

Does decreasing paraglacial sediment supply slow knickpoint retreat?

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ABSTRACT

In four rivers in western Scotland for which there is a well-constrained record of relative base-level fall, the rate of postglacial bedrock erosion is quantified by measuring the concentration of in situ cosmogenic ¹⁰Be on strath terraces downstream of headward-retreating knickpoints. Along-channel gradients in ¹⁰Be exposure age show two distinct trends: upstream younging and constant age, which we interpret as diagnostic of knickpoint retreat and diffusive transport-limited incision, respectively. We show that bedrock channel incision and regional formation of strath terraces began shortly after deglaciation (ca. 11.5 ka), and that knickpoint retreat rates peaked in the early to mid-Holocene. Erosion rates have since decreased by two orders of magnitude, converging in the late Holocene to low rates independent of stream power per unit channel area. We infer this regional slowing in postglacial knickpoint retreat to be the result of the depletion of paraglacial sediment supply over the Holocene, leading to a deficiency in “tools” for bedrock erosion. Our results imply that episodes of major fluvial erosion may be in tune with glacial cycles, and that sediment depletion following glacial-interglacial transitions may be an important cause of bedrock erosion rate variations in rivers draining glaciated landscapes.

INTRODUCTION

How rivers respond to climatic and tectonic forcing is central to the evolution of topography, because river incision drives hillslope erosion that ultimately governs landscape-wide denudation rates (Howard et al., 1994). Recent advances emphasize the mediating role of sediment load on river incision: mobile sediment provides erosional tools, but too much sediment effectively shields channel bedrock from erosion (Sklar and Dietrich, 2001). One key to understanding how climate and tectonics shape the landscape rests with how sediment influences the erosional capacity of rivers (Whipple and Tucker, 2002; Johnson et al., 2009).

Landscapes subject to episodic glaciation are shaped by ice during glacial periods and then by river and slope processes following each glacial-interglacial transition. Where glacioisostatic base-level fall enhances local erosional capacity, a knickpoint may develop into a transient incisional wave that propagates upstream through the channel network (Bishop et al., 2005). The controls on knickpoint retreat are similar to those governing bedrock river incision in general, i.e., discharge, slope, substrate erodibility, and sediment load (Gardner, 1983; Howard et al., 1994). Climate controls river incision via the production and supply of sediment in the landscape, as well as the floods necessary to transport debris and erode bedrock. Considering the copious glacial materials available following deglaciation (Church and Ryder, 1972), we ask whether bedrock river incision is expected to increase or decrease as a result of this large sediment supply. Deep postglacial fluvial gorges imply that the supply of paraglacial sediment “tools” coupled with falling base level is conducive to extremely high incision rates (e.g., Korup and Schlunegger, 2007; Valla et al., 2010).

Success with quantifying the influence of sediment load on bedrock incision is limited by the difficulty of measuring coarse sediment flux in

bedrock rivers, and the modeling uncertainties involved in scaling sediment flux over geologic time scales (Sklar and Dietrich, 2001; Whipple and Tucker, 2002; Valla et al., 2010). Here we circumvent those difficulties by focusing on rivers subject to regional decrease in sediment supply rate over the Holocene. In four rivers in western Scotland for which there is a well-constrained record of relative base-level fall, rates of bedrock erosion are quantified using in situ cosmogenic ¹⁰Be (¹⁰Be) on bedrock strath terraces formed in the wake of headward-retreating knickpoints.

FIELD AREA

Loch Linnhe is the largest fjord in western Scotland (Figs. 1A and 1B), where hills carved from metasedimentary and granitic rocks rise abruptly from sea level to >1 km and induce ~2.2–3.2 m/yr of precipitation. Deglaciation ca. 11.5 ka (Lowe and Walker, 1976) coincided with rapid glacioisostatic rebound in western Scotland, and relative sea level (RSL) fall continued throughout the Holocene (Shennan et al., 2005). Emergent shoreline surfaces, which approximately correlate with the Main Postglacial Shoreline, indicate ~15 m of RSL fall since 9.1 ± 1.3 ka (Figs. 1B and 1C; see also Item DR1 in the GSA Data Repository¹). In order to investigate fluvial responses to this magnitude and timing of base-level fall, we examined 13 rivers (Figs. 1A and 1D).

High sediment availability shortly after deglaciation, followed by depletion, the pattern envisaged by Church and Ryder (1972), is confirmed by the cessation of debris-flow activity ca. 4 ka in Glen Etive (Fig. 1A) (Brazier et al., 1988), reduced late Holocene influx of terrigenous sediment to the Loch Etive fjord (Fig. 1A) (Nørgaard-Pedersen et al., 2006), and regional incision to bedrock of fill terraces ~3 m thick (Ballantyne, 2008). All rivers show clear signs of active incision: from sea level, bedrock channels extend upstream flanked by discontinuous strath terraces (i.e., fragments of abandoned channel bed) that culminate at knickpoints or waterfalls several meters high (cf. Bishop et al., 2005; Jansen et al., 2010), and incised fill terraces.

METHODS

For each of the 13 rivers, long profiles of the channel bed and strath terraces were measured in the field using a differential global positioning system. Retreating knickpoints were identified as zones of abrupt channel steepening flanked by strath terraces downstream (Bishop et al., 2005). A subset of four rivers was selected for detailed analysis on the basis of the uniformity of rocks exposed along reaches with well-developed straths associated with knickpoint retreat (Fig. 2). A regional discharge–drainage area relationship enabled calculation of stream power per unit channel area (see Item DR2).

Bedrock samples were collected for ¹⁰Be analysis at intervals along straths in the four rivers (Fig. 2). Sampled surfaces preserve fluvial abra-

¹GSA Data Repository item 2011175, data on sea level, stream power, cosmogenic nuclides, grain size, and bedrock erosional flux, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

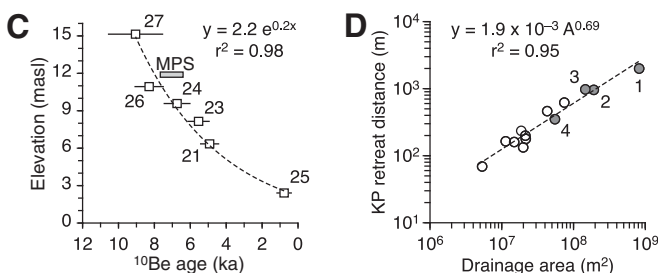
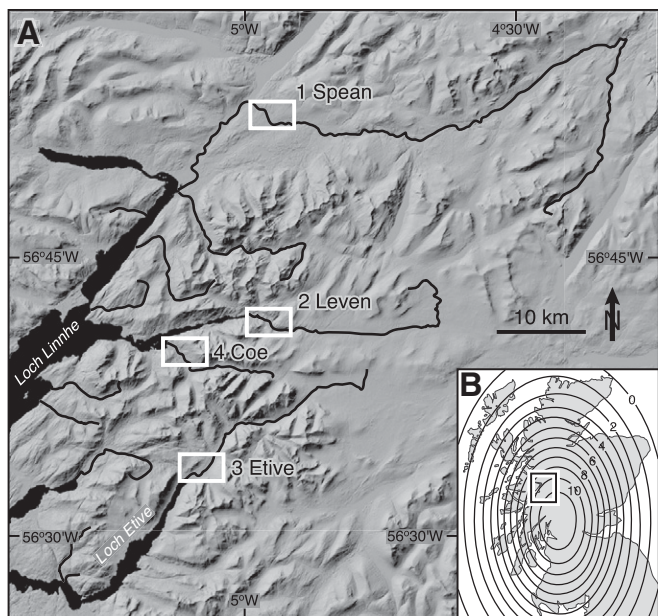


Figure 1. A: Loch Linnhe field area, western Scotland, with 13 rivers (black wiggles) and subset of four, Spean, Leven, Etive, and Coe. **B:** Field area (box), and surface uplift isobases (m) for Main Postglacial Shoreline (Smith et al., 2006). **C:** Six $^{10}\text{Be}_c$ ages ($\pm 1\sigma$ external uncertainty) indicating relative sea-level fall in River Coe relative to Main Postglacial Shoreline (MPS) (labels keyed to Item DR3 in the Data Repository; see footnote 1). **D:** Knickpoint (KP) retreat distance versus drainage area for 13 rivers.

sion morphology consistent with minimal erosion since channel incision and abandonment, and the $^{10}\text{Be}_c$ concentrations are interpreted as terrace abandonment ages (Reusser et al., 2004). Age calculations follow Balco et al. (2008) (see Item DR3 for sampling and analytical information). Knickpoint retreat is a detachment-limited process governed by erosional thresholds in exposed channel bedrock, as opposed to the more diffusive process of transport-limited incision, which is mediated by the capacity to transport a quasi-continuous sediment cover (Howard et al., 1994). The size distribution and hence mobility of bed materials in the four rivers was assessed using standard point-count methods (see Item DR4). Knickpoint retreat creates a diachronous strath confirmed by $^{10}\text{Be}_c$ ages that young upstream, whereas transport-limited incision produces constant strath age downstream. At selected sites in two of the rivers (Leven and Coe), samples were taken from higher channel remnants (fluvially sculpted bedrock ledges) above the more continuous straths in order to quantify vertical incision rates. To provide direct measurement of present-day denudation rates, two samples were collected from the bedrock channel bed of Leven and Coe, augmenting previous measurements from Etive (Kim, 2004).

RESULTS

The strong power-law scaling between knickpoint retreat length and drainage area (Fig. 1D) indicates that the position of each knickpoint

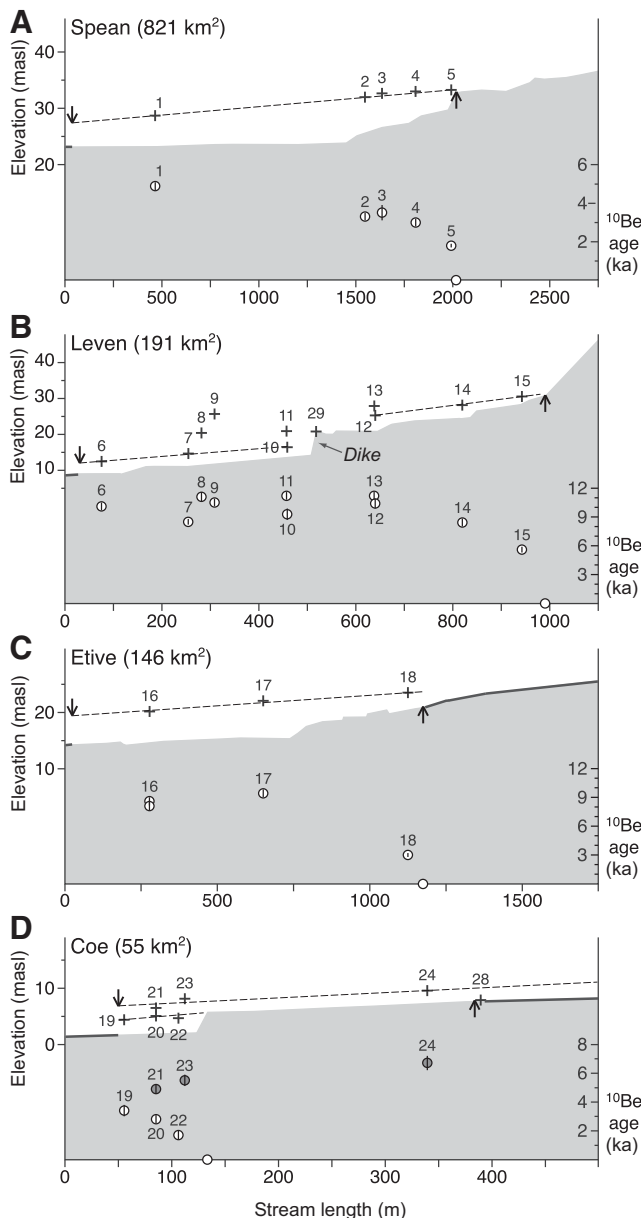


Figure 2. Long profiles (gray shading) for four rivers, with strath terraces (dashes), $^{10}\text{Be}_c$ samples (plus symbols), and $^{10}\text{Be}_c$ ages (circles with verticals indicate $\pm 1\sigma$ internal uncertainty, and assume zero age at knickpoint tips) (masl—meters above sea level). $^{10}\text{Be}_c$ samples (labels keyed to Item DR3; see footnote 1) are plotted as zero-erosion exposure ages (ka), except samples 28 and 29, which are modeled as maximum erosion rates (m k.y.^{-1}). Down arrow is initiation point of postglacial fluvial incision, up arrow is retreating knickpoint, and thick gray line shows continuous alluvial bed cover. In B, knickpoint has retreated to base of 30-m-high waterfall formed in resistant metaquartz-arenite; in D, $^{10}\text{Be}_c$ ages from emergent shoreline (Fig. 1C) are shaded.

is largely independent of substrate, and confirms that knickpoint retreat is a function of either discharge and/or sediment flux via the proxy of drainage area (Bishop et al., 2005; Berlin and Anderson, 2007). Both styles of bedrock erosion, knickpoint retreat and diffusive incision, are evident in the $^{10}\text{Be}_c$ strath ages (Fig. 2), and present-day bedrock reaches maintain a sparse and readily transportable cover, with median grain sizes of 90–260 mm (Item DR4). Simple knickpoint retreat is shown in River Spean from before 4.9 ± 0.2 ka (samples 1–5; Fig. 2A). River

Leven preserves two fragmentary straths that extend downstream (samples 6, 7, and 10) and upstream (samples 12, 14, and 15) of a 4-m-high waterfall on a dike of resistant porphyritic microdiorite (Fig. 2B). The downstream strath shows no age trend, suggesting diffusive incision in the early Holocene, with a transition to knickpoint retreat between 10.4 ± 0.5 ka and 8.4 ± 0.4 ka, implied by the upstream-younging ages (samples 12, 14, and 15). Diffusive incision in the early Holocene is also interpreted from River Etive by samples 16 and 17 (pooled mean = 8.7 ± 0.6 ka), with a change to knickpoint retreat sometime between ca. 8.1 ± 0.4 ka and 3.0 ± 0.2 ka (samples 17 and 18) (Fig. 2C). The River Coe outlet was below sea level in the early Holocene and so bedrock surfaces remained shielded from cosmic radiation at that time (Fig. 2D). Six $^{10}\text{Be}_c$ ages from the emergent upper shoreline surface show a downstream-younging trend consistent with surface uplift and downstream displacement of the shoreline (samples 21 and 23–27; Figs. 1C and 2D). The $^{10}\text{Be}_c$ ages from the strath inset below the emerging surface (samples 19, 20, and 22) indicate knickpoint retreat starting just before 3.4 ± 0.4 ka, following shoreline emergence that had caused $\sim 2\text{--}3$ m of channel bed lowering to the level now marked by the strath.

Knickpoint retreat rates (velocity, V_{KP}) in the four rivers are calculated for the channel segments between strath exposure ages to examine how V_{KP} varied over time. The largest river, Spean, yields the highest V_{KP} of 790 ± 110 m k.y.^{-1} , and V_{KP} has decreased in all four rivers to <20 m k.y.^{-1} (Fig. 3A). Furthermore, these trends are consistent with calculated variations in volumetric rates of channel bedrock erosion (see Item DR5). The steepened knickpoint reaches undergo higher stream power per unit channel area (ω), yet there is no scaling between ω and V_{KP} in the most recently incised channel segment below the knickpoint tip, which is presumably the zone of maximum present-day incision (Fig. 3B). Knickpoints in the four rivers are retreating at essentially the same rate ($13.9\text{--}16.9$ m k.y.^{-1} ; pooled mean = 15.3 ± 2.9 m k.y.^{-1}), while local ω differs ~ 15 -fold.

Independent of knickpoint retreat, vertical channel incision rates are calculated from six paired strath samples and two channel bed sites in Rivers Leven and Coe (Figs. 2B and 2D). The larger Leven incised much more rapidly than did the Coe under the inferred sediment-rich, transport-limited conditions of the early to mid-Holocene (Fig. 3C). However, as with knickpoint retreat, incision rates decreased in the late Holocene, and four channel bed samples (including Etive samples from Kim, 2004) show uniformly low incision rates ($0.07\text{--}0.24$ m k.y.^{-1}) in spite of a 3.5-fold difference in drainage area (Fig. 3C). For two of the sample pairs (9 and 8, and 13 and 12) $^{10}\text{Be}_c$ ages overlap at 1σ , implying either extremely rapid incision (~ 3.3 m k.y.^{-1}), or that these sites are fragments of a preexisting surface exposed via deglaciation rather than fluvial erosion. It is important that the close match between deglaciation (ca. 11.5 ka) and a pooled mean age of 11.2 ± 1.8 ka (samples 8, 11, and 13) fits well with the latter interpretation and, moreover, allays concerns of inherited $^{10}\text{Be}_c$ in these samples.

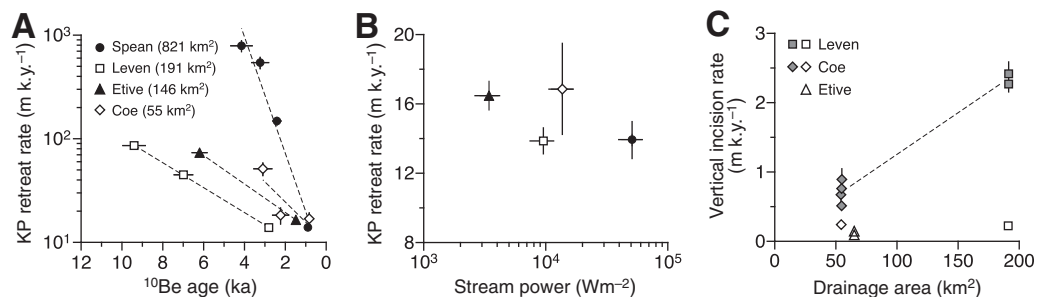
DISCUSSION

The glacial-interglacial transition in western Scotland was a time of high sediment availability thanks to large volumes of unstable glacially-derived material, which was then progressively depleted according to the exponential decay model proposed by Church and Ryder (1972; see also Ballantyne, 2008). Inferred transport-limited channel incision began shortly after deglaciation (Fig. 2), resulting in regional formation of strath terraces and an ensuing phase of erosion that extended into the mid-Holocene, with vertical incision as high as ~ 2.4 m k.y.^{-1} and V_{KP} as high as ~ 790 m k.y.^{-1} (Fig. 3). The paraglacial fill terraces are now all incised to bedrock, and trends in strath age indicate an early to mid-Holocene shift in erosional style from transport-limited incision to knickpoint retreat in at least three of the four rivers analyzed. This shift in erosional style reflects the “tools and cover” effect (e.g., Sklar and Dietrich, 2001, 2004; Whipple and Tucker, 2002; Turowski et al., 2007). Extreme rates of bedrock incision are reported from rivers highly charged with sediment (e.g., Schaller et al., 2005), but whether decreasing sediment flux leads to falling incision rates remains unclear. Laboratory experiments demonstrate that a decrease in sediment availability leading to a deficiency in tools drives down erosion rates (Sklar and Dietrich, 2001). The early stages of sediment depletion in the Loch Linnhe rivers evidently led to bedrock exposure and some incision amid flushing of the alluvial cover, but rivers soon lacked sufficient tools to maintain the rapid erosion of the early to mid-Holocene (cf. Reusser et al., 2004).

The emergent shoreline ages confirm RSL fall (Fig. 1C) as the likely trigger for the bedrock incision at river outlets, though the original knickpoints are well upstream of the present outlets and so remain isolated from ongoing RSL fall. Thus, the declining rate of surface uplift (Fig. 1C) can be ruled out as a cause of decreasing V_{KP} (Fig. 3A). Variations in Holocene flooding can likewise be excluded because, first, a meta-analysis of 84 fluvial ^{14}C ages shows that the frequency of major floods actually increased post-3.8 ka in northern and western Scotland (Macklin et al., 2010), and second, discharge in the four rivers spans an ~ 14 -fold range, which is incompatible with interpreting present-day erosion rates as a function of discharge (see Item DR2). The contraction in drainage area (and hence discharge) as knickpoints retreat upstream can also be ruled out as a source of significant knickpoint slowing, the decreases in drainage areas being only 0.3%–6.8% in the four rivers.

Downstream variation in ω is widely used to predict bedrock river incision rates in the absence of more detailed information on erosional capacity (Howard et al., 1994; Whipple and Tucker, 2002). Present-day knickpoints in the Loch Linnhe rivers correspond to elevated ω values (Fig. 2), but that association says little about temporal variations in erosional capacity because slope and width change considerably as knickpoints retreat. Nor do downstream variations in ω provide a useful proxy for erosion rates, because knickpoint erosion does not scale with ω at present (Fig. 3B). This lack of scaling apparently contradicts the strong scaling between knickpoint retreat distance and drainage area (Fig. 1D). We

Figure 3. A: Knickpoint (KP) retreat rates with best-fit exponential curves. B: Knickpoint retreat rates versus local stream power per unit channel area, calculated from pooled mean of 3–6 cross sections between 20 and 50 m downstream from knickpoint tip to first $^{10}\text{Be}_c$ sample in each river (samples 5, 15, 18, and 22 in Fig. 2). C: Vertical incision rates from Coe (sample pairs 19 and 25, 21 and 20, 23 and 22, and 24 and 28), Leven (sample pairs 8 and 7, and 11 and 10) and Etive (Kim, 2004). Early to mid-Holocene incision rates (shaded) scale with drainage area, unlike present-day rates (open) derived from channel bed samples.



note that early erosion rates in each river scale closely with drainage area (Figs. 3A and 3C), implying that area functioned as a proxy for discharge and sediment flux in the early to mid-Holocene. Subsequently, with the onset of detachment-limited knickpoint retreat, discharge and erosion rate were decoupled (Fig. 3C). The observed scaling in Figure 1D must therefore result from speedy knickpoints that quickly and early establish overall scaling with drainage area before the decoupling. Accordingly, average V_{KP} calculated from the location of present-day knickpoints ($\sim 173\text{--}30\text{ m k.y.}^{-1}$; Fig. 1D) may possibly differ by an order of magnitude from actual instantaneous rates.

Peak rates of postglacial bedrock incision in western Scotland are as much as two orders of magnitude faster than the maximum Cenozoic denudation rate, $23\text{--}33\text{ m.y.}^{-1}$, calculated from apatite (U-Th)/He and fission track analyses (Persano et al., 2007). One explanation for this large disparity is that episodes of accelerated fluvial erosion are in tune with glacial cycles, and sediment depletion following glacial-interglacial transitions may be a pervasive cause of temporally decreasing denudation rates in glaciated landscapes.

CONCLUSIONS

The equivalence of present-day bedrock erosion rates at knickpoints in four rivers leads us to conclude that regional decrease in erosional capacity over the Holocene is unrelated to changes in either discharge or stream power. A base-level trigger due to glacioisostatic rebound probably initiated incision of the sedimentary cover during the early transport-limited phase, and subsequent knickpoint retreat was driven by the flux of water and sediment. Of these two, sediment flux appears to be the rate-limiting factor. We infer the regional slowing in postglacial knickpoint retreat to be the result of the depletion of paraglacial sediment supply over the Holocene, leading to a deficiency in tools for bedrock erosion.

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