Ice-Wedge Thermokarst: Past, Present, and Future

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Abstract

Ice-wedge thermokarst has played an important role in permafrost evolution, and numerous cycles of ice-wedge formation/degradation have occurred through the Quaternary history. Studies of ice-wedge degradation help to explain processes of past ice-wedge thermokarst and predict its future consequences. We developed a conceptual model of ice-wedge degradation/stabilization, which is based on the dynamics of the intermediate layer of the upper permafrost. This model explains high resilience of ice-wedge systems and low probability of formation of large thaw lakes in the continuous permafrost zone. Absence of the intermediate layer at the time of yedoma accumulation and increased precipitation caused very high activity of thaw-lake formation during the Pleistocene/Holocene transition.

Keywords: permafrost; yedoma; ice-wedge degradation; permafrost zones; intermediate layer; thaw-lake basins.

Introduction

Wedge ice is the most common type of massive ground ice. It can be encountered almost everywhere in the continuous permafrost zone and is very common in the discontinuous permafrost zone, especially in its inactive form. Permafrost evolution during the Quaternary time has been largely defined by alternating periods of active ice-wedge development and periods of ice-wedge degradation accompanied by formation of thaw-lake basins. Numerous cycles of ice-wedge formation/degradation that occurred during the late Quaternary have been recorded in Siberia and, to a lesser extent, in northern part of North America. Available data refer mostly to cycles that started in the late Pleistocene and included large-scale thermokarst events, which occurred during the Pleistocene/Holocene transition that caused formation of numerous thaw-lake basins (alases). These transformations have triggered fundamental geomorphic, hydrological, and environmental changes. Generally, ice-wedge degradation starts with an increase in the active-layer thickness (ALT), which affects top parts of ice wedges and eventually may lead to their complete thawing and, under certain conditions, formation of large thermokarst lakes. However, we still do not have clear understanding of rates and mechanisms of this long-term process. Our studies of modern ice-wedge thermokarst define the main stages and patterns of ice-wedge degradation, which help to explain thermokarst processes in the past and predict their consequences in the future.

Ice-wedge development and degradation in the late Quaternary

Syngenetically frozen ice-rich deposits with large ice wedges (known as yedoma or ice complex) were forming very actively within unglaciated areas during full-scale glaciations, while interglacial periods were characterized by increasing thermokarst activity. By the end of the Pleistocene, the accumulation of silt in extremely cold periglacial environments formed yedoma in the vast areas of Eurasia and North America, which were unglaciated during the last Ice Age. Since the end of the Pleistocene, a significant portion of yedoma in all permafrost zones has been destroyed by thermokarst and thermal erosion.

Dramatic changes in the yedoma environment that caused formation of large and deep thaw-lake basins started approximately 12-14 ky BP. Despite a common opinion that the climate warming resulted in a significant increase in the ALT, there is strong evidence that a wetter climate facilitated formation of a thick vegetation mat and transition from dry "tundra-steppe" ecosystem to wet tundra. These processes led to a decrease in the ALT and formation of the ice-rich intermediate layer (IL) above large ice wedges (Shur, 1988). More likely, large-scale thermokarst was not triggered solely by increased air temperatures, but rather by a significant increase in precipitation. This resulted in an accumulation of water in depressions, which led to lake thermokarst, and increased activity of thermal erosion.

Extent of yedoma degradation strongly varies among different permafrost zones (in their modern boundaries) and landscapes. In the continuous permafrost zone, more than 50% of yedoma terrain has degraded within flat lowlands (e.g., Coastal Lowlands of Northern Yakutia in Siberia and northern part of the Seward Peninsula in Western Alaska), while better drainage conditions in uplands of Siberia and Alaska generally prevented large-scale yedoma degradation (e.g., Arctic Foothills of northern Alaska). Thaw-lake basins in this zone have experienced fast peat accumulation and a new cycle of active ice-wedge development, which started immediately after drainage. Currently, the infrequent development of thaw lakes in yedoma occurs mainly in the areas with relatively warm permafrost, such as the Seward Peninsula (Shur *et al*., 2012).

In the discontinuous permafrost zone, yedoma has been almost completely reworked by thermokarst and thermal erosion within poorly drained plains (e.g., Koyukuk and Innoko Flats in West-Central Alaska). In this zone, yedoma occurs mainly in foothills and valleys within the uplands and low mountains, where ice-rich yedoma deposits are commonly overlain by a layer of ice-poor soils (yedoma silt reworked by earlier thermokarst events). Now, this layer protects remnants of yedoma from active thermokarst even in the areas of very warm discontinuous permafrost. Modern ice-wedge development in this zone occurs sporadically (mainly in peatlands) and is not very active. In the sporadic permafrost zone, yedoma remnants probably survived through the Holocene warming in some relatively small areas but it still needs confirmation.

Conceptual model of ice-wedge degradation/stabilization

Widespread degradation of ice wedges has been observed during the last decades in Arctic regions of Eurasia and North America. Despite strong concerns that progressive ice-wedge thermokarst will eventually lead to permafrost degradation, our studies showed that ice-wedge thawing is usually a reversible process in the continuous permafrost zone. We developed a conceptual model of ice-wedge dynamics that identify the main factors affecting ice-wedge degradation and stabilization and the main stages of this quasi-cyclic process (Jorgenson *et al.,* 2015; Kanevskiy *et al*., 2017).

According to this model, vegetation colonization and accumulation of organic matter in the troughs developing over degrading wedges leads to a reduction in soil temperatures, a decrease in the ALT, formation of the new ice-rich IL above stabilizing ice wedges, and rejuvenation of ice wedges. Thus, degradation of ice wedges in the continuous permafrost zone very seldom continues to their complete melting, and in most cases wedges recover.

Vulnerability of ice wedges to thermokarst is controlled by the thickness of the IL of the upper permafrost, which overlies ice wedges and protects them from thawing. A thickness of the IL on top of stabilized ice wedges is usually 2 to 3 times greater than that in undisturbed conditions, which makes the permafrost more resistant to external changes, such as climate change and disturbance. This mechanism explains the very low probability of formation of large thaw lakes in the continuous permafrost zone as a result of ice-wedge thermokarst.

We also presume that wedge-ice volume in the upper permafrost is crucial for formation of thermokarst lakes. In modern environments of the continuous permafrost zone, it is commonly less than 20-30% (e.g., in Holocene deposits of the Arctic Coastal Plain of northern Alaska and within the modern IL above yedoma), which is probably not sufficient. Absence of the protective IL during yedoma accumulation may explain very active degradation of large ice wedges and formation of thaw lakes during the Pleistocene/Holocene transition.

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