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Cryostratigraphy of late Pleistocene syngenetic permafrost (yedoma) in northern Alaska, Itkillik River exposure

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ABSTRACT

Extremely ice-rich syngenetic permafrost, or yedoma, developed extensively under the cold climate of the Pleistocene in unglaciated regions of Eurasia and North America. In Alaska, yedoma occurs in the Arctic Foothills, the northern part of the Seward Peninsula, and in interior Alaska. A remarkable 33-m-high exposure along the lower Itkillik River in northern Alaska opened an opportunity to study the unmodified yedoma, including stratigraphy, particle-size distribution, soil carbon contents, morphology and quantity of segregated, wedge, and thermokarst-cave ice. The exposed permafrost sequence comprised seven cryostratigraphic units, which formed over a period from >48,000 to 5,000 ^{14}C yr BP, including: 1) active layer; 2) intermediate layer of the upper permafrost; 3–4) two yedoma silt units with different thicknesses of syngenetic ice wedges; 5) buried peat layer; 6) buried intermediate layer beneath the peat; and 7) silt layer with short ice wedges. This exposure is comparable to the well known Mus-Khaya and Duvanny Yar yedoma exposures in Russia. Based on our field observations, literature sources, and interpretation of satellite images and aerial photography, we have developed a preliminary map of yedoma distribution in Alaska.

Introduction

The late Pleistocene environment of Beringia, with its severely cold climate and active eolian sedimentation, was extremely favorable to accumulation of ground ice and formation of syngenetic permafrost, which was formed synchronously with sedimentation in unglaciated areas. As a result, extremely ice-rich permafrost (termed "yedoma") was formed and remains one of the most prominent features of the periglacial environment in the Arctic. Yedoma is silt-dominated deposits up to 50 m thick with wide and tall ice wedges. After its formation, yedoma was drastically affected by thermokarst and thermal erosion caused by climate changes during the Pleistocene-to-Holocene transition.

Understanding the nature and distribution of yedoma is of concern because it is widespread in the arctic and subarctic east Siberia and Alaska, and it provides the foundation for diverse arctic and boreal ecosystems that are vulnerable upon permafrost thawing (Jorgenson and Osterkamp, 2005). Thick yedoma deposits reportedly have substantial soil carbon stores that can contribute to greenhouse gases emissions upon permafrost thawing (Zimov et al., 1997, 2006; Walter et al. 2007). Yet there has been little quantification of the structure and distribution of yedoma in Alaska. In this paper, we address these issues by: (1) reviewing existing information on the nature and distribution of yedoma; (2) describing ground ice characteristics of a unique exposure of yedoma along the Itkillik River in northern Alaska; and (3) developing a preliminary map of yedoma in Alaska.

Origin and distribution of Yedoma

Terminology, genesis of the deposit, nature of massive ice, and distribution of yedoma have been controversial for decades. The massive ice is so abundant that in some exposures it appears as a continuous horizontal body with isolated soil inclusions. For a long time it had been described as buried glacier ice. One of the Russian names for such permafrost, "ledoviy complex," reflects the assumption of its glacial genesis and should be literarily translated as a "glacial complex." The translation "ice complex," which is used in modern scientific literature, emphasizes the high ice content of permafrost and is neutral to hypotheses of the ice genesis. Now in Russian and in international literature the term *yedoma* is used more often than the term *ice complex*. Originally, yedoma (Russian *едома*) means "…a flat hill, a remnant of a terrace, a mound, which rises in several dozen meters above surrounding terrain." (Murzaev, 1984, page 197). This folk name was introduced into scientific literature by Birkengof (1933) and describes the remnants of terrain with ice-rich permafrost formed in east Siberia in the late Pleistocene. Now the terms *yedoma suite, yedoma complex*, or just *yedoma* usually describe

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the late Pleistocene syngenetic permafrost, and the term yedoma is used in the permafrost literature mostly as a stratigraphic term for extremely ice-rich silty deposits of late Pleistocene age rather than geomorphic term (Tomirdiaro, 1980; Kaplina, 1981; Zhestkova et al., 1982, 1986; Zimov et al., 2006; Walter et al., 2007; Schirrmeister et al., 2008, in press; Froese et al., 2009; French and Shur, 2010).

Popov (1953) proposed an alluvial genesis of yedoma and most Russian investigators have agreed with him. Other hypotheses for yedoma genesis include colluvial (Gravis, 1969), nival (Kunitskiy, 1989; Schirrmeister et al., 2008, in press) and eolian (Péwé, 1975; Tomirdiaro, 1980; Hopkins, 1982; Carter, 1988; Höfle and Ping, 1996; Begét, 2001). Zhestkova et al. (1982, 1986) proposed a polygenetic origin of yedoma that considers yedoma as a climatic phenomenon and applied the idea of "equifinality," which suggests that similar results may be achieved by various processes and under different initial conditions. They conclude that the leading factors of yedoma formation are cold climate and continuous long-term sedimentation. They also emphasized that yedoma is a gigantic polypedon and that soil-forming processes (from a pedological point of view) played an important role in yedoma formation. Sher (1997) and Sher et al. (2005) support this explanation of the yedoma genesis.

Yedoma is a surficial deposit, ranging generally from 10 to 30 m in thickness, but in some areas it reaches 50 m and sometimes more (Ivanov, 1984; Romanovskii, 1993). Ice wedges typically penetrate the entire sequence of yedoma. The true width of ice wedges varies from 2–3 to 5–6 m (an apparent width of ice wedges can be much more, depending on the direction of their axes towards the plane of exposures). Soils of yedoma between ice wedges typically contain over 70% silt although sandy yedoma deposits also occur. Poorly decomposed rootlets present throughout yedoma and thin organic-rich soil horizons are not rare. High ice content, tall ice wedges, and a specific set of cryostructures are the main diagnostic features of yedoma deposits.

Formation of yedoma took place in the extremely cold, dry, grassy environment called "tundra-steppe" or "mammoth steppe" (Yurtsev, 1981; Kaplina, 1981; Guthrie, 1990; Sher, 1997). Such terrain occupied vast areas of Eurasia and North America in the late Pleistocene. Yedoma does not have a direct analog in permafrost formed during the Holocene. The most similar to yedoma, syngenetic permafrost of contemporary floodplains of arctic rivers, is only 3 to 5 m thick (Shur and Jorgenson, 1998; Fortier and Allard, 2004; Fortier et al. 2006).

Yedoma is widespread in Siberia (Fig. 1), where the total area of its occurrence is about 1 million km^2 (Romanovskii, 1993; Zimov et al., 2006; Walter et al., 2007). In Russia, yedoma has been extensively studied since the 1950s (Popov, 1953, 1967; Katasonov, 1954, 1969, 1978; Vtyurin, 1975; Romanovskii, 1993 and many others), and hundreds of papers on yedoma cryogenic structure and properties are available in Russian. Well known yedoma sequences in Siberia such as Oyogosskiy Yar, Bolshoy Lyakhovskiy Island, Duvanny Yar, Mamontova Gora, Vorontsovskiy Yar, Chukochiy Cape, Kular, Mus-Khaya, Mamontov Klyk, Mamontovy Khayata, Ledoviy Obryv, and Rogozhniy Cape (Fig. 1) were described by Katasonov (1954), Romanovskii (1958), Gravis (1969), Katasonov and Ivanov (1973), Arkhangelov et al. (1979), Kaplina (1981), Tomirdiaro and Chernen'kiy (1987), Gasanov (1981), Shur (1988a), Kanevskiy (1991, 2004), Vasil'chuk (1992), Kotov (2002), Slagoda (2004).

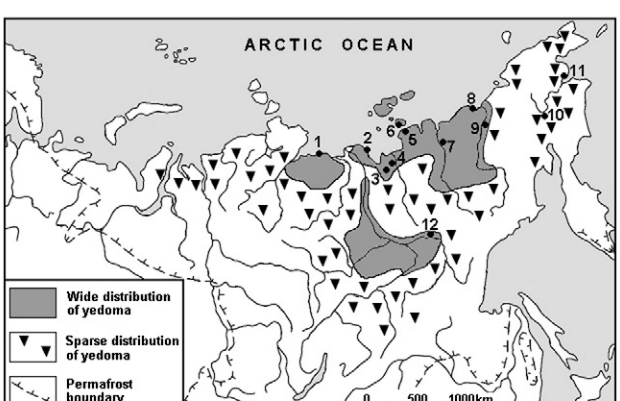

Figure 1. Schematic yedoma occurrence in Russia. Key yedoma sites mentioned in the text: 1—Cape Mamontov Klyk, 2—Mamontovy Khayata, 3—Kular, 4—Mus-Khaya, 5—Oyogosskiy Yar, 6—Bol'shoy Lyakhovskiy Island, 7—Vorontsovskiy Yar, 8—Chukochiy Cape, 9—Duvanniy Yar, 10—Ledoviy Obryv, 11—Rogozhniy Cape, 12—Mamontova Gora. (modified from Romanovskii, 1993; Konishchev, 2009).

During the last decade, a Russian-German research team has performed multidisciplinary studies of yedoma sequences in northern Yakutia (Meyer et al., 2002; Romanovskii et al., 2004; Grosse et al., 2007; Schirrmeister et al., 2008, in press). Alaska is the second largest region of contemporary yedoma occurrence in the world, but publications on the nature, distribution, cryogenic structure and properties of yedoma in Alaska are limited (Williams and Yeend, 1979; Lawson, 1983; Carter, 1988; Hamilton et al., 1988; Hopkins and Kidd, 1988; Shur et al., 2004; Bray et al., 2006; Kanevskiy et al., 2008a). In Canada, yedoma sites were identified in the Klondike area by Fraser and Burn (1997), Kotler and Burn (2000), and Froese et al. (2009).

Itkillik exposure

Jim Helmericks, a long-time resident of the Colville Delta, told us about the exposure in 2006. We studied this exposure in 2006 and 2007. The site (69°34′ N, 150°52′ W) is located at the boundary of the Arctic Coastal Plain and the Arctic Foothills (Fig. 2). The exposure was formed by active river erosion of a large remnant of originally gently undulating yedoma terrain. The surface of the central part of the hill is flat and its elevation is about 33 m above the Itkillik River water level (measured in August 2007). The total length of exposed face exceeded 400 m. The bluff revealed an undisturbed thick section of late Pleistocene syngenetic permafrost (Fig. 2B). Yedoma exposures of similar size and quality are rare and their names are famous in the permafrost literature.

This exposure was not the first one described in this area. Carter (1988) studied two smaller exposures (sites 2 and 3 in Carter's paper). The exposure we studied, as well as Carter's sites 2 and 3, belonged to the same large remnant of continuous flat yedoma plain (Fig. 2C). Carter described site 2 as an actively eroding amphitheater with the exposed face about 15 m high. He interpreted the permafrost as syngenetic, and suggested that it may be common for the area of lower foothills, which he called a silt belt of northern Alaska.

Methods

To assess soil and permafrost characteristics, we described five sites on the exposed bluff and continuous cores from 13 boreholes (Fig. 3). We drilled boreholes from 2.5 to 4.2 m deep with SIPRE corers (7.5 cm and 5 cm in diameter) at various elevations at accessible parts of the exposure. A GPS and a level were used to survey the positions of boreholes and exposures, and their elevations above the Itkillik River water level. The exposure was documented by hundreds of photographs and numerous sketches.

Cryostructures (patterns formed by ice inclusions in the frozen soil) were described using a classification adapted from several Russian and North American classifications (Gasanov, 1963; Katasonov, 1969; Zhestkova, 1982; Murton and French, 1994; Shur and Jorgenson, 1998; Melnikov and Spesivtsev, 2000; French and Shur, 2010). In our yedoma studies in Russia and Alaska, we found that lenticular cryostructure with thin and dense ice lenses and several other similar cryostructures are the most reliable diagnostic features of yedoma soils (Kanevskiy, 1991, 2003; Shur et al., 2004). Figure 4 shows varieties of