View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Edinburgh Research Explorer

THE UNIVERSITY of EDINBURGH

Edinburgh Research Explorer

Erosion during extreme flood events dominates Holocene canyon evolution in northeast Iceland

Citation for published version:
Baynes, E, Attal, M, Niedermann, S, Kirstein, L, Dugmore, A & Naylor, M 2015, 'Erosion during extreme flood events dominates Holocene canyon evolution in northeast Iceland' Proceedings of the National Academy of Sciences, vol. 112, no. 8, pp. 2355–2360. DOI: 10.1073/pnas.1415443112

Digital Object Identifier (DOI):
10.1073/pnas.1415443112

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Proceedings of the National Academy of Sciences

Publisher Rights Statement:
Freely available online through the PNAS open access option.

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

OPEN ACCESS

Download date: 05. Apr. 2019

Erosion during extreme flood events dominates Holocene canyon evolution in northeast Iceland

Edwin R. C. Baynes[a,1], Mikaël Attal[a], Samuel Niedermann[b], Linda A. Kirstein[a], Andrew J. Dugmore[a], and Mark Naylor[a]

[a]School of GeoSciences, University of Edinburgh, Edinburgh EH8 9XP, United Kingdom; and [b]Deutsches GeoForschungsZentrum, D-14473 Potsdam, Germany

Edited by Thure E. Cerling, University of Utah, Salt Lake City, UT, and approved January 16, 2015 (received for review August 11, 2014)

Extreme flood events have the potential to cause catastrophic landscape change in short periods of time (10^0 to 10^3 h). However, their impacts are rarely considered in studies of long-term landscape evolution (>10^3 y), because the mechanisms of erosion during such floods are poorly constrained. Here we use topographic analysis and cosmogenic ^{3}He surface exposure dating of fluvially sculpted surfaces to determine the impact of extreme flood events within the Jökulsárgljúfur canyon (northeast Iceland) and to constrain the mechanisms of bedrock erosion during these events. Surface exposure ages allow identification of three periods of intense canyon cutting about 9 ka ago, 5 ka ago, and 2 ka ago during which multiple large knickpoints retreated large distances (>2 km). During these events, a threshold flow depth was exceeded, leading to the toppling and transportation of basalt lava columns. Despite continuing and comparatively large-scale (500 m^3/s) discharge of sediment-rich glacial meltwater, there is no evidence for a transition to an abrasion-dominated erosion regime since the last erosive event because the vertical knickpoints have not diffused over time. We provide a model for the evolution of the Jökulsárgljúfur canyon through the reconstruction of the river profile and canyon morphology at different stages over the last 9 ka and highlight the dominant role played by extreme flood events in the shaping of this landscape during the Holocene.

bedrock erosion | extreme floods | knickpoints | Iceland | cosmogenic ^{3}He

Extreme floods in both terrestrial and extraterrestrial environments can cause abrupt landscape change that can have long-term consequences (1–5), especially when a geomorphic threshold is exceeded (6). The timescale over which this change is visible is controlled by the ability and efficiency of background processes to reshape the landscape. As a result, progress in understanding both short-term and long-term landscape evolution requires better knowledge of bedrock channel erosion processes and thresholds over the different scales at which geomorphological processes operate (7–10).

The majority of research into extreme flood events has focused on the interpretation of deposited sediments (e.g., refs. 11 and 12) and the reconstruction of the hydraulic conditions prevailing during such events (e.g., refs. 13–15). Further work has defined the geomorphic impact of extreme flood events in proglacial areas close to the source of the flood water (e.g., refs. 16 and 17). Studies that examine the processes of bedrock erosion, especially large canyon formation, during extreme flood events can help establish a diagnostic link between formation processes and morphology in canyons in both terrestrial and extraterrestrial settings, but they remain scarce (e.g., refs. 18–20). Here, evidence for bedrock landscape change during extreme floods along the course of the Jökulsá á Fjöllum River (northeast Iceland) is used to test whether the contemporary landscape morphology reflects erosion during rare extreme events, or longer-term "background" erosional processes.

The Jökulsá á Fjöllum has experienced multiple glacial outburst floods (jökulhlaups) since the Last Glacial Maximum, with peak discharge for the largest flood estimated to be in the order of 0.9×10^6 m^3/s (14, 21). The landscape contains many characteristic landforms associated with extreme flood events, including boulder bars and terraces, dry cataracts such as Ásbyrgi, numerous flood overspill channels, and the Jökulsárgljúfur canyon (Fig. 1) (e.g., refs. 16 and 22–25). The canyon has been carved through a volcanic system that was active 8.5 ka B.P. (26) ~4 km downstream of its head. As the canyon is cut directly through the fissure and associated lava flows and there is no evidence of lava from the fissure flowing into the canyon, the eruption age provides an independent constraint on the maximum age for the formation of the canyon upstream of the fissure (Fig. 1). The impact of the largest flood events has never been tied to the evolution of the bedrock landscape within the Jökulsárgljúfur canyon, as previous studies have focused on sedimentary deposits (e.g., refs. 24 and 25). This study uses topographic analysis and cosmogenic ^{3}He surface exposure dating of fluvial surfaces to determine the erosive impact of extreme flood events and assess the importance, and legacy, of high-magnitude low-frequency events in landscape evolution over multimillennial timescales.

Conceptual Model of Canyon Formation

Large canyons can be formed during extreme flood events through the toppling and removal of blocks in heavily jointed basaltic bedrock (18, 19), once a threshold flow depth has been exceeded (27). Bedrock erosion during extreme floods in such settings is therefore dominated by plucking rather than abrasion, resulting in the formation and upstream propagation of large vertical knickpoints [e.g., Box Canyon and Stubby Canyon, Idaho (18, 19)]. As the knickpoints propagate upstream, rock is removed typically over the thickness of one or more lava flows, exposing pristine rock surfaces to cosmic rays and initiating the accumulation of cosmogenic nuclides. The surface can subsequently

Significance

The importance of high-magnitude, short-lived events in controlling the evolution of landscapes is not well understood. This matters because during such events, erosion processes can surpass thresholds and cause abrupt landscape changes that have a long-lasting legacy for landscape morphology. We show that extreme flood events, during which the flow depth exceeds the threshold for erosion through plucking rather than abrasion, are the dominant control on the evolution of a large bedrock canyon in Iceland. The erosive signature of these events is maintained within a dynamic landscape over millennial timescales, emphasizing the importance of episodic extreme events in shaping landscapes.

EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

Author contributions: E.R.C.B., M.A., L.A.K., and A.J.D. designed research; E.R.C.B., M.A., S.N., L.A.K., and A.J.D. performed research; E.R.C.B., M.A., S.N., L.A.K., A.J.D., and M.N. analyzed data; and E.R.C.B., M.A., S.N., L.A.K., A.J.D., and M.N. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

[1] To whom correspondence should be addressed. Email: e.r.c.baynes@ed.ac.uk.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1415443112/-/DCSupplemental.

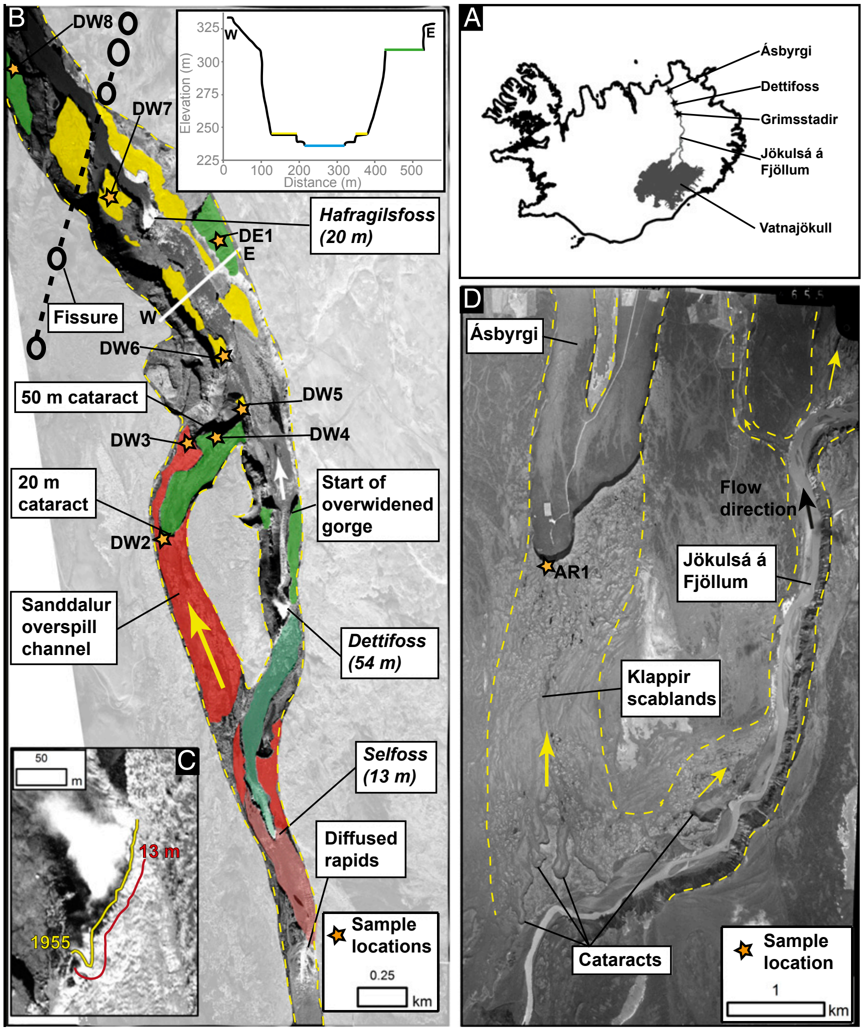

Fig. 1. (*A*) Location map of Iceland showing the Vatnajökull ice cap, the source of the floodwaters, and the course of the Jökulsá á Fjöllum. The locations of the two study sites—the upper 5 km of Jökulsárgljúfur canyon at Dettifoss and Ásbyrgi, 25 km further downstream—are shown with black stars. The location of the gauging station at Grimstadir used for hydrological calculations is also shown. (*B*) Aerial photograph from 1998 of the 5-km study reach at the head of Jökulsárgljúfur canyon. Yellow dashed lines delineate the areas where clear evidence for fluvial erosion is present (landscape outside these areas is shaded to improve clarity). The three large knickpoints are highlighted: Selfoss, Dettifoss, and Hafragilsfoss (height in parentheses), as well as the Sanddalur overspill channel, which contains two cataracts. The volcanic fissure that erupted 8.5 ka ago (black circles show volcanoes) provides an independent constraint on the maximum age of the canyon. Orange stars indicate the locations of the samples collected for surface exposure dating. The upper, middle, and lower terraces are shown in red, green, and yellow, respectively; active fluvial surfaces associated with upper and middle terraces are shown in transparent red and green upstream of Dettifoss. A cross section of the gorge across the line from west to east is inset. (*C*) A zoomed in image of Dettifoss from 1998, with the yellow line showing the digitized position of the waterfall in 1955. Dettifoss has been mostly stable during the 43-y period between the images, with only a small retreat (maximum 5 m) evident on the western side of the channel. If the Jökulsárgljúfur canyon was formed by the progressive retreat of Dettifoss following the fissure eruption (2,500 m in 8.5 ka, equivalent to a rate of 0.3 m/y), we would expect to see a minimum of 13 m of retreat between 1955 and 1998, shown with the red line. (*D*) Ásbyrgi canyon and the Klappir scabland area immediately upstream. This landscape exhibits perfectly preserved landforms that were formed during an extreme flood event, with the Jökulsá á Fjöllum now flowing in a deeply incised canyon to the east.

become abandoned through the retreat of a knickpoint at a lower level, leaving strath terraces above the active channel. If a knickpoint is retreating steadily through time, as would be expected if associated with a normal flow regime, the exposure age of samples from fluvial surfaces would become progressively younger with decreasing distance from the modern knickpoint location (28–30). If, on the other hand, a knickpoint retreated a large distance in a short period, such as during an extreme flood event, the exposure ages would be expected to cluster around the time of that significant erosion event (19). Recognition of the canyon morphology and the measurement of precise exposure ages are therefore key to distinguishing between models of canyon formation.

Canyon Morphology

At the head of the Jökulsárgljúfur canyon, the Jökulsá á Fjöllum becomes deeply incised into the surrounding terrain, with the drop in elevation occurring at three large vertical waterfalls, all within the 5-km-long study reach: Selfoss (13 m high), Dettifoss (54 m high), and Hafragilsfoss (20 m high) (Fig. 1). The underlying bedrock is columnar basalt, with multiple subhorizontal lava flows stacked on top of each other (Fig. 2). The structural control exerted by these lava flows is strong: The river cascades from the top of one lava flow to the top of the flow beneath at the Hafragilsfoss and Selfoss knickpoints, and it drops the height of three lava flows at Dettifoss (Fig. 2). Crucially, the canyon floor is always found to coincide with the top of a lava flow, and

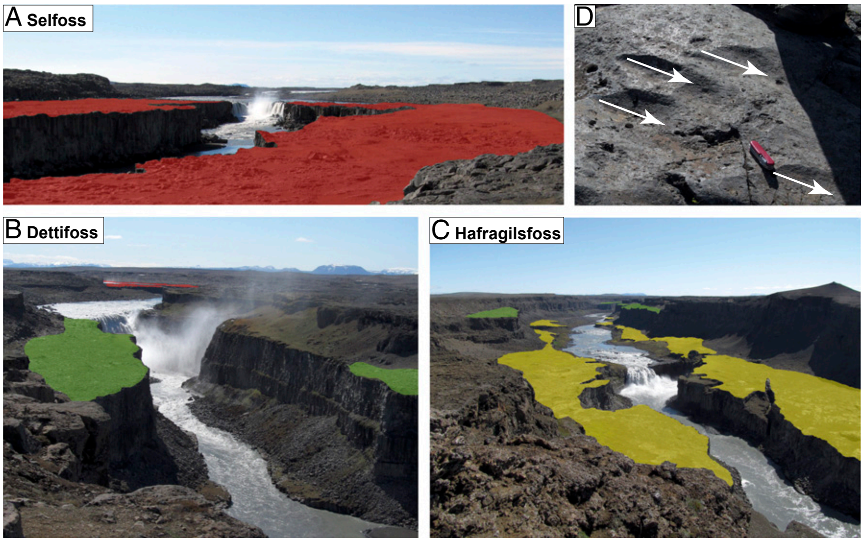

Fig. 2. Photographs of the three large waterfalls within the gorge in the study reach: (*A*) Selfoss (13 m), (*B*) Dettifoss (54 m), and (*C*) Hafragilsfoss (20 m). Highlighted on the photographs are the three strath terraces: the upper, middle, and lower terraces are highlighted in red, green, and yellow, respectively. Evidence for fluvial action on the strath terraces includes small-scale flutes, shown in *D*. The strath terraces correspond to the tops of different lava flows, which can be seen exposed in the canyon walls on each of the photos.

there is no evidence for active vertical incision into the lava flows other than the knickpoints themselves (Figs. 1 and 2). This implies that vertical incision through abrasion is limited and that knickpoint propagation due to the toppling of basalt columns is the dominant mode of erosion in the canyon. This is corroborated by the high width-to-depth ratio exhibited by the Jökulsá á Fjöllum, with the flow depth at Selfoss rarely reaching 3 m during peak summer discharge (*SI Text, Calculation of Flow Depth During Peak Annual Flow*). The Jökulsá á Fjöllum is 150 m wide at Selfoss, which gives a width-to-depth ratio of 50, similar to large alluvial rivers [e.g., ratio of ∼59 for alluvial reaches of the Yellowstone River (31)] rather than actively incising bedrock rivers (e.g., ratio of ∼5 for a range of bedrock rivers incising into high-grade metamorphic or granitic rocks; compilation in ref. 31).

Three strath terrace surfaces are found at different elevations throughout the canyon (Figs. 2 and 3*A*), indicating the position of paleo riverbeds. They too are strongly controlled by the bedrock structure, as each surface corresponds to the top of a lava flow. These terraces have been sculpted by fluvial abrasion, exhibiting bedforms such as flutes and polished surfaces (Fig. 2*D*). The formation of two of the three terraces can be directly associated with the upstream propagation of knickpoints within the present-day canyon: The upper and middle terraces have been abandoned by the retreat of Selfoss and Dettifoss, respectively (Fig. 2 *A* and *B*). The lower terrace is ∼10 m above the active river channel between Dettifoss and Hafragilsfoss (Fig. 2*C*). The 200-m-wide Sanddalur flood overspill channel to the west of Dettifoss contains both the upper and middle terraces, with a 20-m vertical cataract at the transition between the surfaces and a 50-m vertical cataract where it rejoins the main canyon (Fig. 1).

Surface Exposure Ages and Chronology of Flood Events

Samples for surface exposure dating were collected from fluvially polished bedrock surfaces on the strath terraces, both along the modern river and in the overspill channel (Figs. 1 and 3*A*). We assume that the exposure age represents the time at which a given location on the riverbed was exposed to cosmic rays due to the removal of overlying rock by the upstream migration of a knickpoint. We assume that there is negligible subsequent surface erosion and a negligible shielding effect from water in the channel that could reduce the concentration of cosmogenic nuclides; to minimize these potential effects, samples were taken as far away as possible from the center of the channel where water depth and erosion are expected to peak. We also assume that all of the cosmogenic ^{3}He has accumulated since exposure by erosion, rather than during the period between lava flow eruption and subsequent burial under younger flows. We note that the polished rock surfaces on all terraces are made of nonvesiculated, compact lava (Fig. 2*D*). This indicates removal of the very top of the lava flows (either rubbly aa or vesiculated pahoehoe) where inherited cosmogenic ^{3}He concentrations would have been the greatest, either through erosion by water or emplacement of subsequent flows. This therefore limits the potential contribution from inherited cosmogenic ^{3}He from exposure before burial. We acknowledge, however, that there may still be an unquantifiable amount of inherited cosmogenic helium in the samples that may lead to an overestimation of the surface exposure ages.

The surface exposure ages fall into two distinct clusters; the total age ranges of three samples overlap between 5.4 ka and 4.8 ka and those of five samples between 2.3 ka and 1.4 ka (Fig. 3*B*). The uncertainty in the geochemical measurements for sample DE1 is large, but the maximum exposure age is constrained by sample DW8 on the same terrace level further downstream. Due to upstream migration of knickpoints, DE1 cannot have been exposed earlier than DW8, giving a maximum exposure age of 5.4 ka. An analysis of the distribution of ages (*SI Text, Knickpoint Retreat Rates Assuming Progressive Migration*) indicates that, even under the assumption of a progressive migration of knickpoints, large variations in knickpoint retreat rates (from <0.25 m/y to >2 m/y) would be required to produce such an age distribution over the last 8.5 ka. These variations, combined with the overlap of surface exposure ages across multiple terraces (Fig. 3*B*) and limited retreat of the waterfalls over historical times (Fig. 1*C*), lead us to interpret the surface exposure age clusters as indicators of rapid upstream propagation of knickpoints during two periods of intense canyon cutting ∼5 ka ago and ∼2 ka ago (*SI Text, Knickpoint Retreat Rates Assuming Progressive Migration*). Importantly, the ages show that sections of the lower terrace and the overspill channel were exposed simultaneously 2 ka ago, indicating that multiple knickpoints were actively migrating at different elevations at this time. The Sanddalur overspill channel contains samples that have ages in both clusters, which is evidence for erosion in this channel during both the identified canyon cutting periods.

Ásbyrgi, located 25 km downstream of the study reach (Fig. 1), has a very similar morphology to canyons in Idaho, with an amphitheater-shaped canyon head and a vertical headwall, typical of formation during an extreme flood event (18, 19). There is no current overland flow or spring flow into the canyon capable of eroding or transporting the large boulders (size typically ranging between 0.5 m and 3 m) found in the canyon. Furthermore, the Klappir area immediately upstream of the canyon rim exhibits clear scabland morphology reminiscent of other landscapes that have experienced extreme flood events (e.g., ref. 1) (Fig. 1). A sample collected from scoured bedrock in an eroded notch at the rim of Ásbyrgi gives a range for the exposure age of 8.8 ± 1.6 ka to 11.0 ± 1.5 ka (see *Methods* and *SI Text*, *Surface Exposure Dating*, for explanation of upper and lower age limits on each sample), much earlier than either of the age clusters from the samples further upstream. Therefore, we infer that there was an erosive flood event along the Jökulsá á Fjöllum in the early Holocene. The absence of fluvial reworking and the outstanding preservation of the geomorphological features in the Klappir area indicate that the Jökulsá á Fjöllum never reoccupied the Klappir area following this flood event that likely carved the Ásbyrgi canyon. The floodwaters of the subsequent extreme flood events must therefore have been funneled through the modern Jökulsá á Fjöllum canyon further east, although overspilling with minimal erosive impact over the Klappir area cannot be ruled out.

Discussion

This study has identified three periods of intense canyon cutting in two reaches of the Jökulsá á Fjöllum throughout the Holocene. Our exposure ages alone do not allow us to distinguish between the impact of a single flood or a series of flood events during the periods of rapid canyon cutting identified, due to levels of uncertainty. However, previous work has identified one extreme flood event in the early Holocene and one in the late Holocene by dating sedimentary deposits (24); we tie the evolution of the bedrock landscape at Ásbyrgi and at Dettifoss to these early Holocene (~9 ka ago) and late Holocene (1.5–2 ka ago) flood events, respectively. Around 15 km downstream of Dettifoss, a sedimentary sequence containing up to 16 flood layers is believed to record events since 8 ka (24). The youngest two events in this sequence have been dated to 5.0 ka and 4.6 ka (25), consistent with our cluster of exposure ages at ~5 ka. We therefore hypothesize that the knickpoint retreat identified at ~5 ka is the result of one or both of these floods; the older floods identified in the sequence would have contributed to the migration of knickpoints between Ásbyrgi and Dettifoss. We believe the possible influence of inherited cosmogenic ^{3}He is minimal. Firstly, it is unlikely that all ^{3}He is inherited, because samples with different exposure ages are found on a single terrace. Secondly, exposure ages on different terrace levels overlap in two clusters that fit with the timing of floods identified in the stratigraphic record. We acknowledge that all ages are similar on

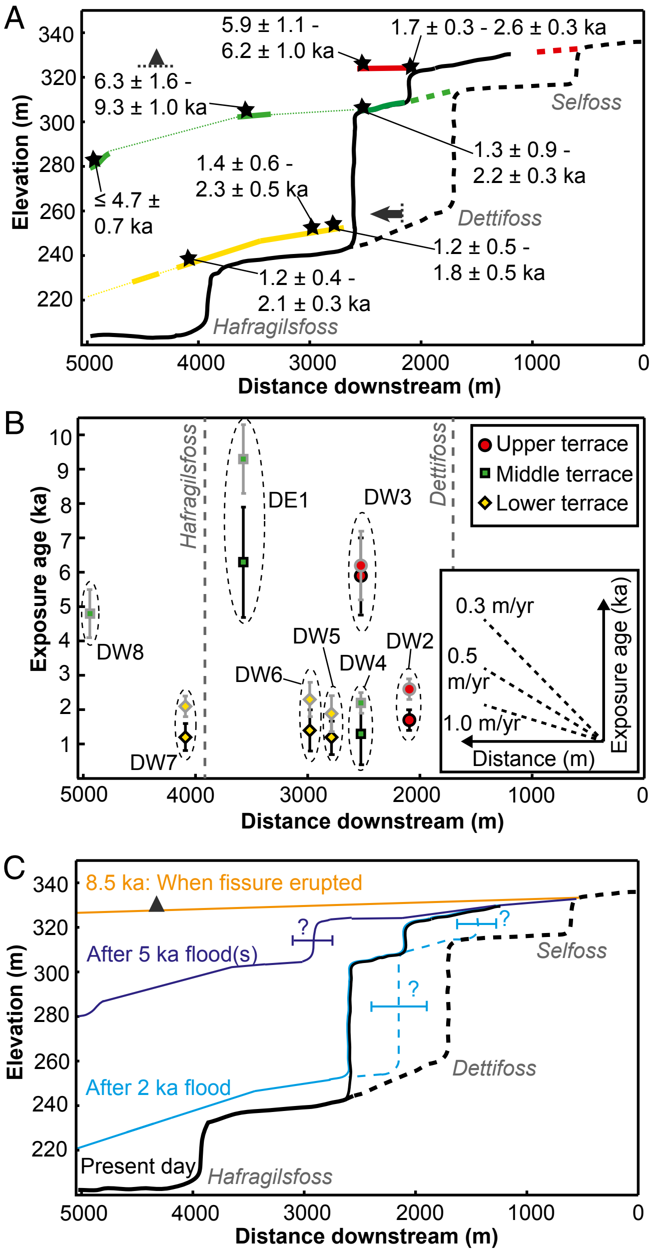

Fig. 3. Surface exposure ages and model of canyon evolution during the Holocene (*A*) Long profile of the Jökulsá á Fjöllum through the study reach shown in black and locations and elevations of the strath terraces shown in red, green, and yellow (same colors as Figs. 1 and 2). Upstream of the confluence between the overspill channel and the main channel, the dashed lines indicate the topography within the main channel and the solid line indicates the topography within the overspill channel (same in *C*). Exposure age ranges are provided for each sample, with the younger age calculated assuming there is no radiogenic ^{4}He in the sample and the older age calculated assuming all ^{4}He is radiogenic in origin (see *Methods* and *SI Text*, *Surface Exposure Dating*). The triangle marks the elevation and the location of the volcanic fissure that erupted 8.5 ka ago. Bold arrow marks the beginning of the overwidened gorge within the main channel. (*B*) Surface exposure age ranges of the samples plotted against distance downstream (minimum age in black and maximum age in gray). Error bars represent the analytic error (2σ) for each sample (*SI Text*). The ages fit clearly into two clusters from 5.4 ka to 4.8 ka and from 2.3 ka to 1.4 ka, demonstrating that large stretches of the terraces were exposed at the same time, interpreted to result from the upstream propagation of knickpoints during extreme flood events during these periods. *Inset* shows lines of age = *f* (distance) corresponding to different knickpoint retreat rates (0.3 m/y, 0.5 m/y, and 1.0 m/y), with 0.3 m/y representing the rate at which Dettifoss would have retreated if retreat were steady since 8.5 ka. *Inset* plotted at the same scale as the main graph, so slope of lines can be directly compared with the distribution of exposure ages. (*C*) Proposed evolution of the canyon during the Holocene. The strath terraces and exposure ages have been used to reconstruct the long profile of the Jökulsá á Fjöllum when the fissure erupted (in orange), after the 5-ka flood event(s) (in dark blue), and after the 2-ka flood event (in light blue). There has been no subsequent erosion since the 2-ka extreme flood event within the overspill channel. Bars with question marks indicate uncertainty on the position of knickpoints (paleo-Dettifoss at 2 ka ago is likely to be where the gorge overwidens).

the lower terrace, which could reflect inheritance (the real exposure age of the surface may be much younger); however, because these ages overlap with other ages on the middle and upper terrace (Fig. 3*B*), we privilege a scenario where inheritance is minimal and the ages reflect the true exposure age.

It is known that there was no incised gorge in the early Holocene when the volcanic fissure erupted onto the surface (Fig. 3*C*), but there was an extreme flood event around this time that carved Ásbyrgi further downstream. The clustering of ages from the middle terrace and the overspill channel shows that there was a second period of intense canyon cutting between 5.4 ka and 4.8 ka that led to ∼40 m of vertical incision at the apex of the fissure and the formation of a knickpoint between the upper and middle terraces (Fig. 3*C*). Our exposure ages show that the entire length of the lower terrace within the study reach (>2.5 km) was exposed during another period of intense canyon cutting ∼2 ka ago, associated with the retreat of the ∼50-m-high knickpoint that makes up Dettifoss. It is hypothesized that this knickpoint retreated to where the canyon is no longer overwidened (where the contemporary river fills the whole width of the canyon; Figs. 1 and 3*C*), with Dettifoss migrating a further ∼500 m to its current location since the last extreme flood event (at an average rate of ∼0.3 m/y). There has also been some erosion since the last extreme flood event further downstream, with the lower terrace becoming abandoned, and we suggest that this has occurred during a series of small flood events, although we do not have direct evidence for this from our surface exposure ages, as it was impossible to collect samples from the bottom of the canyon. We suggest the knickpoints themselves were generated at the coast in the early stages of the Holocene, exploiting weaknesses in the lava flows due to the plucking of large blocks. Once the knickpoints were generated over the height of one or more lava flows, the vertical headwall of the knickpoints was maintained as they propagated upstream through the toppling and transportation of the lava columns.

Calculations based on the model described in ref. 27 indicate that a minimum water depth of 8.1 m would be required to initiate toppling of the basalt columns in the study area, corresponding to a minimum discharge of 3,250 m^3/s at Selfoss (*SI Text, Calculation of Threshold Flow Depth and Discharge for Basalt Column Toppling*). Such discharge is 6 times higher than the maximum peak discharge recorded between 1973 and 1979 in this region (32) and twice the discharge associated with floods that occur approximately twice per century (33).

It is thought that the extreme flood events last for a period of days rather than months or years (34). The rates of knickpoint retreat during the short-lived Jökulsárgljúfur floods (hundreds of meters in days) are far greater than the highest documented long-term knickpoint retreat rates in other rivers of a similar scale, such as the ∼1.5 m/y retreat rate of the Horseshoe Falls at Niagara between 1842 and 1905 (35). The cumulative effect of the two periods of intense canyon cutting in the mid and late Holocene, inferred to represent the effect of two or three extreme flood events, is 100 m of vertical incision at the downstream extent of the study reach over the last 8.5 ka, equivalent to an average of ∼12 mm/y; this rate is similar to some of the most rapidly eroding rivers in tectonically active settings, such as the Nanga Parbat in the northwest Himalayas (36).

Vertical stepped knickpoints generated during extreme flood events can be diffused over time through abrasion and plucking of small blocks (19). This is exemplified by the incised slot gorge at Malad Gorge, Idaho: Following an extreme flood event ∼46 ka that formed an ∼50-m-high waterfall, the Pointed Canyon knickpoint has been retreating at 0.025 m/y for at least the last 33 ka while also diffusing the vertical headwall into a series of smaller steps (19). We do not find evidence for diffusion of the vertical headwalls of Selfoss, Dettifoss, or Hafragilsfoss since the last erosive extreme flood event 2 ka ago, suggesting that the river has not made the transition from the plucking-dominated erosive regime during the floods to an abrasion-dominated erosive regime during background nonflood periods. Potential explanations for this observation include the following.

Firstly, bedload impact is the main driver of erosion and knickpoint retreat by abrasion (37); the persistence of plucking-dominated morphology may therefore be attributed to a combination of high resistance to abrasion of the fresh basalt with limited transport of coarse bedload over the last 2 ka, supported by qualitative field observation of lack of coarse sediment (i.e., coarser than pebble size) upstream of the gorge. Secondly, expected flow depths in a bedrock constriction during the extreme floods would be far greater than the 8.1-m threshold value [modeled flow depths are up to 59 m in constrictions further upstream of our study area (14)], which supports the assertion that the dominant erosion mechanism during the flood events is through column toppling and transportation. Nine small outburst floods inundated the depositional sandur plain downstream of the Jökulsárgljúfur canyon between 1655 and 1730 (38); they may have acted to maintain the vertical headwall of the larger knickpoints, while also contributing to the ∼500-m retreat of Dettifoss, the retreat of Hafragilsfoss, and the abandonment of the lower terrace, possibly through the diffusion of small steps into rapids between Dettifoss and Hafragilsfoss. The recent spatial stability of Dettifoss despite an ∼5-m retreat of the western part between 1953 and 1998 is demonstrated by analyzing historical aerial photographs (Fig. 1*C*), suggesting that a flow depth that exceeds the block toppling threshold has not occurred during this time period. Finally, a key part of the model of knickpoint retreat through block toppling (27) is the destabilizing effect of buoyancy forces acting in the plunge pool at the base of the headwall. There is a small set of rapids upstream of Selfoss, which possibly formed after a small vertical step (in the order of a couple of meters) was diffused through abrasion (Fig. 1*B*). We suggest that the larger plunge pools at the larger knickpoints may act to support the maintenance of a vertical headwall by promoting the collapse of basalt columns. Where knickpoints are not of sufficient size to generate a plunge pool, abrasion will act to diffuse the knickpoint into a series of rapids over time. In our study area, the threshold knickpoint height would be between 2 m and 13 m.

Conclusions

Our work demonstrates the importance of thresholds in landscape evolution, with significant landscape change occurring during extreme floods when a flow depth threshold has been surpassed. Two periods of intense canyon cutting in the mid and late Holocene are identified at the apex of the Jökulsárgljúfur canyon, thought to have been the result of discrete erosive flood events during these periods. The erosive impact of an additional flood in the early Holocene is also identified further downstream at Ásbyrgi. The effects of these floods have dominated the long-term (multimillennial) evolution of the system, with the resulting landscape morphology containing a legacy of rare extreme floods that can be maintained over millennial timescales, despite the occurrence of many other floods of lesser magnitude. Erosion is primarily through the upstream migration of knickpoints associated with the toppling and removal of basalt columns. During each period, up to three >13-m-high knickpoints retreated over distances that could exceed 2 km. The cumulative effect of the extreme floods at the apex of the canyon is up to 100 m of vertical erosion over the last 8.5 ka, equivalent to an average vertical incision rate of ∼12 mm/y. This highlights the importance of high-magnitude, low-frequency flood events in shaping landscapes and the need to consider them when analyzing or forecasting the evolution of landscapes, especially those that are prone to flooding through landslide, moraine, or ice dam failures or subglacial lake outbursts. In landscapes dominated by stacked basaltic lava flows, erosion through the toppling of columns generates a clear morphological signature characterized by vertical knickpoints. Limited bed load sediment transport and plunge pools at the base of high knickpoints may be responsible for the persistence of these morphological features over long periods of time (at least 2 ka).

Methods

Eight samples were collected for cosmogenic ^{3}He surface exposure dating from the main study reach at the head of the Jökulsárgljúfur canyon and one from the scoured rim of the Ásbyrgi canyon. Samples were taken from the upper 5 cm of surfaces that were clearly sculpted by fluvial action with no signs of weathering. Samples were collected from in situ partially plucked blocks showing less than 1 cm horizontal movement, to avoid unnecessary damage within the National Park but ensure that minimum disturbance had occurred since abandonment. We separated 300- to 500-μm-diameter olivine and pyroxene grains after crushing the samples using standard magnetic, heavy liquid, and hand-picking techniques. Each sample was then crushed in vacuo to release the mantle-derived (magmatic) He trapped in inclusions, which was measured using the VG5400 noble gas mass spectrometer at GeoForschungsZentrum Potsdam (39). The remaining He contained within the crystal lattice structure, together with any remaining magmatic He, was released through heating in an ultrahigh vacuum furnace to 1,750 °C, and the gases were again measured in the VG5400 mass spectrometer (40). Exposure ages were calculated using production rates based on a sea-level high-latitude production rate of 124 at g^{-1} y^{-1} (41) and the scaling scheme of Dunai (42) (*SI Text*). A range is given for the exposure ages: The younger ages are calculated assuming that all ^{4}He in the sample is magmatic He with a ^{3}He/^{4}He ratio as determined in the crushing extraction, while the older ages are calculated assuming that all ^{4}He in the sample is radiogenic in origin (i.e., produced by U and Th decay within the sample); 2σ uncertainties are given for both ages. The true exposure age of a sample lies within the given range, but it is impossible to be more specific, because depending on the eruption age of the basalt, the amount of radiogenic ^{4}He produced since eruption may be higher than the total measured concentration of ^{4}He (see *SI Text, Surface Exposure Dating*); thus an unknown fraction of radiogenic ^{4}He may have been lost. Assuming no radiogenic ^{4}He, the ratio of cosmogenic ^{3}He to total ^{4}He was calculated by subtracting the ^{3}He/^{4}He ratio determined in the crushing experiment from that determined in the melt measurement (e.g., ref. 40). Assuming all ^{4}He is radiogenic implies that all ^{3}He measured in the melt measurement is cosmogenic, and this value is used accordingly. Strath terrace level elevations were surveyed in the field using a Total Station.

ACKNOWLEDGMENTS. We thank the Vatnajökulsþjóðgarður National Park for allowing access, sampling permission, and providing logistical support. We thank E. Schnabel for his help with the sample analysis and H. Rothe for the U, Th, and Li determinations by inductively coupled plasma mass spectrometry. We are grateful to A. Codilean, G. Brocard, J. Jansen, R. Fülöp, and T. Thordarson, who helped shape the project during exploratory field trips in 2009 and 2010. We thank two reviewers whose comments greatly strengthened the final version of the manuscript. This work was funded by Natural Environment Research Council Ph.D. Studentship NE/H525270/1 (to E.R.C.B.) and a grant from the Carnegie Trust for the Universities of Scotland (to M.A.).

1. Bretz JH (1923) The channeled scabland of the Columbia Plateau. *J Geol* 31:617–649.
2. Baker VR, Kale VS (1998) The role of extreme floods in shaping bedrock channels. *Rivers Over Rock: Fluvial Processes in Bedrock Channels*, Geophysical Monograph Series, ed Tinkler KJ, Wohl EE (Am Geophys Union, Washington, DC), Vol 107, pp 153–165.
3. Garcia-Castellanos D, et al. (2009) Catastrophic flood of the Mediterranean after the Messinian salinity crisis. *Nature* 462(7274):778–781.
4. Gupta S, Collier JS, Palmer-Felgate A, Potter G (2007) Catastrophic flooding origin of shelf valley systems in the English Channel. *Nature* 448(7151):342–345.
5. Warner NH, Sowe M, Gupta S, Dumke A, Goddard K (2013) Fill and spill of giant lakes in the eastern Valles Marineris region of Mars. *Geology* 41(6):675–678.
6. Schumm SA (1979) Geomorphic thresholds: The concept and its applications. *Trans Inst Br Geogr* 4(4):485–515.
7. Howard AD, Dietrich WE, Seidl MA (1994) Modeling fluvial erosion on regional to continental scales. *J Geophys Res* 99(B7):13971–13986.
8. Whipple KX, Hancock GS, Anderson RS (2000) River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion and cavitation. *Geol Soc Am Bull* 112(3): 490–503.
9. Sklar LS, Dietrich WE (2001) Sediment and rock strength controls on river incision into bedrock. *Geology* 29(12):1087–1090.
10. Whipple KX (2004) Bedrock rivers and the geomorphology of active orogens. *Annu Rev Earth Planet Sci* 32:151–185.
11. Duller RA, Mountney NP, Russell AJ, Cassidy NC (2008) Architectural analysis of a volcaniclastic jökulhlaup deposit, southern Iceland: Sedimentary evidence for supercritical flow. *Sedimentology* 55(4):939–964.
12. Carling PA (2013) Freshwater megaflood sedimentation: What can we learn about generic processes? *Earth Sci Rev* 125:87–113.
13. Baker VR, Benito G, Rudoy AN (1993) Paleohydrology of late Pleistocene superflooding, Altay Mountains, Siberia. *Science* 259(5093):348–350.
14. Alho P, Russell AJ, Carrivick JL, Käyhkö J (2005) Reconstruction of the largest Holocene jökulhlaup within Jökulsá á Fjöllum, NE Iceland. *Quat Sci Rev* 24(22):2319–2334.
15. Carrivick JL (2007) Hydrodynamics and geomorphic work of jökulhlaups (glacial outburst floods) from Kverkfjöll volcano, Iceland. *Hydrol Processes* 21(6):725–740.
16. Carrivick JL, Russell AJ, Tweed FS (2004) Geomorphological evidence for jökulhlaups from Kverkfjöll volcano, Iceland. *Geomorphology* 63(1-2):81–102.
17. Dunning SA, et al. (2013) The role of multiple glacier outburst floods in proglacial landscape evolution: The 2010 Eyjafjallajökull eruption, Iceland. *Geology* 41(10): 1123–1126.
18. Lamb MP, Dietrich WE, Aciego SM, Depaolo DJ, Manga M (2008) Formation of Box Canyon, Idaho, by megaflood: Implications for seepage erosion on Earth and Mars. *Science* 320(5879):1067–1070.
19. Lamb MP, Mackey BH, Farley KA (2014) Amphitheater-headed canyons formed by megaflooding at Malad Gorge, Idaho. *Proc Natl Acad Sci USA* 111(1):57–62.
20. Lamb MP, Fonstad MA (2010) Rapid formation of a modern bedrock canyon by a single flood event. *Nat Geosci* 3:477–481.
21. Carrivick JL, et al. (2013) Discussion of 'Field evidence and hydraulic modelling of a large Holocene jökulhlaup at Jökulsá á Fjöllum channel, Iceland' by Douglas Howard, Sheryl Luzzadder-Beach and Timothy Beach, 2012. *Geomorphology* 201:512–519.
22. Thorarinsson S (1950) Jökulhlaup og eldgos á jökulvatnasvæði Jökulsár á Fjöllum. *Náttúrufræðingurinn* 20:113–133.
23. Tomasson H (1973) Hamfarahlaup i Jökulsá á Fjöllum. *Náttúrufræðingurinn* 43:12–34.
24. Waitt RB (2002) Great Holocene floods along the Jökulsá á Fjöllum, north Iceland. *Flood and Megaflood Processes and Deposits: Recent and Ancient Examples*, eds Martini PI, Baker VR, Garzon G (Blackwell, Oxford), pp 37–51.
25. Kirkbride MP, Dugmore AJ, Brazier V (2006) Radiocarbon dating of mid-Holocene megaflood deposits in the Jökulsá á Fjöllum, north Iceland. *Holocene* 16(4):605–609.
26. Eliasson S (1974) Eldsumbrot i Jökulsárgljúfrum. *Náttúrufræðingurinn* 44:52–70.
27. Lamb MP, Dietrich WE (2009) The persistence of waterfalls in fractured bedrock. *Geol Soc Am Bull* 121(7-8):1123–1134.
28. Jansen JD, Fabel D, Xu S, Schnabel C, Codilean AT (2011) Does increasing paraglacial sediment supply slow knickpoint retreat? *Geology* 39(6):543–546.
29. Seidl MA, Finkel RC, Caffee MW, Hudson GB, Dietrich WE (1997) Cosmogenic isotope analyses applied to river longitudinal profile evolution: Problems and interpretations. *Earth Surf Processes Landforms* 22(3):195–290.
30. Mackey BH, Scheingross JS, Lamb MP, Farley KA (2014) Knickpoint formation, rapid propagation, and landscape response following coastal cliff retreat at the last interglacial sea-level highstand: Kaua'i, Hawai'i. *Geol Soc Am Bull* 126(7-8):925–942.
31. Finnegan NJ, Roe G, Montgomery DR, Hallet B (2005) Controls on the channel width of rivers: Implications for modelling fluvial incision of bedrock. *Geology* 33(3):229–232.
32. Schunke E (1985) Sedimenttransport und fluviale Abtragung der Jökulsá á Fjöllum im periglazialen Zentral-Island. *Erdkunde* 39(3):197–205.
33. Helgason J (1987) *Jarðfræðirannsóknir á Vatnasviði Jökulsár á Fjöllum við Möðrudal* [*Geological Investigations of the Jökulsá á Fjöllum Drainage Basin at Modrudalur*] (Orkustofnun, Reykjavík, Iceland) Rep OS-87005/VOD-01. Available at os.is/gogn/Skyrslur/OS-1987/OS-87005.pdf. Accessed October 6, 2014. Icelandic.
34. Björnsson H (2002) Subglacial lakes and jökulhlaups in Iceland. *Global Planet Change* 35(3-4):255–271.
35. Gilbert GK (1907) Rate of recession of Niagara Falls. *US Geol Surv Bull* 306:1–31.
36. Burbank DW, et al. (1996) Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas. *Nature* 379:505–510.
37. Cook KL, Turowski JM, Hovius N (2013) A demonstration of the importance of bedload transport for fluvial bedrock erosion and knickpoint propagation. *Earth Surf Processes Landforms* 38(7):683–695.
38. Ísaksson SP (1985) Stórhlaup í Jökulsá á Fjöllum á fyrri hluta 18. Aldar. *Náttúrufræðingurinn* 54(4-5):165–191.
39. Niedermann S, Bach W, Erzinger J (1997) Noble gas evidence for a lower mantle component in MORBs from the southern East Pacific Rise: Decoupling of helium and neon isotope systematics. *Geochim Cosmochim Acta* 61(13):2697–2715.
40. Niedermann S (2002) Cosmic-ray-produced noble gases in terrestrial rocks: Dating tools for surface processes. *Rev Mineral Geochem* 47:731–784.
41. Goehring BM, et al. (2010) A reevalution of *in situ* cosmogenic ^{3}He production rates. *Quat Geochronol* 5(4):410–418.
42. Dunai TJ (2000) Scaling factors for production rates of in situ produced cosmogenic nuclides: A critical reevaluation. *Earth Planet Sci Lett* 176(1):157–169.