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.

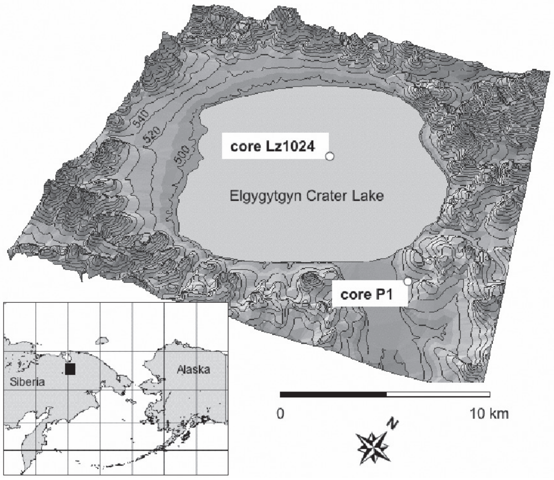

Figure 1. Crater location in NE Siberia (inset) and positions of lake sediment core Lz1024 (67°30.13′N,172°06.46′E) and permafrost core P1. The shoreline is 495 m above sea level.

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 isotope geochemistry), distinct climate-related sediment units have been identified that are primarily controlled by fluctuating carbon, nitrogen, and opal contents and linked to a changing extent of lake ice cover; i.e., “cold + moist,” “cold + dry,” “warm,” and “peak warm” (i.e., Eemian interglacial) (Melles et al. 2007). The sediment units alternate in the last 250 kyr, the time span that is covered by the first recovered sediment cores (Juschus et al. 2007, Nowaczyk et al. 2007). We assume a fairly constant surface denudation processes in the confined catchment of the crater lake, which makes the site a natural laboratory for studying the production of weathering debris in the catchment and its subsequent deposition in the adjacent lake sediment column. Longer core retrieval is planned (Melles et al. 2005), which will yield a climate record more than 3 million years old, since the origin of Elgygytgyn Crater is attributed to a meteoritic impact 3.6 M yr ago (Layer 2000). Thus, there will be the potential to identify the assumed onset of permafrost conditions across the Pliocene/ Pleistocene boundary. The altitude of the lake is 495 m above sea level (a.s.l.), and the highest peaks forming the crater walls are about 900 m a.s.l. Local basement rocks are of volcanic origin and are part of the Late Cretaceous Okhotsk-Chukotka volcanic belt (Belyi 1998, Layer 2000, Ispolatov et al. 2004). The rocks consist largely of andesitic to rhyolitic tuffs and ignimbrites of primarily acidic composition. Some subalkaline basaltic andesites have been identified framing the crater lake to the southwest.

Methods

Indicator data for paleo frost weathering: (I) mineral composition

In terms of sedimentology, the destruction of quartz grains is a basic process during the formation of cryogenic debris. As established in experiments, cryogenic disintegration promotes a relative accumulation of quartz grains in the silt fraction (10–50 microns); whereas fresh feldspars and heavy minerals accumulate in the sand fraction (50–100 microns) (Konishchev 1982). This mineralogically selective weathering is active under water-saturated freezing-thawing cycles (Minervin 1982). Expressed in a so-called *Cryogenic Weathering Index* (CWI), the role of cryogenic weathering in frozen soil formation can be estimated (Konishchev 1998):

$$CWI = (Q_1 / F_1) / (Q_2 / F_2) \qquad (1)$$

where Q_1 is quartz content (%) in the fine fraction; F_1 is feldspar content (%) in the fine fraction; Q_2 is quartz content (%) in the coarse fraction; and F_2 is feldspar content (%) in the coarse fraction.

CWI values greater than 1.0 argue for cryogenic weathering that influences the grain-size dependent mineral composition. Comparison of measurements from regionally distributed sediment samples of Arctic Siberia show that warm-climate sediments clearly can be discriminated from cold-climate samples (Konishchev & Rogov 1993). According to that study, Palaeogene-aged samples have CWI values ranging clearly below 1. Towards the Late Neogene and the Early Quaternary, the CWI values reach 1.7. In the lower and middle Pleistocene, values become as high as 3.3. The Eemian has falling values down to 1.7, before values rise again to a maximum of 3 at Weichselian time. Holocene CWI values range from 1.6 to 2.1. Indication of cryogenic weathering according to the CWI has already been implemented into permafrost modeling spanning the last 400 kyr (Romanovskii & Hubberten 2001). In our study, relative quartz and feldspar contents have been determined using standard x-ray diffractometry methods (Ehrmann et al. 1992, Vogt 1997) on a Philips PW 1820 goniometer that used a CoKα radiation (40 kV, 40 mA).

Indicator data for paleo frost weathering: (II) grain morphology and grain surfaces

Grain shapes and grain surface microtextures of mostly quartz and feldspar are well-established means to characterize sedimentary deposits and infer the environmental history from single grain morphology (Krinsley & Doornkamp 1973, Diekmann 1990, Mahaney 2002). Whereas single grain features are well-defined in the case of aeolian, glacial, and fluvial sediments, comparable features associated with mechanical encroachment in frozen ground is only sparsely documented, but appears distinctive (Konishchev & Rogov 1993, Van Hoesen & Orndorff 2004). Angular outlines and micromorphology such as high relief, sharp edges, and articulate steps are most frequent. They have been found in Holocene samples of Elgygytgyn Crater slope deposits (Schwamborn et al. 2006). Here, considerable amounts of grains are characterized by weathered surfaces; flakiness and microcracks were common features when inspected on SEM imagery. The grain surface features are particularly diagnostic for frozen ground sediments, since their production can be directly linked to the destructive effect of thaw-freeze alternation.

Sedimentary material

Lake sediments from core Lz1024 (Fig. 1) down to 12.2 m sediment depth were first measured for grain size distributions of 43 non-turbidite samples using a laser particle analyser (LS200, Beckman Coulter, Inc.). The studied interval spans the last 220 kyr according to the age model of Juschus et al. (2007). In contrast to Konishchev & Rogov (1993), CWI measurements are based on fractions 2–20 microns and 20–63 microns, since first grain size measurements revealed that lake sediments have a major mode at about 20 microns (Fig. 2). Grain shape and grain surface features have been characterized on at least 20 randomly selected quartz grains in each of 28 lake sediment samples. Chemical treatment of the samples followed standard techniques that are outlined elsewhere (Schwamborn et al. 2006). Hereafter, CWI calculations and SEM analysis have been applied.

Frozen deposits were recovered down to 5 m depth in a slope at the crater margin (P1 in Fig. 1). The dated core material shows a correct age-to-depth relation back into the Late Pleistocene (Schwamborn et al. 2006). For CWI calculation, seven samples have been selected that extend over the Holocene. They serve as a reference of in situ cryogenic weathering of the periglacial landscape.

Results and Discussion

Mineral composition

The clayey silts and silty clays from lake sediment core Lz1024 yielded a mean CWI value of 1.6, whereby the minimum value is 1.0 (11.7 m depth), and the maximum value is 3.5 (11.2 m depth) (Fig. 3). The silty sands and sandy silts from permafrost core P1 have a mean CWI value of 1.1, whereby the minimum value is 0.9 (0.7 m depth), and the maximum value is 1.4 (3.7 m depth) (Fig. 3).

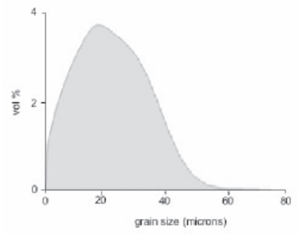

Figure 2. A typical grain size curve of lake sediments displaying the mode at 20 microns (sample from 10.64 m core depth).

All lake sediment CWI values are higher than 1.0 and thus fit well into the range of sediments from the glacial cycles. This argues for the presence of cryogenic conditions throughout the studied time interval. The variability around the mean is independent from sediment units and glacial to interglacial modes (Fig. 3). Several aspects are considered, which influence grain break-up and mixture of cryogenic detritus in the basin. (1) Warm periods are associated with higher temperature gradients in the active layer, thus increasing thermal stress to the grains and subsequent mechanical break-up. (2) Increasing moisture promotes the frequency of microcracking, when water migrates into fissures and subsequently disrupts the grains when crystallizing to ice. Both aspects (1 and 2) are also taking place in soil layers with fluctuating negative temperatures, but to an unknown degree. (3) Varying microclimates at rock surfaces, varying salt concentrations, and biotic encroachment (i.e., lichen growth) contribute to rock fragmentation to an unknown degree (Miotke 1988, Hall & André 2003, Guglielmin et al. 2005). (4) The particle size of source material may vary through time. (5) Soil weathering products that have been eroded and transported into the lake basin are reworked in the

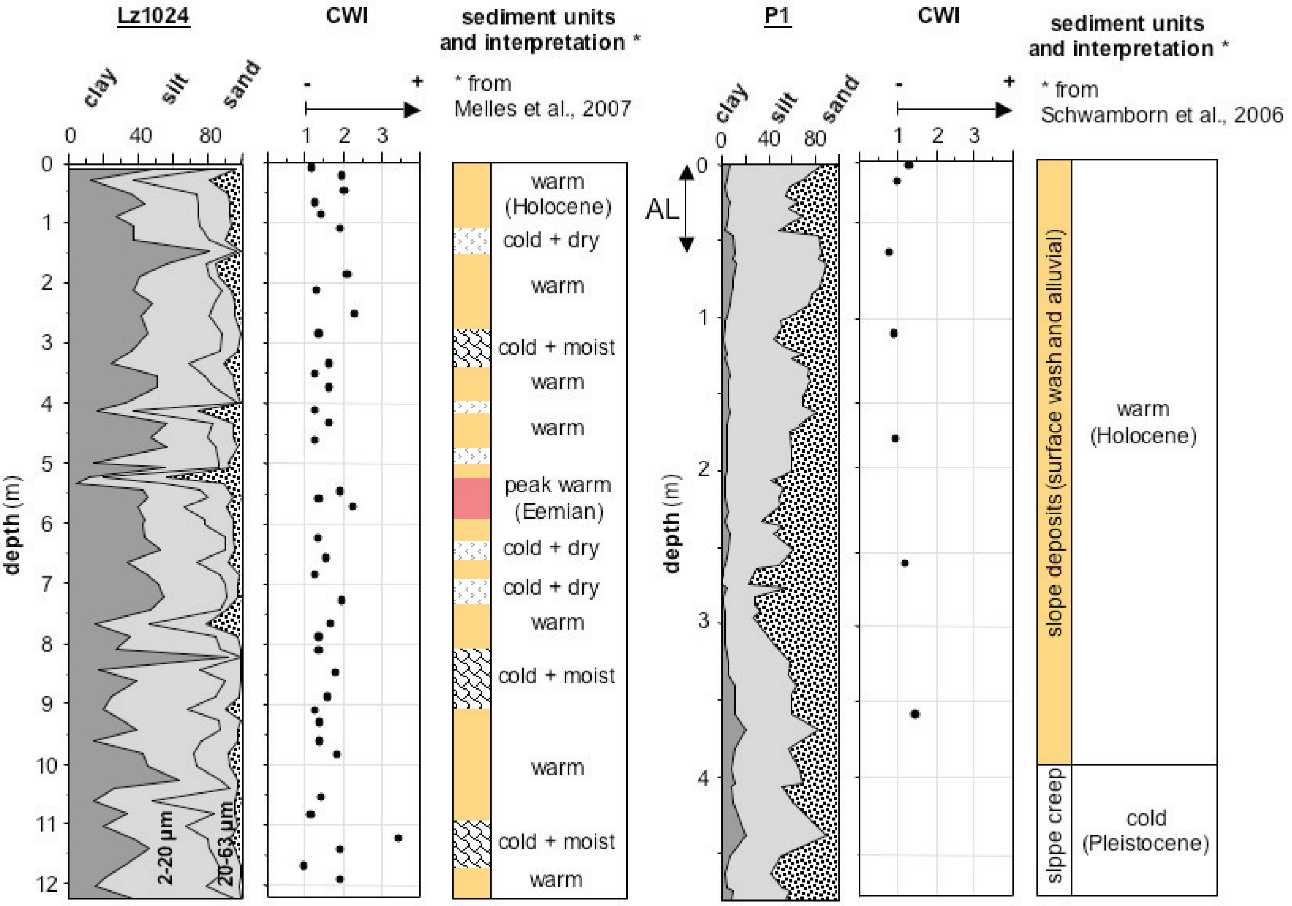

Figure 3. Values of the cryogenic weathering index (CWI) calculated for lake sediment core Lz1024 and permafrost core P1. Basic sediment interpretation schemes are added (see references). AL = Active layer.

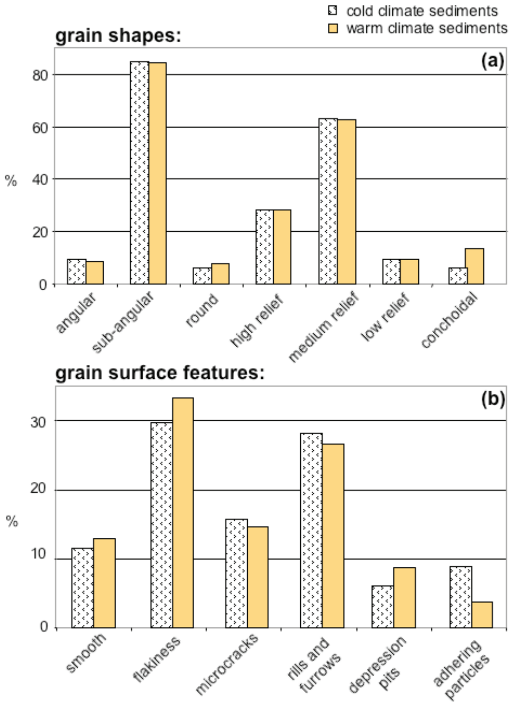

Figure 4. Grain shapes (a) and surface features (b) counted with quartz grains (63–125 microns) from lake sediment core Lz1024 (n=560).

shoals when strong winds from NW or SE lead to a thorough turbulence of the uppermost water column during the open water season. This leads to sediment mixing in the marginal shoals that also may add to blur the original CWI signal. (6) Changing lake levels contribute to sediment mixing, since the exposed and subsequently eroded areas around the lake have changed through time (Glushkova & Smirnov 2007, Schwamborn et al. 2007).

The near-surface permafrost around the lake produces low CWI values under Holocene warm-climate conditions (~1.0). Minor sediment mixing due to transport and reworking processes are associated with the environmental setting of P1 deposits (e.g., hill creep, slope wash, alluvial deposition), since the weathering debris is accumulated in a piedmont setting (Schwamborn et al. 2006).

Grain morphology and grain surfaces

Subangular grains are most common, but angular and round grains can also be found at all lake sediment core depths (Figs. 4, 5). Grains with conchoidal fractures, with smooth surfaces, brittle surfaces, and microcracks occur throughout the lake sediments, but to a lesser extent. Irregular, angular shapes (Fig. 5-1) argue for a short-distance transport, whereas conchoidal features (Fig. 5-4) suggest that pressure occurs either during in situ rock fragmentation or hill creep. Rounded grains (Fig. 5-3) represent the eolian portion that is drifted and deposited in the lake basin. However, estimates of the modern eolian input into the lake sediments yield a portion smaller than 5% (Fedorov pers. com.). V-shaped depression pits occur occasionally and point to grain-to-grain percussion during aquatic transport. Quartz grains exhibit abraded and softened areas, which can act as source areas for silt particles (Figs. 5-5, 5-6). Likewise, microcracks promote separation of silt-sized fragments and conspicuously display the destructive effect of cryogenic widening in the microscale to a varying degree (Figs. 5-7, 5-8). Descriptions of brittle grain surfaces along with microcracks are associated with cryogenic destruction within the thaw-freeze cycles in the uppermost permafrost (Konishchev. & Rogov 1993), or they have been described as crushing features (Van Hoesen & Orndorff 2004). They are present in Elgygytgyn lake sediments, and when medium- to high-relief grains become fragmented due to cryogenic cracking, the connection between SEM and CWI analysis is most obvious.

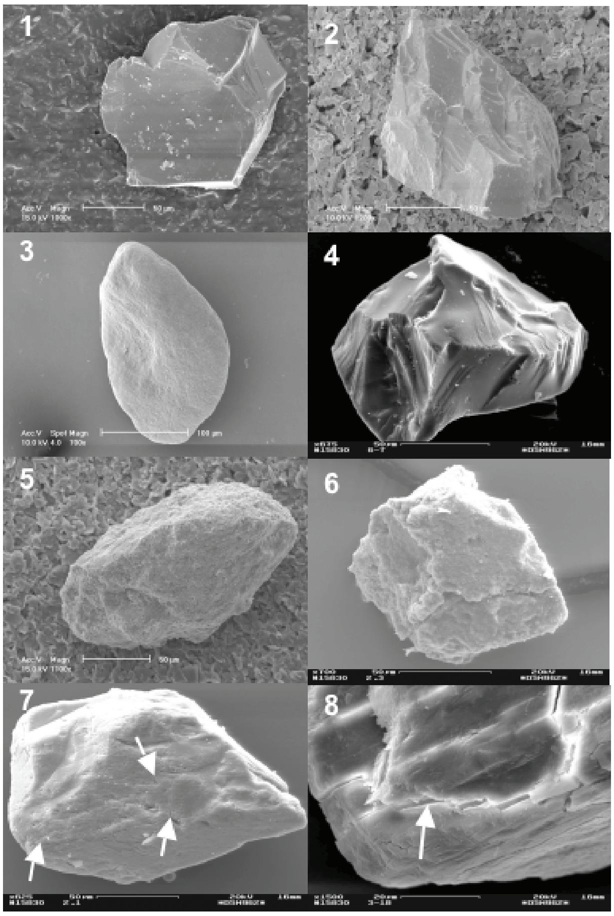

Figure 5. Examples of SEM micrographs from lake sediment quartz grains (63–125 microns); grain shapes: angular (1), subangular (2), rounded (3), conchoidal (4); grain surface features: brittle and flaky surfaces (5 + 6), cryogenic microcracking (7 + 8, see arrows).

The discrimination between cold-climate and warm-climate sediments (Fig. 4) does not exhibit prominent quantitative differences between the two. All characteristics can be identified to varying degrees at all sediment depths. Frost weathering features like brittle surfaces and microcracking demonstrate that traces of cryogenic destruction inherited from permafrost processes are well-preserved within the lake sediment column.

For frozen deposits from the catchment, grain micromorphology assessments are already available (Schwamborn et al. 2006). Angular outlines and microfeatures such as high relief, sharp edges, and articulate steps were most common and were consistently observed for all samples. This was linked to short transport distances from their source rocks. Many grains were characterized by rough and weathered surfaces. Flakiness and microcracks were common features. The grain surface textures appear particularly diagnostic for frozen ground sediments, since their production can be directly linked to the destructive effect of thaw–freeze alternation. Frost weathered surfaces and cryogenic cracking point to the sandy grains as the source areas of silt particles. This highlights in situ disintegration, especially of quartz grains, after they were subject to thaw–freeze dynamics (Konishchev and Rogov, 1993).

Conclusions

Despite some blurring effects (e.g., mixing of detritus resulting from weathering and from depositional processes, and sediment reworking in the lake margins due to lake level changes) CWI and SEM analysis can link lake sediments and frozen slope deposits for paleoenvironment interpretation. The studied sediment properties suggest that cryogenic weathering was persistent around Elgygytgyn Crater Lake for at least the last 220 kyr.

An unknown temporal offset between the creation of cryogenic features in the catchment and the material deposition in the lake has to be taken into account when interpreting the timescale within the paleoenvironmental archives.

The combination of grain size, CWI, and SEM results is considered a helpful technique to identify on- and off-set of permafrost conditions in the area when inspecting future drill cores that go beyond 3 M yr back in time.

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