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Holocene organic-rich sediments within the Curonian Spit coast, the south-eastern Baltic Sea

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Abstract Organic-rich sediments are exposed at a number of onshore and nearshore sites along the Baltic Sea coast of the Curonian Spit. Radiocarbon dating of relict tree stumps, as well as buried and reworked peat and palaeosols, found along the Russian part of the Curonian Spit (villages of Lesnoy and Rybachy) and in the vicinity of Zelenogradsk indicate the formation of these sediments over a wide time period from 7300 cal BP to 300 cal BP. Organic-rich sediments of different stages of the Holocene sand barrier evolution are of interest in terms of environmental protection, as potential accumulators of oil (or other hydrocarbon) pollution and indicators of intensity of coastal erosion. In terms of geochronology, the data have implications for reconstructing the geological history of the Curonian Spit and Curonian Lagoon during the Late Pleistocene and Holocene.

Keywords • *relict peat* • *palaeosol* • *Litorina stage* • *Post-Litorina stage* • *ground-penetrating radar*

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INTRODUCTION

Processes of cross-shore sand and gravel sediment transport caused by the development of coastal accumulation forms – coastal bars, sand ridges, and barriers – are common features of clastic coastal environments. These forms often contain organic-rich horizons (Reading 1996). Detailed understanding of organic layers within these sand-dominated accretion bodies is important as it provides information about the timing and mechanism of key stages in their development, particularly where complications due to tidal ranges are minimized, such as micro-tidal or effectively non-tidal basins. For example, radiocarbon dating of organic-rich lagoon gyttja layers occurring at an altitude of +2.2 m in the sequence of the Vistula Spit, south-eastern Baltic Sea coast, together with other methods (mollusc analyses and dating, pollen and diatom analyses) contributed to a recent hypothesis of the spit formation (Bitinas *et al.* 2008). Similarly, numerous organic-rich layers (e.g. peat and gyttja) were documented in boreholes of the Hel Spit and offshore areas of the Baltic Sea and the Gulf of Gdansk. Based on these findings, it was possible to reconstruct the main environmental changes during the Late Pleistocene and Holocene in the southern Baltic region (Uścinowicz 2003; Uścinowicz *et al.* 2005). During Late Holocene, the south-eastern Baltic Sea coast was influenced by the slow rise of relative sea level. Over the Post-Litorina stage the relative sea level within the study area rose by three metres (Uścinowicz 2006). Under such conditions, mainland beaches (resulting from cross-shore sand transport) and barrier spits (formed by a combination of longshore and cross-shore sediment flows) have started to experience sediment deficiency as manifested by indicators of erosion.

The Curonian Spit is the largest Holocene coastal sandy accumulation form developed along the Baltic Sea coast. The first attempts to interpret the Curonian Spit formation have been done by Prussian investigators – H. von Wichdorff, K. H. Paul, and others – in the first half of the 20th century. V. Gudelis (1998), taking into account a wide distribution of so-called "lagoon marl" (i.e. organic-rich lagoon mud) beneath significant part of the recent Curonian Spit, made a suggestion that at the very beginning of the spit formation this sandy barrier occurred at lower hypsometric level and westward then its recent position. The detailed palaeogeographic reconstructions of the Curonian Spit formation were presented by M. Kabailienė (1997 a, b, c). Under these reconstructions, the number of islands with base forming by till deposits was appeared in the place of the recent Curonian Spit first of all, and only later they geomorphologically were merged as a single spit (Gelumbauskaitė, 2002, 2009; Gelumbauskaitė, Šečkus 2005). According to borehole data within some areas of recent Curonian Spit the tills are locally occurring close to the ground surface, that differs from e.g. Vistula Spit where Pleistocene surface is located at 14–16 m b.s.l (Tomczak, Mojski 1988).

A relatively wide occurrence of peat layers and lenses in geological sequence along the Russian part of the Curonian Spit were found in shallow cores and documented as part of geotechnical investigations (Kharin, Kharin 2006; Badyukova *et al.* 2006; Badyukova *et al.* 2007). The biggest peat deposit (up to ten metres thick) stretches along the southern part of the Curonian Spit. The thickness of this layer decreases northward following the spit axis. There are two different types of peat-bearing layers. The soilless peat layer is located in the southern part of the Curonian Spit – from 0 km (attached part of the Curonian Spit) to 4 km, whereas further to the north (4–16 km and 25–31 km segments) the peat layer contains a substantial admixture of sand particles (Kharin, Kharin 2006). In this part of the spit, the peat covers the till surface or overlies a thin layer of glacio-lacustrine clays. Till surface morphology shows that the peat likely fills a shallow strait and is continuously deposited in beginning of Ancylus stage (Badyukova *et al.* 2010). After severe storms along the coast in the Russian part of the Curonian Spit, lumps of peat (and rarely gyttja) have been found along the coast.

The organic-rich sediment layers outcropping directly on the marine escarpments (i.e., relict dune scarps) of the Curonian Spit near the Lesnoy village have been known to investigators from the 19th century, but the first more detailed investigation was carried out in 1965–1966 by M. Kabailienė (2006), who examined the pollen content of a 20 cm thick peat layer cropping out 2.3 metres above sea level. In 1997, this layer was radiocarbon dated (Uścinowicz 1997).

In the Curonian Spit, buried palaeosols are generally observed outcropping on the slopes of the Great Dune Ridge (adjacent to Nida) located closer to the Curonian Lagoon coast (Gaigalas *et al*. 1991; Gaigalas, Pazdur 2008; Dobrotin *et al*. 2013), whereas in the southern (Russian) part of the spit, several generations of palaeosols were found in relict dune scarps.

The aim of this paper is to present the comprehensive data concerning the distribution and chronology of organic-rich sequences along the southern part of the Curonian Spit, with implications for reconstructing coastal development along this part of the Baltic Sea basin.

MATERIAL AND METHODS

The material for this study was collected during the 2006–2013 summer seasons by the A. P. Karpinsky Russian Geological Research Institute (VSEGEI). Longshore observations within beach and dunes, ground-penetrating radar (GPR) profiling were made accompanied by shallow drilling for geophysical data interpretation, and cross-shore beach profiling.

GPR imaging was aimed to study the geological sequence of the spit coast to determine the structure and thickness of sand layers and trace buried peat and palaeosol horizons. The surveys were carried out along the cross-shore of the spit in the vicinity of the villages Lesnoy and Rybachy. Altogether, 7000 m of GPR profiles were collected that allowed for the fixing more than 750 m extension of peat layers in the coastal zone (Fig. 1). For GPR profiling, a digital SIR–2000 georadar (GSSI, USA) with a transceiver 200 MHz dipole provided penetration depth of up to 5–7 m, with 16–20 cm vertical resolution in unsaturated sands (higher below the water table).

Shallow drill-cores at a depth of 1–2 m were carried out using a hand jumper drill. Altogether, five boreholes were drilled, described and sampled. All samples of buried peat and palaeosols were collected for radiocarbon dating (Table 1). In addition, peat and palaeosols from erosion of dune scarps, as well as relict tree trunks and peat fragments reworked onshore by the waves, were sampled for radiocarbon dating.

Radiocarbon (^{14}C) ages of peat (9 samples), palaeosols (4 samples), wood fragments (4 samples), and gyttja (1 sample) were determined at the Isotopic Centre of the Department of Geology and Geoecology at Herzen State Pedagogical University of Russia (Lab. code SPb-) and the Laboratory of Nuclear Geophysics and Radioecology, Institute of Geology and Geography of the Nature Research Centre, Vilnius, Lithuania (Lab. code Vs-). A single palaeosol sample was dated at the Centre of Isotope Research

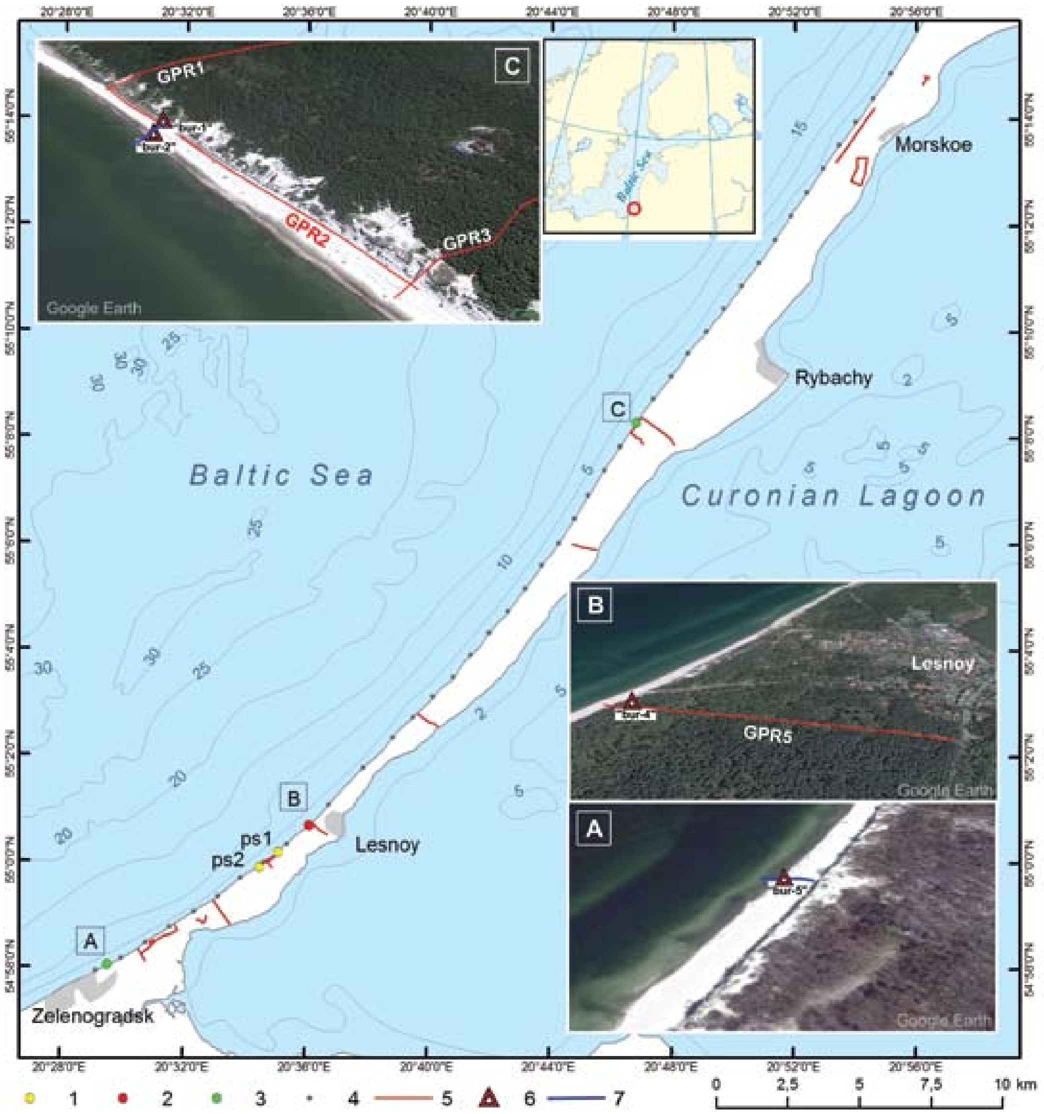

Fig. 1 Locations of study sites. 1 – palaeosols; 2 – peat and palaeosol; 3 – peat and tree stumps; 4 – observation site; 5 – ground-penetration radar (GPR) profile; 6 – shallow borehole; 7 – cross-section shown in Figs 3 and 5

of VSEGEI (Lab. code RGI-). The conventional method employed the application of liquid scintillation counting (LSC) by Quantulus 1220 at the Herzen State Pedagogical University of Russia and Tri-Carb 3170TR/SL at the Nature Research Centre, Vilnius. Benzene synthesis and purification followed standard methodologies (Gupta, Polach 1985; Arslanov 1985; Kovaliukh, Skripkin 1994). All ^{14}C dates were calibrated to calendar years (cal BP) using the OxCal 4.2 programme (Bronk Ramsey *et al*. 2010) with an IntCal13 calibration curve (Reimer *et al.* 2013).

RESULTS

Layers of peat and palaeosols can be observed in the coastal zone of the attached part of the Curonian Spit – in the vicinity of Zelenogradsk and farther north, around the villages of Lesnoy and Rybachy (see Fig. 1). It is noteworthy to mention that relict tree stumps, with their tops protruding above the beach surface, served as indicators of peat exposure in the vicinity of Zelenogradsk and Rybachy (Fig. 2).

Zelenogradsk area. Excavation of the relict tree stump on the beach of Zelenogradsk revealed a branching root system, traced through the 0.5 m thick layer of gravel and pebble deposits toward the dense peat layer. A massive root system permits tree stumps to be preserved despite the intense wave impact of the modern coastal zone (Fig. 3). Currently, the surface of the relict peat layer actually coincides with the shoreline. The results of radiocarbon dating indicate a relatively young time of peat deposition (695–650 cal BP) (sample 12-Bur-5; Table 1).

Lesnoy village area. Along the next (in the northern direction) coastal segment, in the vicinity of Lesnoy, palaeosol layers were discovered in the erosion escarpment of the relict dune. The palaeosol layers were found at 3.7–3.8, 7.2, and 10 metres above sea

Table 1 Radiocarbon (^{14}C) dating results (*1σ interval used throughout the text)

Lab. code	Sample number	Dated material	^{14}C age (yr BP)	Calibrated age BP (1σ confidence interval, 68.2%)	Calibrated age BP (2σ confidence interval, 95.4%)	altitude (m) in situ
Vs-1953	Zeleno-gradsk, sea coast	Wood (stump)	245 ± 35	420–410 (3.3 %) 315–280 (40.9 %) 170–150 (19.0 %)	430–355 (15.2 %) 330–265 (46.5 %) 215–145 (26.9 %)	+0.3
SPb-896	12-Bur-4	Peat	510 ± 25	540–510 (68.2 %)	560–500 (95.4 %)	+0.3
Vs-2281	12-Bur-5	Peat	720 ± 45	695–650 (59.9 %) 580–570 (8.3 %)	735–635 (81.0 %) 595–560 (14.4 %)	–0.1
SPb-850	12-Bur-4-2	Peat	1200 ± 50	1230–1210 (3.8 %) 1190–1060 (64.4 %)	1270–980 (98.4 %)	0
Vs-2280	12-Bur-4-2	Peat	1300 ± 90	1310–1170 (56.7 %) 1160–1120 (6.3 %) 1110–1080 (5.3 %)	1380–1040 (92.8 %) 1030–990 (2.6 %)	–0.1
Vs-1763	TN 21/2	Palaeosol	1510 ± 90	1530–1320 (68.3 %)	1610–1280 (95.4 %)	+7.2
SPb-864	12-Bur-2	Peat	1720 ± 30	1700–1650 (26.0 %) 1630–1560 (42.2 %)	1710–1550 (95.4 %)	–0.6
SPb-849	12-Bur-2	Wood (stump)	1755 ± 80	1780–1750 (5.3 %) 1740–1560 (62.9 %)	1880–1520 (95.0 %) 1460–1440 (0.4 %)	+0.3
Vs-1768	TN 21/3	Palaeosol	1780 ± 80	1820–1610 (68.2 %)	1890–1530 (95.4 %)	+10
RGI-541	5.3_SOIL	Palaeosol	2080 ± 150	2310–2230 (10.9 %) 2190–1880 (57.3 %)	2430–2390 (0.6 %) 2380–1690 (94.4 %) 1650–1630 (0.4 %)	+7.5
Vs-1764	TN 21/1	Palaeosol	2430 ± 50	2690–2630 (14.7 %) 2620–2590 (4.3 %) 2500–2350 (49.1 %)	2710–2350 (95.4 %)	+3.7-3.8
Vs-1544	29 km /1	Wood (stump)	3440 ± 50	3830–3790 (13.3 %) 3770–3740 (6.9 %) 3730–3630 (47.9 %)	3840–3580 (95.4 %)	+0.5
Vs-1553	29 km	Peat	3450 ± 70	3830–3630 (68.2 %)	3900–3550 (95.1 %) 3530–3510 (0.3 %)	+1.5
Vs-1543	29 km /2	Wood (stump)	3460 ± 40	3730–3790 (19.7 %) 3770–3680 (38.8 %) 3670–3640 (9.7 %)	3840–3610 (95.4 %)	+0.5
SPb-696	PRKK-1t	Peat	3500 ± 70	3870–3690 (66.1 %) 3660–3650 (2.1 %)	3970–3590 (95.4 %)	–0.8
SPb-697	PRKK-1t boundary	Peat	4350 ± 100	5260–5180 (8.1 %) 5060–4820 (60.1 %)	5310–4800 (89.6 %) 4770–4690 (4.3 %) 4680–4640 (1.5 %)	–1.4
SPb-694	KKB-64t	Peat	4870 ± 50	5660–5580 (68.2 %)	5720–5570 (81.1 %) 5540–5470 (14.3 %)	trans-ported
SPb-693	KKB-62	Wood (stump)	6250 ± 80	7270–7150 (42.0 %)* 7120–7020 (26.2 %)	7420–7390 (0.8 %) 7330–6940 (94.6 %)	trans-ported
SPb-692	KKB-62t	Peat	6130 ± 70	7160–6940 (68.2 %)	7240–7200 (2.2 %) 7180–6830 (91.8 %) 6820–6790 (1.5 %)	trans-ported
Vs-1647	Lesnoy outcrop	Gyttja	10550 ± 90	12650–12400 (68.2 %)	12710–12140 (95.4 %)	+5.5

level. The lowermost palaeosol horizon occurs in the potential zone of wave influence, especially during intense storms (see Fig. 1, point ps1). It yielded an age of 2500-2350 cal BP (Table 1; sample Vs-1764, TN-21/1).

An escarpment on the sea coast near Lesnoy (see Fig. 1, point ps2) contains a thin layer of organic-rich sediments outcropping directly above the till layers and is located at the foot of foredune as well as palaeosol outcropping on the slope of the relict dune (Fig. 4). During the investigations of this locality in 1965–1966, it was established that pollen in the peat layer contains species characteristic of cold climate (Kabailienė 2006). The same peat layer according to the results of radiocarbon dating aged 11 700 ± 100 uncalibrated years BP (Uścinowicz 1997). The latest research was performed in the same locality but on the newly exposed escarpment and in a slightly different geological section. It has been determined that the lowermost compact gyttja layer (2–3 cm thick; approximately 5.5 meters a. s. l.), enriched by the remnants of small pieces of wood and other plant remains,

Fig. 2 Relict tree stumps on the beach and nearshore in the vicinity of Zelenogradsk. Photo by A. Sergeev, 2011

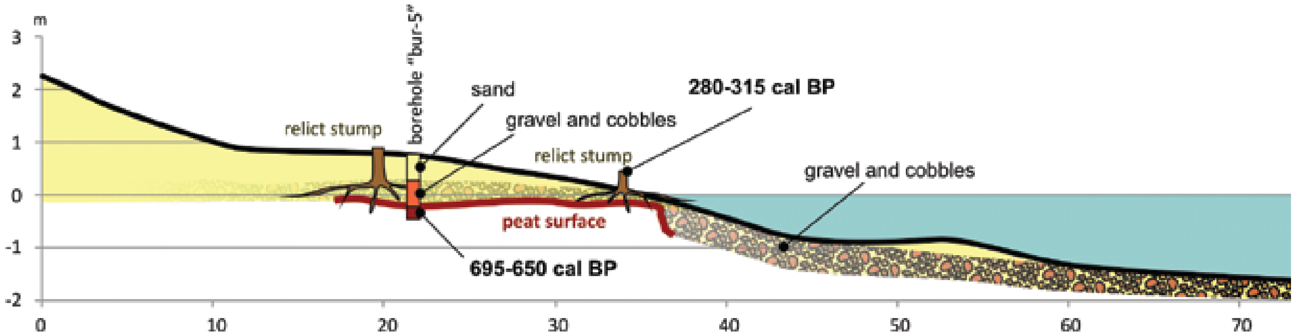

Fig. 3 Geological transect across the beach in the vicinity of Zelenogradsk (see Fig. 1A for location)

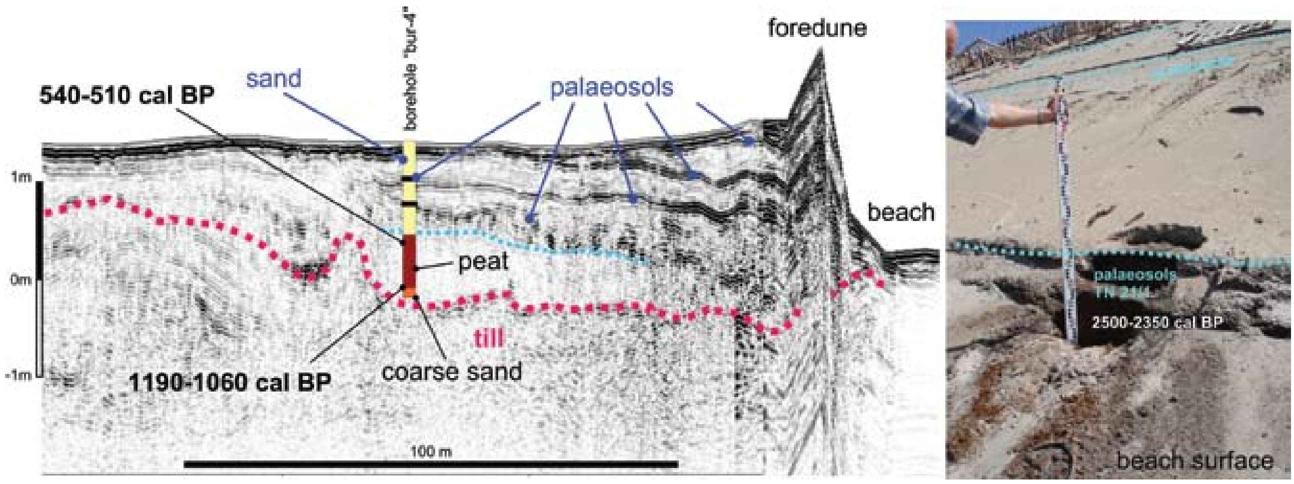

Fig. 4 The peat layer (lens) was revealed as a result of shallow drilling on the beach near the village of Lesnoy (see Fig. 1B for profile location) and the interpretation of the GPR profile (GPR5). Right panel – palaeosol layers exposed along a dune scarp of relict coastal dune 800 m to the south of the GPR5 profile. Photo by V. Bobykina, 2006

does not always crops out directly on the grey till. A thick layer (~35 cm) of fine-grained greenish-grey or dark grey sand with limonite staining and admixture of organic matter occurs in some places between till and gyttja. The age of gyttja is 12650–12400 cal BP (Table 1; sample Vs-1647), whereas the palaeosol outcropping two meters above the gyttja was formed 2190–1880 cal BP (Table 1; sample RGI-541). During major storms, the gyttja horizon can be reached by waves.

At present, peat outcrops are absent in the coastal zone in the vicinity of Lesnoy. Meanwhile, GPR data analyses are permitted to suppose the occurrence of peat layer behind the foredune at a depth of approximately one meter. This supposition was confirmed by shallow drilling. A 0.6-m-thick peat layer found in the drill-core has an absolute altitude of the surface and base of 0.5 m and –0.1 m, respectively (see Fig. 4). It is underlain by coarse-grained sand overlying till. The age of the basal peat is 1190–1060 and 1310–1170 cal BP (Table 1; samples 12-Bur-4-2), whereas the age of the peat from the upper part of the layer is 540–510 cal BP (Table 1; sample 12-Bur-4). The peat lens likely continues toward the beach, with thick top sand layer preventing it from erosion.

Rybachy village area. In the vicinity of Rybachy village (see Fig. 1), the peat layer outcrops in the nearshore bottom, forming a small escarpment (0.5 m of height) as a result of wave impact. In addition, several other outcrops were found along the submarine coastal slope surface (Fig. 5). The surface of the peat layer formed a series of low terraces, which are partly covered by sand. The lower part of the submarine coastal slope is composed by till, which is in turn overlaid by peat. Although only two relict tree stumps were fixed during the field work, GPR survey conducted along the beach revealed several high-amplitude anomalies (hyperbolic point-source diffractions), which are interpreted as buried relict tree stumps (Fig. 6).

Four radiocarbon dates were obtained on samples from the peat layer and relict tree stumps in the vicinity of Rybachy village. The basal peat layer was dated as 5060–4820 cal BP, the age of the peat from the surface of the nearshore bottom is 3870–3690 cal BP, the peat under the root of relict tree yielded 1630–1560 cal BP, and the wooden material from the relict tree stump – 1740–1560 cal BP (Table 1; samples PRKK-1t boundary, PRKK-1t, 12-Bur-2 (peat) and 12-Bur-2 (stump)). The age of organic-rich sediments (tree stumps and peat layer), which have been collected in this area onshore along the coastline in 2006 after a strong storm, is close to the age of peat from the nearshore bottom and varies from 3770 to 3630 cal BP (Table 1, samples 29 km, 29 km/1, 29 km/^{2}) (Fig. 7).

The occurrence of the submarine erosion escarpment in the peat layer indicates intense recent disintegration of these sediments due to wave impact. The bedded structure and low sustainability to erosion cause the detachment of relatively large (up to one meter) pieces of peat. Within all areas where peat layers in the nearshore are not covered and protected by gravel and cobble deposits (e. g., in the vicinity of Zelenogradsk), such large peat blocks are observed after severe storms on the beach surface (Fig. 8). Several of the peat pieces, reworked from the nearshore, were dated as well. The age of these samples varies from 7160 (Fig. 8A) to 5580 cal BP (Fig. 8B) (Table 1; samples KKB-62d, KKB-62t and KKB-64t).

DISCUSSION

Buried peat, covered by friable deposits as a result of base level change, composed of fragments of bog plants, is common in phytocenoses of lagoon coasts. Peat samples are characterized by low moisture content, minor mineral fraction, and a medium degree of decomposition. According to the classification (Kot 1980), peat can be attributed to a "lowland type with prevailing of reeds and sedge". Some parts of peat layers are enriched by the remains of trees.

The widespread peat deposits along the south coast of the Curonian Spit are significant from an ecological point of view. One of the critical points of sustainable development and protection of the fragile environment of the spit is preventing possible oil pollution of the coast (Suzdalev *et al.* 2014). From this point of view, the assessment of coastline sensitivity to petroleum pollution plays an essential role in coastal zone ma-

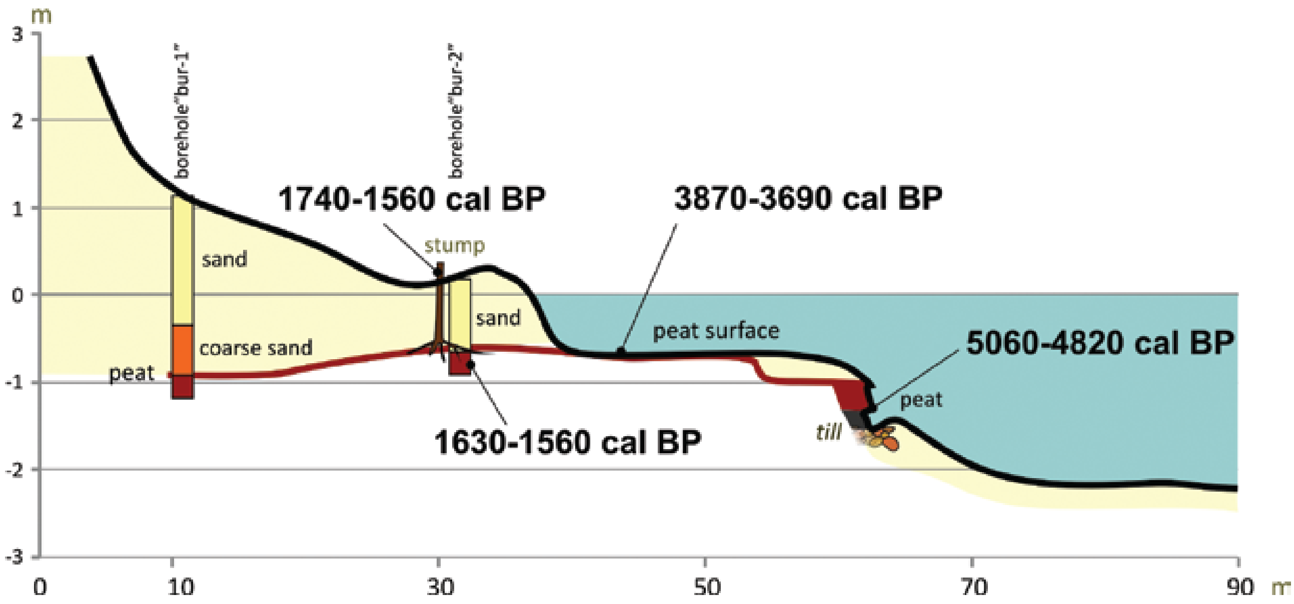

Fig. 5 Cross-shore geological transect in the vicinity of the village of Rybachy (see Fig. 1C for location)

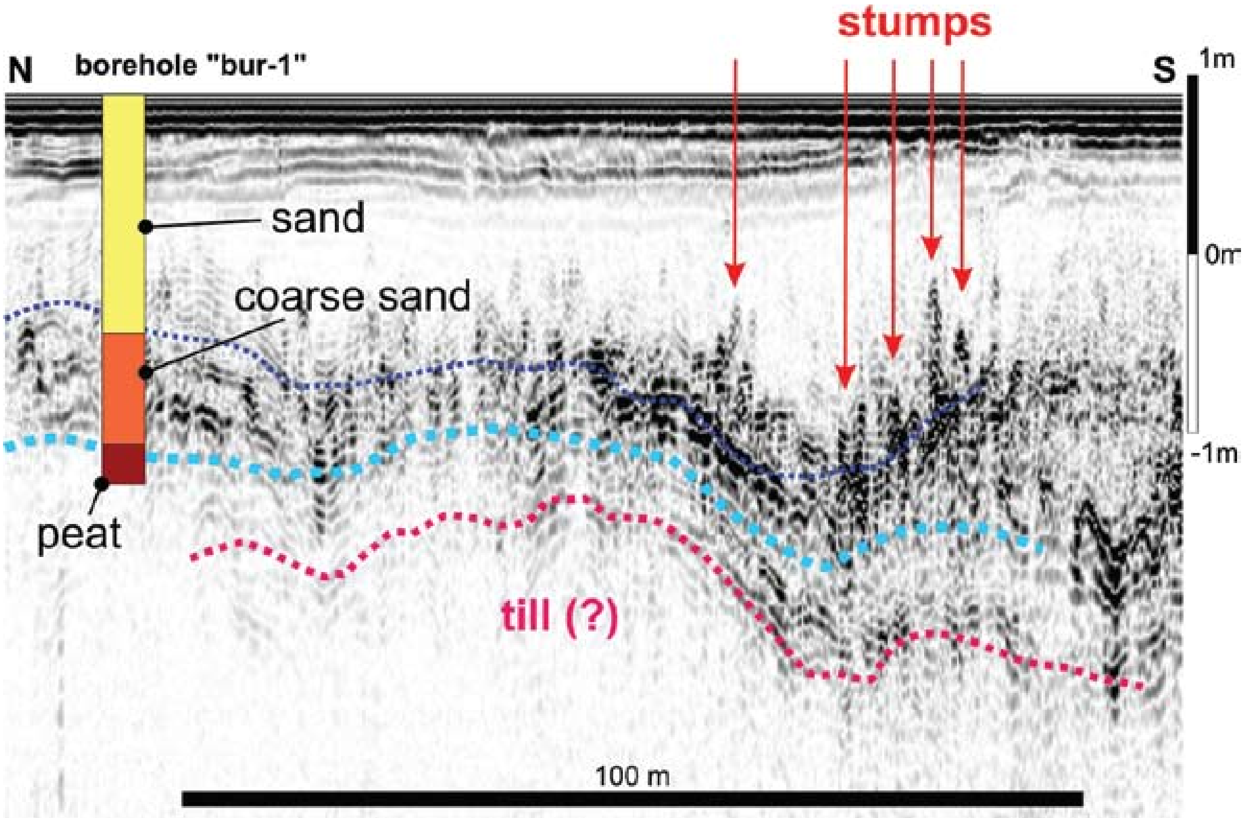

Fig. 6 GPR2 profile along the Baltic Sea beach in the village of Rybachy (see Fig. 1C for profile location)

Fig. 7 Peat exposure along the beachface near the village of Lesnoy after an intense storm in the autumn of 2006. Photo by D. Dorokhov, 2006

nagement. Most vulnerability maps use coastline evaluation based on the Environment Sensitivity Index (ESI) that classifies all world coastal types into ten categories (Gundlach, Hayes 1978). According to the conception of the prevailing of sands in the geological structure of the Curonian Spit, the ESI index for its coast varies from 3 to 5 (Blažauskas, Dorokhov 2014).

The beach monitoring data show that along 34 km of the Baltic Sea coast of the spit from Zelenogradsk to Rybachy the rate of coastal recession during the last 30 years is 1–1.8 m per year, and further beach degradation and increased spit breakthrough during storms is possible (Zhamoida *et al.* 2009). Due to sediment deficiency and coastal erosion acceleration, beach composition gradually changes. In particular, the increase in peat outcrop areas within the coastal zone can significantly enhance ESI. Properties of coasts covered by algae and water plants (ESI 8) in the classification (Gundlach, Hayes 1978) are similar to the peat coasts. Analyses of the geological structure of the Curonian Spit and distribution of the peat deposits suggest that with the acceleration of erosion processes, the occurrence of peat and palaeosol exposures within the coastal zone is likely to increase.

In many cases, organic-rich sediments and relict forests are being cropped out through erosion and retreat, providing valuable facts about coastal development (Devoy *et al.* 1996; Buynevich, FitzGerald 2002; Hart, Peterson 2007). Organic-rich sediments reviewed in this study are formed in the period from 7300 cal BP to 300 cal BP and represent different stages of the Curonian Spit formation during the Holocene. They are relevant objects of interest in terms of environmental protection, as potential accumulators of oil (or related petroleum product) pollution, as indicators of intensity of coastal erosion.

According to data of peat samples location (PRKK-1t boundary, PRKK-1t, 12-Bur-2 formed between 5060 cal BP and 1560 cal BP; Table 1), by the end of Litorina stage the sea-level in the area of southern part of the Curonian Spit was at least 1.4 m lower than nowadays. Since that time it has never exceeded modern sea-level. The youngest peat layers (12-Bur-4, 12-Bur-5, 12-Bur-4-2, 12-Bur-4-2; Table 1) were formed at the altitude about recent sea level, indicating the absence of extreme water level rising.

Comparison of the age and location of studied peat samples with the results of dating of peat from the vicinity of Nida (Gelumbauskaitė 2009) doesn't show any contradictions. Sea-level for Nida area within time period 6500–3000 cal BP could be gradually growing from 5 to 3 m b.s.l. The difference of hypsometric level of the peat layers along the Curonian Spit can be caused by isostatic rebound, rate of which was still high at the end of Litorina time.

CONCLUSIONS

The oldest organic-rich sediments (gyttja) formed 12650–12400 cal BP were found in the coastal outcrop in the vicinity of Lesnoy at 5.5 m a.s.l. Layers of peat and palaeosols outcropping along the Baltic Sea coast, from the nearshore to beach face and foredune scarps of the southern part of the Curonian Spit were formed during the Middle and Late Holocene in the period from 7300 cal BP to 300 cal BP (Atlantic–Subatlantic chronozones, i.e., during the Litorina and Post-Litorina stages). The organic-rich sediments *in situ* on the coast were deposited in the period from 5000 cal BP to 300 cal BP. These layers indicate active erosion processes during Post-Litorina stage.

Actually uninterrupted sequence of last 5000 cal BP dating of organic-rich sediments, sampled below recent sea-level, allowed concluding that during Post-Litorina time the southern part of the Curonian Spit was developing under the slow relative transgression with average rate of about 0.3 mm/year.

The recent position of organic-rich sediments maintains a notable shift in the marine coastline of the southern part of the Curonian Spit during the Middle and Late Holocene. Due to the high Environment Sensitivity Index (ESI) of peat layers, along with the widespread occurrence of these sediments in the nearshore, as well as the probability of their future increase due to erosion, they should be the subject of special attention in environmental geological research of coastal zones.

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