Iron-Oxides and Pedogenesis of Modern Gelisols and Paleosols of the Southern Lena Delta, Siberia, Russia

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Abstract

Five exposures on two arctic islands in southern Lena Delta, Russia, were investigated in order to determine the development of iron-oxides under different pedogenic conditions in permafrost-affected paleosols and to prove their application for describing environmental conditions during pedogenesis of buried soils and the predominant paleoclimate during their development. The samples were collected from the active layer on Samoylov Island as well as from Late Pleistocene and Holocene paleosols on Kurungnakh Island. The amounts of iron extractable by dithionite (Fe_d) and by oxalate (Fe_o) were determined for all samples. The extracts were conducted to determine the forming conditions of paleosols and their iron-oxide contents and to compare them with modern permafrost-affected soils. The iron-oxide amounts characterize well the sedimentation conditions and the paleoclimate of the investigated paleosols. As contributing factors, the organic matter content and the inundation were identified. Additionally, in modern soils, translocation processes within the polygon affect the conditions of the different Fe-fractions.

Keywords: environmental and climate change; Gelisols; iron-oxides; Lena Delta; paleosols; Siberia.

Introduction

Permafrost-affected soils (Gelisols or Cryosols) cover nearly one-fourth of the terrestrial surface in the northern hemisphere. Staudies have been conducted for more than 100 years (Goryachkin et al. 2004). The first studies were exploratory in nature in order to find land for agriculture. Pedoscientists study permafrost-affected soils to learn more of their active physico-chemical processes (Tarnocai 2004). Spatial distribution, genesis and properties of different Cryosols are presented in details by Kimble 2004. However, this does not imply that these soils have been sufficiently investigated.

Pedogenesis in permafrost regions takes place in the active layer above the permafrost table only during the short summer period. On one hand, the cold conditions hinder strong pedogenesis; on the other hand, permafrost preserves records of former soil conditions.

Spatial distribution and genesis of soils in the southern Lena Delta provide a basis for evaluation of the impact of environmental and climate change on permafrost landscapes.

The objective of this study was to prove if crystallized iron-oxides are a useful criterion for estimating environmental conditions of pedogenesis of buried soils and paleoclimate during their development.

Morphological and analytical data are taken into account to understand both properties and genesis of buried soils in ice rich permafrost sediments (so called ice complex) and modern soils in the southern Lena Delta.

Identifying different forms of iron-oxides helps to understand the environment in which active pedogenesis took place. In general paleosols are often characterized by their iron-oxides fractions, and this data facilitates an estimate of the relative age of a given soil-sequence (Arduino et al. 1984, Arduino et al. 1986, Bäumler 2001).

During expeditions to the Lena Delta in 2002 and 2007 investigation of several soil profiles were carried out to determine the development of iron-oxides under different pedogenic conditions in permafrost-affected paleosols and to prove their application for description of environmental conditions of pedogenesis of buried soils and predominant paleoclimate during their development. For understanding the processes of modern pedogenesis, from the active layer of young soils were investigated.

Investigation Area

The study sites are located on Samoylov Island (72°22′N, 126°28′E) and Kurungnakh Island (72°20′N, 126°18′E). The islands are situated at one of the main Lena River channels, the Olenyokskaya Channel in the southern part of Lena Delta (Fig. 1). The Lena Delta is located in northeastern Siberia, where the Lena River cuts through the Verkhoyansk

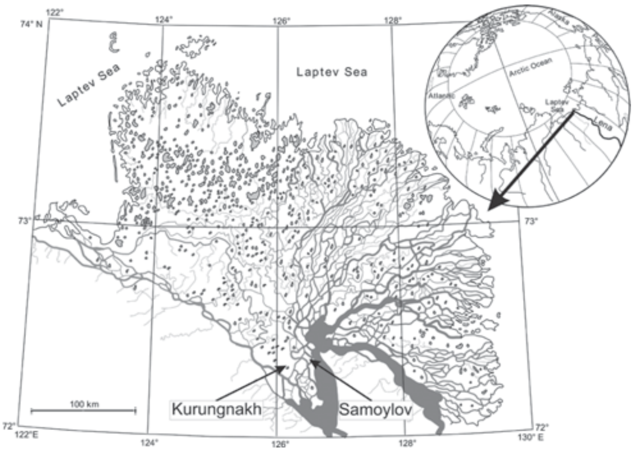

Figure 1. Map of the Lena Delta with study sites.

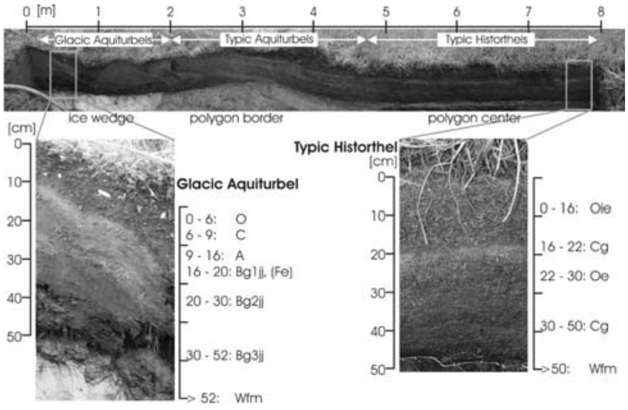

Figure 2. Soil-cross-section of a half of a low-centered polygon on Samoylov Island with the soil-complex of Glacic Aquiturbel and Typic Historthel, according to U.S. Soil Taxonomy.

Mountains Ridge and discharges into the Laptev Sea, which is part of the Arctic Ocean.

Samoylov Island can be divided into two major geomorphological units (Akhmadeeva et al. 1999): the relative young floodplain (0 to 4 m a.r.l. [about river level]) in the western part which is flooded annually in spring, and the higher-elevated (1 to 12 m a.r.l.) river terrace of Late Holocene age, the “first” terrace in the eastern part (Pavlova & Dorozhkina 1999). The first terrace is flooded only during extreme high-water events (Kutzbach 2005).

Kurungnakh Island belongs to the third river terrace complex (up to 55 m a.r.l.) of the Lena Delta. The third terrace is the oldest terrace in the delta. It was formed in Middle and Late Pleistocene (Schwamborn et al. 2002, Kuzmina et al. 2003). This terrace forms autonomous islands along the Olenyokskaya and Bykovskaya Channels. The Kurungnakh Island is located at the southeastern part of Olenyokskaya Channel (Schwamborn et al. 2002).

The climate in the Lena Delta is high-arctic with continental influence and characterized by low temperatures and low precipitation. The mean annual air temperature, measured by the meteorological station in Tiksi located about 110 km (68 stat. mi.) to the southeast directly at the coast of the Laptev Sea, was -13.6°C (7.5°F) during the 30-year period 1961–1990; the mean annual precipitation in the same period was 319 mm. The average temperatures of the warmest month August and the coldest month January were 7.1°C (44.8°F) and -32.4°C (-26.3°F), respectively (ROSHYDROMET 2007), demonstrating the extreme climatic contrasts between polar day and polar night for continental Polar Regions.

Material and Methods

The main soil unit of the first terrace above the floodplains of Samoylov Island is covered mainly by polygonal wet sedge tundra with soil-plant-complexes which consist of ice rich ground, wet and cryoturbated Gelisols (Glacic Aquiturbels) and very wet organic rich Gelisols (Typic Historthels). Typic Historthels are Gelisols that have more than 40%, by volume, organic materials from the surface to a depth of 50 cm (Soil Survey Staff 2006). According the WRB-Classification the Gelisols were classified as Glacic Turbic Cryosols and Haplic Histic Cryosols (Food and Agriculture Organisation, 2006). Typic Historthels were formed in depressed centers of low-centered ice-wedge polygons characterized by high water saturation to the soil surface and high organic matter accumulation due to anaerobic conditions.

Glacic Aquiturbels formed at the elevated borders of the polygons are characterized by prolonged inundation but with less organic matter accumulation and pronounced cryoturbation. Thus Glacic Aquiturbels are Gelisols that have one or more horizons showing cryoturbation in the form of irregular, broken or distorted horizon boundaries, involutions, and accumulation of organic matter on top of the permafrost and ice wedges. They have within 50 cm of the mineral soil surface redox depletions and also aquic conditions during normal years and a glacic layer with its upper boundary within 100 cm of the mineral soil surface (Soil Survey Staff 2006).

Beside these wet and organic rich soils various sandy soil complexes such as Psammorthels and Psammoturbels are typical along the eroded cliffs. They are drier than the Aquiturbels and Historthels (Pfeiffer et al. 1999, Pfeiffer et al. 2000, Pfeiffer et al. 2002). Psammorthels and Psammoturbels are soils that have less than 35%, by volume, rock fragments and a texture of loamy fine sand or coarser in all layers within the particle-size control section (Soil Survey Staff 2006). In the erosional cliff area thermal erosion results in formation of high-centred polygons which are often covered with eolian sands.

Glacic Aquiturbels and Aquic Histurbels are common on Kurungnakh Island as on Samoylov Island. These modern soils are compared with paleosols such as Histels of different degree of decomposition, iron-rich Aquorthels and Aquiturbels of exposures on both islands.

For investigations of paleosols three exposures of 2.1, 2, and 1.2 m thickness were selected on the third terrace of Lena Delta on Kurungnakh Island. The samples were taken during the expedition “LENA 2002” (Kuzmina et al. 2003).

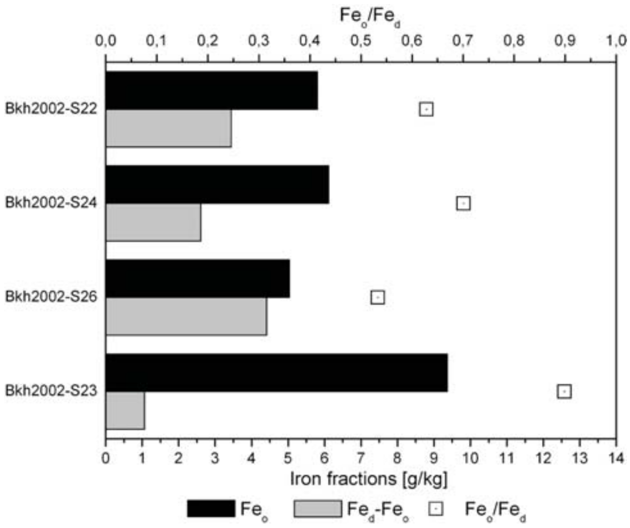

Figure 3. Values of Fe_o, Fe_d-Fe_o, and Fe_o/Fe_d in different soil horizons of profile Bkh2002-S22 to S26. Late Pleistocene paleosol, Kurungnakh Island.

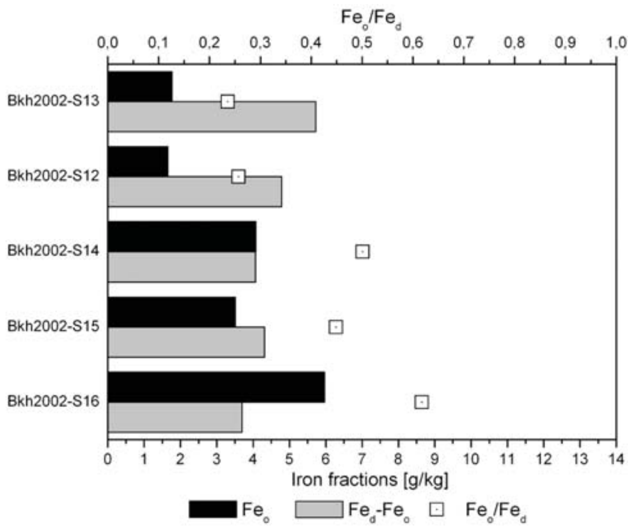

Figure 4. Values of Fe_o, Fe_d-Fe_o, and Fe_o/Fe_d in different soil horizons of profile Bkh2002-S12 to S16. Late Glacial paleosol, Kurungnakh Island.

The third terrace was formed in Middle and Late Pleistocene (Schwamborn et al. 2002). We collected samples of different ages from 5.8 to 40 ky BP (Schirrmeister et al. 2003, Wetterich et al. subm.).

Samples of modern soils have been taken on Samoylov Island during the expedition 'LENA – New Siberian Islands – 2007' in summer 2007 from the active layer of a low-centered polygon (Fig. 2).

Samples were collected from each layer of individual exposures. Pedological descriptions including Munsell soil color, fresh weight and other morphological remarks were made in the field. All analyses were done on the <2mm fraction and data are expressed on an oven-dry basis (105°C).

For pH determination a soil suspension with 0.01 M $CaCl_2$ was prepared and measured after an equilibration time of one hour with pH-Meter Schott CG820.

Total organic carbon (TOC) and nitrogen (N) were determined by VarioMax Elementaranalysator (Elementar Analyse Systeme GmbH).

A special consideration is given to different pedogenically formed iron-oxides to compare recently formed cryosols with paleosols of deeper sediment layers of both islands.

Oxalate-extractable iron (Fe_o) was determined by the method of Schwertmann (1964) at room temperature, in dark with acid ammonium oxalate at pH 3.25. Dithionite-extractable iron (Fe_d) was determined by the DCB method of Mehra & Jackson (1960) with dithionite-citrate buffered by bicarbonate at pH 7.3. Iron in all extracts was determined by Atomic-Absorption-Spectrometer.

To make an estimation of the degree of pedogenesis and relative age of a soil-horizon using analysis of different forms of Fe the following fractions were used: Fe_o as "active" Fe-oxides, probably ferrihydrite, (Fe_d - Fe_o) as Fe-oxides in less "active" well crystallized form, probably goethite and the ratio Fe_o/Fe_d as a degree of activity and pedogenesis.

Results and Discussion

Bkh2002-soil-sample series, Kurungnakh Island (Expedition 2002)

This sample collection represents the paleosols of the third terrace of Lena Delta. The lowest part of the third terrace consists of fluvial sands with low organic matter content (Schwamborn et al. 2002, Wetterich et al. subm.). The accumulation conditions were shallow water similar to the modern flood plains (Schirrmeister et al. 2003). The pedogenesis was characterized by hydromorphic conditions scarce vegetation and a cold dry climate. The unit was radiocarbon dated to >57 ky BP (Schirrmeister et al. 2003). The sand unit is covered by ice complex deposits (17 – 29.5 m a.r.l.). The profile Bkh2002-S22 to S26 (24 – 26.1 m a.r.l.) belongs to the ice complex sequence that was formed during the Late Pleistocene regression (Schwamborn et al. 2002). It is composed of fine grained poorly sorted sediments, thick peaty paleosols and large ice wedges (about 5 m wide and 20 m high). The thick peat layers were found in the lower part of the ice complex. They are thinner in the upper part where sand lenses were often observed. According to radiocarbon ages the entire ice complex sequence was formed between 44 and 17 ky BP in connection with niveo-eolian and slope processes (Schirrmeister et al. 2003, Wetterich et al. subm.). Pedogenesis during this time mirrors relatively warm and wet interstadial climate with tundra-steppe vegetation. Climate conditions with high production of organic matter are clearly recognizable in the extracted iron-oxide values that vary from 5 to 9.4 g/kg for active not crystallized oxides (Fe_o) and 1.1 to 4.4 g/kg for crystallized oxides (Fe_d-Fe_o) (Fig. 3).

High amounts of organic matter as they were found in the peaty paleosols with TOC values from 3.5 to 7.1% (Tab. 1) hinders the transformation of active iron-oxides to more crystallized oxides or even leads to formation of Fe-organic complexes (Cornell & Schwertmann 2004).

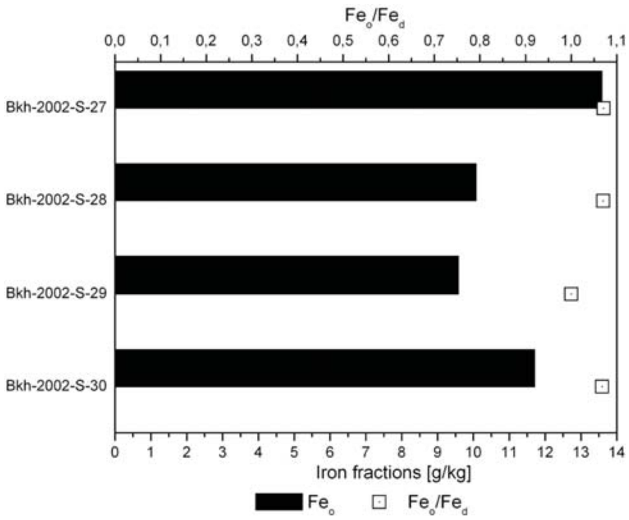

Figure 5. Values of Fe$_o$, and Fe$_o$/Fe$_d$ in different soil horizons of profile Bkh2002-S27 to S30. Early Holocene paleosol, Kurungnakh Island.

According to the high amount of Fe$_o$-fraction the Fe$_o$/Fe$_d$ ratio is relatively high with amounts from 0.5 to 0.9. The highest ratio was measured in the Bkh2002-S23 sample of a peat layer (TOC – 7.1%) that was formed during the wettest and warmest conditions that existed between ca. 44 and 38 ky BP (Schirrmeister et al. 2003).

The pH values vary from 6.9 to 5.5 whereby the moderate acid one was found in the peat horizon with the highest Fe$_o$/Fe$_d$ ratio.

The ice complex is covered by two younger units dated to 17 – 8 ky BP and 6 – 3 ky BP respectively. The first one (29.5 – 33.5 m a.r.l.) was formed under very cold and dry climate with scarce steppe-like vegetation and dry soil conditions (Schirrmeister et al. 2003, Wetterich et al. subm.). It consists of poorly sorted silt deposits with low organic matter content. In this unit Bkh2002-S12 to S16 were sampled (29 – 31 m a.r.l.).

Values of the extracted iron-oxides vary from 1.7 to 6 g/kg and 3.7 to 5.7 g/kg for Fe$_o$-oxides and Fe$_d$-Fe$_o$-oxides respectively (Fig. 4). The Fe$_o$/Fe$_d$ ratio is relatively low in the samples Bkh2002-S13 and S12 with 0.24 and 0.26. With increasing altitude the ratio decreases. The highest ratio of 0.62 was found in Bkh2002-S16 (29 m a.r.l.) sampled of a mixed horizon of sand and peat. Under dry and cold late glacial climate conditions with scarce vegetation and low organic matter content pedogenesis can progress but less intense well-expressed by relatively low iron activity ratio and high amounts of better crystallized iron-oxides indicating dry soil conditions with distinct iron-oxide crystallization.

The TOC values vary from 1.1 to 4.7% and pH values show low variability in the sandy horizons (7.4–7.3). In the mixed horizon there are weakly acid conditions (6.7) corresponding to higher content of organic matter (TOC–4.7%) similar to the last sample of the ice complex profile (Bkh2002-S23).

Samples of the last profile were taken from the youngest unit that was formed in Mid Holocene (6 ky BP). It was comprises of 4 samples (Bkh2002-S27 - S30) taken from

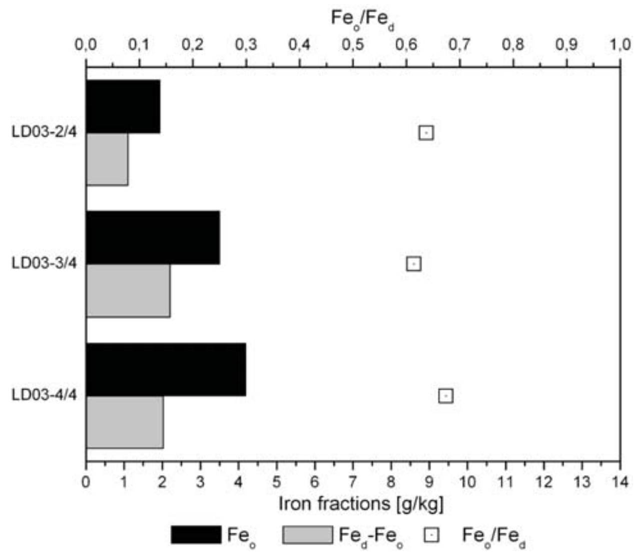

Figure 6. Values of Fe$_o$, Fe$_d$-Fe$_o$, and Fe$_o$/Fe$_d$ in different soil horizons of profile LD03-2/4 to 4/4. Modern Gelisol Typic Historthel, Samoylov Island.

the 33.5 to 34.7 m a.r.l. The values of not crystallized active iron-oxides and Fe-organic complexes are very high and vary from 9.6 to 13.6 g/kg (Fig. 5). Crystallized iron-oxides were not verifiable, because of negative Fe$_o$-Fe$_d$ values.

The Fe$_o$/Fe$_d$ ratio is about 1 and the highest described in this paper. The pH values are acid (4.4 to 4.9) and correspond to the high organic matter content (TOC 3 to 4.6%) throughout the entire profile that consists of grey silt sediments with peat lenses. These sediments with high amounts of organic matter developed because of warmer climate, which caused a vegetation change to tundra-like. According to paleoenvironmental reconstructions (Wetterich et al. subm.) the pedogenesis took place under wet local conditions during this period.

LD-soil-sample series, Samoylov Island (Expedition 2007)

This sample collection which is composed of two active layer profiles represents recent pedogenesis on the first terrace of Lena Delta. The first terrace is of Holocene age and the young floodplains are assumed to represent the active part of Lena Delta. Maximum altitude is 12 m a.r.l. representing the oldest parts of the first terrace. The first terrace is formed by fluvial sediments that change from organic-rich sands at the bottom to silty-sandy peats towards the surface including several layers of eolian sands (Akhmadeeva et al. 1999, Schwamborn et al. 2002). This terrace is characterized by active ice wedge growth, low- and high-centered polygons, and thermokarst lakes.

The investigated profiles were sampled at a cross-section of a typical low-centered polygon (Fig. 2). These modern soils were classified by using U.S. Soil Taxonomy (Soil Survey Staff 2006).

In the polygon center a Typic Historthel (LD03-2/4 – 4/4) (11.85 – 11.5 m a.r.l.) and at polygon rim a Glacic

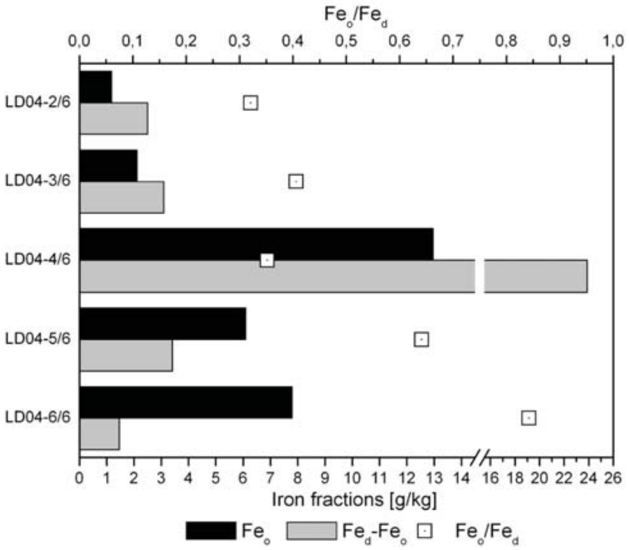

Figure 7. Values of Fe_o, Fe_d-Fe_o, and Fe_o/Fe_d in different soil horizons of profile LD04-2/6 to 6/6. Modern Gelisol Glacic Aquiturbel, Samoylov Island.

Aquiturbel (LD04-2/6–6/6) (11.95–11.5 m a.r.l.) were selected (Figs. 6, 7).

In the polygon center the values of the oxalate extractable iron-oxides (Fe_o) vary from 1.9 to 4.2 g/kg and for crystallized iron-oxides from 1.1 to 2.2 g/kg where the lowest values (Fe_o - 1.9 g/kg, Fe_d-Fe_o – 1.1 g/kg) were found in C-horizon (sample LD03-2/4) containing an eolian sand band at the altitude of 11.85 m a.r.l. (Fig. 6) with very slightly decomposed organic matter with C/N of 25. (Table 1). All horizons of this profile are rich in organic matter (TOC values from 1.8 to 5.5 %) and high C/N values from 23 to 25.2. Due to the organic matter the Fe_o/Fe_d ratio is relatively high. The pH values are strongly acid (4.5 – 4.8) and show low variability (Table 1).

The Fe_o values of the investigated Glacic Aquiturbel (LD04-2/6–6/6) vary from 1.18 to 12.96 g/kg and values of less active iron-oxides vary from 1.1 to 23.87 g/kg. The particularly high values were extracted from the Bg1jj-horizon (sample LD04-4/6) containing an iron band (Figs. 2, 7). This iron band can probably be considered as an enrichment horizon due to element redistribution among recent soil profiles by downward-translocation of mobile iron (Fiedler et al. 2004).

Relatively low values of iron-oxides in C- and A-horizon (samples LD04-2/6 and 3/6) support this hypothesis (Fig. 7) when they are regarded as eluvial horizons. The Fe_o/Fe_d ratio is low in the upper part of the profile. The value increases with increasing depth below ground surface. The upper horizons are first aerated during the slow process of thawing in spring and summer. This leads to the transformation of active iron-oxides to more crystallized oxides in the upper part. The pH values vary from 4.6 to 5.8 with strongly acid values in horizons Bg2jj and Bg3jj (samples LD04-5/6 and 6/6). The organic matter content (TOC) is lower than in the polygon center and shows values from 1.5 to 2.3% (Tab. 1).

Table 1. Analysis data of different soil horizons. Bkh2002: paleosol samples, Kurungnakh Island. LD: modern soil samples, Samoylov Island.

Soil sample	Altitude [m]	pH [$CaCl_2$]	TOC [%]	C/N
Bkh2002 - S27	34.70	4.9	4.6	18.1
Bkh2002 - S28	34.50	4.4	3.6	17.9
Bkh2002 - S29	34.00	4.6	3.8	19.7
Bkh2002 - S30	33.50	4.5	3.0	17.6
Bkh2002 - S13	31.00	7.4	1.7	10.9
Bkh2002 - S12	30.50	7.4	1.1	8.3
Bkh2002 - S14	30.00	7.4	1.4	10.1
Bkh2002 - S15	29.50	7.3	1.6	10.6
Bkh2002 - S16	29.00	6.7	4.7	12.7
Bkh2002 - S22	26.10	6.8	4.3	12.8
Bkh2002 - S24	25.00	6.4	4.2	13.4
Bkh2002 - S26	24.50	6.9	3.5	11.7
Bkh2002 - S23	24.00	5.5	7.1	15.1
LD04-2/6	11.95	5.8	1.6	15.9
LD04-3/6	11.90	5.8	2.3	15.9
LD04-4/6	11.85	4.6	2.1	14.6
LD04-5/6	11.80	4.7	1.9	14.0
LD04-6/6	11.70	4.8	1.5	15.4
LD03-2/4	11.85	4.5	1.8	25.2
LD03-3/4	11.80	4.8	5.5	24.5
LD03-4/4	11.70	4.8	4.2	23.0

Conclusions

The differences in values and ratios of extractable iron-oxides suggest that changes in forms of iron-oxides depend on the main soil material and water conditions. The influence of organic matter on iron-oxide transformation from young and active to more crystallized oxides is in evidence.

Paleosols show clear differentiation according to their stratigraphic position and paleoenvironmental conditions.

Soils that developed under relatively warm and wet interstadial climate (44–38 ky BP) and during the Early Holocene Climatic Optimum (8–6 ky BP) are characterized by relatively low values of well crystallized iron-oxides due to climatically caused high production of vegetation and the negative effect of the organic matter on the crystallization progress. Dry stadial climatic conditions as they were predominant at the end of Late Pleistocene (about 17 ky BP) associated with lower production of biomass and higher aeration of soil horizons principally lead to the formation of varying iron-oxides with relatively high values of the well crystallized fraction.

The results of the investigated modern soils from the active layer are comparable with those of the paleosols. The organic matter content and the seasonal inundation play a major role for Fe-transformation in modern soils. Further elements of modern soils are affected by translocation processes within the polygon. Detailed considerations of processes taking place in polygons during thawed periods have to be included in further investigations.

This approach promises to be more effective when applied to iron-oxides. The identification of texture and minerals and the radiocarbon dating of all samples will be finished. The analysis is still in progress.

Acknowledgments

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