Effect of Permafrost and Palaeo-Environmental History on Soil Formation in the lower Kolyma Lowland, Siberia

Bjarne Holm Jakobsen, Christine Siegert & Vladimir Ostroumov

Abstract

The Geography of soils has been studied in the tundra of the sandy Kolyma Lowland between latitudes 69 ° and 70 ° N. Generally, soils show characteristics indicative of variable intensity of previous fossil Podzol formation in the present day cryoturbated active layer. Hence, the transformation, transfer and segregation of chemical substances in the soil profile can be interpreted as evidence of palaeo-climate changes. Fossil soil features indicate horizon differentiating processes active in a former warmer and wetter climate. The chemical composition reflects a general sequence of pedogenetic translocation processes. Early stages of soil formation primarily involved translocation of weathering products from a carbonic acid weathering system. Inorganic Al-Fe silicate and phosphate materials were translocated into B horizons as the A horizon became more acid. At a later stage the increasing activity of simple organic acids in the A horizons caused a migration of metal-organic complexes and the formation of thin Podzols. These, mostly fossil features, are today characterized by secondary base accumulation, cryoturbation and geochemical processes above a shallow permafrost table. The permafrost table probably acts as a geochemical barrier controlling a system of processes reflecting changes in, e.g. soil water tension and redox conditions.

Keywords

Kolyma Lowland, arctic soil formation, palaeosols.

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Interpretation of soil profile characteristics and the geography of soils must always include considerations of possible effects of "global change", e.g. climate change or changing land use. A high variability of the climate caused by albedo-induced feedbacks is expected in arctic areas at different time and space scales. Studies of soils in arctic areas therefore imply a multiple process approach. The phenomenon of multiple processes in soil genesis is actually a classic idea (Marbut, 1951; Simonson, 1978) and will be discussed in relation to the observed soils in the Kolyma Lowland.

Judged by their morphological features, many soils in arctic areas have presumably experienced a static, nonturbic situation, but are presently influenced by cryoturbation. They often show organic O horizons covering thin humus rich A and eluvial E horizons, followed by B horizons, which normally reach down to the permafrost table. They show evidence of in situ weathering, translocation from O, A and E horizons and redox processes caused by the impermeable permafrost layer and highly variable water content of the active layer. The overall pedogenetic trend is in many cases indicative of a clear palaeoenvironmental change and a system of multiple processes operating within the soil (e.g. Tarnocai et al, 1990, 1991; Jakobsen, 1992; Humlum et al. 1995).

Enrichment with secondary soil chemical elements of the B horizon of sandy arctic soils is known to involve a reaction between the products of weathering and decomposition in situ and elements translocated from O, A and E horizons. These translocated elements comprise both inorganic compounds, e.g. positively charged, mixed aluminium- and iron-silicate and phosphate materials (Farmer et al., 1980; Anderson et al., 1982; Childs et al., 1983, Ugolini et al., 1987, Jakobsen, 1989, 1991) and water-soluble organic-metal complexes (Ponomareva, 1964; Petersen, 1976; De Coninck, 1980). The observed differences in B horizon characteristics are controlled by vegetation and soil moisture and temperature conditions, which influence the occurrence and reactivity of competing proton donors and complex and non-complex forming conjugate bases (Ugolini et al. 1991). Furthermore, there seems to be a pronounced effect of freezing, characteristic in the permafrost environment, on coagulates of metal hydroxides. Porous materials showing high sorption ability may predominate metal precipitates in the soil (Siegert, 1993).

Redox conditions in the active layer of arctic soils are mainly influenced by drainage conditions and organic matter content. Some chemical elements are more soluble during periods of oxygen depletion. The reactivity, mobility and distributional pattern of, e.g. Fe is therefore highly dependent on permafrost conditions, active layer thickness and landscape position (Jakobsen, 1991).

Study Area

During the field trip in July 1994 of the International Society of Soil Science, Cryosols Working Group to the Kolyma Lowland, Yakutia, sandy soils were studied at the tree line and in the tundra. Location and sampling sites for three characteristic sandy mineral soils are shown in fig.1.

The study area lies north of the Polar circle in the lower valley of the Kolyma river, one of the major rivers in North-East Siberia. The Kolyma lowland is the easternmost segment of the vast coastal lowland stretching along the Arctic Ocean. The lowland is generally covered by Late Pleistocene sandy and silty sediments with abundant segregated and polygonally veined ice. The high ice content favours the development of thermokarst processes, and lake thermokarst sinks and plains at various levels constitute outstanding features of the lowland topography.

The climate in the Kolyma lowland is a little milder than in central Yakutia because of the nearness to the sea. Nevertheless, the region has a strong, continental, subarctic climate, with an average annual monthly temperature range of 45.7 °C. Mean temperatures of the coldest and warmest months are -34.8 °C and 10.9°C, respectively. The mean yearly precipitation of c. 225 mm is rather low and occurs mainly from June to October (Gubin et al. 1994). The permafrost is an important aspect of the region. The active layer thickness varies depending on local conditions, reaching a depth of only c. 0.1 m in moss-covered areas and c. 0.5 m in better drained heath covered mineral soils. The forest-tundra of the region is a sparsely forested lichen-larch association with willow coppice, dwarf birch and tundra low shrubs constituting the ground layer. The tussocky grass tundra north of the tree line is dominated by reed-grass.

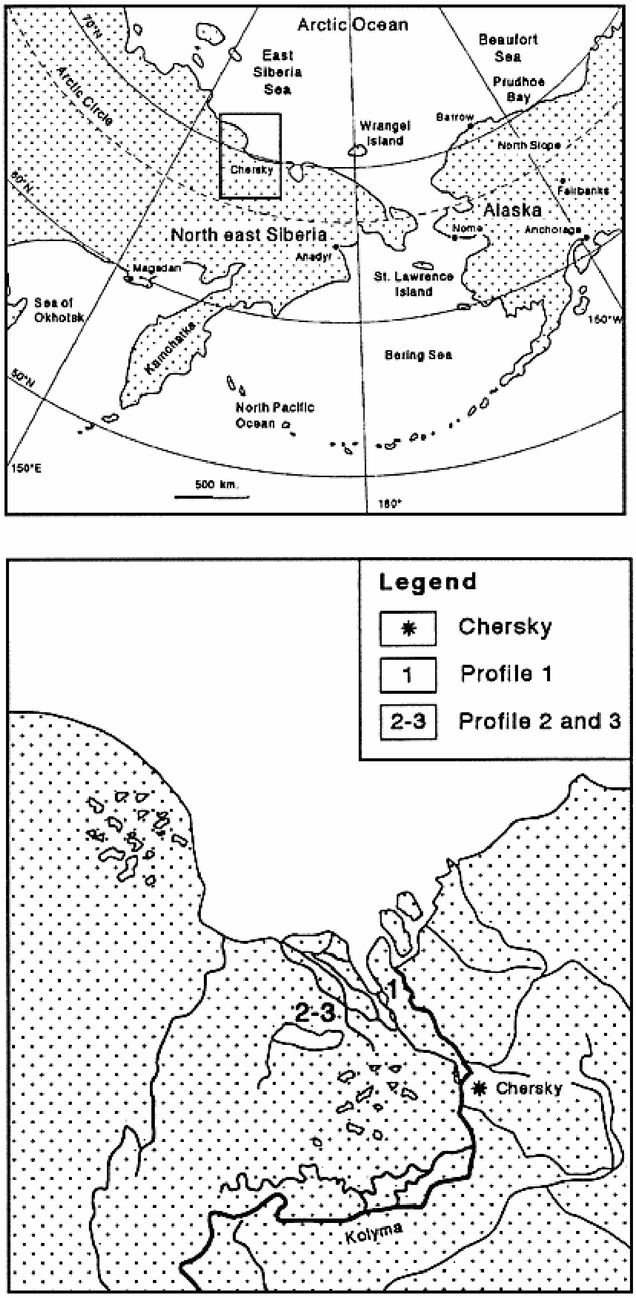

Figure 1: Sites of the studied soil profiles in the Kolyma lowland, Yakutia.

Soil Profiles and Methods

Most soils show intense cryoturbation and are presently influenced by these horizon mixing processes. Profiles 1 and 2 represent the normal range of cryoturbation in level landscape elements. Profile 3, probably a relict earth hummock, has a slight convex crest position enhancing the drainage of the upper part of the active layer and thereby probably reducing cryoturbation. The sandy soils show organic O horizons covering thin humus rich A and eluvial E horizons. B horizons normally extend to the permafrost table at a depth of 40-50 cm.

The investigated soils have been described according to the Guidelines for Soil Profile Description (FAO, 1977). Morphological features are shown in table 1. Profile 1 is formed in slightly gravelly sandy loam (5-7%<2μm), probably a residual glacial deposit with some aeolian influence (Fig. 2). The soil is sited at the present tree line (Fig. 3), on a plain c. 0.5 km east of the Kolyma river showing a slightly undulating relief (69° 12' N, 161°26'E). The vegetation is an open larch-heath tundra showing a rooting of 30-40 cm. Profiles 2 and 3 (69°05'N, 158°95'E)

Figure 2: Soil profile 1.

Table 1: Morphological features of the three studied sandy tundra soils.

Profile/ Horizon	*Depth (cm)*	*Morphological features*
Profile 1		
O	+10-0	Brownish black (7.5YR 3/2), weak fine granular structure, soft, very friable
A	0-2	Brownish black, (5YR 2/2), gravelly sandy loam, weak, fine granular structure
E	2-5	Grayish yellow brown (10YR 4/2), gravelly sandy loam, weak fine granular structure
B1	5-8	Dark reddish brown (5YR 3/2), gravelly sandy loam, weak fine subangular blocky structure
B2	8-20	Dark brown (10YR 3/3), gravelly sandy loam, weak medium subangular blocky structure
BC	20-43	Dark yellowish brown (10YR 4/4), gravelly sandy loam; weak medium angular blocky structure
Cf	43-	Permafrost, frozen and massive
Profile 2		
0	+4-0	Black (5YR 2/1), weak fine granular structure soft, very friable
E	0-3	Grayish brown (10YR 5/2), very fine sand, weak fine and medium subangular blocky structure, slightly hard, very friable
Bs	3-7	Dark brown (7.5YR 3/3), very fine sand, weak fine and medium subangular blocky structure, slightly hard, very friable
Bw	7-17	Dark yellowish brown (10YR 3/4), very fine and, weak fine and medium angular blocky structure slightly hard, very friable
Bg	17-47	Dark yellowish brown (10YR 4/4), common light brownish gray (10YR 6/2) and few light gray (10YR 6/1) redox depletions, and common strong brown (7.5YR 4/6) redox accumulations, very fine sand, weak coarse angular blocky structure, slightly hard, friable
Bf	47-	Permafrost, frozen and massive, increasing redox depletion
Profile 3		
0	+10-0	Very dark brown (7.5YR 2.5/3), very fine platy and granular structure, soft, very friable
AE	0-7	Dark brown (7.5YR 3/2), fine sand, weak medium subangular blocky structure, slightly hard, very friable
EB	7-16	Brown (7.5YR 5/2), fine sand, weak fine subangular blocky structure, slightly hard, very friable
Bs	16-31	Yellowish red (5YR 4/6), fine sand, weak medium subangular blocky structure, slightly hard, very friable
Bg	31-40	Dark brown (10YR 3/3), common dark brown (7.5YR 3/2) redox accumulations, fine sand, weak coarse angular blocky structure, slightly hard, very friable
Bcf	40-	Permafrost, frozen and massive

Figure 3: *The profile 1 site, an open larch forest tundra.*

Figure 4: *The extensive tundra plain west of the lower Kolyma river. Patterned ground polygons and numerous thermokarst lakes dominate the landscape.*

are sited on a nearly level terrace surrounded by thermo karst lakes (Fig. 4). The parent material is probably aeolian influenced sandy outwash and the microrelief is a non-sorted patterned ground dominated by low center polygons. The polygon depressions are wet, have moss and peat covering the sandy outwash and show permafrost at a shallow depth (10-20 cm). The slightly higher lying level terraces, polygon rims and scattered pingo like earth hummocks are not wet but still show aquic conditions. These better drained landscape segments have a dense heath cover of Salix, Lidum, Vaccinium, Carex and lichens (Fig.5). Roots reach c. 30-40 cm into the soil, c. 10 cm above the present, late summer permafrost level (Fig. 6 & 7). All three profiles show distinct eluvial E and illuvial B horizons. Soil profiles 1 and 2 show thin podzolization in the upper 10 cm of the soil and are classified as Pergelic Cryochrepts according to the Soil Taxonomy (Soil Survey Staff, 1975). Soil profile 3 is classified as a Pergelic Haplocryod.

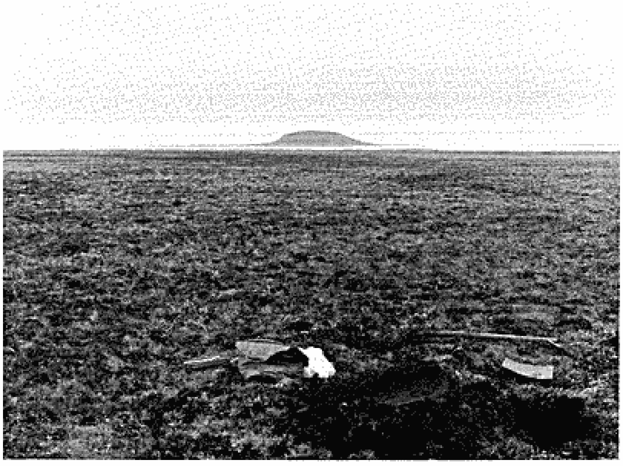

Figure 5: *The densly heath covered terrace landscape at profile 2 shown in figure 6. An active pingo showing a height of c. 50-75 m is seen in the background.*

The following methods were used for analysing the fine earth. pH was measured in distilled water and 0.01 M $CaCl_2$ (1:2.5). Organic carbon was determined by combustion in a LECO induction furnace, and nitrogen by Kjeldhal digestion. Total and inorganic phosphorus were determined spectrophotometrically after extraction of the fine earth heated to 550°C using 12 N sulphuric acid, and by extraction of unheated fine earth. Exchangeable bases were analysed by AAS after extraction by $NaOOCCH_3$ and NH_4OOCCH_3. Exchangeable H and Al were determined by titration after extraction with KCl, with and without addition of NaF. The cation exchange capacity at the actual pH of the soil (ECEC) was calculated as the total amount of exchangeable cations determined by the above mentioned methods. The CEC at a pH of 8.2 was determined by analysing the amount of extractable Na in a sodium saturated soil (Borgaard et al, 1987). Extractable metals were extracted by dithionite-citrate (Mehra and Jackson, 1960) and by pyrophosphate (McKeague, 1967). Acid-oxalate-extraction of Al and Fe was carried out according to McKeague et al., 1966. Al, Fe, Mn, Cu, Zn and Pb in extracts were determined by atomic absorption.

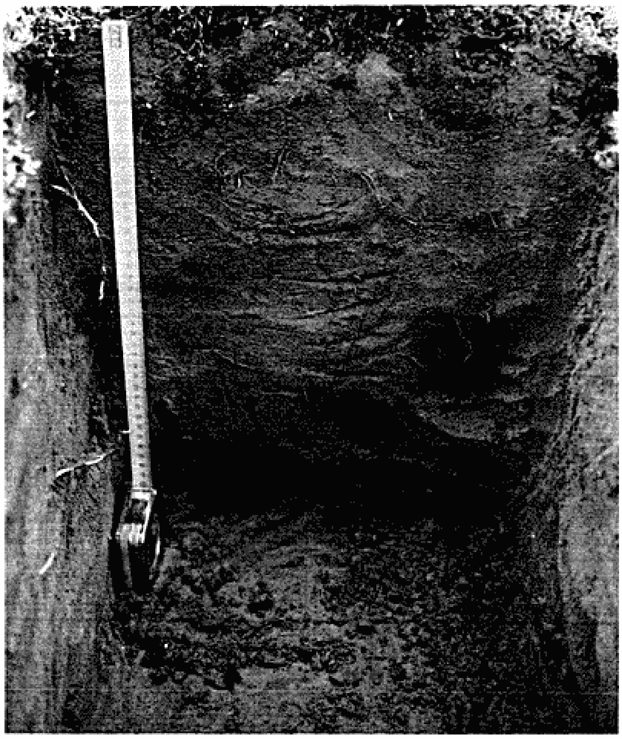

Figure 6: Soil profile 2.

Figure 7: Soil profile 3.

Results

All three soils are strongly acid (pH ($CaCl_2$) 3-4) in the upper soil layer (Figs 8-10). They have accumulated organic matter at the surface of the mineral soil and show weak structure as soil biological activity is low (table 1). - The distribution of organic carbon content in the E horizons, below the organic-rich A horizon, is relatively high, ranging from 1.7-5.1% C (figs 8-10). Translocation processes involving podzolization have not created a second organic carbon maximum in the B horizons. C/N values in A/O horizons in profiles 1,2 and 3 are 18, 31, 13, respectively. C/N values indicate that podzol forming organic complexants should be expected to be more active in profiles 1 and 2. The micro-podzol morphology and the distribution of Fe and Al, having a high affinity for organic complexants, show the greatest influence of metal-organic complexants in profile 2 followed by profile 1, whereas processes in profile 3 seem to be more inorganically controlled.

The distributions of Fe and Al extracted by dithionite-citrate (d), pyrophosphate (p) and acid oxalate (o) treatments show different patterns. Dithionite-citrate showed to be unexpectedly inefficient for the extraction of both aluminium and iron in these permafrost soils. No analytic error could be revealed, but metal segregation processes are interpreted from oxalate and pyrophosphate extracions. Maxima are seen in the upper B horizons directly underlying bleached E horizons in profiles 1 and 2 (figs 8 and 9). These maxima comprise a high content of metals in organo-metallic complexes, extractable by pyrophosphate solutions. In the deeper part of B horizons additional maxima in Fe and Al are observed. In soil profile 1 both iron and aluminum are found in the lower B horizon (BC), mostly in inorganic amorphous compounds extractable by oxalate solutions. In soil profiles 2 and 3 which show redox features (gleying) in the lower soil profile close to the permafrost table, iron dominates the secondary maximum in inorganic metal compounds in the lower B horizons. These maxima of mostly amorphous inorganic metal compounds are parallelled by high contents of inorganic phosphorous (figs 8-10).

The analyses of Mn, Cu, Zn and Pb in soil profiles (table 3) show little or no reactive Mn in these soils. In profile 1,

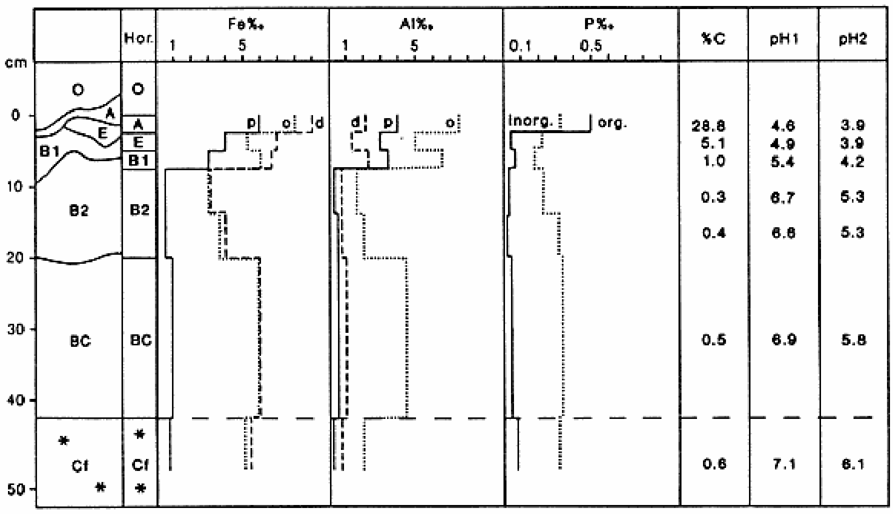

Figure 8: Chemical characteristics of Profile 1. Extractable Fe and Al (p=pyrophosphate extractable, o=oxalate extractable and d=dithionite extractable), organic (org) and inorganic (inorg) P, pH-values (pH1 in water; pH2 in $CaCl_2$) and % C (organic carbon).

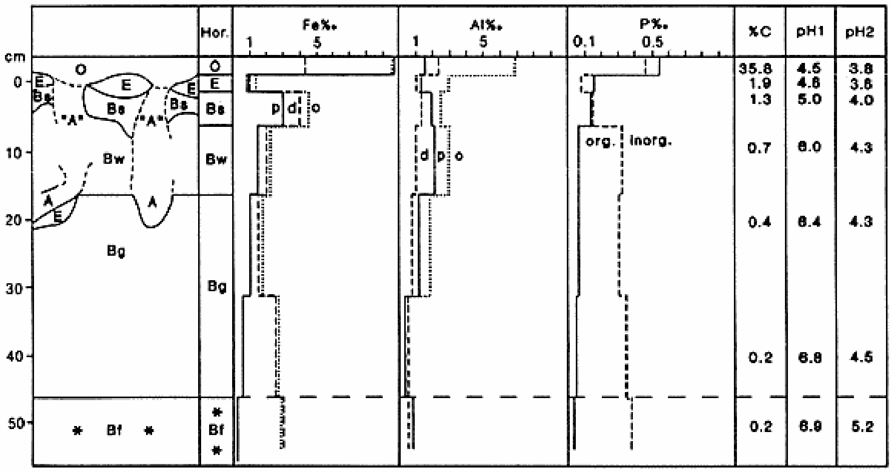

Figure 9: Chemical characteristics of Profile 2.

showing well drained conditions throughout the active layer, manganese occurs, and a slight accumulation of Mn is observed at the permafrost barrier. In the sandy tundra soils both Cu and Zn showed maximum values in soil surface horizons. Zn occurred in small quantities and was restricted to the topsoil layer, whereas Cu is found throughout the soil profiles. Pb is found throughout the active layer and generally seems to have formed a slight accumulation in B horizons. From lake sediment corings, which were carried out during the field trip in the Cherskiy area just south of the sandy tundra, geochemical analyses were carried out. Contents of Cu and Zn showed a sharp increase in the upper few centimetres of lake sediments, probably caused by contamination from industrial activity during the present century (Wendy Eisner:personal communication).

The contents of exchangeable cations (Table 2) and the pH profiles of the soils (figs. 8-10) indicate a high control by reactive aluminum, especially in A, E and upper B horizons. $CEC_{8.2}$-values and the comparison of pH measurements in water and calcium chloride indicate a high potential acidity in both the organic rich A, E and upper B-horizons and in the lower B horizons rich in amorphous metal compounds.

The distribution of exchangeable bases and base saturation shows high values in the organic rich surface horizons controlled by biomass recirculation. Furthermore, the exchangeable sodium percentage values (ESP) are high in

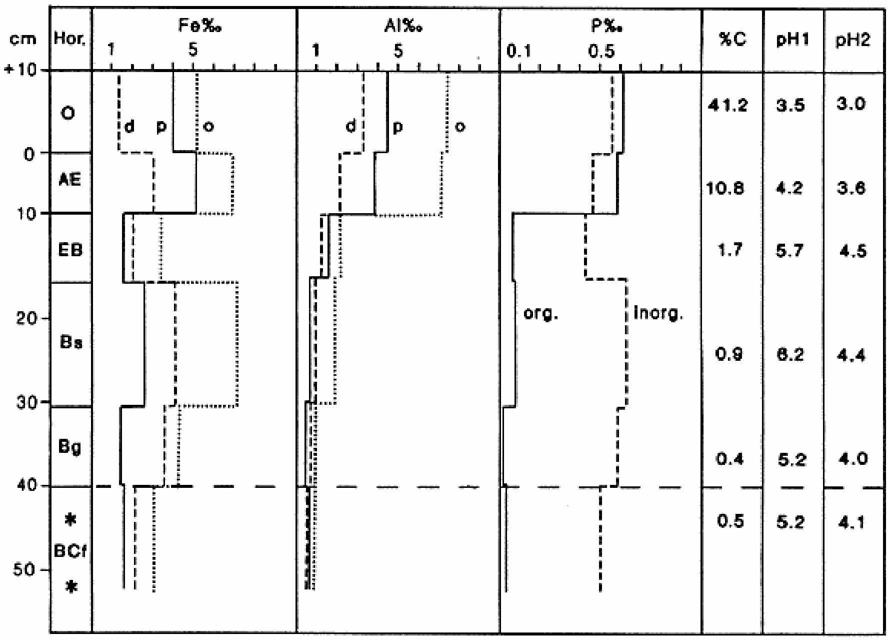

Figure 10: Chemical characteristics of profile 3.

the lower part of the active layer in profile 1 and 2, and in the surface soil of profile 3 (table 2).

Discussion

Soil formation in the lower Kolyma area probably involves a wide range of multiple transformation and translocation processes. The intensity of these processes has most likely changed in the Holocene with the climatic variability during this period (e.g. Tarnocai, 1990). Organic matter accumulation, depth and intensity of weathering, leaching and translocation as a result of different soil water regimes and proton donors, as well as cryoturbation seem to have influenced pedogenesis with a varying intensity.

Soils show different kinds of accumulation of metal compounds (figs 8-10): 1) An accumulation in a mostly thin B horizon directly underlying a bleached E horizon (profiles 1,2 and 3), 2) an accumulation in a B horizon directly underlying the upper "spodic" horizon and 3) an accumulation in a lower B horizon, presumably without any direct coupling to the upper "spodic" horizon.

Mechanisms in soluble metal translocation in sandy materials including "podzolization" probably involve several different processes. In slightly weathered carbonate free sandy soils pedogenesis is controlled by H_2CO_3 induced weathering processes. Weathering products of amorphous aluminium-dominated, possibly mixed iron-silicate materials, can be translocated from still more acid A horizons (e.g. Anderson et al. 1982, Jakobsen, 1991). At somewhat higher pH values in deeper soil layers, the Al-Si rich materials react with in situ weathering products and precipitate as amorphous material linking the particles in porous aggregates. Micro-environments of decomposing organic matter in the subsoil may form organo-metallic compounds: the BC horizon in profile 1 is presumably mainly formed in such a weathering environment. In the lower Bg horizon of profile 2 and in the Bs horizon of profile 3, inorganic iron compounds dominate. Besides, the just mentioned inorganic accumulation mechanism for metal compounds is additionally strongly influenced by iron segregation processes through redox processes in the somewhat poorly drained active layer in these two profiles.

Continued leaching of sandy soils creates acid conditions at the soil surface. The activity of organic acids in complexation and translocation of metals increases as organic complexants and reactive silicate material compete for the formation of mobile metal compounds translocated into the B horizons.

The chemical composition of these translocated metal compounds upon precipitation in the B horizons, and a probable layering of different metal-ligand associations in the "spodic" horizon, will depend on a number of factors.

Table 2: Analyses of soil horizons. Exchangeable cations, cation exchange capacity at the actual pH of the soil (ECEC), and at pH 8.2 ($CEC_{8.2}$), effective base saturation (VE%) and exchangeable percentage sodium (EPS).

Profile/ Horizon	*Ca*	*Mg*	*Na*	*K*	*H*	*Al*	*ECEC*	*$CEC_{8.2}$*	*EV%*	*EPS*
					meq/100g					
Profile 1										
A	3.29	0.76	0.23	0.99	0.06	2.07	7.40	84	71	3
E	0.47	0.08	0.07	0.13	0.27	6.67	7.69	24	10	1
B1	0.26	0.06	0.08	0.06	0.02	2.29	2.77	19	17	3
$B2_{(20-25)}$	0.30	0.07	0.12	0.01	0.04	0.08	0.62	15	80	19
$B2_{(30-35)}$	0.25	0.06	0.15	0.02	0.05	0.05	0.58	15	83	26
BC	0.28	0.07	0.10	0.05	0.02	0.00	0.52	16	96	19
Cf	0.33	0.10	0.12	0.06	0.02	0.00	0.63	15	97	19
Profile 2										
O	1.14	0.56	0.27	0.67	0.00	5.99	8.63	114	31	3
A	0.06	0.03	0.08	0.02	0.05	2.68	2.92	21	8	3
Bs	0.05	0.02	0.05	0.01	0.02	1.75	1.90	17	7	3
Bw	0.04	0.02	0.05	0.01	0.02	0.90	1.04	14	12	5
$Bg_{(20-25)}$	0.07	0.03	0.04	0.02	0.02	0.75	0.93	13	17	4
$Bg_{(35-40)}$	0.06	0.02	0.05	0.04	0.02	0.33	0.52	14	33	10
Bf	0.08	0.03	0.07	0.06	0.03	0.04	0.31	14	77	23
Profile 3										
O	2.73	0.75	1.53	0.63	0.00	6.21	11.85	127	48	13
AE	0.60	0.08	0.22	0.09	0.02	1.97	2.98	52	33	7
EB	0.19	0.04	0.09	0.06	0.03	0.39	0.80	18	48	11
Bs11	0.13	0.04	0.04	0.11	0.02	0.60	0.94	19	34	4
Bg	0.07	0.02	0.04	0.08	0.02	0.97	1.20	17	18	3
Bcf	0.08	0.03	0.05	0.10	0.02	1.04	1.32	17	20	4

These include the intensity and period of complexing ligands from organic acids competing with inorganic complexants, the decomposition rate of the organic complexants, and the chemical micro-environments present in the B horizons. The occurrence of reactive silicate materials in B horizons from in situ weathering and formerly translocation, and intense decomposition of organic compounds may cause a change from metal-organic complexes into mixed, amorphous structures dominated by inorganic Al-Fe-Si compounds. The amount of reactive organic matter in B horizons, either translocated by episodic pulses from the A horizons, or formed by microbial activity in the horizons, is assumed to be the limiting factor for the formation and stability of inorganic Al-Si dominated compounds. The "spodic-like" B1 horizon in profile 1, the Bs horizons in profile 2 and partly the Bs horizon in profile 3 reflect this competitive situation.

A continued general or episodic increase in acidity and activity of organic complexants in A and B horizons may result in a remobilization of materials in B horizons. Materials found in the lower part of spodic horizons may show chemical characteristics of remobilized inorganic metal compounds and more soluble aluminum rich organo-metallic complexes. The Bs-Bw horizon complex in profile 2 can most easily be explained by such remobilization mechanisms, which are also prominent in podzolized soils from other arctic environments in Canada and Greenland (e.g. Jakobsen, 1991).

Hence, the appearance of podzolization processes in the sandy tundra of the lower Kolyma is clearly dependent on local variations in the microenvironment between soil sites and individual soil horizons, as also known from, e.g. the Canadian tundra (Wang and Kodama, 1986 a; Wang et al., 1986 b). Also short-term changes and seasonal variations in process intensity are documented (Milnes and Farmer, 1987; Ugolini and Dahlgren, 1988; Stoner and Ugolini, 1988). Over longer periods, eventually influenced by climate change, the intensity of translocation processes will also change (e.g. Farmer, 1979; Jakobsen, 1991). The mobility of metals and the translocation into Podzol B horizons do not necessarily imply the occurrence of high concentrations of organic complexants in the percolating soil water. However, organic complexants strongly determine the composition and eventual layering of cementing

Table 3: Analyses of soil horizons. Contents of dithionite-citrate extractable Mn, Cu, Zn and Pb.

Profile/Horizon	*Mn*	*Cu*	*Zn*	*Pb*
		0/00		
Profile 1				
A	0	0.08	0.05	0.05
E	0.1	0.10	0	0.05
B1	0.2	0.05	0	0.08
B2$_{(20-25)}$	0.2	0.04	0	0.07
B2$_{(30-35)}$	0.2	0.05	0	0.07
BC	0.6	0.05	0	0.06
Cf	0.5	0.06	0	0.05
Profile 2				
O	0.1	0.08	0.03	0.06
A	0	0.07	0	0.07
Bs	0	0.06	0	0.08
Bw	0	0.07	0	0.08
Bg$_{(20-25)}$	0	0.04	0	0.09
Bg$_{(35-40)}$	0	0.03	0	0.06
Bf	0	0.05	0	0.08
Profile 3				
O	0	0.09	0.02	0.07
AE	0	0.09	0	0.07
EB	0	0.08	0	0.07
Bs	0	0.09	0	0.05
Bg	0	0.07	0	0.05
BCf	0	0.06	0	0.05

materials in podzol B horizons.

The distribution of phosphorous in the sandy Kolyma tundra shows a specific connection to inorganic metal compounds found in the lower part of the profiles. The metal compounds in the soil layers close to the permafrost table originate from amorphous materials, probably generating porous structures and high sorption activity in a unique moisture and temperature regime just above the permafrost table (Siegert, 1993). The reactivity of phosphorous to metal compounds in sandy soils seems to be a competitive situation, where the presence of organic matter can inhibit aluminium oxide crystalization and influence indirectly on the total adsorption of phosphorous on aluminum and iron oxyhydroxides (e.g. Borggaard et al. 1990). The inorganic phosphorous found is probably partly translocated in the early carbonic acid weathering phase and partly remobilized and redistributed to lower soil profile segments due to the high affinity of pulses of organic complexants for metals in the upper soil profile.

The distribution of zinc, cobber and lead in the sandy tundra soils, primarily from industrial pollution, shows that both Cu and Pb are leached into deeper soil layers, whereas a very low content of Zn is only found in the surface layer. The leaching of these metals is controlled by the balance between their retention by colloids and the formation of mobile complexes or chelates (e.g. Jørgensen, 1991). Both Cu and Pb are clearly mobilized in the upper soil horizons, probably by organic complexants. In deeper soil layers, amorphous structures of phosphate and silicate rich materials could partly precipitate these metals in only slightly soluble compounds. Strong binding of Pb, Cu to soil organic matter is normally expected in soils, but leaching of these metals under natural conditions in a podzolic environment is generally observed (e.g. Jørgensen and Willems, 1987).

The enrichment of bases and especially the high content of exchangeable sodium in the lower soil horizons of profile 1 and 2 and in the upper soil horizons of profile 3, most likely reflect a change from a moist period to the present relatively dry and cold, continental conditions. Profile 3 is located in an exposed crest position on an earth hummock. This microsite is presumably uncovered by snow, creating even more favourable conditions for the accumulation of sodium brought to the area as sea spray from the Arctic Ocean. Active cryoturbation is normally observed (profiles 1 and 2) apart from restricted areas of well drained active layers (e.g. profile 3). Both the high level of bases and the cryoturbation are thought to be secondary pedogenic features and are ultimately evidence of a global change. Relict features in soils are well known from the Holocene interglacial periods and found throughout the present Arctic (e.g. Tarnocai, 1990; Jakobsen, 1992).

Conclusions

Soil geography and chemical analyses of soil horizons indicate a probable sequence of processes characterizing major soil development. A first stage of brown soil formation represents a predominant, carbonic acid weathering system. With increasing intensity, mostly in the later part of this stage, leaching takes place of inorganic Fe-Al silicate-phosphate materials accumulating in B horizons, presently probably reaching into the permafrozen soil layers. At a second stage organic acids from accumulating organic residues in O horizons have given rise to the

formation of thin Podzols. This increase in the activity of organic complexants in the soil could be enhanced by a climatic change to more cool and humid conditions. In a third stage, increased cryogenic activity in a thinning active layer is causing the cryoturbic mixing of most soil profiles.

After the last glaciation, favourable climatic conditions in the tundra area resulted in the formation of an A-Bw-C soil profile development. This soil formation took place in a landscape formerly characterized by cryogenic landscape formation. Profile 3, which still shows continuous soil horizons, is probably formed in a relict earth hummock from the glacial/late glacial period, not severely influenced by cryogenesis during the late Holocene climatic cooling. The early Holocene brown soil formation also involved translocation processes, in which mostly amorphous Fe-Al silicate and phosphate materials accumulated in the subsoil. Cryogenesis and permafrost processes did not cause any cryoturbation in that period. Presumably, conditions were generally warm and dry during the early Holocene, which lasted several thousand years. However, the peat formation in high arctic areas of Canada in early Holocene (Tarnocai, 1990) indicate that periods of moister conditions appeared, probably triggering more intense leaching and formation of thin Podzols. The climatic cooling following the Hypsothermal Maximum developed the present dry and cold environment. Controlled by a shallow permafrost depth and low precipitation values, relict features of multiple Podzol formation are mainly influenced by current soil genesis of slight leaching, intense cryoturbation and a secondary enrichment of bases, including sodium brought to the area from the Arctic Ocean.

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