Holocene environmental changes inferred from palaeobotanical data of Curonian Lagoon sediments

Irina Sosnina, Vaida Šeirienė, Alma Grigienė*

Abstract. Environmental development and water level changes in the south-western part of the Curonian Lagoon are reconstructed based on the results of bottom sediment investigations, including data on lithology, diatoms, pollen, and radiocarbon dating. Three stages have been identified in the ~ 10000-year history of the lagoon's development. The diatoms suggest that in the Early Holocene, the southern part of the Curonian Lagoon was a shallow freshwater basin, mainly fed by run-off from the continent. During the Middle Holocene, the study area was a marshy coastal zone. Due to a change in hydrological conditions at the beginning of the Late Holocene, it became an open-water part of the lagoon.

✉ *Irina Sosnina* (irina.sosnina@gamtc.lt)* 🔘 *https://orcid.org/0000-0002-3616-933X*
Vaida Šeirienė (vaida.seiriene@gamtc.lt) 🔘 *https://orcid.org/0000-0002-9477-2321*
Nature Research Centre, Akademijos 2, Vilnius, Lithuania

Alma Grigienė
Lithuanian Geological Survey under Ministry of Environment, S. Konarskio 35, Vilnius, Lithuania
*Corresponding author

INTRODUCTION

The south-eastern region of the Baltic Sea has a dynamic post-glacial formation history, which is reflected in its coastal lagoons. Even though the history of research on the Curonian Lagoon dates back a hundred and fifty years (Schumann 1859; Berendt 1869), there is still no precise standpoint on the process of development of the Curonian Lagoon ecosystem during the Holocene. The first major research work in this field was Benrath's monograph (1934), which attempted to resolve questions of biostratigraphy for the East Prussian coast based on plant fossils. Since then, researchers have amassed a vast database of geological, geographical and ecological records. The most detailed concept of the coastal area and lagoon formation was first described by Gudelis (1959). Based on geological data, he concluded that there were differences in the development of the northern and southern parts of the present lagoon. Specifically, a freshwater coastal lake existed in the southern part and a lagoon of the Littorina Sea existed in the northern part during the Holocene. Later, because of tectonic fluctuations, the Nemunas estuary shifted, which led to the erosion of the barrier between the lake and the bay to form a single water reservoir.

Kabailienė (1967), based on palynological and diatom studies, suggested that at the beginning of the Ancylus Lake stage of the development of the Baltic Sea, there was a single bay that included the northern and central parts of the present lagoon, while the southern part was at a higher level. After the first Littorina Sea transgression (L1), active peat formation began in the coastal area of the bay. During the maximum transgression (L2), the entire bay area, including the coast, was flooded. After regression, the Curonian Spit was formed on a moraine ridge of low hills.

From another point of view, Blazhchishin (1998) formulated the concept of two semi-enclosed lagoons in the modern sea area near the Curonian Spit. He

considered the south-western part of the modern lagoon to be an estuary of the Deyma River after the second Littorina Sea transgression.

Contemporary research, due to the transboundary nature of the area, has focused on various parts of the south-eastern coastal aquatorium. Damušytė (2011) described in detail the development of the northern and central parts of the basin, making a thesis that the presumed onset of the Curonian Spit started before the first Littorina Sea transgression (L1, 8300–8000 cal yr BP, after Damušytė 2011). From the mollusc fauna data, she concluded that the water in the northern and central parts of the palaeobasin was fresh during the mid-Holocene (8200–5000 cal yr BP, after Damušytė 2011).

Palaeographic studies of the southern part of the lagoon have been carried out by several research groups that reached similar conclusions on several issues. In the Early Holocene (11700–9000 cal yr BP, after Sergeev 2015), the southern part of the Curonian Lagoon was above the water level of the Baltic Sea (Yoldia Sea – Ancylus Lake stages) and developed in subaerial conditions (Sergeev 2015; Badyukova *et al.* 2007). Afterwards, a vast bay was formed between the indigenous coast of the Sambia Peninsula and the coastal escarpment within the Rybachy Plateau. At about 8000 cal yr BP, the Littorina Sea waters were ingested into the northern part of the Nemunas River palaeoestuary (Sergeev 2015). In addition, ongoing transgression led to the accumulation of lagoon sediments in the southern and eastern parts of the coastal basin and the filling of the basin depression with the Littorina Sea deposits. The following regression (7500 cal yr BP, after Sergeev 2015) stimulated the formation of a palaeospit stretching from the Sambia Peninsula to the Rybachy Plateau and separating the basin from the sea. Data shows that the mire formation process in the southern part of the lagoon started after 7500 cal yr BP (Napreenko *et al.* 2019). The next Littorina Sea transgression (about 4500 cal yr BP, after Sergeev 2015) intensified peat-forming processes in the highland parts of the basin. In the Late Holocene, a single sand spit was completely formed.

All these concepts share an important conclusion that the area underwent significant changes at the turn of the 7500 cal yr BP and between 4500–4200 cal yr BP. Moreover, the development of the northern and southern parts of the present-day lagoon was heterogeneous. However, the present data do not give any idea of the hydrological regime of the palaeobasin that existed in the southern part of the palaeo-water body. The role of the second Littorina Sea transgression in the formation of the coastal lagoon is still unclear. The timing of the final formation of the integral Curonian Spit along the southern coast of the Baltic Sea has not been determined either.

Within the framework of the presented study, an attempt was made to trace the development of the coastal zone in the root part of the Curonian Spit based on new palaeobotanical data. It is hoped that it will supplement our knowledge of the development of the Curonian Spit and reveal the peculiarities of the formation of the coastal zone of the Curonian Lagoon.

STUDY SITE

The Curonian Lagoon is a transboundary coastal water body connected to the south-eastern part of the Baltic Sea by the Klaipeda Strait. The lagoon area covers 1584 km², and the length of the coastal line is 611.82 km. The mean depth of the lagoon is 3.8 m, and the deepest part of the lagoon, which reaches 5.8 m, is the western part along the Curonian Spit. The pH of the water is alkaline, with an average value of 8.3. In the northern part of the lagoon, there are sporadic inflows of brackish water, which cause irregular fluctuations in salinity in the range of 0–7 psu (Gasiūnaitė *et al.* 2008). In the latter half of the 20th century, agriculture and urban activities became the major sources of P and N, contributing significantly to the current eutrophication processes of the northern and central parts of the lagoon (Vaičiūtė *et al.* 2021). The southern part of the lagoon is characterised by the accumulation of material from the Deyma and Matrosovka River delta and a relatively closed water circulation with lower current velocities, with the wind being the main driver of water mixing. The southern, Russian, part of the lagoon is nearly completely fresh due to discharge from the rivers (Chubarenko *et al.* 2017). The geological structure, poor water exchange, and seasonal salinity fluctuations allow the Curonian Lagoon to be classified as a naturally closed highly eutrophic freshwater basin.

MATERIALS AND METHODS

Coring and sampling

The cores were collected from the southern part of the Curonian Lagoon (N 54°57'55.6", E 20°32'50") and the northern part of the Svinoye raised bog (N 54°58'02", E 20°30'53"), at the southernmost part of the Curonian Spit (Fig. 1). The 3P core, 414 cm long, was taken through the ice with a Russian peat corer in the winter of 2021. It was drilled to a depth of 654 cm from the surface of the lagoon bottom (-240 cm). The 820 cm long SP core was taken with a Russian peat corer in the summer of 2008. The extracted sections were sub-sampled at 1 cm intervals for further analysis in the Laboratory of Quaternary Research at the Nature Research Centre.

Fig. 1 Location of the study sites (SP and 3P cores)

Table 1 Radiocarbon dating results of the studied sediment sections

№	Lab. no.	Depth, cm	Dated material	Radiocarbon age (^{14}C)	Calibrated age interval for 2 σ, yr BP
SP1	VS-1757	40–50	peat	810 ± 40	782–672
3P2	FTMC-EH59-3	408-409	peat	5927 ± 31	6799–6667
3P3	FTMC-EH59-4	567–568	peat	7945 ± 34	8985–8642

Radiocarbon dating and age-depth model

Two samples of the 3P core were dated by the ^{14}C radiocarbon method using accelerated mass spectrometry (AMS) at the Vilnius Radiocarbon Laboratory of the Centre for Physical Sciences and Technology. One sample from the SP core was dated by the ^{14}C radiocarbon method at the Laboratory of Nuclear Geophysics and Radioecology of the Nature Research Centre (Table 1). The radiocarbon dates were calibrated and the age-depth model for the 3P core was plotted using OxCal software, version 4.4 with the calibration curve IntCal20 (Bronk Ramsey 2008; Bronk Ramsey, Lee 2013; Reimer *et al.* 2020). To construct the age-depth model, two AMS data and one value equal to the core surface age (2021 AD) were applied.

Diatom analysis

Diatom analysis was carried out from 240 cm to 654 cm for each 10 cm interval of the 3P section according to standard procedure (Battarbee 1986). One or two drops of the resulting clean suspension were mounted on glass slides, air-dried for a couple of hours, and fixed with Naphrax. A minimum of 500 valves were counted per sample under the Nikon Eclipse Ci light microscope at 1000× magnification. In some samples, due to the lack of diatom shells, 100 valves were considered sufficient. Diatoms were identified following monographs by Krammer, Lange-Bertalot (1988, 1991a, b, 1997), Snoeijs (1993), Snoeijs, Vilbaste (1994), Snoeijs, Potapova (1995), Snoeijs, Kasperovičienė (1996), Snoeijs, Balashova (1998), and Witkowski *et al.* (2000). The

palaeoecological interpretation was based on diatom species with relative abundances ≥ 1%, ecological preferences (fresh, fresh-brackish, brackish-fresh or brackish waters), and life forms grouped into benthic and planktonic. This information was obtained from Barinova *et al*. (2006) and Van Dam *et al*. (1994). The diagram was constructed with Tilia-graph software, version 2.6.1. The zonation of the diatom stratigraphy was based on a visual inspection and a cluster analysis (incremental sum of squares) using CONISS (Grimm 1987).

Pollen analysis

The pollen analysis was performed for the 47 samples from 0 cm to 820 cm for the SP core. Chemical preparation for pollen analyses followed the procedure described by Grichuk (1940) and Erdtman (1936), which includes the treatment of the sediment with a heavy liquid (CdJ 2 + KJ). More than 500 terrestrial pollen grains were counted in each sample. The analysis was performed with a NICON microscope using image expansion 400×. Fægri *et al*. (1989) and Moore *et al*. (1991) pollen atlases were used for the identification of pollen. The percentage calculation of identified taxa is based on the sum of arboreal (AP) plus non-arboreal (NAP) taxa. The diagram was constructed with Tilia-graph software, version 2.6.1. (Grimm 1987).

RESULTS

Lithology. The difference in lithology between the cores is evidence of local variations in the sedimentation process (Fig. 2). However, some generalisations can be made.

According to the lithological description, the SP core material in the basal part is homogeneous sandy clay overlain by organic material. The organic layer consists of peat-sapropel followed by peat. In the upper part of the section, there is a micro-interval of sand (10 cm) preceded by a 14 cm layer of peat with occasional sand inclusions.

The 3P core, like the SP core, is composed of sandy clay at the bottom and an organic layer above, represented by alternating peat and peat-sapropel layers. The wood was found at a depth of 420–415 cm. The core was probably drilled through the tree trunk. At the top of the core, the organic layer is covered by silt material.

Chronology and sedimentation rates. The age-depth model of 3P core section (Fig. 3a) shows that the formation of study deposits began in the Early Holocene (about 10000 cal yr BP) and continued in the Middle Holocene (8800–5000 cal yr BP) with the organic material accumulation rate of about 0.076 cm/year (Fig. 3b). From the 5000 cal yr BP to the modern time, less organic and weakly compacted silty sediments accumulated.

Pollen analysis was performed on the SP core sediment samples from the 0–820 cm depth. Tree pollen dominates the spectra reaching up to 70–80%, and *Pinus*, *Alnus* and *Betula* prevail among them. Broad-leaved trees are not numerous. Dwarf shrub pollen makes up a significant proportion (up to 10%). Herbaceous plants have a high diversity, although the amount of pollen (up to 20%) is not high. Single pollen of aquatic plants is present. According to pollen composition changes, four local pollen assemblage zones (I Sv – IV Sv LPAZ) were singled out (Fig. 4):

I Sv LPAZ (820–800 cm depth) – *Pinus* pollen prevailed (up to 35%), and the pollen curves of *Betula* and *Alnus* increased up to 20%. The herbaceous plants are dominated by *Artemisia* and Cyperaceae. Some pre-Quaternary spores have been found in the sediments of this zone.

II Sv LPAZ (800–270 cm depth) – a share of *Alnus* pollen raised to 40%. *Carpinus* and *Quercus* pollen account for 5% each. *Corylus* pollen varies from 5 to 15%. Poaceae pollen predominates among the herbaceous plants. The lower part of this zone contains
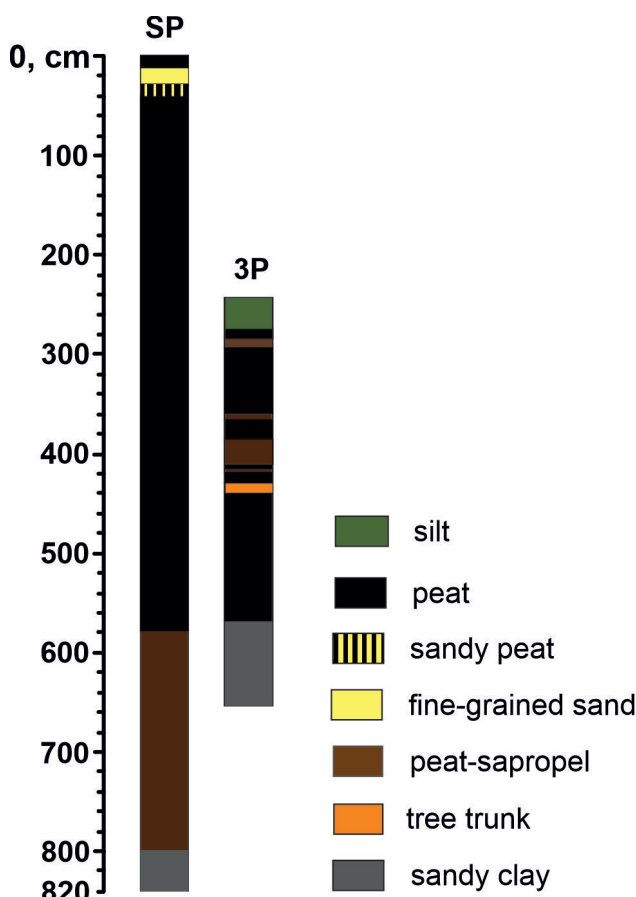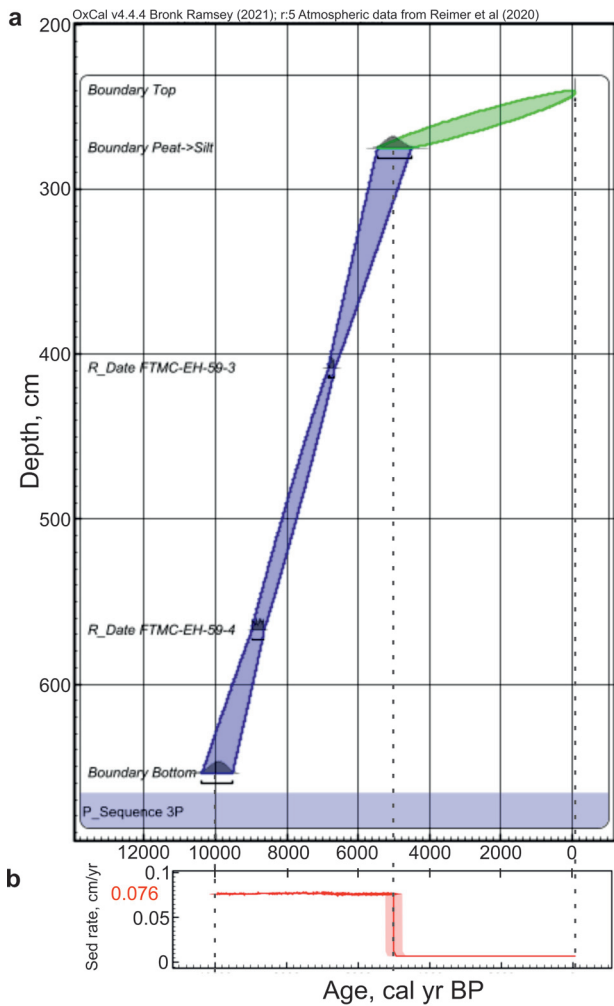

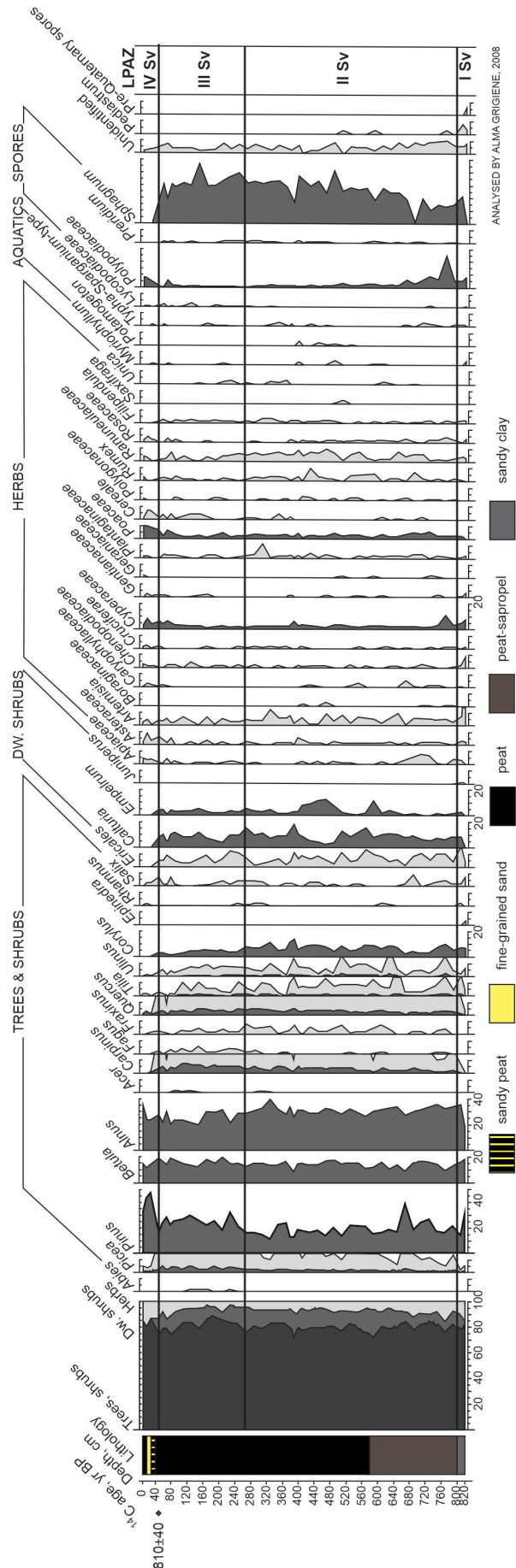**Fig. 2** Lithological structure of the studied sediment sections

Fig. 3 The age-depth model (a) and sedimentation rates (b) of the 3P section

up to 25% of Polypodiaceae spores, whereas in the upper part, there is an increasing number of *Sphagnum* spores.

III Sv LPAZ (270–50 cm depth) – increase in *Picea* pollen (up to 5%). The pollen curves of *Pinus* and *Carpinus* increase slightly, while the pollen curve of *Corylus* decreases. Among the herbaceous plants, Cyperaceae and Poaceae remain dominant. As in the previous zone, the pollen of cereals (Cereale) was found.

IV Sv LPAZ (50–0 cm depth) – a decrease in *Picea* pollen, and an increase in *Pinus* (up to 45%). An increase in grass pollen is also observed (up to 20%). More Cereale pollen is found. Some decrease in *Sphagnum* and an increase in Polypodiaceae spores is observed.

The diatom assemblage compositional changes and stratigraphically constrained cluster analysis were applied for the subdivision of the 3P section to local diatom assemblage zones (LDAZ). In the sediment interval of 240–660 cm, a total of 165 taxa representing 58 genera were identified. Throughout the

Fig. 4 Percentage pollen diagram of the SP section

81

Fig. 5 Ecological preferences of the diatom assemblages of 3P section

core, the most abundant taxa were benthic alkaliphilous diatoms of *Pseudostaurosira brevistriata* species (Fig. 5). Most of the species are fresh-brackish, which indicates the low salinity of the water (Fig. 6).

The LDAZ-1 (660–565 cm) is characterised by the mass diversity and development of benthic fresh-brackish diatoms. The most abundant are *Pseudostaurosira brevistriata* with a maximum number of about 30% of the total sum (580 cm depth), *Staurosira venter* (26.3%) and *Staurosirella pinnata* (27%). The species mentioned are eurytopic taxa occuring in both littoral and pelagic biotopes. They are often found in alkaline, slightly brackish water rich in dissolved mineral salts. Small *Staurosira* spp. reach an optimum in oxygen-rich waters, especially *Staurosirella pinnata* (Cholnoky-Pfannkuche 1968), which also is a calciphilous species, indicating a high content of calcium (Hustedt 1937, 1939).

The benthic taxa of genera *Epithemia* and *Ulnaria* are also characteristic of this zone. Fresh-brackish *Epithemia* spp. are often found in shallow water environments with pH values above 7 and a relatively high oxygen level (around 75% saturation). The studied site at this stage is characterised by a predominantly fresh-brackish and freshwater diatoms complex, with a salinity of less than 1‰ (Van Dam *et al.* 1994). According to pH state, dominant are the alkaliphilous forms which reach the relative abundance of up to 95 %.

Fig. 6 Percentage diatom diagram of the 3P section

In the LDAZ-2 (565–270 cm), the content of the dominant species *Pseudostaurosira brevistriata* almost doubles (~ 60 %). *Pseudostaurosira brevistriata* is a cosmopolitan species which prefers environments with high silica concentrations and pH levels around 7 (Schmidt *et al.* 2004; Milan *et al.* 2015). Meanwhile, the number

of species *Staurosira venter*, *Staurosirella pinnata* and *Staurosirella martyi* considerably decreased. The variety of planktonic taxa (*Actinocyclus normanii*, *Aulacoseira* spp.) increased and reached the maximum (up to 40%) in the middle part of the core (400 cm) mostly because of tychoplanktonic *Staurosira inflata*. This zone also contained several intervals (320 cm, 340–350 cm, 370–380 cm, 485–501 cm, 530–540 cm, 590 cm) where the diatom community was very low or absent.

In the LDAZ-3 (270–240 cm), the highest content of brackish diatoms (up to 20%), mainly *Actinocyclus normanii*, was detected. *A. normanii* is a warm stenothermic species and could be an indicator of an increased eutrophication process (Kiss et al. 2012). At the same time, the number of the centric planktonic diatoms, such as *Stephanodiscuss minutulus* and *Thalassiosira lacustris*, increases in the samples. *S. minutulus* is common in meso- to eutrophic lakes. It reaches its greatest abundance in productive nearshore regions, the mouths of large rivers and coastal embayments (Stoermer, Yang 1969). An increased abundance of *S. minutulus* in paleolimnological records is a strong indicator of cultural eutrophication (Reavie *et al*. 2000). *Thalassiosira lacustris* species can live in fresh to moderately high conductive waters but may be capable of dominating only when moderately brackish conditions exist (Hasle, Lange 1989; Smucker *et al*. 2008).

DISCUSSION

The analysed material allows dividing three stages in the development of the palaeobasin:

The isolated freshwater palaeobasin stage, 10000–8800 cal yr BP (660–565 cm). Sedimentation of sandy clay took place on the vast territory including modern Svinoye raised bog and the southern part of the Curonian Lagoon near Curonian Spit during the Early Holocene proven with the lithology of the lowermost part of the studied cores and published data (Badyukova *et al.* 2007; Sergeev 2015; Napreenko *et al.* 2019). Presumably, the same limnoglacial deposits began to accumulate in the pre-Holocene; however, the sandy clay from the SP core lay down higher than the same sediments from the 3P core and were deposited in a stable terrestrial environment. Meanwhile, sediments from the 3P core may have accumulated in the estuarine zone of the river or several streams (Sergeev 2015). With pollen data, we can suggest that pine trees were a significant component of the vegetation woodland environment. Increases in the abundance of *Betula* and *Alnus* could indicate changes in the local environment, such as shifts in moisture levels that agree with a small peak of *Cyperaceae*, commonly found in wetter habitats, such as marshes. At this stage of development, vegetation is suggested to be a mix of coniferous and deciduous trees and diverse herbaceous

plants indicative of varied ecological conditions. Some *Pediastrum* may be an allochthonous component signalling a nearby freshwater body. The presence of pre-Quaternary spores emphasises the distinction with the overlying Holocene sediments.

Core 3P deposits, on the other hand, could cover the bottom of a body of water due to the constant amount of well-preserved diatom valves. The palaeobasin was freshwater with a salinity of less than 1% (Fig. 5), as indicated by the diatom complex with the mass occurrence of small fragilarioid species such as *Staurosirella pinnata* and *Staurosirella martyi*, which are an important component of of the fresh- and slightly brackish-water water flora (Witkowski *et al.* 1996, 2000). The presence of benthic species of the genera *Amphora*, *Cocconeis* and *Epithemia*, which are common to shallow alkaline lakes with pH > 7, suggests that the alkaline shallow water conditions were favourable for diatom development. The low water level is also evidenced by the trivial presence of plankton species. The presence of a diatom complex with a consistent number of well-preserved valves in the lowest part of core 3P may indicate limnological as well as fluvial water conditions. Some sporadic *Gomphonella olivacea* that are common in streams and rivers and *Gomphonema angustatum* could support that this region in the Early Holocene was one of the supply areas of the fluvial palaeo-network, which filled the low relief part of the Curonian Lagoon (Sergeev 2015).

The coastal wetland stage, 8800–5000 cal yr BP (565–275 cm). Further rapid sedimentation of the organic material in the palaeobasin seems to have taken place under changing environmental conditions, as evidenced by the highly variable lithological composition of the sediments. The varying numbers of diatom frustules including intervals where they are absent also indicate this. More stable environmental conditions are observed during the 8800–8200 cal yr BP. According to diatom analysis data, *Pseudostaurosira brevistriata* and *Staurosira* spp. continued to dominate indicating that water was still alkaline and Si-enriched. The increased diversity and abundance of planktonic species of *Aulacoseira* and *Stephanodiscus* genus is a possible indication of rising water level. There was an increase in the richness of *Staurosira inflata*, a taxon classified by Vos and de Wolf (1993) as a brackish/freshwater tychoplankton species, which is also found in mesotrophic and eutrophic conditions with a high total phosphorus concentration and neutral pH of 6.7 to 7.3 (Rusanov *et al*. 2018). This suggests a varying environment of the littoral zone, influenced by the low brackish water of the Littorina Sea and continental inflows. A relatively low abundance of *Actinocyclus normanii*, a freshwater species with a brackish affinity, may also indicate

Littorina Sea intrusions during this period. Meanwhile, the diatom species composition remained almost unchanged during the period (8200–5000 cal yr BP), but in some intervals, only single frustules or no frustules were found. This may be due to water level fluctuations caused by sea level rise.

The increase in *Alnus* pollen to 40% indicates a significant expansion of black alder forests in the coastal upland region, suggesting that wet conditions prevail. At the beginning of this stage swamps probably formed. This is also indicated by 25% of Polypodiaceae spores. Based on the homogeneity of the material and similar sedimentation rates in both cores studied, it would be possible to assume the existence of a similar primary succession, which was formed on limno-glacial sediments and extended from the southern depression of the Curonian Lagoon to the almost coastal margin of the sea (Svinoye raised bog). However, this small area has some local ecosystems whose development followed slightly different scenarios. Our data suggest that in this period the site was a coastal area of forested marshland, confirmed by deposits of lowland peat with woody remains and mostly benthic diatom complex. Meanwhile, data from the bog central part point to the existence of a shallow water body with gyttja accumulation between 7500–7000 cal yr BP (Napreenko *et al.* 2019).

It is not possible to conclude unequivocally that the water level in this area has risen but given the intervals of sporadic diatom abundance and some taxa with brackish affinity, it can be assumed that fluctuations occurred during this period, causing changes in the species composition of the diatom community and the surrounding vegetation.

The stage of the lagoon littoral zone, 5000 cal yr BP – 2021 AD (275 cm – 240 cm). At this phase of the palaeobasin's development, the sedimentation regime underwent a further change, as the nature of sediments changed – silt with shell material began to be deposited. Some increase in the salinity of the water is observed as indicated by an increase in the number of brackish diatom species. Changing diatom assemblages may also indicate increased eutrophication in the palaeobasin.

While the presence of *Actinocyclus normanii* is observed in samples across the entire 3P section, in the upper part of the column its amount reaches 17% (256 cm), possibly the taxon subsequently spread southwards and, as conditions were favourable enough, actively increased its biomass.

CONCLUSIONS

The new data presented above suggest that the south-western part of the lagoon was isolated from the Baltic Sea during the Early Holocene, up to 8800 cal yr BP. After 8800 cal yr BP, Middle and Late Holocene, the presence of brackish diatoms with breaks in diatom stratigraphy of the sediment core possibly indicates some Littorina Sea intrusions. This is partly consistent with the concept of Gudelis (1959) and Blazhchishin (1998) on the development of the Curonian Lagoon. Gudelis (1959) assumed that the lake existed in the southern part of the modern lagoon during the Littorina Sea stage (at about 7000–6500 cal yr BP), which is supported by the diatoms, but not by the dating results. In the first stage of its development, the palaeobasin could be a coastal lake that later transformed into a littoral zone of the forming lagoon. In this case, the homogeneity of the diatom complex of this zone with the preservation of the dominant species and, at the same time, a notable decline in the diatom population across several horizons can be attributed to fluctuations in the water level. As the content of diatoms with brackish affinity was low, it can be assumed that brackish water inflows were more significant in the northern part of the paleobasin and these taxa migrated. However, our data on changes in the sedimentation and water level rise did not correlate well with the dates of the Littorina Sea transgressions (8300–8000 (L1), 7500–7000 (L2) and 4700–4100 (L3) cal yr BP, according to Damušytė (2011)), making us think that sea level rise did not radically affect the diatom complex of the southern part of the Curonian Lagoon.

REFERENCES

Badyukova, E.N., Zhindarev, L.A., Lukyanova, S., Solovieva, G.D. 2007. Analysis of the geological structure of the Curonian Spit (Baltic Sea) in order to clarify the history of its development. *Oceanology 47(4)*, 594–604.

Barinova, S.S., Medvedeva, L.A., Anisimova, O.V. 2006. Bioraznoobrazie vodoroslej-indikatorov okruzhayushchej sred [Biodiversity of algae-environmental indicators]. Tel Aviv, Pilies Studio, 498 pp. [In Russian].

Battarbee, R. W. 1986. Diatom analysis. In: Berglund B.E. (ed). Handbook of Holocene Paleoecology and Paleohydrology. London: Willey&Sons, 527–570. https://doi.org/10.1002/jqs.3390010111

Benrath, W. 1934. *Untersuchungen zur Pollenstatistik und Mikrostratigraphie von Tonen und Torfen in Randgebieten des Kurischen Haffs unter Berücksichtigung methodischer Fragen [Investigations on pollen statistics and microstratigraphy of clays and peats in marginal areas of the Curonian Lagoon under consideration of methodological questions]*. Königsberg, 124 pp. [In German].

Berendt, G. 1869. *Geologie des Kurischen Haffes und seiner Umgebung: zugleich als Erläuterung zu Sektion 2, 3 und 4 der geologischen Karte von Preussen [Geology of the Curonian Lagoon and its surroundings: also, an explanation of sections 2, 3 and 4 of the geological map of Prussia]*. Königsberg, 130 pp. [In German].

Blazhchishin, A.I. 1998. *Paleogeografiya i ehvolyuciya pozdnechetvertichnogo osadkonakopleniya v Baltijskom more [Palaeogeography and evolution of Late Quaternary Sedimentation in the Baltic Sea]*. Kaliningrad: Yantarny Skaz, 160 pp. [In Russian].

Bronk Ramsey, C. 2008. Deposition models for chronological records. *Quaternary Science Reviews 27(1–2)*, 42–60.

Bronk Ramsey, C., Lee, S. 2013. Recent and Planned Developments of the Program OxCal. *Radiocarbon 55(2–3),* 720–730.

Cholnoky-Pfannkuche, K. 1968. Einige Respirationsversuche an Cyanophyten [Some respiration experiments on cyanophytes]. *Phycologia 7(1),* 4–11. [In German]. https://doi.org/10.2216/i0031-8884-7-1-4.1

Chubarenko, B., Domnin, D., Navrotskaya, S., Stont, Z., Chechko, V., Bobykina, V., Pilipchuk, V., Karmanov, K., Domnina, A., Bukanova, T., Topchaya, V. 2017. Transboundary Lagoons of the Baltic Sea. In: *The Diversity of Russian Estuaries and Lagoons Exposed to Human Influence. Estuaries of the World.* Springer, Cham, 149–189. https://doi.org/10.1007/978-3-319-43392-9_6

Damušytė, A. 2011. *Post-glacial geological history of the Lithuanian coastal area*. Summary of doctoral thesis. Vilnius, 84 pp.

Erdtman, G. 1936. New methods in pollen analysis. *Svensk Botanisk Tidskrift 30*, 154–164.

Fægri, K., Kaland, P. E., Krzywinski, K. 1989. *Textbook of pollen analysis*. New York: John Wiley & Sons Ltd, 328 pp.

Gasiūnaitė, Z.R., Daunys, D., Olenin, S., Razinkovas, A. 2008. Ecology of Baltic Coastal Waters. The Curonian Lagoon. *Ecological Studies 197,* 197−215. https://doi.org/10.1007/978-3-540-73524-3_9

Grichiuk, V.P. 1940. Metodika obrabotki osadochnykh porod, bednykh organicheskimi ostatkami, dlya celej pyl'cevogo analiza [The preparation methodology of the organic poor sediments for the pollen analysis]. *Problemy fizicheskoj geografii [Problems of physical geography] 8,* 53–58. [In Russian].

Grimm, E.C. 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computer & Geoscience 13(1),* 13–35. https://doi.org/10.1016/0098-3004(87)90022-7

Gudelis, V. 1959. Geologicheskaya i fiziko-geograficheskie uslovija zaliva Kurshyu marios i territorii, okajmlyayushchej zaliv [Geological and physical-geographical conditions of the Curonian Lagoon and surrounding territory]. In: K. Jankevicus (ed.), *Kuršių marios*. Mokslas: Vilnius, 7−45. [In Russian].

Hasle, G.R., Lange, C.B. 1989. Freshwater and brackish water Thalassiosira (Bacillariophyceae): taxa with tangentially undulated valves. *Phycologia 28(1)*, 120−135. https://doi.org/10.2216/i0031-8884-28-1-120.1

Hustedt, F. 1937. Systematische und okologische untersuchungen uber die Diatomeen-Flora von Java, Bali und Sumatra nach dem Material der Deutschen Limnologischen Sunda-Expedition "Tropische Binnengewässer, Band VII" [Systematic and ecological studies on the diatom flora of Java, Bali and Sumatra based on the material of the German Limnological Sunda Expedition "Tropical Inland Waters, Volume VII"]. *Archiv für Hydrobiologie, Supplement 15(2)*, 187−295. [In German].

Hustedt, F.1939. Die Diatomeenflora des Küstengebietes der Nordsee vom Dollart bis zur Elbemündung. I. Die Diatomeenflora in den Sedimenten der unteren Ems sowie auf den Watten in der Leybucht, des Memmert und bei der Insel Juist [The diatom flora of the coastal area of the North Sea from the Dollart to the mouth of the Elbe. I. The diatom flora in the sediments of the lower Ems and on the mudflats in the Leybucht, the Memmert and near the island of Juist]. *Abhandlungen des Naturwissenschaftlichen Vereins zu Bremen XXXI*, 572−677. [In German].

Kabaillienė, M. 1967. Razvitie kosy Kurshiu Nerija i zaliva Kurshiu Marios [The development of the spit of the Kuršių Nerija and the Kuršių Marijos bay]. *Voprosy geologii i paleogeografii chetvertichnogo perioda Litvy: Trudy Instituta geologii 5,* 181−207. [In Russian].

Kiss, K.T., Klee, R., Ector, L., Ács, É. 2012. Centric diatoms of large rivers and tributaries in Hungary: morphology and biogeographic distribution. *Acta Botanica Croatica 71*, 311−363. https://doi.org/10.2478/v10184-011-0067-0

Krammer, K., Lange-Bertalot, H. 1988. *Süßwasserflora von Mitteleuropa [Freshwater flora of Central Europe]. Bacillariophyceae. Teil 2: Bacillariaceae, Epithemiaceae, Surirellaceae.* Stuttgart: Gustav Fischer Verlag, 596 pp. [In German].

Krammer, K., Lange-Bertalot, H. 1991a. *Süßwasserflora von Mitteleuropa [Freshwater flora of Central Europe]. Bacillariophyceae. Teil 3: Centrales, Fragilariaceae, Eunotiaceae*. Stuttgart: Gustav Fischer Verlag, 576 pp. [In German].

Krammer, K., Lange-Bertalot, H. 1991b. *Süßwasserflora von Mitteleuropa [Freshwater flora of Central Europe]. Bacillariophyceae. Teil 4: Achnanthaceae. Kritische Ergänzungen zu Navicula (Lineolate) und Gomphonema*. Stuttgart: Gustav Fischer Verlag, 437 pp. [In German].

Krammer, K., Lange-Bertalot, H. 1997. *Süßwasserflora von Mitteleuropa [Freshwater flora of Central Europe]. Bacillariophyceae. Teil 1: Naviculaceae.* Stuttgart: Gustav Fischer Verlag, 876 pp. [In German].

Milan, M., Bigler, C., Salmaso, N., Guella, G., Tolotti, M. 2015. Multiproxy reconstruction of a large and deep subalpine lake's ecological history since the Middle Ages. *Journal of Great Lakes Research 41(4)*, 982–994. https://doi.org/10.1016/j.jglr.2015.08.008

Moore, P. D., Webb, J. A., Collison, M. E. 1991. *Pollen analysis*. Oxford: Blackwell scientific publications, 216 pp.

Napreenko, M.G., Napreenko-Dorokhova, T.V., Subetto, D.A. 2019. Reconstruction of a coastal raised bog development in the proximal part of the Curonian Spit, Kaliningrad Region, Russia, South-Eastern Baltic. *Russian Journal of Earth Sciences 19(6)*, ES6008. https://doi.org/10.2205/2019ES000680

Reavie, E.D., Smol, J.P., Sharpe, I.D., Westenhofer, L.A., Roberts, A.M. 2000. Paleolimnological analyses of cultural eutrophication patterns in British Columbia lakes. *Canadian Journal of Botany 78(7),* 873−888. https://doi.org/10.1139/b00-058

Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R., Friedrich, M., Grootes, P., Guilderson, T., Hajdas, I., Heaton, T., Hogg, A., Hughen, K., Kromer, B., Manning, S., Muscheler, R., Palmer, J., Pearson, C., van der Plicht, J., Reimer, R., Richards, D., Scott, E., Southon, J., Turney, C., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon 62(4)*, 725–757. https://doi.org/10.1017/RDC.2020.41

Rusanov, A.G., Ector, L., Morales, E.A., Kiss, K.T., Ács, É. 2018. Morphometric analyses of Staurosirainflata comb. nov. (Bacillariophyceae) and the morphologically related Staurosiratabellaria from north-western Russia. *European Journal of Phycology 53(3),* 336–349. https://doi.org/10.1080/09670262.2018.1452050

Schmidt, R., Kamenik, C., Lange-Bertalot, H., Klee, R. 2004. Fragilaria and Staurosira (Bacillariophyceae) from sediment surfaces of 40 lakes in the Austrian Alps in relation to environmental variables, and their potential for palaeoclimatology. *Journal of Limnology 63(2),* 171–189. https://doi.org/10.4081/jlimnol.2004.171

Schumann, J. 1859. *Geologische Wanderungen durch Altpreussen [Geological hikes through Old Prussia]*. Königsberg: Hübner & Matz., 228 pp. [In German].

Sergeev, A.Yu. 2015. Paleogeograficheskaya rekonstrukciya rajona Kurshskoj kosy v pozdnem Neoplejstocene–Golocene [Paleogeographic reconstruction of the area of the Curonian Spit in the Late Pleistocene–Holocene]. *Regional'naya geologiya i metallogeniya [Regional geology and metallogeny] 62,* 34–44. [In Russian].

Smucker, N.J., Edlund, M.B., Vis, M.L. 2008. The distribution, morphology, and ecology of a non-native species, Thalassiosira lacustris (Bacillariophyceae), from benthic stream habitats in North America. *Nova Hedwigia 87(1)*, 201−220. https://doi.org/10.1127/0029-5035/2008/0087-0201

Snoeijs, P. 1993. *Intercalibration and distribution of diatom species in the Baltic Sea. Vol. 1*. Upsala: Opulus Press, 130 pp.

Snoeijs, P., Vilbaste, S. 1994. *Intercalibration and distribution of diatom species in the Baltic Sea. Vol. 2*. Upsala: Opulus Press, 125 pp.

Snoeijs, P., Potapova, M. 1995. *Intercalibration and distribution of diatom species in the Baltic Sea. Vol. 3*. Upsala: Opulus Press, 125 pp.

Snoeijs, P., Kasperovičienė, J. 1996. *Intercalibration and distribution of diatom species in the Baltic Sea. Vol. 4*. Uppsala: Opulus Press, 125 pp.

Snoeijs, P., Balashova, N. 1998. *Intercalibration and distribution of diatom species in the Baltic Sea. Vol. 5*. Upsala: Opulus Press, 144 pp.

Stoermer, E.F., Yang, J.J. 1969. Plankton diatom assemblages in Lake Michigan. *Special report of the Great Lakes Research Division*, 47. University of Michigan, 168 pp.

Vaičiūtė, D., Bučas, M., Bresciani, M., Dabulevičienė, T., Gintauskas, J., Mėžinė, J., Tiškus, E., Umgiesser, G., Morkūnas, J., De Santi, F., Bartoli, M. 2021. Hot moments and hotspots of cyanobacteria hyperblooms in the Curonian Lagoon (SE Baltic Sea) revealed via remote sensing-based retrospective analysis. *Science of The Total Environment 769*, 145053. https://doi.org/10.1016/j.scitotenv.2021.145053

Van Dam, H., Mertens, A., Sinkeldam, J. 1994. A coded checklist and ecological indicatorvalues of freshwater diatoms from the Netherlands. *Netherland Journal of Aquatic Ecology 28,* 117−133.

Vos, P.C., de Wolf, H. 1993. Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects. *Hydrobiologia 269/270,* 285−296.

Witkowski, A., Lange-Bertalot, H., Metzeltin, D. 1996. The diatom species *Fragilaria martyi* (Heribaud) Lange-Bertalot, identity and ecology. *Archiv für Protistenkunde 146(3–4),* 281−292. https://doi.org/10.1016/S0003-9365(96)80015-7

Witkowski, A., Lange-Bertalot, H., Metzeltin, D. 2000. *Diatom flora of marine coasts. Iconographia Diatomologica 7*, 925 pp.