Geomorphology 253 (2016) 370–384

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Patterns and rates of riverbank erosion involving ice-rich permafrost (yedoma) in northern Alaska

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ARTICLE INFO

Article history:
Received 2 May 2015
Received in revised form 21 October 2015
Accepted 26 October 2015
Available online 30 October 2015

Keywords:
Thermal erosion
Thermal denudation
Ground ice
Arctic
Itkillik River
Organic carbon

ABSTRACT

Yedoma, a suite of syngenetically frozen silty ice- and organic-rich deposits with large ice wedges that accumulated during the late Pleistocene, is vulnerable to thermal degradation and erosion because of the extremely high ice contents. This degradation can result in significant surface subsidence and retreat of coastal bluffs and riverbanks with large consequences to landscape evolution, infrastructure damage, and water quality. We used remote sensing and field observations to assess patterns and rates of riverbank erosion at a 35-m-high active yedoma bluff along the Itkillik River in northern Alaska. The total volumetric ground-ice content—including wedge, segregated, and pore ice—was estimated to be ~86%. The process of riverbank erosion and stabilization include three main stages typical of the areas with ice-rich permafrost: (1) thermal erosion combined with thermal denudation, (2) thermal denudation, and (3) slope stabilization.

Active riverbank erosion at the main study site started in July 1995, when the Itkillik River changed its channel. The total retreat of the riverbank during 1995–2010 within different segments of the bluff varied from 180 to 280 m; the average retreat rate for the most actively eroded part of the riverbank was almost 19 m/y. From August 2007 to August 2011, the total retreat varied from 10 to almost 100 m. The average retreat rate for the whole 680-m-long bluff was 11 m/y. For the most actively eroded central part of the bluff (150 m long) it was 20 m/y, ranging from 16 to 24 m/y. More than 180,000 m^3 of ground ice and organic-rich frozen soil, or almost 70,000 metric tons (t) of soil solids including 880 t of organic carbon, were transported to the river from the retreating bank annually. This study reports the highest long-term rates of riverbank erosion ever observed in permafrost regions of Eurasia and North America.

1. Introduction

Extremely ice-rich syngenetic permafrost, known as yedoma, is widespread in Alaska and Siberia. In this study, yedoma is used as a term for ice- and organic-rich syngenetically frozen silty sediments accumulated in the late Pleistocene (Kanevskiy et al., 2011; Schirrmeister et al., 2013). These deposits can be more than 40 m thick and they contain large ice wedges of up to 10 m wide, which usually vertically span the whole yedoma sequence. Yedoma in Siberia and North America occupies ~420,000 km^2 (Strauss et al., 2013). It was formed in regions unglaciated during the late Pleistocene as a result of predominantly eolian, fluvial, and slope sedimentation (Tomirdiaro, 1980; Sher, 1997; Romanovskii et al., 2004; Kanevskiy et al., 2011; Schirrmeister et al., 2013; Murton et al., 2015). In the continuous permafrost zone of North America, yedoma is widespread in northern Alaska along the Arctic foothills (Carter, 1988; Kanevskiy et al., 2011; Jorgenson et al., 2014) and in the northern part of Seward Peninsula (Hopkins, 1963; Shur et al., 2012; Ulrich et al., 2014) (Fig. 1). In the discontinuous permafrost zone, yedoma has been observed at numerous sites of interior Alaska (Williams, 1962; Péwé, 1975; Hamilton et al., 1988; Shur et al., 2004; Bray et al., 2006; Kanevskiy et al., 2008, 2012, 2014; Jensen et al., 2013; Nossov et al., 2013) and Canada (Fraser and Burn, 1997; Kotler and Burn, 2000; Froese et al., 2009; Stephani et al., 2014).

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http://dx.doi.org/10.1016/j.geomorph.2015.10.023
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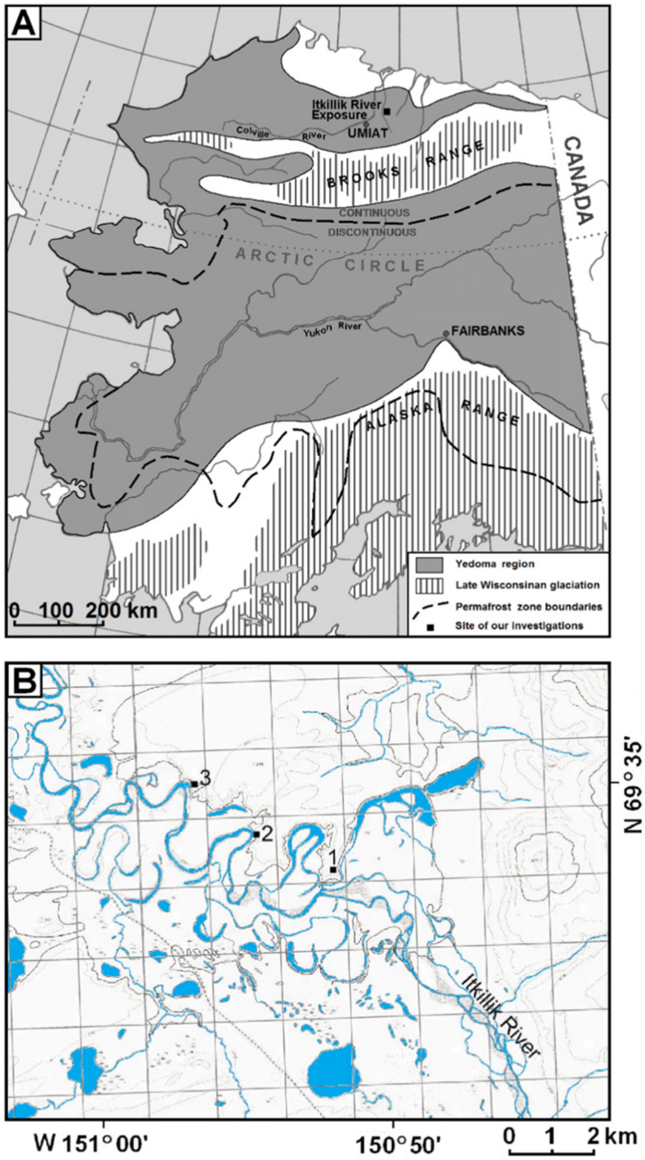

Fig. 1. (A) Location of the study sites. Boundaries of yedoma region (defined as area of potential yedoma occurrence) are shown after Kanevskiy et al. (2011); limits of late Wisconsinan glaciation are shown after Péwé (1975) and Hamilton (1994); and boundaries of permafrost zones are shown after Jorgenson et al. (2008). (B) Topographic map 1:63,360 (U.S. Geological Survey, 1971, based on aerial photographs taken in 1970) with location of study sites (marked with black squares). Study sites were described by Kanevskiy et al. (2011), Strauss et al. (2012b), and Murton et al. (2015) (site 1) and by Carter (1988) (sites 2 and 3).

Yedoma is vulnerable to thermokarst and erosion because of its high ice content and silty composition. Degradation of yedoma is mostly associated with formation of thermokarst lakes, which may result in surface subsidence of more than 20 m (Livingstone et al., 1958; Soloviev, 1962; Czudek and Demek, 1973; Ivanov, 1984; Carter, 1988; Brewer et al., 1993; Shur et al., 2012; Kanevskiy et al., 2014) with large consequences to landscape evolution, infrastructure damage, and water quality (Zaikanov and Kanevskiy, 1992a,b). Yedoma is also prone to river erosion, coastal erosion, formation of thermoerosional gullies, and surface ice-wedge degradation. Thermokarst and thermal erosion of ice-rich sediments creates serious hazards for the environment and infrastructure, which in some cases may require a costly relocation of villages. Coastal and riverbank erosion also releases large amounts of mineral and organic material that is transported to the Arctic Ocean (Reimnitz et al., 1988; Gordeev, 2006; Ping et al., 2011; Lantuit et al., 2013). Release of frozen organic matter upon yedoma thawing leads to changes in biogeochemical cycles and emission of greenhouse gases (Grosse et al., 2011; Strauss et al., 2012a; Schuur et al., 2015).

Processes and mechanisms of coastal, lakeshore, and riverbank erosion of the ice-rich sediments were described by Are (1968, 1980, 1985, 2012), Lawson (1983), Costard et al. (2003) Couture et al. (2008), Hoque and Pollard (2009), Jones et al. (2009, 2011), and Hinkel et al. (2012). Extensive data show that erosion rates in the Arctic are highly variable and strongly dependent on geomorphology and ground-ice content of permafrost (Miles, 1976; Are, 1980, 1985, 2012; Lawson, 1983; Rachold et al., 2000; Vasiliev et al., 2001; Shur et al., 2002; Vasiliev, 2003; Jorgenson and Brown, 2005; Lantuit et al., 2008, 2012, 2013; Jorgenson, 2011). While the average rate of coastal erosion for the entire Arctic coast is ~0.5 m/y, at numerous coastal segments the rates are much higher and vary with time (Lantuit et al., 2012, 2013). For example, Jones et al. (2009) found that for a 60-km segment of the Alaskan Beaufort Sea coast, characterized by 2- to 5-m-high bluffs with extremely ice-rich sediments, mean annual erosion rates reached 6.8 m/y (1955–1979), 8.7 m/y (1979–2002), and 13.6 m/y (2002–2007). Solomon (2005) reported long-term retreat rates of up to 22.5 m/y at some sites in the Mackenzie Delta region of the Beaufort Sea, though such rates in this area were mostly related to wave activity rather than to high ice content of sediments.

Studies of riverbank and coastal erosion in the Russian Arctic revealed that the highest rates of erosion are typical mostly of yedoma bluffs, where they can reach more than 20 m/y (Are, 1985, 2012; Shur et al., 1984, 2002; Grigoriev, 2008; Günther et al., 2013). Long-term rates, however, are much smaller. At different sites of the Laptev Sea and East-Siberian Sea coasts they varied from 2 to 6 m/y (Are, 1985; Grigoriev, 2008), and for the entire coast with yedoma the rates of coastal erosion were estimated to be 2.1 m/y for the Laptev Sea and 1.8 m/y for the East-Siberian Sea (Grigoriev and Rachold, 2003; Grigoriev, 2008).

Most studies of erosion of yedoma bluffs are related to sea shores. Information on rates of riverbank erosion and the suite of successive processes that affect the thawing and collapse of yedoma deposits associated with river erosion is limited. Studies of erosion of yedoma riverbanks are available mainly for the Russian Arctic, where long-term erosion rates of such banks varied from 2 to 6 m/y (Shur et al., 1984, 2002; Are, 1985; Zaikanov and Kanevskiy, 1992a,b; Grigoriev, 2008), which are similar to the long-term rates of coastal erosion. In North America, most studies of riverbank erosion were not focused on the yedoma region. In Canada, long-term erosion rates of the banks of the southern Mackenzie River Delta based on aerial photographs varied from 1 to 11 m/y (Outhet, 1974). In northern Alaska, high erosion rates have been reported for the Sagavanirktok River (Brice, 1973; Scott, 1978) and for the Colville River (Walker and Arnborg, 1966; Walker, 1983; Walker et al., 1987; Walker and Jorgenson, 2011). The total retreat of the 8- to 10-m-high and 1.4-km-long bluff formed by ice-rich deposits with large ice wedges (similar to yedoma), located at the Colville River near the village of Nuiqsut, varied from 3 to 60 m from 1948 to 2004 (Walker and Jorgenson, 2011). Though the highest long-term rates of erosion at this site averaged for the whole observation period were slightly more than 1 m/y, in 1962 alone the retreat of a collapsing bank of about 10 m was reported (Walker et al., 1987). In interior Alaska, extremely fast riverbank erosion was described by Williams (1952) at the north bank of the Yukon River in the Yukon Flats area, where 10-m-deep niches could form in the ice-rich silt in two days, and the riverbank retreat could reach up to 60 m during one summer.

In this study, we describe and quantify the patterns and processes of degradation of the 35-m-high yedoma bluff along the Itkillik River in northern Alaska. The main objectives of this paper are to identify processes involved in degradation and stabilization of a riverbank formed by yedoma; measure short- and long-term rates of riverbank erosion and surface degradation; and assess amounts of mineral soil and organic carbon lost to erosion.