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Yedoma Permafrost Genesis: Over 150 Years of Mystery and Controversy

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Since the discovery of frozen megafauna carcasses in Northern Siberia and Alaska in the early 1800s, the Yedoma phenomenon has attracted many Arctic explorers and scientists. Exposed along coastal and riverbank bluffs, Yedoma often appears as large masses of ice with some inclusions of sediment. The ground ice particularly mystified geologists and geographers, and they considered sediment within Yedoma exposures to be a secondary and unimportant component. Numerous scientists around the world tried to explain the origin of Yedoma for decades, even though some of them had never seen Yedoma in the field. The origin of massive ice in Yedoma has been attributed to buried surface ice (glaciers, snow, lake ice, and icings), intrusive ice (open system pingo), and finally to ice wedges. Proponents of the last hypothesis found it difficult to explain a vertical extent of ice wedges, which in some cases exceeds 40 m. It took over 150 years of intense debates to understand the process of ice-wedge formation occurring simultaneously (syngenetically) with soil deposition and permafrost aggregation. This understanding was based on observations of the contemporary formation of syngenetic permafrost with ice wedges on the floodplains of Arctic rivers. It initially was concluded that Yedoma was a floodplain deposit, and it took several decades of debates to understand that Yedoma is of polygenetic origin. In this paper, we discuss the history of Yedoma studies from the early 19th century until the 1980s—the period when the main hypotheses of Yedoma origin were debated and developed.

Keywords: Yedoma, syngenetic permafrost, late Pleistocene, buried ice, ice wedges, mammoth, Northern Yakutia, Alaska

INTRODUCTION

The term "Yedoma" (Russian "Едома") was historically a folk name for flat hills with gentle slopes or remnants of terraces several dozen meters high (Murzaev, 1984). For scientific descriptions, this term was probably used for the first time by Figurin (1823) and was later introduced into the scientific literature by Birkengof (1933). Originally it was used as a geomorphic term to describe the remnants of terrain with ice-rich permafrost that formed in east Siberia during the late Pleistocene. According to Sher (1997), at least three different meanings of the term "Yedoma" now exist in the Russian literature: 1) a "Yedoma surface" in the geomorphic sense, 2) a "Yedoma Suite" in the stratigraphic sense, or 3) a cryolithological feature implying a special kind of frozen

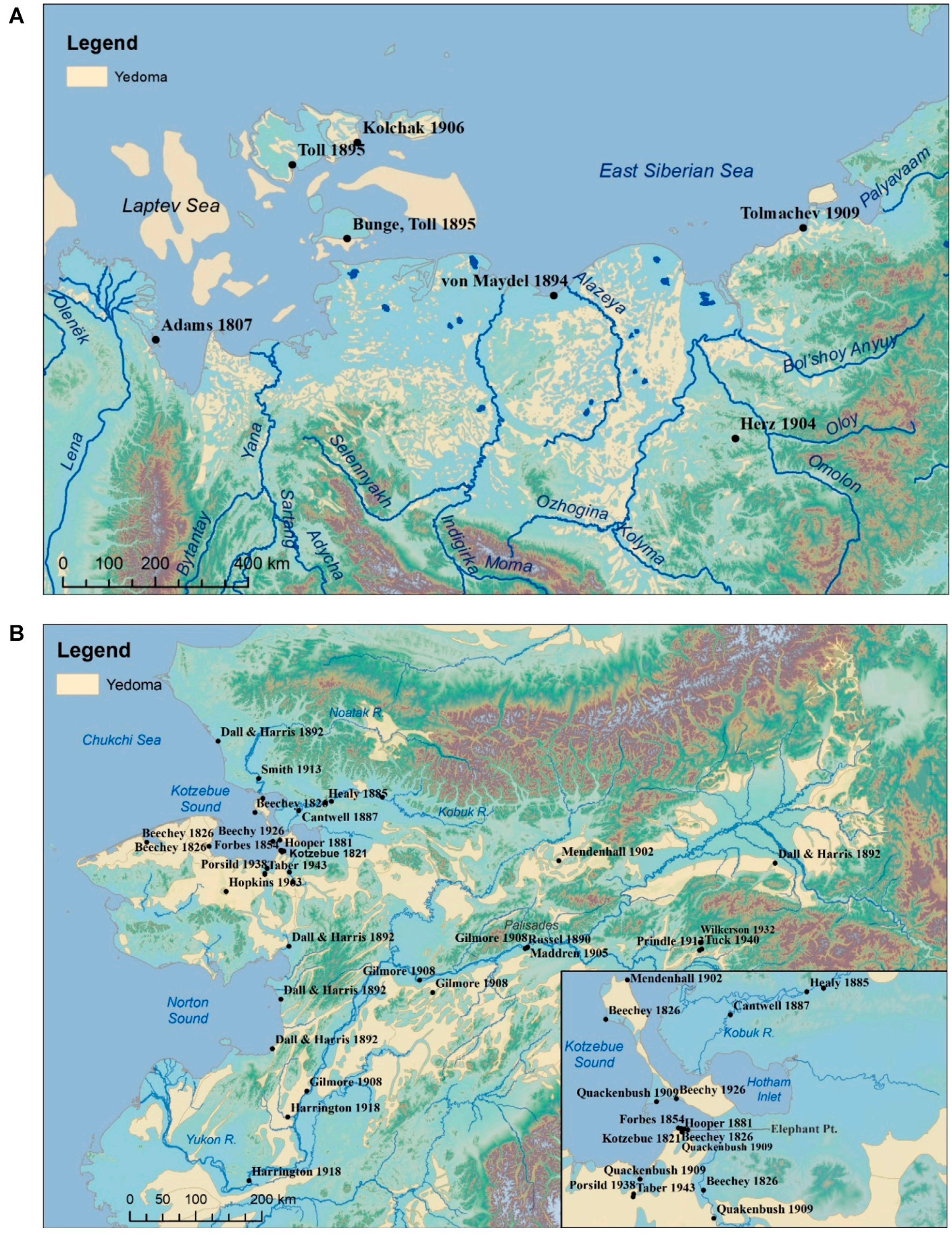

FIGURE 1 | Maps of locations of the first Yedoma sites in Siberia **(A)** and Alaska **(B)**, boundaries of Yedoma region are shown based on Strauss et al. (2021).

sediment, widely distributed in Beringia (area of land bounded by the Lena River in Russia to the west and the Mackenzie Delta in Canada to the east).

In this paper, we use the latter concept of Yedoma to characterize ice-rich silty deposits penetrated by large ice wedges, which resulted from sedimentation and syngenetic freezing in unglaciated areas amidst the last glaciation of the late Pleistocene (Schirrmeister et al., 2013 and references therein). We restrict the Yedoma formation to the late Pleistocene (post MIS five to the end of the last glaciation).

Accumulation of sediment in a former harsh cold climate created this unique and fascinating permafrost type, which has little to no analog in contemporary permafrost formations. Yedoma is also an essential stock of ancient carbon and a treasure of information on the natural history and paleoclimate of Arctic and Subarctic in the late Pleistocene. Yedoma attracted a special interest of native people, explorers, and scientists because of its preservation of remnants of enormous number of extinct animals including mammoths. Since the sensational presentation of the first intact mammoth corpse to the scientific community by Adams in 1807, the interest in Yedoma has continued to grow until the present day.

For over 150 years, supportable hypotheses on Yedoma formation eluded scientists, but recent advances in permafrost science may now have solved the problem. In this paper, we review the history and locations of early Yedoma observations, compare the various explanations that were proposed for its genesis and ice origins, and highlight some of the controversies among scientists defending their ideas.

FIRST YEDOMA FINDING IN SIBERIA

Yedoma, or late-Pleistocene Ice Complex has been known to native people of northeast Siberia and northwest Alaska for centuries. They associated Yedoma with the location of fossil remnants of "prehistoric" animals and looked for it as a source of mammoth tusks. Historically, the ivory market has been enormous, and numerous hunters and traders ("promyshlenniks" in Russia) have scoured the shores of Arctic seas and rivers to find mammoth tusks. Wrangel (1841) mentioned that in 1821 one fossil bone "hunter" brought 8,000 kg of tusks of perfect quality from the New Siberian Islands. He also noted that collectors found the biggest and best tusks on these islands, with smaller quantities located on the northern shore of the Laptev Sea and more seldom findings in southern parts of Siberia. von Toll (1959) mentioned that tusks hunters looked specifically for baydzherakhs (tall conical thermokarst mounds) to find the best quality ivory.

An interest in Yedoma within the scientific community was triggered in the beginning of the 19th century by two findings, one in Russia and the other in Alaska. In Russia, a young biologist named Michael Adams, employed as an adjunct in zoology at the Russian Academy of Sciences, was in Yakutsk in June 1806. A merchant told him that the Tungusian chief Shoumakhov had discovered a whole mammoth carcass on the shore of the Bykovskiy Peninsula (**Figure 1**). Adams was fascinated with the news (**Supplementary Quote S1** in the supplement); he immediately set off on his journey and in a few weeks reached the mammoth site, assisted by Shoumakhov and a crew of 14 people. Adams (1807, 1808) described in detail how Shoumakhov had found an unusually large chunk of ice that separated from the ice cliff in 1799. The following year, Shoumakhov saw two feet of a mammoth revealed from melting ice. It took almost 3 years for the mammoth body to melt free from the ice. In 1804, the Russian merchant Roman Boltunov drew the first sketch of the mammoth. Copies of his sketch made at the time (**Figure 2A**) were sent to Johann Friedrich Blumenbach in Göttingen and Georges Cuvier in Paris. Notes made on the sketch in Blumenbach's handwriting states: "Elephas primigenius in Russia, called mammoth, excavated with skin and hair 1806 in June at the outflow of the Lena into the Arctic Ocean. Roughly drawn as it was found mutilated and filthy." The other notes at the top right of the drawing are from Wilhelm Moritz Keferstein (1833–1870).

When Adams reached the mammoth site, the flesh and internal organs of the mammoth had been eaten by wild animals, but he gathered nearly the entire skeleton as well as some skin and fur. In Yakutsk, Adams bought two mammoth tusks (Shoumakhov earlier had sold the original tusks to Boltunov for 50 rubles) and brought his mammoth to Saint Petersburg where it was reassembled and is on display in the Museum of Zoology (**Figure 2B**). Adams' discovery of the first mammoth skeleton was a world sensation, and his publication was quickly translated into several languages.

Adams described the coastal exposure at the mammoth's location having a clear ice with a nauseating smell. He estimated that the exposure was 3 km long and 60–80 m high. von Baer (1842) thought that this description was an exaggeration. It is unclear how Adams could have evaluated the size of the bluff because at the time of his visit the exposed part of the bluff was 100 steps from the mammoth's position and 160 steps from the sea. The ice was covered by moss and a 50-cm-thick layer of soil that was partially frozen. Adams described mudflows slowly moving towards the sea; he also mentioned soil wedges among ice (**Supplementary Quote S2**).

From the permafrost science point of view, Adams' description of the site was rather disappointing; it is less than one page, and his explanations are difficult even for people familiar with Yedoma to understand. von Baer (1842) tried to make sense of Adams' short description but failed, blaming inaccuracies in Adams' paper (**Supplementary Quote S3**). von Middendorff (1860) noted that Adams' description of the site was unsatisfactory and not trustworthy. von Toll (1897) also found that the explanations in Adams' short description were unsatisfactory and unclear.

Adams' descriptions of the soil and ground ice are confusing. In some translations of his report, originally published in French in 1807, soil wedges were described as lumps or strips of eroded soil among ice floes. Some authors quoting Adams even omitted soil wedges in ice as unimportant detail. Nevertheless, there is a possibility that Adams wrote about soil wedges inside the ice of the exposure itself. Leffingwell (1919) in his short abstract of Adams' paper said: "The mammoth remains were found in the earth wedges between the ice masses." This interpretation is also consistent with the picture (**Figure 3**) drawn by von Toll (1897) who tried to reconstruct what Adams had potentially seen and used it as proof for his own ideas.

With our contemporary knowledge, we interpret Adams' description of the site as: 1) the cliff was not eroded by the sea at the time when Shoumakhov found the mammoth; 2) the cliff was affected by thermal denudation and therefore was not vertical; and 3) the mammoth slid downslope from the site where it thawed out. Overall, the main message gained from this site in the Russian Arctic was the existence of perennially frozen soil

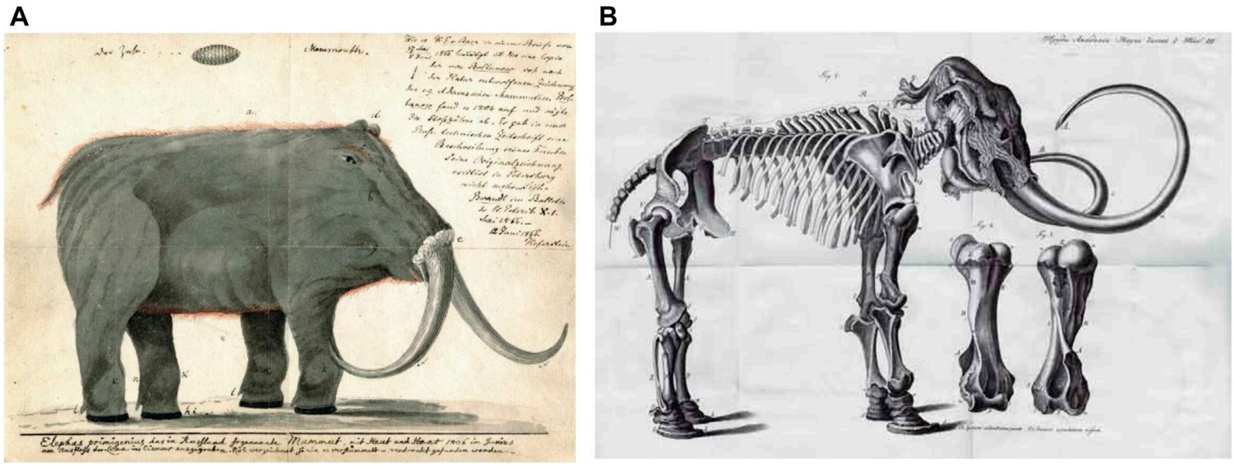

FIGURE 2 | (A)—The world's first reconstruction drawing of a mummified carcass of the so-called "Adams or Lena Mammoth" based on the original sketch by Roman Boltunov (in the Ethnological Collection of the University of Göttingen); **(B)**—Wilhelm Gottlieb Tilesius' etching of the Adams mammoth skeleton (now on display in the Museum of Zoology, Sankt-Peterburg).

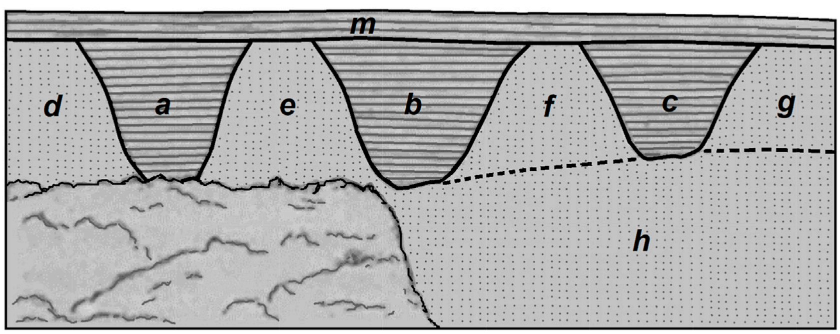

FIGURE 3 | von Toll (1897) perception of Adams (1808) description of a Yedoma cliff in Bykovskiy Peninsula; a, b, c—mineral soil; d, e, f, g, h—ice; m—surficial organic material.

containing large bodies of ground ice and the remnants of mammoths.

FIRST YEDOMA FINDING IN ALASKA

Ten years after Adams' discovery, the Russian ship "Rurik," commanded by Captain Otto von Kotzebue, sailed along the shores of northwest Alaska. On August 8, 1816, the crew found a high exposure of ground ice onshore (**Figure 1**). von Kotzebue (1821) described a remarkable finding made by Dr. Eschscholtz who discovered large masses of pure ice in the 30-m-high coastal bluff. To commemorate this remarkable discovery, von Kotzebue named the bay after Dr. Eschscholtz (**Supplementary Quote S4**). Von Kotzebue mentioned numerous mammoths' teeth and bones exposed at this place; he also provided the latitude (66° 15′ 36" N) that helped later explorers to find the site.

Adelbert von Chamisso (1821), a scientist of von Kotzebue's crew, provided additional descriptions of the exposure in Eschscholtz Bay and compared it to other locations in northern Asia and North America, including the site of Adams' mammoth discovery (**Supplementary Quote S5**). Ludwig Choris (1822), an artist in von Kotzebue's crew, created two paintings of the exposure (**Figure 4**). In **Figure 4A**, stripes of ice are seen that can be recognized as ice wedges, which in the middle of summer are commonly protruding outward relief relative to the columns of dark ice-rich soil that thaws faster than ice. **Figure 4B** shows the exposure at a larger scale, where bodies of ice that are several meters wide are divided by columns of soil.

EMERGING INTEREST AFTER THE FIRST YEDOMA FINDINGS BY ADAMS AND VON KOTZEBUE

For the scientific community, the first Yedoma findings were a sensation. For over 150 years since the works by von Kotzebue

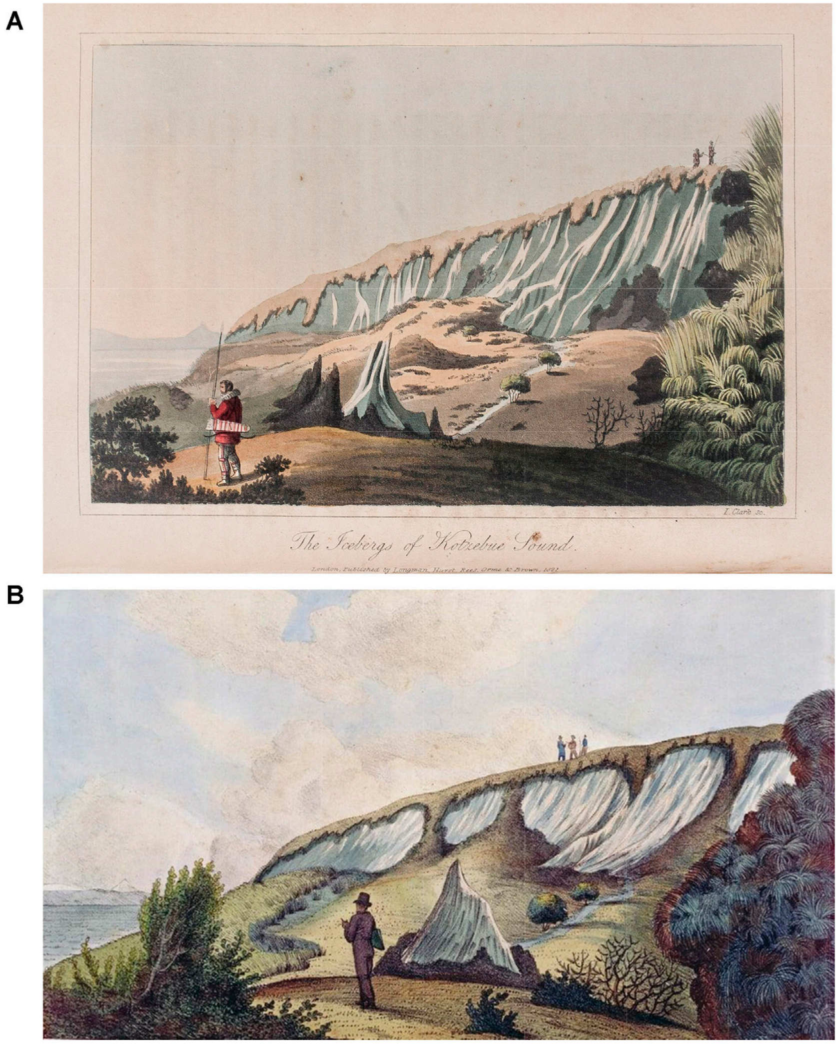

FIGURE 4 | Paintings "The icebergs of Kotzebue Sound" **(A)** and "Vue des Glaces dans le Golfe de Kotzebue (View of the Glaciers of the Gulf of Kotzebue)" **(B)** by Ludwig Choris (1822).

and Adams, attempts to determine the genesis of Yedoma have mainly been focused on the origin of the bodies of massive ice. Soil in Yedoma was often unnoticed or described as a secondary feature filling cavities made by erosion within the massive ice. Discussions focusing on the genesis of ice rather than the origin of the entire formation prevailed until the 1950s.

Alaska

In July 1826, 10 years after von Kotzebue's voyage, Captain Frederic W. Beechey and his crew revisited the site described by von Kotzebue (1821). After observation of the exposure from the boat and a brief inspection it by Mr. Collie, Beechey (1831) concluded that ice was just a coating on the bluff face and the ice was a product of snowdrift or freezing of water running over the surface of the cliff (**Supplementary Quote S6**). With such a perception, in September 1826, Captain Beechey looked at a similar exposure at Cape Blossom on the Baldwin Peninsula (**Figure 1**), which Beechey named after his ship (**Supplementary Quote S7**). The description by Beechey (1831) showed that in front of him was an exposure of ice wedges with intermittent soil columns. He explain ice as imbedded in the indentations in soil of the cliff. Most likely, he misinterpreted the origin of the ground ice in the exposure because he already had made up his mind before closely examining these features.

von Chamisso (1836), a crew member of von Kotzebue's expedition, rejected Beechey's conclusions, and insisted on the accuracy of von Kotzebue's report (von Chamisso, 1821) that described the occurrence of ice as a thick solid body (**Supplementary Quote S8**).

Beechey's crew members A. Collie and Lieutenant E. Belcher provided their opinions on the genesis of the ice (see **Table 1** for different hypotheses on the genesis of massive ground ice within Yedoma). Collie described three possible mechanisms of ground ice formation: 1) from snowdrifts converted into ice by successive thawing and freezing in spring and summer; 2) from water collected in deep fissures and cavities; and 3) from water

TABLE 1 | Hypotheses of the genesis of massive ground ice and respective authors.

Genesis of ice	Author
Ice coatings on the surface of exposure	Beechey (1831)
Glacier or ice sheet	Hooper (1884), Herz (1904), Muir (1917), Obruchev (1931), Saks (1947)
Infiltration ice	Belcher (Beechey, 1831)
Buried lake ice	Dall (1881), Russell (1890), Turner (1886), Mendenhall (1902), Maddren (1905), Grigoriev (1927)
Icing	Tyrrell (1917), Wilkerson (1932), Gusev (1958)
Open system pingo	Porsild (1938)
Firn and snow	Dawson (1894), Geikie (1894), von Toll (1897), Grigoriev (1927), Tolmachev (1903), Ermolaev (1932), Gorodkov (1948), Grave (1944), Gusev (1958)
Segregated ice	Taber (1943)
Wedge ice	Figurin (1823), von Bunge (1887), Leffingwell (1919), Popov (1952)

trickling from the slope above the frozen bluffs. Belcher proposed a hypothesis that water infiltrates every summer to the surface of the frozen soil, where it freezes, and accumulates into a thick horizontal sheet of pure transparent ice (Beechey, 1831).

Russia

In northern Yakutia, Dr. A. E. Figurin, a physician in Anzhu's expedition to the New Siberian Archipelago (1820–1824), observed numerous exposures of muddy ice along Siberian rivers, creeks and seashores of the mainland and islands. The ice mostly had the shape of wedges narrowing to their base. When describing the tundra terrain, he defined Yedoma as hills that appeared almost everywhere and at many places contained ice wedges. The Yedoma surface was covered by tussocks and bare, "mold-covered" spots (Figurin, 1823), which we interpret as frost boils. Figurin also described the formation of 'buyarakhs', which are known as baydzherakhs (conical thermokarst mounds typical of Yedoma) in the modern permafrost literature (van Everdingen, 1998). Figurin's major contribution to permafrost science was the first explanation of the formation of ice wedges caused by frost cracking (**Supplementary Quote S9**).

In his "Excerpts on Siberia," Mathias von Hedenström (1830) also described ice wedges and tried to explain the origin of alternating horizontal layers of ice and soils that he had observed in exposed bluffs of the Yana-Kolyma region of Northern Yakutia. He mentioned that ice wedges sometimes cross these horizontal layers (**Supplementary Quote S10**).

CONTINUING STUDIES IN ALASKA DURING THE 19TH CENTURY

In 1848, Eschscholtz Bay was visited by the ship "Herald" under the command of Captain Henry Kellett in search of the lost Franklin Expedition. The results of the expedition were reported in several volumes covering a general narrative of the cruise as well as the botany and zoology studied at the sites they visited (Seemann, 1853). Ice cliffs in Eschscholtz Bay were described in every volume, but in more detail in the volume on zoology written by the prominent British naturalist Sir John Richardson (1854). He was not part of the crew, however, and his extensive description is based on notes taken by members of the expedition, including H. Kellett, B. Seemann, and J. Goodridge. Richardson (1854) concluded that von Kotzebue (1821) was right about the ice originating as a "solid iceberg" and Beechey (1831) was wrong about the ice in bluff being a superficial coating of water freezing to the bluff face (**Supplementary Quote S11**). However, the issue of relating mammoth remains to a thin layer of soil covering ice remained a problem for Richardson (**Supplementary Quote S12**). Seemann (1853) also concluded that Captain Beechey was wrong in his explanation of the ice being just a coating on the face of the bluff and critically assessed the hypothesis of Belcher who assumed that surface water penetrated through peat and clay and that ice accumulated gradually (**Supplementary Quote S13**).

From the descriptions of several exposures based on notes by Goodridge, it is difficult for us to reconstruct the structure of the bluffs, Goodridge tended to interpret exposures as made of ice, describing one of exposures as "a few icy pillars and detached walls standing twenty feet above the surrounding level surface, and still covered with from seven to ten feet of soil." A description of the cliff is also illustrated by a painting (**Figure 5**), produced by artist W. Fitch from a sketch made by one of the members of the expedition. It would be especially interesting to see this original sketch. In the painting, the exposure is presented as a pure ice with a thin layer of clay and peat over ice.

Kellett and Richardson, who reviewed notes taken by Kellett and two of his companions, discussed several modes for the ice formation and did not come to a credible conclusion. It is interesting that they took literally von Kotzebue's definition "iceberg," while von Kotzebue and von Chamisso did not discuss the mode of ice formation. We think that von Kotzebue used the word "iceberg" just to describe an ice mountain (as "berg" means mountain in German) without any relation to real icebergs. In his memoir on the voyage, von Chamisso mentioned "so-called iceberg" (von Chamisso, 1836).

Dall (1881) visited Eschscholtz Bay in 1880 and compiled detailed descriptions of the exposed bluff. Among other interesting details, he mentioned that the solid ice was penetrated by deep vertical holes, in which organic-rich sediments had been deposited in layers, and appeared as soil cylinders on the exposed face of the bluff (**Supplementary Quote S14**).

In evaluating earlier hypotheses of ice genesis, Dall and Harris (1892) concluded that von Kotzebue and Eschscholtz (von Kotzebue, 1821) were right in their interpretation of the ice formation and that Beechey (1831), who thought that the ice

FIGURE 5 | Painting "The Ice Cliffs in Kotzebue Sound" by the artist W.W. Fitch painted from a sketch made by T. Woodward, one of the members of the expedition. Second half of the 19th century (Museum National d'Histoire Naturelle, Paris).

was a superficial deposit, was wrong (**Supplementary Quote S15**). Given the limitations of earlier explanations, Dall and Harris (1892) developed an elaborate regional scheme for relating an episode of ice formation to changing water levels in the Bering Sea and depositional processes in the surrounding area. They envisioned a land connection or enormous level plain covering much of the present area of the Bering Sea related to uplift of the area during the Miocene (**Supplementary Quote S16**), somewhat the reverse of the land connection caused by lowering of sea level associated with glaciation during the Pleistocene, as currently accepted. While the enormity of fluvial processes creating such widespread deposits is unimaginable given current knowledge, the hypothesis at least sought to address the widespread nature of the deposits, provided a link between ice accumulation and depositional process, and related ice accumulation to development of surface vegetation and soils.

Captain C. L. Hooper (1884) commanding the Revenue Cutter "Thomas Corwin" visited Eschscholtz Bay and Elephant Point near the mouth of the Buckland River in 1880 and 1881. He examined the ice and also found that the explanation given by Beechey was not correct. Hooper made several valuable observations and suggested wedge-ice origin of some of the massive ice bodies (**Supplementary Quote S17**).

John Muir (1917), a member of Hooper's expeditions, defined the massive ice at Elephant Point as buried glacier ice but he also noticed masses of dirty stratified ice of a different origin (**Supplementary Quote S18**).

John C. Cantwell (1887), Lieutenant on the U.S. Revenue Marine steamer "Corwin," described the occurrence of a chain of exposed ice cliffs up to 150 feet high along the Kobuk (Kowak) River starting about 130 km from the mouth (**Figure 6**) (**Supplementary Quote S19**). Cantwell (1896) speculated that maybe it was an old glacier buried beneath the deposits of a more recent inundation, but finally he admitted: "The formation of the remarkable ice cliffs in the lower country is, however, a geological nut which the writer admits his inability to crack."

Findings of Yedoma in Eschscholtz Bay, on the Baldwin Peninsula, and along the Kobuk and Buckland rivers showed vast areas surrounding Kotzebue Sound that were, and in some places still are, underlain by Yedoma, which for thousands of years has been eroded by the sea and rivers. This allows us to hypothesize that Eschscholtz Bay, Selawik Lake, and Hotham Inlet are results of thermokarst processes that have affected original Yedoma. Combined with lagoonal intermediate stages, erosion has formed the modern landscape leaving Yedoma remnants.

Turner (1886) studied the environment of Western Alaska from 1874 to 1881 and tried to explain the origin of the ice bluffs that had been observed at various parts of the coast, especially north of the Bering Strait. He described a hypothetical formation of a thick body of ice resulting from continuous covering of lakes with floating vegetation mats, whose thermal properties protect the ice underneath it from melting during the summer (**Supplementary Quote S20**). Another important factor supporting rapid freezing was a thin layer of snow. Turner evidently was the first to suggest a lacustrine origin for the massive ice exposed in the Yedoma bluffs.

Russell (1890), who made a reconnaissance of the Yukon River for the United States Geological Survey (USGS), visited the Palisades Bluff (**Figure 1B**) and came to the similar idea that the massive ice in these famous bluffs had a lacustrine origin (**Supplementary Quote S21**). Russell's work is of a special interest to permafrost science because it appears that he was the first to

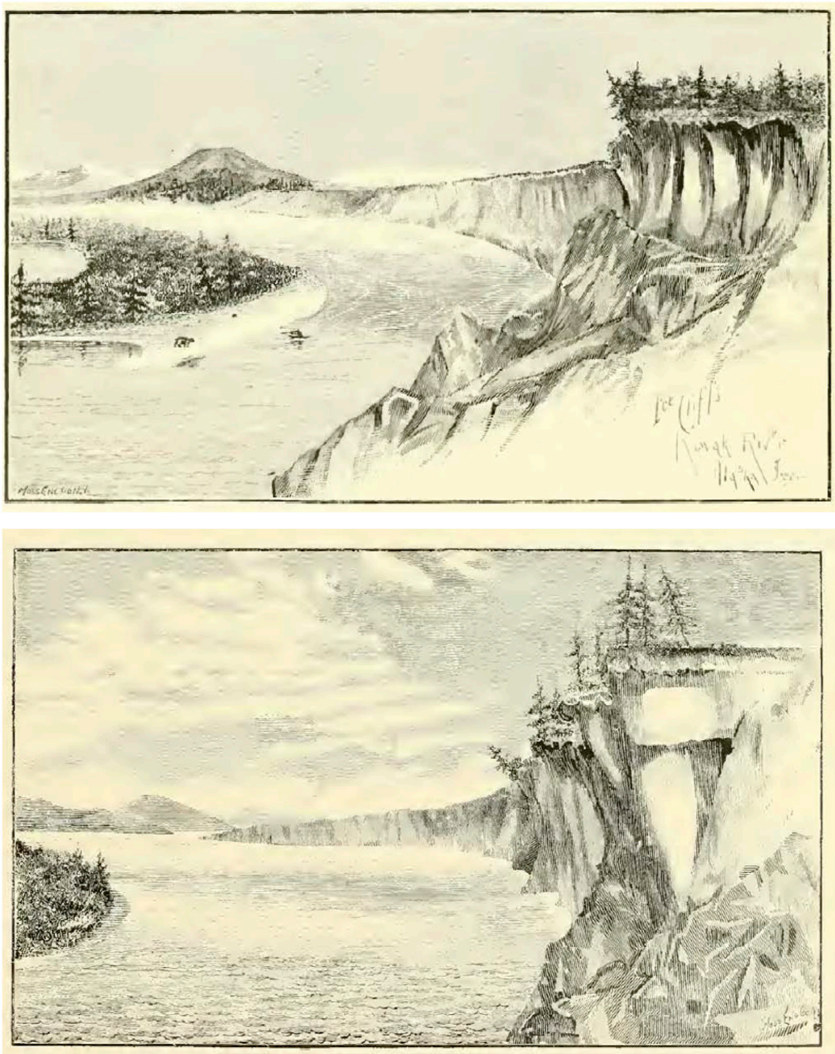

FIGURE 6 | Ice cliffs at the Kobuk River (Cantwell, 1887).

clearly define the process of syngenetic permafrost formation, presuming that under certain conditions deposition and freezing may occur at the same time, which explains the formation of alternating layers of clear ice and soil (**Supplementary Quote S22**).

While crediting Russell (1890) for a clear understanding of syngenetic permafrost formation, we also note that prior to Russel (1890), Lopatin (1876) had described the formation of interbedded ice and sand layers in the winter of 1868 on the Okhotsk Sea coast of the Sakhalin Island. In observing that the surface layers are frozen in winter and thaw during summer, Lopatin presumed that under colder climate these ice layers may be preserved for centuries (**Supplementary Quote S23**). He believed that the ice-rich soil he had described in the Yenisey River Delta could form in a similar way. Dall and Harris (1892) shared the opinions of Turner (1886) and Russell (1890) relating the origin of ice in the cliffs to frozen lakes buried by soil.

Dawson, the Director of the Geological Survey of Canada (1894) generally agreed with Dall and Harris (1892) on the timing of ice formation and the environmental conditions but thought that the ice was a result of snow accumulation. Soil, which was derived from adjacent highlands and deposited by rivers, covered ice and protected it from thawing.

Mendenhall (1902), who made a geological reconnaissance along the Yukon, Kanuti, and Kobuk rivers for the USGS, observed Yedoma exposures along the Kobuk (Kowak) River and Eschscholtz Bay and agreed with Russell (1890) that the ice originated from a frozen lake (**Supplementary Quote S24**).

THE SCIENTIFIC AND PERSONAL CONFRONTATION BETWEEN EDUARD VON TOLL AND ALEXANDER VON BUNGE

Although numerous hypotheses on the origin of Yedoma ice had been proposed since the initial discoveries by Adams (1808) and von Kotzebue (1821), the first serious discussion on the real origin of the massive ice within Yedoma took place between von Toll (1895, 1897) and von Bunge (1883, 1895) at the end of 19th century. These two prominent Arctic explorers were members of the same polar expeditions and talked about the same exposures on the northern shores of Yakutia, including the New Siberian Islands, but came to different conclusions on the origin of Yedoma ice. Their disagreement even took on a personal character. von Toll (1895) wrote an extensive paper, in which one of the main points was to prove that he was right, and von Bunge was wrong. According to von Bunge (1903), von Toll subjected von Bunge's hypothesis to "strict scientific criticism, calling it a "theory" without any reason."

Von Bunge's Theory

Von Bunge (1887) witnessed the formation of frost cracks accompanied by a loud noise "like shots under the surface remaining a distant cannonade," like earlier observations made by Figurin (1823). Von Bunge noted that the cracks penetrated to significant depth. The tundra he observed on the Lena Delta was divided into a myriad of irregular polygons, whose edges were higher than the center. Between the edges of neighboring polygons, there was a narrow trough, which often was used as a path by lemmings. This trough corresponded to a deep crack in the earth filled with ice. Von Bunge speculated that when the spring snowmelt water fills the cracks, it freezes, expands with tremendous pressure and pushes the walls of the crevices apart. By repeated cracking and freezing of snowmelt water, the ice volume around cracks becomes bigger over time.

From his observations of the formation, von Bunge (1895) concluded that huge masses of ice could be formed in this manner. He correctly described the morphology of Yedoma and the nature of ice but found it hard to comprehend how frost cracks could penetrate several dozens of meters in depth and develop the increased width of wedge ice at great depths. He found that an ice wedge, when exposed in coastal bluffs, could present an appearance of a continuous horizontal layer of ice. He also explained the impurities of ice (foliations) and the decrease in the size of ice crystals with depth. Given current knowledge, it is easy to find limitations in von Bunge's descriptions and conclusions, but at the time of his studies he made a significant contribution to our understanding of Yedoma ice formation.

Von Toll's Theory

In contrast, von Toll (1891, 1895) considered the masses of ice on Bol'shoy Lyakhovsky Island as the remnants of a mainland glacier assumed to have covered these islands, as well as the coasts of the continental Siberia from the Khara-Ulakh Ridge to the Chaun Bay (von Maydel, 1894) and extended 200 km south into the mainland. He stated: "No one geologist, looking at such an exposure, would have any reservation that the ice is older than the cracks filled with layers of ice and clay" (in Obruchev (1892) translation of von Toll (1891) paper). However, according to von Bunge (1903), von Toll had not seen Yedoma exposures during the summer when they were not covered with snow. He was relying instead on the outstanding photographs of Yedoma (e.g., **Figure 7**) given to him by von Bunge (von Toll, 1895) (**Supplementary Quotes S25, 26**). Von Toll's own photographs show only a slope covered by snow with just the tops of baydzherakhs visible on the surface. In his publications, von Toll described exposures of the southern shore of Bol'shoy Lyakhovsky Island near the mouth of the Vankina River (**Supplementary Quote S25**) based on the photograph by von Bunge (**Figure 7**, bottom). Von Toll studied crystals of ice taken from the upper part of an exposure. He concluded that "the structure of Quaternary ice layers on the New Siberian Islands speaks in favor of their origin from snow and strongly against the water origin." According to von Toll, the firn had remained at temperature below 0°C the entire time before it was covered with soil, and the growth of ice crystals was not possible (**Supplementary Quote S27**).

Von Toll—von Bunge Disagreement

According to von Toll, von Bunge described his idea for the first time in letters to Shrenk (von Bunge, 1887) and they were written in the winter of 1884 in Sagastyr during a few hours of rest in the midst of hard work, and in a difficult environment, therefore could not contribute to a strictly scientific treatment of the subject. In any case, he said that von Bunge was wrong in his explanation of the massive ice origin and did not solve the problem of the origin of ice that was presented to him. von Bunge (1903) answered von Toll's criticisms (**Supplementary Quotes S28, 29**), emphasizing that von Toll did not see the exposures in the summertime and arguing that by no means the ice could be older than the soil. Although von Bunge was certain of his hypothesis of the formation of ice, he admitted that the problem of the soil and ice origin was very complicated and that future researchers would solve it.

In 1903, while searching for the vanished group of von Toll, Kolchak (1906) visited Faddeevskiy Island where he described 70–80 feet (20–25 m) exposure of Yedoma as a glacier covered with soil and "typical cones of baydzherakhs." He was the first to describe remnants of Yedoma under water along the seafloor (**Supplementary Quote S30**).

CONSEQUENCES OF THE VON TOLL—VON BUNGE DISAGREEMENT ON YEDOMA STUDIES IN RUSSIA IN THE 20TH CENTURY

Summarizing the von Bunge—von Toll disagreement, we can conclude that von Bunge recognized that the focus of studies should have been the soil, while von Toll and others were preoccupied with the ice. Popov (1952) later said that both von Toll and von Bunge were not correct because soil and ice formed simultaneously (syngenetically). We agree with von Bunge that the soil is the primary substance, as the existence of soil sets conditions needed for ice formation.

Nevertheless, for the next 50 years, the majority of leading Russian scientists unequivocally supported von Toll in his dispute with von Bunge. In the introduction of the Russian translation of von Toll's diary (1959) from his voyage on the yacht "Zaria,"

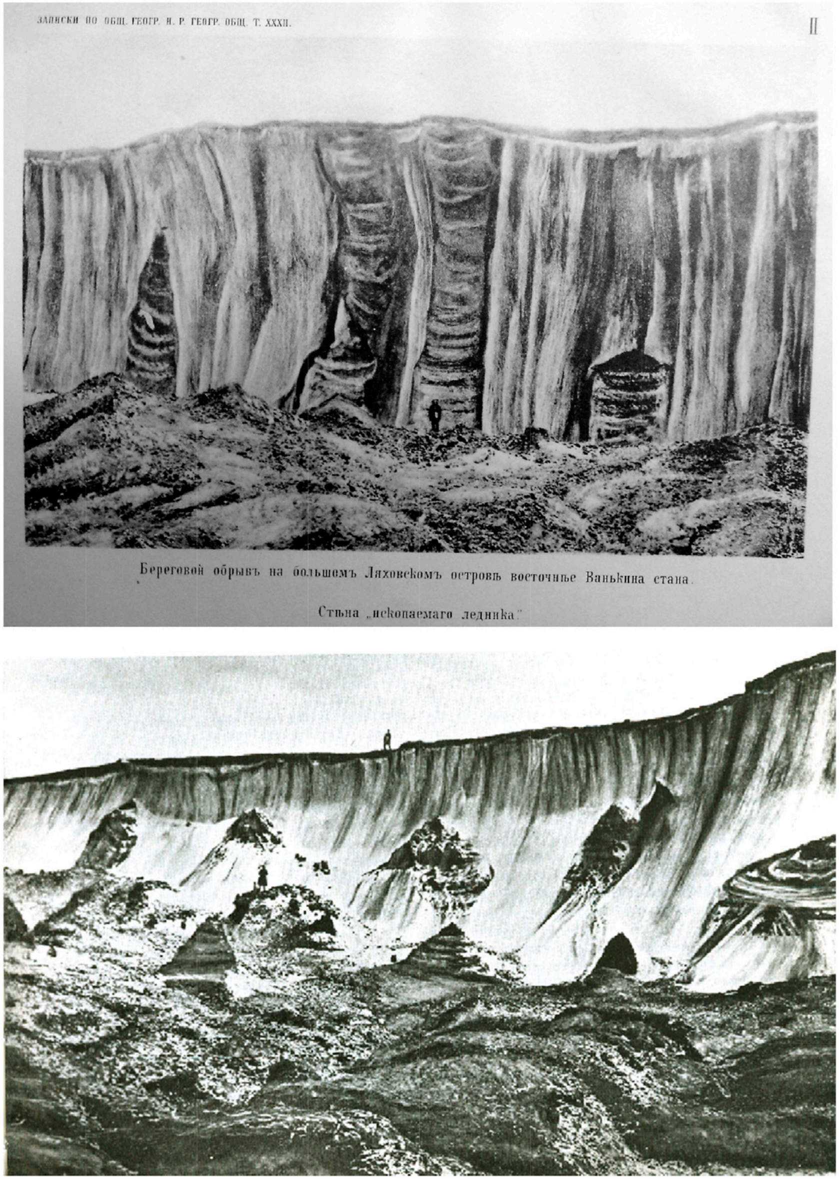

FIGURE 7 | Southern coast of Bol'shoy Lyakhovsky Island, Vankina River mouth, photographs by von Bunge (von Toll, 1897).

Wittenburg (1959), a prominent Arctic geologist, wrote: "von Toll's studies of fossil ice on Bol'shoy Lyakhovsky Island have not been outshined to date. They are included in every textbook on geology and physical geography and translated into many languages."

Many Russian scientists supported von Toll's concepts of buried glacial ice, or at least firn. In 1901, an expedition of the Russian Academy of Sciences recovered a mammoth on the bank of the Berezovka River, a tributary of the Kolyma River. A short description of the site was done by a zoologist, O.F. Herz (1904), as the geologist who was assigned to the trip did not participate. Herz took a photograph of the exposure (**Figure 8**), collected cores of ground ice from the site and ultimately supported a glacial origin of the ice (**Supplementary Quote S31**).

Tolmachev (1903) studied the samples of ice collected by Herz and evaluated their properties, such as unit weight, crystal size and shape, and air bubbles within the ice. Tolmachev stated that the origin of the ice could be easily recognized by its structure, and that ice formed by snow water, even extremely rich in dissolved air, cannot be as porous as snow ice. He concluded that the ice at the Berezovka site was firn. Tolmachev also noted that it would be extremely interesting to study the structure of ground ice and suggested that new observations were necessary to solve all remaining problems, referring to the discussion between von Toll and von Bunge (**Supplementary Quote S32**).

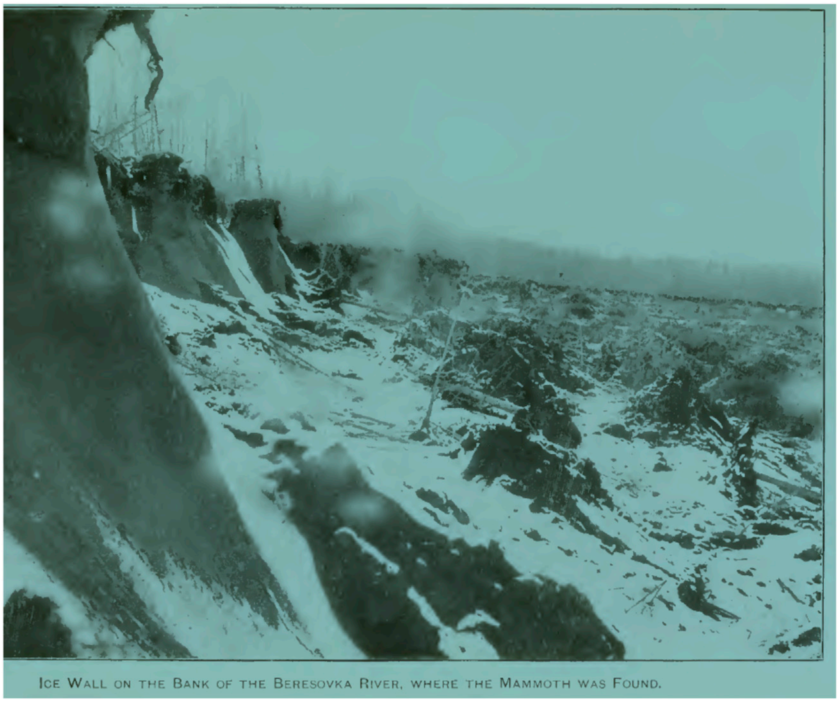

FIGURE 8 | Exposure of yedoma at the Berezovka River (Herz, 1904).

FIGURE 9 | Yedoma exposure at the mouth of the Bol'shaya (Rauchua) River (Tolmachev, 1911).

A few years later, Tolmachev (1906) visited the Yenisey-Khatanga region and admitted that the wedge ice was much more common than he had previously thought (**Supplementary Quote S33)** During his expedition along the shore of the East Siberian Sea, Tolmachev (1911) found that Yedoma occurred widely west of Chaun Bay (**Figure 9**). At that time, he avoided the discussion of Yedoma genesis and described it as tundra sand–clay soil with inclusion of huge bodies of underground ice. The question of the ice's origin had been of interest to Tolmachev for several decades; he identified it as one of the most important problems of Arctic geology (Tolmachev, 1928; Tolmachoff, 1929) (**Supplementary Quotes S34, 35**).

Vollosovich (1909, 1915), who participated in von Toll's expedition, shared von Toll's ideas on the origin of ice. At the Sanga-Yurakh mammoth site, Vollosovich (1909) described two ice horizons separated by a layer of soil and called this layer "the mammoth horizon." Later, Ermolaev (1932) did not find this horizon. In our interpretation, it seems that Vollosovich (1909) described soil accumulated on a thermal terrace as an original horizon. At Bol'shoy Lyakhovsky Island, Vollosovich (1915) also saw two layers of ice in the bluffs, separated by mudflow deposits and attributed them to two epochs of glaciation. In his opinion, the ice represented the remains of snowdrifts.

Sumgin (1927), the founder of the Russian (Soviet) Permafrost Institute, shared the opinion that ground ice of the New Siberian Islands, ice on the shore of the Arctic Ocean to the east of the mouth of the Lena River, and ice in the Lena-Aldan watershed was glacial ice. These ice masses, therefore, were interpreted as having been preserved in the ground from the glacial epochs to present. Sumgin was interested in Yedoma and mammoth fauna associated with it, which he considered as proof that permafrost was not a product of the contemporary climate but a very old formation.

Grigoriev (1927, 1930), a prominent Russian geographer and a founder of the Institute of Geography of the Russian Academy of Sciences, not only fully supported von Toll's opinion on ice formation, but also applied it to the formation of large bodies of massive ice with a thickness of up to 25–30 m in Central Yakutia (**Supplementary Quote S36**). According to Grigoriev (1927) descriptions, massive ice bodies in Central Yakutia consist of two types of ice—firn in the upper part and lake ice below it. Grigoriev (1927, 1930) described the formation of firn as followed: At the onset of a new period of glaciation and therefore a new climate, the rivers that had survived the new uplift of the country began to erode their channels intensively. This river erosion deepened, widened and created a new surface cut into previously deposited sediments. The rivers that had broken up and became separate lakes, underwent a different fate. In these lakes (due to the absence of flowing water), the freezing of water occurred deeper than in the active rivers. Thus, these lakes froze back to the bottom in most cases in winter (as is occurs in some undrained lakes of the area even today). Increased precipitation led to a greater accumulation of snow in the depressions. The snow covered the ice and prevented it from melting in the summer, as it was not able to melt completely under the climatic conditions of the time. Thus, the ice recrystallized into a granular structure, and lake basins were gradually filled with firn, which was deposited on top of lake ice. If at the beginning of this process there was still unfrozen water under the ice, it froze somewhat later, being exposed to the low temperature of the permafrost. In Grigoriev's opinion, the difference between these two types of ice was so obvious that they could not be missed in an exposure or a drilling core.

Ermolaev (1932) studied Yedoma on Bol'shoy Lyakhovsky Island and shared von Toll's opinion on ice genesis, but disagreed with Vollosovich on the existence of the two ice horizons. Ermolaev paid more attention than others to the deposits filling "cracks in ice." He found that soil was homogeneous with the size of most particles in the range 0.05–0.01 mm. This silty soil was interbedded with thin layers of ice, which were curved up at contacts with massive ice. During a summer, these cracks were a drainage pathway for meltwater. Water running from higher elevations, as well as winds, deposited silt over the ice layer. Such a cycle repeated every year and produced a series of silt-ice layers. The volume of ice within the sediment filling these cracks was about 70%. Peat that occurred in these cracks was also brought in by water. Ermolaev found that the structure of the ice was similar to ice from the Berezovka River exposure that was described earlier by Tolmachev (1903). Ermolaev (1932) described the soil wedges, or rather those spaces between the ice walls that were subsequently filled with soil, in relation to the genesis of the ice. Whatever their origin, he considered them a consequence of some coherent system of stresses existing within the whole mass of solid ice and that they could have been caused by a process that involved the entire ice mass. Ermolaev, a mechanical engineer by education, considered a few possible models of ice cracking and concluded that the ice was a glacier, and cracks in the ice were caused by ice folding. Based on his mechanical model, he estimated that the thickness of ice sufficient for such stresses should be 70–80 m. In light of modern knowledge of the origin of Yedoma, we can consider Ermolaev's evaluations as erroneous, and this example shows the importance of developing the correct conceptual models before quantitative modeling.

Vladimir A. Obruchev (1931), a patriarch of Siberian Geology, also supported von Toll's ideas. He believed that this fossil ice also had an extensive distribution along the coast of the Arctic Sea. He considered that most of it was formed during a glacial period and was represented by stagnant ice detached from glaciers during their retreat, with parts of it being remnants of stagnant firn fields (**Supplementary Quote S37**). The remnants of fauna and flora, found very often in wedge-shaped and pillar-like masses of layered sediment deposited among the ice bodies, supported his concept of ice that had formed during the last glaciation.

In 1940, the government of the Republic of Yakutia asked the Obruchev Permafrost Institute to investigate the distribution and properties of buried glacier ice in the vicinities of Abalakh Lake, Central Yakutia, for the purpose of extensive development of the area. Experienced permafrost scientists, such as N.A. Grave, A.I. Efimov, and P.A. Soloviev actively participated in this study and produced numerous reports and papers describing their investigations. According to Grave (1944), a buried firn field had occupied the vast area of the Lena-Aldan watershed; he identified specific locations of buried ice. He documented ice thicknesses of 25–30 m and estimated from the depth of alases (thermokarst basins) that it could reach up to 40 m. Grave presented a preliminary map of buried ice in the region. Based on an example of the exposure of buried ice (**Figure 10**), Grave found great similarity of the structure and shape of buried ice of the Lena-Aldan watershed with the fossil firn field of the North Cape of Bykovsky Peninsula, from which he concluded that they were formed simultaneously. He considered as proven that the fossil ice was formed from accumulations of snow and firn. The ice structure, the absence of moraines, and presence of meadow soil under ice without any traces of ice scouring were to Grave evidence of such a genesis. He noticed, but did not clearly explain, the homogeneous nature of the ice and absence of infiltration ice

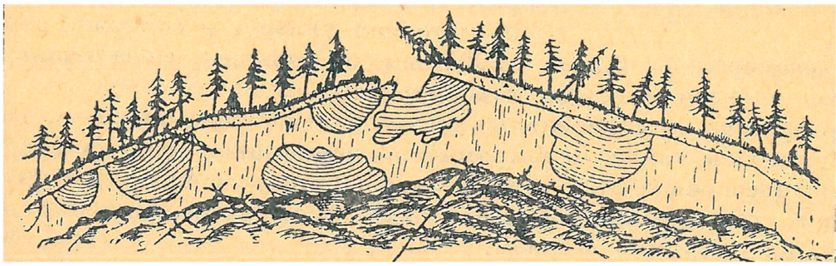

FIGURE 10 | Exposure of "fossil ice" with layered inclusions of soil at the left bank of the Aldan River (Grave, 1944).

in it. Studies driven by this approach regarding the genesis of ice were continued by the Permafrost Institute until 1950 (Shumskii, 1952).

Saks (1947) came to conclusion that the massive ice on the New Siberian Islands is not a thick continuous layer of firn but rather numerous separate snowfields. Gorodkov (1948), a leading Russian Arctic biologist, expressed his opinion on the nature of ice at Kotelny Island. He described the massive ice with inclusions of silt and small air bubbles, which was penetrated by thick wedges of a loess-like deposit and covered with a layer of loess-like silt about 40–60 cm thick. Gorodkov studied the properties of the ice and came to conclusion that it originated from firn. He also explained that soil wedges in ice formed as a result of silt accumulation in depressions that had developed from melting ice (**Supplementary Quote S38**).

Interesting, that Geikie (1894), the author of the monumental monograph on the Ice Age, compared ground ice formations of Northern Alaska with those of Siberia that had been previously described by von Toll and also came to conclusion that they are very similar and represent snowdrifts of a late glacial epoch (**Supplementary Quotes S39, 40**).

YEDOMA STUDIES IN NORTH AMERICA AT THE FIRST HALF OF THE 20TH CENTURY

In North America, ice- and organic-rich silt known to permafrost scientists as Yedoma was named 'muck' by gold miners in Canada and Alaska. Tyrrell (1904, 1917) studied "muck" deposits in the Klondike District, Yukon Territory, Canada. In some areas, he described muck strata up to 30 m thick that contained layers of clear ice. Tyrrell interpreted the ice as an underground icing formed by springs; the vertical veins or dikes of ice in his descriptions indicated positions of former water channels (**Supplementary Quote S41**).

Maddren (1905), who mapped known areas of Quaternary deposits with locations of Pleistocene mammals across Alaska, shared Russell's explanation of ice formation and was passionate about the idea of a lacustrine origin of ground ice (**Supplementary Quote S42**). Maddren was so confident with this idea of ice formation that he even modified Tolmachev's (1903) sketch of the bluff of the Berezovka River and added that the ice is underlined by silt of lacustrine genesis, which was not stated by Tolmachev. Tolmachev's statement was originally written as: "It can be ascertained, however, that the origin of such ice is easy to recognize by its structure. No matter how rich in air dissolved in snow water, it cannot make ice as porous as snow ice" (Tolmachev 1903, p. 133). However, Maddren's translation gave it the opposite meaning: "It may be remarked, the formation of the ice in such a way cannot be deduced from its structure." Maddren appears excessively critical of Tolmachev and overconfident in his own statements as for example, in one of his conclusions on Alaska he stated that there was no evidence that the climate of the Arctic had been colder in the Pleistocene than at present, and there were no ice-rich deposits of the Pleistocene age except glacial (**Supplementary Quote S43**).

A decade later, Leffingwell (1915, 1919) fully supported von Bunge's idea: "The writer leaves the origin of this ice an open question but holds the opinion that the most favorable line of inquiry will be along the lines suggested under the theory of ice wedges" (Leffingwell, 1919, p. 223). He even regretted that he did not know von Bunge's work when he began his studies of ice wedges in Alaska. Commenting on von Bunge's and von Toll's dispute, Leffingwell was surprised that von Bunge's theory did not get support in Russia. He saw some challenging questions in an application of the ice-wedge theory to Yedoma locations (during his work along the Beaufort Sea coast of Alaska, Leffingwell did not observe any Yedoma exposures). Nevertheless, Leffingwell presumed that symmetrically distributed inclusions of earth in Yedoma cliffs were closely related to symmetrically arranged frost cracks; he also figured out that the surface could grow upward because of the pressure that polygonal blocks had experienced from the growing ice wedges (**Supplementary Quote S44**). Earlier in his famous paper on the formation of wedge ice, Leffingwell (1915) was close to our understanding of syngenetic formation of ice wedges: "The usual covering for the ice is muck capped by turf, or peat capped by growing sphagnum (?) moss. As the thickness of this mantle increases by surface growth, the limit of the summer's thawing should rise, thus allowing a constant upward extension of the surface of the ice wedge at the locus of growth" (Leffingwell, 1915, p. 648). Thus, Leffingwell described two cases of "apparent upward growth of the surface." Leffingwell (1915) also commented on Yedoma in Alaska, suggesting that much of the ground ice at the famous bluffs at Eschscholtz Bay could be wedge ice (**Supplementary Quote S45**).

Between 1900 and 1920, ice-rich silt that we interpret as Yedoma was also observed in various parts of Alaska

(**Figure 1B**) by Gilmore (1908), Quackenbush (1909), Prindle et al. (1913), Smith (1993), and Harrington (1918).

Wilkerson (1932), a geology professor at the Alaska Agriculture College and School of Mines (now the University of Alaska Fairbanks), provided detailed descriptions of both the fine-grained, organic-rich silt (muck) and ground ice. He believed that the gold-bearing gravels and overburden soil were frozen soon after deposition, and that the upper portions were thawed each summer with the depth of thawing never quite equaling the depth of freezing. Thus, the thickness of the frozen materials was the result of numerous additions of materials that were frozen shortly after deposition. He argued that the 30–40 feet thickness of the deposits indicated that freezing could not have occurred after the whole thickness of the deposits had been formed. Wilkerson concluded that ice bodies were buried icings (called "glaciers" by the miners and some geologists) that had formed along hillsides by the groundwater seepages. He presumed that the ice was preserved by a protective mantle of muck, gravel, sand, and peat.

To Porsild (1938), the process of ice formation in Yedoma was identical to the formation of an open system pingo as we understand it now. Based on his studies of pingo formation in Canada and Alaska, he presumed that a similar process could lead to formation of sheets of solid ice in the Kotzebue Sound region and on the Seward Peninsula, as well as in other unglaciated parts of Alaska (**Supplementary Quote S46**).

Tuck (1940), a geologist with the USGS, observed Yedoma ("muck") exposures at gold mining sites near Fairbanks, Alaska. He described the fine-grained composition of mineral soil, the abundance of organic material, high water content, and vertebrate remains. He identified three types of ground ice that occurred in: 1) soil pore space and comprised 50% of the total mass; 2) sills from a few inches to 10 feet thick; and 3) dikes (wedges) formed in tension cracks filled with water. Figures in Tuck's paper show that sills and dikes were just different projections of ice wedges. He hypothesized that sills formed at the same time as the muck and, in his opinion, the muck was of aeolian origin and its freezing occurred almost simultaneously with deposition (**Supplementary Quote S47**).

REACHING MODERN TIMES: TABER'S "ORIGIN OF GROUND ICE"

Taber (1943), who spent the summer of 1935 studying permafrost in Alaska, published the first comprehensive monograph on permafrost in Alaska. The content of this important paper, the history of its writing and publication, acceptance by peers, and its legacy were discussed in the recent review by Nelson and French (2021). Here we discuss mainly one chapter of this monograph—"Origin of ground ice"—in which Taber explained his vision of the origin of Yedoma.

In the previous decades before his paradigm-changing monograph, Taber performed outstanding laboratory experiments and developed fundamentals of still valid views on the impact of soil freezing on properties of frozen ground and the associated frost heave (Taber, 1930). There is no doubt that Taber's contribution to permafrost science and engineering was enormous. Taber visited Alaska during the time of extensive active gold mining and observed Yedoma exposures in open pits in both the Fairbanks area and the Seward Peninsula. Taber understood the existence of epigenetic and syngenetic permafrost and indicated that, in an attempt to solve the problems of permafrost formation and the development of ground ice, one should consider four scenarios (Taber, 1943, p. 1504):

1) The deposits were formed during a warmer climate and subsequently frozen as a result of climatic conditions now prevailing;
2) deposition and freezing occurred simultaneously under climatic conditions now prevailing;
3) the deposits were formed during a warmer climate and subsequently froze as a result of a change to a colder Pleistocene climate; and
4) deposition and freezing took place simultaneously during a Pleistocene climate that is colder than what is now prevailing."

In terms of the origin of Yedoma, scenarios 1) and 2) contradict the presence of well-preserved remnants of mammoths and other prehistoric animals whose presence in the deposits is only possible in a frozen state and, therefore, only permafrost formation during the Pleistocene should be considered. Unfortunately, Taber did not discuss details of syngenetic permafrost formation (scenario 4). He applied his understanding of the formation of frozen soil from his laboratory experiments to natural processes and features that were completely new to him.

Taber's experiments reproduced epigenetic permafrost formation in both closed and open systems. The experiments did not include processes representative of simultaneous soil deposition and freezing, the existence of a periodically thawed soil at the surface, and they excluded the possibility of a surface water supply to a soil undergoing freezing. Taber concluded that the Yedoma sediment accumulated before its freezing that occurred downward from the surface, and the ice-rich soil and ice wedges were formed as a result of epigenetic freezing of soil in an open system with water migrating from underlying gravel where it was subjected to hydrostatic pressure.

During his field studies, Taber noticed extremely high water content of soil, yet he did not comment on it. We now know that it is impossible to achieve such high water contents from experiments with epigenetic soil freezing. Taber (1943, page 1526) dismissed all existing hypotheses of ice formation in Yedoma and found that "none of the older hypotheses is competent from the standpoint of physics." Building on his numerous laboratory experiments and interpretation of field observations, Taber outlined a new hypothesis of the origin of ground ice in Yedoma. Its main idea was that ice lenses formed a layered cryostructure and that ice lenses and ice wedges were developed in one process of ice segregation.

Taber separated the accumulation of silt and its freezing in time and stated that "freezing to a depth of several hundred feet, with the formation of great masses of ground ice, required a very long time" (Taber 1943, p. 1533–1534). This "very long time" is

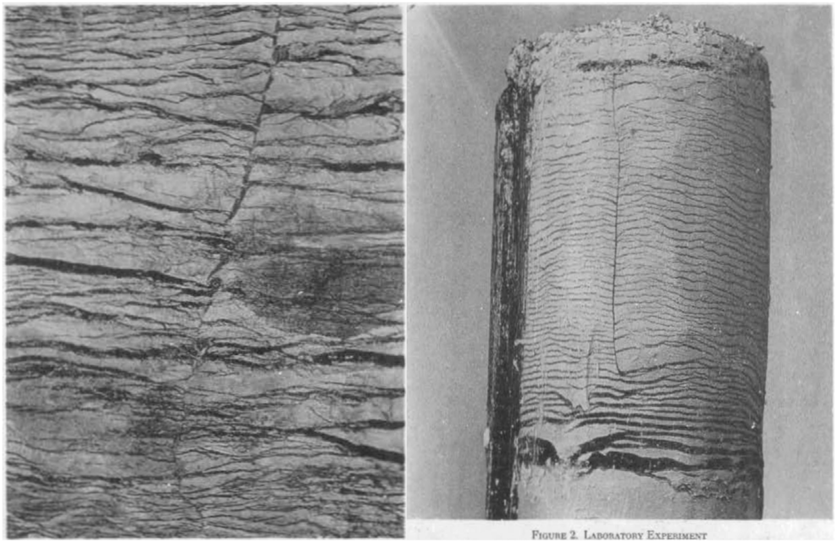

FIGURE 11 | Cryostructures of frozen soils (Taber, 1943). Left—from the exposure in an underground cold-storage excavation at Deering, Alaska; Right—from a laboratory experiment.

critical to Taber's new hypothesis. He believed that the small-scale polygonal structure formed in his experiments, continuing for days, could reach the size of ice-wedge polygons if freezing continued for thousands of years.

To prove his idea, Taber described an exposure in an underground cold-storage excavation at Deering (Alaska), which he found to be among the best and most remarkable exposures that he had ever examined. He compared a photograph of this exposure with a photograph taken from his experiments, and they show a perfect match (**Figure 11**). Unfortunately for Taber, the cryostructure of the exposed soil was not typical of Yedoma based on our present-day knowledge.

In the 1940–1960s, soils that we now identify as Yedoma, were described in various areas of Alaska including Seward Peninsula, the Yukon Flats, and the Yukon-Tanana uplands, and most researchers supported an aeolian genesis of soil (Black, 1951; Péwé, 1955, 1975; Williams, 1962; Hopkins, 1963; Sellmann, 1967).

STUDIES IN GERMANY AND THE FURTHER DEVELOPMENT OF THE ICE-WEDGE THEORY IN RUSSIA AND NORTH AMERICA

Sörgel (1936), studying ice-wedge casts in Thuringia, Germany, stated that "what diluvial ice wedges or wedge crevasses show in shape differences compared to Alaskan ice wedges is explained within the same genetic principle by the special conditions in the periglacial area at the time of diluvial ice wedge formation. These shape differences also confirm the ice wedge nature of the diluvial wedge crevasses." He came to an idea that the accumulation of sediment and formation of wedge ice can occur simultaneously. Earlier, Leffingwell (1915) mentioned such a process in relation to accumulation of peat. Sörgel's paper could have been a very important step in the explanation of Yedoma genesis, even if it had not directly dealt with Yedoma deposits. Unfortunately, this did not happen, and his paper was ignored. Scientists from the Obruchev Permafrost Institute, working in Central Yakutia, were mainly led by Grigoriev's ideas, Arctic geologists in Russia agreed with von Toll, and Taber worked hard to explain wedge ice as segregated.

Another important paper, which could have helped to explain the formation of massive ice in Yedoma, was written by Gallwitz (1949). Based on ice-wedge casts studies in Germany, he distinguished two types of ice wedges (epigenetic and syngenetic) and tried to derive information about permafrost conditions from the ice-wedge shapes. The importance of the Gallwitz' work for understanding of simultaneous formation of ice wedges and accumulation of sediment was stressed by Shumskii (1960).

Alexander I. Popov (1952), a scientist of the Obruchev Permafrost Institute, was the first to propose a hypothesis that led to the solution of the Yedoma formation problem. Working on the Taymyr Peninsula in 1949, Popov described ice wedges in a floodplain deposit and in the first terrace of the Mamontova River. He concluded that the formation of ice wedges takes place on a floodplain and the growth of ice occurs upwards and sideways accompanied by an increase in deposited floodplain sediments. Popov (1952, p. 17) concluded: "If ice growth is related to the mode of sediment accumulation, then we should also consider changes in this environment, i.e., epeirogeny dips and rises of alluvial plains. The correlation between the rate of sinking or uplift of an alluvial plain, the amount of water in the flood, the thickness of the annually accumulated sediment, and its composition determines the conditions of ice accumulation. Depending on the relation of these factors, either thick or thin ice is likely to accumulate, as well as the expansion of wedges sidewise."

FIGURE 12 | Photo of Yedoma by Vollosovich (1909), which was used as an illustration by Popov (1952).

Popov also observed foliations in the ice that were similar to the foliations on photographs taken by von Bunge and published by von Toll (1895). Before his first publication on the origin Yedoma, Popov had not personally seen Yedoma exposures and the photograph (**Figure 12**) in his publication was copied from a work by Vollosovich (1909). Popov extrapolated the processes of syngenetic permafrost formation involving the simultaneous growth of ice wedges that he had observed on a floodplain to the larger scale of Yedoma formation.

In this unifying connection, Popov was primary responsible for resolving the mystery of Yedoma genesis in spite of limiting Yedoma formation to floodplains of Arctic rivers. Popov's idea was proven a few years later by researchers of the Obruchev Permafrost Institute in Northern and Central Yakutia (Shumskii, 1952; Katasonov, 1954; Vtyurin, 1955; Korkina, 1959). (Shumskii (1952), p. 143) wrote about difficulties they encountered during these studies: "The mystery of the nature of the ice was due to its shape and the lack of anything resembling it among modern formations and the lack of direct observation of its formation. The relationship between fossil ice and soil is complicated and it requires hard work to clarify it. Exposures observed in natural environments allowed different interpretations."

Under the impact of Popov's work, Yedoma studies by the Obruchev Permafrost Institute in Central and Northern Yakutia were subsequently based on understanding the syngenetic nature of Yedoma involving sedimentation and ice-wedge formation occurring simultaneously. Among numerous results of these productive studies, there is a clarification of the Yedoma appearance in different projections by Shumskii (1959) which explains a puzzling and often confusing appearance of soil and massive ice in Yedoma exposures (**Figure 13**).

Russian Arctic geologists have had reservations about the explanation for Yedoma formation by permafrost scientists. Gusev (1954, 1958) still considered underground ice of Yedoma as buried firn or buried icings. Ermolaev visited Oyagossky Yar in 1968 and did not recognize ice wedges there (Ermolaev and Dibner, 2009).

Another important problem of Yedoma studies is the origin of sediments that host large syngenetic ice wedges. According to Popov (1967), the most favorable conditions for the syngenetic growth of ice wedges take place on floodplains, deltas, and in other similar depositional environments associated with tectonic lowering of the terrain, and in climate with low snow precipitation. He believed that Yedoma had been formed in such an environment. This was a guideline for numerous scientists in Russia for many decades even though some of them noticed the absence of the channel facies beneath a "floodplain deposit" (e.g., Romanovskii, 1958).

Shumskii et al. (1955) did not limit Yedoma formation to the floodplain environment. They stated (pp. 15–16): "If, simultaneously with the formation of ice wedges, new sediments accumulate on the soil surface—the growth of peatlands in swampy lowlands, alluvium deposits in river floodplains, slopewash at the foot of slopes, etc.—the upper boundary of continuous frozen strata gradually rises as the ground surface rises, and with it, ice wedges grow. Under such conditions, the ice wedges grow not only in width, but also upward, penetrating the accumulating strata of frozen deposits to their full thickness." This important insight had been unnoticed by permafrost researchers studying Yedoma, possibly because the publication addressed geological engineers specifically and not permafrost scientists, and as a result, the alluvial theory had prevailed for years.

An important deviation from the alluvial theory of Yedoma formation was work done by Gravis (1969). His detailed studies of frozen soil in numerous deep boreholes and pits in the foothills of the Kular Range in Northern Yakutia showed that an accumulation of Yedoma with tall ice wedges and typical cryostructures resulted from the accumulation of slope deposits.

Earlier (Schirrmeister et al., 2013) we distinguished between the dominant aeolian Yedoma genesis in Alaska/Canada and varying formation conditions in Siberia. In Russia, the aeolian theory was not popular. While Gravis' work was agreeably

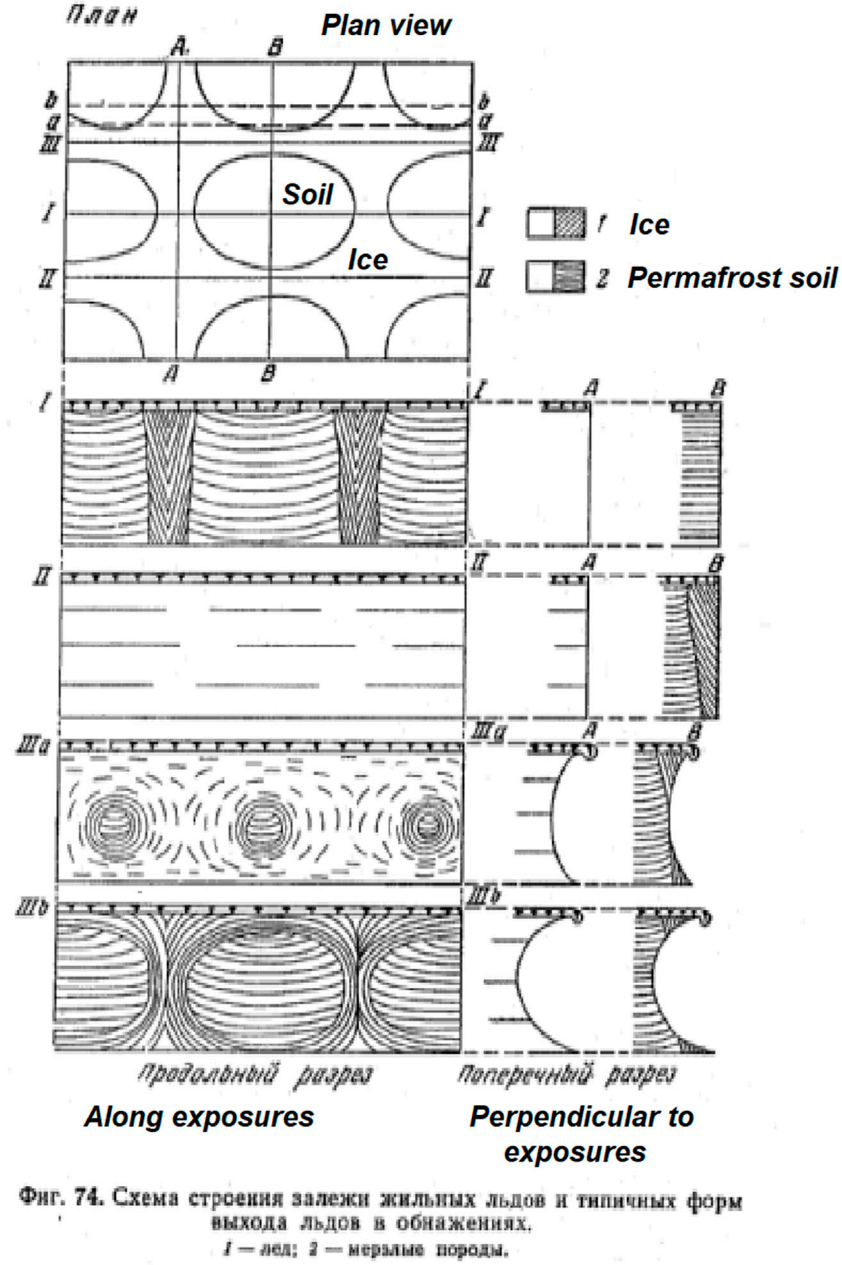

FIGURE 13 | Appearance of ice wedges and adjacent soil in exposures with different projections (Shumskii, 1959). Top image—plan view of the ice-wedge network; I, II, III a, III b—projections along exposures (visual appearance in the exposures); A, B—projections perpendicular to exposures (cross sections).

accepted by many permafrost scientists in Russia, the hypothesis of an aeolian genesis of Yedoma as proposed by Tomirdiaro (1978) met fierce opposition. His appeal to a similar opinion held by Péwé (1955) on the origin of Yedoma in Alaska did not help.

Konishchev (1981) supported the polygenetic origin of Yedoma and presumed that it could form in fluvial, slope, and lacustrine deposits. Zhestkova et al. (1982, 1986) agreed with the polygenetic origin too: they considered Yedoma as a climatic phenomenon because the mode of sediment accumulation did not restrict the formation of Yedoma. They also pointed out the importance of pedological processes and vegetation in the formation of properties of Yedoma and suggested considering Yedoma as a gigantic polypedon.

Extensive Yedoma studies during and after the 1950s had an enormous impact on the permafrost science. We agree with Konishchev (1981), who believed that cryolithology as part of permafrost science was triggered by the study of Yedoma genesis. He divided the study of massive ground ice into two stages. The first stage during the 19th and the first half of the 20th centuries involved the confrontation between supporters of a glacial origin and the proponents of an ice-wedge origin for the development of massive ground ice. A way out of this impasse was the concept of syngenetic growth of polygonal wedge ice and the simultaneous accumulation of host sediments as proposed by Popov, thus opening the door to the second (modern) stage of ground-ice studies.

After the long-held theory of a glacial origin of Yedoma there is tendency now to explain any large body of underground ice as wedge, segregated, or intrusive ice (Dubikov and Koreisha, 1964; Gasanov, 1969; Baulin and Dubikov, 1970; Mackay, 1971). Robust evidence of buried glacier ice has been found in Canada and Russia (e.g., Solomatin, 1986; Kokelj et al., 2017) but, ironically, it is currently difficult to convince the scientific community that buried glacier ice may exist in lowland areas (e.g., Sheinkman, 2017; Vasil'chuk, 2012). Recent findings (Anisimov et al., 2006; Basilyan et al., 2008) showed that buried glacier ice occurs in some parts of the New Siberian Islands, and sites of occurrence, properties and appearance of this ice are different from those that had been described in these areas by von Toll and von Bunge.

The origin of Yedoma is now considered a solved problem. Although discussions on the mode of sediment accumulation at specific Yedoma sites remain open, permafrost scientists agreed that Yedoma is late-Pleistocene syngenetic permafrost penetrated by ice wedges. This common understanding has helped to concentrate the attention of scientists on Yedoma as an outstanding and maybe the best source of information regarding the environment of the late Pleistocene. The number of Yedoma studies has been growing, and Yedoma has become one of the most intensive areas of permafrost research. The most recent synthesis article in English was published in the Encyclopedia of Quaternary Science (Schirrmeister et al., 2013).

CONCLUSION

In the beginning of the 19th century, the scientific world was introduced to an extraordinary geologic feature—Yedoma permafrost. It appeared as a strange combination of big masses of underground ice and deposits containing remnants of extinct Pleistocene animals, including mammoths. Since then, numerous geologists, geographers, and biologists proposed many hypotheses to explain the origin of this feature. They focused their attention predominantly on the ice and didn't consider the soil as an important component of Yedoma. Most of scientists at the time ignored soil completely, while others considered it as later inclusions within the ice. The two-dimensional appearance of Yedoma in exposures was often confusing. Explanations of ice genesis by geologists based on their previous knowledge have been unsuccessful. Features proposed in some hypotheses, like buried lake ice, have never been observed. The obsession with the origin of massive ice in Yedoma blocked scientific studies for many years.

The erroneous opinions of prominent and influential scientists prevailed over the currently accepted idea, proposed by Dr. Alexander von Bunge, and delayed attaining the solution of Yedoma origin for over 50 years. History shows that a mere hypothesis without ways for verification has a very low possibility to be fruitful. Chamberlin (1897) warned of the danger of premature theories: "The habit of precipitate explanation leads rapidly on to the development of tentative theories. The explanation offered for a given phenomenon is naturally, under the impulse of self-consistency, offered for like phenomena as they present themselves, and there is soon developed a general theory explanatory of a large class of phenomena similar to the original one. This general theory may not be supported by any further considerations than those which were involved in the first hasty inspection. For a time, it is likely to be held in a tentative way with a measure of candor. With this tentative spirit and measurable candor, the mind satisfies but the thoroughness, the completeness, the all-sidedness, the impartiality, of the investigation. It is in the tentative stage that the affectations enter with their blinding influence."

The search for the origin of Yedoma shows that when confronting new and extraordinary phenomena, both prominent scientists and young researchers have an equal chance to propose a valuable idea. It is interesting to note that in this controversy two medical doctors—Figurin and von Bunge—were much closer to deciphering the origin of Yedoma than many prominent geologists and geographers of their time. It seems that for a completely new problem, previous experience is not always an advantage but can be a burden that closes the mind to new ideas. As Kuhn (1970) noticed, "a new theory, however special its range of application, is seldom or never just an increment to what is already known. Its assimilation requires the reconstruction of prior theory and the re-evaluation of prior fact, an intrinsically revolutionary process that is seldom completed by a single man and never overnight."

After the mystery of Yedoma origin was generally solved as being syngenetic permafrost penetrated by ice wedges formed during the late Pleistocene, numerous international and interdisciplinary studies have been conducted in Russia, Alaska, and Canada. They have shown that during its formation Yedoma sequestered significant amounts of organic carbon and preserved a treasure of information on the environment of the late Pleistocene including its climate, vegetation, wildlife, and an extensive accumulation of syngenetic permafrost.

AUTHOR CONTRIBUTIONS

YS designed this study and drafted the first version of the manuscript. TJ compiled a map of Yedoma locations mentioned in the manuscript. YS, MK, and AV reviewed the Russian language references, LS and JS reviewed the German language references, and MWJ reviewed the French language references. YS, DF, MK, TJ, and MWJ reviewed the English language references. All co-authors contributed to the manuscript writing and editing process.

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SUPPLEMENTARY MATERIAL

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Supplementary materials

Supplementary quotes

Quote 1 (Adams, 1808, p. 142): "The news of this interesting discovery determined me to hasten my intended journey to the banks of the Lena (River), which I had in contemplation, for the purpose of visiting the shores of the Lena (River), as far as the Frozen Sea; and I was anxious to save these precious remains, which might perhaps otherwise be lost."

Quote 2 (Adams, 1808, p. 132): "I have seen in great thaws, large pieces of earth detach from the hillocks, mixed with the water, and form thick, muddy torrents which roll slowly towards the sea. This earth forms in different places lumps, which sink among the ice."

Quote 3 (von Baer, 1842, p. 58): "Because of the inaccuracies of Adams' single article, it would be a wasted effort to try to form a clear idea of what was valid in his observations."

Quote 4 (von Kotzebue, 1821, p. 219): "It seemed as if fortune had sent this storm, to enable us to make a very remarkable discovery, which we owe to Dr. Eschscholtz. We had climbed much about during our stay, without discovering that we were on real icebergs. The doctor, who had extended his excursions, found part of the bank broken down, and saw, to his astonishment, that the interior of the mountain, consisted of pure ice. At this news, we all went, provided with shovels and crows, to examine this phenomenon more closely, and soon arrived at a place where the back rises almost perpendicularly out of the sea, to the height of a hundred feet; and then runs off, rising still higher. We saw masses of the purest ice, of the height of a hundred feet, which are under a cover of moss and grass; and could not have been produced, but by some terrible revolution. The place which, by some accident, had fallen in, and is now exposed to the sun and air, melts away, and a good deal of water flows into the sea. An indisputable proof that what we saw was real ice, is the quantity of mammoths' teeth and bones, which were exposed to view by the melting, and among which I myself found a very fine tooth. … I called the bay after our physician, Eschscholtz, as it was he that made the remarkable discovery there."

Quote 5 (von Chamisso,1821, p. 298): "The length of the profile, in which the ice is exposed to sight, may be about a musket shot. But it is evident, in the forms of the overgrown declivities of the shore, that the same kind of mountain (ice) occupies a much greater extent. We are already acquainted, from several travels, with similar ice-ground in the north of Asia and America, and among these, particularly, the rocks of ice, covered with vegetation at the mouth of the Lena, out of which the mammoth, the skeleton of which is now in St. Petersburg, was thawed, and on which a cross was erected by Adams, to whom we are indebted for the preservation of the skeleton, and the accounts respecting it."

Quote 6 (Beechey, 1831, p. 339): "That particular formation, which, when it was first discovered by Captain Kotzebue, excited so much curiosity, and bore so near a resemblance to an iceberg, as to deceive himself and his officers, when they approached the spot to examine it, remains to be described. As we rowed along the shore, the shining surface of small portions of the cliffs attracted our attention and directed us where to search for this curious phenomenon, which we should otherwise have had difficulty in finding, notwithstanding its locality had been particularly described for so large a portion of the ice cliff has thawed since it was visited by Captain Kotzebue and his naturalist, that only a few insignificant patches of the frozen surface now remain. The largest of these, situated about a mile to the westward of Elephant Point, was particularly examined by Mr. Collie, who, on cutting through the ice in a horizontal direction, found that it formed only a casing to the cliff, which was composed of mud and gravel in a frozen state. On removing the earth above, it was also evident, by a decided line of separation between the ice and the cliff, that the Russians had been deceived by appearances. By cutting into the upper surface of the cliff three feet from the edge, frozen earth, similar to that which formed the face of the cliff, was found at eleven inches' depth and four yards further back the same substance occurred at twenty-two inches' depth.

The glacial facing we afterwards noticed in several parts of the sound; and it appears to me to be occasioned either by the snow being banked up against the cliff, or collected in its hollows in the winter, and converted into ice in the summer by partial thawing and freezing—or by the constant flow of water during the summer over the edges of the cliffs, on which the sun's rays operate less forcibly than on other parts, in consequence of their aspect. The streams thus become converted into ice, either while trickling down the still frozen surface of the cliffs, or after they reach the earth at their base, in which case the ice rises like a stalagmite, and in time reaches the surface. But before this is completed, the upper soil, loosened by the thaw, is itself projected over the cliff, and falls in a heap below, whence it is ultimately carried away by the tide. We visited this spot a month later in the season, and found a considerable alteration in its appearance, manifesting more clearly than before the deception under which Kotzebue laboured."

Quote 7 (Beechey, 1831, p. 453): "In another excursion which I made along the north side of the sound, I landed at a cape which had been named after the ship (Cape Blossom YS) and had the satisfaction of examining an ice formation of a similar nature to that in Eschscholtz Bay, only more extensive, and having a contrary aspect. The ice here, instead of merely forming a shield to the cliff, was imbedded in the indentations along its edge, filling them up nearly even with the front. A quantity of fallen earth was accumulated at the base of the cliff, which uniting with the earthy spaces intervening between the beds of ice, might lead a person to imagine that the ice formed the cliff, and supported a soil two or three feet thick, part of which appeared to have been precipitated over the brow. But on examining it above, the ice was found to be detached from the cliff at the back of it; and in a few instances so much so, that there were deep chasms between the two. These chasms are no doubt widened by the tendency the ice must have towards the edge of the cliff; and I have no doubt the beds of ice are occasionally loosened, and fall upon the beach, where, if they are not carried away by the sea, they become covered with the earthy materials from above, and perhaps remain some time immured. In some places the cliff was undermined, and the surface in general was very rugged; but it was evident in this, as in the former instance, that the ice was lodged in hollow places in the cliff. While we continued here, we had an example of the manner in which the face of the cliff might obtain an icy covering similar to that in Eschscholtz Bay. There had been a sharp frost during the night, which froze a number of small streams that were trickling down the face of the cliff and cased those parts of it with a sheet of ice, which, if the oozing from the cliff and the freezing process were continued, would without doubt form a thick coating to it."

Quote 8 (von Chamisso, 1836): "I have carefully read and tested Beechey on the subject of this ice bank, and I am unable to do anything else except adhere to the view I expressed in my "Notes and Opinions [Chamisso,1821, p. 298]."

Quote 9 (Figurin, 1823, pp. 199-200): “The country here feels the full force of winter. The terrible cracking of the earth and ice, like a gunshot and cannon thunder, signals the approach of brutal cold. Cracks of ice and earth occur from a cold of 40° Reaumur. Cracks in the earth are so large that they drain lakes into rivers in the midst of winter. … Such events are rather common, and therefore numerous drained lakes are mostly the consequence of extensive and deep frost cracks. Such cracks produce new ice wedges cutting through the ground in different directions. Many wedges of great masses inside the wet and dry soil are due to their formation (possibly) to old ages.”

Quote 10 (von Hedenström, 1830, pp. 119-120): “The composition of the land in the vicinity of the Arctic Sea is an impenetrable mystery of nature. High shores of streams and lakes are composed of thick layers of earth and solid ice. The ice layers for the most part lie horizontally, as do the earth layers. The latter always overlaps the former. Ice wedges, which sometimes cross these layers, are of the later origin, from the breaking up of the whole mass by snow water. How could alternating layers of ice and earth be formed horizontally? All layers originate from gradual undisturbed sedimentation, but how can one imagine a mass of water, frozen in time, being covered again by the same thickness of the earth, and so on.”

Quote 11 (Richardson, 1853, pp. 5-6): “Captain Kellett, Berthold Seemann, Esq., and Dr. Goodridge, with the works of Kotzebue and Beechey in their hands, and an earnest desire to ascertain which of the conflicting opinions enunciated by these officers was most consistent with the facts, came to the conclusion, after a rigid investigation of the cliffs, that Kotzebue was correct in considering them to be icebergs. … The ice-cliffs of Eschscholtz Bay may have had an origin similar to that of the Greenland icebergs, and have been coated with soil by a single or by successive operations.”

Quote 12 (Richardson, 1853, p. 6): “I find it difficult, however, to account for the introduction of the fossil remains in such quantity, and can offer to the reader no conjecture on that point that is satisfactory even to myself.”

Quote 13 (Seemann, 1853, p. 34): “The ice was thought by some of the earlier visitors to be only a superficial coating; but this supposition was disproved in 1849, when enormous portions were found to be separated from the main body, testifying beyond a doubt that it forms part of a solid iceberg. Others, who comprehended the real nature of this lower layer, endeavoured to explain its presence by assuming that the water of the surface penetrated through the peat and clay, gradually accumulated, changed into a mass of ice, and thus caused the rising of the cliffs.This hypothesis at first sight appears plausible, but if examined it falls to the ground. In temperate climates we often find moorlands rising, like a sponge, in consequence of the mass of water which has accumulated in them; in Kotzebue Sound however, where the soil is always frozen at a depth of two or three feet from the surface, no water can possibly sink to the depth of several fathoms [remark: means from six to ten meters], and consequently no rising can take place.”

Quote 14 (Dall, 1881, pp. 107-109): “…it appeared that the ridge itself, two miles wide and two hundred and fifty feet high, was chiefly composed of solid ice overlaid with clay and vegetable mould. … The ice in general had a semi-stratified appearance, as if it still retained the horizontal plane in which it originally congealed. The surface was always soiled by dirty water from the earth above. This dirt was, however, merely superficial. The outer inch or two of the ice seemed granular, like compacted hail, and was sometimes whitish. The inside was solid and transparent, or slightly yellow-tinged, like peat's water, but never greenish or bluish like glacier ice. But in many places the ice presented the aspect of immense cakes or fragments, irregularly disposed, over which it appeared as if the clay, etc., had been deposited. Small pinnacles of ice ran up into the clay in some places, and, above, holes were seen in the face of the clay-bank, where it looked as if a detached fragment of ice had been and had been melted out, leaving its mould in the clay quite perfect. In other places the ice was penetrated with deep holes, into which the clay and vegetable matter had been deposited in layers, and which (the ice melting away from around them) appeared as clay and muck cylinders on the ice-face. Large rounded holes or excavations of irregular form had evidently existed on the top of the ice before the clay, etc., had been deposited. These were usually filled with a finer-grained deposit of clay with less vegetable matter, and the layers were waved, as if the deposit had been affected by current action while going on. … The formation, though visited before, has not hitherto been intelligibly described from a geological standpoint. Though many facts may remain to be investigated, and whatever be the conclusions as to its origin and mode of preservation, it certainly remains one of the most wonderful and puzzling geological phenomena in existence."

Quote 15 (Dall and Harris, 1881, p. 260): "Kotzebue and Eschscholtz correctly described the formation as interbedded ice. Beechey's party, deceived by the mantle of clay, which at the time of their visit had fallen so as to mask the main body of the ice face, concluded that the ice was a superficial deposit. They noted similar deposits of clay more or less associated with ice at numerous other points on the Arctic coast."

Quote 16 (Dall and Harris, 1881, pp. 267-268): "The diminished body of water which would be left in such a case, in connection with the prevalence of the northwest trade winds over this area, would give to this region such a dry climate as characterizes much of Siberia and the Yukon Valley in Alaska. If the elevation took place at the end of the Miocene, as it did in California and Oregon, and as the location and condition of the Nulato sandstones suggests, and if the greatest elevation were toward the west and gradually diminished eastward, we should have conditions favorable for the following results: First, a small precipitation with little snow which with extreme cold and an almost level surface would be unfavorable to the formation of glaciers. Second, the formation by the drainage of the Yukon and other streams coming down from the east of vast shallow lakes of muddy water, the remnants of which in winter, after the escape of the surplus water, might, as now occurs in the same region, freeze solidly to the bottom. Third, the ice thus formed might to a certain extent persist, especially if protected from the sun of the short Arctic summer by a deposit of clay from the spring freshets. Fourth, with a return of a milder climate, though the great mass of this ice might melt and escape with the drainage, that in the more northern and colder region, especially where protected by the clays, might be to some extent conserved and over the clay bogs above it a carpet of Arctic vegetation gradually extend. The wandering vertebrates, attracted by the luxuriant herbage which we know to flourish in such places, might be trapped in the quagmires which the grasses treacherously conceal. Further elevation by affording better drainage would tend to preserve rather than to waste the hidden stores of ice, while the rivers gradually cutting down their channels would expose the formation when it lay along their path. That the moderate elevations which exist in the region were insufficient to start the ice thus formed into motion, and thus inaugurate glaciers, may be accounted for on several grounds. First, under the assumed circumstances the ice would always be formed on the lowest places of the level lowlands, coming there as water, and not as snow pressing from slopes. Second, the ice under conditions of very low temperature is without doubt much more rigid than at higher temperatures and by the hypothesis would more or less thoroughly be incorporated at its base with the tough and rigid frozen mud upon which it formed; in fact, the ice and soil would practically form one body, while ice formed from snow would always behave more like a body extraneous to the soil. Lastly, the very level character of the region would be unfavorable to motion in the ice, as at present on the Arctic coast where we know the land ice is stationary; while in particular localities, where some motion might take place, the character of the Miocene sandstones upon which most of it must have rested in the absence of alluvium is not well suited to retain any evidence of it. These suggestions are offered as a basis for discussion, in considering the anomalous geological conditions of northwestern Alaska, until a greater knowledge of the facts may afford a foundation for some more applicable hypothesis."

Quote 17 (Hooper, 1884, pp. 79-80): "In several places where water has run down over the face of the cliff, in small streams, from the melting snow above, I found holes melted at least thirty feet deep, showing solid walls of clear ice. I also ascended the cliff and dug down from the top in several places, and always came to solid ice, after digging through frozen earth for a few feet. … So far there appears nothing remarkable in the frozen substratum, it being controlled principally by the mean annual temperature of the locality and the internal heat of the earth. But why this frozen substratum should occur at certain places in the form of pure ice does not appear so clear. Whether these ice masses are fragments of the original ice sheet which over-swept the polar regions, or are formed by the waters from the melting snow draining through the soft, light mosses which form the tundra, is a matter for scientific investigation. … A number of wedge-shaped pieces of ice found in the banks around Eschscholtz Bay were probably formed by a small crack in the ground filling with snow and ice, and continuing to enlarge under successive changes from freezing to thawing."

Quote 18 (Muir, 1917, pp. 225-226): "Mingled with the true glacier ice we notice masses of dirty stratified ice, made up of clean layers alternating with layers of mud and sand, and mingled with bits of humus and sphagnum, and of leaves and stems of the various plants that grow on the tundra above. This dirty ice of peculiar stratification never blends into the glacier ice, but is simply frozen upon it, filling cavities or spreading over slopes here and there."

Quote 19 (Cantwell, 1887, p. 48): "For miles along the river in this portion of its course these icy cliffs appear and disappear at regular intervals, so that it is observed that they recur in bends that are parallel with each other, which would seem to indicate that its existence is not due to deposits of ice by the river, else it would be in all of the bends, but that its presence is due to some other cause. If a straight line is drawn through the center of one of these ice-cliffs. and through the E.N.E. and W.S.W. points of the compass. it will not only touch all of the cliffs, but if extended to the sea will touch the coast at a point very near Elephant Point, on Eschscholtz Bay. where. it is well known. A peculiar ice formation in the bluffs has been observed and commented upon by numerous scientific men".

Quote 20 (Turner, 1886, p. 15): "I now saw that the margins of the ponds were being gradually encroached upon by the matting of the grasses, which in the course of time would entirely cover the surface, and in their turn be succeeded by a growth of sphagnum, which by its retention of cold would prevent the ice formed in the water below from being thawed out, and by the cumulation of vegetable matter on its surface decrease the power of the summer's sun to melt the frozen lake for more than a few inches of its depth. These lakes of ice have been the source of the ice bluffs presented on various parts of the coast, especially north of Bering Strait, the accumulation of soil on them introducing the wonderfully attractive masses of plants and flowers spoken of by Arctic voyagers. Another cause that may influence the speedy freezing, and consequent non-thawing of the coast line and moorlands is the fact that the annual snow-fall is probably only half as much or a third less than in the interior, comparatively adjacent. The greater part of the snow which falls on the coast is immediately drifted either into the sea or else far inland. It is rare that a depth of more than 18 inches of snow is found on the low level coast lands. Scarcely a day from November to April passes but that the snow is drifted."

Quote 21 (Russel, 1890, p. 128): "As the moss covers the lakelets more and more completely during a series of years, the ice formed by the freezing of the water in winter is more and more thoroughly protected, and is finally completely shielded from the heat of summer. A body of clear ice is thus formed in the tundra, similar to the strata of ice exposed at certain localities along the coast of Behring Sea and in the banks of the Yukon."

Quote 22 (Russel, 1890, pp. 129-130): "The reason for the great thickness of the frozen layer at these localities seems to be that deposition and freezing went on at the same time. These certainly seem to be the conditions under which the great thickness of frozen material beneath the tundra and in the flood-plains of the larger rivers of Alaska have been accumulated. It seems to me that this must also be the explanation of the origin of all frozen deposits which contain alternating strata of clear ice and of frozen layers of mud and peat like those exposed in the borders of the tundra and along the banks of the Yukon."

Quote 23 (Lopatin, 1876, p. 10): "Now if we imagine an area with a much lower annual temperature than at the Kosunai station on Sakhalin, it is possible that the ice layers, whose existence I have observed for five months, will last a whole year, or, once formed, will last even centuries, until the annual temperature of the area rises again."

Quote 24 (Mendenhall, 1902, p. 45): "Many writers since Kotzebue have discussed the origin of these ice cliffs, but the explanation given by Mr. L. M. Turner, Messrs. E. W. Nelson and C. L. Hooper, and Prof. I. C. Russell seems to be entirely adequate. It is that many of the numerous lakelets scattered about over the tundra are gradually buried by the advance of their mossy borders toward the center. After their burial they are frozen, as is the entire tundra, a few inches below its surface and are later revealed by lateral river cutting, as in the Kowak delta, or by the work of waves, as at Elephant Point, and appear as masses of comparatively clear ice in the general deposit of frozen mud, sands, and vegetable matter."

Quote 25 (von Toll, 1895, p. 89): "The vertical ice wall is from 50 to 70 feet in height. In its upper parts, the ice is overhanging. The ice is covered with a layer of clay only one foot thick. In one place, we see two parallel vertical cracks, reaching an average width of 10 feet crossing the entire thickness of the ice. They are separated from each other by a strip of ice only a few feet wide. The cracks are filled with a suite of horizontal, alternating thin layers of ice and clay. To the right and left of both cracks we see one more of the same kind, but the latter do not reach the surface of the ice."

Quote 26 (von Toll, 1895, pp. 90-91): “These pictures speak more clearly than any description. They show us that the ice is undoubtedly an older formation, and that the parts of the exposure, which stand out among the ice in the form of dark bands, on the contrary, must be of younger origin. To clarify the conditions, apparently being in contradiction, i.e. over younger formations (the strips made with clay) surrounded with older (ice), we can explain only by the following stages in the history of these Quaternary formations. In the first stage, there were extensive ice deposits, which undoubtedly covered the entire island, with the exception of the four mountains. The thickness of these ice masses, unfortunately, cannot be accurately determined, as their base is nowhere to be seen, the apparent thickness varies between 20-70'. This ice surface was obviously fractured and split, or pierced by thin cracks, which cut an entire thickness of the ice. In the second stage, these cracks and channels were gradually filled in layers with thin ice, clay and sand. Only in this way can we logically explain the formation of the conditions of Plate II [**Figure 7**]. … After these processes had played their part, a further stage came on the scene, during the action of which the sediments of the dried-up lakes, together with their fauna, were deposited and covered partly with ice; or bogs were formed over the ice on impermeable soil, which gradually arose from the washed out, or brought by the wind and later frozen clay. Finally, over the peat of the bogs, modern vegetation appeared on the newly formed clay and sandy soil.”

Quote 27 (von Toll, 1895, p. 102): “Under such conditions, it is clear to us that the accretion of grains due to the lack of suitable heat and infiltration could not develop (further) and that the youth glacier sprout, died at birth, became a "stagnant fossil glacier".”

Quote 28 (von Bunge, 1903, p. 205): “I take a liberty to draw your attention to only a few facts mentioned by Baron von Toll, but with which I cannot agree. Among other things, Baron von Toll insists that during his trip along the southern shore of the Bol'shoy Lyakhovsky Island he was able from a distance of about 10 km to distinguish 2 horizons, the upper of which consists of clay and the lower consists of ice. After my visit to this region in the summer of 1886, I can by no means agree with this observation. I think Baron von Toll was misled because the entire coast at the time of his visit was covered with deep snow, and that, as he himself admits, the thickness of the snow cover in some places was 30 feet or more. I am generally inclined to think that if Baron von Toll had seen these places in late summer instead of spring, he would have come to a different conclusion regarding the ice”.

Quote 29 (von Bunge, 1903, p. 209): “I am totally inclined to favor the view described above, which is based on the observation of processes occurring continuously before our eyes and which, for all its simplicity, is quite sufficient to explain ground ice and its formation. However, according to von Baer, simplicity is a mark of truth. I would only add that two completely independent researchers, the Englishman Beachy in the Bering Strait and Lopatin in the Yenisei tundra, have concluded completely identical to my own. Baron von Toll considers ice as a primary formation and the earth (clay) as a secondary deposit, while I, on the contrary, consider ice as a secondary formation in post-Tertiary sediments. If we even agree with Baron von Toll's view that ice is a primary, older formation, how would we explain the formation of clay deposits, extremely rich in plant remains, and the forces that produced them? If we think of general overgrowth, only here and there, where the "artificial field" was lacking, it seems quite incomprehensible where this amount of plant remains could have come from. In general, the origin of the post-Tertiary deposits of Eastern Siberia is a question which has not yet been clarified, but I do not consider myself entitled to speak about it here, and I leave it to future researchers, together with the question of ground ice, which I do not consider concluded in any way with the information given here. If the facts I have presented can contribute in the slightest degree to the solution of this question, I consider that the purpose of this communication has been fully achieved, and I have only to thank you for your kind attention given to me."

Quote 30 (Kolchak, 1906, p. 20): "We reached the steep ice shores of Faddeyevskiy Island. The island, to say it shortly presents a block of ice covered by a relatively thin layer of sediments. The entire south-eastern shore of the island looks like a wall of ice covered at places by collapses of these sediments This thick mass of ice is cut by cracks filled with soil, deeper or shallower ravines and channels of tundra streams and rivers, with typical cones of baydzherakhs on the bluffs and steep slopes. A thickness of ice was difficult to evaluate but 70 to 80 feet is very typical for all the New Siberian islands and maybe for many parts of the Siberian coastline and is encountered everywhere. where bedrock is not exposed to the surface.
Particularly interesting are the indications of the presence of this ground ice below the sea level. The ice sheet is covered in many places with brackish marine clays with the remains of marine mollusks, and these salty clays can be seen even in parts of Faddeyevskiy Island remote from the shore at a height of more than 60-70 feet above the current sea level. There is an indication that the drifting glaciers, which survived the transgression of the sea, are still extending above sea level, forming a permanent ice bottom near the shores of Faddeyevskiy Island and New Siberia, covered only in some places by a thin layer of silty sediments."

Quote 31 (Herz, 1904, p. 21): "Further geological studies will show how the entire area including the exposure was formed, but, although I am not an expert in geology, it is my duty to express my views. In my opinion, the entire area is located on a glacier, which is in the stage of extinction, and in which there were deep crevasses filled with water coming down from the taiga or from a neighboring mountain range and mixed with earth, stones and fragments of trees; subsequently these deposits were covered with a layer of soil, on which developed, no doubt, a rich vegetation, which served as excellent food for mammoths and other animals."

Quote 32 (Tolmachev, 1903, p. 134): "The fact that both researchers, who collected rich material at the same place on the same question, nevertheless radically differ in their interpretation, shows that the matter is not as clear on the spot as it seems to be, and new observations are more than desirable."

Quote 33 (Tolmachev 1906, p. 794): "As for deposits of ground ice, I must say that wedge ice, as von Bunge understands it, is more widespread here than I previously thought. On the contrary, I have not seen a single occurrence of ice where it would be possible to assume its glacial origin. I have not seen ice with moraine, briefly described by von Toll from Anabar Bay."

Quote 34 (Tolmachev 1928, p. 88): "The outcrops of ground ice should be examined and described in detail. Special attention must be paid to the relation of the ice layer to other formations, as well as to the topography of the locality. The question of the origin of ground ice still awaits an acceptable answer"

Quote 35 (Tolmachev 1929, p. 55): "Among many theories trying to explain its origin, no one could be recognized as being fully satisfactory in all cases, although every one of them is good for some particular case. In some instances, stone ice may be even younger than the strata within or below, which it happens to be found being in this case in the nature of a dyke, even of an intrusive one."

Quote 36 (Grigoriev, 1927, p. 45): "The data are so expressive that, at least for the northern part of Eastern Siberia, the presence of fossil ice of post-Pliocene age can be considered established. However, they occur also in the more southern region of Central Yakutia in the lower Aldan River, the Tumar River, near Lake Myurou, on the Vilyui River above Vilyuisk and on the Tyunge River. There we have found blocks of ice with a thickness of up to 25-30 m, covered with frozen loess-like silt and located at a considerable height above the level of the above-mentioned rivers."

Quote 37 (Obruchev, 1931, pp. 59-60): "The majority of fossil ice masses are the product of the glacial period, partly as dead ice, torn away from glaciers during their retreat, partly as the remnants of fixed firn fields. In favor of the glacial age of these glaciers are the remains of fauna and flora, found very often in the wedge-shaped and column-shaped masses of layered sediment, deposited among the ice, according to the observations of von Bunge, von Toll, Vollosovich on the New Siberian Islands, von Toll, Matisen, Hertz and Maydel in different places on the mainland. In the coastal cliffs of the Arctic Sea, the thickness of 15-17 m, sometimes up to 60 m in thickness and in some places represents two layers separated by a thickness of clay with bones of mammals, especially mammoth."

Quote 38 (Gorodkov, 1948, pp. 514-515): "The geographical conditions of northern Yakutia at the beginning of the last glacial epoch, to some extent coinciding with the views of E.V. von Toll [1897]. The glaciation of Yakutia lowlands was stationary, at least in the early stages of its development, and arose due to the accumulation of snow deposits in the depressions of the terrain, which turned into firn and formed the main stratum of ice. … The loess-like silt, widespread in northern Yakutia, is basically of aeolian origin. It was accumulated in firn ice. The modern area of dead ice of the New Siberian Islands represents the Late Pleistocene landscape, once ubiquitous generally along the edge of retreating plain glaciers. The melting of dead ice caused the accumulation of loess-like soil on their surface. These "tundra" layers were eroded by streams, deposited and redeposited in depressions, forming mineral wedges with remains of Quaternary animals. Later, thicker inclusions of redeposited loess-like soil began to protrude on the surface, underlain by ice, in the form of baydzherakhs, and were redeposited again, creating the varieties of deposits, already different in their mineral composition"

Quote 39 (Geikie, 1894, p. 665): "The ice-masses of Northern Alaska are not the relics of any glaciers or ice-sheets, for we have no reason to believe that those tracts have ever been glaciated. They simply represent the drifted snows of glacial times, which accumulated in valleys and depressions outside of ice-covered regions. Protected under a covering of alluvial matter, soil, and peat, they have, in those high latitudes, endured to the present day."

Quote 40 (Geikie, 1894, pp. 705-706): "Baron Toll describes the ice-formation of the Lyakov Islands as a 'dead glacier' but there can be little doubt that it originated in the same way as the similar formations in Northern Alaska. It represents, in short, the congealed snowdrifts of a late glacial epoch, and probably accumulated at a time when tundra- and steppe-conditions prevailed in Central Europe. … Here and there, however, thawing soils and subsoils would-be set-in motion, and, creeping and flowing over the surface of the 'ice-formations,' would cover these to a less or greater depth, and so protect them from the influence of the sun."

Quote 41 (Tyrrell, 1904, p. 236): "Water, issuing from the rock beneath a layer of alluvial material, rises through the alluvium, and in summer spreads out on the surface, tending to keep it constantly wet over a considerable area. In winter, if the flow of water is large, and the surface consists of incoherent gravel, the water will still rise to the surface, and there form a mound of ice. If, on the contrary, the flow from the spring is not large, and the ground is covered with a coherent mass of vegetable material, such as is formed by a sphagnum bog, the spring water, already at a temperature of 32° F., rises till it comes within the influence of the low temperature of the atmosphere above, and freezes. This process goes on, the ice continuing to form downward as the cold of the winter increases, until, a few feet below the surface, but still within the influence of the low external temperature, a plane of weakness is reached in the stratified and frozen vegetable or alluvial deposit, such planes of weakness being generally determined by the presence of thin bands of silt or fine sand. As any outlet to the top is now permanently blocked, the water is forced along this plane of weakness, and there freezes; and thus the horizontal extension of the sheet of ice is begun. While thus increasing in extent, the ice also increases in thickness by additions from beneath, until it has attained a sufficient thickness so that its bottom plane is beyond the reach of the low atmospheric temperature above; after which it continues to increase in extent, but not in thickness or depth. With the advent of the warm weather of summer the growth of the crystosphene ceases, but the cold spring water which continues to rise up beneath it has very little power to melt it, and its covering of moss or muck, being an excellent non-conductor of heat, protects it from the sun and wind, and prevents it from thawing and disappearing. Thus at the advent of another winter it is ready for still greater growth."

Quote 42 (Maddren, 1905, pp. 37-38): "The older elevated ice-beds of the Pleistocene lake basins apparently have been covered and preserved in this way. As exposed today by the lateral cutting of the streams draining their areas the ice-beds have a covering of peat varying from two or three to fifteen feet in thickness. In most cases this protective covering to the ice is composed entirely of vegetable remains." Furthermore, "only where the ice masses formed near the shore lines of the former lakes, and in places where the land rises more or less abruptly, may we expect to find alluvium derived from the nearby slopes on top of the ice or incorporated with its humus covering. The ice phenomenon at Eschscholtz Bay seems to be clearly an example of former lake-shore conditions as is also the locality on the Beresovka River in northeastern Siberia described by Tolmatschov."

Quote 43 (Maddren, 1905, p. 66): "There are no facts to support the contention that the climate of the Arctic and sub-Arctic regions ever has been colder than it is at present. There are no phenomena presented in those regions that require a more severe climate than that now existing to account for them. There are no ice deposits in Alaska, except those of large glaciers, that may be considered of Pleistocene age. There are no ice-beds interstratified with the Pleistocene deposits of Alaska."

Quote 44 (Leffingwell, 1919, p. 223): "Conditions in the New Siberian Islands, where a small amount of earth is included in banks of ice, are radically different from those observed by the writer in Alaska, where a small amount of ice is included in banks of earth. Great modifications in the frost-crack theory, as developed for the Alaskan localities, must therefore be made in order to fit the conditions at the New Siberian Islands. If the long cylinders of earth are extremely compressed polygonal blocks, the surface of the ice must have grown upward to keep pace with the vertically expanding blocks of earth. Another difficulty lies in the great height of the ice cliffs in the New Siberian Islands, in some places 70 feet. Still, the symmetrically distributed inclusions of earth are a strong suggestion that the ground ice there is the result of the growth of ice in symmetrically arranged frost cracks."

Quote 45 (Leffingwell, 1915, p. 654): "The principle of the development of ground-ice wedges is capable of widespread action throughout the region of permanently frozen ground. It is so persistent on the north shore of Alaska that it is to be expected to come into play in similar regions elsewhere. The writer is inclined to believe that much of the ground-ice described in the literature as in horizontal sheets may turn out to be in vertical wedges. In the classical locality at Eschscholtz Bay, no one observer agrees with the others. One says that there is a solid mountain of ice, while a second finds only a thin veneer of ice against the face of the bank. A more careful observer finds scattered outcrops of ice, including at least one vertical dike. In other regions "polygon marks" and vertical markings upon whitish ice are mentioned."

Quote 46 (Porsild, 1938, p. 47): "Future investigation will probably show that in the unglaciated parts of northern Alaska the ground ice or fossil ice, in some places at least, was formed when ground water traveling seaward through pervious subsoils became trapped under the now frozen surface soil, having first caused the local formation of mounds or ridges by hydraulic pressure. The writer has particularly in mind the sheets of solid, clear ice so commonly seen in the Kotzebue Sound region and in the Seward Peninsula; but the homologous formations disclosed by placer mining are common throughout the Arctic, unglaciated parts of Alaska."

Quote 47 (Tuck, 1940, p. 1305): "The thicknesses of muck now seen were not only built up slowly, but freezing occurred almost simultaneously. The winters were long and cold enough for the depth of annual freezing to exceed the summer thawing, so that as the depth of muck increased it always remained frozen. Because of its mode of origin, the muck was saturated with water, giving it its present ice content of around 50 per cent."