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Trace metal distribution in pristine permafrost-affected soils of the Lena River Delta and its Hinterland, Northern Siberia, Russia

I. Antcibor[1], S. Zubrzycki[1], A. Eschenbach[1], L. Kutzbach[1], D. Bol'shiyanov[2], and E.-M. Pfeiffer[1]

[1]Institute of Soil Science, KlimaCampus, Hamburg University, Hamburg, Germany
[2]State Research Center – Arctic and Antarctic Research Institute, St. Petersburg, Russia

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Correspondence to: I. Antcibor (julia.antsibor@uni-hamburg.de)

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Abstract

Soils are an important compartment of ecosystems and have the ability to immobilize chemicals preventing their movement to other environment compartments. Predicted climatic changes together with other anthropogenic influences on Arctic terrestrial environments may affect biogeochemical processes enhancing leaching and migration of trace elements in permafrost-affected soils. This is especially important since the Arctic ecosystems are considered to be very sensitive to climatic changes as well as to chemical contamination. This study characterizes background levels of trace metals in permafrost-affected soils of the Lena River Delta and its hinterland in northern Siberia (73.5° N–69.5° N) representing a remote region far from evident anthropogenic trace metal sources. Investigations on total element contents of iron (Fe), arsenic (As), manganese (Mn), zinc (Zn), nickel (Ni), copper (Cu), lead (Pb), cadmium (Cd), cobalt (Co) and mercury (Hg) in different soil types developed in different geological parent materials have been carried out. The highest concentrations of the majority of the measured elements were observed in soils belonging to ice-rich permafrost sediments formed during the Pleistocene (ice-complex) in the Lena River Delta region. Correlation analyses of trace metal concentrations and soil chemical and physical properties at a Holocene estuarine terrace and two modern floodplain levels in the southern-central Lena River Delta (Samoylov Island) showed that the main factors controlling the trace metal distribution in these soils are organic matter content, soil texture and contents of iron and manganese-oxides. Principal Component Analysis (PCA) revealed that soil oxides play a significant role in trace metal distribution in both top and bottom horizons. Occurrence of organic matter contributes to Cd binding in top soils and Cu binding in bottom horizons. Observed ranges of the background concentrations of the majority of trace elements were similar to background levels reported for other pristine arctic areas and did not exceed mean global background concentrations examined for the continental crust as well as for the world's soils.

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1 Introduction

Heavy metals are naturally present in parent rock and in soils and occur in forms of sulfides, oxides, silicates, and carbonates. They can be adsorbed or bound to natural substances which may govern the elements' migration ability (Dube et al., 2001). However, trace metals are also one of the major groups of anthropogenic contaminants of soils. Arctic ecosystems belong to the most sensitive regions of the world with regard to effects of human impact (Weller, 1995; Gulinska et al., 2003). Examples for anthropogenic sources of heavy metals in the Arctic are the Norilsk industry area in western Siberia and the mining industries of Nickel, Monchegorsk, Zapolyarny in Kola Peninsula (Boyd et al., 2009; Jaffe et al., 1995; Opekunova et al., 2007; Zhulidov et al., 1997b). Their activity leads to substantial pollution of arctic ecosystems across several hundred kilometers (Zhulidov et al., 1997b). Trace metals can reach the Arctic by different paths. Some studies demonstrate that the input of trace metals to the arctic region including both natural and anthropogenic origin could be caused by long-range transport (Barrie, 1985; Barrie et al., 1985, 1992; Pacyna, 1995; Rahn et al., 1997; Rovinskiy et al., 1995; Thomas et al., 1992). Evaluation of anthropogenic impacts on arctic ecosystems requires knowledge on the background levels of trace metals as well as on the landscape distribution of elements in permafrost-affected soils in relation to soil properties.

It is often assumed that the Lena River Delta draining into the Laptev Sea is situated in an almost pristine environment (Nolting et al., 1996). Although the study area is remote, there exists a risk of contamination by heavy metals from anthropogenic sources connected to the settlements. The Lena Delta River region, being geomorphologically heterogeneous, acts as a natural filter that accumulates various materials transported by the Lena River from the south, including pollutants (Lisitsyn, 1994). The distribution of trace metals in water, sediments, air, vegetation and wildlife has been studied in detail (Nolting et al., 1996; Presley, 1997). However, existing data on the presence of contaminants in arctic soils is geographically limited in comparison with

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temperate or tropical regions. Soil acts with a barrier function by adsorbing contaminants and preventing their further migration to aquatic ecosystems for example through seepage water and groundwater (Dobrovol'skiy et al., 1986). However, climate change and anthropogenic impacts may affect the main soil functions such as transformation and filtering of pollutants and interrelated processes and properties (Dube et al., 2001; Weller, 1995).

Permafrost-affected soils are widespread in subarctic and arctic tundra with great amounts of stored organic matter (Tarnocai et al., 2009). Thus, the mean soil organic carbon stock for the upper 1 m of soils of the Holocene terrace of the Lena River Delta has been estimated at $29\,\mathrm{kg\,m^{-2}} \pm 10\,\mathrm{kg\,m^{-2}}$ (Zubrzycki et al., 2012b). This organic matter is capable of forming organo-mineral associations (Höfle, et al., 2012) of the type that bind the majority of trace metals (Davranche et al., 2011; Dube et al., 2001). We assume that the predicted increase of global warming will mobilize the elements within this large reservoir of carbon. This mobilization will intensify biogeochemical cycling within the upper layers of permafrost-affected soils.

The aims of this paper are (1) to provide a first observation of the trace metal content in seasonally thawing layers of permafrost-affected soils of the Lena River Delta region in northern Siberia, and (2) to investigate the landscape distribution of trace metals in soils of the Lena River Delta and its hinterland by analyzing the relations between trace metal concentrations and other soil properties such as carbon and iron oxide contents, soil texture and thaw depth.

2 Study area

The investigation area is located in the northern part of eastern Siberia between 73.5° N and 69.5° N. It covers the delta of the Lena River in the north (TIK01, TIK04, TIK21, Samoylov Island, TIK20) and its nearby hinterland to the south (TIK05, TIK14, TIK13) (Fig. 1). The investigations of the soils were most intense on Samoylov Island in the southern-central Lena River Delta during autumn in 2010. This site is representative

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for the younger delta areas including a Holocene estuarine terrace and various floodplain levels (Boike et al., 2012). Additionally different sites along a north-south transect starting in the arctic tundra in the north of the Lena River Delta and extending to the northern taiga during the expedition "LENA 2009" have been studied (Zubrzycki et al., 2012a).

The study area belongs to the arctic-subarctic climate zone. The mean annual air temperature and the mean annual precipitation, measured by the meteorological station in Tiksi (71°38′ N, 128°52′ E) during the 30-yr period 1961–1990, were −13.6 °C and 319 mm, respectively (ROSHYDROMET, 2011). The mean annual air temperature and annual precipitation of the region farther to the south, measured at the climate reference site in Dzhardzhan (68°49′ N, 123°59′ E) during the period 1998–2011 was −12.4 °C and 298 mm, respectively. The temperature amplitude at the Dzhardzhan reference site is higher than in Tiksi (Zubrzycki et al., 2012a). Because a strong continental climate exists at the study area, the summer period is longer and warmer in the region's south. The predominant winds of this area come from north and north-east (USSR climate, 1968).

According to Grigoriev (1993), the Lena River Delta area can be subdivided into three terraces of different age and various floodplain levels. Arga Island (TIK01) is the northernmost site of the study area. It is located in the north-western part of the Lena River Delta and represents a major part of the so-called second terrace (20–30 m a.s.l.) of the delta (Schwamborn et al., 2002). This site is characterized by coarse-grained sandy sediments, which were formed from the late Pleistocene to late Holocene (Wagner, 2007). The highest third terrace (30–55 m a.s.l.) was formed during the late Pleistocene and is exposed in the western and fragmentarily in the southern part of the delta (Schirrmeister et al., 2003). The deposits of that terrace consist of so-called ice complex enhanced by peaty and sand accumulations overlying sequences of sandy sediments with a high content of segregated ice (Strauss et. al., 2012). This geomorphological unit is represented by Hardang-Sise Island in the west (TIK04) and Sardakh Island in the south-east (TIK21) of the Lena River Delta. The first terrace including

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active floodplains (1–12 m a.s.l.) has been formed since the early Holocene and covers the main part of the eastern delta sector between the Tumatskaya and the Bykovskaya channels (Schwamborn et al., 2002).

The first terrace is assumed to represent the "active" delta with the study sites on Samoylov Island (72°22′ N, 126°31′ E), which have the profile abbreviation prefix PJ. Two dominating geomorphologic processes can be observed on the island. The western part of Samoylov Island represents the middle floodplain (MF) and encompasses sediments that consist of mostly fine to medium sand and silt fractions. Frequent changes of the river water level create different periods of sedimentation and result in the formation of stratified soils and sediment layers which are dominated either by mineral substrates with allochthonous organic matter or pure autochthonous peat. In contrast to the accumulative floodplain site, erosion processes dominate on the eastern part of the island and form an abrasion coast. This part is represented by ancient estuarine (river-marine) terrace (AET), which covers about 70 % of the total area of the island (Akhmadeeva et al., 1999). The high flood-plain (HF) fragmentarily is situated between the east coast of the island and the western border of the estuarine terrace above the MF. It could be interpreted as a thermokarst depression of the terrace above the MF, because it is composed by the same layered plant detritus-sand deposits of the ancient delta flood-plain. It is flooded with water only by high tide (Akhmadeeva et al., 1999). The second site Tit-Ary Island (TIK20), which is also in the first terrace of the Lena River delta, is located in the main Lena River channel south-east of Samoylov. This site is remarkable by the fact that it is one of the northernmost places of the tree-limit line in the Russian Arctic (Zubrzycki et al., 2012a). Polygonal tundra is typical for the landscape units represented at the terrace levels on both islands and is characterized by two different forms: polygon centres that are water saturated and feature a large amount of organic matter due to accumulation under anaerobic conditions, and polygon rims that show evidence of cryoturbation in more or less all horizons of the active layer. They show a distinctly deeper water level and lower accumulation of organic matter (Pfeiffer et al., 2002; Fiedler et al., 2004; Kutzbach et al., 2004).

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The investigation sites of the nearby hinterland are located on the slopes of the Chekanovsky Ridge (Fig. 1) on the western side of the Lena River and represent instances of pronounced visible changes in vegetation cover (Zubrzycki et al., 2012a). They represent the southern tundra (TIK05), forest tundra (TIK14) and northern taiga (TIK13) landscape subzones.

The main soil forming processes in these studied landscapes are cryopedogenesis, which include freezing and thawing, frost stirring, mounding, fissuring and solifluction. According to the Soil Taxonomy Classification (Soil Survey Staff, 2010) we described all the soils studied as Gelisols. The soils of the Arga Island (TIK01), Sardakh Island (TIK21) and Tit-Ary Island (TIK20) of the Lena River Delta belong to the Turbel suborder. The soils of the studied site on Hardang-Sise Island (TIK04) and sites of the hinterland TIK05 (73° N), TIK14 (70° N) and TIK13 (69° N) we described as Orthels (Soil Survey Staff, 2010). The studied sites of Samoylov Island belong to both Turbel and Orthel suborders. The soil of studied site PJ2 was described as Fibristel. They represent elevated rims and water-saturated depressed centers of patterned ground landscape structures. According to the Russian classification all soils of the units between 73° and 70° N (TIK14) belong to the Permafrost type (Yelovskaya, 1987; Desyatkin et al., 1991; Pfeiffer et al., 2000). The soil suborder at the southernmost site TIK13 we determined as a Cryogenic soil due to differences in profile composition and soil structure from the other soils types located on slopes of the Chekanovsky Ridge (Yelovskaya, 1987; Zubrzycki et al., 2012a).

3 Methods

The investigation site ID code, sampling location, and a brief landscape description are shown in Table 1. Field work was carried out in August 2009 and September 2010, when the seasonal thaw depth had reached its maximum as given in Table 2. Representative sites for each unit of the study area were chosen and soil samples were taken from each genetic horizon of the thawed layer and stored in plastic bags. All soil types were determined according to both the US Soil Taxonomy (Soil Survey Staff, 2010) and the Russian classification of Yelovskaya (1987) (Table 2). In the field the following soil characteristics were determined: soil type, skeletal proportion, humus content, decomposition stage of organic matter, soil color, texture shape and size, inclusions, bulk density and root penetration. Macro- and micro relief forms, soil orders, anthropogenic changes, and vegetation cover were described as well. The collected samples were analyzed at the Institute of Soil Science (University of Hamburg).

The air-dried samples were sieved at 2 mm and analyzed for soil acidity (pH) in H_2O extract (ratio 1 : 2.5 and 1 : 25 for soils with low and high organic carbon content, respectively; Bassler 1997, DIN ISO 10390, 2005), electrical conductivity (CG 820 Schott Geraete GmbH, Germany; Cond 330i, WTW, Germany, DIN ISO 11265, 1997) and water content (DIN 18121-1, 1998). The homogenized sieved soil samples were ground and analyzed for organic carbon (OC) and nitrogen (N) content (Vario MAX CNS Element Analyser, Germany, DIN ISO 10694), and grain-size composition of the < 2 mm fraction (Sedimat 4–12, UGT, Germany, DIN ISO 11277, 2002). The pedogenic iron and manganese compounds were extracted and fractioned by dithionite- and oxalate solutions (Mehra and Jackson, 1960; DIN 19684-6). To extract oxalate-soluble iron and manganese 100 mL of oxalate solution (17.60 g $(COOH)_2$ + 28.40 g $(COONH_4)_2$ + 1000 mL bidistilled H_2O) was used. Dithionite-soluble iron and manganese were extracted with 50 mL of complex solution A (70.58 g $C_6H_5O_7Na_3$ + 16.80 g $NaHCO_3\,L^{-1}$ + 1000 mL bidistilled H_2O) and 20 mL of complex solution B (12.325 g $MgSO_4$ 7 $H_2O\,L^{-1}$ + 1000 mL bidistilled H_2O). The resulting extracts were measured using the flame AAS Varian AA 280 Series (Germany). The extraction of Fe, Mn, Zn, Cd, Ni, Cu, As, Pb, Co and Hg, using HCl 30 % and HNO_3 60 %, was performed using a microwave method (Mars Xpress, GmbH, Germany, DIN ISO 11466). The total trace metal content of Cd, Ni, Cu, As, Pb, Co was analyzed using the AAS Varian AA 280 Series (Germany) with a graphite tube. The elemental content of Fe, Mn, and Zn was detected by flame AAS Varian AA 280 Series (Germany). The total content of Hg was detected by Flow Injection Mercury System (FIMS), Perkin Elmer AS 90. Results were expressed in $mg\,kg^{-1}$.

We calculated the trace metals concentrations TM_{vol} ($kg\,m^{-3}$) in top and bottom horizons of studied units per area using the formula:

$$TM_{vol} = C \times BD \quad (1)$$

where C is trace metal concentration in the soil genetic horizon ($mg\,kg^{-1}$) and BD is the bulk density.

To carry out the statistical data analyses the SPSS package version 20.0 and the OriginLab package 8.6 was used. The Principal Component Analysis (PCA) as a method to determine general relationships among metal amounts accumulated in horizons of permafrost-affected soils and general soil properties such as organic matter content, texture and other components was applied. Correlation analysis and multiply linear regression analysis were used to give a quantitative estimation of the relationship between trace metal content and general soil properties.

4 Results

4.1 Physical and chemical soil properties

The general physical and chemical soil properties of all study units of the north-south transect are shown in Table 3. The investigation included four sites with Turbel soil suborder and four sites with Orthel suborder. In general, the studied soils of both suborders were characterized by slightly acidic and neutral conditions besides the unit TIK04 represented by Orthels, where the pH reached 7. Moving along the transect from the north to the south, the mean organic carbon content gradually increased reaching the maxima at the site TIK05 with Orthel soil suborder. The minimum concentration was found at the second terrace represented by Arga Island (TIK01). The grain-size composition for the Turbel suborder sites within the first, the second and the third terraces

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of the Lena River Delta comprised mainly fine-grained sand fractions. The maximum sand fraction was found on TIK01. The third terrace (TIK21) showed the smallest fine-grained sand fraction content but significant silt fraction content. The unit TIK13 was similar in terms of texture composition to the TIK21 study site, as both consist primarily of the silt fraction.

Detailed results of the distribution of standard soil parameters with depth for each studied site on Samoylov Island are presented in Table 4. The studied soil profiles of polygonal rims and polygonal centers had mainly slightly acid environmental reaction in contrast to the study site PJ5 located in the MF. The pH there was determined as slightly alkaline. The smallest contents of organic matter were observed in alluvial soils of PJ5, whereas the polygon centers (PJ2 and PJ4) were enriched by organic matter. The dominant fraction of almost all studied profiles was fine-grained sand. The maximum total sand content (96.8 %) was on the site located on the MF (PJ5). The polygon rim PJ1 of AET was of exceptional interest because the processes of cryoturbation were clearly pronounced. The mean contents of clay and silt material within the soil profile were higher relative to the other study sites. At all study sites, the nitrogen content distribution correlated well with total carbon content ($r = 0.94$, $p < 0.01$).

4.2 Trace elements in soils

The measured trace metal contents are shown in Table 5. The unit TIK01 differs from the other studied sites in its low values of all trace metals with the exception of Mn and Co. The means comparisons test revealed a significant difference in total Ni content between TIK01 and TIK04, TIK20, TIK21, and TIK13, respectively (one-way ANOVA $p < 0.05$). Significant differences in total Zn content were observed between the units TIK01 and TIK04, TIK01 and TIK20, and TIK01 and TIK13 (one-way ANOVA $p < 0.05$). Total average content of Mn was significantly less for the unit TIK01 in comparison with TIK04, TIK20 and TIK21 (one-way ANOVA $p < 0.05$), though all three were characterized by higher Mn concentrations in comparison with other studied sites. All the other units were characterized by similar range of total Fe, Co, Cd, Cu and Hg contents.

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The highest mean concentrations of Zn were found in TIK04, TIK20 and TIK13 sites. Significant differences in total Zn content were revealed between the units TIK04 and TIK05, and TIK13 and TIK14 (one-way ANOVA, $p < 0.05$). The units TIK04 and TIK13 had higher average concentrations of Ni. The mean total amount of As was higher (not significantly) in unit TIK20 than in other units of the transect. The means comparisons test showed the significant difference in total As content between TIK20 and TIK01.

In order to detect a clearer vision of the landscape distribution of trace metals within the north-south transect, we calculated the trace metal concentration per soil volume in the top and bottom soil horizons. The volumetric trace metal contents are shown in Fig. 2. Cd and Hg contents have not been plotted because very low amounts of these elements were detected. Figure 2 shows that the bottom soil horizons contain significantly higher amounts of all measured trace elements in contrast to the top soils (ANOVA one-way, $p < 0.05$). The metal contents of Fe, Mn, Zn, Ni and Co dominated relative to the other metals in both top and bottom horizons of studied units TIK04, TIK21 and TIK20 of the Lena River Delta. The bottom horizon of TIK13 site accumulated higher amounts of Zn, Cu and Pb. The minimal content of Fe, Mn, Zn, Co and As was observed in studied site TIK05.

The mean concentrations of trace elements on Samoylov Island are also presented in Table 5. The total Pb and Hg amounts were comparable to the ones determined at the TIK20 site which is also within the first terrace. The mean contents of total Co were higher in contrast to the TIK20 site, whereas the concentrations of total Ni, As, Fe, Zn and Cu were lower. The mean concentrations of total Cd were comparable with TIK20 of the first Lena River Delta terrace. The amounts of total Mn were just slightly higher the studied site TIK20. However, the high standard deviation of Mn content results from extremely high amounts of this element (with the values of 1200–1400 $mg\,kg^{-1}$) in the bottom soil horizons of studied sites PJ1 and PJ3.

The vertical distribution of total Cu for the Samoylov Island sites PJ1–PJ5 is presented in Fig. 3a. The maximum contents (12.0 and 14.0 $mg\,kg^{-1}$, respectively) were detected in top horizons of soil profiles located on both polygon centers of the first terrace (PJ2) and high floodplain (PJ4) with higher influence of the flooding by the Lena River. The minimum Cu concentrations (1.02 $mg\,kg^{-1}$) we observed in alluvial soils of the middle floodplain (PJ5). Significant positive correlation was found between Cu and organic matter content ($r = 0.86$, $p < 0.05$) (Fig. 3b).

The total Fe content in site PJ1, in contrast to the others, was unequally distributed within the soil profile due to well-developed cryoturbation processes. The ratio of different fractions of Fe-oxides was calculated to estimate the degree of pedogenesis of the soil horizons of the relatively young floodplain (MF) and the first terrace (AET). In Fig. 4 the ratio between so called "active" Fe-oxide Fe_o and well crystallized forms of Fe-oxides (Fe_d-fraction) is shown (Zubrzycki et al., 2008). This ratio was higher in the bottom part of both profiles and it varied from 0.30 to 0.61 within the profile PJ5 of MF and from 0.33 to 0.85 within the profile PJ1 of the AET. The highest Pearson's positive correlation was found between the Fe_d iron-oxide form and total As content ($r = 0.91$, $p < 0.05$).

Figure 5a shows the vertical distribution of total Ni in soil profiles PJ1–PJ5. The amounts of Ni in all studied units slightly increased in bottom horizons close to the permafrost table. The maximum Ni concentration (32.6 $mg\,kg^{-1}$) was observed in bottom silt-sized horizon of MF PJ5. The smallest concentration of Ni (11.2 $mg\,kg^{-1}$) was found in upper sandy horizon of the polygon rim PJ1. In Fig. 5b the strong positive correlation between total Ni amount and the clay fraction in the profiles from Samoylov Island is shown ($r = 0.54$, $p < 0.05$).

Generally, the correlation analysis between trace metals and general soil characteristics showed differences in their distribution between the top and bottom horizons of all studied units. To reveal the relationship between the parameters as well as to cluster variables into groups, the statistical multivariate method PCA (Principal Component Analysis) was applied. The analysis revealed that four principal components for the top soil horizons and three principal components for the bottom soil horizons together contribute to 87.43 % and to 83.04 % of the explained variance, respectively. The eigenvalues and percentages of explained variance to the total variance for the principal components are presented in Table 6. Figure 6 shows the plot of the first and the second principal component resulting from the set of 12 general soil parameters data (variables) and the total metal content of 13 top soil samples (Corg, Fe, Fe_o, Mn, Mn_o, Cd, Cu, Zn, As, Pb, Ni, Co) and 13 bottom samples (Corg, sand, clay, Cd, Cu, Zn, As, Pb, Ni, Fe, Mn, Co), respectively. The factor pattern of the correlation coefficients between the variables and the extracted principal components for the top and bottom soil horizons are shown in Table 7. For the first principal component strong positive correlation coefficients were given to Fe, Pb, Mn, Ni and As for the top soil horizons and to Fe, Zn, Ni and Clay for the bottom soil horizons. For the second principal component strong correlation coefficients, positive and negative, were given to Cu and Fe_o for the top soil horizons and to Cu, C_{org} and Sand for the bottom soil horizons, respectively.

To estimate quantitatively the relations between the trace element contents and general soil characteristics in the top and bottom horizons of the studied sites we applied correlation analysis. As shown in Fig. 6a the Fe-oxide content correlated to the Zn, As, Pb and Ni distribution in studied units TIK04, TIK21 and less in PJ4 and PJ2 studied sites. Significant positive correlations Fe_o–Cu ($r = 0.60$, $p < 0.05$) and Fe_d–Zn ($r = 0.58$, $p < 0.05$) were found. The total Cd content in sites TIK05 and TIK14 was correlated with organic matter content ($r = 0.68$, $p < 0.05$). In bottom horizons the main factors determining the distribution of trace metals were the clay content together with concentrations of Fe- and Mn-oxides (Fig. 6b). The elements Fe and Zn had a strong relationship with the clay fraction for the sites TIK04, TIK20, TIK21 and PJ5. The metals Zn, As, Ni and Pb were bound by Fe-oxides. A significant correlation between Mn-oxide (Mn_d) and Co was found ($r = 0.64$, $p < 0.05$). The occurrence of organic matter in bottom horizons of TIK05 and TIK14 was more significant factor in Cu distribution then the texture and the presence of Fe-oxides. Selected significant Pearson's correlation coefficients between components in the top and bottom horizons are presented in Table 8.

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5 Discussion

The trace metal concentrations found in the investigation area of the Lena River Delta can now be compared with common values of elemental concentrations in the lithosphere. The trace element crustal abundances given by Taylor (1964) and Vinogradov (1957) and total heavy metal content in world soils given by Bowen (1966), shown in Table 9. According to Taylor (1964), the global-scale crystal abundance of Zn, Cd, Cu and Ni account for 83 $mg\,kg^{-1}$, 0.13 $mg\,kg^{-1}$, 47 $mg\,kg^{-1}$ and 58 $mg\,kg^{-1}$, respectively. The concentrations of these elements at the investigated sites were lower: $46 \pm 20\,mg\,kg^{-1}$ of Zn, $0.04 \pm 0.04\,mg\,kg^{-1}$ of Cd, $9.2 \pm 8.3\,mg\,kg^{-1}$ of Cu and $19 \pm 7.1\,mg\,kg^{-1}$ of Ni. The sites showed higher mean concentrations of As ($4.1 \pm 2.3\,mg\,kg^{-1}$) and Hg ($0.02 \pm 0.01\,mg\,kg^{-1}$) compared to the crustal abundance of these elements (Vinogradov, 1957). The average contents of Zn, Pb and Cu in the continental part of the investigated transect were higher than in the Deltaic part. Reading the geochemical map of Russia (Geological Atlas of Russia, Saint Petersburg, 1996) it was found that the western side's valley belt along the Lena River located between 72° and 67° N belongs to so-called litho-chalcohile structural-formational complex (including the elements Pb, Zn, Cu, Hg and As) with element accumulation coefficients in the range 2.5–5. These interpretations support a geological origin for these elements.

The mechanisms of leaching and migration in soils differ for different trace metals (Niskavaara, et al., 1997). It has previously been shown that the transport of Cu to deeper soil layers mostly takes place bound to organic substances, whereas Ni and some other elements as Zn, Cd, Pb etc., are generally transported as acid-mobilized, easily leachable compounds (Borg et.al, 1989; Niskavaara, et al., 1997). Copper levels found at our study sites ($9.2 \pm 8.3\,mg\,kg^{-1}$) were similar to the total heavy metal content in uncontaminated world soils with values of Cu for sandy material of 15 $mg\,kg^{-1}$ (Alekseev, 1987). Results from the transect were also in a similar range with the data of Cu in uncontaminated wetlands represented by polygonal bog peat on Severnaya Zemlya Archipelago, the Taymyr Peninsula (Russia), where the concentration of this

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element ranged from 1.7 to 63 mg kg^{-1} (Zhulidov et al., 1997a). In surface soil horizons, Ni appears to occur mainly in organically bound forms, a part of which may be easily soluble chelates The concentration of Ni in surface soils generally reflects soil-forming processes and also pollution (Kabata-Pendias, 2001) We found that the observed values of Ni (18.6 ± 7.1 mg kg^{-1}) reflected natural geochemical background levels (Taylor, 1964; Vinogradov, 1957) as well as the average concentration of Ni in world soils, (Bowen, 1979) and approximate permissible level of Ni content in sandy and sandy loam soils (Isaev, 1998), which both amount to 20 mg kg^{-1}. Concentrations of Pb (6.9 ± 4.4 mg kg^{-1}), Zn and Cd in soils collected in the investigated sites were in good agreement with the values given by Zhulidov et al. (1997a) for the north-east Siberia tundra zone including types of hydromorphic soils and sedge-moss peat sites. Our measurements of these elements were also less than the heavy metal concentrations determined for the world soils (Bowen, 1979; Saet et al., 1990).

In previous investigations several potential local sources of atmospheric pollution in the River Lena Delta have been detected (Rovinsky et al., 1995). The largest of these are the settlements Tiksi (71°42′55.57″ N, 128°48′46.32″ E) and Kyusyur (70°45′41.71″ N, 127°23′04.71″ E) (Fig. 1). The published average concentrations of trace metals (i.e. Zn, Cu, Ni, Pb and Cd) in the first 10 cm of Tundra Gleysols were considerably lower than background values in the Russian territory published in the Review of the Background State of the Environment in the Territory of the USSR in 1990 (Rovinsky et. al., 1995). The authors suggested that at the investigation area of the Lena River Delta no evident anthropogenic influence is observable, however, there is a risk of an increase of air pollution due to long-range atmospheric transport. Our results obtained for the pilot study site in northern Siberia corresponds to the data published by Rovinsky et al. (1995).

We compared our results with the data obtained for contaminated wetlands of the Russian Arctic provided by Zhulidov et al. (1997b). Thus, the concentrations of Cd (0.04 ± 0.04 mg kg^{-1}), Pb (6.9 ± 4.4 mg kg^{-1}), Zn (46.5 ± 20.4 mg kg^{-1}) and Cu (9.2 ± 8.3 mg kg^{-1}) on the sites of our pilot study area were significantly

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lower than on the polygonal bog peat of the Polar-Ural area (53.0 ± 32.0 $mg\,kg^{-1}$ to Cd, 81.0 ± 59.0 $mg\,kg^{-1}$ to Pb, 520 ± 240 $mg\,kg^{-1}$ to Zn and 440 ± 252 $mg\,kg^{-1}$ to Cu) and the west Siberia tundra zone where the concentrations reached values 8.0 ± 5.0 $mg\,kg^{-1}$ for Cd, 51.0 ± 21.0 $mg\,kg^{-1}$ for Pb, 295 ± 130 for Zn and 80.0 ± 51.0 $mg\,kg^{-1}$ for Cu. Thus, we suggest that the trace metal concentration values found at our study sites in the Lena River Delta are close to natural background concentrations.

We have found for the Samoylov Island's profiles that the parameters of organic carbon, grain-size composition and oxide contents control the trace metal distribution within the depth of soil profile. The common characteristic of the Cu distribution in soil profiles is the accumulation in the top soil horizons (Kabata-Pendias, 2001). This phenomenon results from various factors, but above all, Cu concentration in surface soils could reflect the bio-accumulation of the metal and also recent anthropogenic sources of the element (Kabata-Pendias, 2001). The Cu distribution within the soil profile PJ5 of the middle floodplain differed from the other studied sites on Samoylov Island increasing from the top to the bottom layers. It is assumed that such a distribution of copper within the profile is due to annual flooding which leads to burial of plant material and development of wet conditions in the bottom layers of the studied area. The linear regression analysis of Cu and organic carbon content showed a significant positive relation between these values ($R^2 = 0.73$, confidence interval = 0.95, Fig. 3b).

The amount and distribution of iron oxides in soils are known to influence soil properties such as anion adsorption, surface charges, specific surface area, aggregate formation, nutrient transformation and pollutants retention in soils (Deshpande et al., 1968). The higher values of the Fe-oxide ratio in the bottom part of the investigated profiles on Samoylov Island are related to less pronounced processes of pedogenesis due to their anoxic conditions (Fig. 4). The correlation analysis showed that the trace metal distribution within the profiles of Samoylov Island in many respects depends on the presence of iron oxides. We found a significant positive correlation between the elements As–Fe_o ($r = 0.84$, $p < 0.01$), Ni–Fe_o ($r = 0.53$, $p < 0.01$), Zn–Fe_o ($r = 0.49$, $p < 0.05$), Mn–Fe_d ($r = 0.50$, $p < 0.01$) and Cd–Fe_d ($r = 0.46$, $p < 0.05$). Korobova et al. (2003) suggest that redox-sensitive iron mobilized in swamps and concentrating in the unfrozen layers of permafrost-affected soils (Boike et al., 1999; Fiedler et al., 2004) could be discharged with water under pressure during freezing and thawing processes to form Fe-rich streams. Later, these processes could cause the mobilization of other elements and their further migration and accumulation within the thawing depth of soil profile.

According to Isaev (2004), accumulation and redistribution of trace elements within the soil profile can be related to the parent rock composition. For example, the Ni presence in soils highly depends on its content in the parent rock. Ni distribution in soil profiles is related either to organic matter or to amorphous oxides and clay fractions, depending on soil types (Kabata-Pendias, 2001). The linear regression analysis showed a significant positive relation between Ni content and grain-size composition for all studied sites on Samoylov Island, particularly with clay and silt fractions ($R^2 = 0.8$, confidence interval = 0.95) (Fig. 5b).

The majority of investigated sites were characterized by an increase of Zn, Pb and Ni content above the permafrost table on an adsorbing gleyic layer. The similar trend for the distribution of these elements was observed for permafrost-affected soils of tundra landscapes in the Yenisei River Delta (Korobova et al., 2003). This similarity supports the suggestion that the presence of the permafrost table could cause this increase by acting as a physical barrier to further trace metal dislocation within the profile.

The correlation analysis between element concentrations, grain-size composition, Fe-oxide and organic carbon content revealed a strong relationship between all these components for all investigated soil profiles. The PCA analysis showed that the main role in the distribution of trace metals in top horizons was the organic matter content and Fe-oxides. In the bottom horizons, besides the factors mentioned above, the texture of soils played a significant role in trace metal binding. As distinct from the bottom horizons, we did not find a significant correlation between organic matter content and

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total Cu content in top horizons. This difference may be caused by Cu's stronger tendency, relative to other metals, to form associations with oxygen forms (Evans, 1989).

6 Conclusions

The first measurements of trace metal concentrations in permafrost-affected soils of fluvial landscapes of the Lena River Delta in northeastern Siberia generally showed a high scatter in lateral element distribution as well as its vertical distribution within the profiles. The distribution of trace elements depended on the soil type of investigated profiles. Thus, the investigation sites of the first and the third terrace of the Lena River Delta together with one unit located in the hinterland (TIK13) were characterized by similar amounts of most trace metals. The higher mean content of total Cu and Cd was found in Orthels (Soil Survey Staff, 2010) of site TIK05. The northernmost unit (TIK01) of the transect was characterized by low values of all measured trace metals. Our calculations of volumetric trace metal content showed that the highest accumulation of most of the measured elements was observed in the bottom soil horizons belonging to the so-called third terrace of the Lena River Delta and in the hinterland unit TIK13. Such a distribution of the elements reflects geomorphological features of the investigated area located in both the deltaic part and the hinterland.

We have also revealed that microrelief features can influence element distribution in natural permafrost-affected soils. Thus, comparison of the polygonal rims and centers in ancient estuarine terrace (AET) and high flood-plain (HF) on Samoylov Island showed that values of trace metals were higher in polygon centers characterized by accumulation of organic matter and more moist environments. Higher concentrations of some elements (e.g. Pb, Ni and Zn) were detected in most soil profiles in the deeper soil zones than in the top soil. That supported our suggestion that the permafrost table, acting as a geochemical barrier, retarded further migration of elements into deeper horizons.

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To check the hypothesis that sediment supply by the Lena River could be the source of trace metals input into the delta, we compared the sediments from the relatively young so called middle floodplain (MF) with the soils formed on the first terrace (AET). Higher concentrations of most of the metals were observed in the soil profile PJ5 at the middle flood-plain (MF) compared to the other sites. This profile differed from the profiles representing the more ancient parts of the island. Its soils were described as Typic Aquorthels (Soil Survey Staff, 2010) containing mostly sandy material on the upper part and silty material on the bottom part of the profile. These soils had a more alkaline environmental reaction compared to the soils of the first terrace. This finding suggested that apart from the parent material, the second potential source of trace metals at the middle flood-plain could be allochthonous substance input during annual flooding.

We found that generally such factors as organic carbon content, texture and iron oxides play a significant role in vertical distribution of trace metals within the studied profiles. Our study showed that a strong positive correlation exists between the trace metal content and these parameters.

We assume that changes of environmental conditions such as temperature and precipitation will lead to changes in processes of soil formation. The additional overlap of anthropogenic impacts could cause more intensive leaching of the elements in soils and their further migration to other components of the environment being passed through trophic levels (Presley, 1997). It could also cause changes in soil properties which reduce its barrier function. It is obvious that effects from human activity in some regions are located in close vicinity to contamination sources (Zhulidov et al., 1997b; Ziganshin et al., 2011; Jaffe et al., 1995) as well as remote from them (Thomas, 1992). Our research showed that the concentrations of all the investigated metals are similar to those reported for world soils (Bowen, 1979), uncontaminated soils (Isaev, 2000; Alekseev, 1987) and unpolluted arctic regions (Zhulidov et al., 1997a), indicating that the studied area is pristine from this perspective, however we cannot leave out the fact that pollution of Arctic ecosystems occurs to be due to long-range transport (Rahn

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et. al., 1997). The studied area in northern Siberia can serve as a reference region for determining human influences on permafrost-affected landscapes or comparing similar pristine areas in the Arctic region. However, the existing dataset needs to be expanded. The processes of deposition, accumulation, leaching, translocation and transformation of trace metals in permafrost-affected soils need to be studied in greater detail in order to estimate possible risks from both factors (climate change and anthropogenic pollution) on arctic ecosystems.

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Table 1. General field information of investigation sites.

Sites ID	Sampling location	Landscapes description
North-south transect 2009		
TIK01	73°10′26.29″ N 124°34′29.80″ E	2nd terrace, typical moss/lichen tundra Dominant species: *Carex spec., Cassiope tetragona, Luzula sp., Cladonia sp., Thamnolia vermicularis, Hyloconmium sp.*
TIK04	72°48′31.31″ N 124°54′43.89″ E	3rd terrace, sedge/moss tundra Dominant species: *Carex aquatilis, Poa arctica, Eriophorum medium, Salix sp,, Luzula sp., Saussurea sp.*
TIK21	72°34′24.04″ N 127°14′14.73″ E	3rd terrace, typical polygonal sedge/moss tundra Dominant species: *Carex sp., Poaceae sp., Dryas punctata, Hyloconmium sp.*
TIK20	71°59′11.55″ N 127°02′35.29″ E	1st terrace, forest herbs/lichen/moss tundra Dominant species: *Ledum palustre, Betula nana, Carex sp., Eriophorum medium., Luzula sp., Pedicularis sp., Hyloconmium sp., Aulacomnium sp.*
TIK05	71°10′26.29″ N 124°34′29.80″ E	Hinterland, slope of Chekanovsky Ridge, herbs/moss southern tundra Dominant species: *Betula nana L., Ledum palustre L., Cassiopea tetragona, Vaccinium vitis-idaea L., Polygonum viviparum, Hyloconmium sp.*
TIK14	70°55′22.76″ N 125°33′3.13″ E	Hinterland, slope of Chekanovsky Ridge, shrub/moss forest tundra Dominant species: *Betula nana L., Ledum palustre L., Eriophorum medium*
TIK13	69°23′56.83″ N 123°49′33.96″ E	Hinterland, slope of Chekanovsky Ridge, Larix/shrub/moss northern taiga Dominant species: *Larix Sibirica, Betula nana, Alnus crispa, Salix sp., Empetrum nigrum, Ledum palustre, Hyloconmium splendens*
Samoylov Island 2010		
PJ1	72°22′17.66″ N 126°29′11.66″ E	1st terrace, elevated herbs/lichen/moss polygon rim Dominant species: *Dryas octopetala L., Salix glauca L, Stereocaulon alpinum, Thamnolia vermicularis, Dactylina arctica, Hylocomnium sp, Aulacomnium sp.*
PJ2	72°22′17.66″ N, 126°29′11.66″ E	1st terrace, sedge/moss polygon center Dominant species: *Cares aquatilis, Eriophorum medium, Hylocomnium sp.*
PJ3	72°22′19.46″ N, 126°28′42.74″ E	High floodplain, poorly defined herbs/moss polygon rim Dominant species: *Salix sp., Arctagrostis arctostaphulos, Aulacomnium sp.*
PJ4	72°22′19.55″ N, 126°28′41.77″ E	High floodplain, sedge/moss polygon center Dominant species: *Carex sp., Arctagrostis arctostaphulos, Aulacomnium sp.*
PJ5	72°22′51.61″ N, 126°28′28.37″ E	Middle floodplain, srub/sedge cover Dominant species: *Dischampsia Caespitosa, Arctophila fulva, Salix sp.*

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Table 2. Soil classification of investigation sites according to Soil Survey Staff (2010) and to Russian soil classification (Yelovskaya, 1987).

Sites ID	Thaw depth, cm	Soil Survey Staff (2010)	Russian Soil Classification (Yelovskaya, 1987)
North-south transect 2009			
TIK01	57.0	Typic Psammoturbel	Permafrost Alluvial Turfy Typical
TIK04	39.0	Folistic Haplorthel	Permafrost Turfness-Gley Typical
TIK21	24.0	Typic Aquorthel	Permafrost Silty-Peat-Gley
TIK20	30.0	Typic Aquiturbel	Permafrost Peatish-Gley Typical
TIK05	26.5 ± 3.5	Ruptic Historthel	Permafrost Peat
TIK14	39.0	Typic Aquorthel	Permafrost Silty-Peat-Gley
TIK13	49.0	Typic Haplorthel	Cryogenic Soil
Samoylov Island 2010			
PJ1	61.0	Typic Aquiturbel	Permafrost Turfness-Gley Typical
PJ2	40.0	Typic Fibristel	Permafrost Peat
PJ3	40.0	Typic Histoturbel	Permafrost Peatish-Gley
PJ4	50.0	Typic Histothel	Permafrost Peat-Gley
PJ5	91.0	Typic Aquorthel	Permafrost Alluvial Turfness Typical

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Table 3. The mean values of standard soil characteristics of the studied units along the transect (Zubrzycki et al., 2012a).

Sites ID	pH	Texture (%) Clay	Silt	Sand	C (%)	N (%)	C/N ratio
North-south transect 2009							
TIK01 ($n = 4$[a]) t[b]	5.2 ± 0.5	3.8 ± 1.4	6.5 ± 6.3	90 ± 7.2	1.4 ± 1.4	0.08 ± 0.08	15 ± 3.1
TIK04 ($n = 2$) o	7.0 ± 0.6	20	75	4.7	5.4 ± 4.2	0.38 ± 0.26	14 ± 1.5
TIK21 ($n = 2$) t	4.8 ± 0.2	21	65	14	5.4 ± 4.1	0.32 ± 0.25	17 ± 3.9
TIK20 ($n = 3$) t	5.1 ± 0.3	24 ± 3.2	45 ± 1.7	31 ± 5.0	3.8 ± 3.7	0.20 ± 0.15	17 ± 0.1
TIK05 ($n = 5$) o	4.2 ± 0.4	n.d.[c]	n.d.	n.d.	40 ± 4.9	1.88 ± 0.25	22 ± 3.5
TIK14 ($n = 5$) o	4.4 ± 0.6	11 ± 1.8	31 ± 2.4	58 ± 4.2	11 ± 16	0.41 ± 0.39	21 ± 8.8
TIK13 ($n = 3$) o	5.3 ± 1.1	22 ± 1.2	63 ± 0.93	16 ± 2.1	7.4 ± 8.9	0.27 ± 0.28	24 ± 5.8

[a] n – number of the measurements, [b] t – Turbel soil suborder, o – Orthel soil suborder. [c] – not determined.

Table 4. Vertical distribution of pH, grain-size composition, carbon and nitrogen content in studied sites on Samoylov Island.

Horizon index[a]	Depth cm	pH	Fraction	Texture (%) Clay	Silt	Sand	C (%)	N (%)	C/N ratio
AET. PJ 1 Polygon rim (72°22′17.66″ N, 126°29′11.66″ E)									
Ajj1	0–3	5.64	n.d.[b]	n.d.	n.d.	n.d.	4.12	0.20	20.56
Ajj2	–13	5.79	silty sand	3.69	27.5	68.8	2.28	0.16	14.58
Bjjg1	–16	5.10	sandy silt	6.80	52.2	41.0	3.95	0.26	15.05
Bjjg2	–24	5.20	silty sand	6.62	27.9	65.5	1.87	0.12	15.37
Bjjg3	–44	6.58	loamy sand	5.03	21.8	73.2	0.91	0.07	12.75
Bjjg4	–61	5.63	silty sand	8.74	43.9	47.4	3.31	0.20	16.77
AET. PJ2 Polygon center (72°22′17.66″ N, 126°29′11.66″ E)									
Oi	0–10	5.51	n.d.	n.d.	n.d.	n.d.	11.6	0.423	27.56
Oie	–18	5.46	n.d.	n.d.	n.d.	n.d.	9.46	0.274	34.55
Oe1	–30	5.37	n.d.	n.d.	n.d.	n.d.	5.92	0.174	33.95
Oe2	–40	5.51	n.d.	n.d.	n.d.	n.d.	7.31	0.214	34.14
HF. PJ3 Polygon rim (72°22′19.46″ N, 126°28′42.74″ E)									
Oi	0–7	6.05	n.d.	n.d.	n.d.	n.d.	11.3	0.34	33.50
Ajj1	–13	6.10	loamy sand	3.47	19.2	77.3	2.48	0.14	18.43
Ajj2	–29	6.87	loamy sand	4.24	24.0	71.8	1.31	0.10	13.44
Bjjg1	–35	6.50	sand	1.69	4.77	93.6	0.30	0.03	10.42
Bjjg2	–40	5.60	silty sand	6.22	27.2	66.5	1.25	0.10	12.91
HF. PJ4 Polygon center (72°22′19.55″ N, 126°28′41.77″ E)									
Oi	0–10	6.22	n.d.	n.d.	n.d.	n.d.	15.9	0.44	35.98
Oe	–22	5.75	n.d.	n.d.	n.d.	n.d.	12.3	0.49	25.31
Bjjg1	–31	5.87	loamy sand	3.55	13.0	83.5	1.15	0.07	15.75
Bjjg2	–50	5.97	silty sand	4.90	27.0	68.1	1.12	0.08	14.21
MF. PJ5 (72°22′51.61″ N, 126°28′28.37″ E)									
Ajj	0–8	7.07	silty sand	5.02	26.3	68.8	1.12	0.09	12.86
B(jj)g1	–24	7.16	sand	2.06	1.96	96.0	0.37	0.03	12.47
B(jj)g2	–29	7.22	loamy sand	3.43	9.43	87.1	0.85	0.06	13.83
B(jj)g3	–33	7.17	sand	4.47	10.5	85.1	4.01	0.18	22.23
B(jj)g3	–37	7.18	sand	3.53	10.0	86.5	1.75	0.10	18.01
B(jj)g4	–55	7.36	loamy silt	10.1	60.2	29.7	2.87	0.19	15.03
Bjjg4	–76	7.33	loamy silt	9.65	56.3	34.1	3.32	0.22	15.41

[a] According Soil Survey Staff (2010), [b] not determined.

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Table 5. Mean values of the trace metals and standard deviations (STD) determined in the soils of investigated units in northern Siberia (mg kg^{-1}).

Metal	Cd	Pb	Ni	Cu	As	Fe	Mn	Zn	Co	Hg
TIK01 (location: 73°10′26.29″ N, 124°34′29.80″ E) $n = 4$[a]										
Mean	0.02	2.7	6.3	2.4	1.3	6500	161	15.2	17.4	0.007
STD	0.01	0.72	2.46	3.01	0.06	1140	18	5.82	7.44	0.003
TIK04 (location: 72°48′31.31″ N, 124°54′43.89″ E) $n = 2$										
Mean	0.05	9.5	30	13	5.9	39000	605	73	20	0.01
STD	0.02	0.14	3.9	5.2	1.2	7200	30	4.3	1.3	0.004
TIK21 (location: 72°34′24.04″ N, 127°14′14.73″ E) $n = 2$										
Mean	0.003	8.5	24	9.5	4.9	29000	559	55	24	0.02
STD	0.001	1.1	0.79	2.0	0.24	9500	229	3.4	3.8	0.001
TIK20 (location: 71°59′11.55″ N, 127°02′35.29″ E) $n = 3$										
Mean	0.02	8.5	27	14	9.4	39000	237	69	25	0.02
STD	0.03	1.7	5.6	12	3.9	14000	64	7.1	2.8	0.01
TIK05 (location: 71°10′26.29″ N, 124°34′29.80″ E) $n = 5$										
Mean	0.07	5.5	16	24	2.9	15000	30	19	14	0.01
STD	0.03	4.1	6.0	14	0.84	4900	27	5.6	3.2	0.004
TIK14 (location: 70°55′22.76″ N, 125°33′3.13″ E) $n = 5$										
Mean	0.13	5.0	14	6.6	4.9	24000	123	41	14	0.02
STD	0.16	1.5	6.1	4.3	2.0	18000	63	19	5.0	0.02
TIK13 (location: 69°23′56.83″ N, 123°49′33.96″ E) $n = 3$										
Mean	0.18	12	23	19	4.3	39000	289	77	21	0.01
STD	n.d.[b]	1.8	5.9	3.0	0.9	12000	76	3.7	2.0	0.01
Samoylov Island. AET. PJ 1 Polygonal rim (location: 72°22′17.66″ N, 126°29′11.66″ E) $n = 6$										
Mean	0.05	6.4	19	5.0	4.0	23000	464	54	64	0.02
STD	0.02	1.1	5.1	1.8	3.0	9200	367	8.6	41	0.01
Samoylov Island . AET. PJ2 Center of polygon (location: 72°22′17.66″ N, 126°29′11.66″ E) $n = 4$										
Mean	0.04	13	20	11	3.4	19000	249	48	49	0.01
STD	0.01	12	3.2	0.93	0.28	1900	158	10	24	0.01
Samoylov Island. HF. PJ3 Rim of polygon (location: 72°22′19.46″ N, 126°28′42.74″ E) $n = 5$										
Mean	0.03	4.6	17	4.3	3.0	15000	517	38	39	0.01
STD	0.01	0.82	3.4	2.8	0.61	2900	512	9.7	14	0.01
Samoylov Island. HF. PJ4 Center of polygon (location: 72°22′19.55″ N, 126°28′41.77″ E) $n = 4$										
Mean	0.04	5.3	18	8.1	2.9	16 000	323	40	45	0.01
STD	0.03	1.1	4.9	5.6	0.80	3390	228	11	18	0.004
Samoylov Island. MF. PJ5 (location: 72°22′51.61″ N, 126°28′28.37″ E) $n = 8$										
Mean	0.05	7.0	21	4.8	4.9	26000	330	56	89	0.03
STD	0.03	2.2	7.0	3.4	1.3	7500	103	18	20	0.01

[a] Number of the measurements, [b] not determined.

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Table 6. Eigenvalues and percentage of variance to the total variance for extracted principal components.

Principal components	Eigenvalue	Percentage of Variance	Cumulative percentage
Top soils			
PC1	5.128	42.73	42.73
PC2	2.517	20.98	63.71
PC3	1.790	14.92	78.63
PC4	1.056	8.80	87.43
Bottom soils			
PC1	4.999	41.67	41.67
PC2	3.163	26.36	68.02
PC3	1.802	15.01	83.04

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Table 7. Factor loading matrix for the first four (top soil horizons) and the first three (bottom soil horizons) principal components.

Variable	PC1	PC2	PC3	PC4
Top soils				
Fe	0.38	0.16	0.017	−0.28
Pb	0.38	0.21	0.15	−0.07
Mn	0.37	−0.10	−0.10	0.42
Ni	0.37	0.19	−0.21	0.01
As	0.35	0.22	0.18	−0.19
Mn_o	0.33	−0.12	−0.19	0.53
Corg	−0.30	0.35	0.07	0.23
Zn	0.23	0.10	0.60	0.09
Cd	−0.20	0.21	0.56	0.19
Fe_o	−0.12	0.43	−0.40	−0.09
Co	0.12	−0.39	0.07	−0.54
Cu	0.02	0.56	−0.13	−0.16
Bottom soils				
Fe	0.42	0.10	−0.15	–
Zn	0.42	−0.06	0.10	–
Ni	0.39	0.17	0.24	–
Clay	0.38	−0.07	−0.23	–
Pb	0.30	0.32	0.10	–
Mn	0.31	−0.24	0.07	–
As	0.28	0.12	−0.27	–
Corg	−0.21	0.44	0.07	–
Sand	−0.13	−0.47	0.05	–
Co	0.12	−0.30	0.55	–
Cu	−0.08	0.51	0.11	–
Cd	0.01	0.12	0.67	–

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Table 8. Selected significant Pearson's correlation coefficients (r) between trace elements contents and general soil characteristics in top and bottom horizons of studied sites ($p < 0.05$).

Components	r	Components	r	Components	r	Components	r
Top soils ($n = 13$)							
Corg-Cd	0.68	Corg-Fe_o	0.58	Corg-pH	−0.73	Corg-Mn	−0.52
Mn-Ni	0.69	Mn-Pb	0.64	Mn-Fe	0.58	Mn-pH	−0.52
Fe-Pb	0.86	Fe-As	0.82	Fe-Ni	0.73	–	–
As-Pb	0.77	As-Ni	0.66	As-Zn	0.62	–	–
Ni-Pb	0.70	Ni-pH	0.59	–	–	–	–
Pb-Zn	0.63	–	–	–	–	–	–
Fe_o-Cu	0.60	–	–	–	–	–	–
Bottom soils ($n = 13$)							
Corg-Cu	0.80	Corg-pH	−0.61	Corg-Mn	−0.58	Corg-Zn	−0.52
Clay-Fe	0.84	Clay-Zn	0.75	Clay-Mn	0.66	Clay-Ni	0.61
Mn-Zn	0.66	Mn-pH	0.65	Mn-Fe	0.50	Mn-Ni	0.48
Fe-Zn	0.83	Fe-Ni	0.79	Fe-As	0.76	Fe-Pb	0.70
Ni-Zn	0.88	Ni-Pb	0.73	Ni-Hg	0.66	–	–
As-Ni	0.48	As-Zn	0.48	–	–	–	–
Pb-Zn	0.54	–	–	–	–	–	–
Zn-Hg	0.52	–	–	–	–	–	–

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Table 9. Trace elements crustal abundance and total heavy metals content in world soils (Bowen, 1966) ($mg\,kg^{-1}$).

Metal Author	Cd	Pb	Ni	Cu	As	Fe	Zn	Hg
Taylor (1964)	0.20		75	55	1.80		70	
Vinogradov (1957)	0.13	10	58	20	1.7	38	60	0.004
Bowen (1966)	0.06	10	40	20	6		50	

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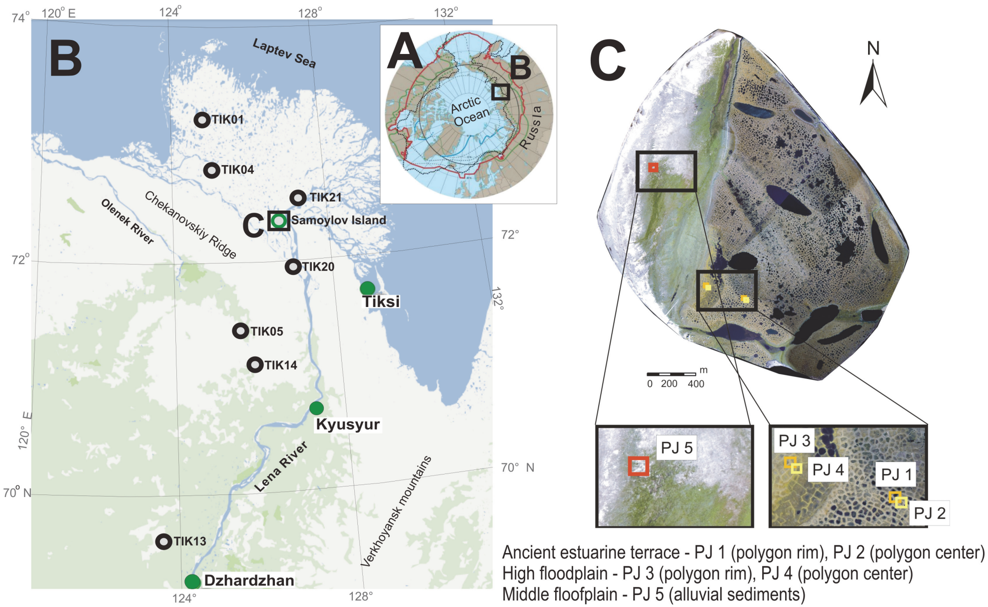

Fig. 1. Maps of the study showing **(A)** the position of the study area in the circum-arctic, **(B)** an overview of the area in northern Siberia with location of study sites investigated in 2009, and **(C)** overview of Samoylov Island with study sites positions investigated in 2010. The maps are based on Google & Geocentre Consulting, AMAP and "orthorectified aerial picture of Samoylov, 2007" (SPARC-group, Alfred Wegener Institute, Potsdam).

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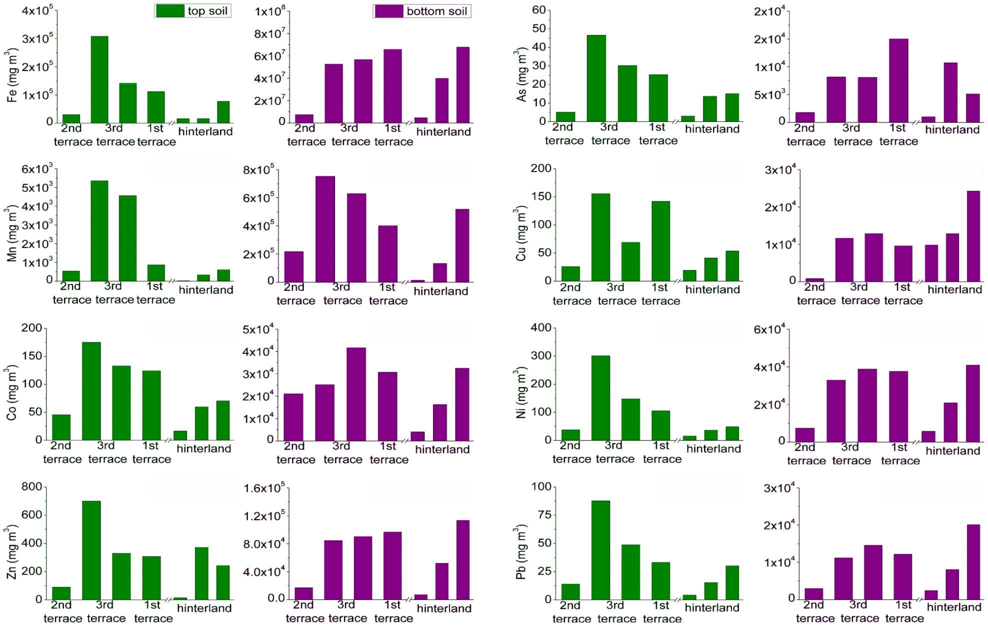

Fig. 2. Trace elements volumetric concentrations in top and bottom soil horizons of investigated sites of the north-south transect in northern Siberia (mg m^{-3}). 1st terrace (TIK20), 2nd terrace (TIK01), 3rd terrace (TIK04, TIK21), hinterland (TIK05, TIK13, TIK14).

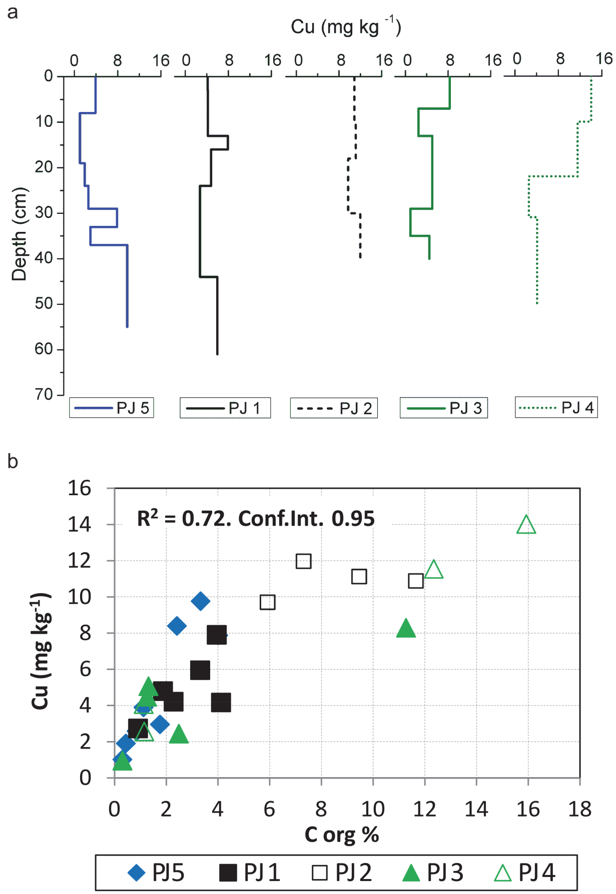

Fig. 3. Concentration of total Cu **(a)** and relationship between Cu and carbon content of soil profiles from Samoylov Island **(b)**. $R^2 = 0.72$, Confidence interval = 0.95.

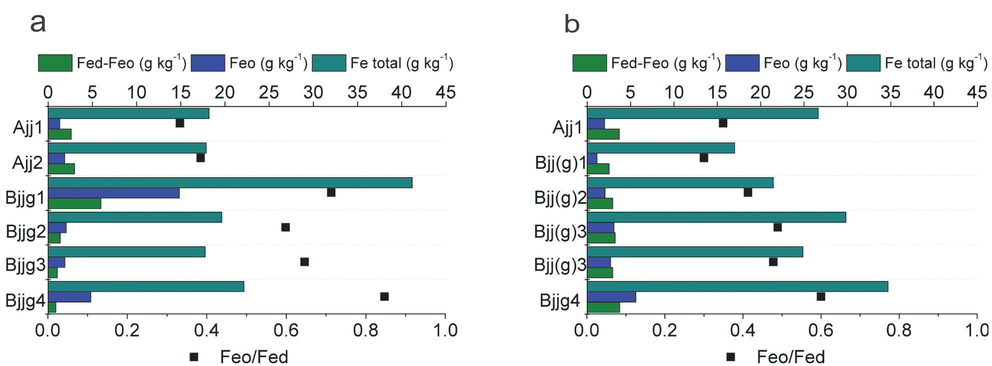

Fig. 4. Vertical distribution of iron in soils of polygon rim PJ1 of the ancient estuarine terrace **(a)** and alluvial soils of the middle floodplain PJ5 **(b)**, where Fe_d is well crystallized forms of Fe-oxides, Fe_o is poorly crystallized forms of Fe-oxides and Fe_{total} is total amount of iron in soil.

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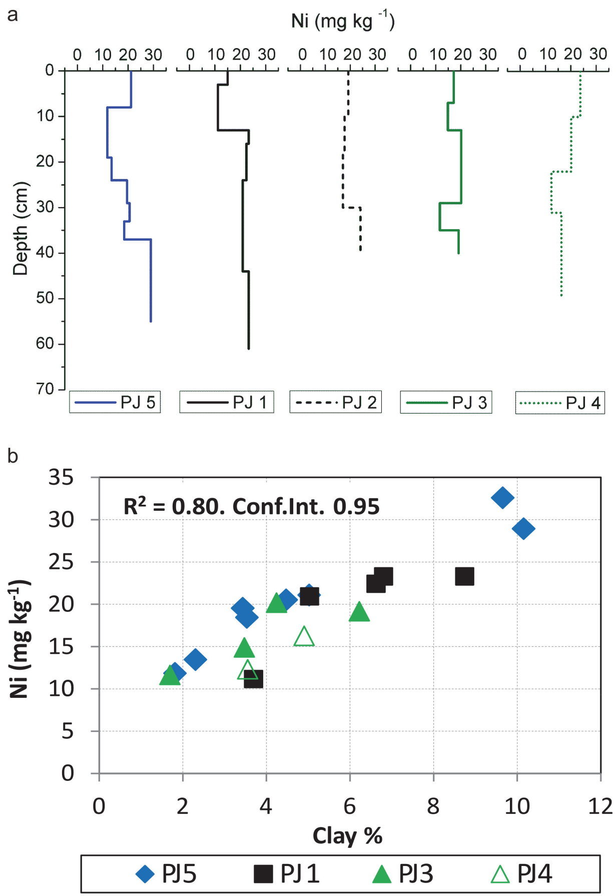

Fig. 5. Concentration of total Ni (**a**) and relationship between Ni and clay fraction of soil profiles from Samoylov Island (**b**). $R^2 = 0.80$, Confidence interval = 0.95.

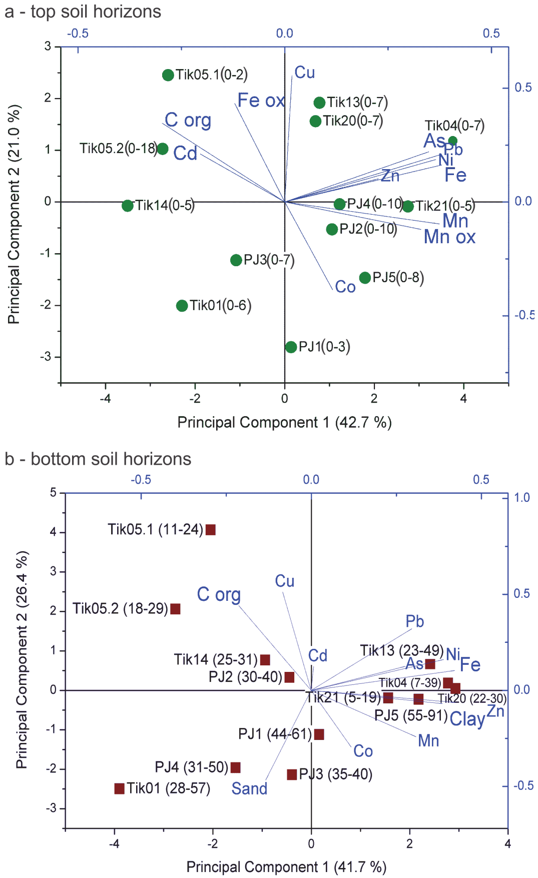

Fig. 6. Position map of samples based on principal components 1 and 2. The depth of genetic horizons is given in parenthesis.

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