Quaternary Research 75 (2011) 584–596

Contents lists available at ScienceDirect

Quaternary Research

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

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

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ARTICLE INFO

Article history:
Received 18 June 2010
Available online 17 January 2011

Keywords:
Syngenetic permafrost
Ground ice
Late Pleistocene
Yedoma
Alaska

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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doi:10.1016/j.yqres.2010.12.003

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).

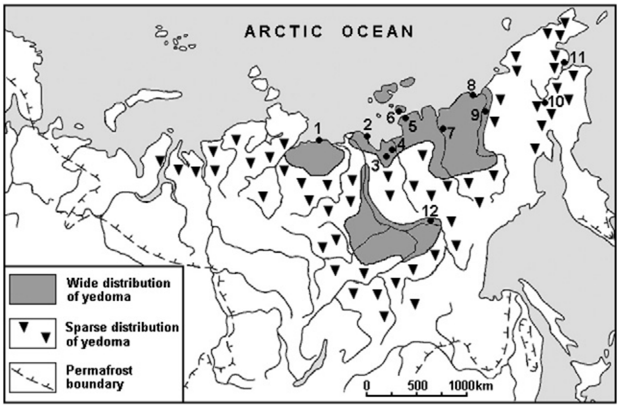

Figure 1. Schematic yedoma occurrence in Russia. Key yedoma sites mentioned in the text: 1—Cape Mamontov Klyk, 2—Mamontovy Khayata, 3—Kular, 4—Mus-Khaya, 5—Oyogosskiy Yar, 6—Bol'shoy Lyakhovskiy Island, 7—Vorontsovskiy Yar, 8—Chukochiy Cape, 9—Duvanniy Yar, 10—Ledoviy Obryv, 11—Rogozhniy Cape, 12—Mamontova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

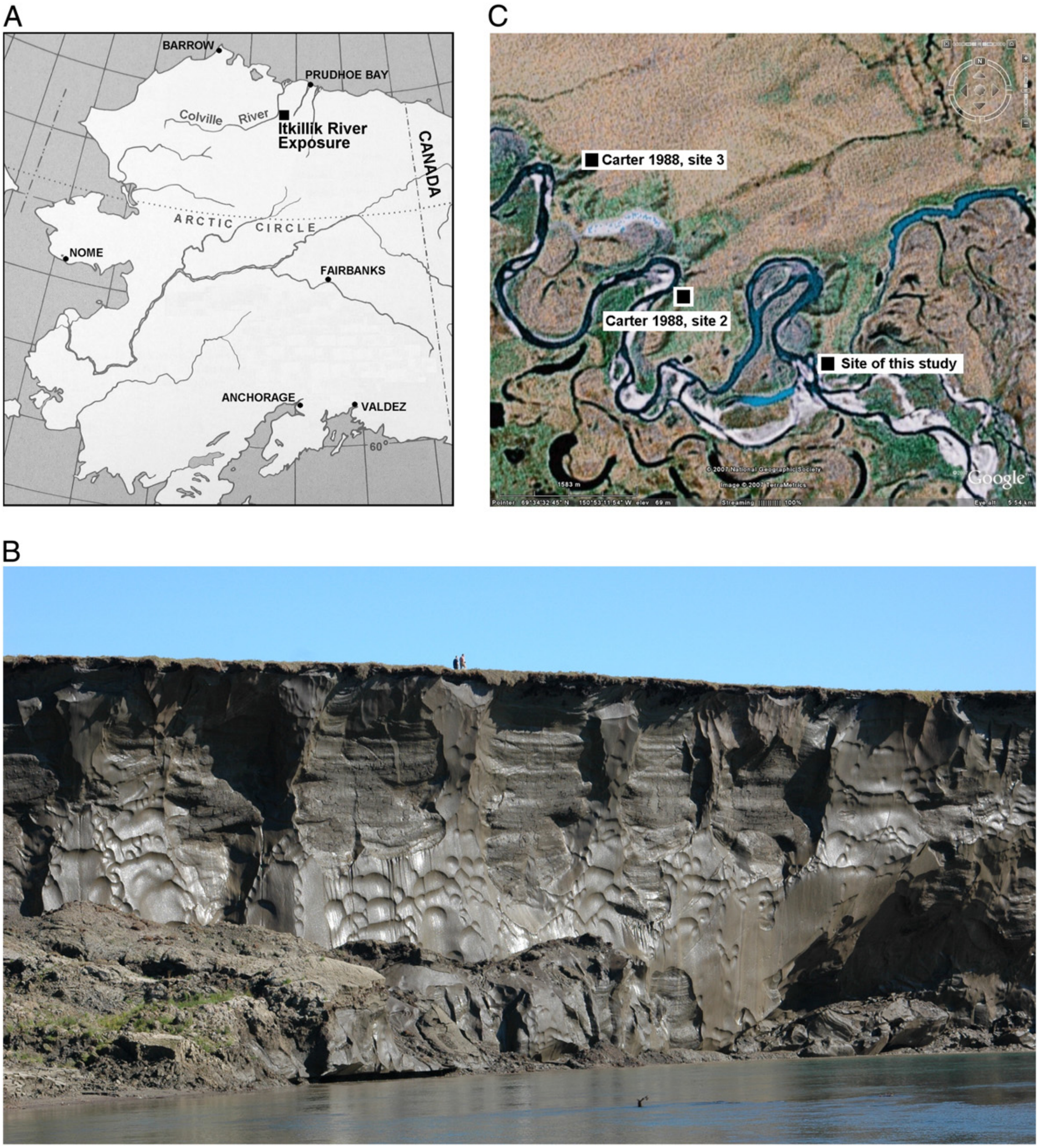

Figure 2. (A) Location of our study site along the Itkillik River. (B) Central part of the Itkillik River exposure (32.7 m high above the river), August 2007. Two people stand above the bluff for scale. (C) Location of the Itkillik River exposures, studied by Carter (1988) and by the authors of this paper in 2006–2007.

these cryostructures, which we term *micro-cryostructures*. Micro-cryostructures contain thin (less than 1 mm) densely spaced ice lenses.

Numerous soil samples were analyzed to determine particle-size distribution, ice and carbon contents, and radiocarbon dates. The grain size distribution was determined on eight samples using sieve and hydrometer analyses (ASTM D422, 1998). Ice content of the sediments was determined on 96 samples by oven-drying (90 °C, 72 h). Gravimetric water content was measured for bulk samples taken from the bluff. Both gravimetric and volumetric water contents were calculated for borehole cores. The area occupied by wedge ice in the exposure was estimated with the ImageJ software, version 1.37v on black and white composite drawings based on photographs.

Twenty soil samples were analyzed for Total C and N on dried soils using a Leco CHN furnace (Spark, 1996, pp. 967–977) and for Total Calcium Carbonate (Burt, 2004, method 6E1c) by the Soil Testing Laboratory at the Colorado State University. Organic carbon (OC) was calculated as the difference between Total C and the C fraction in Total Carbonate. Radiocarbon dating was performed on 11 samples of peat and twigs by National Ocean Sciences AMS Facility, Woods Hole Oceanographic Institution.

A preliminary map of yedoma distribution in Alaska was developed by interpretation of Landsat and Quickbird satellite imagery and aerial photography, in combination with knowledge gained from our field studies and from literature.

Results and discussion

Cryostratigraphy of Itkillik exposure

The Itkillik exposure was subdivided into seven cryostratigraphic units (Fig. 3C): (1) active layer and transient layer with thickness from 0.5 to 1.0 m; (2) contemporary intermediate layer from 0.5–1.0 to 1.5 m depth; (3) yedoma silt with “thin” ice wedges from 1.5 to 13–14 m depth; (4) yedoma silt with “thick” ice wedges from 13–14 to

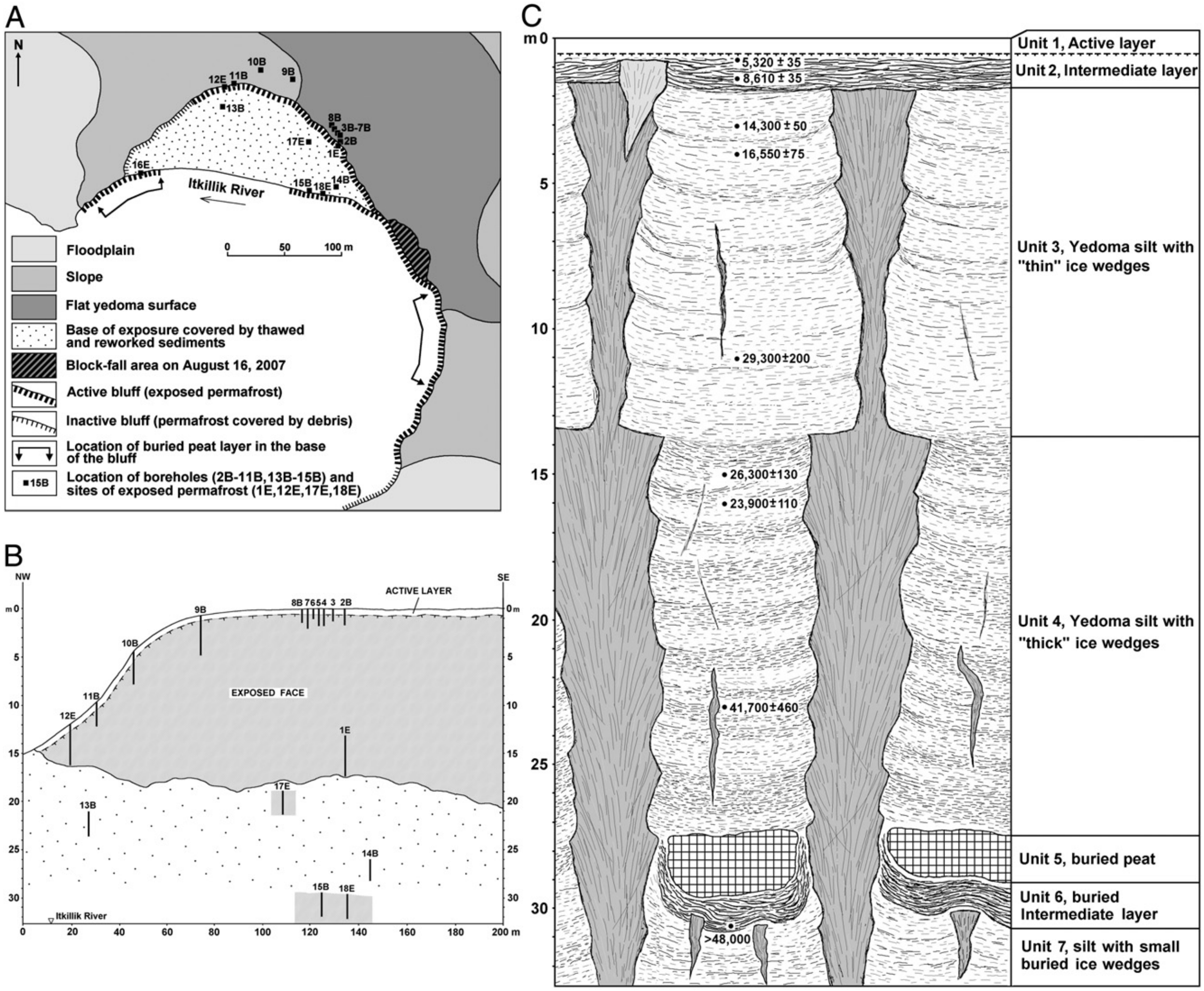

Figure 3. (A) Geomorphic map of the Itkillik River exposure. (B) Location of boreholes (2B–11B, 13B–15B) and sites of sampling of exposed permafrost (1E, 12E, 17E, 18E). (C) Cryostratigraphic units of the Itkillik yedoma (ice wedges width not to scale) and radiocarbon age of deposits, ^{14}C yr BP.

27–28 m depth; 5) buried peat layer from 27–28 to 29–31 m depth; 6) buried intermediate layer from 29–31 to 30–32 m depth; and 7) silt with small buried ice wedges from 30–31 to 32.7 m depth. The three last units were not continuous throughout the entire length of the exposure. Arrows in Figure 3A show locations of buried peat in the exposure. All these units are described below and the cryogenic structure of soils and their water contents are summarized in Figure 5.

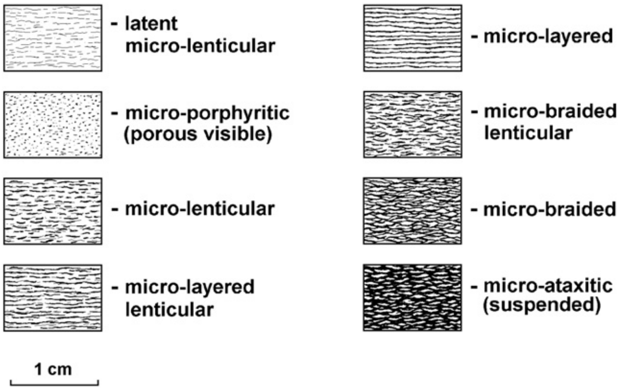

Figure 4. Micro-cryostructures typical of syngenetic permafrost (ice is black).

Unit 1—active and transient layers

The thaw depth measured on August 13, 2007 at the main yedoma surface varied from 35 to 86 cm with an average depth of 62 cm. The thickness of organic material (moss and peat) in the active layer varied from 4 to 43 cm. Mineral soil of the active layer was brown-gray silt with fine sand. The active layer was underlain by a transition zone consisting of transient and intermediate layers (Shur, 1988a,b). The contact between the active and the transient layers had a reticulate cryostructure with prominent vertical ice veins (Figs. 5 and 6A). The gravimetric water content of soil in the transient layer varied from 35% to 55%. The transient layer is the uppermost part of permafrost that occasionally joins the active layer (Yanovsky, 1933; Shur, 1975, 1988a,b). The thickness of the transient layer varies widely depending on climate and soil, but in most of cases does not exceed 30% of the active-layer thickness (Shur et al., 2005).

Unit 2—intermediate layer

The intermediate layer is formed by a gradual decrease of the active-layer thickness after termination of sedimentation (Shur, 1988a,b). This layer is extremely ice-rich and usually is 0.5 to 1.5 m thick. Thinning of the active layer can be caused by succession of vegetation, peat accumulation, changes of surface conditions, and other various local factors (Shur, 1988a,b; Lewkowicz, 1994; Mackay, 1997).

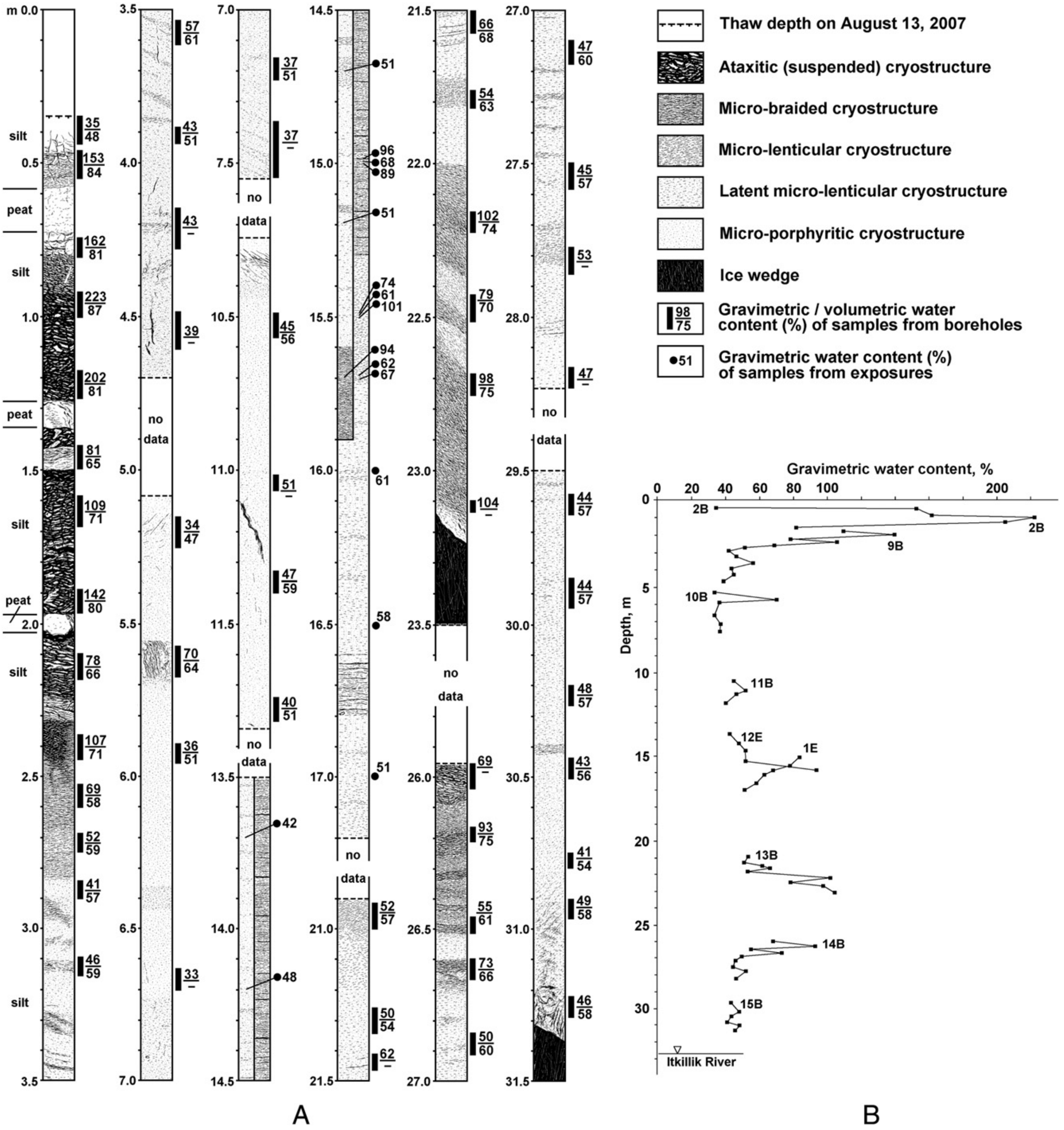

Figure 5. (A) Cryogenic structure and water content. Combined data from separate cores and exposures (locations are shown in Figs. 3A, B): 2B—0–1.5 m; 9B—1.5–4.7 m; 10B—5.1–7.55 m; 11B—10.25–11.44 m; 12E—13.5–15.9 m; 1E—13.5–17.2 m; 13B—20.9–23.5 m; 14B—25.95–28.23 m; 15B—29.5–31.5 m. (B) Gravimetric water content of Itkillik yedoma, combining data from separate cores (labeled B according to Figs. 3A, B) and exposures (labeled E).

The intermediate layer was described in seven boreholes (2B–8B in Fig. 3). The maximum thickness of the intermediate layer (measured above ice wedges of Unit 3) was 108 cm (borehole #2B) and averaged 50 cm. The soil of the intermediate layer was mostly yellow-gray organic silt with some clay and very fine sand, and occasional inclusions of peat. The layer was dominated by ataxitic (suspended) cryostructure (Fig. 6B). A size of soil inclusions in the ice matrix varied from 0.3 × 0.8 cm to 1.0 × 3.0 cm with spacing from 0.2 to 2.0 cm. Gravimetric water content of soil in the intermediate layer varied from 54% to 223% and averaged 148%. Relatively small active ice wedges were observed in the intermediate layer. Radiocarbon age of Unit 2 ranged from 5,300 to 8,600 ^{14}C yr BP (Table 1, Fig. 3C).

Unit 3—yedoma silt with thin ice wedges

At ~1.5–2.5 m depth (borehole 9B), sediments with ataxitic (suspended) cryostructure were similar to those of the intermediate layer (Fig. 5A). Gravimetric water content varied from 78% to 142% and averaged 109%. From 2.5 m, ataxitic cryostructure graded into micro-braided cryostructure (Fig. 6E), and the water content decreased with depth.

In the depth interval 2.8–5.0 m depth (borehole 9B), the soil was yellow-gray silt with small and rare inclusions of organic matter in the form of poorly decomposed rootlets and twigs, mostly with latent micro-lenticular ("latent" in terms of cryostructural descriptions means that ice lenses are hardly visible with naked eye) and micro-

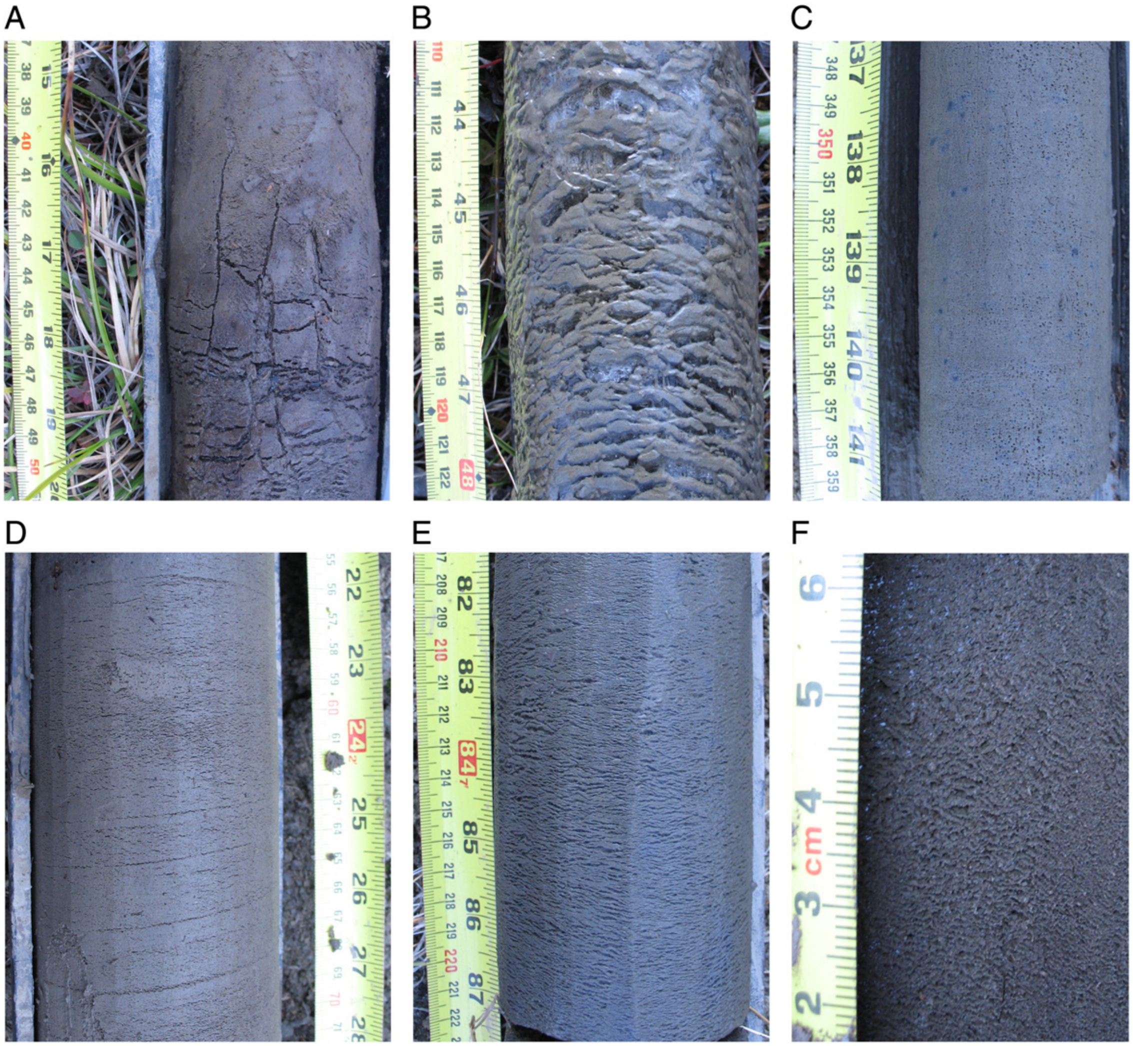

Figure 6. Examples of cryogenic structure of the Itkillik River sequence. (A) Reticulate cryostructure of the transient layer (borehole 2B, depth 0.37–0.52 m). (B) Ataxitic cryostructure of the intermediate layer (borehole 5B, depth 1.10–1.23 m). (C) Micro-porphyritic cryostructure (borehole 9B, depth 3.92–4.05 m). (D) Latent micro-lenticular cryostructure combined with micro-layered (borehole 13B, depth 21.45–21.65 m). (E) Micro-braided cryostructure (borehole 9B, depth 2.50–2.65 m). (F) Cryostructure transitional from micro-braided to micro-ataxitic (site 12E, depth 15.7 m).

porphyritic (Fig. 6C) cryostructures. Isolated vertical ice veins up to 0.3 cm thick were observed from 3.5 to 4.6 m. Gravimetric water content of soil in this interval varied from 39% to 57%.

At 5.0–7.5 m depth (borehole 10B), the sediment was similar to the previous interval. The ice content was low; cryostructures varied between micro-porphyritic and latent micro-lenticular. Ice lenses typically were <0.2 mm thick and inclined. Gravimetric water content in this interval varied from 33% to 37%.

At 10.3–11.9 m depth (borehole 11B), the soil was uniform gray silt with a prevailing micro-porphyritic cryostructure. Gravimetric water content varied from 40% to 51%. At 11.1–11.3 m, an inclined ice vein up to 0.8 cm thick was observed.

The ice wedges of this unit were wide at the top (about 3–4 m) and their width decreased significantly with depth. At the bottom part of the unit (at depths from 6–8 to 13–14 m) it rarely exceeded 1–2 m. The distance between wedges varied from 7 to 10 m.

Radiocarbon age of the Unit 3 ranged from 14,300 to 29,300 ^{14}C yr BP (Table 1, Fig. 3C).

Unit 4—yedoma silt with thick ice wedges

This unit differs from the unit above mainly by wider ice wedges whose width reached 5–7 m. The water contents of silt were also greater than those of the Unit 3. Micro-cryostructures prevailed in this unit. Radiocarbon age of the Unit 4 ranged from 23,900 to 41,700 ^{14}C yr BP (Table 1).

From 13.5 to 15.6 m depth (site 12E), soil was gray silt with rare small inclusions of organic matter. The main cryostructure was micro-porphyritic. Gravimetric water content varied from 42 to 51%. From 15.6 to 15.9 m depth, silt was ice-rich; cryostructures varied from micro-braided to micro-ataxitic (Fig. 6F). The visible ice content varied from 30% to 50%, and gravimetric water content was 94%.

Soil at the sampling site 1E was yellowish-gray silt with inclusions of rootlets and twigs. At 13.5–15.3 m depth, the soil was ice-rich; its cryostructure varied from micro-braided to micro-lenticular with several ice layers (so-called belts in the Russian permafrost literature) 0.2–0.8 cm thick and spaced 1.5–10 cm apart. Gravimetric water contents varied from 68% to 96%. At 15.3–15.7 m depth, the soil had micro-lenticular cryostructure and gravimetric water contents from 61 to 101%. Cryostructure of soil from 15.7 to 17.2 m was mainly latent micro-lenticular and gravimetric water contents decreased downward from 61% to 51%. At 16.6–16.8 m depth, several ice “belts” 0.2–1.0 cm thick spaced 1.0–5.0 cm apart were observed.

From 20.9 to 23.2 m depth (borehole 13B), soil was brownish-gray silt with small inclusions of organic matter. From 20.9 to 22.0 m, cryostructure was mostly latent micro-lenticular (Fig. 6D) and gravimetric water content was 50–66%. At 22.0–23.2 m depth, soil

Table 1
Age of the Itkillik yedoma with depth, based on radiocarbon (^{14}C) and thermoluminescence (TL) analyses.

Depth, m	Type of analysis	Age	Lab. number	Material	Reference
0.7	^{14}C AMS	5,320±35[a]	OS-66781	peat	This study
1.3	^{14}C AMS	8,610±35[a]	OS-66782	peat	This study
3.0	^{14}C AMS	14,300±50[a]	OS-66783	twigs	This study
4.0	^{14}C AMS	16,550±75[a]	OS-66784	twigs	This study
7.4	TL	12,600±700	Alpha-3292	loess	Carter (1988), Site 3
11.0	^{14}C AMS	29,300±200[a]	OS-66785	twigs	This study
15.0	^{14}C AMS	26,300±130[a]	OS-66786	twigs	This study
15.0	^{14}C	28,610±270[a]	USGS-1151	fine-grained org.	Carter (1988), Site 2
15.0	^{14}C	32,300±1500[a]	I-11,530	fine-grained org.	Carter (1988), Site 2
16.0	^{14}C AMS	23,900±110[a]	OS-66780	twigs	This study
17.2	^{14}C	21,580±310[a]	AA-2361	herbaceous plant	Carter (1988), Site 3
17.4	TL	21,800±1200	Alpha-3291	loess	Carter (1988), Site 3
20.0	TL	34,700±2200	Alpha-3290	loess	Carter (1988), Site 3
23.0	^{14}C AMS	41,700±460[a]	OS-66787	fine-grained org.	This study
28.0	^{14}C AMS	15,500±65[a,b]	OS-66776	twigs	This study
30.9	^{14}C AMS	>48,000[a]	OS-66777	peat	This study
31.8	^{14}C AMS	>47,500[a]	OS-66778	fine-grained org.	This study

[a] ^{14}C yr BP.
[b] Date probably invalid.

had micro-braided to micro-lenticular cryostructure and gravimetric water contents from 79% to 104%. Wavy ice lenses were inclined with the angle increasing downwards from 20° to 70°. At 23.2 m, the borehole reached the inclined boundary with the ice wedge.

Soil in the interval 26–28.2 m (borehole 14B) was gray silt with small and rare inclusions of organic matter (twigs, rootlets). To the depth 26.7 m, silt had micro-braided and micro-lenticular cryostructures and gravimetric water contents from 55% to 93%. At 26.7–28.2 m, prevailing cryostructure was latent micro-lenticular. Gravimetric water contents varied from 45% to 53%.

At 29.5–31.3 m (borehole 15B), the soil was gray silt with mostly latent micro-lenticular cryostructure and gravimetric water contents varied between 41% and 49%. From the depth of 30.9 m, inclined ice lenses were observed with angles reaching 50–60°. At 31.3 m, the borehole reached the inclined boundary with the ice wedge. Above the wedge, the soil included numerous sub-vertical ice veins up to 0.2 cm thick.

Generally, the silt of units 3 and 4 was uniform with occasional indistinct subhorizontal lamination. Bands visible in the exposed face are related mainly to cryogenic features (e.g., ice belts) rather than sedimentational.

Unit 5—buried peat below yedoma

A buried peat layer (Fig. 7) was observed at the base of the bluff in the western and eastern parts of the exposure (Fig. 3A). In the western part of exposure (site 16E), dark-brown peat grading with depth into ice-rich organic silt with medium sand occurred from 28 to 31.5 m depth (Fig. 7B). The lower part of the bluff was covered by slumped sediments. Radiocarbon age of the peaty silt (site 16E, 30.9 m) was 48,000 ^{14}C yr BP (Table 1, Fig. 3C), which may represent a minimum age for the deposit.

In the eastern part of the exposure (Fig. 7A), the buried peat layer was observed from 27 to 29 m depth. In some parts of the bluff, the peat formed a single layer up to 2 m thick while in other locations it contained two layers divided by organic-rich silt. The ice wedges of Unit 4 intruded through the peat layer and penetrated into the underlying sediments, below the Itkillik River water level (Fig. 7A).

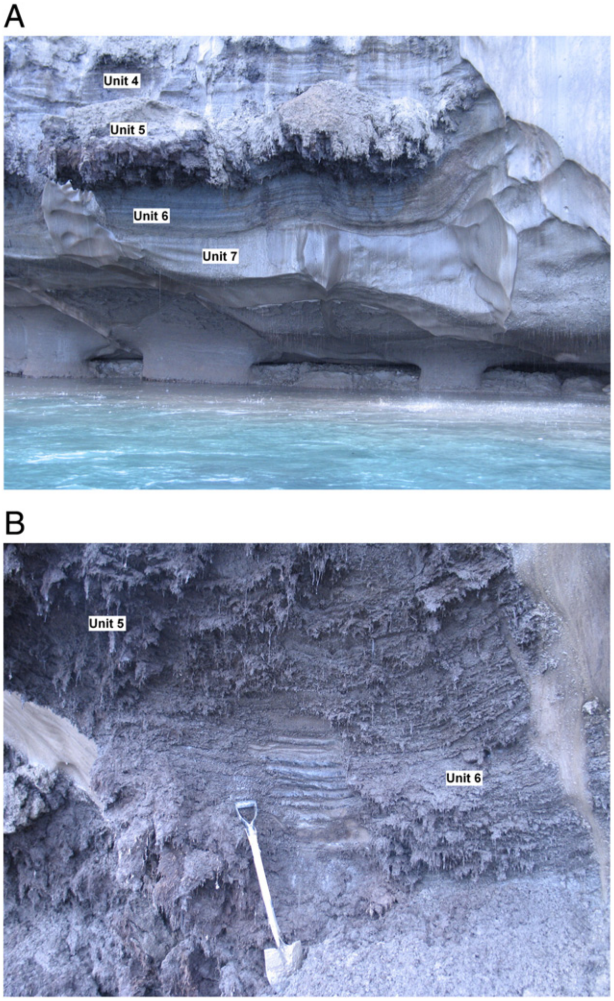

Figure 7. (A) Buried peat and underlying sediments with small ice wedges (Units 5–7), east part of the Itkillik River exposure, depth 27–32.7 m. (B) Buried peat and intermediate layer (Units 5–6), sampling site 16E, depth 29.5–32 m. Note thick ice "belts" above the handle of shovel.

The boundary between units 5 and 4 represents a major climatic shift from warmer, wetter conditions to a dry and cold period with eolian activity. Peat layers of similar age associated with middle Wisconsinan/Karginsky interstadial were described in several yedoma exposures in Russia (Kaplina, 1981; Tomirdiaro, 1980; Tomirdiaro and Chernen'kiy, 1987; Hopkins, 1982).

Unit 6—buried intermediate layer

In the east part of exposure, a buried ice-rich intermediate layer was located from 29 to 30 m between the buried peat layer and an underlying silt layer, which contained small buried ice wedges (Fig. 7A). The layer had ataxitic (suspended) cryostructure with numerous ice "belts" up to 5–7 cm thick, which is typical of the intermediate layer (Fig. 7B).

The occurrence of buried intermediate layers in association with buried peat is typical of yedoma. In northern Yakutia, such layers can compose up to 20–30% of entire yedoma sections (Kanevskiy, 1991, 2004). They indicate periods of slower sedimentation, changing climatic or environmental conditions. Very often such layers can be observed right below the layers of buried peat or organic soils (Gubin, 2002; Kanevskiy, 2004) similarly to Unit 6 of the Itkillik exposure.

Unit 7—silt with short ice wedges

This unit was observed in the eastern part of the exposure at 30–32.7 m depth. The soil was composed of silt similar to soil of units 3 and 4 and contained a few short ice wedges <0.7 m wide and 2.5–3 m high. The thick wedges of Unit 4 penetrated at places through this unit to below the Itkillik River water level. Development of thick ice wedges displaced soils of unit 7 upward along the sides of wedges, so that mineral soil separated ice wedges from the buried peat (Fig. 7A). This discontinuity in the peat beds could also occur due to the accumulation of peat only in the wet central parts of low-centered polygons.

Soil particle size

Particle-size distribution in eight soil samples showed little variation with depth (Table 2). The sample from 1.4 m represents the intermediate layer, while the other samples represent yedoma silt of units 3 and 4. Soils were composed mainly of silt (56% to 83%), with some sand (8% to 23%) and clay (3% to 22%). There was a slight trend of increased sand percentages with depth.

Cryostructures

Micro-cryostructures dominated in the Itkillik yedoma (Figs. 4 and 5A). Examples of these cryostructures are shown in Figures 6C–F. In the Itkillik yedoma, layers of relatively ice-poor soil were interrupted by layers of soil with so-called belt cryostructure. These relatively thin (up to 1 cm thick) "belts" were made of high concentrations of short and thin ice lenses or continuous distinct ice layers. Soils with "belt" cryostructure had greater water content than soils with micro-lenticular or micro-porphyritic cryostructure. Prevalence of micro-cryostructures differentiated yedoma (Units 3 and 4) from the intermediate layers overlying and underlying yedoma (Units 2 and 5), which had mostly ataxitic (suspended) cryostructure and much thicker ice "belts" (Figs. 6B and 7B). Occurrence of thick ice belts, which protruded out a few centimeters from the bluff face produced specific belt-like appearance shown in Figs. 7A, B.

Visible ice contents of soils with micro-cryostructures usually increase in the following order: latent micro-lenticular, micro-porphyritic (porous visible), micro-lenticular, micro-layered lenticular, micro-layered, micro-braided lenticular, micro-braided, micro-ataxitic (suspended). However, very small size of ice inclusions, especially in soil with latent micro-lenticular or micro-porphyritic cryostructures, make it difficult to recognize them even to an observer experienced in field studies of different types of permafrost. Ice lenses often become visible only when the soil slightly thaws. This explains why soils with these cryostructures are often described as ice bonded with non-visible ice. Ice contents of soil with micro-cryostructures vary widely and can be extremely high, despite the small size of ice lenses. Gravimetric water contents for such soils vary from 35% to 40% (for latent micro-lenticular and micro-porphyritic cryostructures) up to 100–200% (for micro-braided and micro-ataxitic).

Ice contents of silt

Gravimetric water contents of soil of the Itkillik yedoma varied widely with depth (Fig. 5B). For the intermediate layer (Unit 2), the average water content was 148%. The average gravimetric water content for yedoma (Units 3 and 4) was 59%. The water content of the Itkillik yedoma was lower than in many yedoma sections we have studied in Alaska and Russia. For example, gravimetric water content of soil in yedoma exposed in the CRREL Permafrost tunnel varied from 80% to 240% with average value about 130% (Bray et al., 2006; Kanevskiy et al., 2008a).

Cryogenic structure and ice contents of sediments were correlated with the thickness of adjacent ice wedges. For example, within Unit 3 the minimal thickness of wedges occurred at depths from 5–6 m to 12–14 m. In this interval, there was little deformation of ice "belts" and sediment layers near the wedges. This part of the section had water contents ranging from 30% to 50%, with the lowest values at 5–7.5 m. Gravimetric water contents of sediments increased downward from the 14–15 m, which corresponded to the boundary between Units 3 and 4. Average gravimetric water content was 50% for unit 3 and 63% for Unit 4.

Ice wedge morphology and volume

The Itkillik yedoma had very high content of wedge ice, in contrast to the relatively low water content due to pore and segregated ice in the silt. There were four generations of wedge ice, which we attributed to four periods of formation (Fig. 3C). Relatively thin and short Holocene ice wedges occurred within the intermediate layer (Unit 2). These wedges can be still active. Holocene ice wedges were found both in boreholes and in the exposure. In the exposure, such wedges were up to 1–2 m wide and up to 3–4 m tall, triangular in shape, and had an opaque white color due to numerous air bubbles and lack of sediment inclusions. The ice was mostly clear and colorless, with very thin (less than 0.2 mm in diameter) vertically oriented cylindrical air bubbles. The ice wedges protruded through the intermediate layer and penetrated the uppermost part of the late Pleistocene permafrost.

Ice wedges in Unit 3 were relatively wide at the top (up to 3–4 m) and their width decreased gradually with depth. In lower part of the unit (at depths from 6–7 to 13–14 m), the width of ice wedges rarely exceeded 1–2 m. The wedge ice had well-developed vertical foliation formed by silt particles, which were brought in thermal cracks by water during formation of ice veins. The ice had a yellowish-gray color, presumably due to silt inclusions and dissolved organics, and contained spherical air bubbles up to 1.5 mm in diameter. The spacing between ice wedges varied from 7 to 10 m. Thin secondary ice wedges and veins were observed at different depths between large primary ice wedges.

Ice wedges in Unit 4 were up to 5–7 m wide and their width remained fairly constant with depth. Their total vertical size could not be

Table 2
Particle-size (mm) of soils, %.

Depth, m	Sand					Silt					Clay
	1–2 mm	0.5–1	0.25–0.5	0.125–0.25	0.063–0.125	0.031–0.063	0.016–0.031	0.008–0.016	0.004–0.008	0.002–0.004	<0.002 mm
1.4	0.1	0.1	1.4	3.7	3.7	27.9	26.6	9.3	1.8	4.1	21.3
3.6	0.1	0.3	4.3	2.6	3.3	28.1	24.1	11.6	3.7	3.3	18.6
7.5	0.0	0.1	1.8	4.1	5.7	23.0	31.1	9.1	4.6	2.5	18.1
11.8	0.1	0.1	2.2	3.2	4.1	14.6	30.1	15.9	4.6	3.1	22.0
17.0	0.2	0.8	5.4	0.6	0.6	13.3	27.5	20.4	8.0	5.0	18.3
21.5	0.1	0.4	7.7	2.8	4.6	7.1	21.2	19.1	8.0	5.8	23.2
26.9	0.2	0.4	4.0	4.1	4.5	18.8	58.7	3.4	1.5	0.9	3.4
31.3	0.0	0.1	2.5	8.3	11.7	15.9	22.6	10.8	4.1	3.0	21.0

determined because most of them continued below the Itkillik River water level. Unit 4 also had thin secondary ice wedges between thick primary ice wedges. Ice wedges in Unit 7, located at the bottom of the exposure beneath the peat layer, were less than 0.7 m in width and 2.5–3 m in height. The spacing between ice wedges varied from 3 to 8 m.

The syngenetic ice wedges of Units 3 and 4 were easily distinguished from the upper Holocene ice wedges, which were white, had no soil inclusions, and contained more air bubbles. The ragged lateral margins of ice wedges of Units 3 and 4 (Figs. 2B, 3C, 8A) were related to the syngenetic nature of wedges: width of wedges fluctuated with depth because elementary ice veins in wedge ice started from different depths, since contraction cracking occurred during continuing sedimentation. So-called shoulders of ice wedges reflected periods of sedimentation slowdown (Katasonov, 1954; Shumskii, 1959; Popov, 1967; Vtyurin, 1975; Romanovskii, 1993).

The composite black-and-white images of ice wedges appearance in August 2006 and August 2007 were combined from numerous photographs (Fig. 8A). Based on measurements of the areas occupied by wedge ice in the 240-m central section of the exposure in 2006 and 2007, wedge-ice volume varied from 40% to 52% in units 2–3, and was about 78% in units 4–7. On average, wedge ice occupied 57% of the entire exposed bluff (Table 3).

Total volumetric ice content including wedge ice, pore ice and segregated ice between ice wedges was 90% in Unit 4 and 83% for the entire bluff (Fig. 8B). Based on an average bluff height of 32.5 m, the volume of ice was ~27 m^3 per m^2 of surface area.

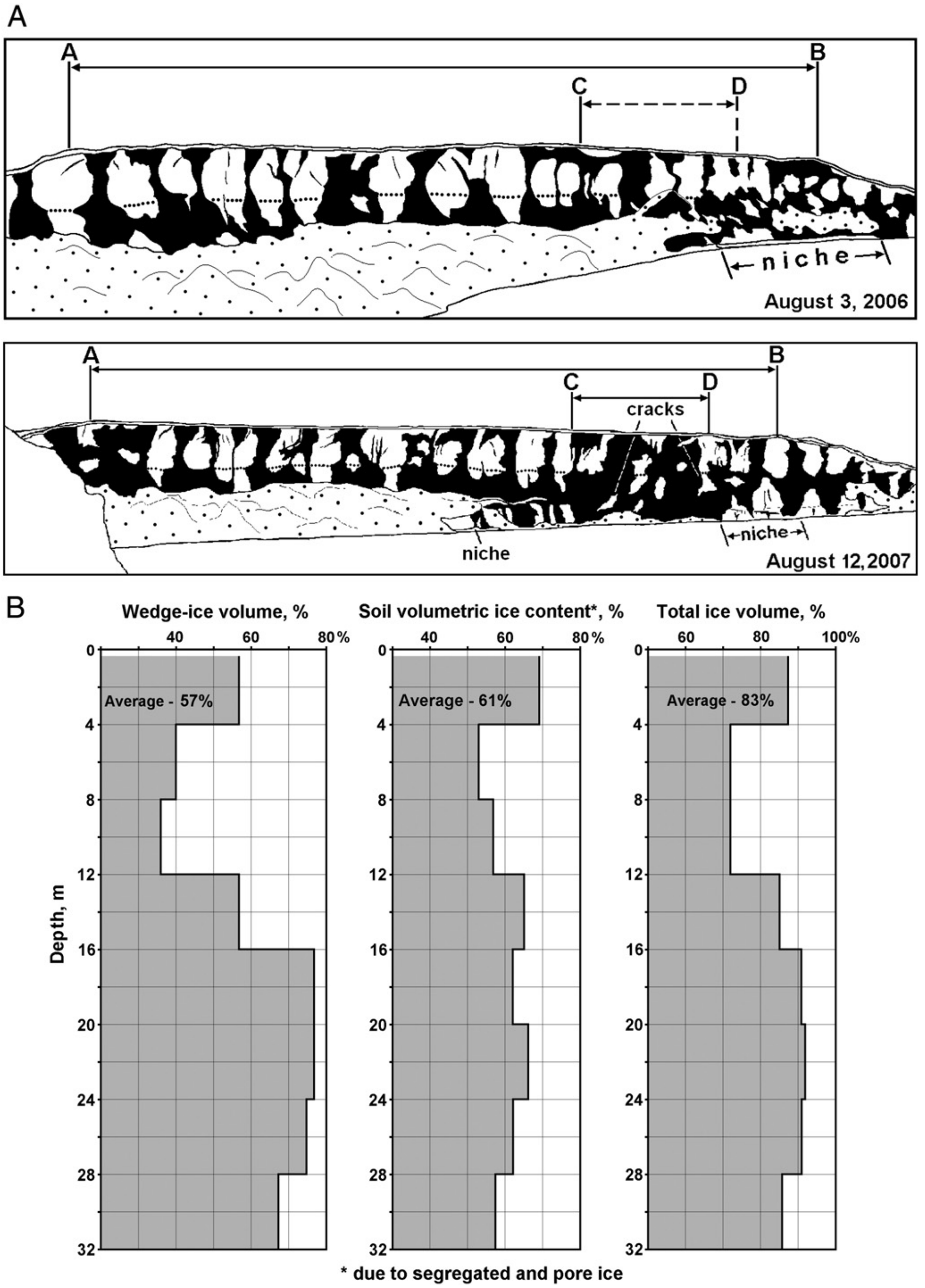

Figure 8. (A) Appearance of wedge-ice (black) on August 3, 2006 and August 12, 2007. AB—central part of the bluff with flat Yedoma surface, the length is 240 m; CD—area of block-fall on August 17. Dotted line shows the boundary between Units 3 and 4. (B) Percent volume of wedge, segregated, and pore ice with depth in the Itkillik River exposure.

This high volume of ice in the Itkillik yedoma is consistent with estimates by Tomirdiaro and Chernen'kiy (1987) for several yedoma sites in Russia. Thawing of this extremely ice-rich material can cause a dramatic decrease in elevation of the ground surface. The total thaw settlement of the Itkillik Yedoma can reach 20 m. That is why depths of thaw-lake basins in yedoma often reach 20–30 m or more (Williams and Yeend, 1979; Ivanov, 1984; Carter, 1988; Hopkins and Kidd, 1988; Kanevskiy, 2004; Shur et al., 2009; Stephani et al., 2009).

Thermokarst-Cave Ice

The term "thermokarst-cave ice" initially was suggested by Shumskii (1959) to describe bodies of massive ice formed by the freezing of water trapped in underground cavities cut in the permafrost by running water. In North America, this type of ice was described as "pool ice" by Mackay (1997). Process of underground thermal erosion was observed by French (2007) and Fortier et al. (2007). Studies of yedoma in the CRREL permafrost tunnel revealed thermokarst-cave ice bodies up to 2 m in thickness and 6 m in width, which were underlain by soil with the reticulate-chaotic cryostructure (Shur et al., 2004; Fortier et al., 2008). In exposed part of Itkillik yedoma, we found several bodies of thermokarst-cave ice in the middle and the lower parts of the bluff. Their width varied from 0.4 m to 3 m and their thickness varied from 0.1 to 1 m. Thermokarst-cave ice in the Itkillik yedoma also occurred in combination with reticulate-chaotic cryostructure in the underlying silt.

Carbon stocks

Soil carbon in the 31.3-m-deep Itkillik profile comprised mostly inorganic carbon (IC). IC contents in the active layer were 1.5–1.9% and increased to 2.6–4.6% in samples of frozen silt taken from yedoma soil in between the ice wedges. Mean IC contents in the active layer (1.7%) were about one-half of values in the permafrost (3.7%). In contrast, organic carbon (OC) contents were 2.8–8.2% in the active layer and decreased to from 0.01% to 1.7% in the permafrost. Mean OC in the active layer (5.5%) was 12 times greater than that in the permafrost (0.4%). OC contents of the Itkillik yedoma are relatively low in comparison with many other yedoma sequences (Zimov et al., 2006; Schirrmeister et al., in press).

When OC contents were summed by layers, carbon stocks calculated from the single profile were 32.5 kg/m^2 for the top 1 m, 29.4 kg/m^2 for the 1–13.5 m increment and 79.9 kg/m^2 for the 13.5–31.3 m increment, totaling 141.8 kg/m^2 for the entire soil column of 31.3 m with the horizontal sequence of 1 m^2. When carbon stocks were adjusted for ice-wedge volume (OC assumed to be near zero in wedge ice), the carbon stocks dropped to 32.5, 16.2, and 20.0 kg/m^2 for the three increments, respectively, and totaled 68.7 kg/m^2 for the entire 31.3 m.

At the Itkillik site, OC made up only 11% of the total carbon contents due to the high carbonate concentrations in the deposit of wind-blown silt. About 83% of the total volume of the bluff was comprised of ice. Thus, evaluation of the volume of ice is critical to the accurate estimation of carbon contents of ice-rich permafrost.

Table 3
Volume (%) of ice wedges in section AB of the bluff (based on Fig. 7A).

Date of observation	Units 2–3	Units 4–7	Entire yedoma
August 3, 2006	39.6	78.3	52.3
August 12, 2007	51.9	78.5	62.4
2006 and 2007, average	45.2	78.4	57.3

Time of Yedoma formation

The yedoma deposits of units 3 and 4 were formed from more than 48,000 to 14,300 ^{14}C yr BP (Table 1, Fig. 3C), based on 11 radiocarbon dates from our study and six dates (three radiocarbon and three thermoluminescence dates) obtained earlier from two nearby exposures by Carter (1988). The two youngest dates of Holocene age, 5,320 ± 35 and 8,610 ± 35 ^{14}C yr BP, represent the development of the intermediate layer (depths are 0.7 m and 1.3 m, correspondingly). Dates obtained by Carter (1988) generally match our data. In permafrost with well developed ice wedges, however, dates do not always correlate well with depths in part because soil is often pushed upward along ice wedges (Shur and Jorgenson, 1998; Fortier and Allard, 2004). At 15-m depth, there was a wide range of dates that corresponds to the transition from unit 3 to unit 4.

Using Beringian terminology (Anderson and Lozhkin, 2001; Elias and Brigham-Grette, 2007) we can conclude that greatest part of the section was formed during the middle Wisconsinan/Karginsky interstadial and late Wisconsinan/Sartan glaciation. The Itkillik yedoma formation was synchronous with the time of formation of yedoma in Russia, where most known dates vary from more than 55,000 to 13,000 ^{14}C yr BP (Kaplina, 1981; Tomirdiaro and Chernen'kiy, 1987; Schirrmeister et al., in press).

Yedoma in Alaska

Our preliminary map of yedoma occurrence in Alaska (Fig. 9) shows that yedoma is widespread across both arctic and boreal regions. Yedoma is abundant along the lower portion of the Arctic Foothills, in the northern part of Seward Peninsula, and in numerous areas in Interior Alaska. Data for the map combine our field observations in different parts of Alaska, an analysis of satellite and aerial imagery, and an analysis of published sources.

Specific yedoma landforms include: (1) low flat hills with gentle slopes penetrated by deep thaw lakes and divided by erosional valleys and drained thaw-lake basins (alases and alas valleys), (2) flat lowlands (alas plains) with isolated yedoma remnants, and (3) small-size thermokarst landforms such as baidzharakhs (conical thermokarst mounds) and deep troughs above degrading ice wedges. We based these characteristics on our studies of yedoma in Russia and Alaska. In Alaska, we studied yedoma on the North Slope (exposures in the Oumalik Lakes area, Itkillik River and Jago River), on the Seward Peninsula (areas of Devil Mountains and Cape Espenberg with an aerial reconnaissance of the northern half of the Seward Peninsula), and in Interior Alaska (Boot Lake, Hess Creek, Erickson Creek, and Fairbanks areas). Yedoma terrain is easy to recognize in tundra, but it is obscured by forests in boreal regions. During mapping, we differentiated yedoma that could be reliably identified by the analysis of satellite and aerial imagery from potential locations for which existing data were not conclusive.

Most authors, whose information contributed to the map, described sections of ice-rich permafrost but did not mention its syngenetic nature and nor the origin of massive ice (especially in early papers). However, their descriptions of massive ice, as well as photos and sketches, help to identify yedoma with high confidence. Ice-rich syngenetic permafrost similar to yedoma in Russia was mapped on the Alaskan North Slope (Carter, 1988) and on uplands surrounding the Yukon Flats (Williams, 1962). Areas of loess (windblown silt) distribution in Alaska were identified by (Black, 1951; Hopkins, 1963; Péwé, 1975; Muhs et al., 2003; Muhs and Budahn, 2006). Significant parts of these loess areas are still frozen and contain considerable amount of wedge-ice, but in southern parts of the discontinuous permafrost zone in Alaska permafrost has mostly degraded during the Holocene and occurrences of yedoma are rare and hard to identify. The most intensive data on yedoma in central Alaska came from investigations in the CRREL permafrost tunnel near Fairbanks where

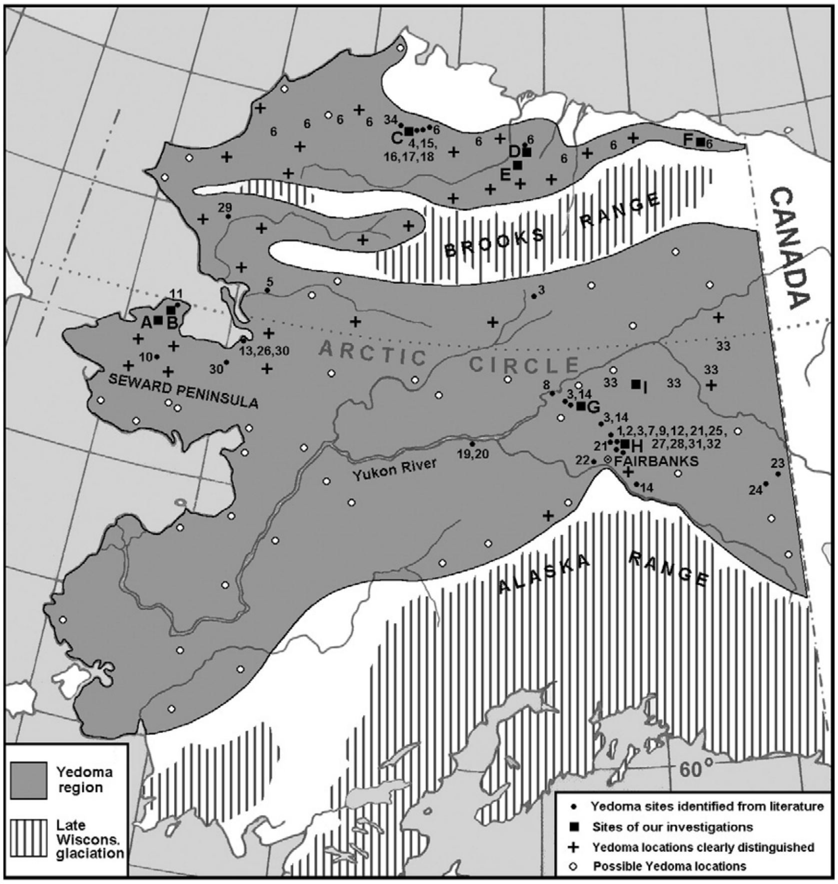

Figure 9. Preliminary map of yedoma distribution in Alaska. Sites of our field investigations: A—Devil Mountains; B—Cape Espenberg; C—Oumalik; D—Itkillik River; E—Umiat; F—Jago River; G—Erickson Creek, Hess Creek; H—CRREL Permafrost tunnel; I—Boot Lake. Other yedoma locations are identified on the basis of analysis of satellite and aerial imagery. Limits of late Wisconsinan glaciation are shown after Péwé, 1975; Hamilton, 1994. Yedoma sites identified from the literature sources: 1. Black, 1978; 2. Bray et al., 2006; 3. Brown and Kreig, 1983; 4. Brewer et al., 1993; 5. Cantwell, 1887; 6. Carter, 1988; 7. Fortier et al., 2008; 8. Hamilton, 1979; 9. Hamilton et al., 1988; 10. Hopkins, 1963; 11. Hopkins and Kidd, 1988; 12. Kanevskiy et al., 2008a; 13. Kotzebue, 1821; 14. Kreig and Reger, 1982; 15. Lawson, 1982; 16. Lawson, 1983; 17. Lawson, 1986; 18. Livingstone et al., 1958; 19. Maddren, 1905; 20. Matheus et al., 2003; 21. Meyer et al., 2008; 22. Péwé, 1975; 23. Porter, 1986; 24. Porter, 1988; 25.Prindle, 1913; 26. Quackenbush, 1909; 27. Sellmann, 1967; 28. Shur et al., 2004; 29. Smith, 1913; 30. Taber, 1943; 31. Tuck, 1940; 32. Wilkerson, 1932; 33. Williams, 1962; 34. Williams and Yeend, 1979.

only the lower 7 m of 17-m-thick yedoma section are exposed (Sellmann, 1967; Hamilton et al., 1988; Shur et al., 2004; Bray et al., 2006; Fortier et al., 2008; Kanevskiy et al., 2008a).

Substantial areas in Alaska that lack yedoma, such as Brooks Range, Alaska Range, and Copper River Basin, were glaciated during the late Pleistocene (Péwé, 1975; Hamilton, 1994). The absence of yedoma in the northern part of the Arctic Coastal Plain is in the stark contrast to comparable regions in the Russian Arctic that were unglaciated during the late Pleistocene and where yedoma widely occurs. This lack of yedoma triggered a hypothesis that the Arctic Coastal Plain of northern Alaska was glaciated during the late Pleistocene (Shur et al., 2001; Jorgenson and Shur, 2008; Kanevskiy et al., 2008b).

Conclusions

Yedoma formed under long-term continuous soil deposition in severely cold environment of the late Pleistocene, which was favorable to accumulation of thick bodies of ice-rich syngenetic permafrost. Yedoma in Alaska is widespread and in many areas well preserved. The exposure along the Itkillik River in northern Alaska is one of the best yedoma exposures in the Arctic. By its structure and time of formation, the Itkillik yedoma is similar to well known yedoma sequences in Russia, such as the Mus-Khaya, Duvanny Yar, and Chukochiy Cape. The Itkillik exposure reveals an undisturbed yedoma sequence formed during more than 40,000 yr. The exposure presents unique opportunities to compare Pleistocene syngenetic permafrost of Siberia and Alaska in conjunction with more general Beringia studies. Our permafrost study of stratigraphy, cryostructures, massive ice, and chronology of the Itkillik yedoma provides baseline information for future work on climate, ecosystems, and other environmental components of the late Pleistocene in northern Alaska.

Acknowledgments

Study was funded by the National Science Foundation (NSF) grants ARC-0454939, ARC-0454985, EAR-0630257, and Alaska EPSCoR, funded by the NSF grant 0701898 and the state of Alaska. We would like to thank CH2M HILL Polar Services, helicopter pilots Troy Cambier and Pele Tierney for their logistical support, James and Teena Helmericks for their hospitality and for pointing the site for us, and Mathew Dillon for his help in laboratory. Comments and suggestions by the Associate Editor and two anonymous reviewers helped to improve this paper.

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