughout the NW Himalaya is made particularly challenging as it involves processes that operate across a variety of temporal and spatial scales. Despite the controls of alpine headwater evolution remaining elusive, this is the first study to quantify the rates of rockwall slope erosion in Garhwal, and has helped to demonstrate the importance of rockfall processes and the lateral erosion of slopes within mountain sedimentary systems.

Conclusion

Rockwall slope erosion has been defined for the upper Bhagirathi catchment by measuring $^{10}$Be concentrations in sediment samples from three medial moraines of Gangotri glacier system. The concentrations are corrected for accumulation of $^{10}$Be between the source rockwall and the medial moraine. Accumulation along the length of the medial moraines is found to be negligible. The $^{10}$Be sample concentrations ($1.1 \pm 0.2$ to $2.7 \pm 0.3 \times 10^{5}$ at/g SiO$_2$) therefore reflect rates of slope erosion only. The slope erosion of the upper Bhagirathi catchment is best reflected by the SD$_{h}$ moraine rates, which range from $2.4 \pm 0.4$ to $2.5 \pm 0.5$ mm/a. These rates affirm that $\sim$2.5 m of lateral slope erosion through periglacial processes can be achieved across a single millennium in this catchment, and $>65$ m when extrapolated for the whole of the Holocene. Slope erosion is therefore sufficient to affect sediment flux and glacier dynamics in upper Bhagirathi, in addition to helping set the pace of topographic change at the catchment head.

The rockwall slope erosion rates ($2.4 \pm 0.4$–$6.9 \pm 1.9$ mm/a) exceed the averaged catchment-wide ($0.1 \pm 0.001$ to $5.4 \pm 0.5$ mm/a; Figure 7) and erosional exhumation ($1.5 \pm 0.5$ mm/a; Figure 7) rates of Bhagirathi and the Garhwal region, indicating that erosion at the headwaters can outpace downstream reaches and the wider catchment. A possible explanation is that the high-altitude periglacial settings of upper Bhagirathi have a greater sensitivity to external forcing such as a shift in climatic conditions, than the wider catchment or mountain range. The variance found between the rates of landscape denudation may also be due to the difference in the nature and resolution of the erosion records.

Rockwall slope erosion rates are higher in upper Bhagirathi compared to the catchments of Chhota Shigri in the Lahul Himalaya and Baltoro glacier in the Central Karakoram. Comparisons were made between the erosion datasets of these three

Figure 8. Comparisons between $^{10}$Be concentrations ($10^{5}$ at/g SiO$_2$) for Bhagirathi, Chhota Shigri (1: Scherler and Egholm, 2017) and Baltoro (2: Seong et al., 2009) glaciers (uncertainties expressed to 1σ). (A) Beryllium-10 concentrations. (B) Catchment area ($r^2$ value provided for all catchment data). (C) Glacier area. (D) Mean catchment elevation. (E) Mean rockwall slope (slope calculated from 0.001 km$^2$ catchment grid cells). (F) 3-km-radius relief. (G) Mean annual temperature for Bhagirathi (Bhambri et al., 2011), Chhota Shigri (Wagnon et al., 2007) and Baltoro (Mihalcea et al., 2006, 2008). (H) Annual rainfall for Bhagirathi (Bhambri et al., 2011, Srivastava, 2012), Chhota Shigri and Baltoro (TRMM rainfall record [1998–2005]; Bookhagen and Burbank, 2006). (Colour figure can be viewed at wileyonlinelibrary.com)
study areas with catchment parameters and regional climate records, including catchment and glacier area, mean elevation and slope, 3-km-radius relief and annual temperature and rainfall. A tentative relationship is evident between erosion and precipitation, where more rapid slope erosion was recorded in the monsoon-influenced Lesser and Greater Himalaya, compared with the semi-arid interior of the orogen. No other individual catchment attribute was found to offer a dominant control on the rates of slope erosion in the NW Himalaya.

We were unable to confidently link rockwall slope erosion with climate-topography. We conclude that rockwall slope erosion in the three study areas and then more broadly across the NW Himalaya is likely governed by individual catchment dynamics, which vary across space and time. The frequency and magnitude of rockfall and avalanche events is therefore determined by a set of preconditioning factors unique to each catchment, and one or more local and/or regional forcing factor. By continuing to decipher the rates and controls of rockwall slope erosion, we will improve our understanding of the role and importance of periglacial processes in the morphological development of mountain ranges and contribute to future studies of sediment flux and wider landscape change across the orogen.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**Figure S1.1.** Images of the sampling locations for the investigated medial moraines of the Gangotri glacier system. White line denotes the moraine ridge.

**Figure S1.2.** Cross-sections of the sampling locations for the investigated medial moraines of the Gangotri glacier system.

**Figure S2.1.** Photomicrographs of the $C_{\text{sd}}$ sample from the $SD_{m}$ medial moraine. A) Image of moraine surface at the $C_{\text{sd}}$ sampling site. B) Image of fine-coarse sand sediment fractions taken using digital microscope. C) SEM image (200x mag) of silt-clay fraction.

**Figure S2.2.** SEM images of Gangotri medial moraine samples. $C_{\text{sd}}$ i) 350x mag ii) 500x mag iii) 1000x mag $C_{\text{mag}}$ i) 80x mag ii) 350x mag iii) 500x mag iv) 1000x mag $C_{\text{120x}}$ i) 120x mag ii) 200x mag iii) 650x mag iv) 150x mag v) 120x mag vi) 250x mag $C_{\text{mag}}$ i) 120x mag ii) 350x mag iii) 500x mag iv) 1000x mag v) 200x mag vi) 1000x mag.

**Figure S2.3.** Particle size distribution of Gangotri medial moraines of the Gangotri glacier system. White line denotes the moraine ridge.

**Figure S2.4.** Mean weight percentages per $\Phi$ interval of medial moraine samples from Gangotri glacier and comparisons derived from Owen et al. (2003). These comparisons include supraglacial debris from Rakhoti, Chungphur and Glacier de Chélon (Owen et al. 2003) in addition to Glacier de Tsidjéjére Nourve (Small 1983), Breidamerkurjokull, Sore Buchananisen, and the Glacier d’Argentiére (Boulton 1978).
Figure S2.5. Roundness and Sphericity Index for individual grain size fractions of Gangotri medial moraine samples. A) coarse-medium gravel, B) fine gravel, C) coarse-medium sand, D) fine sand, E) silt-clay, F) sample summary (appears as Fig. x).

Figure S2.6. Clast shape of Gangotri medial moraine samples (ternary diagrams using methods of Graham and Midgley, 2000). upper) Clast shape categories defined by Snead and Folk (1958).

Figure S2.7. Percentage surface weathering of quartz sand grains for the Gangotri glacier medial moraines.

Figure S2.8. Diffraction patterns of the clay component of Gangotri medial moraine samples (CT: 1.0 s, SS: 0.05°). A) G_{sup1}. B) G_{sup2}. C) G_{sup3}. D) G_{sup4}. E) G_{sup5}. F) G_{sup6}.

Table S2.1. Percentage grain size distribution of Gangotri medial moraine samples.

Figure S3.1. Slope map with hillshade for the upper Bhagirathi catchment.

Figure S3.2. A) Example $^{10}$Be production rate map for the Kirti. B) Accumulation of $^{10}$Be during burial, englacial transport and exhumation between rockwall and medial moraine for the Kirti tributary catchment. Additional $^{10}$Be inventory is 2500 at/g (u: mean glacier surface velocity [20±5 m/a], XELA: 3400 m.)

Table S3.1. Analytical model variables to calculate the $^{10}$Be inventory gained during transport of rock particles from bedrock slope to medial moraine.

Table S3.2. Potential $^{10}$Be accumulation in sediment from medial moraine.

Data S1. Supporting information