The Yedoma Suite of the Northeastern Siberian Shelf Region: Characteristics and Concept of Formation

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Abstract

The Yedoma Suite is well exposed along coasts and riverbanks in the northeastern Siberian Arctic. The cryotexture of these mostly ice-supersaturated deposits is similar at most sites—ice bands and reticulated ice lenses. The Yedoma Suite is considered a sequence of buried cryosols, formed under predominantly subaerial conditions. It represents an important terrestrial carbon reservoir (TOC 2–5-wt%). The multimodal grain size distribution does not reflect primarily aeolian accumulation, but rather a mixture of various periglacial transport and accumulation processes based on the concept of nival lithogenesis. The Yedoma Suite age lies in the MIS-3 and MIS-2 periods and, in rare cases, already starts during MIS-4. The palaeoecology of the Yedoma Suite can be summarized in the term "Tundra Steppe," combining both tundra and steppe environmental features. The present occurrence of the Yedoma Suite remains is closely related to low mountain ridges surrounding the northern and northeastern Siberian shelves. The concept of nival lithogenesis is presented, explaining the origin of source material and transport medium.

Keywords: cryolithology; late Pleistocene; northeastern Siberia; palaeo-environment; yedoma.

Introduction

The term *yedoma* is often associated with describing possible reactions of permafrost to global warming (Zimov et al. 2006, Walter et al. 2006, Walker 2007). The word *yedoma* probably originated in Kamchatka and described a boggy site or an elevated meadow-like flat plain. It entered science via the expeditions of Vitus Bering in Siberia during the 18th century. Initially, the term *yedoma* was of geomorphologic origin and described the hills separating thermokarst depressions in East-Siberia, especially in the Yana-Indigirka and Kolyma Lowlands (Kolosov 1947, Baranova & Biské 1964, Mursaev 1984, Tomirdiaro 1980). These mounds were considered to be erosional remnants of former accumulation plains. In this sense, yedoma described a special geomorphological relief type in Siberian permafrost regions, directly formed by thermokarst and thermoerosion (Solov'ev 1959, 1989).

The stratigraphical term *Yedoma Suite* was later adopted for middle Pleistocene horizons in the northeastern Siberian Lowlands (Lavrushin 1963, Vas'kovsky 1963). This stratigraphical position was moved to the late Pleistocene based on faunal studies at the Duvanny Yar site in the Kolyma Lowlands (Sher 1971), which became the stratotype for the Yedoma Suite. This categorization was finally confirmed by the decision of the Interdepartmental Commission on Quaternary Stratigraphy of the Soviet Union in Magadan in 1982 (Sher 1987).

Early genetic conceptions of the Yedoma Suite include glacier-dammed basin sediments (Grosswald 1998), alluvial genesis (Rozenbaum 1981), deltaic formation (Nagaoka et al. 1995), proluvial and slope deposits (Slagoda 2004, Gravis 1969), cryogenic-aeolian (Tomirdiaro et al. 1984, Tomirdiaro & Chernenky 1987), and nival deposits (Galabala 1997) as well as polygenetic origins (Sher et al. 1987).

The deposits of the Yedoma Suite represent unique late Pleistocene palaeoenvironmental archives for a large region of the Northern Hemisphere lacking major glacial records. Within the Russian-German project, System Laptev Sea, these deposits were studied with a multidisciplinary approach (cryolithology, sedimentology, palaeontology, palaeobotany, geochronology, mineralogy, isotope geochemistry, GIS, remote sensing) during the last ten years. We here present a first review of some general results on the overarching features of the Yedoma Suite in the Laptev Sea region and a concept of its formation.

Study Region

Since 1998, we have studied the characteristics of the Yedoma Suite at 15 well-exposed sites on the Laptev Sea and the East Siberian Sea coasts, and in the Lena Delta (Fig. 1). These sites are situated in the lowland plains of the continental shelf on both sides of the current seismically active boundary of the Eurasian and the North American continental plates.

Characteristics of the Yedoma Suite

Occurrence and geomorphology

The occurrence of the Yedoma Suite in the study region is closely related to low mountain ridges (ca. 200 to 400 m a.s.l.) surrounding the northern and northeastern Siberian shelves, which are the major sediment sources for the Yedoma Suite. In the western Laptev Sea and the Lena Delta region the occurrence of the Yedoma Suite is strongly connected with the coastal mountains of the Pronchishchev, Chekanovsky, and Kharaulakh Ridges. Heavy mineral studies at various sites have shown that these ridges are a main source of sediment (Siegert et al. 2002, Schwamborn et al. 2002, Schirrmeister et al. 2003). Therefore, foreland accumulation plains were the areas of the formation of the Yedoma Suite. In the eastern part of the study region, the exposed granite and basalt intrusions on Bol'shoy Lyakhovsky Island and Cape Svyatoy Nos as well as the fault ranges on Bel'kovsky, Stolbovoy, and Kotel'ny Islands serve as source areas for sediments of the Yedoma Suite. The distribution of the ice-rich sequences is easily identified by frequent thermokarst depressions or lakes (Grosse et al. 2005, 2006, 2007).

The Yedoma Suite exposes permafrost cliffs in 10- to 40-m-high horseshoe-shaped thaw slumps or thermocirques along sea coasts and riverbanks (Fig. 2).

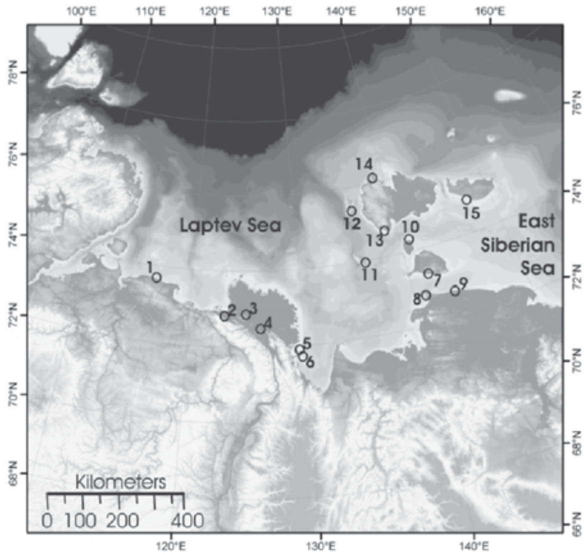

Figure 1. Study sites of the Yedoma Suite between 1998 and 2007. 1: Cape Mamontov Klyk. 2: Ebe Basyn Sise Island. 3: Khardang Island. 4: Kurungnakh Island. 5: Bykovsky Peninsula. 6: Muostakh Island. 7: Bol'shoy Lyakhovsky Island. 8: Syatoy Nos. 9: Oyogos Yar coast. 10: Maly Lyakhovsky Island. 11: Stolbovoy Island. 12: Bel'kovsky Island. 13: Kotel'ny Island. 14: Cape Anisy. 15: Novosibir Island.

Cryolithology

The cliffs are composed of ice wedge bodies and columns of frozen deposits between them, representing vertically or diagonally cut polygonal ice wedge systems. Therefore foliated syngenetic ice wedges of 2–5 m width and 10–40 m height, and separate thermokarst mounds of 2–5 m in diameter and up to 10 m height are the most characteristic features of Yedoma Suite erosion cliffs. Compared to the ice wedges, the intrapolygonal deposits are more resistant to thawing processes because they have a smaller ice content and contain stabilizing peaty paleosol layers alternating with silty-sand layers. These features of continuous permafrost sequences are the result of long-lasting and stable cryogenesis and landscape conditions.

The cryotexture of the Yedoma Suite is quite similar at all of the study sites. The general texture is layered. Ice bands (1–10 cm) alternate with sediment interlayers of variable thickness. These interlayers contain numerous small ice lenses as well as reticulated ice lenses. The frozen sediment sequences are frequently ice-supersaturated, resulting in gravimetric ice contents of 60 to 120% on average (Fig. 3).

Such cryotextures are typical for sediments formed in poorly drained landscapes with a near-surface permafrost table. The formation of these ice bands is a sign of stable surface conditions and stable active-layer depths over a certain time period, resulting in ice aggradation at the top of the permafrost table. The stable isotope signature of ice wedges shows light values for all study sites (site mean

Figure 2. The Yedoma coast at Bol'shoy Lyakhovsky Island. The cliff is about 30 m high (photo: S. Wetterich, July 2007).

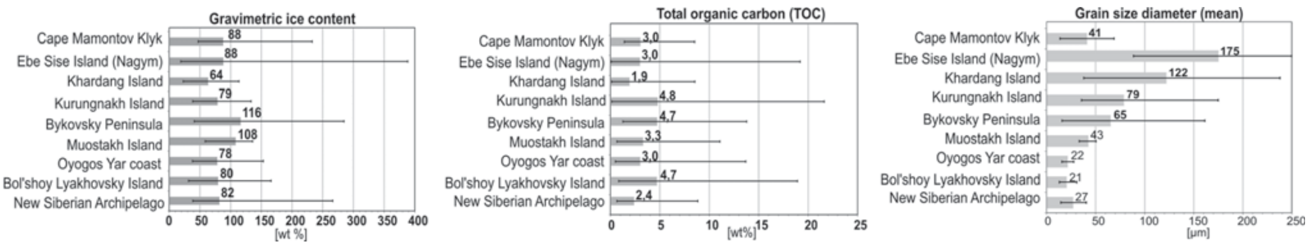

Figure 3. Variation in ice content, TOC content of peat inclusions and sediment, and grain size diameter between various sites of the Yedoma Suite (mean: bar; range: line).

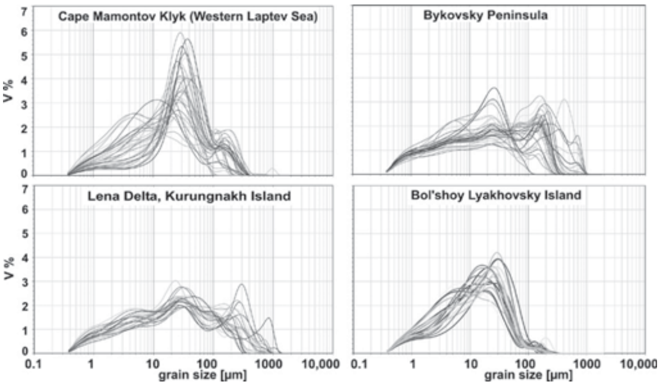

Figure 4. Typical grain-size distribution patterns of the Yedoma Suite at various sites.

values: δD -230 to -260‰, $\delta^{18}O$ -28 to -31‰, d-excess about -6‰) reflecting very cold winter temperatures and moisture sources which are isotopically different from Holocene and modern ones (Meyer et al. 2002a, b).

Organic carbon and grain-size parameters

The Yedoma Suite includes buried cryosols marked by brownish horizons, as well as peat inclusions and/or numerous twigs and leafs. Cryoturbation patterns of 0.5 to 1 m thickness are very common. The organic carbon content is relatively high (1 to > 20 wt%, in average 2 to 5 wt%). Wood fragments and peat are present, with numerous small filamentous rootlets and dispersed organics detritus.

The fine-grained sediments composing the Yedoma Suite are poorly sorted and differ in grain-size parameters from site to site (Fig. 4). Multimodal grain-size distribution patterns reflect a mixture of transport, accumulation, and re-sedimentation processes. Therefore, we conclude that this type of sediment in the Laptev Sea region is not primarily of aeolian origin, a view that is still widely reflected in the scientific literature using the generalizing term "Arctic loess" (e.g., Tomirdiaro 1982, Walker 2007).

Summarizing the special cryolithological and sedimentological characteristics, it is concluded that the frozen deposits of the Yedoma Suite accumulated in a special periglacial facies. The term "Ice Complex" (Soloviev 1959, p. 49) is used for these deposits.

Age determination and stratigraphy

The age of the Yedoma Suite was determined by radiocarbon AMS analyses of about 300 samples and some luminescence datings (Schirrmeister et al. 2002a, 2003, 2008, Grosse et al. 2007, Andreev et al. 2008). The geochronologically determined onset of the Yedoma Suite accumulation varies between about 55 ky BP at the New Siberian Islands and 27 ky BP at the western Laptev Sea coast. The latest deposition is dated between 28 ky BP at the New Siberian Islands and 17 to 13 ky BP in the western Laptev Sea. Unconformities are frequent, up to 20 ky, and probably caused by thermokarst and thermoerosion. The Yedoma Suite predominantly covers the Kargin and Sartan period of the Russian late Pleistocene stratigraphy, which corresponds to the MIS-3 and MIS-2 of the global classification. At Bykovsky Peninsula, the Yedoma Suite is somewhat older, and already started during the Zyryan period (MIS-4) (Meyer et al. 2002a, Schirrmeister et al. 2002b). In general, the lower boundary contrasts sharply with the underlying deposits, which often are fluvial sands with peat layers or loess-like floodplain deposits. These deposits are U/Th and luminescence-dated between 60 and 100 ky). The upper boundary is characterized by separate, locally confined Holocene deposits on top of the Yedoma Suite (Andreev et al. 2004, Krbetschek et al. 2002, Schirrmeister et al. 2003, Grosse et al. 2007).

Table 1. Palaeoenvironmental stages of northeastern Siberian Arctic lowlands during the late Quaternary (inferred from multiproxy analysis of permafrost records, Andreev et al. 2002, 2008).

Allerœd 12 ky	• Tundra with higher bioproductivity • Warming climate • First thermokarst depressions
Sartan 30 - 12 ky	• Sparse grass-sedge tundra • Cold and dry summers, very cold winters • Ice Complex formation
Kargin ca. 50 - 30 ky	• Tundra steppe with high bioproductivity • Relatively warm summers, cold winters • Ice Complex formation
Zyryan ca. 100 - 50 ky	• Sparse grass sedge tundra • Extreme cold and dry climate • Widespread fluvial, lacustrine, and floodplain deposits • Begin of local Ice Complex formation

Palaeoecology (Table 1)

New data for the faunal and floral composition during the formation of the Yedoma Suite in the study region were collected and analyzed within our project "System Laptev Sea" and described in numerous palaeoecological papers (e.g., Andreev et al. 2002, Bobrov et al. 2004, Kienast et al. 2005, Kuznetsova et al. 2003, Sher et al. 2005, Wetterich et al. 2005). The findings are in good agreement with studies; e.g., of Anderson & Lozhkin (2001). The special floral and faunal communities that existed during Yedoma Suite formation disappeared approximately at the Pleistocene-Holocene transition. The palaeo-biosceonosis is called Mammoth Steppe or Tundra Steppe, combining both tundra and steppe features. The climate was more continental in the late Pleistocene Arctic than today, with colder winters and warmer summers and, therefore, stronger seasonal gradients in temperature and precipitation (Meyer et al. 2002a/b, Kienast et al. 2005, Schirrmeister et al. 2002b, 2003, 2008, Wetterich et al. 2008).

Formation of the Yedoma Suite

To explain the formation of the Yedoma Suite, we use the concept of nival lithogenesis proposed by Kunitsky (2007). Several geological processes are important for its formation and can be summarized in four stages (Fig. 6):

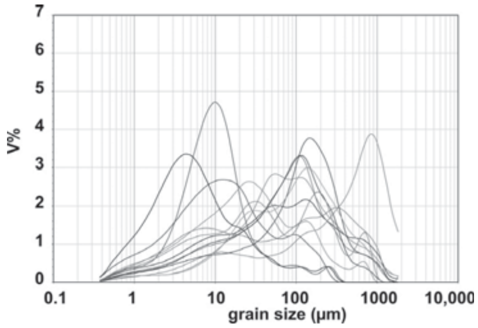

Figure 5. Grain-size distribution curves of clastic remains in various modern snow patches studied around the Laptev Sea.

1. Accumulation of windblown snow together with plant and mineral detritus in numerous perennial snowfields (névés) in topographic features of hills and low mountain ranges (e.g., steep slopes, valleys, cryoplanation terraces, Fig. 6a). Similar processes, but at a smaller scale, are observed today at numerous sites in northeastern Siberia, where nival processes are an essential relief-forming factor (Kunitsky et al. 2002).

2. A concentrated detritus mat forms due to repeated thawing of accumulating snow, transport of detritus by meltwater, and downslope accumulation of plant and mineral debris. Intense freeze-thaw cycles and wet conditions around and below the perennial snowfields support the formation of fine-grained material by frost weathering (Fig. 6b). Such processes are also observed in modern snowfield areas. Grain-size analyses of modern clastic material show similar multimodal patterns as the Yedoma Suite (Fig. 5).

3. Discharge of clastic and organic detritus proceeded by snowfield meltwater runoff. Fine-grained debris was subsequently distributed by alluvial, fluvial, proluvial, and partly also aeolian transport to piedmont plains, cryoplanation terraces or large alluvial fans (Fig. 6c).

4. Ice Complex formation consisted of concurrent processes of sediment accumulation, ground ice segregation, syngenetic ice wedge growth, sediment reworking, peat aggradation, cryosol formation, and cryoturbation (Fig. 6d).

The formation of huge polygonal ice wedge systems and thick continuous sequences of frozen deposits is closely related to the persistence of stable, poorly drained, low-topographic gradient accumulation plains.

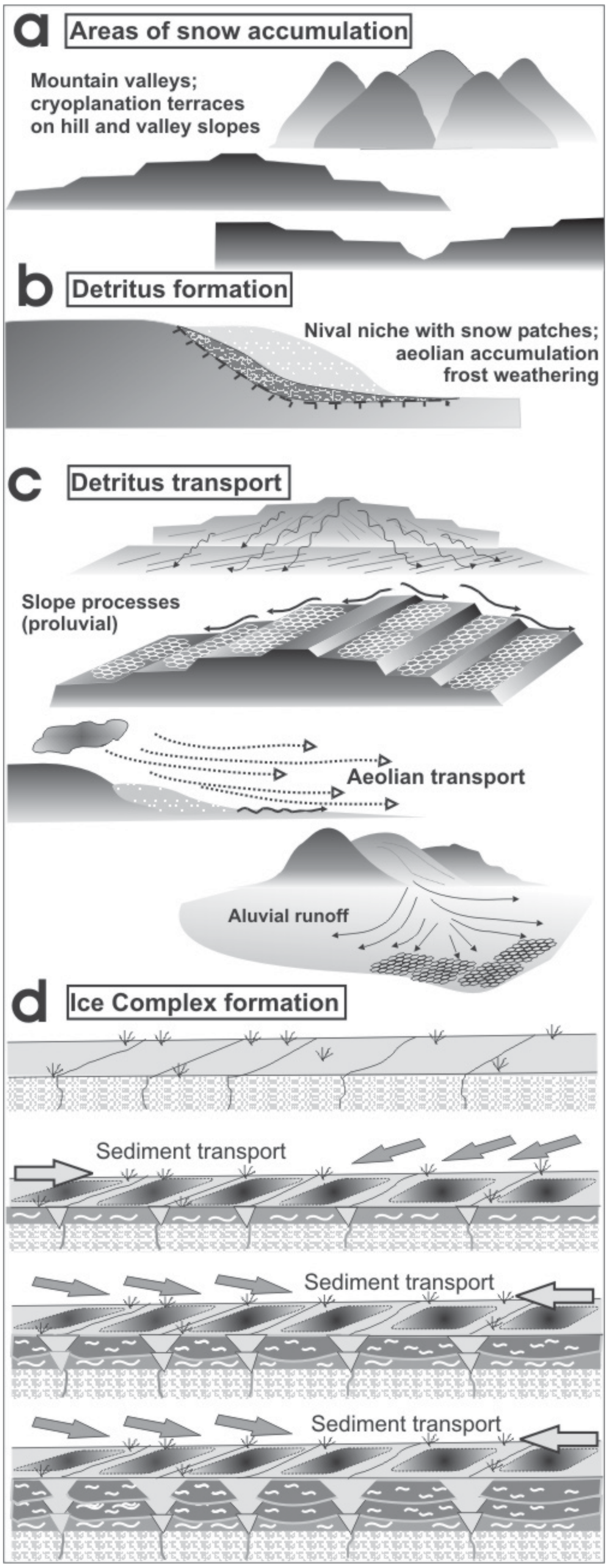

Figure 6. Scheme of Yedoma Suite formation.

Conclusions

The Yedoma Suite is an important paleoenvironmental archive that spans large regional and chronological gaps in the proxy information of the late Pleistocene Arctic. Consistent cryolithological, sedimentological, and palaeo-ecological features (Tab. 2) reflect similar environmental conditions for a wide variety of sites, representing a special periglacial facies.

Concluding, the Yedoma Suite includes a massive carbon and freshwater reservoir susceptible to release by global warming. In order to estimate and calculate the role of these widespread ice- and organic-rich frozen deposits in Siberia in a future warming Arctic, we must improve our knowledge of their characteristics and origin. The specific combination of strongly continental climate and the local landscape permitted syngenetic formation of ice wedges and organic-rich, ice-supersaturated sequences, called Ice Complex or the Ice Complexes of the Siberian Arctic.

Table 2. Typical features of the Yedoma Suite in the shelf region of northeastern Siberian.

Cryolithology	Ice-supersaturated, syngenetic ice wedges, segregation ice
Sediment	Poorly sorted, organic-rich silty sand
Formation age	80 to 12 ky BP
Stratigraphy	(MIS-4) to MIS-2
Palaeoecology	Tundra Steppe/Mammoth Steppe
Climate	High continental, arid
Genesis	Nival lithogenesis, alluvial, proluvial, and aeolian accumulation
Landscape	Lowland plains and cryoplanation terraces
Terminology	Ice Complex deposits compose the Yedoma Suite, which is preserved in Yedoma hills

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Mid- to Late-Quaternary Cryogenic Weathering Conditions at Elgygytgyn Crater, Northeastern Russia: Inference from Mineralogical and Microtextural Properties of the Sediment Record

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Abstract

Two sediment-mineralogical properties were tested as proxy data reflecting the intensity of cryogenic weathering. They were applied to lake sediments from Elgygytgyn Crater Lake in Chukotka, Siberia, and to frozen deposits from the catchment that serve as a reference for in situ weathering conditions. (1) The relative amounts of quartz and feldspar in different silt fractions yield the so-called cryogenic weathering index (CWI). High CWI values, as deduced from the samples, are related to the mineralogically selective weathering resulting from freeze-thaw cycles in the upper permafrost. (2) Image analysis of scanning electron micrographs (SEM) of quartz particles allows characterization and semi-quantification of grain morphology and surface features stemming from frost weathering (i.e., flaky surfaces, microcracking). The constant presence of cryogenic weathering signals both in lake sediments and frozen deposits suggests the long-term prevalence of stable permafrost conditions in the area at least since 220 ka.

Keywords: cryogenic weathering; quartz-feldspar ratio; microtextural properties; paleoenvironment reconstruction.

Introduction

Today, the majority of Siberian landmasses are subject to permafrost conditions. This is also the case for most of the Quaternary (Kaplina 1981, Brigham-Grette 2004, Hubberten et al. 2004). Nonetheless, until now no continuous record has been available that could be used to demonstrate variability of permafrost conditions for that time, nor have any suitable proxy data been tested. Such a sediment record could now become available through studies at Elgygytgyn Crater Lake in northeastern Siberia.

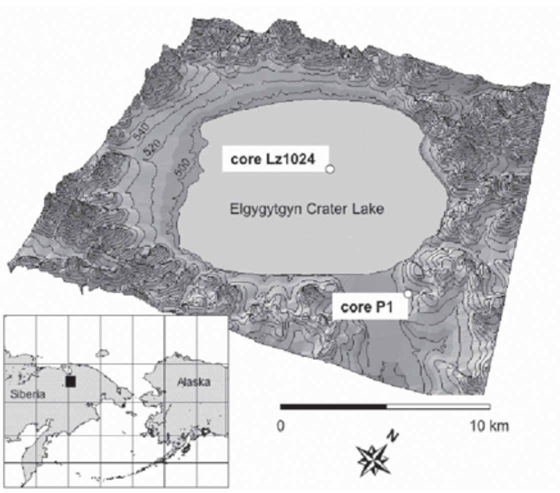

Figure 1. Crater location in NE Siberia (inset) and positions of lake sediment core Lz1024 (67°30.13′N,172°06.46′E) and permafrost core P1. The shoreline is 495 m above sea level.

Frost weathering, slope dynamics, and fluvial outwash are among the main surface processes, and they trigger erosion and detrital sediment transport into the lake basin. Continuous periglacial denudation is assumed for the Quaternary (Glushkova & Smirnov 2007). Tracing signals of cryogenic weathering from the catchment into the lake basin provides a direct land-to-lake linkage within paleoenvironmental reconstruction and will enlighten the permafrost history of non-glaciated NE Siberia. The development of a sediment-mineralogical approach to obtain proxy data for cryogenic weathering is the content of this paper. We use material from former coring into the lake and frozen deposits of the catchment (Melles et al. 2005).

Environmental Setting

Elgygytgyn Crater Lake, 12 km in diameter and 170 m in water depth at maximum (Fig. 1), holds sediments that mirror glacial to interglacial cyclicity and regional environmental change at millennial time resolution (Nowaczyk et al. 2002). The sediments consist of clayey silts and silty clays with occasional sand layers (Asikainen et al. 2007). Based on sedimentological data (physical properties, organic, and