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Large thermo-erosional tunnel for a river in northeast Greenland

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ABSTRACT

Thermo-erosional river bank undercutting is caused by the combined action of thermal and mechanical erosion of the permafrost by Arctic rivers whilst the overlying sediment withstands collapse temporarily. Here, we report the discovery of a large thermo-erosional tunnel that formed in the banks of a meltwater-fed stream in northeast Greenland in summer 2015. The tunnel was observed over eight days (14–22 July), during which period the tunnel remained open but bank-side slumping increased. Stream solute load increased immediately downstream and remained high 800 m from the tunnel. Whilst this field observation was opportunistic and information somewhat limited, our study provides a rare insight into an extreme event impacting permafrost, local geomorphology and stream habitat. With accelerated climate change in Arctic regions, increased permafrost degradation and warmer stream water temperature are predicted thereby enhancing potential for thermo-erosional niche development and associated stream bank slumping. This change could have significant implications for stream physicochemical habitat and, in turn, stream benthic communities, through changes in aquatic habitat conditions.

1. Introduction

Thermo-erosional niches are river bank undercutting resulting from the combined action of thermal and mechanical erosion (Walker et al., 1987): running water infiltrates cavities in the frozen active layer, forming underground tunnels, from where fast water current and warmer water temperatures, relative to the frozen ground, simultaneously thaw and erode the permafrost (Walker and Arnborg, 1966; Perreault et al., 2016). Whilst water temperature has been identified as the principal factor influencing thermo-erosional niche development, ice, sand and silt content in the permafrost are also important considerations (Dupeyrat et al., 2011). Thermal erosion is most prevalent in the High Arctic landscape due to (1) higher river flows during summer peak snowmelt and (2) the presence of permafrost which strengthens the river banks but permits larger amounts of bank undercutting, and large slump blocks when the banks finally collapse (Scott, 1978). Whilst the most common type of thermo-erosional niche occurs along stream banks or coastal areas where the above sediment collapses eventually, they can also be created without the sediment above the niche collapsing, forming tunnels. However, due to their tendency to occur in these remote environments, large tunnel forming thermo-erosional niches have rarely been reported. Most reports of large-scale thermo-erosional niches have been from Alaska and Canada and have been formed through ice wedge thaw (eg. Fortier et al., 2007; Godin and Fortier, 2012; Veillete et al., 2015 Kanevskiy et al., 2016). Limited information is available from other areas of the Arctic. To increase our knowledge on this phenomenon and create a pan-Arctic record, here we report and describe a large thermo-erosional tunnel over a stream in northeast Greenland.

2. Methods and data

2.1. Site description

The snowmelt-fed stream Aucellaelv is in close proximity to the Zackenberg research station at 74°28′ N, 20°34' W in the Northeast Greenland National Park (Fig. 1). The mean annual air temperature is −9.1 °C and the warmest month is July with a mean temperature of 5.8 °C. The mean precipitation is 261 mm and falls mainly as

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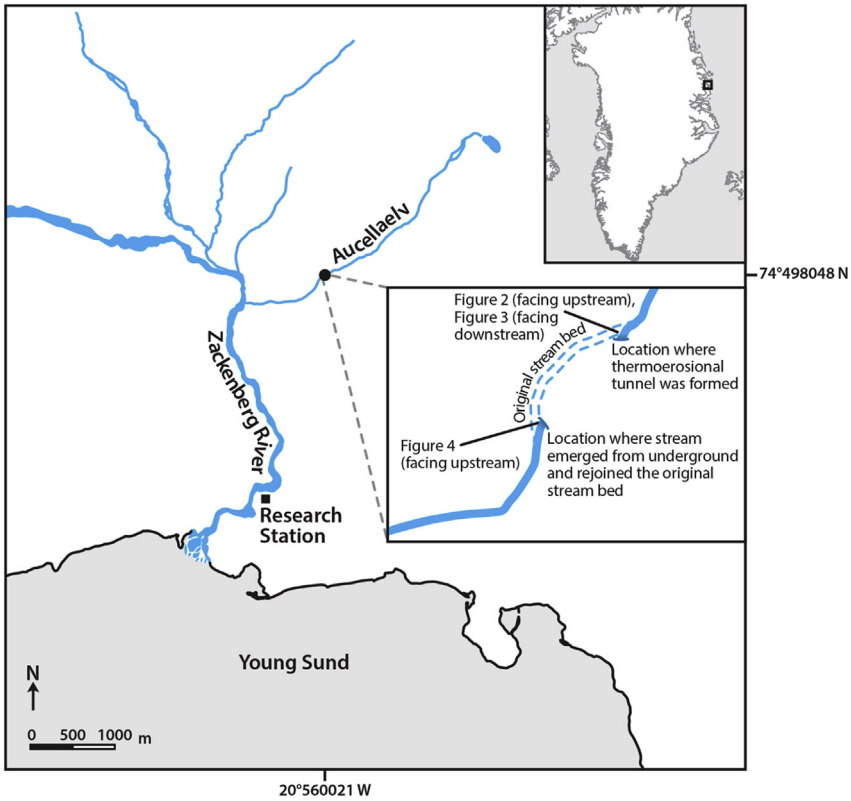

Fig. 1. Study area showing location of the thermoerosional tunnel and points from which Figs. 2–4 were taken.

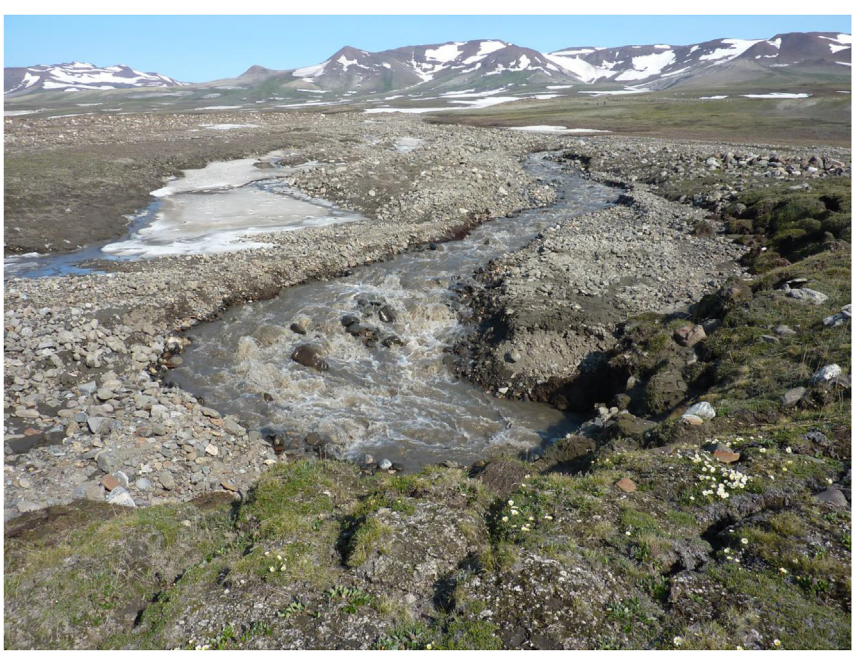

Fig. 2. Aucellaelv looking upstream at the point of the thermo-erosional niche. At the bottom of the photograph, the stream can be observed to go underground. Photo: Catherine L. Docherty.

snow (Hansen et al., 2008). The site was located on lower mountain slopes within a wide horizontal valley formed by glacial erosion approximately 10,000 years before present (Mernild et al., 2007; Bennike et al., 2008). Zackenberg is an area of continuous permafrost, with depth modelled to be 200–300 m deep and varying active layer thickness between 0.3 and 0.65 m (Christiansen et al., 2008). The region is composed of Cretaceous and Tertiary sandstones with loose sediment of weak compaction that is susceptible to erosion (Hasholt and Hagedorn, 2000) and is held together largely due to its frozen nature. Ice wedge polygons occur within

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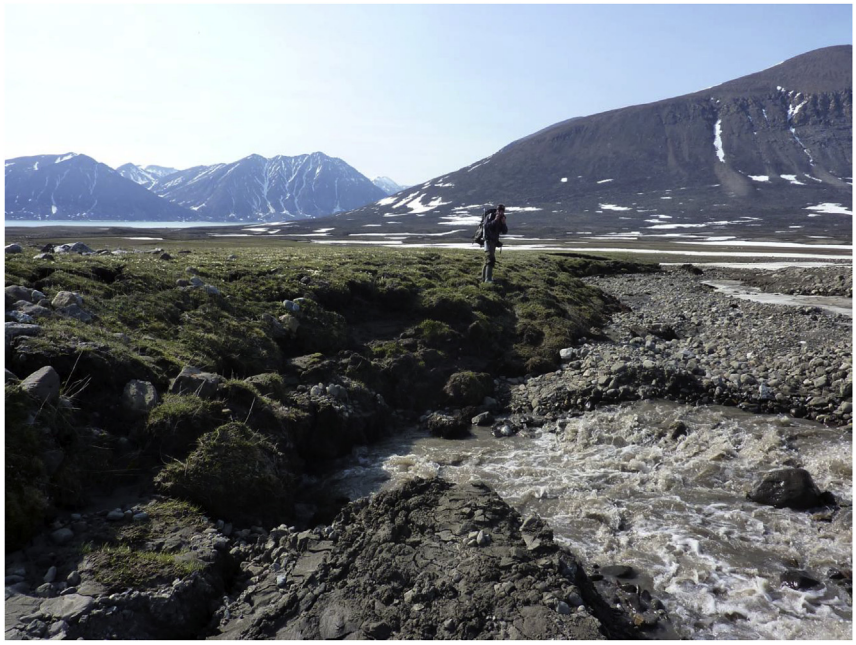

Fig. 3. Looking downstream, the entry point of the thermo-erosional niche and associated slumping. Photo: Catherine L. Docherty.

the area and signs of thermal erosion have been observed before in the area along the banks of the larger Zackenberg River after an extreme flood event (Christiansen et al., 2008), however this did not result in tunnel formation.

The Aucellaelv channel has been characterised as having low channel stability and as being highly mobile with stream channel observed to shift course by 1 m after an extreme storm event (personal observation). Suspended sediment concentration was high (>1100 mg/L). The Aucellaelv floodplain consisted largely of boulders, cobbles and silt; and there was limited vegetation in close proximity to the stream. The streams in this region are frozen typically to the stream bed between late September and early June, when thawing coincides with peak summer snowmelt.

2.2. Observation and description of thermo-erosional niche

First observed on 14th July 2015, the entire stream had 'disappeared' underground through a self-formed tunnel at approximately 1.5 m below the surface, leaving the above soil intact, and travelled for approximately 70 m before re-emerging downstream into the original stream channel. It is unknown how long the tunnel had been in existence before this date. A large amount of slumping was present at the entry point due to a loss of soil stability and compaction (Fig. 2; Fig. 3), with slump blocks undergoing fluvial erosion as they were unable to be transported downstream due to the tunnel roof blocking passage. Less slump blocks were present at the point of exit (Fig. 4) due to them being transported away in the flow. Water temperature was 4 °C and water velocity was relatively high (discharge 976 L/s, average velocity within reach 0.59 m/s). Water samples were collected at the entry and exit of the tunnel, filtered in the field using Whatmann GF/F filter papers and analysed for major ions. Higher concentrations of all major ions were found downstream, with Mg concentration increasing from 1.66mg/L^{-1} to 2.72mg/L^{-1} and Na increasing from 2.84mg/L^{-1} to 4.05mg/L^{-1} (Table 1) due to the erosion of permafrost acting as a major source of ions (Rasch et al., 2000). Approximately 800 m downstream of the tunnel, dissolved solute concentration remained high and in some cases, was slightly higher than directly below the thermo-erosional tunnel exit (Table 1).

The tunnel was still present on 22 July, eight days after first observation; however, bank-side slumping had increased around the niche throughout that time. Due to the logistical difficulties of fieldwork in northeast Greenland, it was not possible to conduct a long-term study on the evolution of this process and consequently, it is unknown how much longer the tunnel remained. Whilst Aucellaelv had been classified as having a low stability channel, no prior observation of such an event had been reported for Aucellaelv or elsewhere in the Zackenberg region.

Whilst other documented thermo-erosional tunnels have formed in a vertical direction due to meltwater runoff melting ice wedges, leading to waterfall and sinkhole formation previous to tunnel development (eg. Fortier et al., 2007; Godin and Fortier, 2012), the horizontal formation of this tunnel in the river bank infers that the thermo-erosional tunnel reported in this paper was not caused by ice wedge thaw. We propose that the relatively warm stream temperature of 4 °C of Aucellaelv combined with high velocity of the meltwater thawed the frozen sediment in the river channel and created the observed tunnel.

3. Discussion and conclusions

3.1. Potential implications and processes in a changing climate

Whilst these events are rarely observed, they may become more frequent in the future. By the end of the 21st century air temperature in northeast Greenland could increase by up to 18 °C on current winter temperatures, with more modest increases on summer temperatures (Stendel et al., 2008). Precipitation is predicted to increase by up to 60%, falling as snowfall during the winter but more commonly as rainfall throughout the summer (Stendel et al., 2008). The increase in nivation processes, permafrost degradation and larger spring floods will play a large role in reshaping local geomorphology, causing permafrost degradation to increase. Ice wedges will become increasingly exposed to thermal erosion as water temperatures warm and flow increases through increased meltwater inputs. Thus, permafrost thaw can have a large

Fig. 4. Looking upstream, the exit point of the thermo-erosional niche. Photo: Simon Rosenhøj Leth.

Table 1
Major cations in stream water upstream and downstream of the tunnel. All cations measured in mg L^{-1}.

Site	Mg	Na	K	Ca	S	Si
Upstream	1.66	2.84	0.10	7.62	5.44	0.66
0 m downstream	2.72	4.05	0.16	10.54	8.67	0.84
800 m downstream	2.67	4.56	0.2	9.91	9.05	0.94

impact on the landscape (Kokelj and Jorgenson, 2013) and on stream ecosystems through changes to physicochemical habitat (Christiansen et al., 2008; Callaghan et al., 2011; Kokelj et al., 2013; Thienpont et al., 2013; Chin et al., 2016). Increased sediment and ionic load and changes to channel stability are known to cause declines in macroinvertebrate abundance and community structure with consequent effects on the food web in these fragile stream systems (Chin et al., 2016).

In Zackenberg, the formation of a thermo-erosional tunnel led to increased ionic load in stream water and low stream bank stability, modifying the stream ecosystem over a large area. The high dissolved solute concentration at a distance from the tunnel, which in some cases was higher than directly below the tunnel exit, was due to a combination of the time taken for in-stream process to release solutes from suspended sediment, and additional contributions from downstream bankside sediment erosion and dissolution. As it is unknown how long the tunnel remained, the persistence of the impact on stream hydrochemistry and channel stability are unknown. Permafrost research has received a large amount of attention in some parts of the Arctic (eg. Alaska, Canada), but in Greenland it has received little attention. Zackenberg is the most intensively studied region in high-Arctic Greenland (Christiansen et al., 2008), but even so, no thermo-erosional tunnel had been reported previously in the area or had been witnessed by the scientists that had spent numerous summers in the area. Typical models and simulations for predicting permafrost thaw are generally unable to predict localised thaw events that have potential to transform landscapes through erosion and hydrological processes, as they are unable to account for the large spatial variability in ground thermal regime that is typical in Arctic regions (Westermann et al., 2014). For this reason, reporting of localised thaw events is vital to advance our understanding of their impact on local geomorphology. This paper provides vital insights into Greenlandic permafrost dynamics allowing us to understand the influence of extreme degradation events on the local landscape and adding to the increasing body of literature on thermo-erosional niche development. Increased documentation of underground tunnel development around the Arctic is necessary to understand how widespread the phenomenon is, and to understand the variety of conditions that lead to its formation.

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