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Pedogenesis of a Retisol with fragipan in Karelia in the context of the Holocene landscape evolution

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Abstract Fragipan is a compacted but non-cemented subsurface horizon, considered as a pedogenic horizon, but the mechanism of its formation is not well understood. The main hydro-consolidation hypothesis involves a collapse of soil structure when it is loaded and wet, resulting a reorganisation of pore space. Soils with fragipan never have been marked in Russian soil maps. In the South Karelia, located in Eastern Fennoscandia (34.50921 E and 61.33186 N, 110 m asl) we studied a soil profile of Albic Fragic Retisol (Cutanic), developed in the glacial till of Last Glaciation with flat sub-horizontal topography under an aspen-spruce forest. The aim of this study was to demonstrate how the fragic horizon was formed in the Retisol located in South Karelia. Observations were made in each soil horizon using micromorphological method, particle size analysis and the study of mineralogical composition of clay fraction by X-ray diffraction. The analysis of the morphological description combined with the laboratory data have led us to the conclusion that the consolidation of the fragipan occurred after the textural differentiation of the profile, following the Atlantic Optimum, and does not depend on the presence of swelling clay minerals. The well-developed argic horizon was probably formed around 6000 years ago, under climatic conditions more favourable for clay illuviation than in present time. Fragipan is supposed to be developed during the Sub-Boreal cooling.

Keywords *• soil genesis • illuviation clay • Holocene soil*

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INTRODUCTION

Soils are sensitive to the environmental conditions. In North-Western Europe the soils were developing since deglaciation in the terminal Pleistocene and throughout the Holocene and suffered periods of contrasting climate and environmental changes. The records of those changes are present in the pollen assemblages from the peat sequences and lacustrine sediments accumulated in the landscape depressions (Yelina, Filimonova 2007; Dolukhanov *et al.* 2009). Some upland soils developed under good drainage conditions have evidences of different stages of soil formation for this period in their profiles. The relicts of Late Pleistocene sedimentary and cryogenic processes were registered e.g. in the loess soils of the East European Plain (Makeev 2009) and in the slope soils of Central Europe as periglacial cover beds (Kleber, Terhorst 2013). Variable well preserved evidences of different climatic phases of the Holocene were detected in the soils of Eastern Europe, especially within forest-steppe zone (Alexandrovskiy 1983, 2000). Most of these soil records were obtained from the soils of the European regions outside the limits of the Last Glaciation. Soils developed in the circum-Baltic region within the Valday (Weichselian) glaciation area also have complex profile developed in response to landscape evolution (Nikonov *et al.* 2005; Rusakov *et al.* 2007) and thus contain rich "soil memory" (see Targulian, Goryachkin, 2004).

A common and informative element of the European mid-latitude soil profiles is the fragic horizon, often interpreted as a relict feature (Habecker *et al.* 1990; Ciolkoszet *et al.* 1995; Payton 1992, 1993a, 1993b; van Vliet, Langohr 1981). Fragic horizon (IUSS Working Group WRB 2014), also known as fragipan (Keys to Soil Taxonomy 2014), is a compacted but non-cemented subsurface soil horizon which restricts the penetration of roots and water; it has a specific coarse prismatic blocky structure and high bulk density. Even though the fragipan is considered to be a pedogenic horizon, its genesis is not well understood yet. A review of fragipan studies in the USA (Bockheim, Hartemink 2013) presents a broad list of possible hypotheses for its formation. Originally fragipans were supposed to be irreversible-cemented by silica (Winters 1942), but even at that time some scientists tended to explain its formation rather by strong compaction (Nikiforoff 1948). The cementation hypothesis does not fit into the current definition of fragipan: the air dried fragments have to slake when they are submerged in water (WRB 2014; Keys to Soil Taxonomy 2014).

There are several alternative explanations of the fragipan formation through reorganization of soil matrix due to combination of some physical and/or chemical processes (Bryant 1989; Bockheim, Hartemink 2013). Many authors considered that this structural collapse takes place as a result of frost heave in the presence of permafrost under periglacial conditions (Fitzpatrick 1956; Gallardo *et al.* 1988). This theory cannot explain the fragipan formation in tropical regions, where the glaciation has never been registered during the soil formation time.

The main "Bryant hydro-consolidation" hypothesis, involves a collapse of soil structure when it is "loaded and wet", and in this case clay is believed to be responsible for compaction by linking coarser particles (Assalay *et al.* 1998). This hypothesis is confirmed in recent studies (Szymanski *et al.* 2012; Nikorych *et al.* 2014; Falsone *et al.* 2017) and can be applied for areas that were not affected by glacial or periglatial conditions during the consolidation.

The fragipans have been mapped primarily in the USA and Europe but have never been registered in soil maps of Russia. For this reason it is important to investigate its genesis when in was firstly noted in Karelia, in the northern part of European Russia. There are numerous publications about the deglaciation in Karelia with many data about the age of exposed sediments (Saarnisto, Saarinen 2001; Svendsen *et al.* 2004). The study site is located within the area of Luga deglaciation stage of the Valday (Weichselian) glaciation. The parent material was exposed to the surface around 13–14.2 ha (Svendsen *et al.* 2004). The particular interest of this study is the fragipan that was not previously studied directly in the zone of Valday glaciation. This soil profile was previously presented on the field tour of International Conference of Soil Classification (Field Workshop Guidebook of the International Conference, 2004), where specialists of both international (WRB and Soil Taxonomy) and Russian soil classification teams have defined this soil as Aquic Fraglossudalfs (or Aquic Fragic Glossic Udic Alfisols) (Galbraith 2004) according to Soil Taxonomy (2003).

The main goal of this study was to understand how the fragic horizon appeared in the Retisol profile in Karelia that was formed during the Holocene, and what kind of processes is responsible for its formation. We further try to relate the Retisol and fragipan formation with the Holocene regional landscape history.

MATERIAL AND METHODS

The soil profile is located in the southern part of the Republic of Karelia in North-Eastern Russia (34.50921 E and 61.33186 N, 110 m asl). In this area (Fig. 1), the period with temperatures higher than 5°C is 140–160 days long, and there are more than 100 days a year with the temperature higher than 10°C. The mean annual temperature is 2°C and annual precipitation is 600 mm. According to the Soil Taxonomy, this soil is characterized by the Udic soil moisture regime and Cryic Interfrost soil temperature regime.

The soil profile was classified as an Albic Fragic Retisol (Cutanic) (IUSS Working Group WRB 2014), and it is developed in the glacial till of Last Glaciation on the sub-horizontal watershed surface under an aspen-spruce forest. Detailed morphological description of the soil profile was followed by sampling following the genetic horizons: bulk samples for physical and mineralogical characteristics as well as blocks with undisturbed structure for thin sections were collected. For the morphological and mineralogical analyses the following methods were employed:

Geophysical methods

The ground penetrating radar (GPR) and time domain reflectometry (TDR) were used on the initial stage of research to detect spatial behavior of soil horizons and in particular to check the lateral extension of the fragipan in a soil cover. In this study, OKO-2

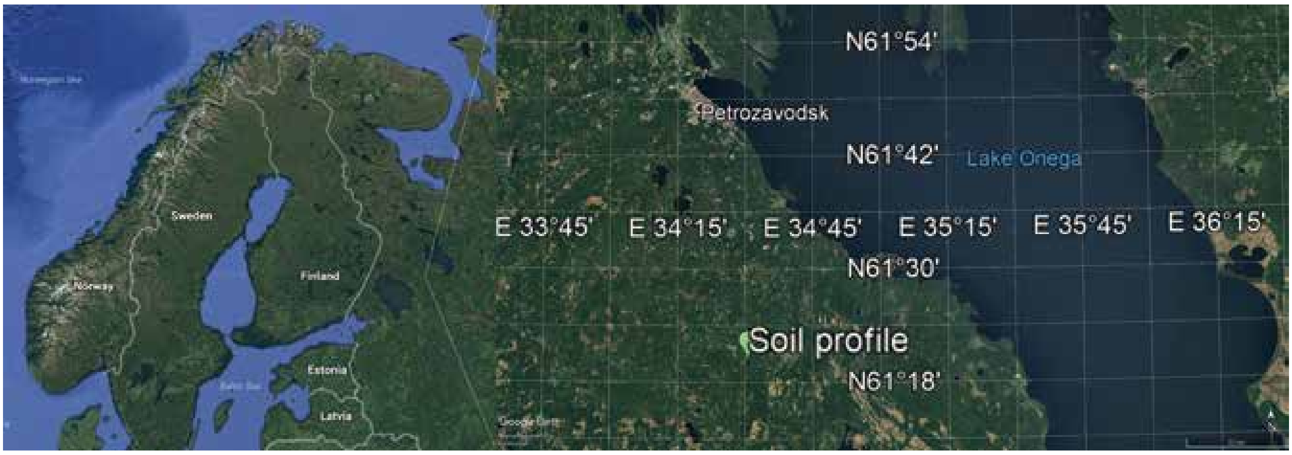

Fig. 1 A schematic map of the study area

GPR with an antenna unit with a central frequency of 1700 MHz (Logis-Geotech, Russia) was used, permitting sounding down to 1 meter depth with a vertical resolution of at least ±3 cm. Measurements were taken from individual profiles with a scanning step of 5 cm. TDR observations were performed by the TDR 200 measurement system with CS635-L probe (Campbell Scientific, USA). Measurements were taken each 5 cm across the cross-section, with ε and σ readings recorded simultaneously. After the reference data for interpretation have been gathered on the main soil pit (*lfc*), for the detailed study by GPR we realized running from *lfc* to the additional soil pit *lfv* on the distance of 52 m with the same soil and at the same geomorphological position, to track the spatial distribution of fragipan.

Particle size analysis

Laser analyser Microtrac Bluewave (Microtrac, USA) was used to determine the particle size distribution in soil samples. The speed of circulation was 50% of the maximum. Calculation of results was made with the following parameters. Particles were described as absorbing (absorption coefficient – 1) and of irregular shape, refractive index of distilled water – 1.33. Equipment software takes into account the fact that refractive index of absorbing particles does not significantly affect the results. Selected parameters are in agreement with early studies (Sochan *et al.* 2014). Samples were previously prepared by horn type ultrasonic disruptor (Stepped Solid Horn 1/2'', Digital Sonifier S-250D, Branson Ultrasonics, USA). The output of ultrasonic power was calibrated calorimetrically by the generally accepted method (North 1976). Ultrasonic dispersion energy was 450 J · ml-1. Then the sample aliquot (few ml) was placed directly to sample dispersion controller unit of analyser and processed. The upper limits of fractions were established based on Schoeneberger *et al.* (2012). Thus, the upper limit for the clay fraction is 0.002 mm, for silt 0.05 mm and for sand 2.0 mm.

Mineralogical composition of clay fraction by X-ray diffraction (XRD)

Clay size fraction (<2 μm) was separated by sedimentation in distilled water according to Stoke's law using the most unaggressive method (Moore, Reynolds 1997).

From the <2 μm fractions, air-dried oriented samples of clay saturated with Mg were obtained by pipetting some drops of the suspensions onto a glass slide, which was then dried at 30°C for a few hours (Moore, Reynolds 1997). Ethylenglycol solvation of the slides was achieved by exposing them to ethylenglycol vapor at 70°C for 24 hours.

Measurements were made using an EMPYREAN XRD diffractometer operating with an accelerating voltage of 45kV and a filament current of 40 mA, using CuKα radiation, nickel filter and PIXcel 3D detector. All samples were measured with a step size of 0.04° (2θ) and 40 s of scan step time.

Clay sample was examined by XRD in the air-dried form (AD), saturated with ethylenglycol (EG) and after heating (550°C). The preparations were measured over a 2θ angle range of 2–70° (air-dried) and 2–30º (glycolated and heated) at a speed of 1°(2θ)/min.

Clay species were estimated in semiquantitative form, from oriented preparations using simple peak weighting factors. For area estimation we used Fityk (Wojdyr 2010), a program for data processing and nonlinear curve fitting, simple background subtraction and easy placement of peaks and changing of peak parameters.

Micromorphological analysis

The micromorphology of soil horizons was studied in thin sections (30 μm thick) prepared from undisturbed soil samples impregnated at room temperature with the resin Cristal MC-40 using a standard procedure (e.g., FitzPatrick 1984). Micromorphological observations were performed under petrographic microscope OLIMPUS and the descriptions followed the terminology of Bullock *et al.* (1986) and Stoops (2003). The preparation of soil thin sections has been compounded by the presence on numerous rock fragment of different size class, so it was difficult to take the undisturbed sample.

RESULTS

The investigated Retisol profile (Fig. 2) was 1 m depth and contained abundant boulders from the top down to the bottom. Some of them had slightly rounded elongated shape; they were oriented vertically in a pit. The rock fragments on the bottom of the soil pit had a flat slightly rounded shape and were oriented horizontally. This soil had a clear texture differentiation, an argic horizon and albeluvic tonguing. The details of soil description are listed in Table 1. In the field description we marked the fragipan in EBx and Btx horizons, located between EB and Bt horizon. In the 'fragic' part of the profile there were some well-defined differences in the structure and composition of soil material, and also in the distribution of Fe-Mn nodules.

At the first stage of the geophysical studies, the reference interpretation model was obtained from the *lfc* soil pit. After sounding by GPR and TDR, the resultant data were compared to the established ho-

Fig. 2 The studied soil profile

Table 1 Main morphological properties of the soil profile. Codes according to Guidelines for soil description (FAO 2006)

Horizons	Depth cm	Boundary	Munsell colour (wet)	Structure	Coatings	Concentrations	Rock fragments	Roots
		D_T		G_T_S	A_K	A_K_S_Sh_H_N_C	A_S_Sh	A_D
O	0–2	A_W	–	–	–	–	C_BL_S	M_ F
Ah	2–8	A_W	10YR4/1	WE_GR_VF	N	N	C_BL_S	M_ F
E	8–20	C_W	10YR7/3	ST_PL_ME	N	F_C_F_R_H_FM_BR	C_BL_S	C_MC
EB	20–35	C_W	10YR6/4	WE_PL_ME	N	V_C_F_R_H_FM_BR	C_BL_S	C_MC
EBx	35–40	A_I	10YR4/4	WE_PR→PL_ CO→ME	N	N	C_BL_S	N
Btx	40–55	C_W	7,5YR3/4	WE_PS_FI	C_ST	N	C_BL_S	N
Bt	50–85	G_W	5YR3/4	MO_SB_FI	M_C	F_S_V_I_S_FM_BL	C_BL_S	V _ C
BC	85–100	–	10YR4/4	WE_SB_FI	F_C	F_S_V_I_S_FM_BL	C_BL_F	N

Horizon boundary: (D) distinctness: A = abrupt, C = clear, G = gradual; (T) topography: S = smooth, W = wavy, I = Irregular.

Structure: (G) grade: WE = weak, MO = moderate, ST = strong; (T) type: SB = subangular blocky, PR = prismatic, PS = subangular prismatic, GR = granular, PL = platy; (S) size class: VF = very fine/thin, FI = fine/thin, ME = medium.

Coatings: (A) abundance: N = none, F = few, C = common, M = many; (K) kind: C = clay, ST = silt coatings.

Concentrations: (A) abundance: N = none, V = very few; F = few; (K) kind: C = concretion, S = soft segregation; (S) size class: F = Fine; (Sh) shape class: R = rounded (spherical), I = irregular; (H) hardness: H = hard, S = soft; (N) nature: FM = iron-manganese; (C) colour: BR = brown, BL = black.

Rock fragments: (A) abundance: C = common; (S) size class: BL = boulders and large boulders; (Sh) shape class: F = flat, S = subrounded.

Roots: (A) abundance: N = none, V – very few, C = common, M = many; (D) diameter: F = fine, MC = medium and coarse.

rizon interfaces (Fig. 3A). The comparisons clearly showed that all the structural elements of the soil pit were manifested in the electrical properties. The plot for σ represented with a high degree of probability the conductivity (i.e. soil mineralization). It demonstrated that the conductivity changed from 3.6 · 10-4 to 10.1 · 10-4 S/m and increased with depth, and that specific step change regions were observed at -35 – -40 and -75 – -85 depths, corresponding to the EB(x) and BC horizons. The plot for ε showed that this parameter is less variable, the range of values being 2.5–5.2, and the sharpest transition occurred at the -20 depth (Ah–E boundary) where the value shift of one conditional unit was observed.

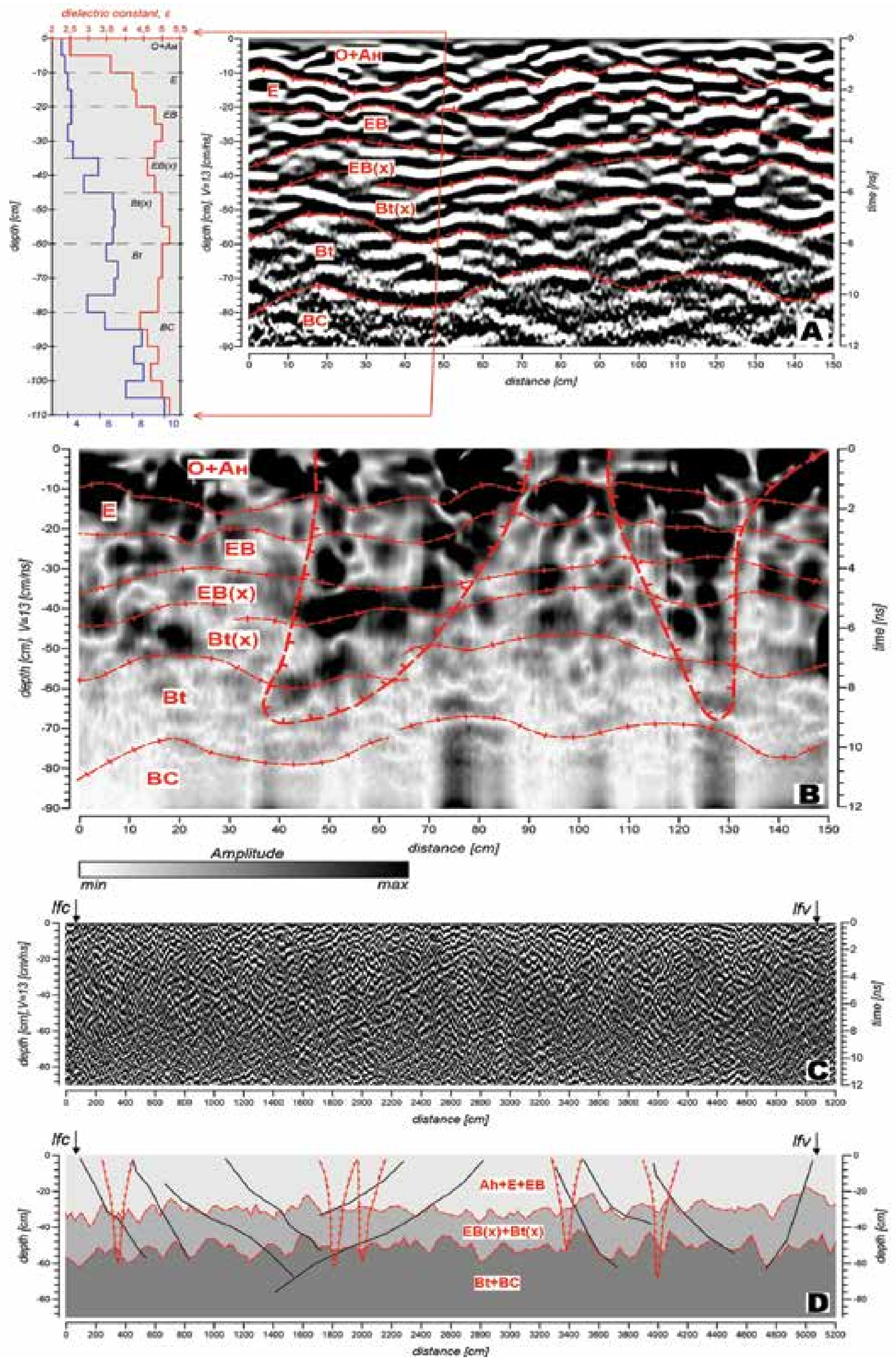

Fig. 3 Geophysical investigations: A – in *lfc* soil pit: left – TDR plot, right – GPR profile; B – amplitude profile, running from *lfc* to *lfv*; C – GPR profile; D – the interpretation model

Moving over to radargram analysis we recorded that in addition to the above mentioned boundaries it contained numerous extra reflections generated by internal variation of the composition, presence of boulders, roots, etc. The greatest contrast was observed at the Ah–E, EB–EB(x), Bt(x)–Bt boundaries, securing their reliable mapping throughout the study area.

Based on the available GPR profile with mapped soil boundaries (Fig. 3A) we obtained an amplitude profile (Fig. 3B). The structural boundaries were not visualized by the amplitude profile, but it clearly showed two areas with high reflection intensity (40–80 and 110–140 points), which could be interpreted as areas of precipitation seepage from the surface to the underlying horizons. This fact was corroborated by σ measurements by TDR data. Normally, the average conductivity is $\sigma = 6 \cdot 10\text{-}4$ S/m, whereas in the infiltration area it increases to $25 \cdot 10\text{-}4$ S/m. In addition to moisture migration areas, local maximums in the amplitude profile might indicate high stoniness of all horizons.

After reference data for interpretation have been gathered, a detailed study of the GPR profile running from lfc to lfv soil pit became possible (Fig. 3C). Relying on the established criteria, we developed the interpretation model and located the Ah + EB + E – EB(x) + Bt(x) and EB(x) + Bt(x) – Bt + BC boundaries, between which the studied fragipan horizon was situated (Fig. 3D). It was traced all along the GPR profile, showing a relatively steady thickness of ca. 15 cm. The boundaries were tortuous, suggesting there are numerous streaks with a vertical span of around 10 cm from overlying to underlying horizons. Also, a number of above-mentioned large infiltration areas were observed along the GPR profile. An interesting finding in the radargram was subtabular reflecting boundaries with different incidence directions (black lines in Fig. 3D). These boundaries do not correspond to specific soil horizons, but most probably represent some structural characteristics or, possibly, a bedding deformation of the entire surveyed formation.

The micromorphological observations demonstrated the indicators of various pedogenetic processes that took place in the studied soil profile (Fig. 4).

The Ah horizon was rich in roots and detritic organic material of different stages of decomposition (Fig. 4A). It had a complex microstructure with a combination of granular and isometric crumby aggregates. Dark organic pigment with heterogeneous distribution caused combination of dark-coloured and light-coloured micro-zones.

In the E (Fig. 4B) horizon we observed well-developed platy structure formed by a dense net of sub-horizontal fissures. Bleached loosely packed coarse sand and silt grains were dominant in the soil material. The structural aggregates demonstrated clear micro-zonality of the spatial distribution of different size fractions: prevailing bleached coarse grains were located in the lower part of platy units and close to the pores whereas fine material (silt with admixture of clay) was concentrated in the central and upper parts (Fig. 4B). This structure and micro-zonality resembled the "banded fabric" described by Van Vliet-Lanoë (2010). Furthermore, Fe-Mn nodules were widespread in the groundmass with rounded shapes and sharp boundaries (Fig. 4B).

All these properties were presented in the EB horizon (Fig. 4C), but the platy aggregates in this horizon were thinner, the Fe-Mn nodules were smaller although still having similar rounded shape.

The EBx horizon (Fig. 4D) showed strong differences with the overlying horizon. At the micromorphological scale, it demonstrated very compact homogeneous structure with no signs of platy aggregates. At the same time, it still had concentrations of bleached uncoated sand and silt material which showed signs of grain size micro-zonation: lenses of finer silty material alternate with the concentrations of sand grains. There were few brownish clayey areas in which sometimes illuvial clay coatings were observed. The latter however were deformed, fragmented and not related to the pores. The Fe-Mn nodules in this horizon were few; they were smaller, had irregular shape and diffuse boundaries.

The Btx horizon (Fig. 4E) was also a very compact horizon. It still had some concentrations of bleached coarse material; however brown clayey areas were dominant. Clay coatings were more frequent and less deformed than in the EBx horizon. There were some Fe-Mn nodules, with irregular shape and diffuse boundaries.

In the underlying Bt horizon the groundmass was enriched in clay and had brown colour. Large Fe-Mn mottles of irregular shape were frequent (Fig. 4G). Clay coatings filled a large part of available pore space (Fig. 4F). The larger ones were laminated and had strong interference colours (Fig. 4F). Few illuvial pedofeatures were deformed, fragmented and incorporated in ground mass that was a result of turbation processes.

The BC horizon (Fig. 4H) again had quite compact structure, coarse grains of various sizes were immersed in the clayey groundmass (porphyric c/f related distribution). Clay coatings and Fe-Mn mottles were small and few. We observed rock fragment containing clay coatings much larger than in the pores; we concluded that this feature was derived from parent material.

The texture analysis results are presented in the Table 2. All the horizons fell into the silt loam texture class. We paid major attention to the profile distribution of the sand sub-fraction contents as indicators of

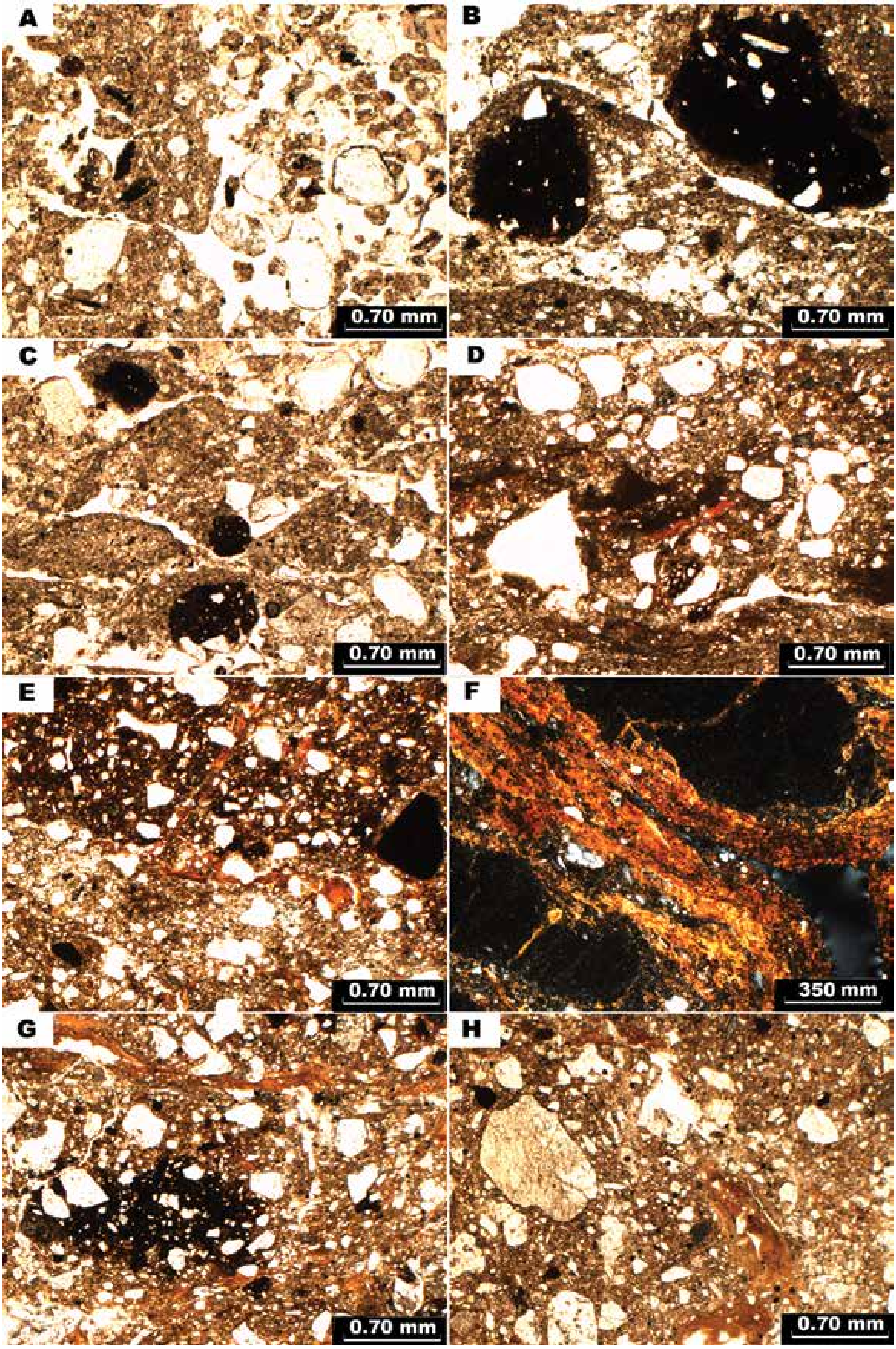

Fig. 4 Micromorphology of the Retisol genetic horizons; PPL – plane polarized light, N+ – crossed polarizers. A – coprogenic granular aggregates, fragmented plant residues; A horizon, PPL. B – platy structure, Fe-Mn nodules, banded fabric; E horizon, PPL. C – thin platy aggregates, small Fe-Mn nodules; EB horizon, PPL. D – compact structure, thin deformed clay coating, EBx horizon, PPL. E – neighbouring bleached and brown clayey microzones; Btx horizon, PPL. F – thick laminated clay coating with strong interference colours; Bt horizon, N+. G – illuvial clay coatings, ferruginous mottle; Bt horizon, PPL. H – porphyric c/f related distribution, thin clay coating; BC horizon, PPL

the lithological discontinuity. Nevertheless, there was almost no variation in subdivisions of sand fraction in each compared layer directly superimposed on the other. We further applied one of the criteria proposed by the WRB (IUSS Working Group 2014): as far as the soil is poor in coarse sand fraction; we calculated profile variations of the medium to fine sand ratio. The difference between the values of this coefficient in the neighbouring horizons reached maximum 15%, whereas the value not less than 25% is required as a reliable indicator of lithic discontinuity. The silt content was slightly higher in the upper part of the profile, and tended to decrease slowly in the argic horizon. The highest value was found in the E horizon, and the lowest was in the Bt horizon. The distribution of the clay material was much more differentiated: it was around 9% in the upper part of the profile and reached 15% at the bottom. The main change was detected in the transition from the EBx horizon to the Btx horizon.

The results of micromorphological and textural analysis were strongly connected with clay mineral composition. The clay minerals composition was complex in the studied soil (Fig. 5). The clay mineralogy of the profiles was composed by illite, chlorite, vermiculite, mixed layered and in lower amount by smectite and kaolinite. Smectite was confirmed by a strong (001) diffraction peak at about 14Å in air-dried condition that shifted to about 17Å in ethylene glycol treated samples and collapsed to 10Å after heating

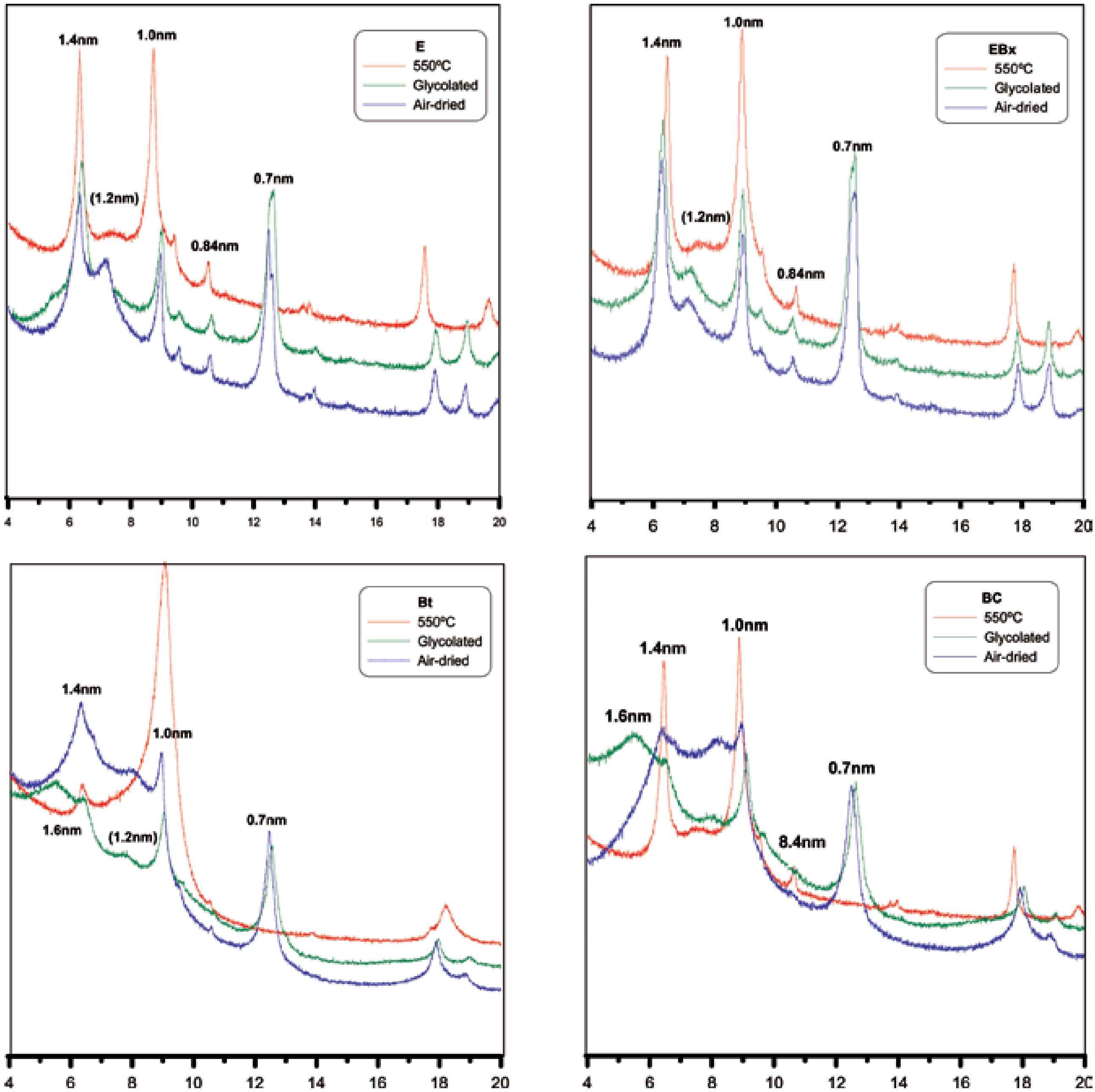

Fig. 5 X-ray diffraction patterns of clay fractions

Table 2 Particle size distribution of the soil profile and variation of the medium to fine sand ratio in horizons directly superimposed on the other

Horizons	Coarse Sand	Medium Sand	Fine Sand	Silt	Clay	Medium Sand/ Fine Sand
Volume, %						
Ah	1	17	7	56	9	15
E	2	17	6	57	9	3
EB	1	18	6	55	10	14
EBx	1	17	7	55	10	5
Btx	1	17	7	53	14	5
Bt	1	19	8	49	13	5
BC	1	16	7	52	15	

at 550°C. Vermiculite was not affected by ethylenglycol treatment and collapsed to 10 Å after heating while illite and chlorite profiles were unaffected by ethylenglycol solvation and heating. The discrimination between kaolinite and chlorite was complex due to the presence of the different peaks of other clay minerals and several heating experiments had to be carried out. By heating to 550ºC kaolinite becomes amorphous and its diffraction pattern disappears. In few samples kaolinite was identified in high resolution XRD measurements, because this mineral has the 002 peak at 24.9º and chlorites have their 004 reflection at 25.1º.

The presence of shoulders on ~14Å peak in most of the samples indicated the presence of illite-smectite mixed layer (I/S), which was determined in quantitative form after decomposing the spectra (air-dried and ethylenglycol treated samples) using profile fitting techniques.

Some of clay minerals were present in each soil horizon, for example chlorite, vermiculite and illite. The others occurred only in a specific part of the profile. The mixed layer minerals occurred almost in each horizon, except for the BC. The strongest differentiation was observed for smectites. These clay minerals were abundant only in the lower part of the profile, starting from the Btx horizon whereas in the upper eluvial part they were present as minor components.

DISCUSSION

We tried to reconstruct the formation of the Retisol during Holocene since the soil was formed after the deglaciation that happened in this area around 13–14.2 ha.

The typical soils of the Karelian region are Podzols (Classification and diagnostics of soils of the USSR 1987; Russian Soil Classification System 2001) due to the abundance of sandy deposits in this part of the country. The studied soil profile was formed in loamy glacial sediments and thus has an argic horizon at the depth of more than 50 cm and strong textural contrast: clay depletion together with strong bleaching in the upper horizons and clay increase in the medium and lower parts of the profile. The lateral continuity of this type of horizons was confirmed by the GPR profile measurements.

The verification of the litological uniformity versus discontinuity was one of the research tasks. As described above we applied the criterion proposed by WRB (IUSS Working Group WRB 2014): profile variations of the medium to fine sand ratio. As shown in Table 2 the differences between the neighboring horizons never exceed 15% whereas the shift of 25% is proposed as an indicator of discontinuity. These results fit well into macro- and micromorphological observations: in all the horizons we found a variety of coarse particles (from stones to silt) of similar sizes, shapes and mineralogical composition. Presence of stones in all horizons as a prominent feature was also detected by geophysical methods.

A notorious change related to the coarse material consists in the increase of silt fraction in the upper horizons. Frequently this tendency in the profiles of the Pleistocene periglacial area of Europe is explained by the input of eolian dust (e.g. Kleber, Terhorst 2013). We think that the alternative (or complementary) explanation of silt increase due to cryogenic fragmentation of coarser – sand and gravel – particles should be also considered, as proposed by Sedov and Shoba (1996). The process of physical breakdown of coarse mineral grains affected by freeze-thaw cycles is widely known and well documented experimentally; this process is known to produce silt-size particles (Konischev, Rogov 1994). It was shown that this breakdown could be accelerated when frost action is combined with the acid chemical weathering in the upper horizons of boreal forest soils (Leporsky *et al.* 1990). Taking into account this previous research and considerable resource of coarse particles in the studied profile we suppose that cryogenic fragmentation should be responsible at least partly for the silt accumulation in the upper horizons. Anyway if addition of eolian dust had taken place it could provide only minor admixture and did not result in the formation of a specific upper stratum and major lithological discontinuity – as shown by grain size and morphological criteria.

As far as no signs of a major lithological discontinuity have been detected, we suppose that differences in particle size distribution were generated predominantly by pedogenic processes. High clay content in the lower part of the profile is explained by clay illuviation, evidenced by the clay coatings observed in the thin sections especially abundant in the Bt horizon. Another mechanism of clay differentiation could be related to acid weathering of unstable clay minerals. Strong differentiation of clay mineral assemblages within the profile with strong decrease in the smectites, the most weatherable components, in the upper soil horizons proves this assumption (Targulian *et al.* 1974, Tonkonogov *et al.* 1987).

What combination of soil forming factors could be responsible for such strong clay migration process? Since we know that this soil was formed during the Holocene, we revised published data about paleoecological records for Karelia for this period.

During the Holocene, the climate conditions in Karelia were changing, and in some periods were different from the actual conditions. Thus, around 6000 years ago, the vegetation in this area was characterized by such trees like *Quercus, Tilia, Ulmus*, that are common in broad-leaved forests (Sandgren *et al.* 2004; Yelina, Filimonova 2007). The southern taiga zone was at that time up to 66° of North Latitude, so the studied soil developed under warmer temperature regime and had less acidity due to the composition of litter. The texture differentiation most likely took place at that time, so we could associate the formation of strong clay coatings with the Atlantic period of the Holocene. During the succeeding period around 3000–3500 years ago this area suffered relative fall of the temperature and was covered by boreal (north taiga) pine and spruce forests (Yelina, Filimonova 2007; Dolukhanov *et al.* 2009).

The consolidation took place in the lower part of the EB horizon and the upper part of the Bt horizon, that is confirmed by the interpretation of GPR observations. The micromorphological analysis has shown that compaction occurred in the material which already had features of eluvial (bleached microzones) and illuvial (deformed clay coatings) processes, typical for the transitional horizons of a Luvisol profile. At the same time a frost-induced feature – grainsize microzonation – developed in EBx. We suppose that the formation of the fragic horizon happened after the texture differentiation, probably during the Sub-Boreal period.

The upper E and EB horizon have well-developed platy structure that was formed because of recent ice lensing during seasonal freezing. The current seasonal cryogenic aggregation and the bioturbation are destroying the consolidated part and involve it into the modern soil formation. We also attribute the stagnic (surface redox) processes which produce rounded Fe–Mn nodules in the E and EB horizons to the modern active soil forming processes as well. The material of the albeluvic tongues has the same properties as the entire E horizon, but is more compact.

Fragipan horizon, although being partly inherited feature, has an important influence on the present day soil processes and regimes. Geophysical investigations showed strong spatial differentiation of soil hydrological characteristics associated with fragipan structure. Along glossic features there are directions of preferential water flow, demonstrated by higher water content in the radargram and amplitude profile of geophysics observations. Taking into account that the major part of fragipan has low permeability and that according to the GPR profile it is laterally continuous, we suppose that it is a major factor of water logging and stagnic processes in the overlying E and EB horizons.

Recent investigations connect the fragipan formation with high concentration of swelling clay minerals (Szymanski *et al.* 2012; Nikorych *et al.* 2014). In the case of Karelian fragipan, there are no smectite clay minerals in the EBx horizon; they appear only in the lower horizons. This feature also correlates with a texture class analysis, because the argic horizon is enriched with clay minerals if compared to the textural composition of the albic horizon. The smectites are the most unstable component of clay minerals complex (Targulian *et al.* 1974). Probably, their accumulation in the lower part of the profile happens because of the preferential mobilization by the illuviation processes and/or because those minerals were selectively destroyed in the upper part of the profile with more aggressive weathering conditions.

CONCLUSIONS

We consider that in the studied soil profile the fragipan, the high density soil horizon, the features of eluvial, gleyic and turbation processes are less intensive than in overlying and underlying soil horizons as it was developed in the transitional zone of Albic Retisol profile. We also suppose that the compaction process has occurred in a Sub-Boreal period after a previous illuviation took place during the Atlantic optimum. The consolidation of fragipan is not connected with swelling clay minerals in the case of Karelia Retisol profile.

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