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Ground ice in the upper permafrost of the Beaufort Sea coast of Alaska

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ABSTRACT

Ground ice in the upper permafrost of the Beaufort Sea coast of Alaska was studied from 2005 to 2008 at 65 field sites located between Point Barrow and the Canadian border. The main terrain units in the studied area include (1) the primary surface of the coastal plain; (2) drained-lake basins; (3) low foothills (yedoma); (4) deltas and tidal flats; and (5) sand dunes. Wedge ice is the main type of massive ground ice, and ice-wedge polygons occurred on nearly all land surfaces. The volumetric content of wedge ice for the area varies from 3% to 50% between various terrain units with average value of about 11% for the entire coast. The highest content of wedge ice (about 50%) is typical of yedoma terrain, which occurred in a small segment at the coast of the Camden Bay. At the primary surface of the western region of the Arctic Coastal Plain, wedge-ice content reached almost 30%, with an average value of about 14%. Slightly smaller values were estimated for the primary surface of the eastern region of the Arctic Coastal Plain and for old drained-lake basins. Other types of massive ground ice included thermokarst-cave ice, ice cores of pingos, and a rare occurrence of folded massive ice at Barter Island. The content of segregated ice in organic and mineral soils between ice wedges was very high at most of the study sites. The total average volumetric ice content (due to wedge, segregated, and pore ice) for the whole area was 77%, ranging from 43% in eolian sand to 89% in yedoma.

1. Introduction

Quaternary sediments of the coastal region of northern Alaska contain a high amount of ground ice of different types (Black, 1983; Brown and Sellmann, 1973; Ferrians, 1988; Hussey and Michelson, 1966; Jorgenson et al., 2003; Jorgenson, 2011; Kanevskiy et al., 2008, 2011b; Leffingwell, 1915, 1919; Ping et al., 2011; Pullman et al., 2007; Shur and Jorgenson, 1998). In the adjacent areas of the Beaufort Sea coast of Canada, ground ice was described by Rampton and Mackay (1971), Pollard and French (1980), Harry et al. (1988), Pollard (1990), Mackay and Dallimore (1992), Burn (1997), Mackay (1997), French (1998), Kokelj et al. (2002), Kokelj and Burn (2005), Murton (2005, 2009), Burn and Zhang (2009), and Morse et al. (2009). These studies indicate that the terrain characteristics and cryogenic structure of soils in the coastal region of the Canadian Arctic and Alaska have many similarities. However, numerous bodies of tabular massive ice have been described in Canada, while in Alaska folded massive ice bodies have been observed only at Barter Island (Jorgenson and Shur, 2008; Kanevskiy et al., 2008, 2011b).

Leffingwell (1915, 1919) made the first systematic study of ground ice in the Arctic Coastal Plain of Alaska. His pioneering work on the nature and properties of wedge ice had been unmatched for almost 50 years and remains one of the most important studies in permafrost science. Contemporary research of ground ice on the Arctic Coastal Plain began with works by Black (1952, 1983) and Brown (1967, 1969). Black (1952) studied ice-wedge polygons and the frequency of thermal cracking of permafrost and ice-wedge formation. Brown (1969) provided data on the chemical composition of ice wedges. Brown and Sellmann (1973) found that the volume of ground ice is commonly up to 80% in the upper 2 to 4 m of permafrost, in large part due to the presence of interstitially segregated ice. Jorgenson et al. (1998) and Shur and Jorgenson (1998) described impact of terrain evolution in the Colville River Delta on ground-ice accumulation and the soil cryostructure formation. Jorgenson and Shur (2007) studied the formation of ground ice in drained-lake basins. Pullman et al. (2007) evaluated potential thaw settlement of soils. Almost all works on permafrost structure and properties were conducted in the western region of the Beaufort Sea coast of Alaska (BSCA). Information on ground ice in the eastern

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region of the BSCA has not been greatly improved after Leffingwell (1919).

Evaluation of types and volumes of ground ice in the upper permafrost of the BSCA is important for engineering and environmental evaluations and is essential to quantification of the fluxes of carbon and sediments into the Beaufort Sea and to understanding the response of permafrost terrain to climate change. Upper permafrost to a depth of 2 to 3 m is usually ice-rich and has a specific set of cryostructures (patterns in frozen soil formed by segregated ice) that differs greatly from underlying permafrost (Brown and Sellmann, 1973; Pollard and French, 1980; Shur, 1988a,b). This part of permafrost is the first to be affected by climate warming and various environmental impacts including fire and development, which lead to an increase in thickness of the active layer and thawing of the upper permafrost. Thaw settlement associated with thawing of the upper part of permafrost is detrimental to roads and airfields. Upper permafrost is a storage for organic matter and a source of carbon (Ping et al., 2008b, 2011).

Our 2005–2008 study was a part of a project on the evaluation of the carbon stock in the upper permafrost of the BSCA (Ping et al., 2011). The lack of quantification of volume of ground ice obscures an assessment of soil carbon stocks (Ping et al., 2008b, 2011) and the flux of carbon from soil affected by coastal erosion (Jorgenson and Brown, 2005). The recent increase in coastal erosion (Jones et al., 2009; Jorgenson and Brown, 2005) has intensified the release of organic carbon from eroded soil (Jorgenson et al., 2003; Ping et al., 2008b, 2011).

Ground ice is one of the dominant factors affecting the rate of coastal erosion in the Arctic. Jorgenson and Brown (2005) found that the volume of segregated ice and wedge ice has a greater effect on erosion rates than the exposure of a shore to large, open water fetch. Similarly, Shur et al. (2002) found that high ice content increases the rate of thermal denudation of soil from bluffs, and that the denudation rate of exposed ice-rich permafrost can be greater than the average rate of thermal erosion.

We have studied abundance and distribution of ground ice in the upper permafrost through sampling and testing upper permafrost at 65 sites distributed along the entire 1957-km-long Beaufort Sea coast of Alaska from Point Barrow to the Canadian border (Fig. 1). Specific objectives of our ground-ice study were to classify and describe ground-ice characteristics, quantify the volume of massive, pore, and segregated ice in the upper permafrost to a depth of 2 to 3 m, and evaluate the distribution of ground ice in relation to terrain units along the BSCA.

2. Study area

The coastal part of the Arctic Coastal Plain is a lowland with the flat surface. Most bluffs along the BSCA vary in height between 2 and 4 m. Only at several locations the bluffs rise up to 10 m above the sea level. Several rivers and numerous creeks run through the Arctic Coastal Plain and form their deltas there.

BSCA belongs to the Arctic climatic zone of Alaska (Selkregg, 1975). Freezing index along the coastal plain is practically uniform and reaches about 4800 degree-days below 0 °C. Thawing index decreases from east to west from 290 degree-days above 0 °C (Barter Island) to 240 degree-days above 0 °C (Barrow). Mean annual air temperature is −11.3 °C at Prudhoe Bay, −12.3 °C at Barrow, and −12.4 °C at Barter Island. Mean annual precipitation does not exceed 200 mm.

The surficial deposits of the main surface of the BSCA are presented by Quaternary sediments of different origins comprising the Gubik Formation (Black, 1964; Brigham, 1985; Dinter et al., 1987; Gryc et al., 1951; Rawlinson, 1993). According to engineering-geologic maps of northern Alaska (Carter, 1983a; Carter and Galloway, 1985; Carter et al., 1986; Williams and Carter, 1984; Williams et al., 1977), surficial deposits in the coastal area have mostly marine origin. Marine sediments (mainly silt and clay) include some glacial erratics. The marine deposits are attributed to several Quaternary transgressions, which have been identified for coastal regions in Alaska (Brigham-Grette and Carter, 1992; Hopkins, 1967; O'Sullivan, 1961; Sellmann and Brown, 1973). These deposits have been modified in part by thermokarst, lacustrine, and paludification processes, resulting in an abundance of lake-basin deposits that mantle a significant part of the coastal plain. Lakes can form as water-filled depressions or as thermokarst lakes and lake basins typically undergo multiple stages of evolution (Jorgenson and Shur, 2007). Mineral soils in the mature drained-lake basins are usually overlain by a layer of peat. Other surficial deposits include eolian, alluvial, and deltaic silts and sands. A possible occurrence of glacial deposits at

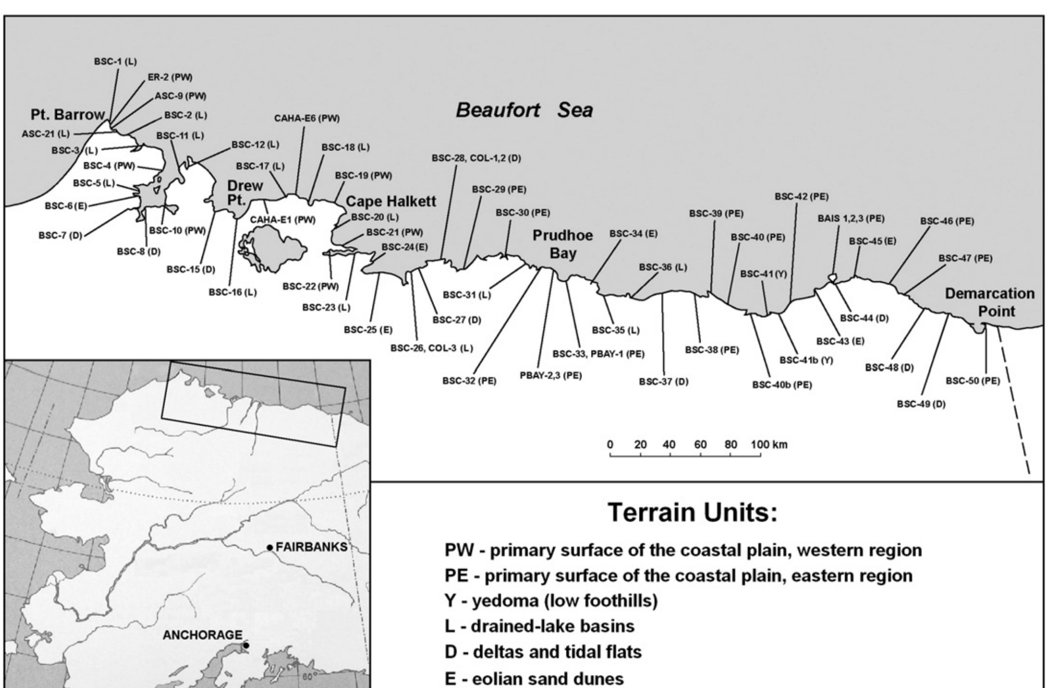

Fig. 1. Location of field sites studied in 2005–2008 along the Beaufort Sea coast from Point Barrow to the Canadian border.