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Transformation of terrestrial organic matter along thermokarst-affected permafrost coasts in the Arctic

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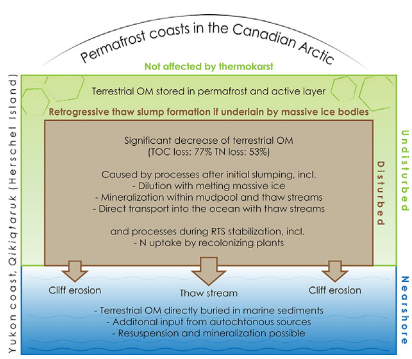
HIGHLIGHTS

- Terrestrial organic matter (OM) is transformed by RTS before entering the ocean.
- RTSs induce drastic organic carbon and nitrogen losses of 77 and 53%, respectively.
- Loss is caused by dilution with melting massive ice and mineralization of OM.
- Heavier portions of OM are directly buried in nearshore marine sediments.
- The Canadian Arctic is a key region for OM transformation, as RTS are ubiquitous.

GRAPHICAL ABSTRACT



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ABSTRACT

The changing climate in the Arctic has a profound impact on permafrost coasts, which are subject to intensified thermokarst formation and erosion. Consequently, terrestrial organic matter (OM) is mobilized and transported into the nearshore zone. Yet, little is known about the fate of mobilized OM before and after entering the ocean. In this study we investigated a retrogressive thaw slump (RTS) on *Qikiqtaruk* - Herschel Island (Yukon coast, Canada). The RTS was classified into an undisturbed, a disturbed (thermokarst-affected) and a nearshore zone and sampled systematically along transects. Samples were analyzed for total and dissolved organic carbon and nitrogen (TOC, DOC, TN, DN), stable carbon isotopes (δ^{13}C-TOC, δ^{13}C-DOC), and dissolved inorganic nitrogen (DIN), which were compared between the zones. C/N-ratios, δ^{13}C signatures, and ammonium (NH_4-N) concentrations were used as indicators for OM degradation along with biomarkers (*n*-alkanes, *n*-fatty acids, *n*-alcohols). Our results show that OM significantly decreases after disturbance with a TOC and DOC loss of 77 and 55% and a TN and DN loss of 53 and 48%, respectively. C/N-ratios decrease significantly, whereas NH_4-N concentrations slightly increase in freshly thawed material. In the nearshore zone, OM contents are comparable to the disturbed zone. We suggest that the strong decrease in OM is caused by initial dilution with melted massive ice and immediate offshore transport via the thaw stream. In the mudpool and thaw stream, OM is subject to degradation, whereas in the slump floor the nitrogen decrease is caused by recolonizing vegetation. Within the nearshore zone of the ocean, heavier portions of OM are directly buried in marine sediments close to shore. We conclude

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that RTS have profound impacts on coastal environments in the Arctic. They mobilize nutrients from permafrost, substantially decrease OM contents and provide fresh water and nutrients at a point source.

1. Introduction

The Arctic is most affected by changing climate more than any other region on Earth. Models project a greater temperature increase than the global mean by the end of the 21st century, resulting in drastic impacts on Arctic environments (Collins et al., 2013; Forbes et al., 2011). Permafrost-affected soils in northern latitudes contain about 1300 Pg of organic carbon (OC), of which about 800 Pg are permanently frozen (Hugelius et al., 2014), and 66 Pg nitrogen (N) in the uppermost 3 m (Harden et al., 2012). With warmer climate conditions, permafrost thaws and organic matter (OM) that has been preserved for millennia is subject to degradation. That leads to increased greenhouse gas emissions and, ultimately, climate warming - a process known as the permafrost carbon feedback. However, due to the complexity of environmental processes, the intensity of this feedback remains unclear (Schaefer et al., 2014; Schuur et al., 2015). Besides being released as greenhouse gases, OM can be redeposited on land or transported to aquatic systems where it can be further mineralized in the water column or buried in sediments (Cory et al., 2013; Letscher et al., 2011; Vonk et al., 2014; Woods et al., 2011).

Thermokarst is a widespread phenomenon in the Arctic, characterized by ground disturbance and subsidence processes caused by the thawing of ice-rich permafrost (Czudek and Demek, 1970; Grosse et al., 2011; Schuur et al., 2008). It is of particular importance for the mobilization of OM, as it triggers its release by disturbing the frozen ground (Abbott et al., 2015; Abbott and Jones, 2015; Bowden et al., 2008; Vonk et al., 2013). Thermokarst in upland, inland, sub-Arctic, and High Arctic permafrost regions, was intensively studied focusing on the lability of permafrost carbon, greenhouse gas emissions, release of nutrients (e.g., nitrogen, phosphorus, sulfur), and impacts on aquatic systems (Abbott et al., 2015; Cassidy et al., 2016; Frey et al., 2007; Kokelj et al., 2013; Turetsky et al., 2007). However, only a few studies are available on coastal thermokarst, which is ubiquitous along the ice-rich permafrost coasts in the Arctic, and on the fate of OM within the coastal environment (Lantuit et al., 2012a; Lantuit and Pollard, 2008; Pelletier and Medioli, 2014).

Retrogressive thaw slumps (RTS) are one of the most widespread thermokarst forms (Jorgenson and Osterkamp, 2005; Kokelj and Jorgenson, 2013; Krieger, 2012). Along with other degradation landforms, like active layer detachments and gullies, RTS can affect up to 1 to 2% of continuous permafrost areas (Krieger, 2012). RTS are widespread in the unlithified and ice-rich coastal parts of the western Canadian Arctic and are currently expanding in size and area (Lantuit and Pollard, 2008; Lantz and Kokelj, 2008; Pelletier and Medioli, 2014; Segal et al., 2016). RTS systems are typically active over decades and continuously mobilize terrestrial OM from permafrost, which has major impacts on the environment (Lantuit and Pollard, 2008; Lantz and Kokelj, 2008).

In this study, we investigate a coastal RTS located on *Qikiqtaruk* - Herschel Island (Yukon Territory, Canada) and its effects on OM characteristics. The objectives of this study are (i) to quantify and compare OM contents in undisturbed and disturbed (thermokarst affected) zones of a RTS, (ii) to assess the transformation processes of OM after disturbance, and (iii) to track the fate of terrestrial OM in the nearshore zone. We hypothesize that OM stored in undisturbed coastal parts is substantially altered by thermokarst formation before entering the nearshore zone. We further hypothesize that OM mobilized from permafrost is subject to substantial degradation.

2. Study area

Our study area is *Qikiqtaruk* - Herschel Island (69°34′N; 138°55′W), which is situated approximately 2 km off the Yukon coast in the western Canadian Arctic (Fig. 1). The climate is polar continental, with mean annual air temperatures between −9.9 and −11 °C (1970 to 2000) and precipitation between 161 and 254 mm year^{-1} (Burn, 2012). The dominant wind direction is NW, with storms frequently observed in late August and September (Solomon, 2005). Herschel Island is an ice-thrust moraine ridge formed by glaciers during the Late Wisconsin Glaciation (23 to 18 ka BP) and consists of unconsolidated and commonly fine-grained former marine and glacigenic sediments (Blasco et al., 1990; Fritz et al., 2012). The island is underlain by continuous permafrost and characterized by polygonal tundra, valleys, and a rolling landscape that reaches a maximum elevation of 183 m above sea level (de Krom, 1990; Rampton, 1982). Permafrost on *Qikiqtaruk* is extremely ice-rich with mean ice volumes ranging between 30 and 60 vol%, and up to values >90 vol%, when underlain by massive ground ice beds (Couture and Pollard, 2015; Fritz et al., 2015; Lantuit et al., 2012a). The active layer depth generally ranges between 40 and 60 cm in summer (Burn and Zhang, 2009; Kokelj et al., 2002). The vegetation on *Qikiqtaruk* is lowland tundra dominated by graminoids and dwarf shrubs, with a relatively species-rich forb flora and a well-developed moss layer (Kennedy et al., 2001; Myers-Smith et al., 2011; Smith et al., 1989). The open water season for the Beaufort Sea is 3 to 4 months (Dunton et al., 2006). Within that time frame, thermokarst and erosion processes affect the coastline and can trigger RTS. These systems are abundant on *Qikiqtaruk* and have doubled in area since 1950 (Lantuit and Pollard, 2008). The mean coastal erosion rate is 0.45 m year^{-1} (between 1970 and 2000), with strong erosion at sites with RTS systems and during storm events in autumn (Atkinson, 2005; Lantuit and Pollard, 2005; Obu et al., 2016; Solomon, 2005).

3. Methods

3.1. Fieldwork and sampling

We sampled active layer and permafrost sediments within the RTS "Slump-D" and marine sediments of the nearshore zone in the summers of 2013 and 2014 (Fig. 2). A summary of metadata for the samples is available in the Supplementary material (Table A.1). The RTS was divided into different zones and subzones based on direct field observations and Normalized Differenced Vegetation Index (NDVI) values (see Supplementary material, Fig. A.1). The NDVI was derived from a high-resolution multispectral satellite image (GeoEye, 1.84 m multispectral resolution, acquired on 2011-09-08). We used the framework suggested by Lantuit and Pollard (2008) and classified the RTS into an *undisturbed zone* and a *disturbed zone*, which was affected by thermokarst (Table 1, Fig. 2). The undisturbed zone was further classified into the subzones *active layer* (AL) and *permafrost* (PF), and the disturbed zone into *mudpool* (MP), *transition zone* (TZ) and *slump floor* (SF). Moreover, we defined the *thaw stream* (TS) as the main channel draining the *disturbed zone*. The marine area adjacent to the RTS was classified as *nearshore zone*, with *marine sediments* from a short core (MS-SC) and surface sediments (MS-SU).

In total, 136 samples were taken on land and offshore (Fig. 3). The sampling design was based on GeoEye imagery. A fishnet raster was applied to determine sampling sites and avoid biased sampling within the