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Geological Structure and Composition of the Curonian Spit (Baltic Sea)

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Abstract—The paper presents new data on geology of the Curonian Spit based on results of the study of data on the engineering-geological transect compiled during the construction of gas pipe in the Russian sector of the spit. The data show that, along with eolian sand, peat deposits recovered in both its Russian and Lithuanian sectors make up a significant portion of the spit (data on the Lithuanian sector are adopted from the available literature). Based on new data, existing concepts on geology, paleogeography, geoecology, and stability of the Curonian Spit are discussed and refined.

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The Curonian Spit, where the Russian and Lithuanian national parks have been created, is included into the UNESCO list of natural memorials. The spit represents an ephemeral feature in the geological time scale. This sand deposit known as “Curonian–Neria Bar,” according to (Gudelis, 1954) appeared in the Holocene owing to a combination of favorable conditions. Changes of these conditions may result in its destruction.

Recent data on composition and structure of the Curonian Spit allow us to supplement and revise the existing concepts of geological–paleogeographic conditions of its origin and geoecology. These data show that, along with eolian and marine sands, slightly decomposed peat deposits play a considerable role in the spit composition. This fact is important for evaluation of stability and paleogeographic reconstruction of the spit. We hope that consideration of these data and prompt measures would help to increase the spit stability to the continuously changing environment.

The Curonian spit is a young geological structure that appeared in the Middle–Late Holocene as a result of sediment transport by coastal currents and wind. It represents a typical erosional-accumulative body (Boldyrev, 1998; Zenkovich, 1962) related to the erosion of cliffs on the Sambian Peninsula and bottom sediments of the Baltic Sea (Fig. 1). The spit assumed its present-day position and appearance approximately 3–5 ka ago at the Littorina and post-Littorina stages (Blazhchishin, 1998).

The Baltic Sea underwent a complicated evolution before the development of its present-day shape. After the disappearance of ice sheet 14–13 ka BP, the sea passed through the Baltic Ice Lake, Yoldian, Ancyllian, and Littorina stages marked by repeated rises and falls of the water level. The sea level changes are sufficiently well recorded by cliffs, coastlines, and bottom terraces in the southeastern Baltic Sea and submarine slope of the Sambian Peninsula (Fig. 2).

The coastline was located 20–30 km seaward relative to its present-day position at the Ancyllian stage (9–8 ka BP). The end of this stage was marked by the formation of small spits adjacent to eastern margins of the Sambian Peninsula and Rybachii Plateau that represented a coastal ledge at that time. The present-day position of the spit was mainly developed during the third phase of the Late Littorina transgression (5.5–5 ka BP). The spit continues to evolve today. The sea level rise, block movements of the earth’s crust, human activities on the shelf and in the coastal zone, as well as many other processes affect alongshore sediment flows that sustain the sediment supply for the spit growth. Present-day destruction of the submarine slope and avandune is mainly observed in the spit root zone (Fig. 1) and some other places. The destruction largely depends on specific geological features and the composition of sediments in the spit.

In this paper, we analyze data on the engineering-geological investigations carried out within the Russian sector of the spit in 1997–2003. Existing concepts of the geological structure, paleogeographic setting, and stability of the Curonian Spit as a geological body are discussed. Published data on the Lithuanian sector of the spit are also considered. As shown by the example of Tusla Spit in the Black Sea, these issues have not only geoecological significance. They also infringe on political and economical interests of neighboring states. They have become especially pressing in the modern period of global climate warming and sea level rise.

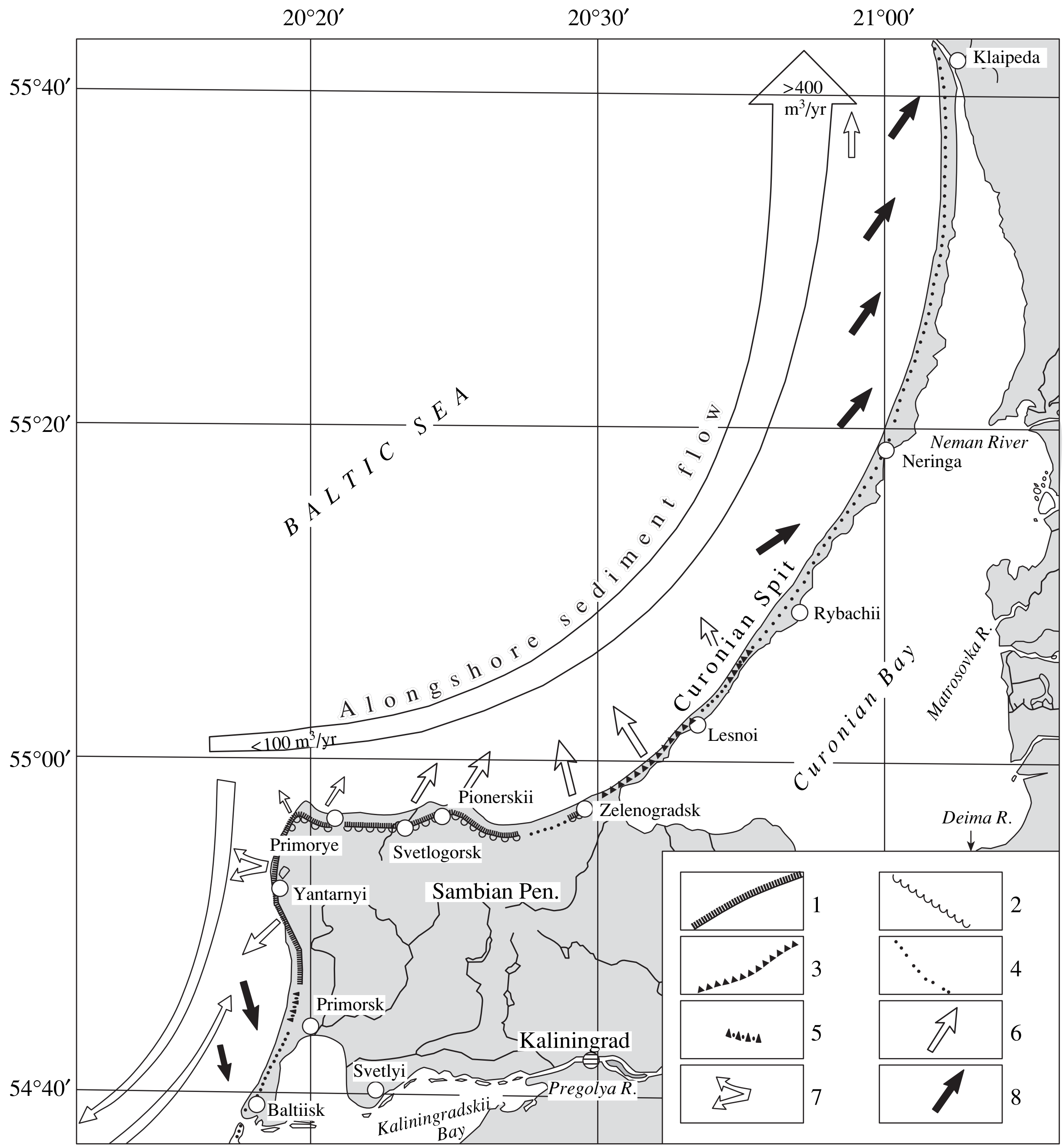

Fig. 1. Position of the Curonian Spit in the coastal lithodynamic system of the Southeastern Baltic Sea. Based on modified and supplemented (Orlenok et al., 2004). (1–5) Coastal sections characterized by the following present-day processes: (1) abrasion, (2) sliding-slumping, (3) destruction of avandunes, (4) accumulation, (5) stabilization; (6) direction of sediment transport from the coast and formation of alongshore sediment flows (numbers show the approximate capacity of sediment flow, m^3/yr); (7) pulp discharge from the Yantarnyi amber factory (up to 10^6 m^3/yr); (8) settling of sediments from the alongshore sediment flows.

GEOLOGICAL STRUCTURE AND COMPOSITION OF THE SPIT

According to the model (Gudelis, 1954) widely accepted today, the Curonian Spit consists of sand dunes, including immobile dunes of first generation, mobile dunes of second generation, and avandunes (Fig. 3). Their thickness (or height) reaches 60 m.

Gudelis (1954) demonstrated that modern marine sands and dunes overlie lagoonal marl 2–3 m thick. In some cases, the plastic marl is squeezed out by the gravity load of the overlying high dunes to form cross-bedded imbricate layers that are exposed on the Curonian Bay side of the spit.

Recent data allow us to supplement and revise the concept of the geological structure, composition, and

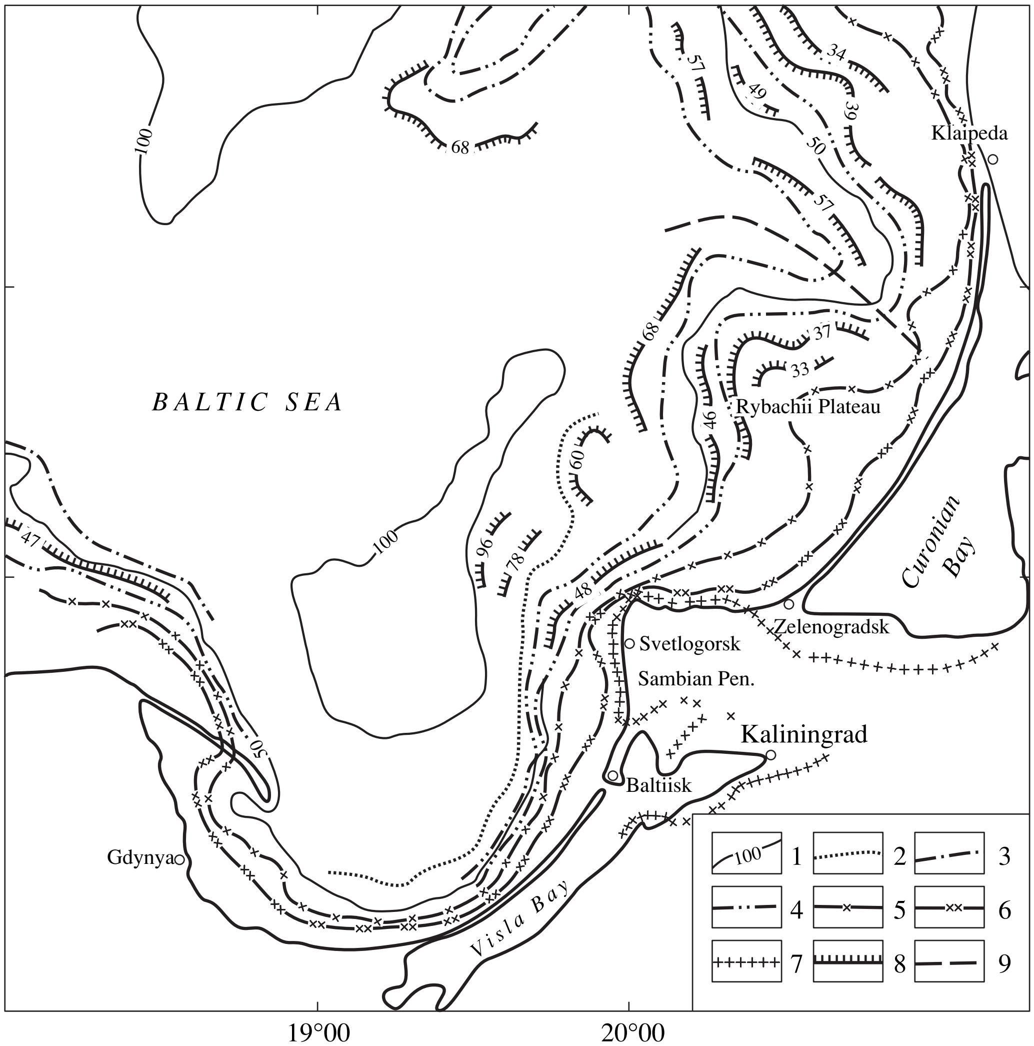

Fig. 2. Position of ancient coastlines and terraces on the bottom of the southeastern Baltic Sea and the Sambian Peninsula (Kharin, 1986). (1) Contours, m; (2–8) ancient cliffs and sea levels: (2) Baltic Ice Lake (75–70 m); (3) Yoldian (62–55 m); (4) first Ancyllian (42–35 m); (5) first Littorina (32–27 m); (6) second Littorina (20–16 m); (7) third Littorina (0–3 m); (8) submarine terraces of unknown relationship with certain Baltic Sea stages (numbers show water depth of the terrace top); (9) axis of the Pra-Neman valley.

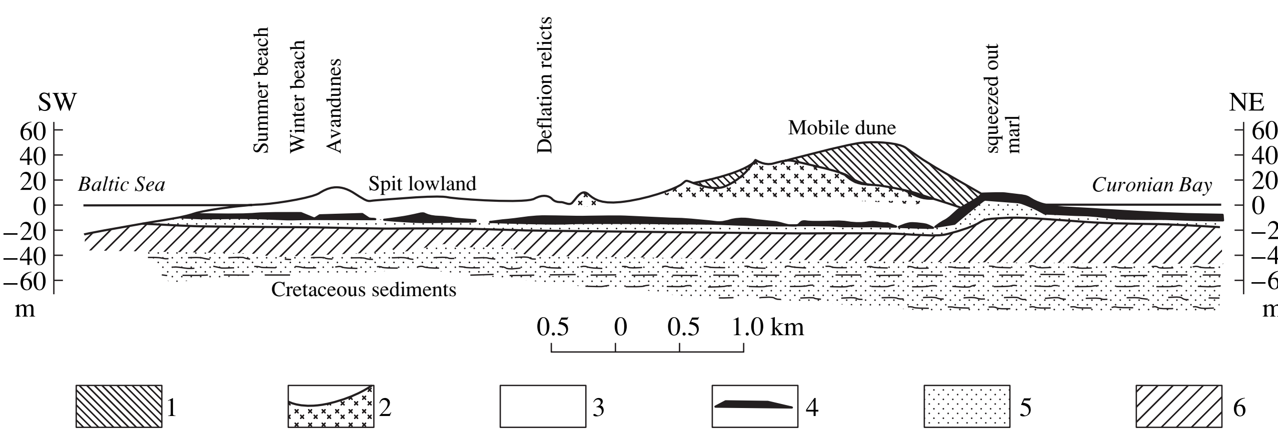

Fig. 3. Schematic cross section of the Curonian Spit. Based on modified and supplemented (Gudelis, 1954). (1) Dune of second generation (mobile); (2) dune of first generation with fossil forest soil; (3) modern marine and eolian sand; (4) lagoonal sediments (lagoonal marl); (5) ancient marine sand; (6) boulder loam (Pleistocene moraine).

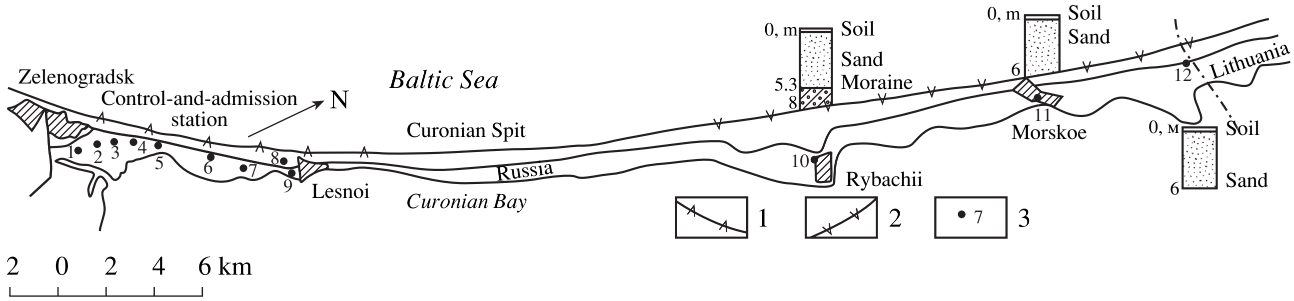

Fig. 4. Location of engineering–geological boreholes drilled along the gas pipe track in the Curonian Spit. (1, 2) Coastal sites marked by the following processes: (1) destruction of avandunes, (2) accumulation; (3) borehole position and number.

development of the Curonian Spit. Borehole cores recovered during the geological mapping and engineering-geological survey in 1997–2003 provided especially valuable information. They also support the idea about an ephemeral nature of the spit. Many peat deposits recovered by drilling along with friable sand strata created a quite unstable geological body. As proved by observations and demonstrated in many publications, sands of the Curonian Spit cannot withstand the destructive wave and wind activity. So far as we know, nobody has discussed the possible influence of peat deposits on the spit stability up to date, apparently owing to underestimation of their contribution to the spit structure. Although peat was recovered in some boreholes, these findings did not attract much attention (Bitinas et al., 2000; Korneevets, 1998).

The most interesting data on geological structure of the Russian sector of the spit were obtained during engineering-geological investigations along the gas pipe track in 1997 (Kharin and Kharin, 1998). The transect follows almost along the spit axis (Fig. 4) and comprises 12 boreholes (up to 10 m deep) located at a distance of 0.8–2.2 km from each other. In addition, several boreholes were drilled at building sites in settlements.

The Curonian Spit is 98 km long and 0.8–3.8 km wide. The transect extends over 49 km from the spit root near the town of Zelenogradsk to the Lithuanian border. Boreholes were not drilled in the middle Russian sector of the spit between the Lesnoi and Rybachii settlements. Thus, one-half of the Russian sector of the spit has been studied by boreholes. The section between the spit root (eastern outskirts of Zelenogradsk) and Settlement of Lesnoi (Fig. 5) is best studied.

The geological cross section extending from the town of Zelenogradsk to the Settlement of Lesnoi (depth from +4 to –10 mbsl) and further to the Lithuanian border is composed of Holocene eolian sand with intercalated peat deposits (Figs. 4, 5). The sand sequence with peat deposits directly overlies the Pleistocene moraine loam. Neither lagoonal marl, nor any other signs of lagoonal or lacustrine facies were recovered by the boreholes.

Judging from the data obtained, glacial moraine deposits serve as a basement for the Curonian Spit. The morainic basement is recovered at depths ranging from –5.2 to –5.6 mbasl near the Settlement of Lesnoi and at a depth of –4.6 m in borehole 5 approximately 3 km from the beginning of the transect (Fig. 5). The top of moraine deposits gradually deepens to –10 m further to the southwest (boreholes 2 and 3). Irregularities in the basement relief may represent either relict primary topography of the moraine surface or secondary features. For example, the Pleistocene moraine locally exposed near the Lesnoi, Rybachii, and Morskoe settlements (Badyukova et al., 2004) represents relicts of a frontal moraine ridge, along which the spit accumulated during the Late Littorina transgression. Secondary depressions in the spit basement were formed as a result of denudation of the moraine after or during its accumulation. The denudation affected not only the moraine deposits, but also the overlying sediments of the spit.

The valley-shaped depression in the moraine loam located at the spit interval of 1–4 km also likely belongs to secondary denudation features (Fig. 5). The valley is up to 4 km wide and has a maximum depth of ~10 m below the present-day spit surface. The depth relative to valley banks is ~5 m.

Pleistocene moraine deposits consist of a very stiff gray, dark gray, or brown boulder-gravel loam. It contains 10–20% of gravel, pebbles, and boulders. A layer of bluish gray loam without gravel and pebbles overlies the boulder loam in boreholes 1–3. The bluish gray loam is 0.8 m thick in borehole 1. The moraine loam is overlain by sand, which is replaced by a lens-shaped peat deposit in the depression of 1–3 km at the southwestern end of the transect. The peat deposit is up to 10 m thick at the depression axis, and its bottom occurs at a depth of 9.6 m from the spit surface, i.e., 7.4 mbsl. Maximum width of the peat lens is at least 4 km. The peat becomes thinner and gradually gives way to sand in the northeast both within the depression and on the moraine rise. The peat deposit shows a narrowing trend. The southwestern boundaries of the deposit beyond the depression have not been outlined. It is most likely

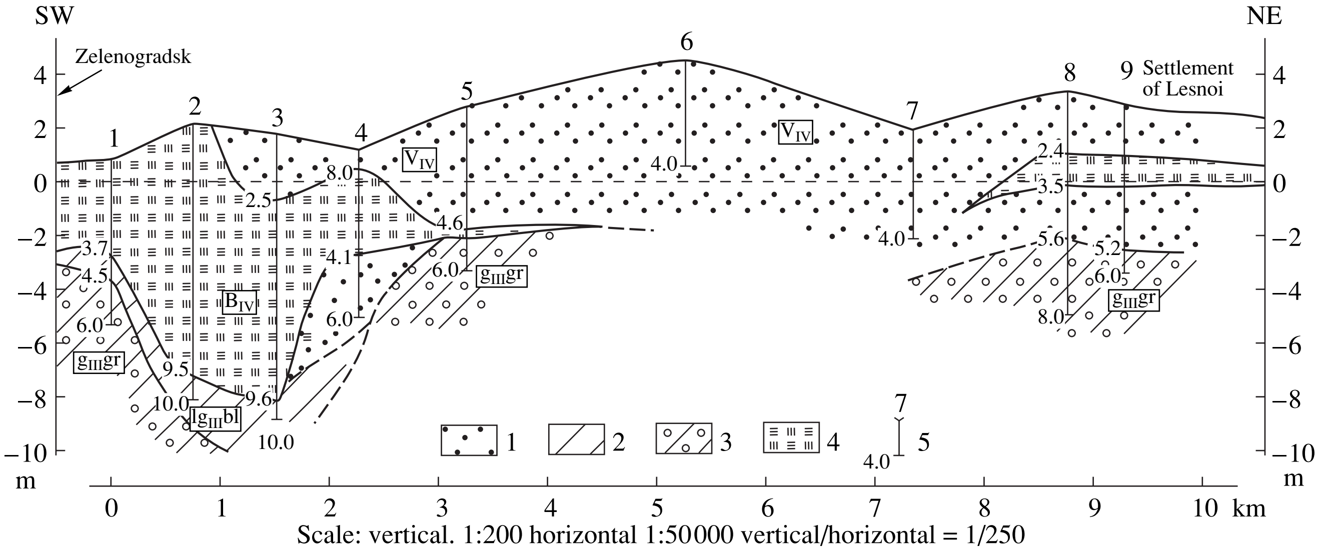

Fig. 5. Geological transect along the gas pipe track based on boreholes 1–9 drilled in the Curonian Spit sector extending from the town of Zelenogradsk to the settlement of Lesnoi. (1–4) Sediments: (1) medium-grained quartz–feldspar sand; (2) bluish gray loam; (3) brown, dark gray, and gray loam with pebbles and gravel (10–20%); (4) brown sedge–cane peat with various (from low to high) degrees of decay; (5) borehole number and depth (m). (V_{IV}) modern eolian deposits; (B_{IV}) modern biogenic deposits; (lg_{III} bl) Upper Pleistocene lacustrine-glacial deposits of the Baltic glaciation stage; (g_{III} gr) Upper Pleistocene moraine deposits of the Grudas glaciation stage (subsuite).

restricted by the bedrock coast of the Sambian Peninsula.

Boreholes 8, 9, and others drilled near or within the Settlement of Lesnoi recovered another ~1-m-thick peat lens in the middle part of a 5.6-m-thick sand sequence. The sand is underlain by moraine deposits composed of boulder loam (Fig. 5). Lagoonal sediments were not recovered by the boreholes.

The data presented above show that plant remains, which later produced peat, accumulated synchronously with the eolian sand sequence. The plant remains in the peat deposits are represented by sedge and cane that continue to grow today on coasts of the Curonian Bay.

FORMATION CONDITIONS OF PEAT DEPOSITS WITHIN THE CURONIAN SPIT

Peat deposits are known to form in peatbogs, lagoons, and other environments, where abundant plant remains accumulate in anoxic conditions that are favorable their preservation. Peat deposits of the Curonian Spit are unique, because they occur within eolian sand sequences without any signs of bog or lagoon facies.

How can the peat deposits form under such conditions? We believe that these deposits are reworked (allochthonous) bodies. Judging from their geological setting, the plant remains mentioned above accumulated in straits or channels, which provided water exchange between the Baltic Sea and Curonian Bay. The largest straits of the modern Klaipeda Strait type existed during a long time and worked out erosional valleys up to 4 km wide and 10 m deep. Until recently, such a strait with erosional valley cut into the moraine loam existed in the spit root area. Its deepest axial part (thalweg) was located at the first kilometer of the spit.

The channel was filled with plant debris mainly delivered from the bay. The dominant sedge–cane composition of the peat supports this suggestion. The delivery of plant debris was uneven and reached the highest intensity during the formation of the widest middle part of the peat deposit (4 km). Other peat lenses (e.g., the lens located near the Settlement of Lesnoi) also formed at the same time. This area, probably, incorporated a shallow channel that was rapidly filled with the plant debris.

In terms of the intensity of peat deposit formation in the Curonian Spit, one can identify two development phases: (1) the early (transgression) phase marked by expansion of peat deposition areas; (2) the later (regression) phase characterized by reduction of these areas and burial of peat deposits beneath the sand. It is interesting that the first phase also witnessed sand drifts into the strait and valley, where the plant debris accumulated. This is well observed in borehole 4 (Fig. 5). The second phase included two episodes of more stable and one episode of intense sand drift into the strait and plant debris accumulation (borehole 3).

Constant invasion of the straits by sand bars from the sea also likely promoted the accumulation of plant debris in channels between isolated segments of the spit. The bars prevented the transport of plant debris to the sea. Owing to water saturation and condensation, the floating and suspended debris settled on the strait floor that accumulated seasonal-climatic beds enriched in plant remains. Anoxic environment in such areas promoted the transformation of plant debris into peat. Repeated changes of water level in the Baltic Sea and Curonian Bay could lead to reworking and secondary accumulation of the peat deposits. This type of origin is probably typical of rounded fragments of the redeposited peat scattered on the modern beach of the Curonian Spit. R.V. Abramov kindly presented us a sample of redeposited peat found in the modern beach sand on the elevated cliff break at 29th km of the spit.

DISCUSSION

The new data presented above allow us to revise existing concepts of formation conditions of the Curonian Spit, in particular, the model proposed by Gudelis (1954). They provide certain evidence for a long-term existence of other large straits (in addition to the Klaipeda Strait) in the Curonian Spit, for example, in its southwestern part. We propose the name Zelenogradskii for this paleostrait that likely disappeared quite recently.

The geological history of the spit comprises some episodes marked by the appearance of many small straits that separated the spit into isolated islands. The shallow straits existed for only a short time. They were rapidly filled with plant debris delivered from the bay and covered by eolian sand.

Large straits and paleostraits, such as Klaipeda, Zelenogradskii, and, possibly, Pra-Neman (Fig. 2), existed for a longer time that was comparable to that of spit formation. They had enough time to cut wide and sufficiently deep channels in the Pleistocene boulder loam underlying the spit. The straits experienced several phases of degradation and expansion. The Zelenogradskii Strait was ultimately filled with peat (partially, with sand).

Thus, the allochthonous peat deposits apparently represent an alien facies for the surrounding eolian sands. Sand and peat (plant detritus) deposits accumulated simultaneously on the rough surface of the Pleistocene moraine loam. As mentioned above, irregularities of the Pleistocene moraine surface can represent both relicts of the primary moraine topography preserved after marine abrasion and secondary features formed during the bottom erosion in straits (channels) of the Curonian Spit. The secondary irregularities were filled with peat, sand, and loam. Waterlogged areas, which could appear during the evolution of the Curonian Spit, fostered in situ (autochthonous) formation of peat. Such areas exist today, but they probably appeared not long ago when separate sand islands merged to form a single spit slightly drained in some places.

The presence of peat deposits within the sand body must be reflected in geoecology of the Curonian Spit. Let us to consider the possible consequences of such combination. Peat deposits weaken the primarily unstable spit body. Therefore, the sea can, first of all, break through large peat accumulations and thus restore the previous straits. Compaction and decrease in thickness of peat deposits inevitably lead to sinking of the spit surface and appearance of lowlands almost at the sea level. Such sinking areas occur near the spit root, where the peat thickness is up to 10 m. The mouth of borehole 1 is located at 0.5 masl. Further compaction of the peat may lead to subsidence of the surface below the sea level (from –3 to –5 m). The formation of lakes and waterlogged areas on lowlands on the spit surface (hereafter, spit lowland) is possibly related to such subsidence depressions located above the peat deposits.

In addition to the Zelenogradskii paleostrait, valley-like depressions across the spit basin strike are also noted near the Settlement of Morskoi and south of the Settlement of Rybachii (Badyukova et al., 2004). Paleostraits filled with peat could also exist here.

We have to consider that, in addition to deflation (Boldyrev, 1998) or deflation and accumulation (Badyukova et al., 2004), processes of subsidence and waterlogging over the peat deposits might likely contribute to the formation of spit lowlands, in particular, lowlands oriented across the spit strike.

Peat is known to ignite spontaneously. Underground fires have not been recorded in the spit so far. However, one cannot exclude their probability, especially, in droughty years. When the groundwater level falls during such periods, oxygen can penetrate sand, reach the peat deposits (to a depth of 3–5 m), and trigger their self-ignition. Cases of water temperature rise to 40–60°C in wells of the Settlement of Lesnoi.[1] Desiccation and self-ignition of the peat may also be provoked by too large intake of groundwater from wells and boreholes. Burning of a peat deposit must result in its collapse and subsidence of the spit surface.

Attention should be paid to the absence of lagoonal marl beneath the sand strata in boreholes drilled in the Russian sector of the Curonian Spit. This fact casts doubt on the idea of Gudelis (1954) supported by several researchers (Blazhchishin et al., 1982; Romanova, 1991; Blazhchishin, 1995). According to this idea, the Curonian Spit (sand accumulations) migrated toward the Curonian Bay and overlapped the lagoonal sediments of the bay. Such migrations possibly occur in the Lithuanian sector of the spit, where eolian processes are more intensive.

CONCLUSIONS

The discovery of rather large peat deposits among eolian sands in the Curonian Spit is important for geomorphology, paleogeography, and geoecology of not only this spit, but also other similar structures and the Baltic Sea as a whole.

[1] V.V. Orlenok proposed another explanation for the appearance of hot water in wells of the Curonian Spit. He attributed this phenomenon to remote Carpathian earthquakes (see publications in the newspaper *Kaliningradskaya Pravda* in 2003 and 2004).

Like other analogous sand bars in the Baltic Sea bottom, the Curonian Spit is an ephemeral structure formed in the Holocene due to the combination of many favorable conditions. Changes of these conditions can destroy the spit and the existing ecological equilibrium, resulting in regional bio- and geoecological catastrophes.

Sea breaks across the spit and formation of new straits or channels, which would disturb the spit integrity and increase salinity in the bay, are among the most dangerous and real threats for the Curonian Spit. This danger will progressively increase with the intensification of greenhouse effect and World Ocean level rise.

Even at the present-day Baltic Sea level, the threat of seawater break across the spit to the bay has appeared repeatedly in some of the Curonian Spit sections during storms. The root zone of the spit (0–2 km) located near the town of Zelenogradsk, where a strait existed recently and peat deposits formed, is among such sections.

According to calculations made by the Lithuanian geologist O. Pustel'nikov (personal communication), the Klaipeda Strait and the northeastern part of the Curonian Bay are intensely accumulating sediments mainly delivered by the Neman River runoff and alongshore sand drifts. The runoff through this strait will cease in 20–30 years, resulting in rise of the Curonian Bay level and overflow of its water to the Kaliningrad Bay via the Matrosovka, Deima, and Pregolya rivers. However, the overflow would be insufficient to compensate the Curonian Bay level rise to the spit-breaking values. Pustel'nikov supposes that the break would occur between the Morskoi and Duny settlements, i.e., in the middle part of the spit near the Lithuanian border.

We agree that the break is possible from both the bay and the sea side. However, we suggest that the break is most probable in the spit area composed of a weak unstable material, such as peat. Among the discovered peat deposits, the largest deposit occurs in the spit root area (near the town of Zelenogradsk). Danger of the erosion of this deposit increases if the level of either the Baltic Sea or the Curonian Bay would rise. We suppose that precisely this area is most vulnerable from the point of view of the breakthrough of water, destruction of the Curonian Spit, and restoration of the paleostrait.

We have to note that peat deposits of the Curonian Spit are insufficiently studied. Their geological and paleogeographic significance are poorly understood. This statement is also valid for other spits in the Baltic Sea.

ACKNOWLEDGMENTS

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