frontiers | Frontiers in Earth Science

ORIGINAL RESEARCH
published: 04 May 2022
doi: 10.3389/feart.2022.789421

Cryolithostratigraphy of the Middle Pleistocene to Holocene Deposits in the Dmitry Laptev Strait, Northern Yakutia

Vladimir Tumskoy[1,2]* *and Tatiana Kuznetsova*[3]*

[1]Laboratory of General Geocryology, Melnikov Permafrost Institute SB RAS, Yakutsk, Russia, [2]Pacific Oceanological Institute, Russian Academy of Sciences, Vladivostok, Russia, [3]Department of Paleontology, Faculty of Geology, Lomonosov Moscow State University, Moscow, Russia

The northernmost part of continental Yakutia in the Dmitry Laptev Strait region developed under non-glacial conditions during the Quaternary period. During cooling periods, ice-rich deposits with syngenetic ice wedges, called the Ice Complex, formed here. During periods of warming, they partially thawed under thermokarst lakes and a peculiar complex of lacustrine-boggy deposits (the Alas Complex) was formed. The article presents a description of ice-rich deposit sequences in several Ice Complex horizons and their transformation in lake taliks from the Middle Pleistocene to the Holocene (MIS 7—MIS 1). The Oyogos Yar section structure is considered as an example using additional geological data from the southern coast of Bol'shoy Lyakhovsky Island. Specific examples show the results of changes in the structure of sections via cryogenic processes—ice wedge formation and thawing. We confirm that cryogenic processes are important factors, along with accumulation and erosion processes, which change the geological and cryolithological structure of the sections. It is shown that to clearly understand the stratigraphic subdivision of Quarternary deposits in areas of Ice Complex development, geological and analytical studies of the sections are insufficient; an elucidation of the sequence of sediment freezing and thawing and the resulting cryolithogical phenomena is necessary.

Keywords: cryostratigraphy, Late Pleistocene, Yedoma ice complex, Oyogos Yar, Dmitry Laptev Strait

OPEN ACCESS

Edited by:
Alexandra Veremeeva, Institute of Physical-Chemical and Biological Problems in Soil Science (RAS), Russia

Reviewed by:
Thomas Opel, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), Germany
J. Murton, University of Sussex, United Kingdom

***Correspondence:**
Vladimir E. Tumskoy
vtumskoy@gmail.com
Tatiana V. Kuznetsova
tatkuz2012@mail.ru

Specialty section:
This article was submitted to Cryospheric Sciences, a section of the journal Frontiers in Earth Science

Received: *04 October 2021*
Accepted: *05 April 2022*
Published: *04 May 2022*

Citation:
Tumskoy V and Kuznetsova T (2022) Cryolithostratigraphy of the Middle Pleistocene to Holocene Deposits in the Dmitry Laptev Strait, Northern Yakutia. Front. Earth Sci. 10:789421. doi: 10.3389/feart.2022.789421

INTRODUCTION

The Arctic coast of Yakutia has long been known for findings of the remains of mammoth fauna mammals. The existence of low-temperature permafrost during almost the entire Quaternary Period contributed to quick burying of dead animals and their good preservation for thousands of years. The overwhelming majority of findings of large mammal remains were made in ice-rich Yedoma deposits with thick ice wedges (Kuznetsova and Starodubtseva, 2009). In the middle of the 20th century, these remains were recognized as constituting their own layer, named the "Mammoth Horizon" (Gusev, 1958). A few years later, this horizon was renamed the Yedoma Suite (Vas'kovsky, 1963), after which "Yedoma" became a generic term for such deposits (Schirrmeister et al., 2013). Unique findings of representative mammoth fauna remains from yedoma deposits take place almost every year, including at Oyogos Yar. For example, in 2009, the well-preserved body of a mammoth named Yuka was found here (Boeskorov et al., 2012, 2013).

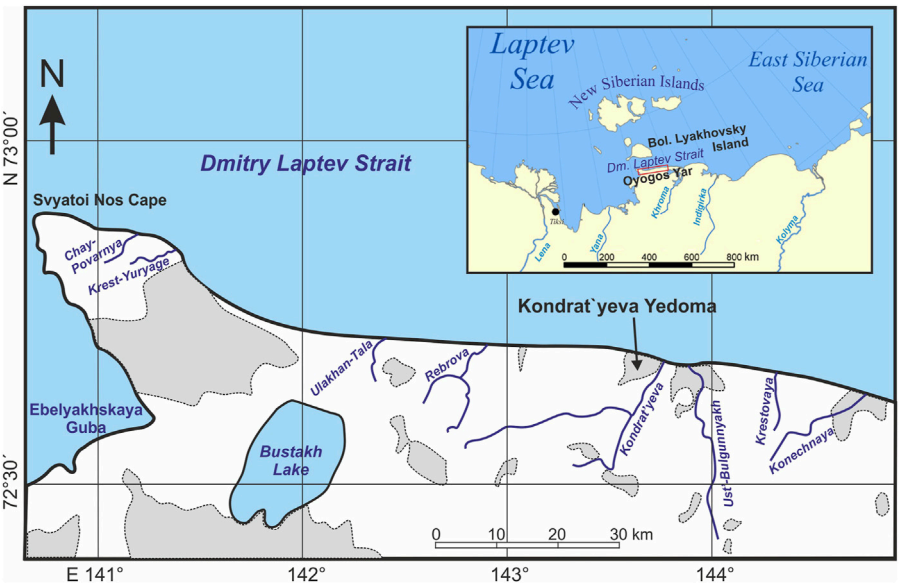

FIGURE 1 | Location map of the study region. The gray areas with dotted outlines are Yedoma highlands.

Oyogos Yar refers to the southern coast of the Dmitry Laptev Strait, which connects the Laptev and East Siberian seas and is 50–60 km wide (**Figure 1**). In the west, it begins at Cape Svyatoy Nos and stretches for 106 km eastward to the mouth of the Kondrat`yeva River. In the east, Oyogos Yar ended 6 km to east from the mouth of Konechnaya River. Several rivers fall into the sea over the entire stretch of Oyogos Yar. The longest of them—the Kondrat`yeva River—is only about 50 km long.

The steep coastal cliffs near Cape Svyatoy Nos are several dozen meters high. They are composed of Cretaceous volcanogenic-depositional formations (Prokhorova and Ivanov, 1973). From the cape east to the mouth of the Chay-Povarnya River, the cliffs become less steep and lose height. To the east of the Krest-Yuryage River, the surface level near the coast gradually drops; only frozen loose Quaternary deposits are present in this section. The coastal zone at this site resembles large bottoms of drained thermokarst lakes, which have merged to form alases. Individual uplands called "yedoma" (gray areas on **Figure 1**) rise among them. On sites where the coastline intersects the alases, the height of the coastal cliff is 10–15 m. The yedoma uplands reach a height of 30–40 m, forming higher and often terraced cliffs, but there are only a few such places along the coast. In the western part of Oyogos Yar, the yedoma meets the seacoast to the east of the Krest-Yuryage River mouth for a stretch of about 6 km. A small yedoma upland is located 5 km east of the Rebrova River mouth; here, the mammoth named Yuka was found in the upland's lower cliff (Boeskorov et al., 2012, 2013). The largest yedoma upland, located west of the Kondrat`yeva River, stretches along the coast for about 5 km. We will henceforth call it the Kondrat`yeva Yedoma (**Figure 1**). Its maximum height is 41 m above sea level (a.s.l). There are two more yedomas to the east, near the mouths of the Ust-Bulgunnyakh and Konechnaya rivers.

Despite the long history of research at Oyogos Yar, there is still no agreement on the age, origin, and even sedimentation conditions of the deposits exposed in its outcrops. This is explained by the location of the cliff's deposits within a zone of continuous syncryogenic permafrost with a high volumetric ice content, reaching 80%–90% in places. The history of the geological development of these deposits in the Pleistocene and Holocene includes not only stages of deposition and erosion but also periods of cryogenic transformation (freezing and thawing), which significantly changed not only the composition and structure of the deposits but also their deposition conditions. Currently, continuous permafrost 500–700 m deep with a mean ground temperature of −11 to −10°C at a depth of 15–20 m is distributed in the Oyogos Yar area (Geocryology of USSR, 1989).

The goal of the present article is to discuss contemporary understandings of the cryolithological structure and stratigraphy (cryolithostratigraphy) of the Oyogos Yar coast Quarternary deposits.

PREVIOUS RESEARCH HISTORY

Oyogos Yar has been known since the times when the Cossacks developed the Siberian north (the first half of the 17th century), but geological research in this area began in the first half of the 19th century with studies of the southern coast of Bol'shoy Lyakhovsky Island and more northern islands. From the beginning of the 19th century to the middle of the 20th century, this region has seen the geographical and geological expeditions of M.I. Gedenshtrom (1830), P.F. Anzhu (1849), A.A. Bunge (1887), E.V. Toll (1897), K.A. Vollosovich (1930), and M.M. Ermolaev (1932). Their research revealed a wide

TABLE 1 | Local stratigraphic chart of the Dmitry Laptev Strait region Middle Pleistocene–Holocene deposits and the correlation of these deposits with general and regional stratigraphic scales.

General stratigraphic chart			Marine isotopic stages (MIS) (Pillans, Gibbard, 2012)	Age, ka	Regional stratigraphic chart of the north-east of Siberia (Resheniya, 1987)		Local stratigraphic chart of the dmitry Laptev Strait area	Cryostratigraphic type of deposits	
Period	Epoch	Stage	1		Modern		Holocene (Hal)	alas complex and other deposits	
Quaternary	Holocene			11,7	Yedoma superhorizon	Sartan	Yana suite (Van)	Ice Complex	
	Pleistocene	Upper	2	29		Molotkov	Oyogos suite (01^{1}g)	Ice Complex	
			3	57		Oyogos			
			4	71	Kazantsev		Krest-Yuruakh suite (KrY)	alas complex	
			5	126					
							Bychchagy suite (Bch)	Ice Complex	
		Middle	6	191	Keremesit superhorizon		Kuchchugui suite (Kch)	Syncryogenic cryofacies (Kch-S)	tabler cycofaciess (Kch-T)
			7	243			Zimov'e layer (Zim)	alas complex and relic active layer	
			8	301			Yukagir suite (Yuk)	Ice Complex	

distribution of thick ground ice in this area and the presence of a great number of mammoth fauna mammal bones in the permafrost.

Astronomer E. F. Skvortsov and topographer N. A. Iyudin completed the first detailed description and topographic survey of Oyogos Yar in 1909 (Skvortsov, 1914, 1930). After this, over the course of many years, researchers who visited Northern Yakutia did not work at the cliff itself. Until the end of the 1950's, understanding of the stratigraphy and structure of Quaternary deposits in the Dmitry Laptev Strait area was based on data obtained on the New Siberian Islands and was described in a series of general works (Grigoriev, 1932; Spizharskiy, 1940; Saks, 1948; Lobanov, 1957; Zagorskaya, 1959).

The upper ice-rich horizon of Dmitry Laptev Strait area deposits was considered to be a result of the existence of a specific type of slow-moving glaciation, termed the Novosibirsk type, in the Pleistocene (Toll, 1897), which was transformed during the Holocene. According to Ermolaev (1932), its remains were called "ice facies", which formed low watersheds, and the local depressions dividing them were called "aly facies". Presently, such watersheds are called yedoma, while the depressions between them are called alas basins (drained thermokarst depression). In 1958, Gusev proposed a stratigraphic coastal lowland column (Yana-Indigirka and Kolyma lowlands together), which identified for the first time a "mammoth horizon" occupying a particular stratigraphic position and connecting the bone-bearing layers with the main masses of ground ice, which Gusev considered fossil aufeis (Gusev, 1958).

Geological data on the age and structure of Oyogos Yar Quaternary deposits, which have not lost their value to this day, were obtained during the work of a thematic expedition of the Permafrost Institute of the Academy of Sciences of the Soviet Union in 1952–53. The work was conducted in the valley of the Yana and Indigirka rivers under the leadership of P.A. Shumskiy, N.F. Grigoriev, and P.F. Shvetsov. In the spring of 1953, a group formed by N. F. Grigoriev and T. P. Kuznetsova inspected Oyogos Yar and the southern coast of Bol'shoy Lyakhovsky Island (Kuznetsova, 1965). As a result of this reconnaissance work, deposits occurring under ice-bearing layers of the yedoma "mammoth horizon", represented by loams with faint wavy horizontal layering, were described for the first time. It was proven for the first time that the main mass of ground ice in the Yana-Indigirka Lowland of Yakutia is represented by ice wedges, rather than by glacial ice. As a result, a working chart of Quaternary deposit stratigraphy was proposed (Vtyurin et al., 1957), which matched M.M. Ermolaev's chart.

N. N. Romanovskii worked on the Complex Physical-Geographical Expedition of the Arctic Research Institute in 1956 and on the expedition of the Geological Research Institute (NIIGA) in 1957. He was the first to describe in detail the frozen deposits and ground ice outcrops of the southern Bol'shoy Lyakhovsky Island coast and the western part of Oyogos Yar (Romanovskii, 1958; 1961a,b). N. N. Romanovskii was the first to consider the Quaternary deposits of this region from the perspective of their cryostratigraphy. He described in detail the low ice-content

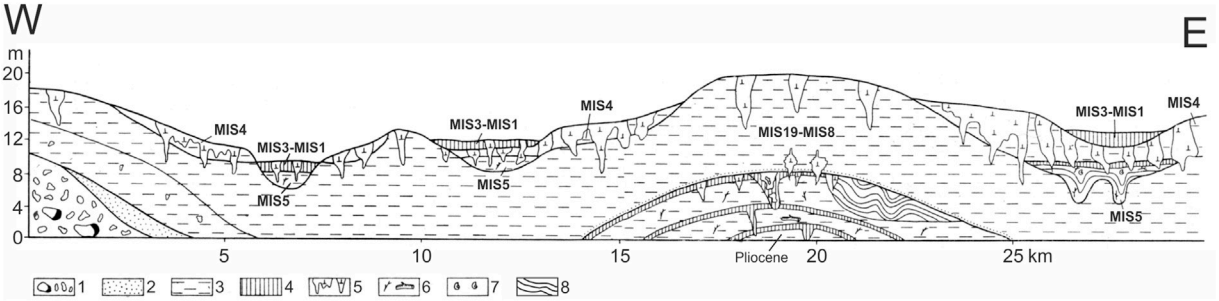

FIGURE 2 | Schematic section of deposits in the Oyogos Yar outcrop (Konishchev and Kolesnikov, 1981). Legend: 1—coarse clastic material; 2—sand; 3—silty loam; 4—peat; 5—ice wedges; 6—plant remains; 7—freshwater mollusk remains; 8—silty loams with lenticular layering. MIS—marine isotope stage.

loam horizon with poorly defined wavy layering, which he attributed to Middle Pleistocene lagoon deposits. Later, V. I. Kayalainen and Yu. N. Kulakov named this horizon the Khromskaya Suite, which, they concluded, has a littoral marine genesis and a mid-Late Quaternary age (Kayalainen and Kulakov, 1965).

N.N. Romanovskii gave particular attention to the contact between lagoon loams and overlying deposits, which was complicated by numerous concave structures that he called "draping permafrost structures" (Romanovskii, 1958) and identified as ice wedge casts. N.N. Romanovskii attributed overlying ice-rich deposits with ice wedges to various facies of floodplain alluvium, while Kayalainen and Kulakov (1965) related them to shoreline marine and lacustrine-boggy deposits connected by a facies transition. The latter authors named these deposits the Oyogos Suite. Its age, based on the findings of *Mammuthus Primigenius,* was determined to be Late Pleistocene.

A significant accomplishment of N. N. Romanovskii is his consideration of the question of thermokarst depression formation and the accumulation of deposits in these basins. He recognized within them taberal, lacustrine, and alas-specific (polygonal-boggy) deposit facies (Romanovskii, 1961a). These facies and related deposits were named the "alas complex" (Kaplina, 2009).

In 1965, around the Svyatoi Nos Cape and to the south, work to estimate the presence of tin was performed by NIIGA researchers S. M. Prokhorova, O. A. Ivanov, S. I. Andreev, and others. As a result, a local stratigraphic column was created (Prokhorova and Ivanov, 1973). According to this column, the remains of mammoth fauna representatives characterize several suites of Middle and Late Pleistocene age at this point. Low ice content loams with wavy layering described earlier were named the Kuchchugui horizon, which combined the Kuchchugui Suite itself in the Dmitry Laptev Strait area, the Khromskaya Suite in the Khroma River basin, and the Allaikhovskaya Suite in the Indigirka River basin. Genesis was viewed as lacustrine-lagoon for the Kuchchugui and Khromskaya suites and alluvial for the Allaikhovskaya Suite, following Lavrushin (1963). Later, by the decision of the Interdepartmental Stratigraphic Committee (Resheniya, 1987), the Kuchchugui horizon was abolished, and the three aforementioned suites were joined into the Keremesit superhorizon (**Table 1**).

For the first time, in this stratigraphic chart, deposits composing draping permafrost structures (as cited in Romanovskii, 1958) were named as an individual subdivision: the Krest-Yuryakh Suite. These deposits were recognized as lacustrine and attributed to the beginning of the Late Pleistocene. All suites represented by morphogenetic ice-rich deposits (Ice Complex) were joined into the Oyogos horizon: Oyogos, Vorontsov, Muskhain, and other suites. They compose the top part of yedomas and contribute to the formation of the third floodplain terrace of the Yana and Indigirka river valleys. Most researchers consider the genesis of these suites' deposits to be alluvial and lacustrine-alluvial, while some have viewed it as eolian (Tomirdiaro, 1980).

In 1977, researchers of the Department of Cryolithology and Glaciology of the Faculty of Geography of Moscow State University, V.N. Konishchev and S. F. Kolesnikov, worked at the Oyogos Yar outcrop, studying its structure and composition (Konishchev and Kolesnikov, 1981). They compiled the first published Oyogos Yar deposits' section (**Figure 2**) and confirmed the exact structure of the section, which had been described earlier by Ivanov (1972).

During the Permafrost Institute's expedition fieldwork at Oyogos Yar, G.F. Gravis obtained the first radiocarbon dates from Oyogos Suite deposits (Gravis, 1978), to which D.K. Bashlavin's dates were later added (Kaplina and Lozhkin, 1982). Six dates from *in situ* peat lenses showed an age from >41,000 (MAG-545) at the base of the suite to 34,200 ± 2,300 (MAG-544) at a height of 30 m above sea level.

In 1993–1994, a joint expedition of the Permafrost Institute of the Siberian Branch of the Russian Academy of Sciences (SB RAS) and the Institute of Low Temperature Science (Sapporo, Japan) worked on the outcrops at the southern coasts of Bol'shoy Lyakhovsky Island and Oyogos Yar. During the work, new radiocarbon dates for peat interlayers in the Oyogos Yar section were obtained. An accelerator mass spectrometry (AMS) date of 22,940 ± 390 (NUTA-3521) was obtained at a depth of 1 m below the surface, and two infinite dates were obtained lower (Nagaoka et al., 1995).

In the mid-1990s, A. A. Arkhangelov found deposits with ice wedges on the southern coast of Bol'shoy Lakhovsky Island, and in the western part of Oyogos Yar, the age of which was estimated to be one million years based on paleomagnetic data and the results of

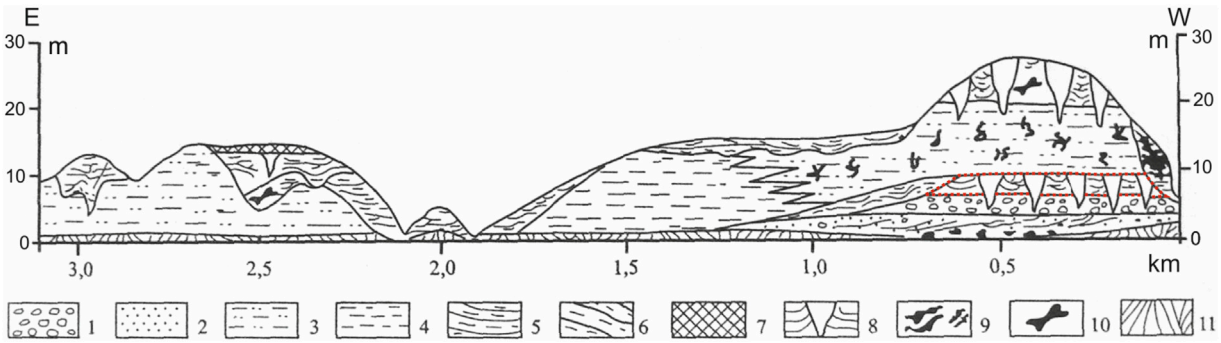

FIGURE 3 | Structure of the Quaternary deposits section 7.5 km east of Cape Svyatoy Nos (as cited in Nikolsky and Basilyan, 2004). The Yukagir Suite is indicated by the red dotted outline. Legend: 1–gravel with sand and loam layers; 2—oblique sands with casts; 3—thin layered loamy sands with grass rootlets; 4–more aleuritic thin layered loamy sands; 5—aleurites with ice wedges; 6—Pleistocene and Holocene alas complexes; 7—peat; 8—ice wedges; 9—woody remains; 10—remains of large mammals; 11—talus.

thermoluminescence dating (Arkhangelov, 1996). A.A. Arkhangelov correlated these deposits with the Olyor (Sher, 1971) and Serkinskaya (Ivanov, 1972; Prokhorova and Ivanov, 1973) suites of Pliocene-early Pleistocene age. However, further research showed that Arkhangelov's understanding was in error (Nikolskiy et al., 1999; Schirrmeister et al., 2002; Nikolskiy and Basilyan, 2004).

The briefly discussed history of cryolithological and stratigraphic research in the Dmitry Laptev Strait area, including at Oyogos Yar itself, shows that only toward the end of the 20th century were the main geological bodies identified and the local stratigraphic column compiled (**Table 1**); the description of the local stratigraphic column, however, was not widely accepted (Resheniya, 1987). The permafrost evolution, the relationship between the identified bodies, and the age and genesis of the deposits remained poorly studied, and the results were often contradictory until the end of the 20th century.

In 1996, 1999, and 2001, researchers of the Geological Institute RAS, P. A. Nikolskiy and A. E. Basilyan, worked in the Svyatoy Nos Cape area and in the western part of Oyogos Yar. They studied the section at the northern coast of the Svyatoy Nos Peninsula, where they designated the aforementioned deposits with ice wedges, described by A. A. Arkhangelov, as the Yukagir Suite (Nikolskiy et al., 1999; Nikolskiy and Basilyan, 2004). In 1999, 2002, and 2007, a joint Russian-German expedition worked on the Dmitry Laptev Strait outcrops within the "Laptev Sea System" program, and in 2004, a group within the Russian-American archeological project "The High-Latitude Arctic and Humans" worked here as well. The authors of the article conducted cryolithological and paleontological research into the structure and stratigraphy of the frozen Quaternary deposits on these expeditions (Kunitsky et al., 2000, Schirrmeister et al., 2003, 2008; Tumskoy and Basilyan, 2006, 2009; Tumskoy, 2012). The results of their fieldwork are the main content of this article.

Prior to describing the section construction, it is essential to call attention to one important term, the Ice Complex. We will not discuss in detail the meaning of "Ice Complex" because that is a separate, complex subject, but in the present article, Ice Complex refers to syncryogenic frozen deposits, which have been accumulated during cool climate periods of different durations and contain syngenetic ice wedges that form a closed polygon network. Using this definition, it is possible to distinguish Ice Complexes of different ages, which are divided by either interstadial deposit horizons or strongly pronounced thaw unconformity contacts of a regional or local scale. Three such Ice Complexes of different ages were identified in the Dmitry Laptev Strait area (Tumskoy, 2012). Later studies made it possible to identify four Ice Complexes (Wetterich et al., 2019). The MIS 4–MIS 3 aged Ice Complex deposits, which form the yedoma uplands, are called the Yedoma Ice Complex (Schirrmeister et al., 2013).

CRYOLITHOLOGICAL STRUCTURE OF THE OYOGOS YAR SECTION

The Quaternary deposits exposed in the Oyogos Yar outcrop largely match the deposits studied in the section at the Bol'shoy Lyakhovsky Island southern coast (Andreev et al., 2004; Schirrmeister et al., 2002, 2008, 2011; Tumskoy, 2012; Wetterich et al., 2011, 2014, 2016, 2019, 2021). Owing to this, the stratigraphy and deposition conditions of the deposits on Bol'shoy Lyakhovsky Island and in the Oyogos Yar area can be taken into consideration together. However, there are also certain differences that reflect the different tectonic positions of the strait's coasts.

The Oyogos Yar section can be divided into two parts. On the northern coast of Svyatoy Nos Peninsula, from its cape to approximately the Chay-Povarnya River mouth, Quaternary deposits occur on bedrock represented mainly by Early Cretaceous basaltic andesites and their tuffs, broken by granodiorites. To the east of the Krest-Yuryage River mouth, the coast for more than 120 km is composed entirely of frozen unconsolidated deposits.

Unlithified deposits, more ancient than those described in the Bol'shoy Lyakhovsky Island section, are exposed within Oyogos Yar at two areas. The first is located on the northern coast of the Svyatoy Nos Peninsula in the coastal outcrop near the mouth of

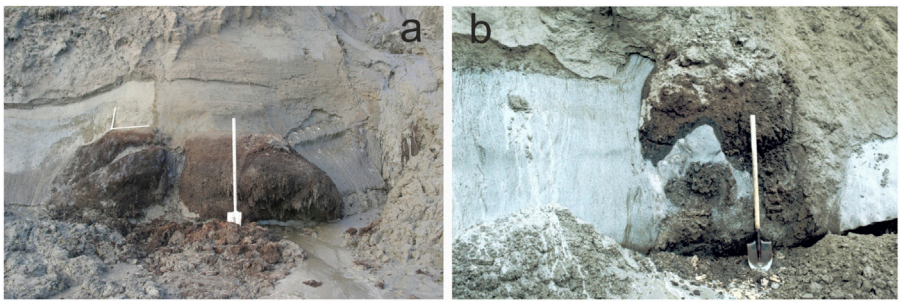

FIGURE 4 | Polygonal autochthonous peat lenses with ice wedge generation **(A)** and with partially thawed Yukagir ice wedges **(B)** on Bol'shoy Lyakhovsky Island.

the Chay-Povarnya River. The section structure (**Figure 3**) and formation history of this location are discussed in detail in the articles of P. A. Nikolskiy and A. E. Basilyan (Nikolskiy et al., 1999; Nikolskiy and Basilyan, 2004). The second outcrop of the ancient deposits is located between the mouths of the Ulakhan-Tala and Rebrova rivers. It was apparently first described at the end of the 1970's (Konishchev and Kolesnikov, 1981). The deposits and structure of these two sites differ significantly from each other, which complicates their direct comparison.

At the base of the coastal cliff on the northern coast of Cape Svyatoy Nos, grayish-yellow sands with lenses containing gravel and small rock debris are exposed, as well as lens-like loam interlayers with remains of carbonized vegetation detritus. The total thickness of this deposit is approximately 3 m. Ice wedge casts up to 1.5 m in height and composed of ice rich loams are situated at the top of the gravel-debris lenses. The top of the layer contains another ice wedge casts composed of overlain and enclosing deposits (both horizons of the casts are not shown on the general section in **Figure 3**). The height of the wedge casts reaches 2 m. Higher up, poorly sorted rock debris beds occur in an enclosing sandy loam layer with lens-like interlayers of ice-rich loams. The cryogenic texture of the rock debris beds is massive; that of the loams is inclined-reticular.

Yukagir Suite and Zimov`e Layer

A sandy layer with gravel and rock debris is overlain by ice rich light bluish-gray loams (**Figure 3**) described by P. A. Nikolskiy and A. E. Basilyan (Nikolskiy et al., 1999) on the Svyatoi Nos Cape and named the Yukagir Suite (**Table 1**). The same deposits were also identified in 1999 on Bol'shoy Lyakhovsky Island (Tumskoy and Basilyan, 2006, 2009), and described and dated (Schirrmeister et al., 2002; Meyer et al., 2002; Andreev et al., 2004; Blinov et al., 2009; Tumskoy, 2012; Wetterich et al., 2014, 2019). The Yukagir Suite deposits are 3 m thick at Oyogos Yar and reach 4.5 m on Bol'shoy Lyakhovsky Island. The deposits are characterized by a high ice content; ice belt cryogenic structures with a belt thickness of up to 2 cm are typical for them. Two generations of ice wedges are developed in this suite. The first generation is represented by syngenetic ice wedges up to 1.5 m wide with no less than 5 m between them (**Figure 3**); the second is represented by syngenetic wedges up to 0.5 m wide that fracture the polygons of the first generation (the second generation is described only on Bol`shoy Lyakhovsky Island). The first generation's ice wedges penetrate approximately 2 m into the underlying deposits. The genesis of these deposits is supposedly slope (Nikolskiy and Basilyan, 2004; Tumskoy, 2012). Nikolskiy and Basilyan (2004) estimate the Yukagir Suite deposits to be of Middle Pleistocene age (390–220 ka), while Tumskoy (2012) estimates the age to be 250–200 ka as determined by U-Th datings of overlying peats (Schirrmeister et al., 2002) on Bol`shoy Lyakhovsky Island. The latest U-Th data from Yukagir Suite peat are about 200 ka (the average between 178 ± 14 and 221 ± 27 according to different models of U-Th age determination) (Wetterich et al., 2019). The Yukagir Suite deposits resemble an Ice Complex in their cryolithological characteristics.

To the east, the Yukagir Ice Complex on Svyatoy Nos Peninsula is overlain by inclining and gradually lateral disappear sandy loams with lenses of shingle beds and sand with gravel and a massive cryogenic texture (**Figure 3**) (Nikolskiy and Basilyan, 2004). In terms of contact type, they resemble a lens that is included in or leaning against the Yukagir Ice Complex deposits. In Bol'shoy Lyakhovsky Island sections, polygonal autochthonous peat lenses 1.0–1.2 m thick occur on partially thawed ice wedges and ice rich deposits of the Yukagir Ice Complex (**Figure 4**). The author's point of view differs from that of our colleagues (Schirrmeister et al., 2002; Wetterich et al., 2019), who believe that these peat lenses are a part of the Yukagir Ice Complex.

A 0.3–0.6 m thick layer that is represented by yellowish-gray cryoturbated loams containing rock debris (**Figure 5**) overlies the deposits of the Yukagir Ice Complex, the sandy loam lenses, and the peat lenses enclosed within it. The concentration of debris near the top of the horizon indicates that it underwent cryogenic heaving. Overall, this layer covers the top of the underlying deposits and was viewed as a relic active layer (Tumskoy, 2012). In a later publication, this relic active layer is named the Zimov`e stratum (Wetterich et al., 2019).

All described deposits on the Svyatoi Nos Cape and Bol'shoy Lyakhovsky Island, which are enclosed within the Yukagir Ice Complex or overlay it, are identified by V. E. Tumskoy as the Zimov`e Layer ("Zimov inskaya Thickness" in the initial thesis, Tumskoy and Basilyan, 2006; Tumskoy, 2012). These deposits are envisaged to be the result of thermokarst and thermodenudation development of ice-rich Yukagir Ice Complex deposits and can be

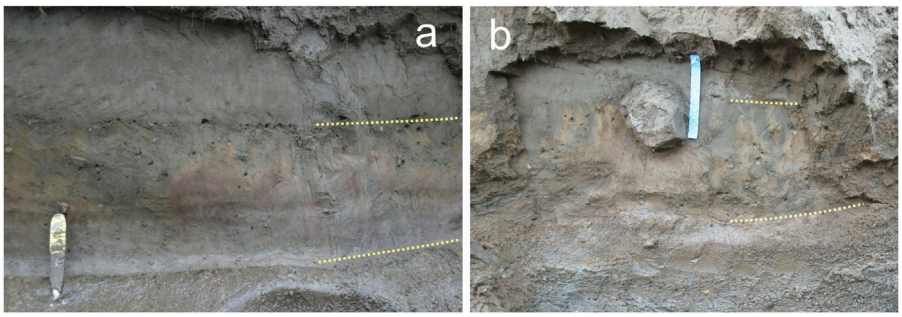

FIGURE 5 | Zimov`e stratum is a relic active layer over Yukagir Ice Complex deposits on the Svyatoi Nos Cape **(A)** and Bol`shoy Lyakhovsky Island **(B)**. The yellow dotted lines show the top and bottom of this stratum.

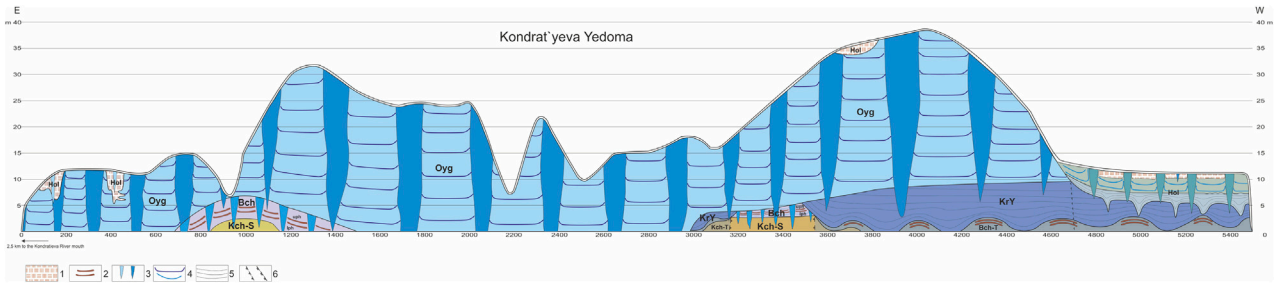

FIGURE 6 | Cryolithostratigraphic structure of the Kondrat`yeva yedoma section on the Oyogos Yar at a site 2.5–8 km west of the Kondrat`yeva River mouth. Legend: 1—peat, 2—lenses of polygonal autochthonous peats and peaty aleurites, 3—ice wedges of different generations, 4—ice belt cryogenic structures in syncryogenic deposits, 5—stratification of sediments in deposits, and 6—boundaries between taberal and non-thawed deposits. The unit`s symbols explained in **Table 1** (in addition: Bch-T stands for Bychchagy Ice Complex taberal deposits).

described as fragments of an alas complex formed as the result of partial thawing of the Yukagir Ice Complex. The age of the Zimov`e Layer peat lenses was determined to be about 200 ka using U-Th dating (Schirrmeister et al., 2002; Wetterich et al., 2019).

Ancient unconsolidated deposits occur as an extended arched uplift at the second Oyogos Yar site (between the mouths of the Ulakhan-Tala and Rebrova rivers at a distance of 15–25 km from West in **Figure 2**). Their top reaches a height of 8–10 m a.s.l. and gently slopes down both westward and eastward. In the section, two types of these deposits are seen. The first type is present as relatively homogenous gray and light bluish-gray loams with autochthonous peat lenses up to 0.3 m thick. The second type is present as alternating layers of aleurites, loams, and peaty loams, where casts of the wrapping structure with a polygon network 8–12 m between casts occur. These deposits have been described (Konishchev and Kolesnikov, 1981) but, despite a visible thickness of approximately 10 m, have not been studied in detail yet. Their age has not been determined.

Yukagir Suite and Zimov`e Layer deposits are not exposed within the studied Kondrat`yeva Yedoma section. The most ancient deposits that are exposed here at the base of the coastal cliff are Kuchchugui Suite deposits of the Keremesit superhorizon (**Figure 6**).

Kuchchugui Suite

A peculiarity of Kuchchugui Suite deposits on both coasts of the Dmitry Laptev Strait is that they are represented by deposits of two types. They were not differentiated in the works of the first researchers (N. N. Romanovsky, V. I. Kayalaynen, Yu.N. Kulakov, O. A. Ivanov, V. N. Konishchev et al.). Later, they were viewed as two varieties that had formed under different conditions–subaerial and subaqueous (Kunitskiy, 1996; Andreev et al., 2004). Tumskoy (2012) argued for their single sedimentational origin but demonstrated that these layers differ in the cryogenic history of development. He marked two Kuchchugui Suite deposit cryofacies—syncryogenic (Kch-S in **Figure 6**) and taberated (Kch-T in **Figure 6**). The geological age of these cryofacies sediments is the same because the contact between them is a thaw unconformity, not a sedimentological type (Tumskoy, 2012, 2021). Based on their position in the section, micropaleontological study results, and an infinite radiocarbon dating age (Nikolskiy and Basilyan, 2004), most researchers estimate these layers to have a Middle Pleistocene age. A single infrared stimulated luminescence (IRSL) date of 112.5 ± 9.6 ka obtained from the top part of the Kuchchugui Suite deposit section at Oyogos Yar (Opel et al., 2017) indicates that the formation of these deposits was possible until the beginning of the MIS 5.

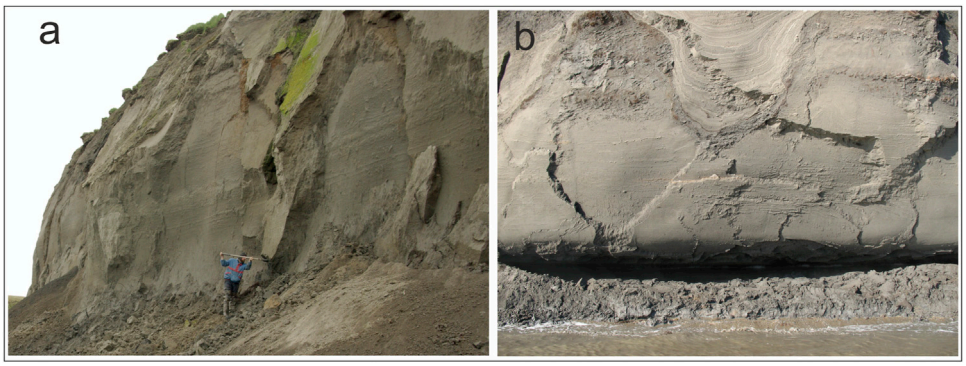

FIGURE 7 | Kuchchugui deposits: **(A)** syncryogenic cryofacies on Oyogos Yar (yellow-greenish color mark modern lichens on the outcrope`s wall) and **(B)** taberated cryofacies (under Krest-Yuryakh`s casts) on Bol`shoy Lyakhovsky Island.

Deposits of the **syncryogenic cryofacies** within the Kondrat`yeva Yedoma are exposed at two sites approximately 1 and 3.4 km west of the Kondrat`yeva River mouth (**Figure 6**).

These deposits were exposed at the base of the visible part of the section for distances of approximately 200 and 400 m, respectively. The lowest of the suite's deposits is positioned below sea level, and the top of the suite's deposits is positioned at a height of approximately 3 m a.s.l. The deposits consist of brown, grayish-brown, and yellowish-gray loams and dusty loamy sands with a high plant detritus content (**Figure 7A**). Faint horizontal and fine wave horizontal layering is typical for them owing to changing layer color and the distribution of plant detritus. The layers are 1–5 mm thick. In addition to detritus, the deposits are enriched in places by thread-like rootlets 10–15 cm long. Rounded subhorizontal peat inclusions up to 10 cm diameter are seen. In places, the layering is disrupted by a series of small wedge-like deformations. They occur in individual layers, with vertical lengths from 1 to 2–3 cm and widths of no more than 1 cm. Visually, they resemble traces of small desiccation cracks. Syncryogenic cryofacies deposits have a low gravimetric ice content usually not exceeding 30%–40%. The cryostratigraphy is relatively homogenous and is characterized by prevailing massive and microlens textures. Ice wedges within syncryogenic cryofacies of the Kuchchugui Suite were described in the Kondrat`yeva Yedoma (Opel et al., 2017) and in other places. Very narrow, up to 10–15 cm wide, epigenetic ice wedges permeating Kuchchugui Suite deposits are noted in outcrops near Cape Svyatoy Nos (Nikolskiy and Basilyan, 2004) and Bol'shoy Lyakhovsky Island (Tumskoy, 2012). Syngenetic ice wedges up to 0.5 m wide in the bottom part of Kuchchugui Suite are described west of the Kondrat`yeva Yedoma in outcrops closer to the Ulakhan-Tala River (Konishchev and Kolesnikov, 1981, **Figure 2**) and on Bol'shoy Lyakhovsky Island (Tumskoy, 2012). In both places, the structure of the syngenetic ice wedge upper parts has specific feature—higher than level with maximal wide, they make narrow upward and disappear through 0.5–1 m. Ground-ice wedges (sand-ice wedges) up to 0.75 m wide were described within Kondrat`yeva Yedoma by Th. Opel (Opel et al., 2017) and in Bol`shoy Lyakhovsky Island by first author. Larger syngenetic wedges up to 1.5–2 m wide are noted only in the middle part of the described cryofacies on Bol'shoy Lyakhovsky Island (Tumskoy, 2012).

Taberated cryofacies of Kuchchugui Suite deposits are distributed in Oyogos Yar outcrops much more widely than are syncryogenic cryofacies. The term "taberated" is used in the Russian scientific literature (Romanovskii, 1961a, 1993) to refer to deposits with low ice content, which thawed within taliks. Taberated deposits preserve the main peculiarities of structure (lamination and so on) after they have thawed, unlike taberal deposits, which form as a result of thawing of very ice-rich deposits and which completely lose their initial sediment structure. The bottom of the taberated deposits of this cryofacies is exposed only near the arched uplift by the Ulakhan-Tala River, and the nature of the contact with underlying deposits has not been studied yet. In Kondrat`yeva Yedoma sections, 2–3 m thick taberated cryofacies deposits are described at the base of the western part of the yedoma massif.

The taberated cryofacies are represented by dense bluish-gray and light bluish-gray loams, often dusty, with numerous dark gray and black spots 1–1.5 cm in size (**Figure 7B**). The loams have a well-defined thin, uneven horizontal, and fine wavy layering; the layers are 2–10 mm thick. The ice content is insignificant (the gravimetric ice content is not more than 30%–40%), and the cryogenic textures are massive. Except for the bottom ends of ice wedges that protrude into this layer from overlying deposits, massive ice is entirely absent in the deposits.

The lateral transition between the two described cryofacies is usually subvertical or gently inclined. The width of the contact zone does not exceed 5–10 m. Taberated cryofacies deposits always occur on syncryogenic cryofacies deposits in the case of inclined contact.

Kuchchugui Suite deposits were initially viewed as lagoon (Romanovsky, 1961b), lacustrine-lagoon (Ivanov, 1972), or lacustrine (Nikolskiy and Basilyan, 2004) in origin. During the course of the work on Bol'shoy Lyakhovsky Island and Oyogos Yar traces of erosional scours within syncryogenic cryofacies deposits, syngenetic ice wedges, interlayers of sod cover in the original bedding, and other indications of a subaerial origin of the deposits were found (Tumskoy and Basilyan, 2006, 2009). German researchers adhere to an alluvial origin of the

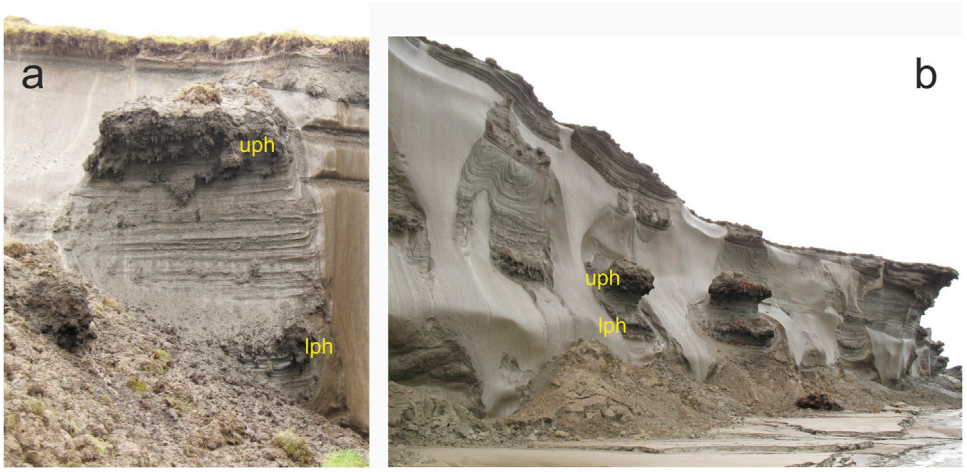

FIGURE 8 | Bychchagy Ice Complex deposits with two horizons of polygonal autochthonous peat lenses: **(A)** Oyogos Yar (height of outcrop is 3 m) and **(B)** Bol'shoy Lyakhovsky Island (uph–upper peat horizon, lph—lower peat horizon; height of outcrope is 12–15 m).

Kuchchugui Suite deposits, attributing them to floodplain deposits (Opel et al., 2017). Earlier, V. E. Tumskoy suggested that these deposits represent a complex of syncryogenic fluvioglacial deposits with ice wedges related to the degradation of the glacial cover in the northeast of the New Siberian Islands (Tumskoy, 2012). Afterwards, they were subjected in places to thawing within lake taliks. At sites where the deposit kept its initial sedimentation structure and cryostratigraphy, it is represented by syncryogenic cryofacies deposits, and at sites where the deposits thawed and were transformed into taliks, these deposits are represented by taberated cryofacies. The formation of taberated cryofacies is linked by the authors of the present study to the formation of Krest-Yuryakh Suite deposits; this formation is described below and took place during the first warm interglacial of Late Pleistocene (MIS 5).

Bychchagy Suite

The deposits of Kuchchugui Suite syncryogenic cryofacies are overlain by deposits that were first noted in 2004 (Tumskoy and Basilyan, 2006, 2009) on the southern coast of Bol'shoy Lyakhovsky Island. Based on their cryolithological features, these deposits are attributed to the Ice Complex and identified as their own stratigraphic subdivision, the Bychchagy Suite, which was identified by V. E. Tumskoy on the southern coast of the Dmitry Laptev Strait in 2007 in the Kondrat`yeva Yedoma section. Bychchagy Suite deposits have not yet been found in other places at Oyogos Yar. The Bychchagy Suite always occurs directly atop the deposits of the Kuchchugui Suite syncryogenic cryofacies; it is 3–4 m thick at the site located closer to the mouth of the Kondrat`yeva River and about 2–2.5 m thick 3.5 km away from the river mouth (**Figure 6**). The thickness of the Bychchagy Suite reaches 6–8 m on Bol'shoy Lyakhovsky Island (Tumskoy, 2012). Contact with Kuchchugui Suite deposits is gradual, but well-defined. In sections, the Bychchagy Suite transitions up the section into the Yedoma Ice Complex, but stratigraphically Krest-Yuryakh Suite deposits are positioned between them.

Bychchagy Suite deposits (**Figure 8**) are represented by ice-rich gray or brown-gray sandy loams and loams with individual rounded peat inclusions up to 10 cm in diameter. The cryostratigraphy depends on ice belt structures; the ice belt thickness ranged from 1–2 cm to 3–5 cm, and belts were positioned from 5 to 15 cm apart from each other. Between ice belts, microlens-like and sometimes reticular structures with ice lens thickness of up to 1 mm prevail. Large syngenetic ice wedges up to 3 m wide are developed in the deposits. They form a closed polygon network with a distance of approximately 12–15 m between the axes of the ice wedges. The total volumetric ice content of these Ice Complex deposits reaches 80%–90%.

A distinguishing peculiarity of Bychchagy Suite deposits is two horizons of very peaty dusty sandy loams or peat bogs. Each horizon is represented by individual peat lenses occurring at approximately the same level between ice wedges (**Figure 8**).

These deposits are divided vertically by a layer of icy loams or sandy loams as described above. The thickness of the peaty lenses on the southern coast of Bol'shoy Lyakhovsky Island is 1–1.5 m, and the vertical distance between lenses reaches 3–4 m. The thickness of the lenses in Kondrat`yeva Yedoma sections is reduced to 0.8–1 m, and the distance between them is 1–2 m. At the base of the lenses, the remains of mossy and grassy vegetation are present as rounded or wedge-like inclusions 10–20 cm in diameter, enclosed in icy deposits. Upward, toward the top of the lenses, the quantity of the inclusions increases, and near the top, the inclusions merge into a single peat body. The lenses are traced as the upper and lower peat horizons (**uph** and **lph** in **Figures 6**, **8**) for hundreds of meters along the outcrop, disrupted by later erosional scours. Ice wedges of a second generation up to 1 m wide that divide the ground blocks in the middle often begin between the top and bottom

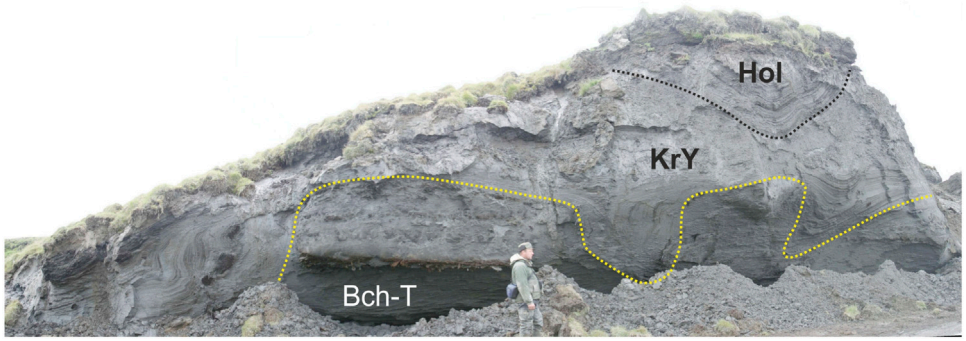

FIGURE 9 | Krest-Yuryakh Suite deposits (KrY) form ice-wedge casts as the result of Bychchagy Ice Complex thawing. In this section (Oyogos Yar), there are taberal Bychchagy Ice Complex (Bch-T) deposits with a thawed peat lens and the Holocene ice-wedge cast (Hol) as a result of yedoma Ice Complex thawing.

peaty lenses. They are 3–5 m in vertical length and sometimes penetrate into underlying deposits.

Bychchagy Suite deposits are viewed by the authors as lacustrine and bog in origin and in places, possibly, as lacustrine-alluvial deposits. They formed under cold, but more humid conditions compared to Kuchchugui Suite deposits, which is evidenced by their isotopic composition and significantly higher ice content (Meyer et al., 2002; Wetterich et al., 2016). The age of the deposits is determined by the authors, according to their stratigraphic position and specific composition, to be the early beginning of the Late Pleistocene (the beginning of the Eemian warming, MIS 5). Infinite radiocarbon dates and the results of U-Th dating of the polygonal peaty lenses confirm this: 126 + 16/–13 and 117 + 19/–14 kyr for the bottom, 93 ± 5 and 89 ± 5 kyr for the top horizons means that the accumulation period of the Bychchagy Suite is MIS 5e-5b (Wetterich et al., 2016).

Krest-Yuryakh Suite

Krest-Yuryakh Suite deposits are positioned stratigraphically higher than the Bychchagy Suite (Ivanov, 1972). They are widely distributed in sections on both coasts of the Dmitry Laptev Strait, occurring as individual lenses from 1-2 to 10 m thick and stretching from several dozen meters to several kilometers in length. Within Oyogos Yar, Krest-Yuryakh deposits were studied in the bottom part of Kondrat'yeva Yedoma (**Figure 6**) and in sections to the west of Cape Svyatoy Nos (Nikolskiy and Basilyan, 2004). These deposits may also occur at other sites, but those occurrences would be below sea level.

Krest-Yuryakh deposits are represented by gray and blue-gray loams, with plant detritus including fragments of shrub twigs and roots up to 5–8 cm in diameter. Entire valves of genus *Pisidium* shells (Pfeiffer, 1821) and their fragments are often present. The deposits are layered, and the thickness of the individual layers varies from a few millimeters to 1–2 cm. Small current ripple structures composed of diagonal layers less than 1 mm thick are present within many layers. The primary lamination has been destroyed by a series of subvertical fractures with amplitude 1–3 cm. Ferruginization of deposits along the fractures yields an ochre coloration 1–2 cm wide. Cryogenic textures in the loams are massive; ice lenses less than 1 mm thick, which are oriented parallel to the layering, are rarely seen. Overall, the deposits are very dense and dry, and the gravimetric ice content of the deposits does not exceed 15%–20%.

Krest-Yuryakh deposits were first viewed as lacustrine (Ivanov, 1972). It was long thought that they formed as a result of the thawing of Kuchchugui Suite deposits, but given the insignificant ice content, this appears to be almost impossible. In the beginning of the 21st century, it was suggested that these lacustrine deposits are the result of lake thermokarst development in icy Bychchagy Suite deposits (Tumskoy and Basilyan, 2006, 2009); moreover, sites of the section were found in which the geological contact between deposits is exposed (Tumskoy, 2012). Krest-Yuryakh lacustrine deposits form relatively thin lenses enclosed in the Bychchagy Suite. The bottom of the lenses forms a well-defined network of rounded ice wedge casts (previously described as draping permafrost structures (Romanovskii, 1958), which were formed as the result of Bychchagy Suite Ice Complex thawing (**Figures 7B**, **9**). The distance between casts is about 10–15 m, and the vertical size is 3–5 m. The layering of the lacustrine deposits in the casts has a well-defined draping form. The layering above the lacustrine deposits gradually changes to horizontal and the vegetation detritus content in the deposits decreases. Highly condensed and partially deformed lenses of peaty material occur everywhere in brownish loams between the pseudomorphs. Overall, two horizons of peaty lenses have been formed, which, together with the loams which contain them, the authors view as taberal formations (thawed remains) of the Bychchagy Suite peat lens.

Almost everywhere, the top horizons of the Krest-Yuryakh Suite deposits are scoured and exhibit a distinct erosional boundary with overlying deposits. A horizon of polygonal peats up to 2 m thick containing a network of ice wedges up to 2–2.5 m thick and covering the section of lacustrine loams was found only on Bol'shoy Lyakhovsky Island near the Vankina River (Tumskoy, 2012). Thus, the complete section of Krest-Yuryakh deposits consists of taberal formations which formed after the thawed Bychchagy Ice Complex, and lacustrine and

FIGURE 10 | Yedoma Ice Complex deposits on the Kondrat`yeva yedoma coastal bluff. The height of the bluff is 15 m.

lacustrine-boggy (specifically alas) deposits of peat bogs with ice wedges that cover the section. Such a structure is completely identical to the structure of Holocene Alas Complex deposits, which has been studied extensively on the Yana-Indigirka lowland of northern Yakutia (Romanovskii, 1961a), so we can discuss a Krest-Yuryakh Alas Complex. Taliks formed beneath Krest-Yuryakh lakes, within which underlying deposits thawed and froze again. The transformation of part of the Kuchchugui syncryogenic cryofacies into a taberated cryofacies and its partial diagenesis is attributed specifically to Krest-Yuryakh Alas Complex development.

The formation of Krest-Yuryakh Suite deposits was previously attributed to the beginning of the Late Pleistocene and linked to the first Pleistocene warming period (Ivanov, 1972; Prokhorova and Ivanov, 1973). Environmental conditions of sedimentation, composition of the deposits, pollen spectra, and findings of woody remains attest to this. A single IRSL dating of Krest-Yuryakh deposits is 102.4 ± 9.7 ka (Opel et al., 2017); this date contradicts dating from Bychchagy peat lenses. The direct geological contact between the Bychchagy Ice Complex and the Krest-Yuryakh deposits is observed near the Van`kina River on Bol'shoy Lyakhovsky Island (Tumskoy, 2012) where Krest-Yuryakh deposits lie over or are embedded within the Bychchagy Ice Complex. The same contact on Oyogos Yar has not been described until now. This indicates that the Krest-Yuryakh thermokarst lacustrine deposits are younger than the Bychchagy Suite.

Yedoma Superhorizon

Krest-Yuryakh Suite deposits are overlain by Yedoma Ice Complex deposits (**Figure 10**), which are marked stratigraphically as the Oyogos Suite of the Yedoma superhorizon (**Table 1**) in the Dmitry Laptev Strait area (Prokhorova and Ivanov, 1973; Resheniya, 1987). These deposits reach 30–35 m thickness in the Oyogos Yar area (**Figure 6**).

The composition of the Yedoma Ice Complex deposits in Northern Yakutia changes horizontally and vertically, contrary to the widespread opinion about its homogeneity (Tomirdiaro, 1980). It varies from dusty sandy loams to dusty loams and is represented in places by almost pure aleurites (Schirrmeister et al., 2011). The color of the deposits changes from yellowish-brown to gray and brownish-gray, depending on peatiness. A typical feature of the Ice Complex deposits is the presence of numerous peat inclusions of rounded and wedge-like shape, which gravitate to the central parts of the ground column between the ice wedges. The diameter of the peat inclusions usually does not exceed 10–15 cm. Wedge-shaped inclusions have a height of approximately 20–30 cm and are oriented radially downward from the middle of the polygonal blocks.

A peculiarity of the structure of all Yedoma Ice Complex sections is the cyclic repetition of the cryostratigraphical structure of the polygonal blocks (Popov, 1953; Vasil'chuk, 2017). Ice belts, thick lenticular cryogenic structures, have developed at the base of each cryogenic cycle. The belts in this part of the cryogenic cycle usually have a subhorizontal orientation and where they contact ice wedges either meet them perpendicularly or bend upward insignificantly. Within one cryogenic cycle, the belt thickness increases up the section, and the distance between belts decreases. The degree of ice belt bending increases upward near the ice wedges within each cryogenic cycle. From approximately the middle of the cryogenic cycle in the central part of the ground column between ice wedges, there is an increase in the content and size of peaty inclusions. In the top part of the section, they can form lenses of almost pure peat. The total ice volume barely changes at different levels of the cryogenic cycle, constituting 40%–50%; only the cryostratigraphy changes. Syngenetic ice wedges reach a vertical length of 30 m and more, and their width is 3–4 m on average, increasing to 6–8 m in places. There are second generation ice wedges in places.

The Yedoma Ice Complex is underlain by Bychchagy or Krest-Yuryakh Suite deposits. The contact with Bychchagy Suite deposits manifests in different ways. In some places, partially thawed ice wedges, or erosional downcuts, or changes in deposit composition are seen, while in other places visible contact is missing. In the latter case, possibly deposition was not disrupted or, for some reason, disruption may have occurred but is not manifested in the section. The contact with Krest-Yuryakh Suite deposits is clearly visible. Such a contact usually has an erosional nature and is marked by an interlayer of peaty material 0.1–0.2 m thick. Most likely, this interlayer formed as a result of erosion and redeposition of Bychchagy peaty horizons and of peat bogs covering the Krest-Yuryakh deposit section. Krest-Yuryakh Suite deposit layers, which are oriented subhorizontally at the level of contact, are often cut by this interlayer with insignificant angular unconformity.

The contact of the Yedoma Ice Complex with underlying deposits is a horizon that can be used to reconstruct the relief of the surface which existed in the beginning of MIS 4. Currently, the level of the lower thermoterrace in many yedoma uplands forms because the less icy deposits below this contact are more resistant to thermoabrasion, thermal denudation, and erosion than the more ice-rich Yedoma Ice Complex deposits above. However, Oyogos Yar thermoterraces may have formed throughout the thickness of Yedoma Ice Complex deposits (**Figure 6**).

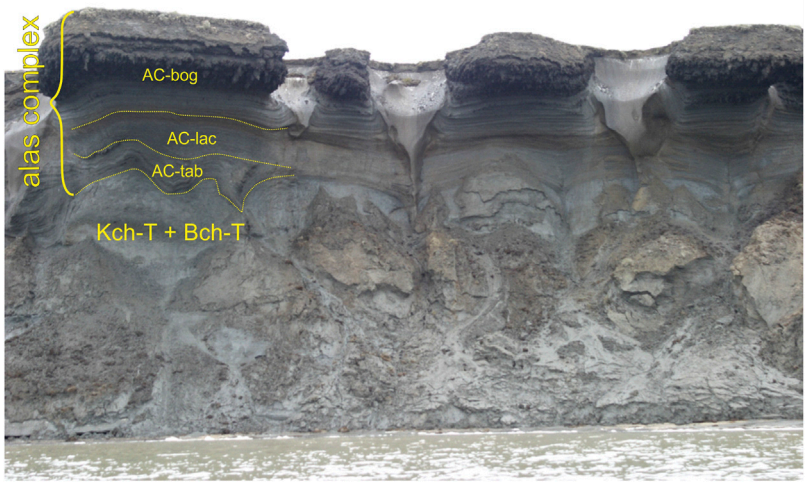

FIGURE 11 | Typical structure of the Holocene Alas Complex with taberal (AC-tab), lacustrine (AC-lac), and lacustrine-boggy (AC-bog) facies. The coastal section of the alas depression is located on Bol`shoy Lyakhovsky Island. Kch-T + Bch-T—taberated deposits of Kuchchugui and Bychchagy Suites. The height of the outcrope is 12 m.

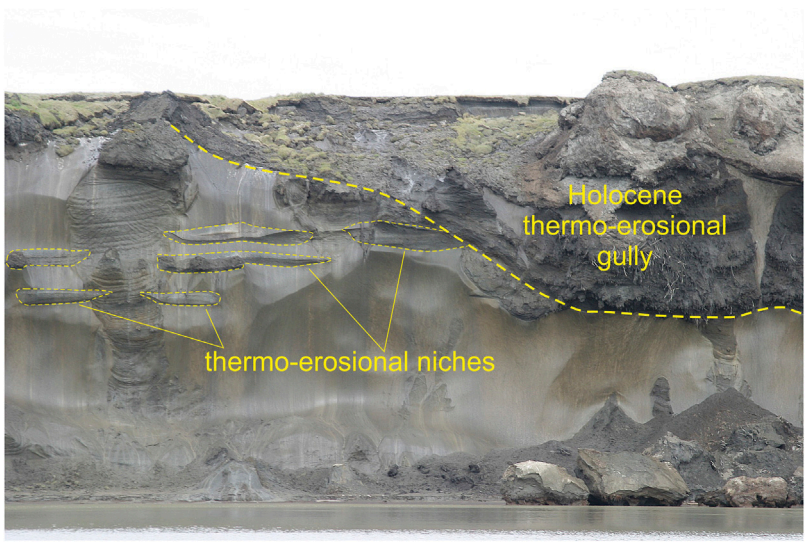

FIGURE 12 | Holocene thermo-erosional gully and niches in the yedoma Ice Complex.

On the northern coast of Svyatoy Nos Peninsula, the bottom of the Yedoma Ice Complex occurs at heights up to 19–20 m a.s.l. (Nikolskiy and Basilyan, 2004). To the east, the Ice Complex bottom drops to 5–8 m a.s.l. and then rises to 12–15 m a.s.l. again in the vicinity of the arched uplift near the Ulkhan-Tala and Rebrova rivers. To the east of the arched uplift, the elevation of the bottom gradually decreases to approximately 10 m a.s.l. in the western part of the Kondrat`yeva Yedoma. In the eastern part of this yedoma, for more than 2 km, the bottom of the Yedoma Ice Complex is positioned below sea level, rising insignificantly higher than sea level further east. To the east of the mouth of the Krestovaya River, the bottom declines below sea level again. The overall tendency of the bottom of the Ice Complex to decline in elevation is apparently tectonic in nature, while local slumps are related to erosional scours.

The genesis of Yedoma Ice Complex deposits in the Oyogos Yar area remains under discussion. Different researchers have suggested it to be lacustrine-allulvial (Romanovskii, 1961b; Konishchev and Kolesnikov, 1981), eolian (Tomirdiaro, 1980), and alluvial-proluvial (Gravis, 1996). In our opinion, the genesis of these deposits may

differ in different parts of the coast, although lacustrine-alluvial genesis apparently dominates.

The age of the deposits was determined by a series of final radiocarbon dates obtained for the top part of the Oyogos Suite section (from 49 to 32 ka.; Gravis, 1978; Kaplina and Lozhkin, 1982; Tomirdiaro et al., 1982; Opel et al., 2017) and by infinite dates for lower horizons. Overall, Yedoma Ice Complex deposit accumulation began during the first climatic cooling of the Late Pleistocene (MIS 4) and continued until the middle of the Molotkov Epoch (the relatively warm interstadial MIS 3).

In the second half of the Late Pleistocene, in the period from 32 ka to the beginning of the Holocene, an accumulation of deposits analogous in structure, which are cryolithologically the same as an Ice Complex but were developed more locally, took place within river valleys, in erosional downcuts, and under some slopes. Such deposits were found on Bol'shoy Lyakhovsky Island (Wetterich et al., 2011, 2014; Tumskoy, 2012). It may be that they also exist within Oyogos Yar since they have peat dates of 22.940 ± 390 ka BP (NUTA-3521) in the top part of the section (Nagaoka et al., 1995), but they have not yet been clearly defined geologically. Overall, they were identified as a separate stratigraphic unit (Sartan Ice Complex) called the Yana Suite (Tumskoy, 2012), but this matter requires further study.

Holocene Alas Complex

Widespread deposits of the Holocene Alas Complex on the territory of northern Yakutia are positioned stratigraphically higher than the Yedoma Ice Complex. The same stratigraphic position has a Holocene cover layer also. Like Yedoma Ice Complex deposits, the Holocene Alas Complex deposits are morphogenetic, forming the bottoms of alas basins which divide yedoma hills. Alas Complex deposits are genetically linked to the formation, evolution, and degradation of thermokarst lakes and their basins. They resemble a complex of parageneticaly interrelated deposits among which taberal formations and lacustrine and alas-specific (lacustrine-boggy) deposits (**Figure 11**) are usually emphasized (Romanovskii, 1961a). The thickness of the Alas Complex deposits within Oyogos Yar does not usually exceed 10 m and depends mainly on the thickness of lacustrine and alas-specific deposits. The structure of the Alas Complex deposits is quite well studied (Katasonov, 1960, 1982; Romanovskii, 1961a; Ospennikov and Trush, 1974; Kaplina, 1981, 2009; Wetterich et al., 2009).

Alas Complex taberal formations resemble Yedoma Ice Complex deposits, which thawed beneath a lake and were partially reworked within the thermokarst basin. In the Dmitry Laptev Strait area, on both Bol'shoy Lyakhovsky Island and at Oyogos Yar, deposits from the Bychchagy Ice Complex, which thawed together with the Yedoma Ice Complex, are included in the composition of both Bol'shoy Lyakhovsky Island and Oyogos Yar in many cases (**Figure 7**). Furthermore, Yana Suite Ice Complex deposits can participate in Alas Complex formation too. In cases when taberal formations of the Alas Complex are identified in sections, they are represented by dusty gray, brownish-gray, or light bluish-gray loams, which are not layered and often have randomly distributed vegetation remains or peaty inclusions within deposits. The thickness of the taberal deposits can reach 2–3 m. In overall composition, including paleontological content, they correspond to Ice Complex deposits which did not thaw.

Taberal deposits are overlain by lacustrine deposits; the thickness of these lacustrine deposits does not exceed several meters. Taberal deposits are usually represented by gray and brownish-gray loams with inclusions of vegetation detritus including pieces of peat and wood and shrub vegetation. Freshwater shells of the genus *Pisidium* no more than 1–1.5 cm length can sometimes be found. A distinguishing difference between lacustrine deposits and taberal formations is the extent of lamination. Layers are a few millimeters to 1–2 cm thick. Bedding is parallel, horizontal, or wavy, and sometimes structures of underwater landslides 1–2 m in size can be seen.

Lacustrine-boggy (alas-specific) deposits cover the Alas Complex section. They are represented by polygonal peat bogs from 1 to 2.5 m thick, which are penetrated by a system of syngenetic ice wedges up to 2–4 m wide and 5–6 m high.

At the base of the Alas Complex developed, ice-wedge casts can usually be found, which are an integral part of the Alas Complex structure. Such casts can be seen in the base of almost all Oyogos Yar alas deposits. They are completely identical in origin to Krest-Yuryakh Suite casts but often have a wedge-like shape. They are filled with taberal material and lacustrine deposits with strongly deformed layering.

The formation of thermokarst lakes and taliks beneath them began about 13–12 kyr BP (Kaplina and Lozhkin, 1979; Kaplina, 2009). The thickness of the taliks, as calculations show (Tumskoy et al., 2001), did not exceed 100–150 m even in favorable conditions. If a talik took over an area on which not only a Yedoma but also a Bychchagy Ice Complex was developed, the latter thawed in the talik and formed pseudomorphs and taberated underlying Kuchchugui Suite deposits. If the talik under a Holocene lake formed in an area of Krest-Yuryakh deposit distribution where casts after Bychchagy ice wedges had formed earlier, the underlying Kuchchgui Suite deposits were taberated (thawed and refrozen) twice: initially during the period of Krest-Yuryakh thermokarst lake development, and later in the Holocene.

Alas Complex deposits occur as lenses which stretch along the coast for a distance of several hundred meters to 4–5 or more kilometers. These lenses are enclosed in Yedoma Ice Complex deposits. Their lateral contacts with the latter are clearly seen in places. These are erosional-cryogenic contacts from 50 to 200 m long horizontally, which have a gentle slope toward the center of the alas basins. The cryolithological relationship of the Alas Complex and Yedoma Ice Complex deposits unequivocally shows that the former deposits are younger, positioned higher stratigraphically, and formed at the very end of the Late Pleistocene and in the Holocene. Numerous radiocarbon dates also indicate this: The beginning of lacustrine deposit deposition is dated to 14–11 k.a., while the end of alas peat bog formation is dated to 1,000 years ago or earlier (Kaplina, 2009; Opel et al., 2017).

Thermodenudation occurred, and small lakes that did not develop into full-sized large thermokarst lakes formed in places

on the yedoma hills' surface in parallel to the formation of the Alas Complex in thermokarst basins. Increasing thawing depth beneath such lakes led to the emergence at the top of the Yedoma Ice Complex of small depressions in the form of subsidence troughs, which are currently composed of very ice-rich peaty dusty loams up to 2–3 m thick with ice belt cryogenic structures and small ice wedges. Schematically, they are shown in the top part of the section at the 3,700 m mark (**Figure 6**). Very thin taberal deposits over the Yedoma Ice Complex and boggy deposits can be identified by their composition. Paleontologically such subsidence depressions will contain fauna that matches the temporal interval of the thawed Yedoma Ice Complex, but can also include younger Holocene flora and fauna remains.

Deposits of the first floodplain terrace and floodplains of all river valleys (from Chay-Povarnya to Konechnaya), including coastal-marine deposits, also belong to the Holocene at Oyogos Yar, but they are not discussed here.

It is important to pay attention to proluvial-deluvial deposits of the thermal erosion system. These deposits are widely distributed on the coasts of the Dmitry Laptev Strait, including at Oyogos Yar. The thermal erosion developed with particular intensity at the beginning of the Holocene and at the Holocene optimum; some gullies also continue to grow intensely today. Ice-rich deposits and ground ice contribute to the formation of thermo-erosional gullies. These gullies differ from other types due to their formation in frozen ground; frozen ground can retain steep vertical sides during erosion. Thermal pits and numerous horizontal thermo-erosional niches with an extent of up to 10–15 m long can form inside them at different levels (**Figure 12**). Subsequently, thermo-erosional gullies can fill with thawed and relocated material from the slopes of the gully and freeze again.

CONCLUSION

We managed to answer some questions about the structure of frozen Quaternary sediments on the coast of the Dmitry Laptev Strait after field work including detailed geological and cryolithostratigraphic investigations. The boundaries of the main geological bodies exposed in the coastal sections of the Dmitry Laptev Strait were clearly established. An identical structure was revealed within both the Oyogos Yar and the southern coast of Bol'shoy Lyakhovsky Island. The Middle Pleistocene deposits found in Yukagir Ice Complex deposits (MIS 8 or 7) and the Kuchchugui Suite (MIS 6) included relatively ice-poor strata with rare syngenetic ice wedges. The complex Zimov`e layer deposits (MIS 7?) included the ancient alas complex deposits and a relic active layer. The Kuchchugui deposits accumulated in subaerial conditions as fluvial-glacial (?) deposits. The Bychchagy Suite Ice Complex (MIS 5e-5b) with two specific polygonal peat horizons covered the Kuchchugui Suite. The thermokarst lake deposits of the Krest-Yuryakh Alas Complex suite formed as a result of thawing during MIS 5a climatic warming. According to the conditions of occurrence, composition, and structure, the Krest-Yuryakh Alas Complex cannot be considered as part of the Kuchchugui Suite.

The sediments of the Bychchagy Suite served as a very ice-rich substrate for the development of massive lacustrine thermokarst at the beginning of the Late Pleistocene (MIS 5), which is now represented by the sediments of the Krest-Yuryakh Suite. Despite the insufficient number of available Bychchagy and Krest-Yuryakh suite datings (Wetterich et al., 2016), the geological relationship between these suites and their sequence of formation are beyond doubt. Convincing evidence has been obtained, based on direct geological observations, of the existence of two cryofacies of the Kuchchugui Formation—syncryogenic and taberated.

On the whole, the cryolithostratigraphic subdivisions identified on both sides of the Dmitry Laptev Strait turned out to be identical and well diagnosed. This made it possible to reconstruct the history of the geological development of this territory starting from the end of the Middle Pleistocene to the present. However, for chronological accuracy of geological reconstruction, we need tens of new datings of pre-Yedoma superhorizon deposits (from MIS 8 to MIS 5). We hope that collecting these essential data will be possible in the future.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

VT and TK designed the study and wrote the manuscript.

FUNDING

The Russian-German "Laptev Sea System" program supported this work. The work of VT was also supported by Russian-American scientific project "Zhokhov-2000" led by V. V. Pitulko and sponsored by the private scientific Rock Foundation (New York, United States). The Russian Science Foundation (the grant #21-77-30001) also supported this study.

ACKNOWLEDGMENTS

We thank all German and Russian participants of the expeditions for their help. We thank Thomas Opel and Julian Murton for valuable comments that greatly helped to improve the paper. The authors are especially grateful to Lutz Schirrmeister for their help at all stages of preparing the article.

REFERENCES

Andreev, A., Grosse, G., Schirrmeister, L., Kuzmina, S., Novenko, E., Bobrov, A., et al. (2004). Late Saalian and Eemian Palaeoenvironmental History of the Bol'shoy Lyakhovsky Island (Laptev Sea Region, Arctic Siberia). *Boreas* 33, 319–348. doi:10.1080/03009480410001974

Anzhu, P. F. (1849). "Opis` Beregov Ledovitogo Morya, Mezhdu Rek Olenek I Indigirka, I Severnykh Ostrovov Leytenanta Anzhu. 1821, 22 I 23 Godov (Description of the Arctic Ocean Coasts between Olenek and Indigirka Rivers and Northern Islands after Lieutenant Anzhu)," in *Reviews of the Hydrography Department of Marine Ministry* (Sankt-Petersburg: Marine typography Publ.), 147. Iss. VII. (in Russian).

Arkhangelov, A. A. (1996). "O Rannikh Etapakh Formirovaniya Mnogoletney Merzloty Na Severe Yakutii I Vozrast Drevnikh Reliktov Podzemnogo Oledeneniya (Initial Periods of Permafrost Formation at the Yakutian north and Age of Old Relic of Ground Glaciation)," in *Razvitie Oblasti Mnogoletney Merzloty I Periglatsialnoy Zony Severnoy Evrazii I Usloviya Rasseleniya Drevnego Cheloveka (Evolution of the Permafrost Area and Periglacial Zone of the Northern Eurasia and Residential Conditions of Old Humans)* (Moscow: Publ. in Institute of Geography AN SSSR), 102–109. (in Russian).

Boeskorov, G. G., Protopopov, A. V., Mashchenko, E. N., Potapova, O. R., Kuznetsova, T. V., Plotnikov, V. V., et al. (2013). Novye Nakhodki Iskopaemykh Mlekopitayushchikh Unikal'noi Sokhrannosti V Mnogoletney Merzlote Yakutii (New Findings of Fossil Mammals of the Unique Preservation in Yakutian Permafrost). *Doklady Earth Sci.* 452 (4), 461–465. (in Russian). doi:10.1134/s0012496613050116

Boeskorov, G. G., Protopopov, A. V., Mashchenko, E. N., Potapova, O. R., Tikhonov, A. N., Kuznetsova, T. V., et al. (2012). Predvaritel'nye Dannye Ob Unikal'nykh Nakhodkakh Mlekopitayushchikh Lednikovogo Perioda Na Yano-Indigirskoy Nizmennosti (Preliminary Data of the Unique Findings of the Ice Age Mammals on the Yana-Indigirka Lowland). *Bull. North-East Fed. Univ.* 9 (4), 10–16. (in Russian).

Bunge, A. A. (1887). Predvaritel'nyi Otchet Ob Ekspeditsii Na Novosibirskie Ostrova (Preliminary Report of the Expedition on New Siberian Islands). *Bull. Imperator's Russ. Geogr. Soc.* XXIII (1-6), 573–591. (in Russian).

Geocryology of USSR (1989). in *Eastern Siberia and Far East*. Editor E. D. Ershov (Moscow: Nedra Publ), 515.

Ermolaev, M. M. (1932). "Geologicheskii I Geomorfologicheskii Ocherk Ostrova Bol'shogo Lyakhovskogo (Geological and Geomorphological Review of the Bol'shoy Lyakhovsky Island)," in *Polyarnaya Geophizicheskaya Stantsia Na Ostrove Bol'shom Lyakhovskom (Polar Geophysical Station on the Bol'shoy Lyakhovsky Island)* (Leningrad: Proceedings of SOPS, Yakutian series), 7, 147–223. (in Russian).

Gedenshtrom, M. M. (1830). "O Ledovitom More (About of Polar Sea)," in *Otryvki O Sibiri (Essay about Siberia)* (Sankt-Petersburg: Typography of medical Department Publ.), 105–132. (in Russian).

Gravis, G. (1978). "Cyclic Nature of Thermokarst on the Maritime plain in the Upper Pleistocene and Holocene," in Third International Conf. on Permafrost. English translation of twenty-six of the Soviet papers. Part I, Edmonton, Canada, 245–257.

Gravis, G. F. (1996). "Allyuvialno-prolyuvialnaya Model' Formirovaniya Mnogoletnemerzlykh Tolshch Na Flyuvial'nykh Ravninakh Kriolitozony (Alluvial-Proluvial Model of Frozen Deposits Formation on the Fluvial Lowlands of Cryolithozone)," in *Abstracts of the First Conference of Russian Geocryologists* (Moscow, Russia: Lomonosov Moscow State University), Vol. 1, 186–192. (in Russian).

Grigoriev, A. A. (1932). "Ob Oledenenii Territorii Yakutii V Chetvertichnyi Period (To the Glaciation of Yakutia at the Quaternary)," in *Proceedings of the Committee for Quaternary Investigation* (Leningrad: Academia of Science Publ.), 31–42. (in Russian).

Gusev, A. I. (1958). K Stratigrafii Chetvertichnykh Otlozhenii Zapadnoi Chasti Primorskoi Ravniny (To the Stratigraphy of Quaternary Deposits of the Western Part of Coastal lowland). *A. Collection Papers Geology. Arctic* 80 (5), 79–86. (in Russian).

Ivanov, O. A. (1972). "Stratigrafiya I Korrelyatsiya Neogenovykh I Chetvertichnykh Otlozhenii Subarkticheskikh Ravnin Vostochnoi Yakutii (Stratigraphy and Correlation of Neogene and Quaternary Deposits on the Subarctic Lowlands of the Eastern Yakutia)," in *Problemy Izucheniya Chetvertichnogo Perioda (Problems of Investigation of the Quaternary)* (Moscow: Nauka Publ.), 202–211. (in Russian).

Kaplina, T. N. (2009). Alasnye Kompleksy Severnoi Yakutii (Alas Complexes of the Northern Yakutia). *Earth's Cryosphere* XIII (4), 3–17. (in Russian).

Kaplina, T. N. (1981). "Istoriya Merzlykh Tolshch Severnoi Yakutii V Pozdnem Kainozoe (History of Frozen Grounds in the Northern Yakutia at the Late Cenozoic)," in *Istoriya Razvitiya Mnogoletnemerzlykh Porod Severnoi Evrazii (History of Permafrost Evolution at the Northern Eurasia)* (Moscow: Nauka Publ.), 153–181. (in Russian).

Kaplina, T. N., and Lozhkin, A. V. (1979). Vozrast Alasnykh Otlozheniy Primorskoy Nizmennosti Yakutii (Radiouglerodnoe Obosnovanie) (Age of an Alas Complex Deposits of Yakutian Coastal lowland (14C Evidence)). *Izvestiya SSSR (Proceedings Sssr), Ser. Geol.* 1979 (2), 69–76.

Kaplina, T. N., and Lozhkin, A. V. (1982). Vozrast "Ledovogo Kompleksa" Primorskikh Nizmennostei Yakutii (Age of an Ice Complex on the Coastal lowland of Yakutia). *Izvestiya SSSR (Proceedings Sssr), Ser. Geogr.* 2, 84–95. (in Russian).

Katasonov, E. M. (1982). "Alasnye Otlozheniya I Taberal'nye Obrazovaniya Yakutii (Alas Deposits and Taberal Formations of the Yakutia)," in *Geologiya Kainozoya Yakutii (Cenozoic Geology of the Yakutia)* (Yakutsk: Yakutian branch of SO AN SSSR Publ.), 110–121. (in Russian).

Katasonov, E. M. (1960). Ob Alasnykh Otlozheniyakh Yanskoi Primorskoi Nizmennosti (About Alas Deposits of the Yana Coastal lowland). *Geologiya i geofizika (Geology geophysics)* 2, 103–112. (in Russian).

Kayalaynen, V. I., and Kulakov, Yu. N. (1965). "Osnovnye Cherty Istorii Geologicheskogo Razvitiya Yano-Indigirskoy (Primorskoy) Nizmennosti V Neogen-Chetvertichnoe Vremya (Main Peculiarities of the Geological History of the Yana-Indigirka (Primorskaya) lowland at the Neogene and Quaternary," in *Antropogenovyi Period V Arktike I Subarktike (Quaternary Period in the Arctic and Subarctic)* (Moscow: Nedra Publ.), 56–64. (in Russian).

Konishchev, V. N., and Kolesnikov, S. F. (1981). Osobennosti Stroeniya I Sostava Pozdnekaynozoiskikh Otlozhenii V Obnazhenii Oyogosskii Yar (Peculiarities of the Structure and Composition of Late Cenozoic Deposits in the Outcrop Oyogos Yar). *Probl. cryolithology* IX, 107–117. (in Russian).

Kunitskiy, V. V. (1996). "Khimicheskiy Sostav Skvoznykh Ledyanykh Zhil Ledovogo Kompleksa (Chemical Composition of through Ice Wedges of Ice Complex)," in *Kriolitozona I Podzemnye Vody Sibiri. Chast' 1. Morfologiya Kriolitozony (Cryolithozone and Ground Water of the Siberia. Part 1. Morphology of Cryolithozone)* (Yakutsk: Permafrost Institute publ.), 93–117. (in Russian).

Kunitsky, V., Schirrmeister, L., Grosse, G., et al. (2000). "Paleoclimate Signals of Ice-Rich Permafrost Deposits," in *Berichte zur Polarforschung. Reports on Polar Research. Russian-German Cooperation System Laptev Sea 2000. The expedition Lena 1999*, 354, 187–263.

Kuznetsova, T. P. (1965). "O Chetvertichnykh Otlozheniyakh S Podzemnym L'dom Na Yano-Indigirskoy Nizmennosti I O-Ve Bol'shom Lyakhovskom (About Quaternary Deposits with Ground Ice on the Yana-Indigirka lowland and Bol'shoy Lyakhovsky Island)," in *Podzemnyi Led (Underground Ice)* (Moscow: Moscow University Publ.), 120–132. (in Russian).

Kuznetsova, T. V., and Starodubtseva, I. A. (2009). "Mamonty I Istoriya Geologicheskogo Izucheniya Poberezh'ya Morya Laptevykh I Novosibirskikh Ostrovov (Mammoths and History of Geological Investigations of the Laptev Sea Coasts and New Siberian Islands)," in *Sistema Morya Laptevykh I Prilegayushchikh Morey Arktiki: Sovremennoe Sostoyanie I Istoriya Razvitiya (System of the Laptev Sea and the Adjacent Arctic Seas: Modern and Past Environments)* (Moscow: MSU Publ.), 481–500. (in Russian).

Lavrushin, Yu. A. (1963). "Allyuviy Ravninnykh Rek Subarkticheskogo Poyasa I Periglyatsial'nykh Oblastei Materikovykh Oledenenii (Alluvium of plain Rivers in Subarctic Zone and Periglacial Zones of Cover Glaciations)," in *Trudy Geologicheskogo Instituta an SSSR (Proceedings of the Geological Research institute of Academia of Science USSR)*, 87, 253. (in Russian).

Lobanov, M. F. (1957). "Geologicheskoe Stroenie Novosibirskikh Ostrovov (Geological Structure of the New Siberian Islands)," in *Geologiya Sovetskoy Arktiki (Geology of the Soviet Arctic). Proceedings of the Research institute of Arctic Geology*, 81, 484–503. (in Russian).

Meyer, H., Dereviagin, A., Siegert, C., Schirrmeister, L., and Hubberten, H.-W. (2002). Palaeoclimate Reconstruction on Big Lyakhovsky Island, north Siberia?

hydrogen and Oxygen Isotopes in Ice Wedges. *Permafrost Periglac. Process.* 13, 91–105. doi:10.1002/ppp.416

Nagaoka, D., Saljo, K., and Fukuda, M. (1995). "Sedimental Environment of the Yedoma in High Arctic Eastern Siberia," in Proc. of the Third Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1994, Tsukuba, Hokkaido, Japan, 8–13.

Nikol'skiy, P. A., and Basilyan, A. E. (2004). "Mys Svytoi Nos – Opornyi Razrez Chetvertichnykh Otlozhenii Severa Yano-Indigirskoy Nizmennosti (Svyatoi Nos Cape – the Main Section of Quaternary Deposits at the north of Yana-Indigirka lowland)," in *Estestvennaya Istoriya Rossiyskoi Vostochnoi Arktiki V Pleistotsene I Golotsene (Natural History of the Russian East Arctic in Pleistocene and Holocene)* (Moscow: GEOS publ.), 5–13. (in Russian).

Nikol'skiy, P. A., Basilyan, A. E., and Simakova, A. N. (1999). "Novye Dannye Po Stratigrafii Verkhnekaynozoiskikh Otlozheniy V Rayone Mysa Svyatoi Nos (New Data on Stratigraphy of Upper Cenozoic Deposits Around the Svyatoi Nos Cape," in *Landshaftno-klimaticheskie Izmeneniya, Zhivotnyi Mir I Chelovek V Pozdnem Pleistotsene I Golotsene (Landscape and Climate Changes, Fauna and Human at the Late Pleistocene and Holocene)* (Moscow: Institute of Geography publ.), 51–60. (in Russian).

Opel, T., Wetterich, S., Meyer, H., Dereviagin, A. Y., Fuchs, M. C., and Schirrmeister, L. (2017). Ground-ice Stable Isotopes and Cryostratigraphy Reflect Late Quaternary Palaeoclimate in the Northeast Siberian Arctic (Oyogos Yar Coast, Dmitry Laptev Strait). *Clim. Past* 13, 587–611. doi:10.5194/cp-13-587-2017

Ospennikov, E. N., and Trush, N. I. (1974). L'distost' Alasnykh I Ozerno-Allyuvial'nykh Otlozheniy Yano-Omoloiskogo Mezhdurech'ya I Metodika Ee Polevogo Opredeleniya. *Merzlotnye issledovaniya (Geocryological investigation)* XIV, 35–42. (in Russian). doi:10.5194/cp-13-587-2017

Popov, A. I. (1953). Peculiarities of Lithogenesis on Alluvial plains under Severe Climate, *Izvestiya an SSSR [Bulletin of Academia of Science, USSR]. Series Geography*, 1953 (2), 29–43. (in Russian).

Prokhorova, S. M., and Ivanov, O. A. (1973). *Olovonosnye Granitoidy Yano-Indigirskoi Nizmennosti I Svyazannye S Nimi Rossypi (Tin-Bearing Granitoids of the Yana-Indigirka lowland and Associated with Them Placers)*. Leningrad: Nedra Publ., 229. (in Russian).

Resheniya (1987). "Resheniya Mezhvedomstvennogo Stratigraficheskogo Soveshchaniya Po Chetvertichnoi Sisteme Vostoka SSSR (Decisions of the Interdepartmental Stratigraphic Meeting on the Quaternary System of the East of USSR)," in *Explanation Reports to the Regional Stratigraphic Charts of Quaternary Deposits of East of USSR* (Magadan: SVKNII DVO AN SSSR Publ.), 241. p. (in Russian).

Romanovskii, N. N. (1961a). Erozionno-termokarstovye Kotloviny Na Severe Primorskikh Nizmennostey Yakutii I Novosibirskikh Ostrovakh (Thrermokarst-Erosional Depressions on the north of Coastal Lowlands and New Siberian Islands). *Merzlotnye issledovaniya (Geocryological investigation)* I, 124–144. (in Russian).

Romanovskii, N. N. (1958). Merzlotnye Struktury Oblekaniya V Chetvertichnykh Otlozheniyakh (Draping Permafrost Structures in Quaternary Deposits). *Nauchnye doklady Vysshey shkoly (Scientific Rep. High School), Geol. geographical Sci.* 3, 185–188. (in Russian).

Romanovskii, N. N. (1961b). O Stroenii Yano-Indigirskoi Primorskoi Allyuvialnoi Ravniny I Usloviyakh Ee Formirovaniya (About Structure of the Yana-Indigirka Coastal Alluvial plain and Conditions of it Formation). *Merzlotnye issledovaniya (Geocryological investigation)* II, 129–138. (in Russian).

Romanovskii, N. N. (1993). *Osnovy Kriogeneza Litosphery (Fundamentals of Lithosphere's Cryogenesis)*. Moscow: Moscow State University Publ., 336. (in Russian).

Saks, V. N. (1948). Chetvertichnyi Period V Sovetskoi Arktike (Quaternary Period in the Soviet Arctic). *Trudy Arkticheskogo NII (Proceedings Arctic Res. institute)* 201, 131. (in Russian).

Schirrmeister, L., Froese, D., Tumskoy, V., Grosse, G., and Wetterich, S. (2013). "Permafrost and Periglacial Features | Yedoma: Late Pleistocene Ice-Rich Syngenetic Permafrost of Beringia," in *The Encyclopedia of Quaternary Science*. Editor S. A. Elias (Amsterdam: Elsevier), 542–552. doi:10.1016/b978-0-444-53643-3.00106-0

Schirrmeister, L., Grosse, G., Kunitsky, V., Meyer, Y., Derevyagin, A., Kuznetsova, T., et al. (2003). "Permafrost, Periglacial and Paleoenvironmental Studies on New Siberian Islands," in *Berichte zur Polarforschung. Reports on Polar and Marine Research. Russian-German Cooperation System Laptev Sea. The Expeditions Lena 2002*, 466, 195–314.

Schirrmeister, L., Kunitsky, V., Grosse, G., Wetterich, S., Meyer, H., Schwamborn, G., et al. (2011). Sedimentary Characteristics and Origin of the Late Pleistocene Ice Complex on north-east Siberian Arctic Coastal Lowlands and Islands – A Review. *Quat. Int.* 241 (1-2), 3–25. doi:10.1016/j.quaint.2010.04.004

Schirrmeister, L., Oezen, D., and Geyh, M. A. (2002). 230Th/U Dating of Frozen Peat, Bol'shoy Lyakhovsky Island (Northern Siberia). *Quat. Res.* 57, 253–258. doi:10.1006/qres.2001.2306

Schirrmeister, L., Wetterich, S., Kunitsky, V., Tumskoy, V., Dobrynin, D., Derevyagin, A., et al. (2008). "Palaeoenviromental Studies on the Oyogos Yar Coast," in *Berichte zur Polarforschung. Reports on Polar and Marine Research. The Expedition Lena – New Siberian Islands 2007*, 584, 85–265.

Sher, A. V. (1971). *Mlekopitayushchie I Stratigrafiya Pleistotsena Krainego Severo-Vostoka SSSR I Severnoi Ameriki (Mammals and Pleistocene Stratigraphy of the North-East of USSR and Northern America)*. Moscow: North-East of USSR and Northern America.

Skvortsov, E. F. (1914). Lensko-Kolymskaya Ekspeditsiya 1909 G. (Lena-Kolyma Expedition, 1909). *Izvestiya Imperatorskogo Russkogo Geograficheskogo Obshchestva (Bulletin of the Imperator's Russian Geographic Society*, 50 (7), 401–428. (in Russian).

Skvortsov, E. F. (1930). "V Pribrezhnykh Tundrakh Yakutii (Dnevnik Astronoma Lensko-Kolymskoy Ekspeditsii 1909 G. (On the Coastal Tundra of the Yakutia. Diary of the Leno-Kolyma Expedition's Astronomer in 1909)," in *Izvestiya Komiteta Po Izucheniyu Yakutskoy SSR (Proceedings of the Committee for Yakutian SSR Investigation)* (Leningrad: Academia of Science Publ.), XV, 1–244. (in Russian).

Spizharskiy, T. N. (1940). Chetvertichnoe Oledenenie Leno-Indigirskoy Oblasti (Quaternary Glaciation of the Lena-Indigirka Region). *Problemy Arktiki (Problems of the Arctic)* 11, 70–81. (in Russian).

Toll', E. V. (1897). "Iskopaemye Ledniki Novosibirskikh Ostrovov, Ikh Otnoshenie K Trupam Mamontov I K Lednikovomu Periodu (Fossil Glaciers of New Siberian Islands, that Relationship with mammoth Cadavrs and)," in *Sankt-Petersburg* (Moscow: Imperator's Academia of Science Publ), XXXII, 139. (in Russian).

Tomirdiaro, S. V., Chernen'kiy, B. I., and Bashlavin, D. K. (1982). "Lessovo-ledovaya Formatsiya Shel'fovogo Tipa I Obnazhenie Oyagosskii Yar (Loess-Ice Formation of Shelf Type and Oyogos Yar Outcrop)," in *Merzlotno-geologicheskie Protsessy I Paleogeografiya Nizmennostey Severo-Vostoka Azii (Cryogenic Processes and Palaeogeography of the Lowlands of North-East of Asia)* (Magadan: SVKNII DVNC AN SSSR publ), 30–53. (in Russian).

Tomirdiaro, S. V. (1980). *Lessovo-ledovaya Formatsiya Vostochnoi Sibiri V Pozdnem Pleistotsene I Golotsene (Loess-Ice Formation of East Siberia in Late Pleistocene and Holocene)*. Moscow: Nauka Publ., 184. (in Russian).

Tumskoy, V. E., and Basilyan, A. E. (2006). "Opornyi Razrez Chetvertichnykh Otlozheniy Ostrova Bol'shoy Lyakhovskii (Novosibirskie Ostrova) (The Main Section of Quaternary Deposits on the Bol'shoy Lyakhovskii Island (New Siberian Islands)," in Abstracts of the international conference "Problems of correlation of Pleistocene events on the Russian North", Sankt-Petersburg, 106–107. (in Russian).

Tumskoy, V. E., and Basilyan, A. E. (2009). "Stratigrafiya Chetvertichnykh Otlozheniy Beregov Proliva Dmitriya Lapteva (Stratigraphy of Quaternary Deposits on the Coasts of Dmitry Laptev Strait)," in Abstracts of the VI Russian conference on the Quaternary "Fundamental problems of Quaternary: results and main directions of future investigations", Novosibirsk, 592–593. (in Russian).

Tumskoy, V. E. (2021). Cryolithostratigraphy and Cryofacies Analysis. *Earth's Cryosphere* 25 (4), 3–16. (in Russian). doi:10.15372/kz20210401

Tumskoy, V. E. (2012). Osobennosti Kriolitogeneza Otlozheniy Severnoi Yakutii V Srednem Pleistotsene – Golotsene (Peculiarities of Cryolithogenesis of Deposits in Northern Yakutia in the Middle Neopleistocene-Holocene). *Earth's Cryosphere* XVI (1), 12–21. (in Russian).

Tumskoy, V. E., Romanovskii, N. N., and Tipenko, G. S. (2001). "Formirovanie Talikov Pod Termokarstovymi Ozerami Na Severo-Vostoke Yakutii: Rezul'taty Modelirovaniya (Talik Formation under Thermokarst Lakes on the north-east

of Yakutia)," in *Abstracts of the Second Conference of the Russian Geocryologists, Moscow*, 2, 292–300. (in Russian).

Vasil'chuk, Yu. K. (2017). "Cycles in Stratigraphy of Yedoma Deposits. Part 1," in *Arktika I Antarktika [Arctic and Antarctica]*, 2017, 62–83. (in Russian).

Vas'kovsky, A. P. (1963). "Ocherk Stratigrafii Antropogenovykh (Chetvertichnykh) Otlozhenii Krainego Severo-Vostoka Asii (Stratigraphy Review of the Anthropohen (Quaternary) Deposits of the Far North-East of Asia)," in *Geologiya Koryakskogo Nagorya (Geology of the Koryak Upland)* (Moscow: Geology of the Koryak Upland), 143–168. (in Russian).

Vollosovich, K. A. (1930). Geologicheskie Nablyudeniya V Tundre Mezhdu Nizhnimi Techeniyami Rek Leny I Kolymy (Geological Observations in the Tundra between the Lower Parts of Lena and Kolyma Rivers). *Proc. Committee Invest. Yakutian ASSR* 15, 299–357. (in Russian).

Vtyurin, B. I., Grigoriev, N. F., Katasonov, E. M., Kuznetsova, T. P., Shvetsov, P. F., and Shumskii, P. A. (1957). "Mestnaya Stratigraficheskaya Shema Chetvertichnykh Otlozhenii Poberezh'ya Morya Laptevykh (Local Stratigraphic Scheme of Quaternary on the Coast of the Laptev Sea)," in *Proceedings of Interdepartmental Meeting for Preparation of Uniform Stratigraphic Charts of Siberia, 1956* (Leningrad: Publ. in Gosud. nauch. -tech. izd-vo neftyanoi i gorno-toplivnoi lit-ry), 564–572. (in Russian).

Wetterich, S., Meyer, H., Fritz, M., Mollenhauer, G., Rethemeyer, J., Kizyakov, A., et al. (2021). Northeast Siberian Permafrost Ice-Wedge Stable Isotopes Depict Pronounced Last Glacial Maximum Winter Cooling. *Geophys. Res. Lett.* 48, e2020GL092087. doi:10.1029/2020GL092087

Wetterich, S., Rudaya, N., Kuznetsov, V., Maksimov, F., Opel, T., Meyer, H., et al. (2019). Ice Complex Formation on Bol'shoy Lyakhovsky Island (New Siberian Archipelago, East Siberian Arctic) since about 200 Ka. *Quat. Res.* 92 (2), 530–548. doi:10.1017/qua.2019.6

Wetterich, S., Rudaya, N., Tumskoy, V., Andreev, A. A., Opel, T., Schirrmeister, L., et al. (2011). Last Glacial Maximum Records in Permafrost of the East Siberian Arctic. *Quat. Sci. Rev.* 30, 3139–3151. doi:10.1016/j.quascirev.2011.07.020

Wetterich, S., Schirrmeister, L., Andreev, A. A., Pudenz, M., Plessen, B., Meyer, H., et al. (2009). Eemian and Late Glacial/Holocene Palaeoenvironmental Records from Permafrost Sequences at the Dmitry Laptev Strait (NE Siberia, Russia). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 279, 73–95. doi:10.1016/j.palaeo.2009.05.002

Wetterich, S., Tumskoy, V., Rudaya, N., Andreev, A. A., Opel, T., Meyer, H., et al. (2014). Ice Complex Formation in Arctic East Siberia during the MIS3 Interstadial. *Quat. Sci. Rev.* 84, 39–55. doi:10.1016/j.quascirev.2013.11.009

Wetterich, S., Tumskoy, V., Rudaya, N., Kuznetsov, V., Maksimov, F., Opel, T., et al. (2016). Ice Complex Permafrost of MIS5 Age in the Dmitry Laptev Strait Coastal Region (East Siberian Arctic). *Quat. Sci. Rev.* 147, 298–311. doi:10.1016/j.quascirev.2015.11.016

Zagorskaya, N. G. (1959). "Novosibirskie Ostrova (New Siberian Islands)," in *Chetvertichnye Otlozheniya Sovetskoy Arktiki (Quaternary Deposits of the Russian Arctic).* Editors V. N. Saks and S. A. Strelkov (Moscow, Publ. Gosud. nauch.-tech. izd-vo lit-ry po geologii i okhrane nedr SSSR), 200–211. (in Russian).

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.