# Yedoma: Late Pleistocene ice-rich syngenetic permafrost of Beringia

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## Abstract

Yedoma is a permafrost deposit widely distributed across the Arctic and found exclusively within the unglaciated regions in northern Siberia, Alaska, and the Yukon, which are the core regions of Beringia. Yedoma deposits accumulated during the late Pleistocene Stage and are characterized by their predominantly fine-grained texture and association with syngenetic permafrost formation. The very high ground ice content is most commonly present as pore ice and wedge ice that formed contemporaneously with sediment deposition. In the last decade, research has transitioned from debates about the origin of the Yedoma deposits towards increasing attention on the large carbon and nitrogen pools in Yedoma, their vulnerability to thaw, and increasing mobilization as the climate has warmed across the Arctic. In addition to classical cryolithological and sedimentological research, new methods such as stable isotope paleoclimate reconstruction and ancient sedimentary DNA studies have been more widely applied to better understand the characteristics of Yedoma deposits and helped emphasize their value as archives of Quaternary climate and paleoecological conditions during Ice Age Beringia.

## Keywords

Alaska; Biogeochemistry; Canada; Cryolithology; Geochronology; Paleoenvironment; Permafrost; Quaternary; Siberia; Stable isotopes; Yedoma definitions; Yedoma distribution

## Key points

- Definitions of the Yedoma term.
- Distribution of late Pleistocene Yedoma Ice Complex.
- Characteristics of the late Pleistocene Yedoma Ice Complex in Russia, Alaska, and Canada.
- Cryolithological and paleoenvironmental study results.
- New directions of Yedoma research.

## Introduction

Scientific interest in Yedoma has grown rapidly over the last decade because of the increasing evidence of thaw affecting these deposits in a rapidly warming Arctic and the increased vulnerability of Yedoma permafrost carbon to mobilization. This accelerating transformation of the Yedoma regions has resulted in shifting objectives of Yedoma studies. Along with the growing sophistication of traditional paleoenvironmental studies, several new approaches have been introduced. As a result, Yedoma research is expanding in both the number of studies and the variety of methods applied in the decade following the publication of the second edition of the Encyclopedia of Quaternary Science (Schirrmeister et al., 2013). At the time of writing, in late 2023, nearly 300 publications about Yedoma studies, mostly in English and Russian, have appeared since the last edition.

## Historical use of Ice Complex and Yedoma

Solov'ev (1959) first defined the term 'Ice Complex' as frozen deposits of various age, composition, genesis, and thickness containing numerous ice wedges. Ice Complex deposits of Late Pleistocene age are often referred to as 'Yedoma', or formally as the 'Yedoma Ice Complex' to distinguish them stratigraphically from deposits of older Ice Complexes. Yedoma deposits are widely distributed on the East Siberian coastal plains (Lena–-Anabar, Yana–-Indigirka, and Kolyma lowlands) as well as on the New Siberian Archipelago (Fig. 1). However, they also occur along large river valleys in more southerly regions of East Siberia and at higher altitudes of 200 to 600 m above sea level (asl) in Alaska and the Yukon Territory of Canada.

According to Sher (1997), at least three different meanings of the term ''Yedoma'' are distinguished in the original Russian literature:

(1) A 'Yedoma surface' in the geomorphic sense describes hills separated by thermokarst depressions and thermo-erosional valleys in northeastern Siberian lowlands. These surfaces were considered former accumulation plains built of the Late Pleistocene Yedoma Ice Complex.
(2) The 'Yedoma Suite'in the formal, stratigraphic sense; radiocarbon ages suggest that many of the Yedoma Ice-Complex sequences formed during the Late Pleistocene from ca. 60 and 13 ka BP, during marine isotope stages (MIS) 4 to –2.
(3) The 'Yedoma Ice Complex' in the cryolithological sense implies a special kind of frozen sediment widely distributed in Beringia. This usage is the one adopted in this chapter, encompassing distinctive ice-rich silt and silty sand penetrated by large syngenetic ice wedges, resulting from sedimentation and syngenetic freezing and driven by certain climatic and environmental conditions across Beringia during the Late Pleistocene.

Based on cryolithological, paleoecological, and geochronological studies at the key site of Duvanny Yar on the lower Kolyma River, the stratigraphic position of the 'Yedoma Suite' was considered Late Pleistocene (Sher et al., 1987). The upper, Late Pleistocene horizon of Duvanny Yar represents the stratotype of the 'Yedoma Suite', recorded by a 40- to 50-m-thick sequence characterized by heterogeneous gray-brown sandy silt with a layered cryostructure and syngenetic ice wedges up to tens of meters high and several

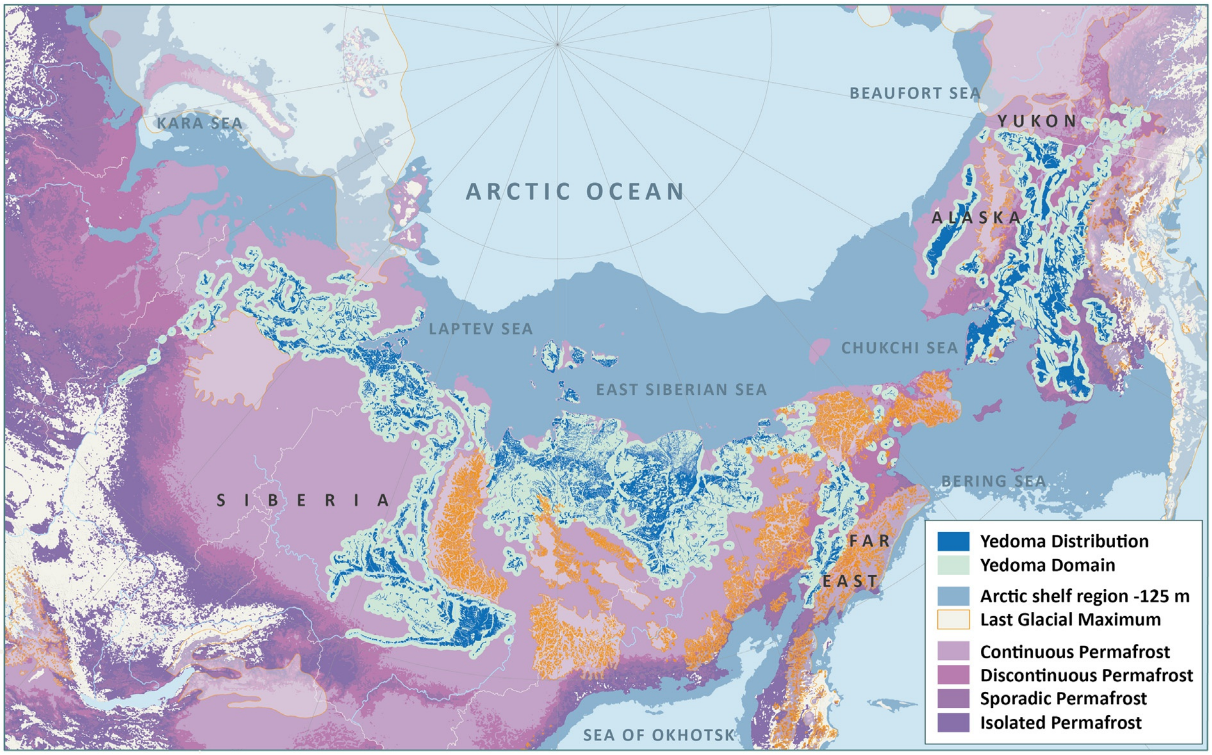


**Fig. 1** Distribution of Yedoma Ice Complex deposits and the Yedoma domain in the Siberian and North American Arctic and Subarctic (according to Strauss et al., 2021, 2022a). Permafrost extent (Obu et al., 2018), LGM glaciation Ehlers et al. (2011), and Arctic shelf areas (Beringia) based on a 125 m sea-level low stand bathymetric data from ETOPO2 (2006) are shown for context. The map was compiled by Sebastian Laboor (AWI).

meters wide (Murton et al., 2015). The sediments contain plant remains mostly as grassroots and lenses of fine-grained plant detritus as well as paleosols. Bones and teeth of Late Pleistocene megafauna are common in this deposit.

Similar ice-rich and largely fine-grained Yedoma Ice Complex deposits are widely distributed in Arctic and sub-Arctic Beringia and partly beyond and may locally exceed 50 m in thickness. The deposits, owing to their syngenetic freezing and the long-term presence of permafrost, preserve a diversity of exceptional paleoenvironmental archives, including proxies such as fossils, ancient DNA, and relict ice, and host a globally significant and potentially vulnerable reservoir of organic compounds (see entry on Organic matter storage and vulnerability in the permafrost domain, Strauss et al., 2024a). Here, we provide insight into the history of Yedoma research, terminology, and important properties, present modern ideas on the formation of these ice-rich sediments, and summarize newly applied methods and results.

## Yedoma Ice-Complex distribution

The deposits of the Yedoma Ice Complex are widely distributed across Beringia and even beyond. Beringia is considered to extend from the Taymyr Peninsula through eastern Siberia and Alaska to the Yukon Territory, united by aspects of the existing Late Pleistocene 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, as well as local mountain glaciation to the south (Fig. 1). Extreme continental climate conditions during the Last Glacial Maximum (LGM) are related to the widespread exposure of the broad continental shelf of the Arctic Ocean during glacial sea-level low stands and a likely perennial Arctic sea-ice cover. Due to the lack of widespread glaciation, much of Beringia preserves an exceptional sedimentary record of Late Pleistocene environmental change and periglacial conditions.

Grosse et al. (2013) published a map of the distribution of Late Pleistocene ice-rich syngenetic permafrost of the Yedoma Ice Complex in east and central Siberia. Strauss et al. (2021, 2022a) estimated the current, pan-Arctic Yedoma area. They quantified the Yedoma domain—a region that includes Yedoma remnants, drained thermokarst lake basins, and thermo-erosional valleys formed due to Yedoma degradation—as occupying a total land area of $\sim$2.587,000 km$^2$ of the circum-Arctic and sub-Arctic (Fig. 1). Within the Yedoma domain region, the area underlain by Yedoma Ice Complex deposits is $\sim$480,000 km$^2$, with the largest area in north-eastern Siberia (81%) and the smallest in North America (19%) (Fig. 1). Yedoma area is located within the tundra and taiga zones (35% and 65%, respectively). Due to the highly dissected relief of Yedoma landscapes by thermokarst and thermo-erosion, especially pronounced in Arctic lowlands, the Yedoma area can be overestimated at mapping scales of 500,000–1,000,000 (Veremeeva et al., 2021). High-resolution mapping of the Yana-Indigirka and Kolyma lowlands using remote-sensing data showed the overestimation of Yedoma area on geological maps of 1,000,000 scale to be about two times (Shmelev et al., 2017).

Original Yedoma plains formed by the end of LGM (ca. 20 ka BP). Climate warming, which started during the end of the Late Pleistocene, significantly degraded the plains by thermokarst, thermo-erosion and thermo-denudation processes during the Holocene (Kanevskiy et al., 2014; Morgenstern et al., 2021; Veremeeva et al., 2021) (Fig. 2). For north-eastern Siberia, radiocarbon dating of peat and lacustrine deposits revealed that thermokarst lakes mostly started at 13–12 ka BP, and their subsequent drainage led to the formation of drained lake basins with residual lakes (alases), and the Yedoma-alas relief was formed mainly by ca. 10–8.5 ka. BP (Kaplina, 2009). Similar development of Yedoma relief has been identified in western central Alaska by Kanevskiy et al. (2014). Based on detailed cryostratigraphic analysis, radiocarbon dating, and landscape mapping, these authors proposed a conceptual model of Yedoma terrain evolution since the Late Pleistocene. It comprises four stages of Yedoma degradation and five stages of subsequent permafrost aggradation-degradation (Fig. 2).

Such degraded landforms dominate the modern lowland relief and dissect remnants of Late Pleistocene accumulation plains and valley terraces into Yedoma hills and uplands. The morphology of Yedoma uplands is an important indicator of relief development in the Holocene and reflects the impact of exogenic and endogenic factors on relief formation (Veremeeva and Glushkova, 2016).

The distribution of the Yedoma Ice Complex relates to several distinct geomorphologic settings. One setting adjoins low-elevation coastal mountains, which served as the main sediment sources for the Yedoma Ice Complex. Heavy-mineral compositions of Siberian Yedoma sites suggest a dominantly local origin of the frozen deposits, including the Yedoma Ice Complex, rather than long-distance transport (Schirrmeister et al., 2022a). Gently inclined foreland accumulation plains and valley floodplains underlain by ice-wedge polygon systems were the original landscape for the accumulation of Yedoma deposits (Fig. 3). A second geomorphologic setting in the hinterland of Yedoma areas are 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 on Bel'kovsky, Stolbovoy, and Kotel'ny islands of the New Siberian Archipelago. These elevations are often shaped by cryoplanation terraces and framed by cryopediments (see entry on Cryoplanation terraces and cryopediments), indicating strong periglacial weathering and erosion processes. A third setting comprises extended lowland areas farther from mountain ranges. Although these distal areas are currently dominated by large and numerous thermokarst basins and lakes, Yedoma hills and uplands are common, indicating their former widespread occurrence, such as in the coastal lowlands of north-eastern Siberia and northern Alaska. Yedoma Ice Complex deposits also occur in Central Yakutia in terraces of the Lena and Vilyu rivers. Additionally, valley terraces of various extents are also common dispersal areas (e.g., the Tumara and Dyanuschka valleys west and southwest of the Verkhoyan Mountains).

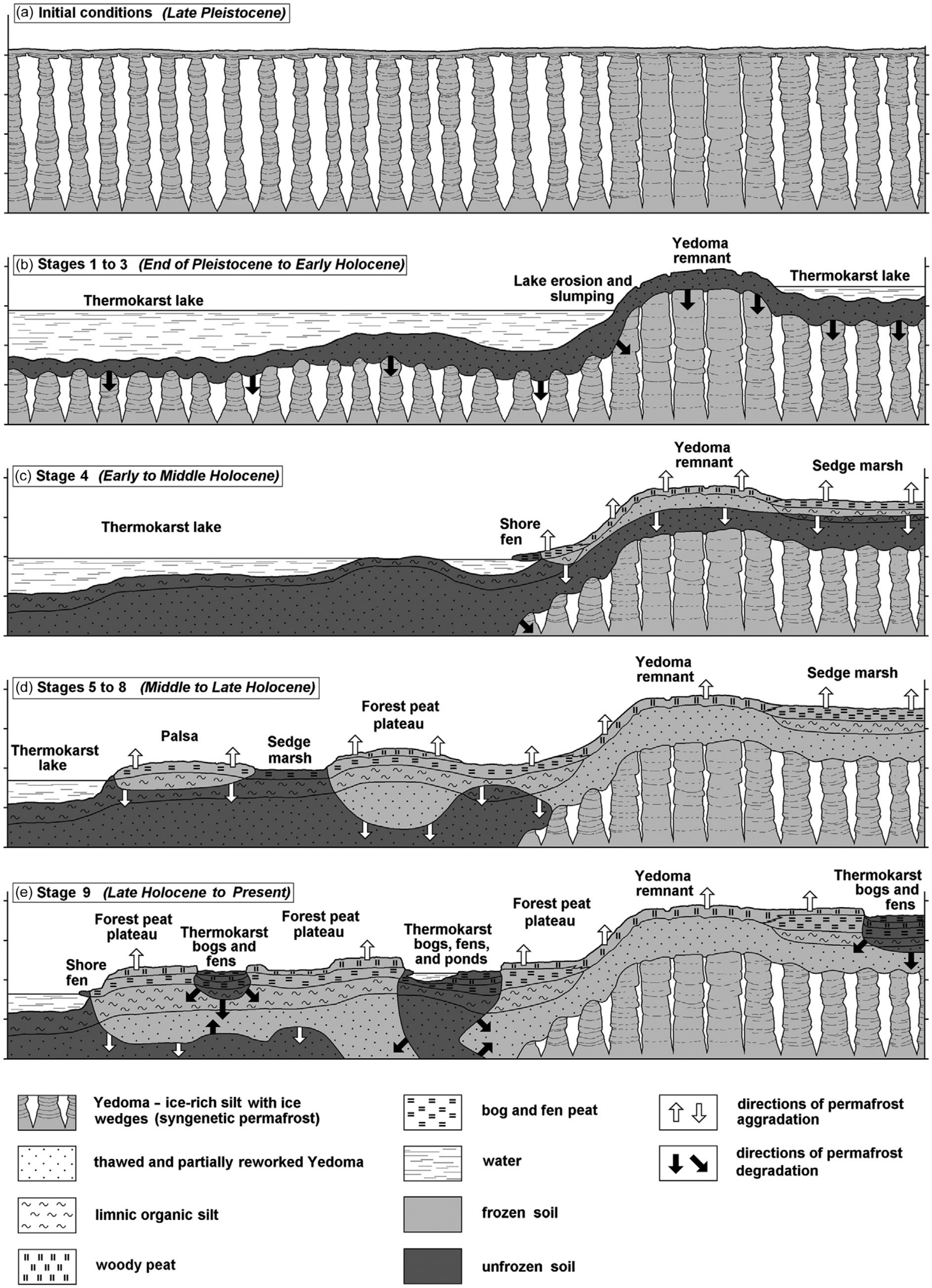


**Fig. 2** Conceptual model showing the stages of Yedoma terrain development from the Late Pleistocene to the present (not to scale) by Kanevskiy et al. (2014).

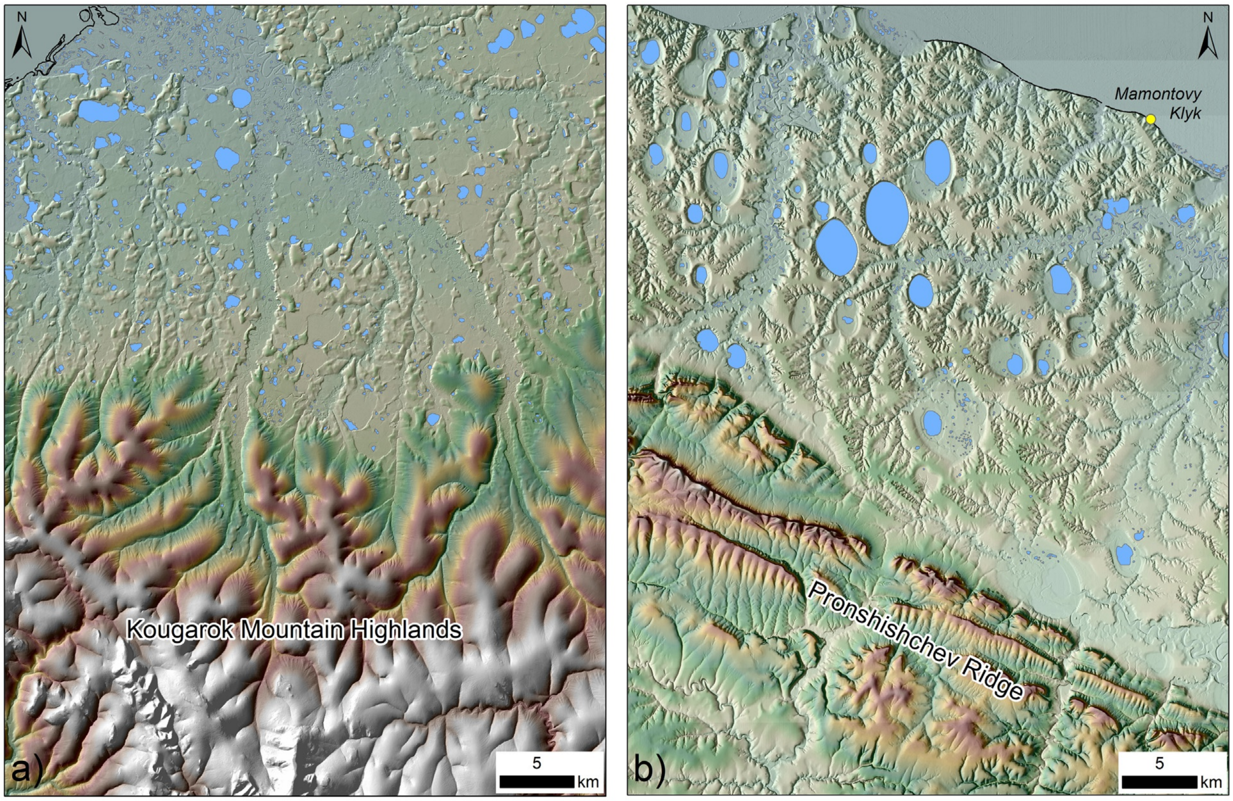


**Fig. 3** Typical landscapes of the Yedoma region are characterized by hillslopes smoothly covered with a blanket of Yedoma deposits, Yedoma uplands inset with thermokarst lakes and basins, as well as numerous river valleys and small, branched thermo-erosional valley systems. (a) Airborne IfSAR digital elevation model (DEM) with hillshade of the northern Seward Peninsula in west Alaska; (b) ArcticDEM with hillshade of the Mamontovy Klyk region in the western Laptev Sea coastal plain in front of the Pronchishchev Ridge. Maps compiled by Guido Grosse (AWI).

Important indicators of Yedoma deposits are retrogressive thaw slumps on coastal bluffs, lake shores, or river banks (Fig. 4a, b, e, f). These sites expose large ice wedges 2 to 5 m wide and up to tens of meters high in their retreating headwalls, and residual thermokarst mounds formed due to the ice-wedge melting on slump floors (Fig. 4c and d). The ice wedges, associated sediments and thermokarst mounds are parts of the Late Pleistocene polygonal ice-wedge systems representing the Yedoma deposits. Generally, such exposures are formed by the interplay of active thermo-denudation, thermo-erosion, and slumping of ice-rich permafrost (Fuchs et al., 2020; Shur et al., 2021). The exposed sediments and ground ice in rapidly retreating steep bluffs and terraces often provide access for paleoenvironmental and cryolithological studies of the still-frozen (ancient permafrost) deposits. A prominent example is the Batagay megaslump in the Yana Upland of interior Yakutia—the largest retrogressive thaw slump on Earth, currently exceeding 80 ha in area. Here, the Yedoma Ice Complex constitutes a major part of the cryolithological inventory overlying much older permafrost deposits (Murton et al., 2023).

Most landscape types underlain by Yedoma Ice Complex deposits are characterized by large, relatively flat plains with low hydrological gradients conducive to the long-term formation of syngenetic ice-wedge polygon systems. Poorly-developed drainage in the Beringian environment, with its cold-arid climate, was presumably an important factor for the formation of the Yedoma Ice Complex. It is likely that Yedoma deposits also accumulated on vast areas of the Beringian shelves exposed by lower sea level during the Late Pleistocene (Gavrilov et al., 2003).

Broad equivalents to the Siberian Yedoma Ice Complex occur in Arctic and sub-Arctic regions of unglaciated Alaska and Yukon (i.e., eastern Beringia) (Kanevskiy et al., 2011). In tundra areas of western and northern Alaska, its presence is recognized by deep thermokarst lake basins within thick ice-rich permafrost (Fig. 3a). In areas farther south, Yedoma deposits are usually obscured by forest cover but have been identified in boreholes or exposed in open-pit mines (Fig. 3d), mining tunnels, and thaw slumps on lakes and streams. In general, interior Yukon and Alaska host Yedoma Ice Complex deposits in steeper areas than their counterparts in Siberia. Yedoma deposits in eastern Beringia also extend into the present-day discontinuous permafrost zone. In the Fairbanks (Alaska) and Klondike (Yukon) regions, where Yedoma-like deposits have been best studied, they are mainly distributed on north- and east-facing slopes and within narrow valleys along hillslopes.

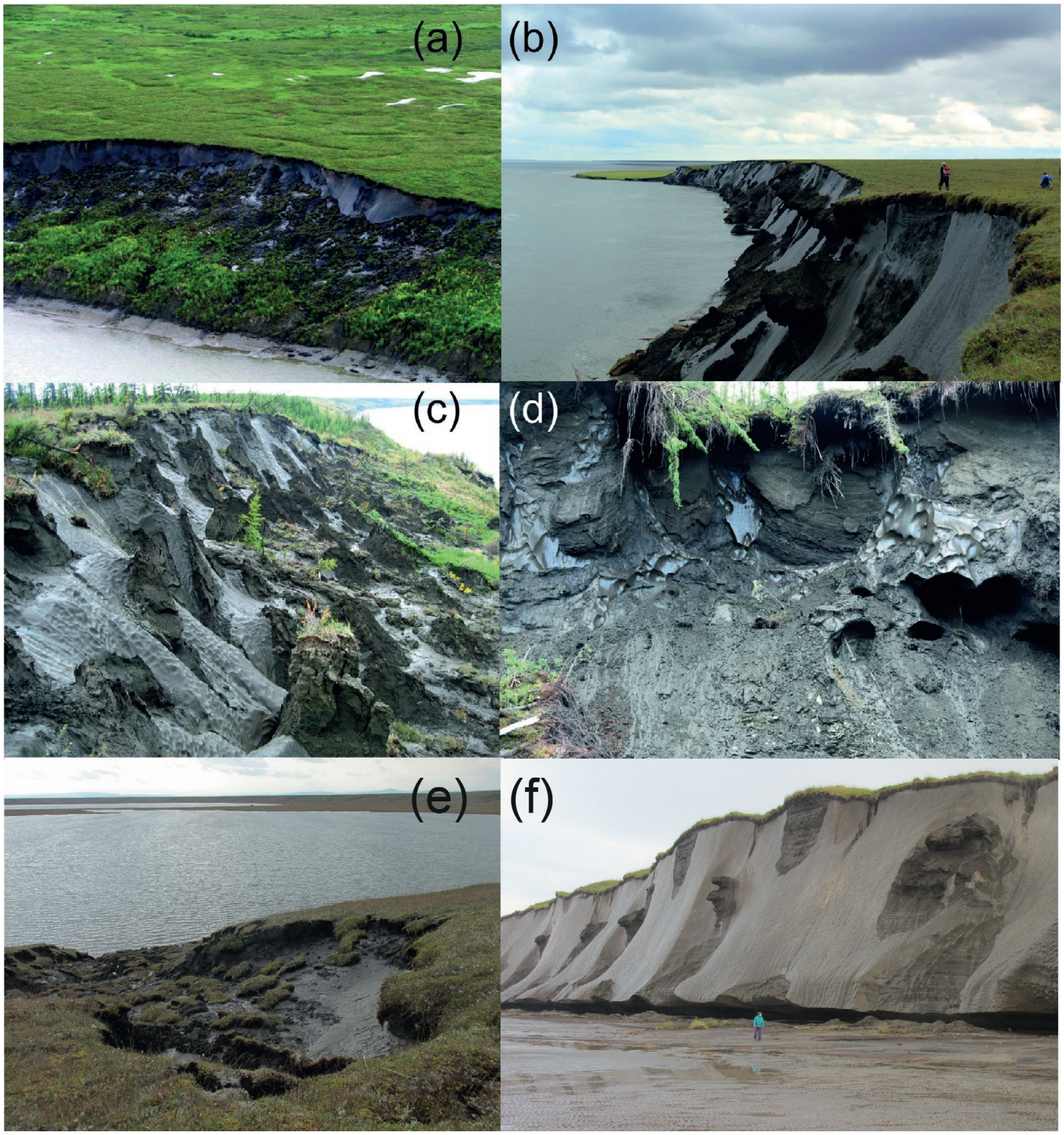


**Fig. 4** Examples of eroding Yedoma: (a) a thaw slump at the Colville River, Alaskan North Slope; (b) a cliff on Sobo-Sise Island in the Lena River Delta, eastern Siberia; (c) a retrogressive thaw slump with thermokarst mounds at Duvanny Yar, Kolyma River, eastern Siberia; (d) exposure at Little Blanche Creek, Klondike Goldfields, Yukon, Canada; (e) initial stage of thaw-slump formation at Bykovsky Peninsula, eastern Siberia; and (f ) cliff showing a headwall with large exposed ice wedges, Mamontovy Khayata, Bykovsky Peninsula. Images: Jens Strauss, Lutz Schirrmeister, Guido Grosse, and Aleksandra Veremeeva.

## Yedoma Ice Complex in Siberia and the Russian Far East

The processes that formed the Yedoma Ice Complex in Siberia and the Russian Far East are still disputed, and some differences in understanding between researchers working in western and eastern Beringia remain. These differences largely reflect the contribution of eolian processes in Yedoma formation, particularly the interpretation of these sediments as being primarily loess amongst researchers in Yukon and Alaska. In contrast, researchers working in Siberia have proposed several hypotheses about the origin of the Yedoma Ice Complex, including alluvial, glaciolacustrine, deltaic, proluvial (i.e., alluvial-fan deposits), colluvial, cryogenic-eolian, nival, and polygenetic processes. Zhestkova (1982) and Sher (1997) suggested a polygenetic origin in which Yedoma Ice Complex deposits accumulated under different sedimentation regimes. Similar landscape and relief characteristics, climate conditions, prevailing periglacial processes, and short-distance sediment sources largely controlled the formation. An overarching similarity between different Yedoma deposits of different locations is the presence of large syngenetic ice wedges, and the remains of Late Pleistocene mammoth fauna and tundra–steppe flora within sandy to silty deposits.

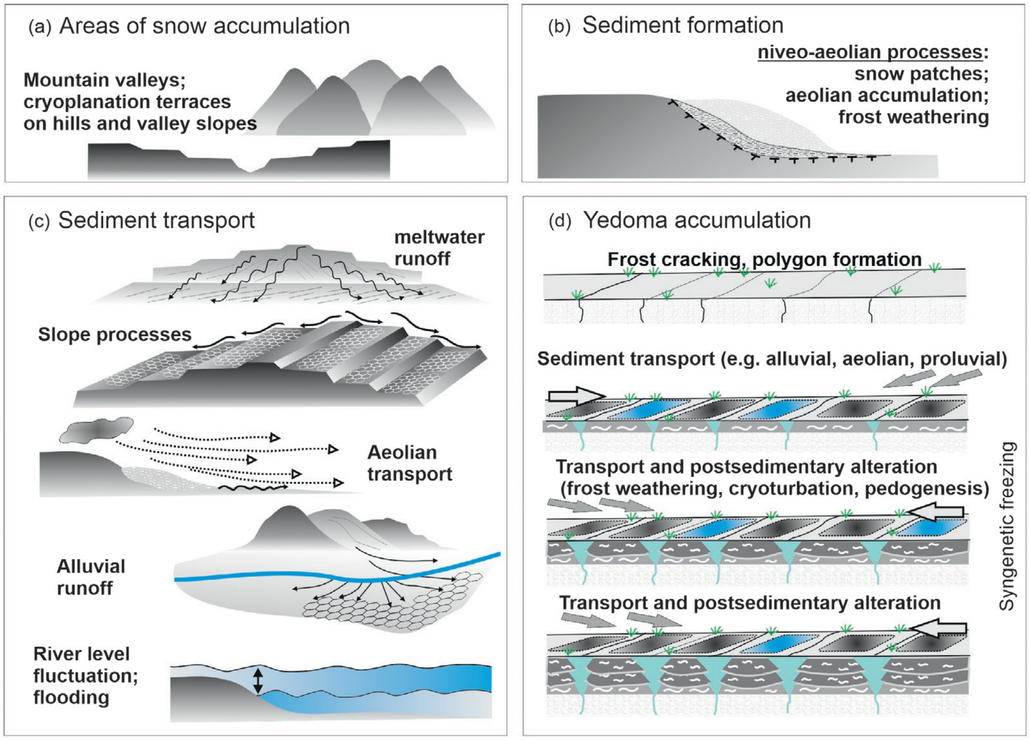


**Fig. 5** The polygenetic origin of Yedoma Ice Complex including (a) primary accumulation, (b) sediment formation, (c) material transport, and (d) accumulation, including post-sedimentary periglacial alteration. Modified from Schirrmeister L, Dietze E, Matthes H, Grosse G, Strauss J, Laboor S, Ulrich M, Kienast F, and Wetterich S (2020) The genesis of Yedoma Ice Complex permafrost—Grain-size endmember modeling analysis from Siberia and Alaska. *E&G Quaternary Science Journal* **69**: 33–53. https://doi.org/10.5194/egqsj-69-33-2020.

A comprehensive concept of Yedoma Ice-Complex formation combines processes of cryogenic weathering, material transport and accumulation, and relief shaping under cold–arid climate conditions (Schirrmeister et al., 2020). Here, the Yedoma Ice Complex represents a characteristic periglacial facies whose formation was controlled by the interaction of several climatic, landscape, and geological preconditions typical for non-glaciated Arctic areas (Fig. 5). Initially, mixtures of windblown snow, plant, and fine-grained mineral detritus accumulated in numerous, perennial snow fields (nivation; Fig. 5a). Around their margins and beneath the snowfields under wet conditions (Fig. 5b), such material and attached organic matter were transported downslope by seasonal meltwater runoff (Fig. 5c). This fine-grained detritus was then transported farther by various alluvial, proluvial, colluvial, slope wash, solifluction, permafrost creep, and eolian processes to foreland plains, cryopediments, alluvial fans or valley terraces. As a result, different types of Yedoma deposits accumulated, with variable grain-size distributions depending on local conditions. As sediment aggraded in flat accumulation areas, polygonal ice-wedge systems developed syngenetically (Fig. 5d). Over thousands of years, these recurrent processes of snowfield accumulation, frost weathering, snow melt, meltwater transport, and secondary sediment transport processes led to accumulation of decameter-thick Yedoma deposits. An alternative conceptual model of Yedoma Ice Complex formation, emphasizing eolian transport and deposition of cold-climate loess and limited reworking by colluvial processes, has been presented by Murton et al. (2015).

The formation of the Yedoma Ice Complex typically consisted of several concurrent periglacial processes. These included syngenetic sediment and organic matter accumulation and freezing, ice segregation, frost cracking and 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 ice-wedge systems and thick, continuous sequences of frozen deposits indicate the persistence of poorly-drained accumulation areas with low topographic gradients. The proposed cryolithogenic model of Yedoma formation integrates several previous concepts and emphasizes the polygenetic character of Yedoma Ice Complex deposits (Schirrmeister et al., 2020). It also identifies different material sources, transport pathways, and accumulation conditions in periglacial landscapes to build up such fine-grained, ice-rich deposits under extreme cold-climate conditions.

In Siberia and the Far East, Yedoma deposits predominantly date from MIS 3 and 2. The onset of Yedoma formation—based on radiocarbon ages—varies between about >55 ka BP on the New Siberian Islands (Wetterich et al., 2014) and 27 ka BP at the western Laptev Sea coast (Schirrmeister et al., 2008). The latest deposition is dated between 22 ka BP on the New Siberian Islands (Wetterich et al., 2021a) and 17–11 ka BP in the western Laptev Sea (Schirrmeister et al., 2008). Unconformities within Yedoma Ice-Complex sequences are common, encompassing up to 20 ka, and likely reflect permafrost degradation by thermokarst and thermo-erosional processes. In general, the basal layers of the Yedoma Ice Complex contrast sharply with the underlying deposits—often fluvial sands with peat layers or fine-grained floodplain deposits—dated by $^{230}Th/^{234}U$ and luminescence to ages of 100–60 ka (Schirrmeister et al., 2011). A thaw unconformity commonly characterizes the upper boundary of Yedoma and underlies locally confined Holocene deposits on top of Yedoma hills.

## Yedoma in Alaska

As in Siberia, early work on the origins of ice-rich permafrost deposits in northwestern North America was controversial. Scholars argued that these deposits, often referred to as 'muck' deposits, in Alaska and Yukon might have been produced by lacustrine, estuarine, eolian, residual weathering, or fluvial processes, or their interaction (e.g., Taber, 1943). The term 'muck' originated from the gold mining vernacular and was applied by the miners to the frozen, fine-grained sediment containing large amounts of organic matter, including vertebrate remains and ice bodies, and commonly overlying gold-bearing gravels (Tuck, 1940; Shur et al., 2022). This means that muck includes all frozen deposits of various ages and origins overlying the gold-bearing gravels mined in Alaska and the Yukon, including Holocene deposits.

Following work by Péwé (1955), who argued strongly for an eolian origin of the fine-grained sediments within the muck, all scholars have accepted a predominantly eolian origin. No other formation hypotheses have emerged since the late 1950s. This contrasts with the studies of Siberian ice-rich Yedoma deposits, and likely both reflects differences in the overall paleoenvironmental and depositional setting as well as perhaps a more generous consideration of loess formation in the North American literature relative to the concept of Yedoma in Siberia. Only in recent years have scholars increasingly referred to the syngenetic ice-rich deposits of Late Pleistocene age in Alaska and the Yukon Territory as Yedoma (Kanevskiy et al., 2011, 2016), and the more general term muck is less used in the scientific literature.

Many of the areas with Yedoma Ice Complex deposits in North America are associated with uplands with extensive foreland accumulation plains and large river valleys with wide floodplains like the North Siberian coastal lowlands and 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 mantling foothills and hilltops are commonly found above alluvial terraces or sheltered behind bedrock obstacles and have been unambiguously interpreted as loess (Péwé, 1975; Muhs et al., 2008). However, it should be noted that these upland silt deposits often are not ice-rich and differ significantly from Yedoma Ice Complex deposits as described in valley-bottom settings (e.g., Péwé, 1975; Froese et al., 2009). The loess genesis was recently supported by Gaglioti et al. (2018) for occurrences on the Arctic Coastal Plain. According to Kanevskiy et al. (2016) and Jorgenson et al. (2008), Yedoma Ice Complex deposits in Alaska occur along the lower portion of the Arctic Foothills, in the northern part of the Seward Peninsula, and numerous areas in Interior Alaska.

In Péwé's original work (Péwé, 1975) and that of earlier researchers, the valley-bottom 'muck' deposits were considered to be 'reworked loess' derived from mixing of mobilized upland silts with organic material, accumulated syngenetically with permafrost growth in valley-bottom settings and interbedded with primary airfall 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' describes sediments dominated by coarse silt and fine sand grain sizes, much of which is likely primary airfall loess. However, evidence of secondary, short-distance redeposition by snowmelt or sheet flows may also be present. Loess from MIS 2 is relatively thin on upland sites, whereas thick accumulations dating to that time are present in valley-bottom sites. This suggests either a thickening of those sediments in valley bottoms or that these valleys acted as sediment traps while upland surfaces—with sparse vegetation cover and thus low friction—may have been bypassed by these sediments (Muhs et al., 2008). Jensen et al. (2016) updated this model of primary loess accumulation based on loess records in interior Alaska that are supported by tephra stratigraphy and magnetic susceptibility spanning the past 150,000 years. They suggested that loess accumulation was particularly strong during transitions between glacials and interglacials/interstadials, when loess production, surface roughness, and wind intensity were all relatively moderate. At the same time, during full-glacial and interglacial periods, accumulation rates were lower. Deposition of the upland silt in interior Alaska is generally well-constrained by the associated tephra stratigraphy of a dozen volcanic ashes over the last 150,000 years (e.g., Jensen et al., 2016). However, these tephra beds are rare in the valley-bottom sites (e.g., Kanevskiy et al., 2022).

In eastern Beringia, Yedoma development largely dates to the Late Pleistocene. Péwé (1975) argued for a consistent climatically-driven period of ice-rich loess sedimentation, the deposits of which he named the Goldstream Formation. This formation post-dated a significant thaw of permafrost during the last interglacial and likely covers the Late Wisconsin period. Subsequent workers have dropped these formal definitions, but based on radiocarbon ages and tephrochronology, most of the Yedoma deposits date to MIS 3 and MIS 2. Radiocarbon ages are fairly consistent in Alaska for a major period of Yedoma development during MIS 3 and 2, beginning around 42 ka BP and continuing until ca. 11 ka BP (Kanevskiy et al., 2011, 2022; Schirrmeister et al., 2016). Commonly, the cessation of Yedoma sedimentation is marked by a pronounced unconformity assumed to be in the early Holocene at many sites (ca. 10 ka BP; e.g., Fraser and Burn, 1997) associated with organic-rich sedimentation, but recently, this has been shown in some areas to be nearer 13 ka BP (Monteath et al., 2023). In Alaska, recent studies of Yedoma Ice Complex deposits have focused on the well-known CRREL permafrost tunnel near Fairbanks that exposes fine-grained frozen sequences containing syngenetic ice wedges (Kanevskiy et al., 2022). However, Yedoma deposits have also been identified in western Alaska on the Seward Peninsula (Lenz et al., 2016), Baldwin Peninsula (Jongejans et al., 2018), and in strongly degraded form in the Koyukuk-Innoko Flats (Kanevskiy et al., 2014). A Yedoma site with characteristics very similar to northeast Siberian sites, including large syngenetic ice wedges several meters wide and tens of meters deep and sediments with very high excess ice content, has been reported from the Itkillik River in the Arctic Foothills (Kanevskiy et al., 2011, 2016; Shur et al., 2021). These Yedoma deposits accumulated between >48 and 14.3 ka BP.

## Yedoma in Canada

In Canada, Yedoma deposits occur in central Yukon Territory, mainly along the Yukon River and its tributaries, and are largely known for gold-mining activities in the Klondike area that have created excellent exposures for study (Froese et al., 2009; Monteath et al., 2023). However, remnants of these syngenetic deposits are also known from outside this region, where thaw slumps have exposed them in the southern Ogilvie Mountains (e.g., Lacelle et al., 2009) and along the Alaska Highway in southwestern Yukon (Pumple et al., 2015), suggesting a much wider distribution.

The most detailed studies of Yedoma deposits in northwestern Canada come from the Klondike Goldfields area, where the deposits are well-dated and constrained by extensive tephra stratigraphy, dating deposits and correlating sites between MIS 4 and MIS 2, with isolated Yedoma-like remnants extending back into the early-Middle Pleistocene (Froese et al., 2009). These studies indicate consistent records 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 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. Notably, 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.

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). Extensive work on the paleoecology of plant, insect, and small mammal remains has also provided insight into landscape processes associated with Yedoma sedimentation. Dozens of arctic ground squirrel nests are well-established from both MIS 4 and MIS 2 cold-stage deposits in the Klondike area (Zazula et al., 2006, 2011). Arctic ground squirrels are extinct from the region today. However, their former presence indicates that soils were better drained, and active layers in the Yedoma deposits were thicker at the sites than they are today. Modern arctic ground squirrels require thick active layers (0.9–1.0 m) (Zazula et al., 2005), while the modern site surfaces where these fossils have been found have active layers typically thinner than 0.6 m. Plant and insect fossils from the arctic ground squirrel middens are exceptionally preserved in the Yedoma deposits and indicate that the loessal silts accumulated in an open, grass- and forb-rich steppe-tundra community in both MIS 4 and MIS 2, suggesting that these deposits are a recurrent feature of cold stages during the Late Pleistocene of Beringia.

## Cryolithology

Yedoma sequences include buried cryosols marked by brownish horizons as well as the inclusion of organic matter and peat. Evidence of past cryoturbation, highlighted by the presence of organic matter, is common. According to Schirrmeister et al. (2020), the poorly to very poorly sorted clastic sediments range in grain size dominantly from fine-grained silt to medium-grained sand and sometimes contain coarse-grained sand and single gravel particles (sorting 1.0–3.5, mean grain size 2.6–600 μm). Grain-size characteristics differ from site to site as well as within horizons at single locations. The presence of multi-mode grain-size distributions (Fig. 6) suggests a range of transport processes and underscores the importance of re-deposition of silts with coarser grain sizes. Heavy-mineral analyses suggest that Siberian Yedoma Ice Complex deposits are mainly the result of local and polygenetic formation (including local eolian relocation) superimposed by cryogenic weathering and varying climate (Schirrmeister et al., 2022a).

Cryogenic structures in Yedoma Ice Complex deposits, particularly syngenetic ice wedges (several meters wide and up to several tens of meters high), are similar at most study sites (Fig. 2). 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 (see entry on Ice wedges and related structures). Thin horizontal ice lenses several mm thick or net-like reticulate ice veins subdivided by up to 2–4 cm-thick ice bands are common. 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.

The frozen sediment sequences commonly contain excess ice, with mean gravimetric ice contents of $42 \pm 15$ wt%. Considering that ice wedges account for about 50% by volume of most Yedoma Ice Complex sequences, the total volumetric ground ice content likely ranges from 65% to 90%. Stable-isotope signatures of ground ice ($\delta^{18}O$, $\delta D$) are used as a proxy for winter paleotemperatures (the most negative $\delta^{18}O$ and $\delta D$ values reflect the coldest temperatures) and moisture sources (see entry on Ice wedges and related structures). Late Pleistocene ice-wedge ice reflects very cold winter temperatures and moisture sources that are isotopically distinct from Holocene values. In combination with direct radiocarbon dating of organic material from ice wedges, such chronologies allow reconstruction of major climatic trends on a millennial scale, such as LGM cooling (Wetterich et al., 2021a). The stable-isotope signatures of ice wedges from Alaska and Canada vary between −29 and −24‰ for MIS 2 and between −30 and −21‰ for MIS 3 (Porter et al., 2016; Porter and Opel, 2020). In Siberia, they are between −37 and −26‰ for MIS 2 and −35 and −27‰ for MIS 3 (Porter and Opel, 2020; Opel et al., 2019, Fig. 7).

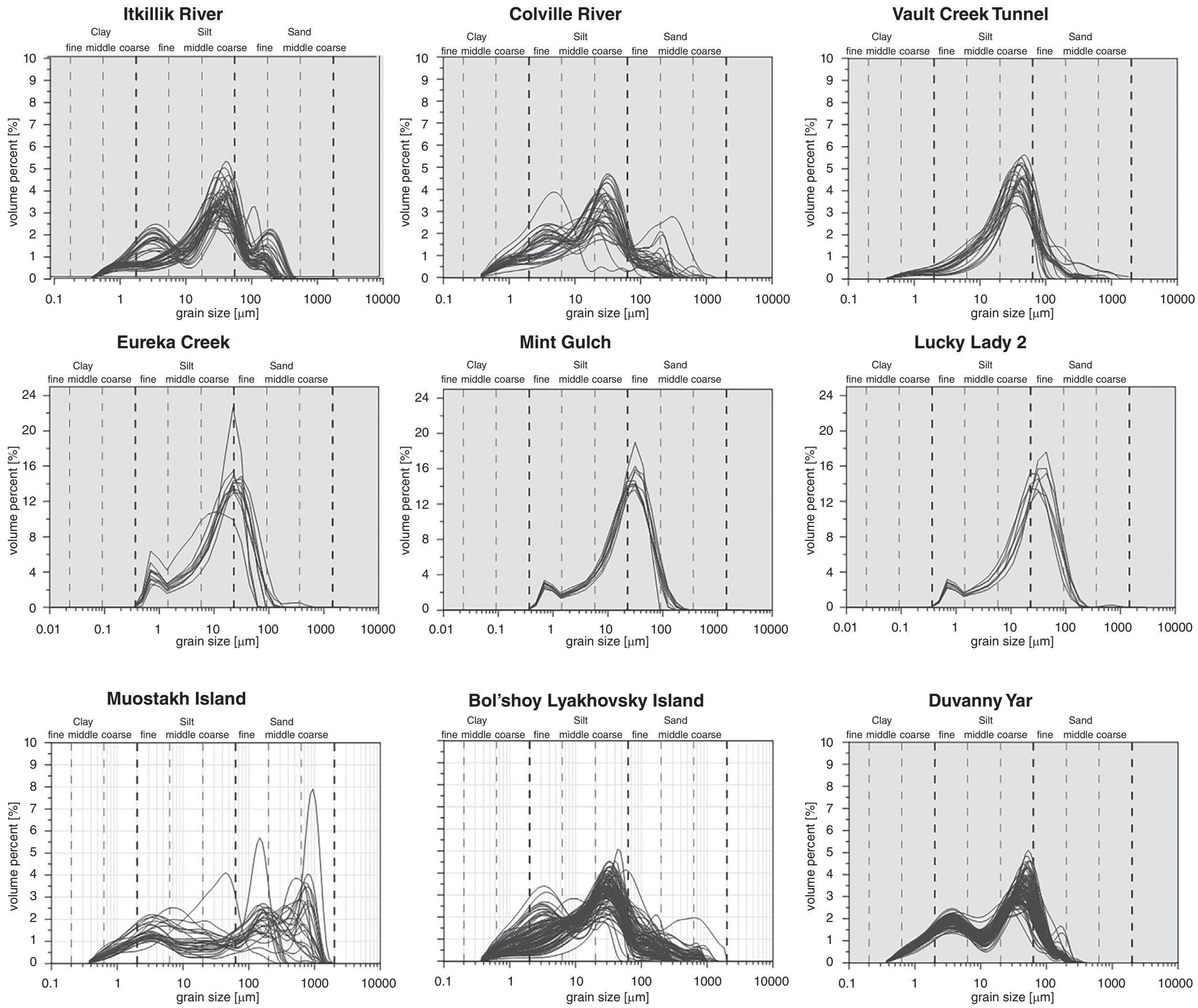


**Fig. 6** Grain-size distribution curves from Yedoma Ice Complex deposits of different sites in Alaska (upper row), eastern Siberia (lower row) according to Schirrmeister et al. (2020), and the Canadian Klondike Goldfields (middle row). Note the different scales of the y-axis for the Canadian analyses.

The total organic carbon (TOC) content in Yedoma Ice Complex deposits is variable (<1 to >20 wt%) and relatively high (site-specific averages from 1.2 to 4.8 wt%; Schirrmeister et al., 2011). Woody macrofossils, peat, numerous tiny filamentous rootlets, and dispersed organic detritus are present. Detailed studies of paleosols within Yedoma deposits indicate that much of the organic matter accreted as root detritus from graminoid vegetation under periglacial conditions. Thaw unconformities truncating ice wedges, syngenetic ice wedges with pronounced shoulders, and cryoturbated paleosols all record episodic changes in sedimentation and paleo-active-layer depths. The $\delta^{13}C$ values of bulk organic material range from about −29 to −24‰, indicating that only freshwater aquatic and sub-aerial terrestrial environments contributed this material to accumulating Yedoma deposits. Variations in TOC content, C/N ratio, and $\delta^{13}C$ values (Fig. 8) relate to changes in bioproductivity, intensity, and character of cryosol formation, different degrees of organic matter decomposition, and plant associations. High TOC contents, high C/N ratios, and low $\delta^{13}C$ values reflect less-decomposed organic matter under anaerobic conditions, characteristic of the interstadial MIS 3. During cold stages like MIS 2, TOC was less variable and generally low, indicating more stable environments with reduced bioproductivity and low C/N ratios. High $\delta^{13}C$ values reflect relatively dry, aerobic conditions.

## Fossils and paleoenvironmental archives

Late Pleistocene plant and animal fossils are numerous and often exceptionally preserved in Yedoma deposits (Guthrie, 1990), making Yedoma deposits arguably the best-preserved archive of past life on the planet. Ongoing research has used the fossil record to reconstruct past environments of Beringia through a combination of proxies such as pollen, plant macrofossils, mammals, and

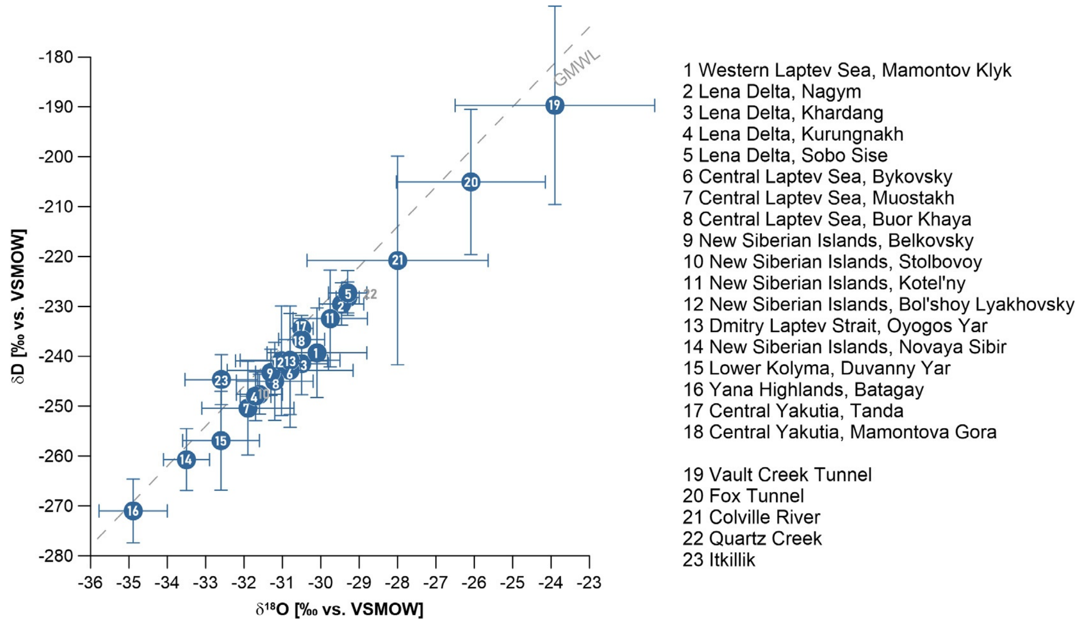


**Fig. 7** Comparison of stable-isotope data from ice wedges in the Yedoma Ice Complex attributed to the MIS 3 interstadial (about 50–30 ka). Modified from Opel T, Murton JB, Wetterich S, Meyer H, Ashastina K, Günther F, Grotheer H, Mollenhauer G, Danilov PP, Boeskorov V, Savvinov GN, and Schirrmeister L (2019) Past climate and continentality inferred from ice wedges at Batagay megaslump in the Northern Hemisphere's most continental region, Yana Highlands, interior Yakutia. *Climate of the Past* **15**: 1443–1461. https://doi.org/10.5194/cp-15-1443-2019.

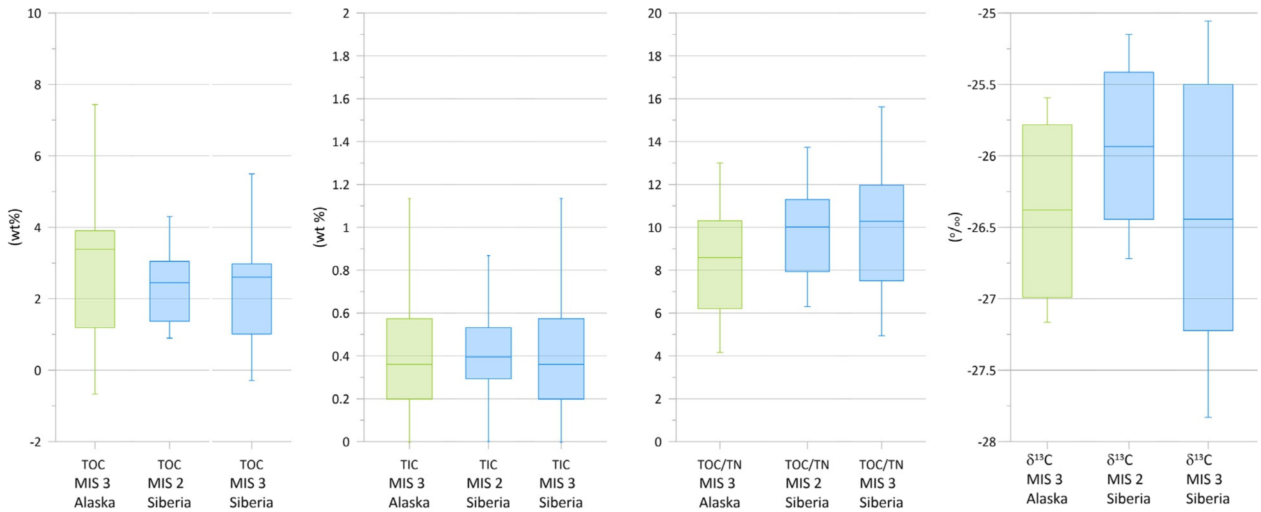


**Fig. 8** Compilation of organic carbon characteristics of Yedoma Ice Complex deposits from 700 samples of MIS 3 age and 170 samples of MIS 2 age.

aquatic and terrestrial invertebrates for quantitative and qualitative reconstructions (e.g., Neretina et al., 2020; Wetterich et al., 2021b). Additionally, fossil biomolecules such as biomarkers are increasingly applied to characterize preserved organic matter (Jongejans et al., 2022), and sedimentary ancient DNA (sedaDNA) has provided largely unparalleled insight into past vegetation composition (Zimmermann et al., 2017; Murchie et al., 2021; Courtin et al., 2022).

The Beringian mammoth fauna preserved in Yedoma Ice Complex deposits is characterized by the prevalence of wooly mammoth (*Mammuthus primigenius*) and complemented by horse (*Equus caballus*), bison (*Bison priscus*), and caribou (*Rangifer tarandus*). Less commonly, fossils of the Pleistocene Western camel (*Camelops hesternus*), the Pleistocene musk ox (*Ovibos pallantis*), wooly rhinoceros (*Coelodonta antiquitatis*), and saiga antelope (*Saiga* sp.) are recovered. Fossils of carnivores such as cave lions (*Panthera leo spelaea*), short-faced bears (*Arctodus simus*), and wolves (*Canis lupus*) are generally rare. Some of these species occurred either in West Beringia (Siberia), such as the wooly rhinoceros, or in East Beringia (Canada and Alaska), such as the Pleistocene Western camel and the short-faced bear. In contrast, others were widely distributed across Beringia. The grazing fauna, much of it collected from detrital fossils recovered from Yedoma Ice Complex exposures across Beringia, have been linked to Late Pleistocene environments by radiocarbon dating (e.g., Kuznetsova et al., 2022; Reuther et al., 2015). Although rare, mummified or freeze-dried carcasses recovered from these sites highlight the role of permafrost in preserving the Late Pleistocene paleontological record (e.g., Boeskorov et al., 2014).

Paleobotanical materials are equally well-preserved within Yedoma Ice Complex deposits and, in particular, have become better understood through plant macrofossils recovered from these deposits. For example, the combined study of pollen, charcoal, plant macrofossils, and insects recovered from the Batagay megaslump in eastern Siberia revealed that meadow steppes analogous to modern communities formed the primary vegetation during Yedoma formation. In contrast, cryophilous species diagnostic of tundra-steppe vegetation was unexpectedly scarce (Ashastina et al., 2018). Instead, larch stands in the region indicated relatively warm summers with a mean annual temperature of the warmest month (MTWA) higher than 10 °C. Thus, the region served as northern tree refugium, and the high continentality of the inland location of Batagay is reflected in the paleoecological proxy data.

The Late Pleistocene Yedoma environments combined both cold tundra and dry steppe environments and are often characterized as the Mammoth Steppe in eastern Beringia (e.g., Guthrie, 1990; Zazula et al., 2005) or tundra-steppe in western Beringia (e.g., Yurtsev, 1982). In palynological records from the Laptev Sea region of western Beringia, this is reflected in the dominance of herbs such as dwarf shrubs like *Salix*, *Alnus*, and *Betula* (Andreev et al., 2011). Such interpretation is generally confirmed by combined pollen and sedaDNA results (Zimmermann et al., 2017).

The combined application of different paleo-ecological proxies promises an improved understanding of past ecosystem states and dynamics (e.g., Wetterich et al., 2021b; Monteath et al., 2023) and should, therefore be fostered in future study designs to obtain more detailed information.

## New study directions of the last about 10 years

In addition to well-established methods, new approaches or improvements to existing methods have been used in recent years. There are also numerous, new study sites in all Yedoma regions (Fig. 9). The full version of the study site distribution can be found at https://apgc-map.awi.de/#yedoma. A recent overview of new results can be found in the research topic "Yedoma Permafrost Landscapes as past Archives, Present, and Future Change Areas" by Schirrmeister et al. (2022b).

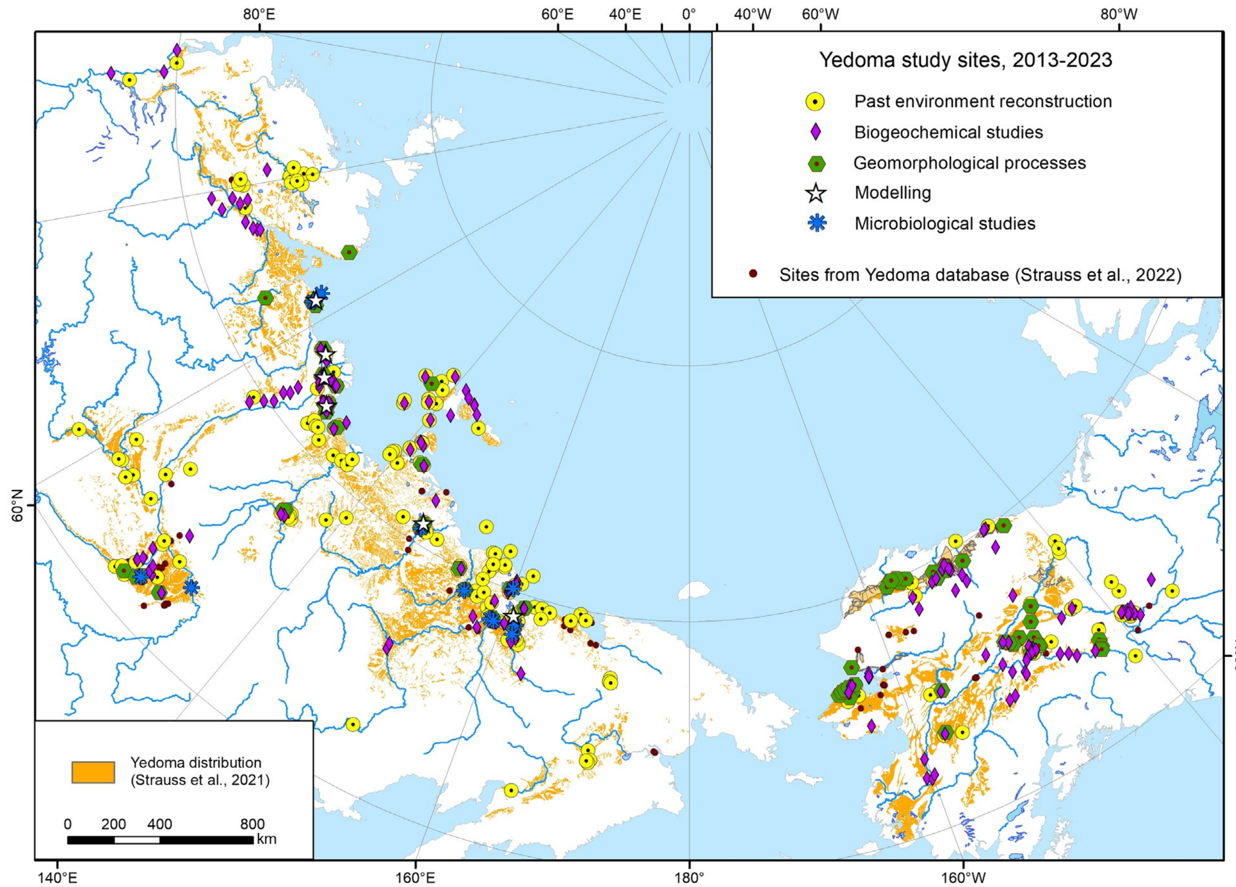


**Fig. 9** Map showing Yedoma study sites referenced in the Arctic Permafrost Geospatial Centre (APGC; https://apgc-map.awi.de/#yedoma).

The most well-studied Yedoma regions in Siberia are coastal regions of the Laptev Sea (Lena Delta, New Siberian Islands), lower Kolyma River, and central Yakutia. In Alaska they are the North Slope, Seward Peninsula, and central Alaska. In north-western Canada they comprise the Klondike Goldfields. However, due to their remoteness and difficult access, significant Yedoma regions are still not studied, especially inland parts of coastal lowlands in Siberia, the western part of central Yakutia, and inland and southwestern regions of the Yedoma domain in Alaska.

Analysis of sedaDNA in combination with pollen and insect analyses from Yedoma Ice Complex deposits has enabled reconstruction of Late Pleistocene vegetation dynamics (e.g., Courtin et al., 2022; Monteath et al., 2023; Murchie et al., 2022). A single gram of Yedoma sediment (frozen silty sand) can contain up to a billion fragments of DNA from ancient plant, animal, and microbial sources (Murchie et al., 2020). The latter has tended to dominate samples, making accurate reconstructions of the plant and animal communities challenging. The recent advent of targeted enrichment methods using sedaDNA (Murchie et al., 2020, 2021) has opened new possibilities for reconstructing past life from Yedoma Ice Complex deposits. This has enabled reconstruction of coupled plant and faunal communities in exceptional detail from Late Pleistocene Yedoma deposits, recording the Mammoth Steppe and its collapse at 13.2 ka BP (Murchie et al., 2021). Also, exceptional DNA preservation in these deposits has allowed full mitochondrial genomes of megafauna (horse, mammoth, and bison) from $<1$ g of Yedoma deposits (Murchie et al., 2022).

New ecological studies and reviews of the boreal steppe provide an improved conceptual overview of past and present vegetation distributions (e.g., Edwards et al., 2018). New studies of tephrochronology and paleomagnetism have significantly improved the age control for Yedoma deposits in eastern Beringia (e.g., Jensen et al., 2016). The characterization of organic matter, dissolved organic carbon in ground ice and frozen sediments (Ma et al., 2019), as well as nitrogen (Strauss et al., 2022b, 2024b), play an increasingly important role in Yedoma studies.

Modern methods are used and further developed to elucidate the role of microorganisms in Yedoma sediments (e.g., Monteux et al., 2020). Recently, ancient sedaDNA has been used to reconstruct microbial community changes along with key functional gene pathways associated with changing plant and megafauna over the last 40 ka (Murchie et al., 2023). These approaches allow a better understanding of the greenhouse gas potential of these sediments and their subsequent sediment degradation (e.g., Heslop et al., 2019) and clearer reconstruction of processes of organic matter transformation into greenhouse gases by studying biomarkers (e.g., Jongejans et al., 2022; Zhang et al., 2017).

Regarding the distribution of Yedoma Ice Complex deposits, satellite remote sensing in connection with geographical information system (GIS) methods and combined with digitized older geological maps has been increasingly applied in recent years (e.g., Strauss et al., 2021, 2022a; Veremeeva et al., 2021). Studies of permafrost degradation and thermokarst lakes in Yedoma regions play a crucial role, especially in connection with changes due to global warming (e.g., Kanevskiy et al., 2014). In addition, geophysical methods are increasingly being used to differentiate spatial and subsurface structures of Yedoma Ice Complex deposits (e.g., Schennen et al., 2016).

## Conclusions

Yedoma Ice Complex deposition in Beringia was fostered by a very cold, dry continental climate that promoted intense periglacial weathering, transport, and accumulation of fine-grained deposits. Deposition resulted in syngenetic permafrost growth in unglaciated regions over several tens of thousands of years during the Late Pleistocene. The presence 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. In the interior regions of Yukon, Alaska, and Yakutia, Yedoma deposits are more variable, reflecting the variation of local site conditions with topography. Paleoenvironmental reconstructions indicate the presence of cryoxeric steppe-tundra vegetation communities. Distinct cryolithological characteristics define Yedoma Ice Complex deposits, such as the dominance of silt, the presence of large, syngenetic ice wedges, and often ice-rich ground. In Siberia, Yedoma deposits are preserved in elevated erosional remnants in thermokarst landscapes, as well as in extended foothills of mountain ranges. In the previously unglaciated region of Alaska and the Yukon Territory, Yedoma Ice Complex deposits occur primarily in foothill regions, on north-facing slopes, and within narrow valleys. In summary, Yedoma is a special type of periglacial or cryogenic facies typical of cold stages of late Pleistocene Beringia.

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