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Ground-penetrating radar study of the Rahivere peat bog, eastern Estonia

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Abstract. The current case study presents results of the ground-penetrating radar (GPR) profiling at one of the Saadjärve drumlin field interstitial troughs, the Rahivere bog, eastern Estonia. The study was conducted in order to identify the bog morphology, and the thickness and geometry of the peat body. The method was also used to describe the applicability of GPR in the evaluation of the peat deposit reserve as the Rahivere bog belongs among the officially registered peat reserves. Fourteen GPR profiles, ~100 m apart and oriented perpendicular to the long axis of the depression, covering the bog and its surrounding areas, were acquired. In order to verify the radar image interpretation as well as to evaluate the velocity of electromagnetic waves in peat, a common source configuration was utilized and thirteen boreholes were drilled on the GPR profiles. A mean value of 0.036 m ns^{-1} corresponding to relative dielectric permittivity of 69.7 was used for the time–depth conversion. Radar images reveal major reflection from the peat–soil interface up to a depth of about 4 m, whereas drillings showed a maximum thickness of 4.5 m of peat. Minor reflections appear from the upper peat and mineral soil. According to the borehole data, undecomposed peat is underlain by decomposed one, but identifying them by GPR is complicated. Mineral soil consists of glaciolimnic silty sand in the peripheral areas of the trough, overlain by limnic clay in the central part. The calculated peat volumes (1 200 000 m^3) were found to exceed the earlier estimation (979 000 m^3) that was based solely on drilling data. Ground-penetrating radar, as a method that allows mapping horizontal continuity of the sub-peat interface in a non-destructive way, was found to provide detailed information for evaluating peat depth and extent.

Key words: ground-penetrating radar, bog, peat, deposit, relative dielectric permittivity, Saadjärve drumlin field, Vooremaa, Estonia.

INTRODUCTION

The Rahivere bog (centred at 58°41′32″N; 26°43′26″E; Fig. 1) is located within a trough between drumlins in the east-central part of the 1200 km^2 Saadjärve drumlin field, eastern Estonia. The bog is a 1.3 km long and 0.8 km wide ellipsoid that occupies an area of ~0.91 km^2. It is elongated in the direction of neighbouring drumlins (Ronivere-Aluküla drumlin in the northeastern and Rahivere drumlin in the southwestern side) oriented 310–320° to 130–140°, which is a common orientation for the whole drumlin field and the Late Weichselian ice sheet flow between the Otepää and Pandivere phases about 12 600–12 050 yr BP (Pirrus & Raukas 1996). In the Rahivere area the bedrock is composed of Llandoverian lime- and dolostones overlain by a thin cover of Middle Devonian sand- and siltstones (Rattas & Piotrowski 2003). The bedrock is covered by Middle and Upper Pleistocene till beds and stratified glaciofluvial and glaciolimnic deposits up to 61 m thick in a top-drumlin core closest to Rahivere (No. 439, located ~4.5 km westwards from Rahivere; Rattas & Kalm 2001). Post-glacial clay, gyttja, lake lime and peat fill the interstitial troughs in the Saadjärve drumlin field (e.g. Pirrus et al. 1987). All swamps in the area have developed from post-glacial lakes (Rõuk & Raukas 1989). Several of the wider and deeper troughs in the field still host water bodies, but most have become swampy. Raised bogs like Rahivere are rare.

Earlier, Rahivere has been studied in the course of regional prospecting for peat deposits (Allikvee & Orru 1979). On the basis of data from 13 cores and topographic data, the bog and economically important reserves of 979 000 m^3 on 0.54 km^2 were outlined. The reserves are divided into undecomposed (77 000 m^3) and underlying (well-) decomposed (902 000 m^3) peat. Raised and transition bog *Sphagnum* peat with a mean thickness of 1.84 m (max 3.6 m) were reported to occur mainly in the central, bare area (~0.2 km^2) and in the closest forested surroundings, whereas fen peat (mean thickness 1.04 m, max 1.7 m) prevails in the fringe of the studied site. The surrounding forested area has been drained, because Rahivere is located in a watershed with outflows to the south and northwest. Small, old, hand-cut peat pits occur in the southwestern side of the bog. As Rahivere is one of the few bogs preserved in the area, Allikvee & Orru (1979) recommended to save it from exploitation and to study the reasons for relatively rapid bog-formation instead.

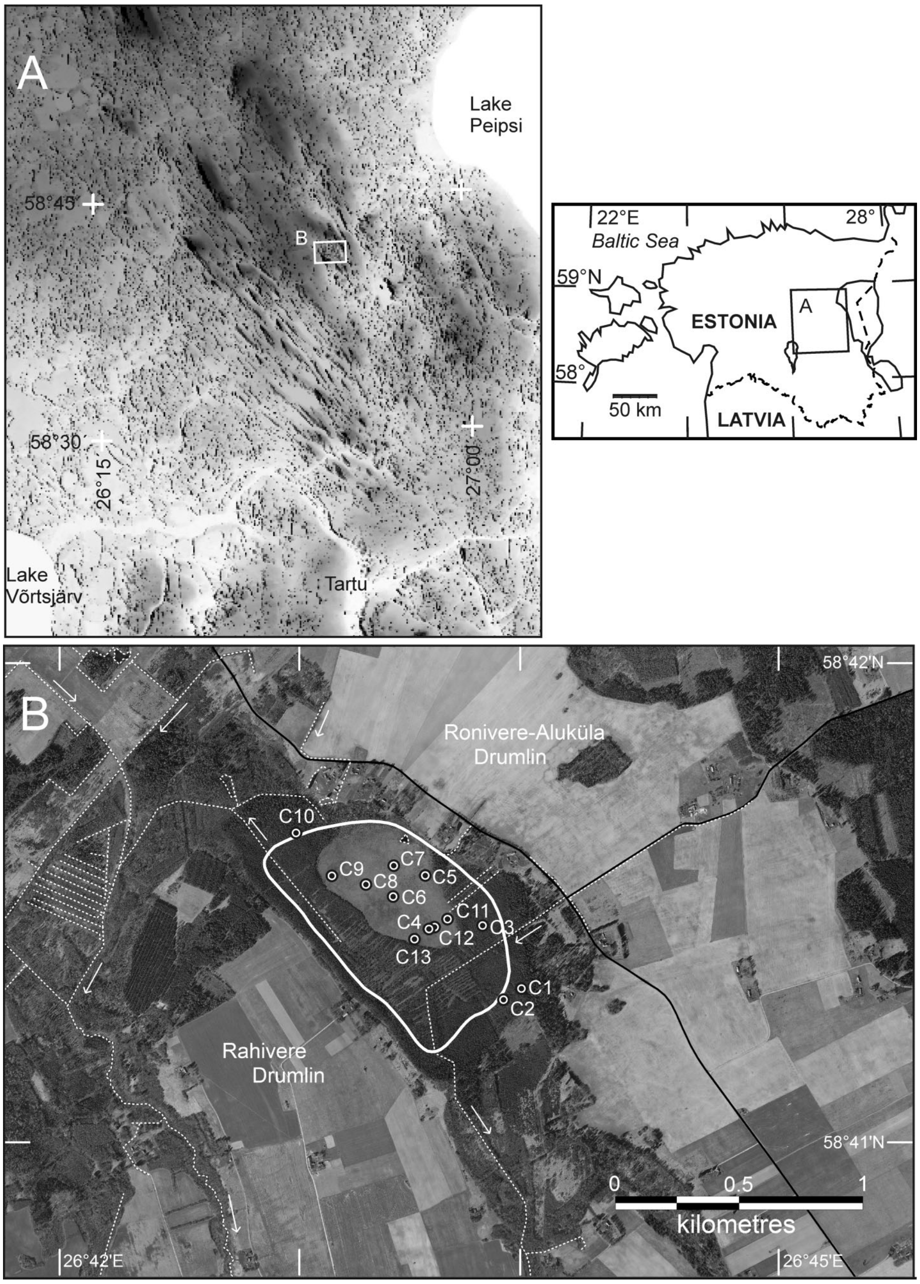

Fig. 1. (A) Digital Terrain Model of the Saadjärve drumlin field in eastern Estonia with location of the Rahivere bog. (B) Aerial photograph of the Rahivere bog and neighbouring drumlins. The white outline of the bog originates from a report by Allikvee & Orru (1979). Locations of cores of the present study are shown by dots, and labelled (for descriptions see Table 1). The photo, location of ditches (white dotted lines) and flow directions (white arrows) were obtained from datasets of the Estonian Land Board.

The present study describes the results of the ground-penetrating radar (GPR) profiling combined with coring at Rahivere in order to identify the geometry of the interstitial trough. It also describes the applicability of GPR in the evaluation of peat reserves. Domestically, the technique of combining the GPR data with coring has only been applied while studying hydrogeological conditions in the Selisoo bog in northeastern Estonia (unpublished data by the authors). Internationally, the method has been widely applied in peat studies already for several decades mainly because it provides a high-resolution and non-invasive way to map the depth to the mineral beds, i.e. thickness of peat. However, the stratigraphic information on the peat profile which can be obtained from GPR measurements is less clear. The method is effective as moisture content changes occur at the interfaces of peat and soil, causing reflections of the electromagnetic wave (EMW). The moisture content changes are related to the type and density of sediment and its organic matter content (e.g. Warner et al. 1990). Peat materials are characterized by high porosity and water content as saturated water contents are reported to vary from nearly 100% for undecomposed *Sphagnum* moss peat in near-surface horizons to about 80% for decomposed peat in deeper horizons (Boelter 1968). The significant drop in moisture content in the mineral soil under peat results in large-amplitude EMW reflections from the peat–soil interface. In several cases this circumstance has allowed successful identification of the base of a peatland (e.g. Bjelm 1980; Meyer 1989; Mellet 1995; Comas et al. 2005). Often coring has been used along with GPR not only for correlating the reflections with stratigraphy, but also for adjusting the velocity of the EMW (V_{EMW}), closely related to the dielectric permittivity (ε) of the sediment, in order to convert travel-time into the depth scale.

METHODS

The GPR surveys were performed with a Zond 12-e system by Radar Systems Inc., using common offset configuration with co-polarized 300 MHz centre frequency shielded antenna oriented perpendicular to the profile. Fourteen GPR profiles, ~100 m apart and oriented perpendicular to the long axis of the depression, covering the bog and its surrounding areas, were created by pulling the antenna at walking speed (Fig. 2). The GPR signals were triggered at constant spacing (5 cm) by an odometer wheel and coordinated with the help of a portable GPS instrument (Altina GGM309; position accuracy 5–25 m) connected to the radar. To amplify the reflections and reduce the noise level, stacking of eight measurements was applied. Data were recorded using 300–500 ns time windows. Zero-time position (representing the first break record) was computed automatically by the radar device software.

The GPR data post-processing was performed with the Prism2 software (Radar Systems, Inc. 2005). A signal saturation correction (‘band-pass’ filter) was applied to the recorded data to remove low-frequency (<100 MHz) induction effects. For better visualization of deeper reflections a time-dependent gain was used. The most prominent reflection from the interface between the overlying peat and mineral soil was traced by clicking on it at about every 10 m, thus, avoiding short-wavelength undulations due to hummocky terrain. Coordinates and two-way travel time (TWT) were attributed to every click (locations are shown in Fig. 2).

Most of the field measurements were performed in February 2009 with additional tests in July 2009. The EMW velocities were estimated using (i) a depth-to-target method, which consists of calculating the velocity required

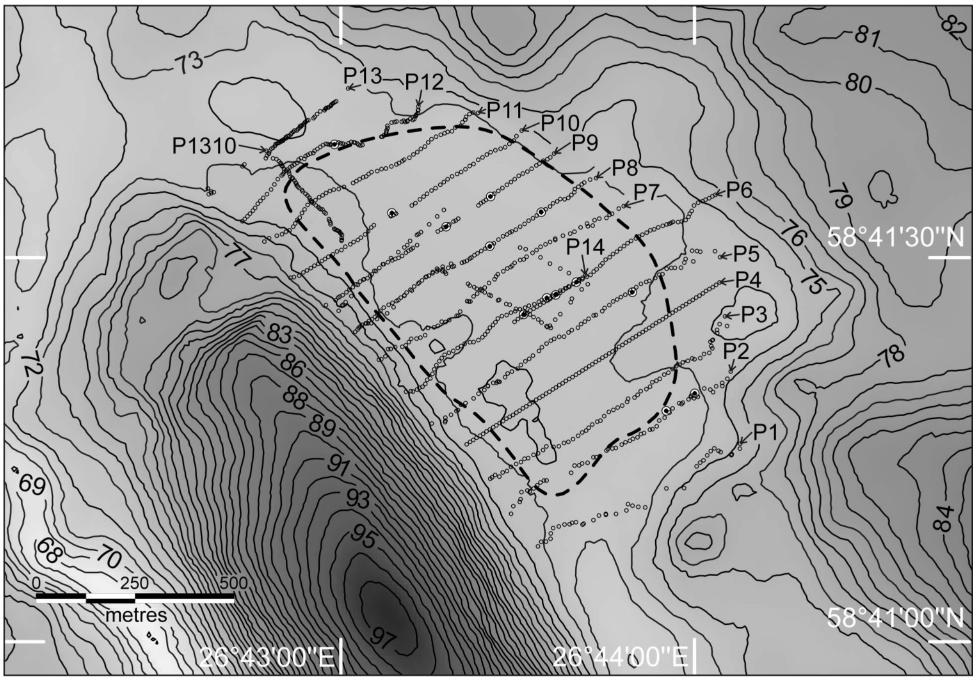

Fig. 2. Topographic elevations (m) at Rahivere as derived from the airborne photogrammetrical data (Estonian Land Board). The dashed outline of the bog originates from the report by Allikvee & Orru (1979). Locations of GPR-based peat thickness estimates are shown by dots and labelled by profiles (P).

for the best fit between a GPR peat thickness estimate and drilling (see Fig. 1 for locations and Table 1 for descriptions), and (ii) common source configuration (Daniels 2004) in three locations (cores 11, 12 and 13), each in four perpendicular directions combined with drillings and profiles. For the latter configuration the transmitting and receiving antennas with frequencies of 300 and 500 MHz were used, respectively. Thirteen peat cores were obtained manually with a 0.5 m long sample chamber and qualitatively described in the field. The likely sinking effects in the summer season due to the load of operators and instruments were not taken into consideration.

Table 1. Location and description of the Rahivere cores and EMW-related parameters estimated at the same site

Core No.	Geographic location & date	Depth, m	Description	TWT, ns	V, m ns^{-1}	ε_r (–)
1	58°41′17.74″N;	0.00–0.70	Undecomposed peat	80.4	0.038	64.7
	26°43′56.68″E	0.70–1.50	Decomposed peat			
	27 February 2009	1.50–1.55+	Silty sand			
2	58°41′16.40″N;	0.00–0.55	Undecomposed peat	89.2	0.035	74.5
	26°43′52.10″E	0.55–1.55	Decomposed peat			
	27 February 2009	1.55–1.60+	Silty sand			
3	58°41′26.16″N;	0.00–1.80	Undecomposed peat	98.0	0.037	66.7
	26°43′47.57″E	1.80–1.85+	Silty sand			
	27 February 2009					
4	58°41′25.98″N;	0.00–1.30	Undecomposed peat	250.0	0.034	74.3
	26°43′34.18″E	1.30–3.95	Decomposed peat			
	27 February 2009	3.95–4.35	Gyttja			
		4.35–4.85+	Clay			
5	58°41′32.96″N;	0.00–1.95	Undecomposed peat	102.1	0.039	61.7
	26°43′33.85″E	1.95–2.00+	Silty sand			
	27 February 2009					
6	58°41′30.37″N;	0.00–1.15	Undecomposed peat	194.3	0.034	75.7
	26°43′25.61″E	1.15–3.15	Decomposed peat			
	27 February 2009	3.15–3.35	Gyttja			
		3.35–5.05+	Clay			
7	58°41′32.10″N;	0.00–1.20	Undecomposed peat	175.9	0.036	68.0
	26°43′18.91″E	1.20–3.20	Decomposed peat			
	27 February 2009	3.20–5.40+	Clay			
8	58°41′34.40″N;	0.00–1.15	Undecomposed peat	178.8	0.035	70.2
	26°43′26.04″E	1.15–2.90	Decomposed peat			
	27 February 2009	2.90–3.20	Gyttja			
		3.20–4.90+	Clay			
9	58°41′33.40″N;	0.00–1.65	Undecomposed peat	226.5	0.035	72.1
	26°43′10.52″E	1.65–4.00	Decomposed peat			
	27 February 2009	4.00–4.35+	Clay			
10	58°41′39.16″N;	0.00–1.80	Undecomposed peat	93.1	0.039	60.1
	26°43′1.99″E	1.80–1.95+	Clay			
	27 February 2009					
11	58°41′27.17″N;	0.00–1.00	Undecomposed peat	125.6	0.037	67.1
	26°43′38.89″E	1.00–2.30	Decomposed peat			(67.2)
	22 July 2009	2.30–2.40	Clay			
		2.40–2.60+	Silty sand			
12	58°41′26.20″N;	0.00–1.00	Undecomposed peat	191.4	0.035	73.4
	26°43′35.58″E	1.00–3.35	Decomposed peat			(70.1)
	22 July 2009	3.35–4.30	Clay			
		4.30–5.00+	Silty sand			
13	58°41′24.72″N;	0.00–1.20	Undecomposed peat	134.4	0.037	65.0
	26°43′30.47″E	1.20–2.50	Decomposed peat			(66.4)
	22 July 2009	2.50–2.70+	Clay			

TWT = two-way travel time, V = speed of the electromagnetic wave, ε_r = relative dielectric permittivity estimated by the depth-to-target and common source techniques (the latter is given within parentheses).

Topographic elevations were derived from the airborne (2007) photogrammetrical data (~1000 data points per 1 km^2; flight altitude 4670 m; vertical/horizontal resolution 0.3–0.6/0.4 m) by the Estonian Land Board and were gridded by the authors (Fig. 2). The elevation data were found to reflect general topography well, but, of course, do not contain the smallest local variations that cause some high-frequency undulations of reflections seen in radar images. The TWT data were converted into depth, thus, the altitude of the top surface of the underlying mineral soil was obtained. The data were gridded (5 m × 5 m) by kriging, a method (e.g. Stein 1999) that allows creation of reliable interpolations based on spatially varying observations. The volume of peat was calculated with the help of the MapInfo software package by Pitney Bowes Software Inc. Maps of the thickness of peat and topography of the peat's basal surface were compiled.

RESULTS

Coring

Peat deposits (Table 1) were divided into undecomposed (fibric) and underlying decomposed (sapric) black muddy highly humified (up to H9 according to the von Post humification H scale) peat, whereas the boundary between the two types was sharp. The maximum thicknesses (3.9 and 4.0 m) of peat, which correspond to the maximum thickness of 4.4 m described by Allikvee & Orru (1979), were recorded in cores 4 and 9 (Fig. 1) in the central part of the depression. The thicknesses of undecomposed and decomposed peat were 0.55–1.95 m and 0–2.65 m, respectively. Decomposed peat was missing in the cores extracted along the side of the bog. In deeper parts of the basin peat was underlain by a few decimetres thick (max. 1.7 m by Allikvee & Orru 1979 was not reached by the present study) greenish gelatinous layer of gyttja and greenish-grey limnic clay often containing remains of millimetre-scaled shells. In shallower parts glaciolimnic silty sand, impenetrable for the hand corer, forms a direct base for peat. Thus, the drilling data refer to a post-glacial lake that existed in the depression prior to the formation of the swamp and bog.

Velocity calibration

The EMW velocities were estimated using a depth-to-target method. The procedure was repeated at all drilling sites (Table 1) and the mean EMW velocities were considered to represent the best velocity for calibration. The relative dielectric permittivity (ε_r) values were found to be relatively high, varying between 60.1 and 75.7, corresponding to V_{EMW} values from 0.034 to 0.039 m ns^{-1}. The mean of ε_r from all 13 determinations is 69.7 with the standard deviation of 5.1, whereas there is almost no difference between the winter (69.9 ± 5.5) and summer (69.0 ± 4.4) measurements. The mean value of 69.7 that corresponds to $V_{\mathrm{EMW}} = 0.036$ m ns^{-1} was used while converting the TWT into depth. The result corresponds to the ε_r values obtained by the common source technique at four individual perpendicular profiles at three sites (C11–C13), revealing apparent ε_r values ranging from 60.8 to 76.3, depending on the topography of the reflector surface between peat and mineral soil. The mean values from different sites (Fig. 3, Table 1) give an overall mean of 67.9 ± 1.9.

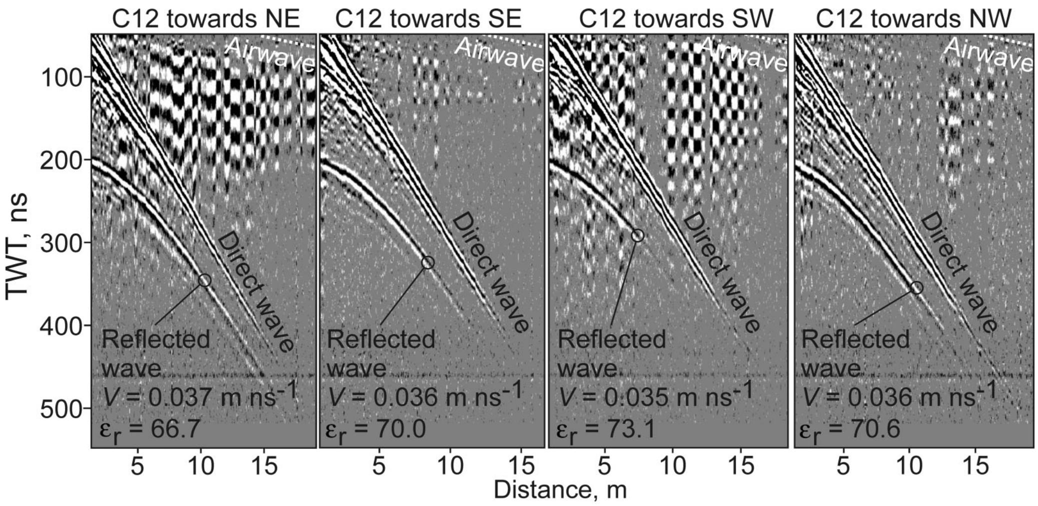

Fig. 3. Radar images obtained by the common source technique (Daniels 2004) in location C12 (Fig. 1, Table 1) at 0-distance. The radar images were headed into four perpendicular directions as indicated in the headings. Hyperbolic reflections from the base of peat were used to determine the speed of the EMW and relative dielectric permittivity (ε_r) of peat. The results differ mainly because the reflecting surface is tilted.

Ground-penetrating radar surveys

The GPR profiling results combined with coring data are illustrated by three typical radar images in Fig. 4 and selected segments of images in Fig. 5. A prominent reflector detected and confirmed on GPR profiles is distinguishable to a depth of about 4 m. The reflection originates from the boundary between the overlying peat (and gyttja) and the underlying late- and post-glacial lake sediments (silty sand and clay). The reflector deepens towards the long axis of the depression with a dip generally <0.5°. The dip is slightly larger in the

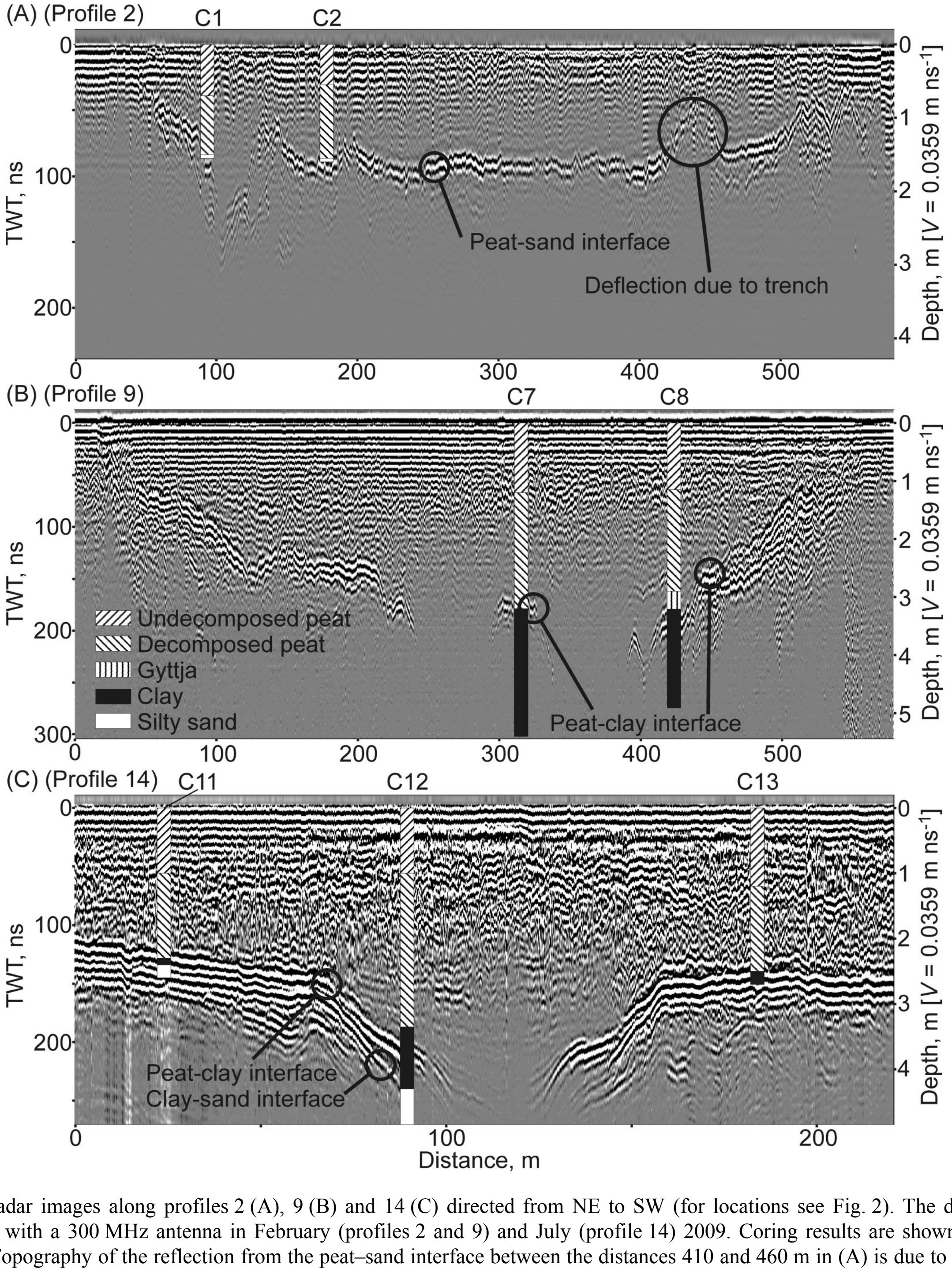

Fig. 4. Radar images along profiles 2 (A), 9 (B) and 14 (C) directed from NE to SW (for locations see Fig. 2). The data were collected with a 300 MHz antenna in February (profiles 2 and 9) and July (profile 14) 2009. Coring results are shown in each profile. Topography of the reflection from the peat–sand interface between the distances 410 and 460 m in (A) is due to a narrow ~1.5 m deep trench perpendicular to the profile. Drainage has caused a decrease in dielectric permittivity (increase in EMW velocity) and virtual deflection of the reflector. Note the differences in vertical exaggeration.

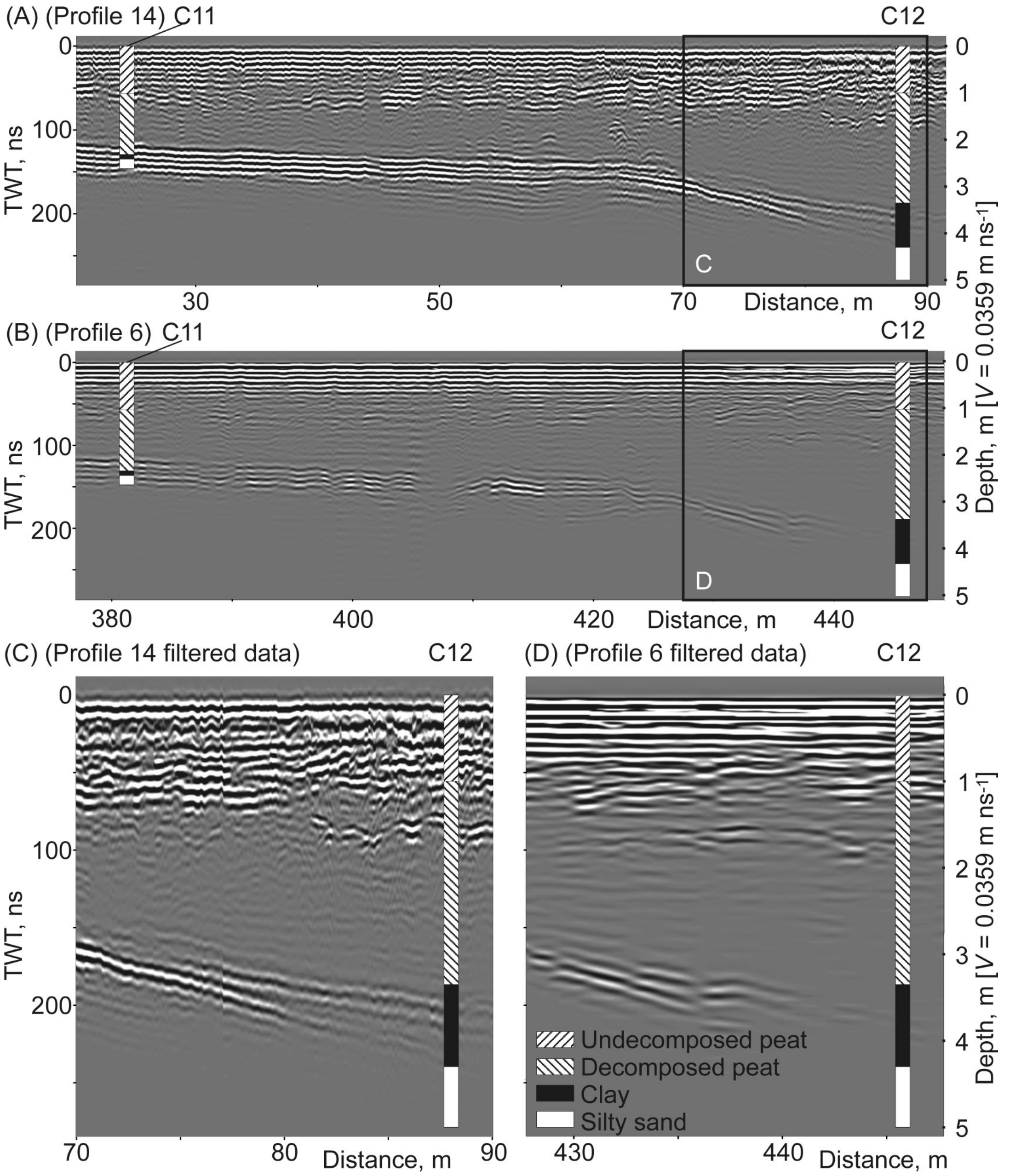

Fig. 5. Selected segments of radar images along two closely located profiles [14 (A) and 6 (B)] directed from NE to SW (for locations see Fig. 2), which were recorded with a 300 MHz antenna in winter (February, profile 6) and summer (July, profile 14) seasons in 2009. The images shown in (C) and (D) are close-up views of the areas in (A) and (B), respectively. (A) and (B) are based on original data after gain only, whereas (C) and (D) are filtered (identically: gain + spatial (1 m) low pass filter) to visualize different patterns originating from undecomposed and decomposed peat. Coring results are shown in each profile. Note the differences in vertical exaggeration.

sharper southwestern edge of the bog and smallest between the altitudes of 69.5 and 70.5 m (Fig. 6A), resembling a terrace-like feature that may refer to an old shoreline. This is a few metres above the highest water level of proglacial lakes at the Siimusti–Kaiu ice-marginal stage (13 800–13 600 yr BP; Rosentau et al. 2007), which was the closest northern position to Rahivere during the ice retreat. Therefore, isolation of the trough and location in a watershed caused a relatively high water level.

Two deep but narrow elongated (~500 m long, 50–100 m wide) incisions down to an altitude of 68 m, with

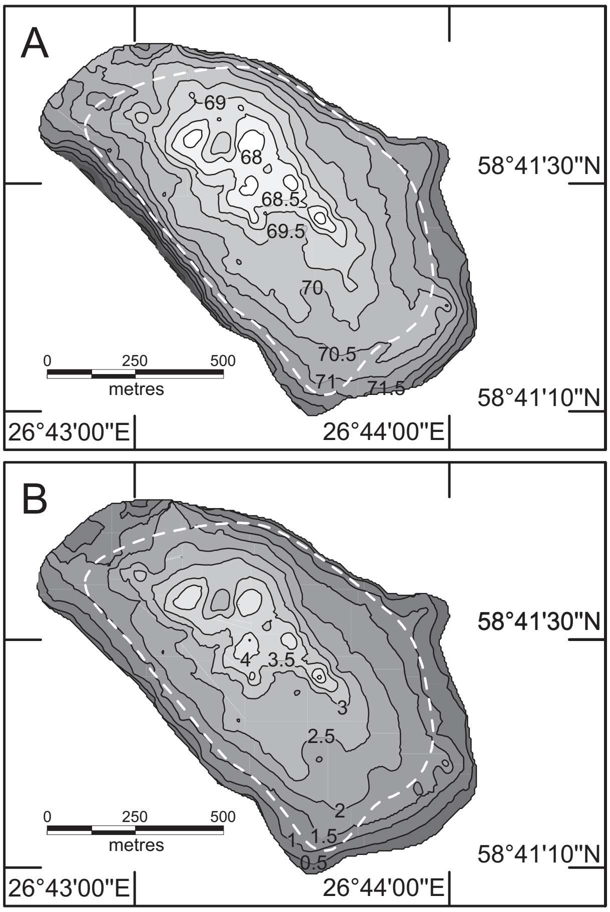

Fig. 6. (A) Topography of the basal peat surface (m a.s.l.) as based on GPR studies and photogrammetrical data. (B) Thickness of peat (m) in the Rahivere bog. The white dashed line indicates the boundary of the peat deposit by Allikvee & Orru (1979). The current outline is drawn by occurrences of peat.

a maximum dip of slopes ~2.5° exist in the central part of the depression (Figs 4 and 6). The incisions are elongated in the direction of drumlins, whereas a set of two incisions is separated by a narrow ridge (Fig. 4B), which is better pronounced in the northwestern side of the bog. The incisions are filled with limnic clay. No signal is obtained from the deep bottoms (interface with sand/till) of these incisions, but the direction of their elongation suggests their primary glacial origin. Within the incisions the EM signal is gradually weakened with depth, possibly mainly because of the higher electric conductivity of the clayey infill which tends to attenuate the radar wave significantly. The effect of high conductivity also induces attenuation of the EMW beyond the limits of the bog in areas (e.g. slopes of drumlins) where glacial till forms the uppermost subsurface. There, the signal is lost within the first 50 ns (TWT) and no considerable reflections originate due to homogeneous subsurface texture.

In the slopes of the depression no clear reflections originate from the interface between silty sand and till but some wavy reflections are seen within sand. Generally, these reflections are short and tilted towards the centre of the depression. A thin layer of gyttja identified in three cores under the peat does not clearly differentiate in radar images. Most likely the physical properties of gyttja are too similar to those of decomposed peat.

In spite of the sharp boundary between undecomposed and decomposed peat in the cores, the difference in radar images is not sufficiently clear for delimiting that boundary. The overlying undecomposed peat differs from the decomposed counterpart in a higher intensity and larger amount of spatially elongated reflections, but no sharp unambiguously comprehensible boundary in the pattern exists (Fig. 5). Decomposed peat occasionally reveals overturned V-shaped reflections from less-decomposed components, remnants of wood, for example, but such features can be found within the undecomposed peat body as well. The existence of several alternative levels for the interpretation of the peat decompositional boundary might be an indication that this boundary is more transitional than it appears to be in cores. As the intensity of reflections is a function of gain, we were unable to delineate the boundary between the two decompositional types of peat.

DISCUSSION

Ground-penetrating radar surveys are widely used to investigate the thickness and stratigraphy of peat in wetlands. It is also used to identify peat structure, boundaries between peat and lake sediments (Slater & Reeve 2002), sedimentological histories of wetlands, and ecological aspects by determining temporal changes in biogenic gas content in peat soils (Comas et al. 2008). To meet the specific aims of the studies, the GPR method is often combined with other available methods like peat coring (Rosa et al. 2009), and electric (Kettridge et al. 2008) and hydraulic (Lowry et al. 2009) conductivity surveys. Penetration depth of the GPR signal in peatlands is usually good (may reach >10 m) because of the low electrical conductivity and sharp increase in water retention capacity between peat and mineral sediment. Owing to extensive studies, several V_{EMW} and ε_{r} determinations of peat exist worldwide, which are summarized by Lowry et al. (2009). Compared to other geological media, the reported velocities (0.033–0.049 m ns^{-1}) are low and relative permittivities high (40.7–81) mainly due to high content of water in peat, and are in accordance with the results ($V_{\mathrm{EMW}} = 0.0359 \pm 0.0016$ m ns^{-1}; $\varepsilon_{\mathrm{r}} = 69.7 \pm 5.1$) from Rahivere.

Slight seasonal differences in permittivities can be attributed (i) to different temperatures of peat water and biogenic gas (e.g. Comas et al. 2008) contents, (ii) to effects of snow and ice and (iii) to effects of the load of operators and instruments in the summer season. During the campaign in February 2009 the bog was covered by a 10–15 cm thick layer of snow and occasionally (in a few central locations where peat was saturated with water) ~10 cm of the topmost peat was frozen. Assuming that snow was compacted by antennas to a uniform thickness of 10 cm and a relative dielectric permittivity (ε_{r}) of snow (~2 at a density of 500 kg m^{-3}; Godio 2009), the additional effect of snow to radar images stayed below 1 ns. The local effect of ice ($3 < \varepsilon_{\mathrm{r}} < 4$; Davis & Annan 1989) could be a few nanoseconds towards fastening the EMW velocity, thus, towards underestimation of the thickness of peat. Underestimation of peat thickness could also be caused by the load of operators and instruments especially during coring, and is greater in the summer season.

Another seasonal effect is demonstrated in Fig. 5 while comparing the winter (February 2009) result with the results from the closely located profile made in summer (July 2009). The winter radar image includes more horizontal and parallel features within the first 50 ns (TWT) which are likely produced by reflections from the interfaces between snow, ice and peat. These reflections complicate the interpretation of the uppermost subsurface, including the definition of the boundary between decompositional types of peat.

In spite of the possible errors described above, cored peat thicknesses correspond relatively well (Fig. 7) to those calculated from the GPR data. Slight undulations have a common nature as GPR tends to reveal greater thicknesses in deeper parts of the bog. Most likely this is caused by the extent of water-saturation: at the drained edges of the Rahivere bog where peat is thinner, non-saturated conditions of subsurface prevail, whereas the central part with a thick peat body is fully water-saturated. As the actual value of ε_{r} is lower and V_{EMW} higher at the drained edges than the mean values (69.7 and 0.036 m ns^{-1}, respectively), the calculated depth to the mineral base (thickness of peat by GPR) is somewhat lower. Water-saturation is responsible for a slight (up to 0.2 m) statistical deviation at the deepest locations, but there the thickness of peat measured with GPR is higher than the real thickness. A prominent effect of drainage was observed in profile 2 (Fig. 4A) that crossed a deep excavated trench in the southern part of the bog. It is obvious due to virtual upward deflection of the reflective interface between peat and sand. The deflection and thus dewatering of the top layers of peat extend to tens of metres from the trench.

The degree of decomposition determines the physical properties of peat. Undecomposed peat has low bulk density (10–52 kg m^{-3}; Boelter 1968) and high fibre content; therefore, it contains many large pores and may have a total porosity as high as 97% (Päivänen 1973). As peat decomposes it becomes denser and its porosity reduces to 81–85% for highly decomposed peats (Boelter 1969). Theoretically, if peat is fully water-saturated, the undecomposed peat has a higher water content and ε_{r}, thus, V_{EMW} is lower compared to the decomposed counter-

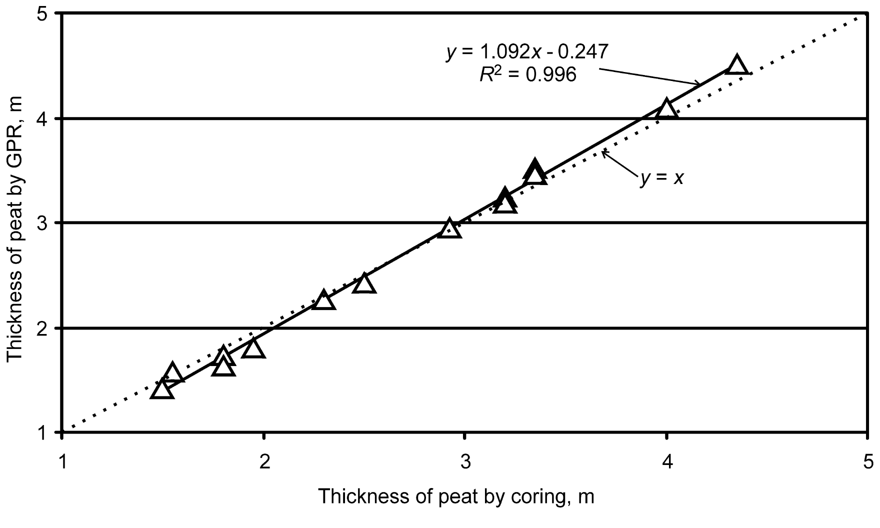

Fig. 7. The GPR-estimated peat thicknesses of the Rahivere bog are in good agreement with coring data with only small systematic deviations, probably due to variations in water-saturation.

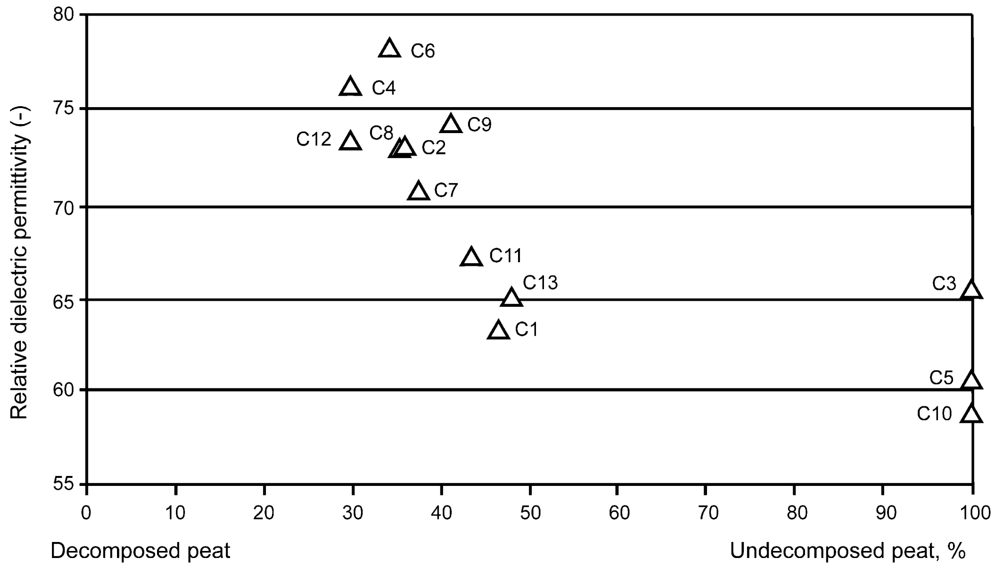

Fig. 8. Percentage of undecomposed peat within the cores (C1–C13) vs relative dielectric permittivity that is based on the total thickness of peat at the coring site and GPR data.

part. Our study did not reveal such a relationship (Fig. 8); on the contrary, the data suggest that incomplete saturation overwhelms the effect of variations in densities and porosities. To prove the suggestion, additional calibration of the GPR data against decompositional types of peat combined with saturation is needed.

According to our results, the volume of peat and gyttja within the Rahivere bog is 1 542 000 m^3. Within the officially registered deposit area (0.54 km^2; outline shown in Fig. 6) of the bog, excluding the volume of the acrotelm (95 000 m^3; data from Allikvee & Orru 1979), the total volume of peat with minor gyttja (estimated <50 000 m^3) is less (1 200 000 m^3), but still notably more than the officially registered volume (979 000 m^3). We suggest that the main reason for the difference is the different methods employed. Volume calculations in the present study are based on ~1000 data-points, which is significantly more than 13 manual corings by Allikvee & Orru (1979). Volumes in the latter study were based on the mean thickness of peat multiplied by the area; a method that is highly dependent on the location of cores. On the other hand, the volumes calculated by modern methods depend on the method of the interpolation of the surface and other user-defined variables (e.g. the grid size). Our comparative calculations show that the volumes calculated for surfaces created by different interpolation methods (spline, natural neighbour, inverse distance weighted, triangular irregular network) vary up to ~10%. The boundary of the peat deposit is usually located at the 1 m isoline. The comparison in Fig. 6B shows that the outline of the deposit by Allikvee & Orru (1979) coincides well with the 1 m isoline on the northeastern side of the trough, but is located inwards on the other sides.

Studies of Estonian peat deposits, including determination of the volume, are regulated by the Ministry of the Environment. According to the regulation, the grid of exploration has to be 100 m × 100 m or 200 m × 200 m, depending on the size and geological complexity of the wetland. Manual coring at every node of the grid through peat is required. The thickness and volume of the undecomposed and decomposed varieties have to be measured with accuracies of 0.05 m and 1000 m^3, respectively. Usage of GPR definitely increases the accuracy of studies by providing precise information on the total thickness of peat in areas between the cores. It also reduces the number of cores required as well as uncertainties associated with interpolation between the cores. If GPR is used before coring, radar images can be used to locate the corings into critical positions. The used frequency of 300 MHz theoretically satisfies the peat layer determination accuracy (0.05 m) as within the environment with permittivity of 70 the vertical resolution is 0.03 m (vertical resolution of GPR is equal to one fourth of the wavelength; Rial et al. 2008). However, the present study demonstrates that distinguishing the decompositional types of peat needs further calibration of the gain applied to the radar images (or more sophisticated interpretational tools) and the result is likely more successful if the GPR data are obtained in a warm season.

CONCLUSIONS

Ground-penetrating radar provides a continuous image of the peat-mineral contact and thus, can be used as an independent technique for peat volume estimate. For this purpose careful calibration of the data with coring and independent GPR measurements (common source or common receiver techniques) are needed to provide a reliable velocity for the EMW in peat. In the surveyed bog the mean EMW velocity was 0.036 m ns^{-1} that is very similar to V_{EMV} values of peat found in the literature. The study revealed the dependence of the EMW velocity on the level of water-saturation of peat that outweighs the effect of decomposition on the V_{EMV}. The boundaries between undecomposed and decomposed peat types and gyttja did not produce uniquely interpretable reflections.

The base of the Rahivere peat bog has been sculptured by the glacier, which is evidenced by elongation of the interstitial trough in the drumlin field and direction of the deeper incisions (oriented 315° to 135°) within it. Before peat started to form, the trough was occupied by post-glacial lakes. It is evidenced by glaciolimnic sands and limnic clays filling the trough and, especially, the incisions. A terrace-like feature likely referring to the vicinity of an old shoreline occurs at the altitude between 69.5 and 70.5 m. Comparison of the altitude with those by regional studies of the highest water levels of pro-glacial lakes hints at a higher and, thus, isolated position of the Rahivere trough.

According to the present study, the volume of peat and gyttja in the Rahivere bog is 1 542 000 m^3. Within the officially registered area (0.54 km^2) of the deposit, excluding the volume of the acrotelm, the total volume is less (1 200 000 m^3), but still more than the official one (979 000 m^3). The results convince that GPR provides additional detailed information on the boundaries and thickness of peat deposits in mires, but cannot serve as an independent method without drilling.

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Rahivere turbaraba uuringud georadariga

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On esitatud Vooremaa idaosas paikneva Rahivere raba geofüüsikaliste (georadari) uuringute tulemused, kirjeldades raba morfoloogiat ja turbalasundi paksust. Lisaks on hinnatud georadari kasutusvõimalusi turba mahtude määramisel ja võrreldud saadud tulemusi Keskkonnaregistrisse kantud geoloogilistel uuringutel saadud tulemustega. Interpretatsioonid baseeruvad neljateistkümnel voortevahelise nõo pikiteljega risti kulgeval umbes 100-meetrise vahega koostatud radariprofiilil, mis katsid raba ja ulatusid külgnevate voorte nõlvadele. Elektromagnetlainete turbas levimise kiiruse hindamiseks puuriti profiilidele turbapuuriga 13 puurauku ja lisaks kasutati georadari nn ühise saatja meetodit. Hindamise tulemusel kasutati ajaskaala muutmisel sügavusskaalaks elektromagnetlainete kiirust 0,036 m ns^{-1}, millele vastab suhtelise dielektrilise läbitavuse väärtus 69,7. Radariläbilõigetel ilmnesid selgeimad peegeldused turba ja mineraalpinnase piirpinnalt, kuid nõrgemad peegeldused tulenesid ka turbalasundi seest. Turba paksus ulatub pisut üle 4 meetri, olles suurim kahes nõo pikiteljega paralleelses "sisselõikes". Absoluutkõrgusel 69,5 kuni 70,5 meetrit ilmneb pikemaaegsele veeseisule viitav terrassilaadne moodustis. Radari andmete alusel arvutatud turbalasundi maht (1 200 000 m^3) ületab Keskkonnaregistrisse kantud mahu (979 000 m^3).