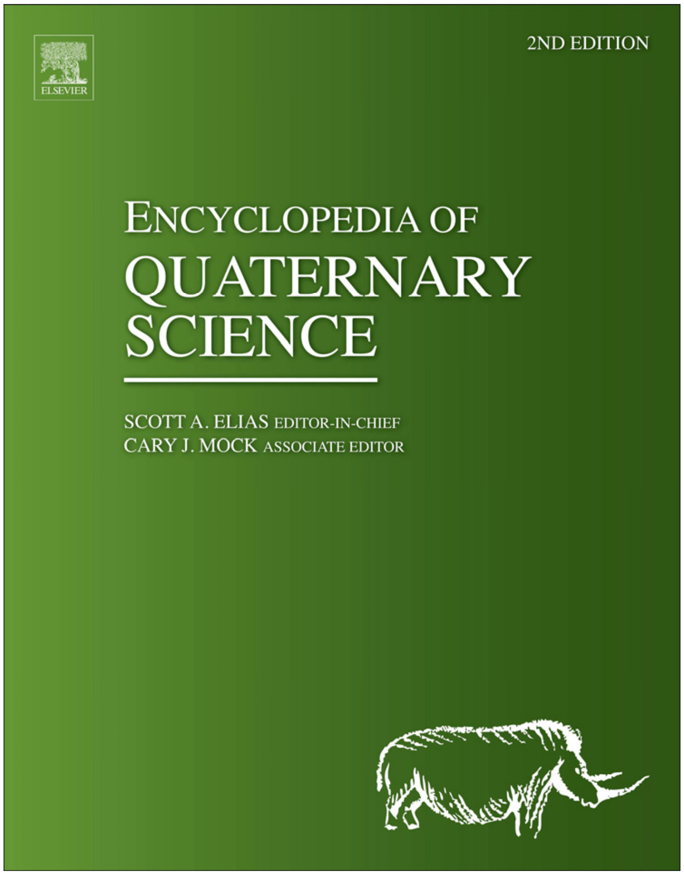

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Yedoma: Late Pleistocene Ice-Rich Syngenetic Permafrost of Beringia

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Introduction

Beringia represents the largest contiguous area of the Arctic that remained unglaciated during the late Pliocene and Pleistocene. Hulten (1937), the Swedish biogeographer, invoked the concept of Beringia to explain the distribution of Arctic and boreal plants around the Bering Strait. He originally considered Beringia to include only the area of the continental shelf exposed when lowered sea level connected eastern Asia with North America. Today, Beringia is considered more broadly to extend from the Taymyr Peninsula through Alaska to the Yukon Territory, united by aspects of the cold-adapted flora and fauna of the region and the lack of glaciation. This area was located between the Eurasian Ice Sheet to the west and the Laurentide and Cordilleran ice sheets to the east (**Figure 1**). Extreme continental climate conditions were connected to the presence of a largely exposed continental shelf, a likely perennial Arctic sea-ice cover, and the existence of large ice sheets to the east and west. By virtue of the lack of glaciation, much of Beringia preserves an exceptional sedimentary record of Pleistocene environmental change.

Across this broad region, vast tracts of ice-rich and largely fine-grained sediments are present. These deposits are found in the Arctic and Subarctic areas of Beringia, and locally exceed 50 m in thickness. The deposits, owing to the presence of permafrost, preserve a diversity of exceptional paleoenvironmental archives, including mammals (e.g., Guthrie, 1990), paleobotanical remains (e.g., Giterman et al., 1982), ancient DNA (e.g., Shapiro and Cooper, 2003), and relict ice (e.g., Kaplina and Lozhkin, 1984), and host a globally significant, and potentially vulnerable, reservoir of organic carbon (e.g., Zimov et al., 2006). While many aspects of their composition and paleoenvironmental history are agreed upon, details of their formation lack consensus, particularly regarding the strict role of eolian processes. These differences are most pronounced among workers in western Beringia (Siberia), while in eastern Beringia (Alaska and Yukon), a general consensus exists. This article reviews the history of research, terminology, characteristics, and differing ideas on the formation of the ice-rich deposits and their paleoenvironmental significance.

Terminology

The terminology for the ice-rich, syngenetically frozen deposits varies across Beringia. These deposits are often referred to as 'Ice Complex' (in Russian: ledovyi kompleks) or 'Yedoma' in Siberia, while in North America, other terms such as 'muck' or retransported silt could be partially considered as equivalent terms (Froese et al., 2009; Péwé, 1975; Shur et al., 2004).

Solov'ev (1959) first defined Ice Complex as frozen deposits of various age, composition, genesis, and thickness, with numerous ice wedges. Ice Complex deposits of late Pleistocene age are widely distributed on the East Siberian coastal plains (Lena-Anabar, Yana-Indigirka, and Kolyma lowlands) as well as on the New Siberian Archipelago, but they also occur in more southerly regions of East Siberia along large river valleys (**Figure 1**).

According to Sher (1997), at least three different meanings of the term 'Yedoma' exist in the Russian literature: (1) a 'Yedoma surface' in the geomorphic sense, (2) a 'Yedoma Suite' in the stratigraphic sense, or (3) a cryolithological feature implying a special kind of frozen sediment, widely distributed in Beringia ('cryolithology' is a Russian term, not widely used in North America, for the study of the genesis, structure, and lithology of frozen earth materials; van Everdingen, 1998). The latter concept of Yedoma is the one used in this article, encompassing distinctive ice-rich silts and silty sand penetrated by large ice wedges, resulting from sedimentation and syngenetic freezing, and driven by certain climatic and environmental conditions during the late Pleistocene. The term 'Ice Complex' is often used synonymously with 'Yedoma' in this sense.

The term 'Yedoma' was originally used in the geomorphic sense to describe the hills separating thermokarst depressions in northeastern Siberia, especially in the Yana-Indigirka and Kolyma lowlands (e.g., Tomirdiaro, 1996). These surfaces were considered to be former accumulation plains, composed of late Pleistocene Ice Complex deposits, cross-cut to varying extents by thermokarst basins. In this sense, Yedoma can also describe a periglacial relief type formed by thermokarst processes (Solov'ev, 1959).

Initially, the stratigraphic term 'Yedoma Suite' was adopted for middle Pleistocene horizons in the northeastern Siberian lowlands (Vas'kovsky, 1963). Based on cryolithological, paleoecological, and geochronological studies at the key site of Duvanny Yar on the lower Kolyma River (**Figure 1**), the stratigraphic position of the 'Yedoma Suite' was considered to be only late Pleistocene (Sher et al., 1987). The upper late Pleistocene horizon of Duvanny Yar represents the stratotype of the 'Yedoma Suite' (e.g., Zanina et al., 2011), recorded by a 40- to 50-m-thick Ice Complex sequence that is characterized by heterogeneous gray-brown sandy silt with a layered cryostructure and syngenetic ice wedges up to tens of meters high. The sediments contain grass roots and lenses of fine-grained plant detritus as well as paleosols (Zanina et al., 2011). Fossil teeth and bones of the late Pleistocene megafauna are common (Sher et al., 1979). Radiocarbon dates from Duvanny Yar suggest that much of the Ice Complex formed during the late Pleistocene from ca. 40 and 13 ka (^{14}C) BP (Vasil'chuk et al., 2001).

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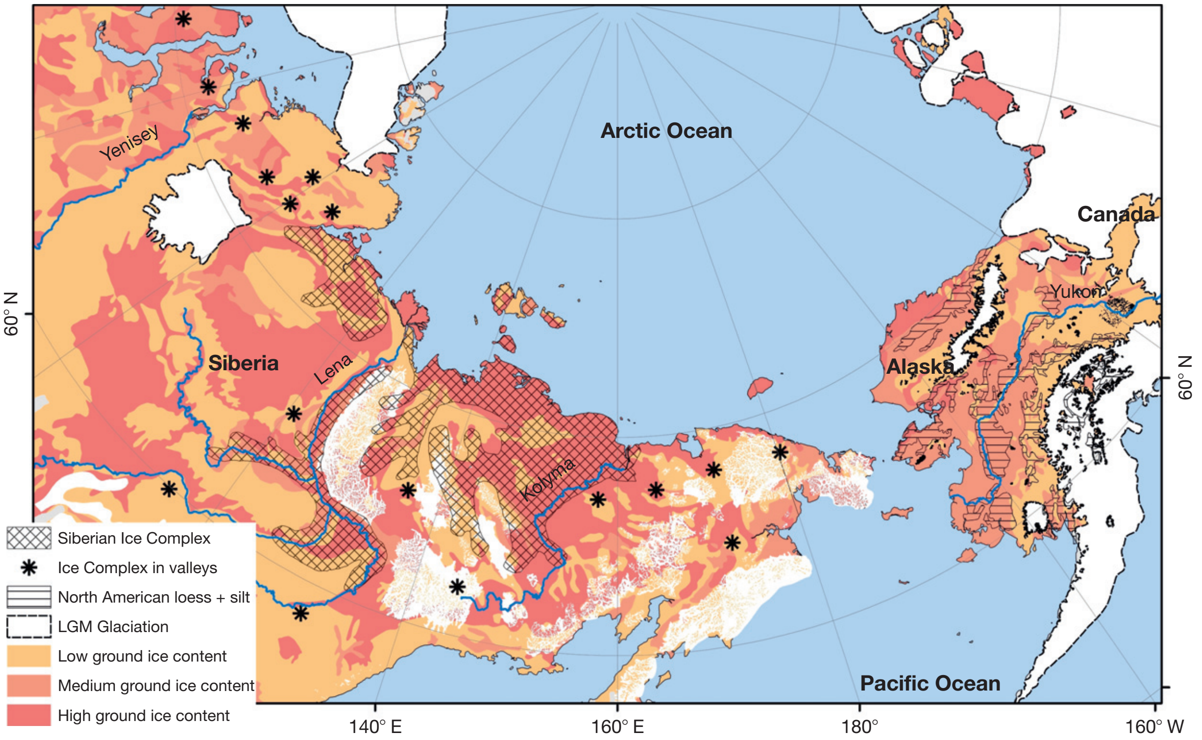

Figure 1 Distribution of ice-rich permafrost deposits in Arctic and Subarctic lowlands in the region of late Pleistocene Beringia (according to Romanovskii, 1993, for Siberian Ice Complex; Wolfe et al., 2009, for North American loess; Ehlers and Gibbard, 2003, for LGM Glaciation; and Brown et al., 1997, for ground ice content).

Figure 2 Syngenetic ice wedges with full and partial thaw surfaces. The presence of shoulders on the ice wedges (white arrows) indicates the position of the paleoactive layer and the nature of episodic sedimentation of the loessal silts on the surface of an ice-wedge polygonal ground network; to either side of the shoulders, some ice wedges are fully truncated at these levels. Sediments date to ca. 30 ka BP, Quartz Creek, Klondike area, central Yukon. Photo shows a vertical section ca. 5–6 m high. Photograph by D. Froese.

In North America, where the research history of ice-rich deposits is closely related to placer gold-mining activities, they are often given the name 'muck' as they are a common overburden for gold-bearing fluvial deposits (Fraser and Burn, 1997; Péwé, 1975). However, the term 'muck' originates from the gold mining vernacular and is generally not used in a strict genetic or stratigraphic sense, and thus, it is not restricted to late Pleistocene ice-rich deposits. For example, Péwé (1975) indicated that 'muck' can also encompass Holocene ice-rich silts, which would be inconsistent with Yedoma as commonly defined. In recent work, the term 'muck' is therefore not frequently used, but instead these deposits are typically referred to as simply ice-rich silts or perennially frozen silts, emphasizing both their typical grain size and the presence of permafrost.

In North America, syngenetic ice-rich silt deposits, thought to be broad equivalents to the Siberian examples, occur in lower segments of the Arctic Foothills, in the northern part of Seward Peninsula, in numerous areas in Interior Alaska (Kanevskiy et al., 2011), and the Klondike region of Yukon Territory (Froese et al., 2009). The Klondike sites, by virtue of the gold-mining activities, have created excellent exposures for study (Figure 2). Similar to the Russian examples, Yedoma deposits in Yukon and Alaska are dominated by silt-sized particles, abundant organic matter, ice-rich syngenetic permafrost, and ice wedges and may reach 40 m in thickness. These deposits, when wet, are commonly nearly black in color from the abundant organic matter. Perhaps their most distinctive property, however, is the pungent odor they give off from the incompletely decomposed organic matter that is exposed as they thaw. Although these deposits are largely of late Pleistocene age, the presence of distal, dateable volcanic ash (tephra) within some of them indicates a middle Pleistocene age (Froese et al., 2008, 2009; Reyes et al., 2010).

Following Sher (1997) and Kanevskiy et al. (2011), this article uses the term 'Yedoma' to describe ice-rich syngenetic permafrost that developed extensively under late Pleistocene cold-climate conditions in unglaciated regions of Eurasia and North America.

Distribution

Yedoma deposits are widely distributed across Beringia (Figure 1). In eastern Siberia, their presence in lowlands is reflected in the modern distribution of thermokarst lakes developed on ice-rich permafrost (Figure 3). Thermokarst depressions with lakes and thermoerosional valleys shape the modern lowland relief and dissect remnants of late Pleistocene accumulation plains into Yedoma hills and uplands. Other indicators of the presence of Yedoma deposits are thaw slumps on coastal bluffs several hundred meters wide and several tens of meters deep (Figure 4), lake shores, and river banks. These sites expose thermokarst mounds as well as large ice wedges 2–5 m wide and up to tens of meters high. These ice wedges, associated sediments, and thermokarst mounds (Figures 5 and 6) are parts of former polygonal ice-wedge systems that developed over long time periods. Generally, these exposures are formed by active thermoerosion and slumping of ice-rich permafrost, exposing sediments and ground ice in rapidly retreating steep bluffs and terraces, and allowing access to still-frozen sediments in vertical profiles.

The distribution of Yedoma in Northeast Siberia relates to a number of distinct geomorphological settings. One type of setting fringes low-elevation coastal mountains, which served as the main sediment sources for Yedoma. Heavy-mineral studies suggest a dominantly local origin for the sediments rather than long-distance transport of the silts which make up the main clastic component of Yedoma. Gently inclined

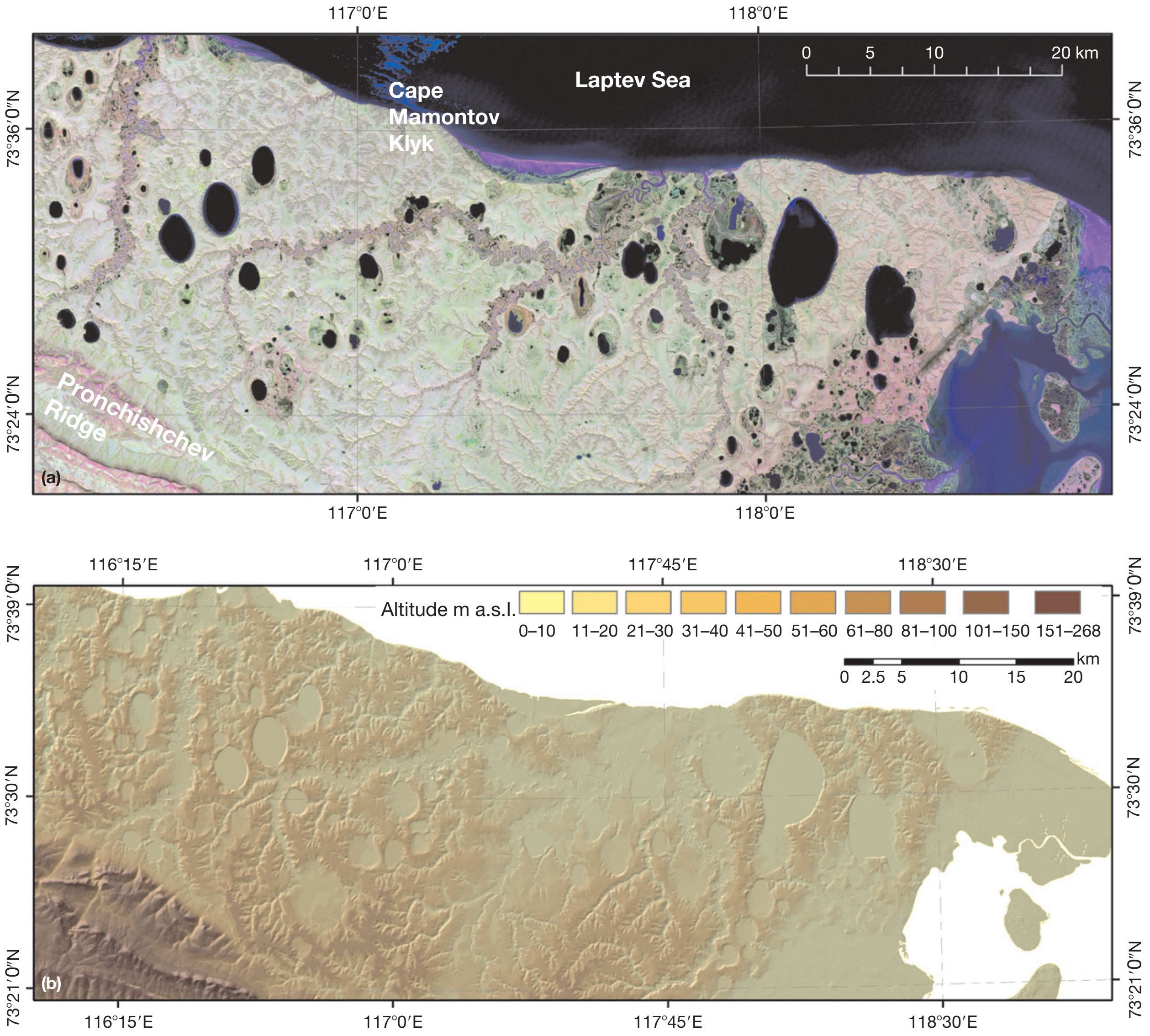

Figure 3 Yedoma landscape at the western Laptev Sea coastal plain in front of the Pronchishchev Ridge characterized by Yedoma hills, thermokarst basins, and numerous small-branched thermoerosional valley systems and larger river valleys: (a) satellite image Landsat-7 ETM + and (b) digital elevation model (adapted from Grosse et al., 2006).

Figure 4 Yedoma hill with a retrogressive thaw slump ca. 300 m long and 80 m wide at the southern coast of Bol'shoy Lyakhovsky Island (New Siberian Archipelago). The slump headwall exposing large ice wedges is ca. 25 m high. Photograph by S. Wetterich.

Figure 5 Syngenetic ice wedges and intrapolygon frozen sediment columns of a Yedoma exposure at the southern coast of Bol'shoy Lyakhovsky Island (New Siberian Archipelago). Photograph by V. Tumskoy. Person for scale.

Figure 6 Syngenetic ice wedges and intrapolygon frozen sediment columns of a Yedoma exposure in the Colville River Valley (Alaska North Slope). Photograph by G. Grosse. People for scale.

foreland accumulation plains underlain by widespread ice-wedge polygon systems were the original landscape for the accumulation of Yedoma deposits in the North Siberian lowlands during the late Pleistocene. A second geomorphologic setting in the hinterland of Yedoma areas comprises separate bedrock elevations (100–400 m high), for example, the granite domes on Bol'shoy Lyakhovsky Island (New Siberian Archipelago) and Cape Svyatoy Nos (Laptev Sea), and short fault ranges as found on Bel'kovsky, Stolbovoy, and Kotel'ny islands of the New Siberian Archipelago. These elevations are often shaped by cryoplanation terraces (Figure 7(a)) and framed by cryopediment areas, indicating strong periglacial weathering processes (Figure 7(b)). A third setting is found in extended lowland areas further away from mountain ranges. Although these distal areas are currently dominated by large and numerous thermokarst basins and lakes, Yedoma hills are commonly present between them, indicating their former widespread occurrence, such as in the Yana-Indigirka lowland. Yedoma deposits are also present in Central Yakutia in terraces of the lower parts of large mountain valleys.

All aggradational landscape types where Yedoma occurs are characterized by large, relatively flat surfaces with low hydrological gradients that are conducive to the long-term formation of syngenetic ice-wedge polygon systems. Poorly developed drainage in the late Pleistocene environment of Beringia, with its cold-arid climate, was presumably an important factor for Yedoma formation. It is likely that accumulation of Yedoma deposits also took place on vast areas of the Beringian shelf that were exposed during the late Pleistocene (Romanovskii et al., 2000).

Broad equivalents to Siberian Yedoma also occur in the Arctic and Subarctic regions of unglaciated Alaska and Yukon, or eastern Beringia. In tundra areas of northern Alaska,

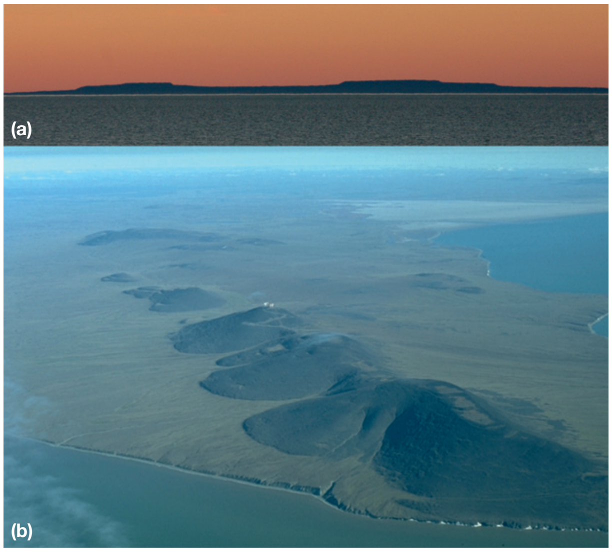

Figure 7 Hinterland of Ice Complex accumulation areas: (a) Cryoplanation terraces of the Cretaceous granite dome at Cape Shalaurova on Bol'shoy Lyakhovsky Island, New Siberian Archipelago, shaped by intense periglacial weathering, and (b) Cretaceous granite domes on Cape Svyatoy Nos, Laptev Sea, surrounded by cryopediments. Photographs by S. Wetterich and H. Meyer, AWI Potsdam.

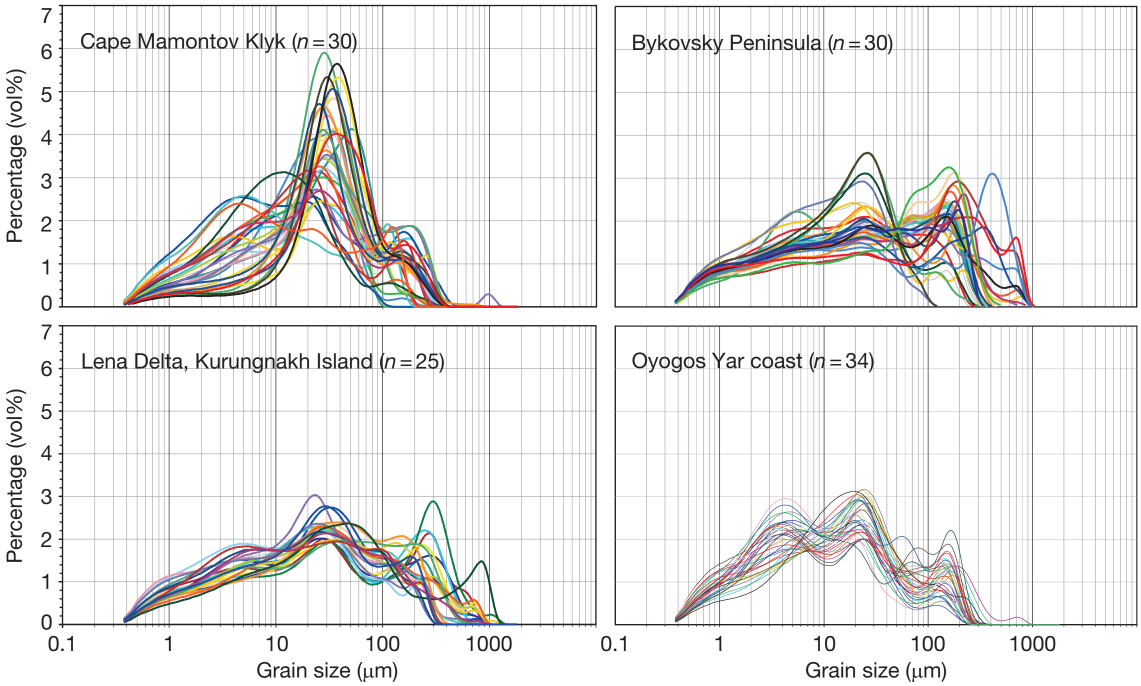

Figure 8 Grain-size distribution curves from Yedoma deposits of different sites in the Laptev Sea region according to Schirrmeister et al. (2011b).

Yedoma is readily recognized where deep thermokarst lake basins are inset into thick ice-rich permafrost. In areas further south, within the modern boreal forest, Yedoma is obscured by forest cover. In general, the interior of Yukon and Alaska includes Yedoma deposits in areas of greater relief than their counterparts in Siberia, and Yedoma occurs further south into the present-day discontinuous permafrost zone (50–90% underlain by permafrost). In the Fairbanks and Klondike regions, where these deposits are best characterized, their distribution strongly reflects local site conditions. In these areas, Yedoma is found on north- and east-facing slopes and within narrow valleys along hillslopes.

Cryolithology

Yedoma sequences include buried cryosols marked by brownish horizons as well as the inclusion of organic matter and peat (**Figures 5 and 6**). Evidence of past cryoturbation, highlighted by the presence of the organic matter, is common. The poorly sorted clastic sediments range in grain size dominantly from silt to fine-grained sand and sometimes contain coarser-grained sand and gravel (Trask sorting 1.5–9, mean grain size 10–300 μm). Grain-size characteristics differ from site to site as well as within horizons, but modal grain size of nearly all samples is within the silt and fine sand range (Fraser and Burn, 1997; Sanborn et al., 2006). The presence of multimode grain-size distributions (**Figure 8**) suggests a range of transport processes and underscores the importance of redeposition of silts with coarser grain sizes. Heavy-mineral analyses of Siberian Yedoma suggest significant differences in detrital composition between sites, indicating different local sediment sources of the hinterland (Schirrmeister et al., 2011b).

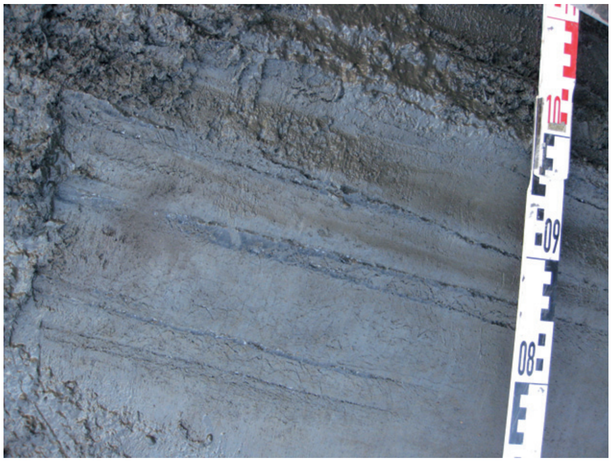

Figure 9 Mineral sediment with ice bands and fine lens-like reticulate cryostructures and some brownish plant detritus-rich patches typical of Yedoma deposits from the Buor Khaya Peninsula, Laptev Sea. Photograph by J. Strauss, AWI Potsdam.

Cryogenic structures in Yedoma deposits, in particular, the presence of syngenetic ice wedges, are similar at most study sites. Ice wedges often have pronounced shoulders and partial thaw surfaces, indicating the episodic nature of sedimentation and permafrost aggradation with varying active-layer depth on the polygonal ground network (**Figure 2**). Thin horizontal ice lenses or net-like reticulated ice veins subdivided by up to 2–4-cm-thick ice bands are common (**Figure 9**); they indicate enrichment in segregated ice near the permafrost table under subaerial conditions, including inundated polygonal ponds, by a slowly aggrading soil surface, changing active-layer thickness, and freezing under poorly drained conditions (e.g., Romanovskii, 1977).

The frozen sediment sequences commonly contain excess ice, with gravimetric ice contents (ratio of the mass of liquid water and ice in a sample to the dry mass of the sample, expressed as a mass percentage, van Everdingen, 1998) of 70 to >100 wt% (Schirrmeister et al., 2011b); this corresponds to an ice content of 30 to more than 60 wt% for the sediment columns of Yedoma exposures. Considering that ice wedges account for about 50% by volume of most Yedoma sequences, the total volumetric ground ice content likely ranges from 65 to 90%.

Figure 10 Graminoid-rich paleosol with roots overlying ice wedge, marking the paleoactive layer when the soil was formed. The paleosol is cross-cut by a syngenetic ice wedge (vertical arrow at left) and includes beds of Dominion Creek tephra (82 ± 9 ka; horizontal arrow), marking early MIS 4 cold conditions in Yukon. Ice axe is 80 cm long. Adapted from Froese et al. (2009).

Stable isotope signatures of ground ice ($\delta^{18}O$, δD, d-excess) are used as a proxy for winter paleotemperatures (the most negative $\delta^{18}O$ and δD values reflect the coldest temperatures) and moisture sources. Late Pleistocene ice-wedge ice reflects very cold winter temperatures and moisture sources that are isotopically distinct from Holocene values (e.g., Meyer et al., 2002; Vasil'chuk, 1992; Wetterich et al., 2011).

Total organic carbon (TOC) content in Yedoma deposits, based on more than 700 analyses from 14 Siberian sites, is variable (<1 to >20 wt%) and relatively high (site-specific averages from 1.2 to 4.8 wt%; Schirrmeister et al., 2011a,b). Woody macrofossils and peat are present, along with numerous small filamentous rootlets and dispersed organic detritus. Detailed studies of paleosols within Yedoma deposits indicate that much of the organic matter accreted as root detritus from graminoid vegetation under periglacial conditions (**Figure 10**; Sanborn et al., 2006). Thaw unconformities truncating ice wedges, syngenetic ice wedges with pronounced shoulders (**Figure 2**), and cryoturbated paleosols, all record episodic changes in sedimentation and paleoactive-layer depths. The $\delta^{13}C$ values of bulk organic material range from about −29 to −24‰, indicating that only freshwater aquatic and subaerial terrestrial environments contributed this material to the formation of Yedoma deposits (Schirrmeister et al., 2011b). Variations in TOC content, C/N ratio, and $\delta^{13}C$ values (**Figure 11**) relate to changes in bioproductivity, intensity and character of cryosol formation, and different degrees of organic matter

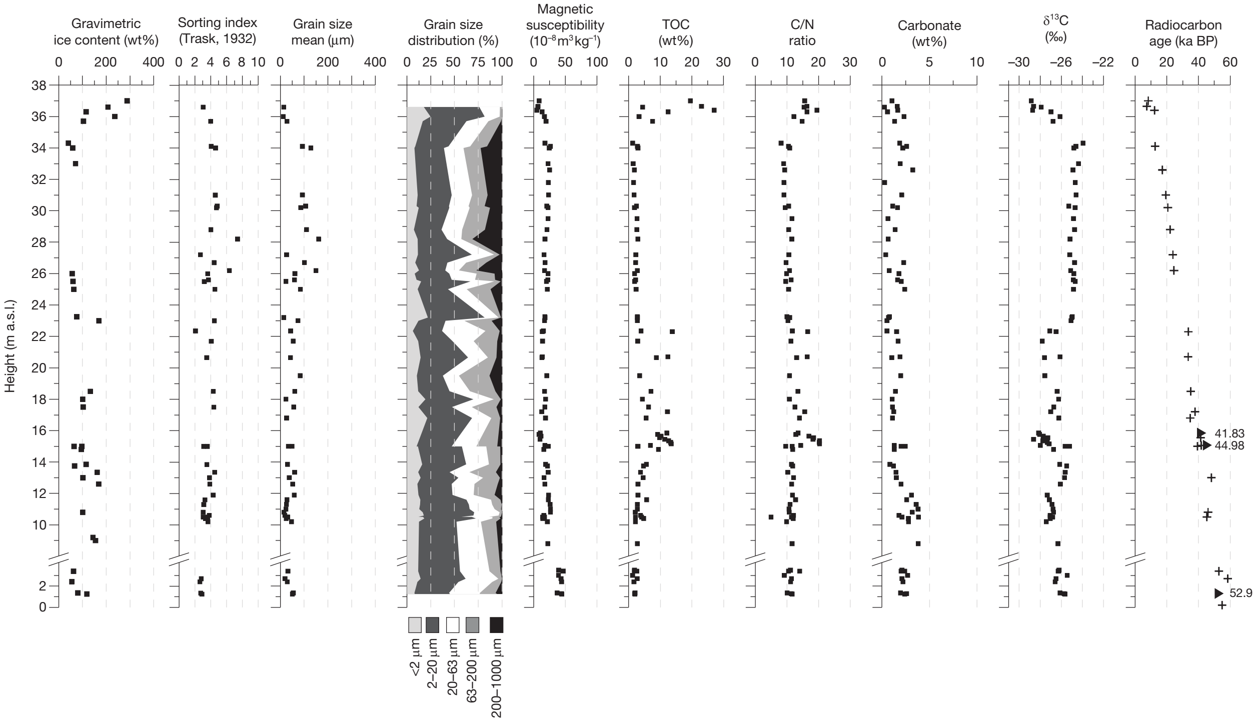

Figure 11 Compilation of cryolithological parameters of the Yedoma sequence and the Holocene cover from Bykovsky Peninsula, Laptev Sea according to Schirrmeister et al. (2011b).

decomposition, as well as variations in plant associations. High TOC contents, high C/N ratios, and low δ^{13}C values reflect less-decomposed organic matter under anaerobic conditions, which were characteristic of the interstadial Marine Isotope Stage (MIS) 3. During cold stages, such as MIS 2, TOC was less variable and generally low, indicating more stable environments with reduced bioproductivity and low C/N ratios. High δ^{13}C values reflect relatively dry, aerobic conditions.

Fossils and Paleoenvironmental Archives

Yedoma deposits are among the most productive hosts for preserving Pleistocene fossils in the northern hemisphere (Guthrie, 1990), and because of the presence of permafrost, they provide exceptional preservation conditions, unequaled elsewhere (Shapiro and Cooper, 2003). Intense research over the past decades has already been undertaken to use the fossil record to describe past environments of Beringia through a combination of proxies such as pollen, soils, plant macrofossils, insects, mammals, ostracods, or testate amoebae for quantitative and qualitative reconstructions (e.g., Sher et al., 2005; Wetterich et al., 2008; Zazula et al., 2007).

Across Alaska, Yukon, and Siberia, the mammoth fauna remains preserved in Yedoma are dominated by mammoth (*Mammuthus primigenius*), horse (*Equus caballus*), bison (*Bison priscus*), and caribou (*Rangifer tarandus*). Fossils of less common species are recovered occasionally, including camel (*Camelops hesternus*), musk ox (*Ovibos pallantis*), woolly rhino (*Coelodonta antiquitatis*), and saiga antelope (*Saiga* sp.). Carnivores such as cave lion (*Panthera leo spelaea*), short-faced bear (*Arctodus simus*), and wolf (*Canis lupus*) are also rare. Some of these species occurred only on one side of the Bering Land Bridge (such as the wholly rhino in Siberia, and camel and short-faced bear in eastern Beringia), while others were widely distributed across Beringia. The grazing fauna, much of it collected from detrital fossils recovered from Yedoma exposures across Beringia, have been linked to late Pleistocene environments of the region through radiocarbon dating (e.g., Sher et al., 2005). Mummified or freeze-dried carcasses recovered from these sites, although rare, highlight the role of permafrost in preserving the late Pleistocene paleontological record (Guthrie, 1990; Shapiro and Cooper, 2003).

Paleobotanical materials are equally well preserved within Yedoma and, in particular, have become better understood through plant macrofossils recovered from these deposits. For example, in eastern Beringia, plant macrofossils from Arctic ground squirrel (*Spermophilus parryii*) nests, seed caches, and burrows are dominated by grasses, dryland sedges, sage, and a wide variety of flowering forbs (e.g., Zazula et al., 2007). Together, these plants indicate open grass- and forb-rich steppe tundra in eastern Beringia, developed on largely well-drained substrates during MIS 2 (Froese et al., 2009).

Palynological analyses from the Yedoma indicate a dominance of herbs (e.g., *Artemisia*, Caryophyllaceae, Asteraceae), grasses (e.g., Poacea, Cyperacea), and to a lesser extent, dwarf shrubs (e.g., *Salix*, *Alnus*, *Betula*). According to Andreev et al. (2011), the period of Yedoma formation in Siberia was characterized by sparse grass-sedge tundra growing in an extremely cold and dry climate during MIS 4, tundra-steppe vegetation with higher productivity in a more moderate and humid climate during MIS 3, and sparse grass-tundra present in the cooler and drier climate of MIS 2. Nevertheless, the presence of algal spores and remains of other aquatic organisms (e.g., hydrophytes, ostracods) found in many samples indicates the existence of small freshwater ponds in low-center polygons. In addition, spores from dung-inhabiting fungi indicate the widespread occurrence of mammoth fauna species during the time of Yedoma formation (Sher et al., 2005). Floral and faunal communities that existed when Yedoma formed disappeared approximately at the Pleistocene–Holocene transition. The paleoecosystem associated with Yedoma, often called Mammoth Steppe or steppe tundra in eastern Beringia (e.g., Guthrie, 1990) or Tundra-Steppe in western Beringia (e.g., Yurtsev, 1982), combined elements found in both cold tundra and dry steppe environments. The climate was more continental in the late Pleistocene Arctic than today, and reconstructions from Siberia indicate colder winters and warmer summers, suggesting stronger seasonal gradients in temperature and precipitation (e.g., Andreev et al., 2011). Because of the polygonal patterned ground relief, the tundra-steppe landscape was characterized by a patchwork-like distribution of vegetation communities at a local scale.

Formation Processes

Yedoma in Northeast Siberia (Western Beringia)

The processes that formed Yedoma in western Beringia are disputed, and some differences of interpretation remain between researchers of western and eastern Beringia. These differences largely reflect the prominence attributed to eolian processes, and in particular, the interpretation of the silts as being primarily loess by researchers in Yukon and Alaska. In contrast, workers in Siberia have, in recent decades, proposed several hypotheses about the origin of Yedoma, including alluvial, glaciolacustrine, deltaic, proluvial and colluvial, cryogenic-eolian, nival, and polygenetic processes (for an overview, see Schirrmeister et al., 2011b). Zhestkova (1982) and Sher (1997) proposed a polygenetic origin in which Yedoma deposits accumulated under different sedimentation regimes, but were largely controlled by similar landscape and relief characteristics, climate conditions, periglacial processes, and sediment sources. An overarching similarity is the presence of large syngenetic ice wedges and remains of the late Pleistocene mammoth fauna and tundra-steppe flora.

A broad concept of Yedoma formation that combines processes of cryogenic weathering, material transport and accumulation, and relief shaping under cold-arid climate conditions was proposed by Kunitsky et al. (2002). According to this cryolithogenetic concept (cryolithogenesis: formation of sedimentary materials in the permafrost regions, according to Yershov, 2004), Yedoma represents a characteristic periglacial facies whose formation is controlled by the interaction of several climatic, landscape, and geological preconditions typical for nonglaciated Arctic lowlands (**Figure 12**). Initially, mixtures of windblown snow, plant, and fine-grained mineral detritus accumulated in numerous perennial snow fields that were topographically protected not only among hills and low mountain ranges, but also on terrain edges (e.g., steep slopes, valleys, and cryoplanation terraces; Figure 12(a)). Around their margins and beneath the snowfields, intense freeze-thaw cycles associated with wet conditions (frost weathering) formed additional fine-grained sediment (Figure 12(b); Konishchev and Rogov, 1993; Kunitsky et al., 2002). Some of this sediment and associated organic matter was transported downslope by runoff from seasonal meltwater (Figure 12(c)). This fine-grained detritus was then transported further by a variety of processes (alluvial, proluvial, colluvial, slope wash, solifluction, permafrost creep, and eolian) to foreland plains, cryopediments, or large alluvial fans. As a result, different types of Yedoma deposits accumulated, with variable grain-size distributions, dependent on local environmental conditions. As sediment aggraded in flat accumulation areas, polygonal ice-wedge systems developed syngenetically (Figure 12(d)). Over thousands of years, these recurrent processes of snowfield accumulation, snow melt, and meltwater transport and secondary sediment transport processes led to the accumulation of thick Yedoma deposits on wide plains. On a smaller scale, similar phenomena can be observed today on numerous slopes and terrain steps in northeastern Siberia, where nivation is an essential geomorphological factor (Kunitsky et al., 2002).

The typical Ice Complex formation therefore consisted of several concurrent cryogenic processes, including sediment accumulation and freezing, ice segregation, syngenetic ice-wedge growth, sediment reworking, peat aggradation, cryosol formation, and cryoturbation, all promoted by enduring and harsh continental climate conditions. The formation of large polygonal systems of ice wedges and thick continuous sequences of frozen deposits recorded the persistence of accumulation areas that were stable and poorly drained, and had low topographic gradients. In short, the proposed cryolithogenic model integrates several previous concepts and emphasizes the polygenetic character of Yedoma deposits. It also identifies several sediment sources, weathering processes, and pathways by which sediments in typical periglacial landscapes can build up such fine-grained ice-rich deposits under extreme cold-climate conditions.

In Siberia, Yedoma deposits predominantly date from MIS 3 and 2. The initiation of Yedoma formation, based on radiocarbon dates, varies between about >55 ka BP on the New Siberian Islands and 27 ka BP at the western Laptev Sea coast. The latest deposition is dated between 28 ka BP on the New Siberian Islands and 17–13 ka BP in the western Laptev Sea. Unconformities within Yedoma sequences are common, encompassing up to 20 ka, and likely record thermokarst and thermoerosion processes. In general, the basal layers of Yedoma contrast sharply with the underlying deposits – often fluvial sands with peat layers, or loess-like flood plain deposits – dated by ^{230}Th/^{234}U and luminescence to an age of 100–60 ka (Schirrmeister et al., 2011b). The upper boundary of Yedoma is characterized by a thaw unconformity and separates locally confined Holocene deposits on top of Yedoma hills.

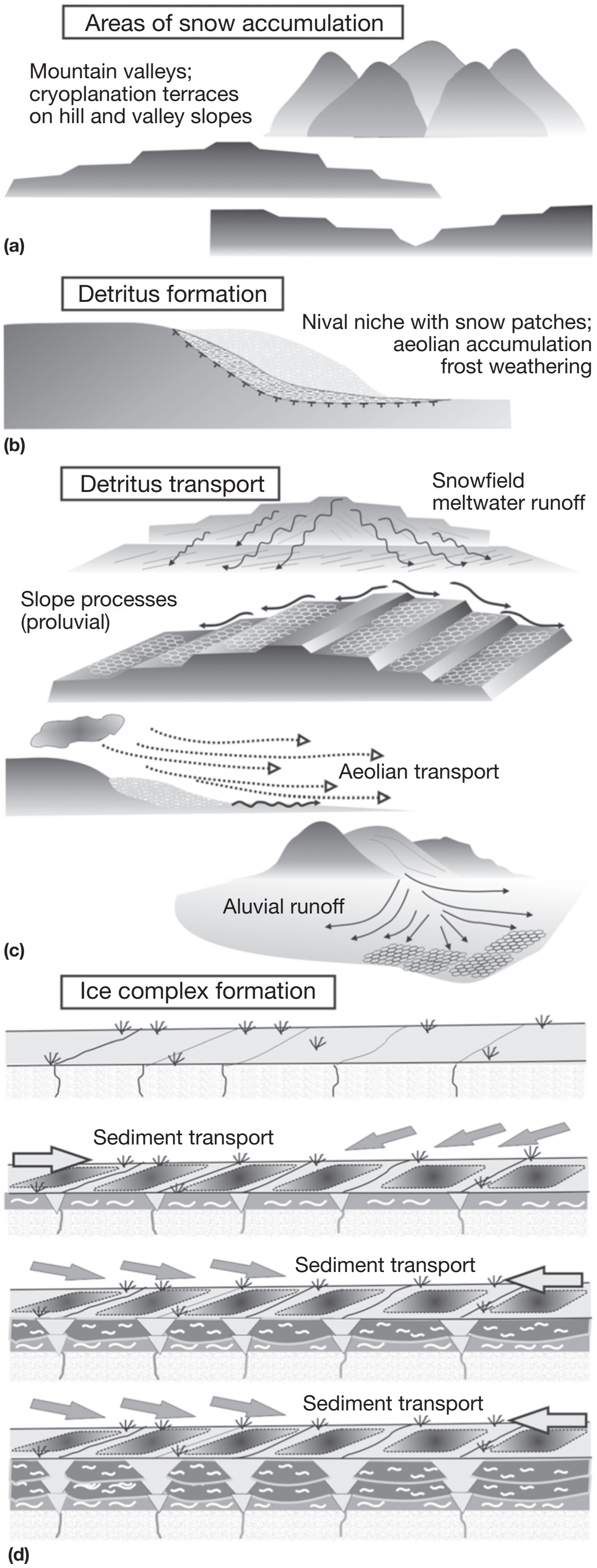

Figure 12 Landscape characteristics and development stages (a–d) during late Pleistocene Yedoma formation in Siberian Arctic lowlands (according to Schirrmeister et al. (2011b)). The arrows in part d indicate the various types of sediment transport described in the text (e.g., alluvial, proluvial, colluvial, eolian).

Alaska and Yukon 'Muck': Eastern Beringia Equivalents of Yedoma

As in Siberia, early work in northwestern North America was controversial, and workers argued that the silts, or later 'muck' deposits, in Alaska and Yukon may have been produced by lacustrine, estuarine, eolian, residual weathering or fluvial processes, or their interaction (e.g., Taber, 1943). Following work by Péwé (1955), who argued strongly for an eolian origin, all workers have accepted a predominantly eolian origin for these sediments. In fact, no other ideas have been seriously entertained since the late 1950s. This likely reflects differences in the overall setting of these deposits, and perhaps a more generous consideration of loess in the North American literature relative to the concept of Yedoma in Siberia.

Loess is the most widely distributed surficial material in the nonglaciated areas of Alaska and Yukon (Péwé, 1975). Many of the areas with Yedoma in North America are associated with uplands and valleys, and to a lesser degree with extensive accumulation plains similar to the North Siberian shelves, resulting in the common differentiation into 'upland silt' and valley-bottom 'muck' deposits. These differences have been important in the development of ideas concerning the genesis of these deposits. Upland silts mantle hilltop exposures and are commonly found on alluvial terraces or sheltered behind bedrock obstacles, and have been unambiguously interpreted as loess (Muhs et al., 2008; Péwé, 1975). However, it should be noted that these upland silt deposits are not ice-rich and differ significantly from Yedoma deposits as described in valley-bottom settings (e.g., Bray et al., 2006; Froese et al., 2009; Péwé, 1975).

In Péwé's original work and that of earlier researchers, the valley-bottom 'muck' deposits were considered to be 'reworked loess' derived from mixing of upland silts with organic material, accumulated syngenetically with permafrost growth in valley-bottom settings, and interbedded with primary airfall-derived loess. At some sites, well-developed bedding and sandy lenses indicate fluvial influence during deposition, but these beds are relatively minor at most sites. Commonly, the loess-adjective 'loessal' is used to describe material dominated by coarse silt and fine sand grain sizes, much of which is likely primary airfall loess, though evidence of secondary, short-distance redeposition by snowmelt or sheet flows may also be present (e.g., Froese et al., 2009; Sanborn et al., 2006). Loess from MIS 2 is relatively thin on upland sites (Muhs et al., 2008), whereas thick accumulations dating to that time are present in valley-bottom sites (Guthrie, 1990; Péwé et al., 1975). This suggests that either the sediments accumulated thickly in valley bottoms or these valleys acted as sediment traps, while upland surfaces, with sparse vegetation cover and, thus, low friction, may have been bypassed by these sediments (cf. Muhs et al., 2008).

The degree of mixing of the valley-bottom 'muck' deposits has been an open question, and throughout the 1970s and 1980s likely discouraged much paleoenvironmental work on these sites. However, increasingly large numbers of radiocarbon ages, typically on plant macrofossils, show few inversions in sedimentary sequences and argue for the stratigraphic coherence of these archives and their suitability for paleoenvironmental reconstruction (Froese et al., 2009; Zazula et al., 2007).

A detailed study of paleosols within Yedoma deposits in the Klondike area, correlated between sites by distinctive distal tephras dating to MIS 2 and 4, confirms a consistent record of sedimentation, with syngenetic permafrost aggradation interrupted by periods of soil development between sites in valleys 20 km apart (Sanborn et al., 2006). These authors showed that the valley-bottom silts underwent only limited weathering. Micromorphological evidence from the soils indicated that the organic matter within the sediments, primarily fine graminoid detritus, accreted mainly by below-ground inputs of root detritus as the surface sediments aggraded with loessal inputs (Sanborn et al., 2006). Importantly, the correlation of these consistent soil properties and timing of loess and syngenetic permafrost aggradation argue for regional controls on sedimentation rather than local site conditions.

In eastern Beringia, Yedoma formation largely dates to the late Pleistocene. Péwé (1975) argued for a consistent climatically driven period of ice-rich loessal sedimentation, which he named the Goldstream Formation. This formation postdated a significant thaw of permafrost during the last interglacial (MIS 5e) and likely dates through the Wisconsinan. Subsequent workers have dropped the formal definition, but based on radiocarbon ages and tephrochronology, most of the Yedoma deposits date to late MIS 3 and MIS 2. Radiocarbon ages are fairly consistent between interior Yukon and Alaska for a major period of Yedoma development during MIS 2, beginning around 30 ka BP and continuing until ca. 11.5 ka BP (Fraser and Burn, 1997; Hamilton et al., 1988; Zazula et al., 2007). A pronounced unconformity at ca. 10 ka BP marks the degradation of these surfaces and is characterized by organic-detritus-rich sedimentation above the thaw unconformity sediments (Fraser and Burn, 1997). Earlier Yedoma sedimentation during MIS 4 is well documented in central Yukon through the presence of the Sheep Creek-K tephra (ca. 80 ka; Froese et al., 2009). At each time slice where these deposits are recognized, and paleoenvironmental reconstructions are available, the reconstructions indicate the aggradation of the loessal silts in an open, grass- and forb-rich steppe-tundra community, suggesting that these deposits are a recurrent feature of cold stages during the Pleistocene of Beringia (Froese et al., 2009).

In Alaska, more recent studies of Yedoma deposits have focused on the well-known CRREL permafrost tunnel near Fairbanks that exposed fine-grained frozen sequences containing syngenetic ice wedges (Bray et al., 2006; Hamilton et al. 1988; Kanevskiy et al. 2008; Shur et al., 2004). A Yedoma site with very similar characteristics to Northeast Siberian sites is reported from the Itkillik River in the Arctic Foothills (Kanevskiy et al. 2011). These Yedoma deposits cover the period between >48 and 14.3 ka BP.

Conclusion

During the late Pleistocene cold stages in Beringia, Yedoma deposition was favored by a cold, dry climate that precluded widespread glaciation of lowlands and low mountain ranges, and resulted in intense periglacial weathering, sediment transport, accumulation, and syngenetic permafrost growth for several tens of thousands of years. The overall characteristics of Yedoma in Siberia (West Beringia) and North America (East Beringia) are given in **Table 1**. The formation of large polygonal ice-wedge systems and sequences of ice-rich silty deposits tens of meters thick was closely related to the persistence of stable, poorly drained, and flat to gently sloping accumulation areas in the lowlands of Siberia and northern Alaska. Within the interior of Yukon and Alaska, Yedoma deposits are more

Table 1 Typical features of the Yedoma deposits

	West Beringia (Siberia)	*East Beringia (Alaska and Yukon)*
Formation age	80–12 ka BP	
Stratigraphy	MIS 4–MIS 2	
Terminology	Ice Complex, Yedoma Suite	'Muck' deposits or syngenetic late Pleistocene perennially frozen ice-rich silts
Landscape	Stable, poorly drained areas with low topographic gradient	
Distribution	East Siberian Arctic lowlands and large river valleys, foothills	Foothills and lowlands in northern Alaska; north easterly exposures and within narrow valleys in interior Yukon and Alaska
Sediment	Poorly sorted, organic-rich silt and silty sand	Organic-rich silt and silty sand; largely related to eolian sedimentation
Ground ice	Ice saturated or supersaturated, syngenetic ice wedges, segregation ice	
Paleoclimate	Highly continental, cold arid	
Paleoecology	Tundra steppe/Mammoth steppe, cryoxeric vegetation, Mammoth Fauna	
Genesis	Syngenetic permafrost of multiple origins depending on region: nival, alluvial, proluvial–colluvial, sheet flow, soil creep, or eolian sedimentation	Largely eolian sedimentation (airfall loess) with syngenetic permafrost, but locally, other deposits may be interbedded

variable, reflecting the variation of local site conditions with topography. Paleontological reconstructions of the environment during Yedoma formation indicate the presence of cryoxeric steppe-tundra communities. Yedoma deposits are defined by distinct cryolithological and sedimentological characteristics, and are preserved today in elevated erosional remnants in thermokarst landscapes termed Yedoma hills in Siberia, while in the previously unglaciated region of Alaska and the Yukon Territory, these deposits are found mostly in foothill regions, on north-facing slopes, and as fill in narrow valleys. In summary, Yedoma must be considered as a special type of periglacial or cryogenic facies typical of cold stages of late Pleistocene Beringia.

See also: **Paleoclimate Reconstruction:** Pliocene Environments. **Plant Macrofossil Records:** Arctic Eurasia.

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