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LAGOON SEDIMENTS IN THE CENTRAL PART OF THE VISTULA SPIT: GEOCHRONOLOGY, SEDIMENTARY ENVIRONMENT AND PECULIARITIES OF GEOLOGICAL SETTINGS

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Abstract. Lagoon gyttja layers occurring in anomalously high position (up to 2.5 m above the present-day sea level) are known from the central part of the Vistula Spit (Kaliningrad region of the Russian Federation). Complex investigations of lagoon sediments (gyttja, sand), including radiocarbon (^{14}C) dating as well as mollusc, pollen and diatom analyses, have been carried out in 2004–2005. The results of these investigations indicate that the lagoon sediments were deposited in the Late Subboreal–Early Subatlantic period in a shallow freshwater, overgrown basin periodically influenced by brackish water. The anomalously high level of the lagoon gyttja is determined by neotectonic activity of Earth’s crust blocks.

Key words: gyttja, lagoon sediments, neotectonics, Vistula Spit, Baltic Sea.

INTRODUCTION

The outcrops of black grey lagoon gyttja in the central part of Vistula Spit (in the Kaliningrad region of the Russian Federation, 3.5 km from the state border with Poland) have been known since 1993 (Fig. 1). They are described as sediments deposited during the Limnea transgression of the Baltic Sea (Badiukova *et al.*, 1996). In the published geomorphologic scheme of the Vistula Spit, the area occupied by the above-mentioned organic sediments is mapped as a low lagoon terrace (Solovjova, Badiukova, 1997). According to these authors, a strait between the Baltic Sea and the Vistula Lagoon existed in this place. Other investigators of this region (Solovjov, 1971) also maintain the existence of straits across the Vistula Spit. In 2000, investigators from the Atlantic Branch of P.P. Shirshov Institute of Oceanology made a detailed mapping of two areas of lagoon sediments in the northern part of the Vistula Spit. The top of lagoon sediments in the first, more southwestern, area has been fixed at the altitudes ranging from +2.0 to +2.5 m. In the second area, located about 0.5 km to NNE from the first one, the top of gyttja layer has been determined at the altitude of +1.8 m. An attempt to explain the anomalously high level of the lagoon sediments was the main reason for their detailed researches carried out by a group of investigators in 2004–2005. Thus, there were two main topics of complex researches: when the lagoon sediments were formed and how to explain their present-day position.

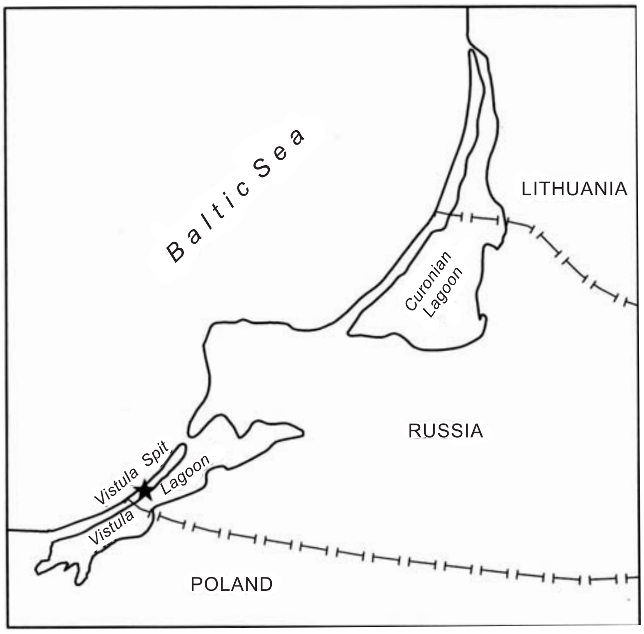

Fig. 1. A general sketch map

Location of the study area is indicated by an asterisk

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GEOLOGICAL SETTINGS

According to the data of mapping carried out by V. Bolderev and colleagues in 2000 (unpublished report), the lagoon gyttja in the largest, more southwestern area has a form of a bay with a ragged coastline. It covers the area of about 27 hectares of the Spit (Fig. 2, enlarged area). Distribution of gyttja along the present coast of the Vistula Lagoon is interrupted by wash erosion: gyttja is exposed in the cliff of the height varying from 2–2.5 to 5–6 m (Fig. 2, cross-section A). The top of gyttja occurs at the altitudes of +2.0 – +2.5 m, the thickness of the layer reaches up to 0.5–0.7 m. Thin

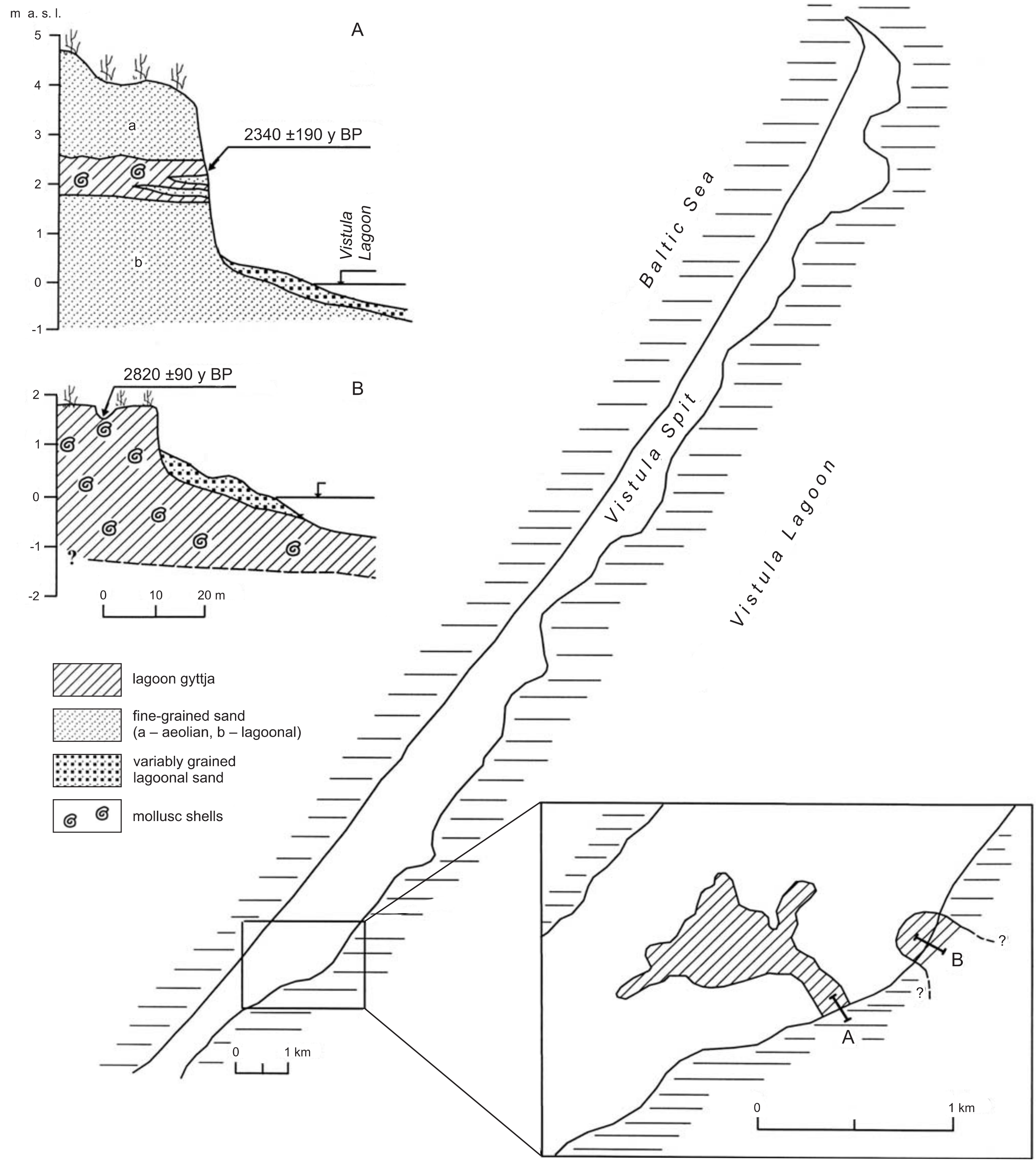

Fig. 2. Location of lagoon gyttja in the central part of the Vistula Spit (enlarged area) and geological settings of the investigated sections (geological cross-sections along lines A and B)

Fig. 3. The lagoon gyttja setting in the central part of the Vistula Spit (cross-section A)

Fig. 4. Truncation of the lagoon gyttja layer (cross-section A)

interlayers (up to 5–10 cm) of fine-grained lagoon sand are intervening into the monolithic layer of gyttja in some places (Fig. 3). Dark gray sandy lagoon gyttja is rich with remnants of molluscs. Signs of bioturbation are observed below the gyttja layer – in the fine-grained greyish-yellow lagoon sand. This sand layer has a massif texture, but sub-horizontal lamination or ripples are observed in some places. Lagoon gyttja is covered by aeolian sand in some peripheral areas. In the zones of truncation of lagoon gyttja, a thin layer (up to 20–30 cm) of lagoon sand usually covers the gyttja (Fig. 4). The uppermost layer of aeolian deposits is represented by greyish- and brownish-yellow massive (or with poorly marked laminae) sand. Both lagoonal and aeolian sand is very similar: the granulometric composition shows the strong predominance of the particles of ∅ 0.5–0.25 mm, accounting for 82–83% of the total amount of the sediments.

Lagoon gyttja of the smaller area, located to the NNE from the larger one, covers about 4 hectares of the Spit. The top of the sediments is at the altitude of +1.8 m (Fig. 2, cross-section B). Thus, visual thickness of the gyttja layer is about 1.8 m, but the same gyttja was traced at the lagoon bottom to the depth of 1.3 m, i.e. it is possible to suggest that the gyttja is more than 3 m thick. The lagoon gyttja is dark grey in colour, it has a massive texture and is very rich in mollusc fauna.

RESEARCH METHODS

The present authors conducted field investigations in both of the above-mentioned areas of lagoon sediments in the Vistula Spit (sediment description, measurements, sampling, photos, *etc.*) in May 2004. The integrated investigations of lagoon sediments, including mollusc, pollen and diatom analyses as well as radiocarbon (^{14}C) dating, have been carried out from June 2004 to June 2005. In the smaller area of the lagoon gyttja, all investigations were concentrated in one profile (Fig. 2B), while in the larger area, only radiocarbon (^{14}C) dating was made directly on geological profile A (Fig. 2A). The samples for mollusc, pollen and diatom analyses were taken at some distance (about 15 m to SSW) from geological profile A where the gyttja layer is more thicker and monolithic – the cliff is 2.5 m high and there is no aeolian deposit cover above the gyttja (Fig. 3, left side of photo).

RADIOCARBON DATING

Radiocarbon (^{14}C) dating of the lagoon gyttja (bulk sample) in section A was made at the depth of 1.5 m (measured from the cliff's edge), i.e. at the altitude of +2.2 m (Fig. 2A). Remnants of mollusc shells (*Unio pictorum* Linnaeus) were the object of dating in section B. The sample was taken at the depth of 0.4–0.6 m from a pit excavated on the top of a 1.8-m high cliff (i.e. from altitudes of +1.4– +1.2 m) (Fig. 2, B). Radiocarbon analysis of both the samples was carried out by J. Mažeika and R. Petrošius at the Radioisotope Research Laboratory of Institute Geology and Geography in Lithuania.

MOLLUSC ANALYSIS

A sample of mollusc remnants was collected at the depth of 0.5–0.8 m (i.e. at the altitude of +2.0–+1.7 m) in section A. Another sample was taken from the pit on the top of section B (altitudes +1.4–+1.2 m), i.e. this from the same place and depth as the sample collected for radiocarbon dating. The identification of molluscs was based on relevant monographs (Danilovskij, 1955; Glöer, Meier-Brook, 1998; Skompski, 1991, 1996; Šivickis, 1960). The composition of mollusc species is shown in histograms with the total amount of individuals indicated (Figs. 5, 6). Mollusc analysis was carried out by A. Damušytė at the Geological Survey of Lithuania.

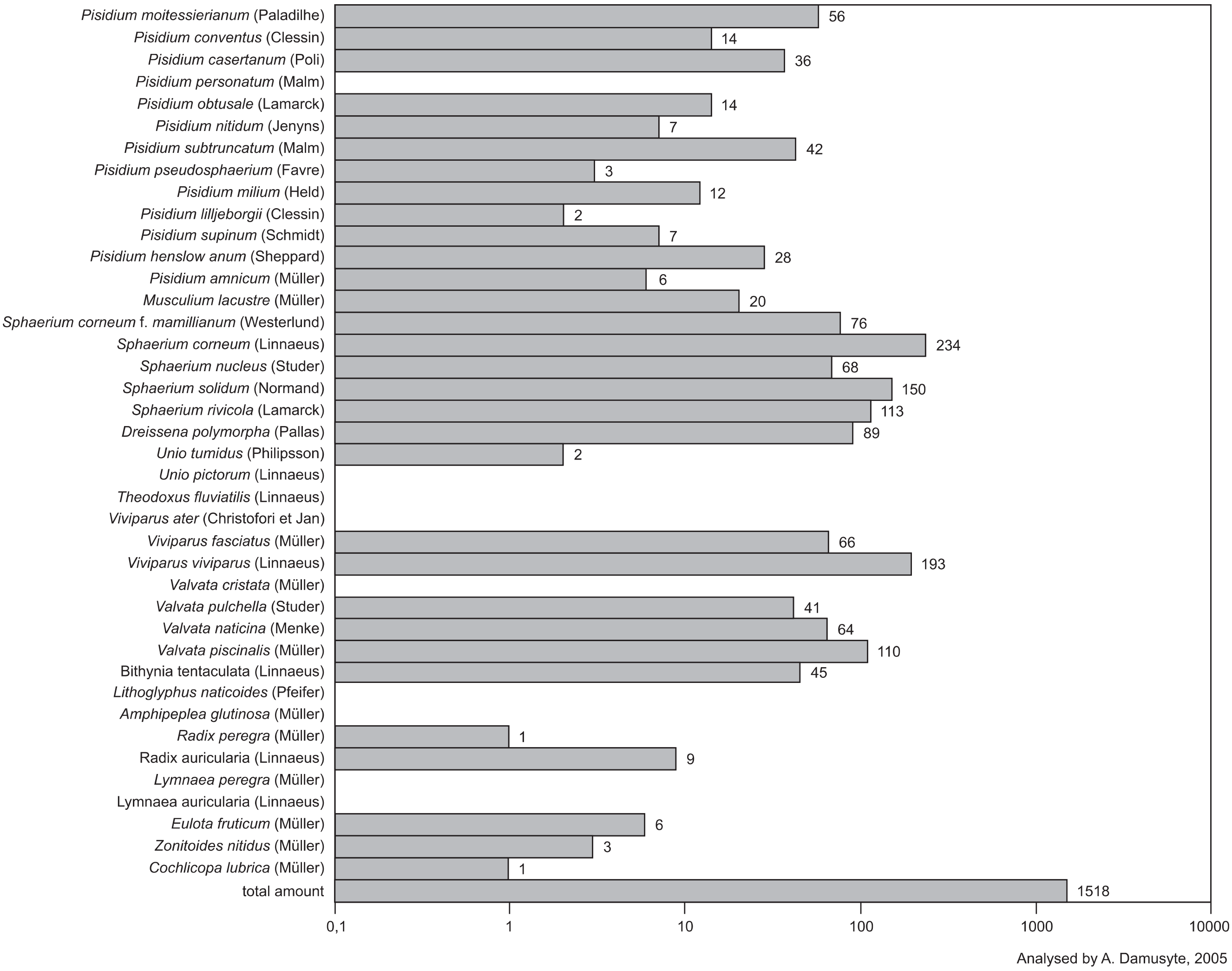

Fig. 5. Mollusc composition in section A

POLLEN ANALYSIS

The samples for pollen studies were collected at the depth of 0.3–1.7 m in section A (measured from the top of a 2.5-m high cliff) from each 5 cm section of sediment; in the section B – at the depth of 0.35–1.7 m (measured from the top of a 1.8-m high cliff) from each 20 cm section. All the samples were first boiled for 5 min in 10% KOH. Those which contained carbonates were subsequently treated with 10% HCl. Coarse mineral particles were removed by decanting, and macroscopic plant remains by sieving through a 0.25 mm mesh sieve. Fine mineral particles were separated according to the Grichuk's method (Grichuk, Zaklinskaya, 1948) using KJ and CdJ_2 heavy liquids (density 2.22 mg/cm^3). The organic fraction was treated by the standard acetolysis method (Erdtman, 1960). The material was mounted in glycerine and the minimums of 1000 arboreal pollen grains per sample were counted. Pollen percentage values were calculated as percentage of the total sum of terrestrial plants (trees, shrubs and herbs). The percentage of aquatic plants and pteridophyta (X) was calculated on the pollen sum + X for each separate component. The monograph of Faegri and Iversen (1989) was used for pollen identification. The results of pollen analyses of the sediments are presented in complete pollen percentage diagrams (Figs. 7, 8). The pollen analysis was performed by A. Grigienė at the Geological Survey of Lithuania.

DIATOM ANALYSIS

Diatom analysis was made on the same samples that were collected for pollen analysis (each sample was separated into two pieces – for pollen and diatom analyses). The samples were processed with 10% HCl and 30% H_2O_2 to remove carbonates and organic matter, respectively. The diatom frustules were separated from finer mineral matter by repeated decantation. Heavy liquid was used for separation of diatoms from coarse mineral matter. Slides were prepared with Naphrax as a mounting medium. Diatoms were identified using a Leica light microscope, magnification ×1000. A minimum of 500 diatom valves were

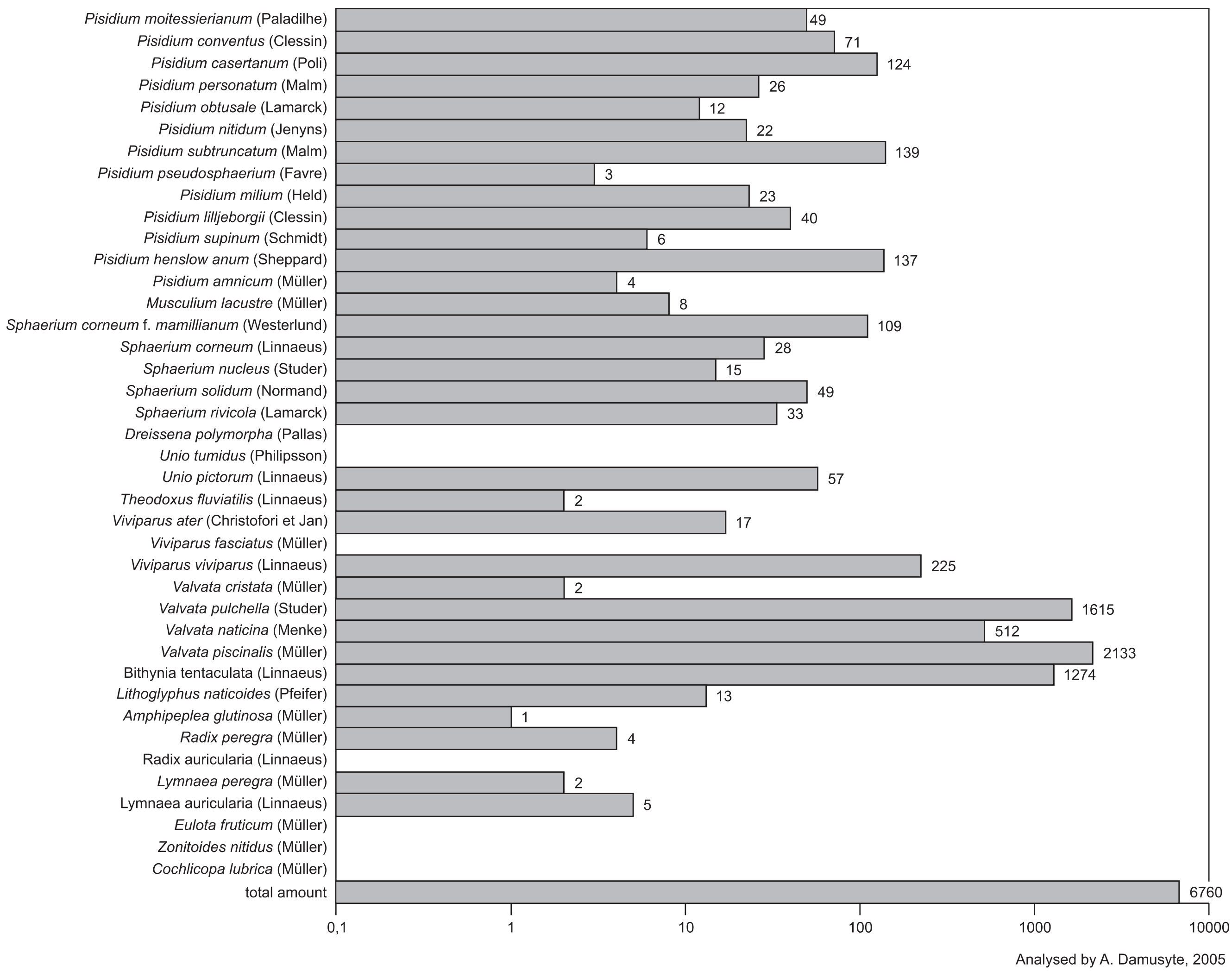

Fig. 6. Mollusc composition in section B

counted for each sample, except in section A where the density of diatom valves was very low in most samples.

The diatom identification was based on taxonomic monographs and books (Khursevich, Loginova, 1980; Krammer, Lange-Bertalot, 1986, 1988, 1991a, 1991b; Snoeijs, 1993; Snoeijs, Vilbaste, 1994; Snoeijs, Potapova, 1995; Snoeijs, Kasperovičienė, 1996; Snoeijs, Balashova, 1998). Data concerning the ecology of the diatom taxa were compiled from the previous references.

The percentage of species was calculated for samples containing more than one hundred diatoms in total. Diatom diagrams show only those diatom species whose content is more than one percent per sample. Black-coloured curves in the diatom diagram of section B indicate the real percentage of the species; nearby displayed grey-coloured curves – the curve enlarged 10 times (Figs. 9, 10). Diatoms were analysed by G. Vaikutienė at the Faculty of Natural Sciences of the Vilnius University.

RESULTS AND INTERPRETATIONS

RADIOCARBON DATING

According to the radiocarbon (^{14}C) analysis, the lagoon gyttja in section A was deposited at 2340 ±190 calibrated years BP (or 2310 ±190 conv. ^{14}C years BP; lab. index Vs – 1545). The age of mollusc shells in section B is 2820 ±90 calibrated years BP (or 2690 ±90 conv. ^{14}C years BP; lab. index Vs – 1497). Taking into account that the age of mollusc shells could be influenced by a basin effect, the real age of mollusc shells could be younger by about 300–400 years, i.e. the real absolute age of molluscs could be approximately the same as the age of lagoon gyttja in section A.

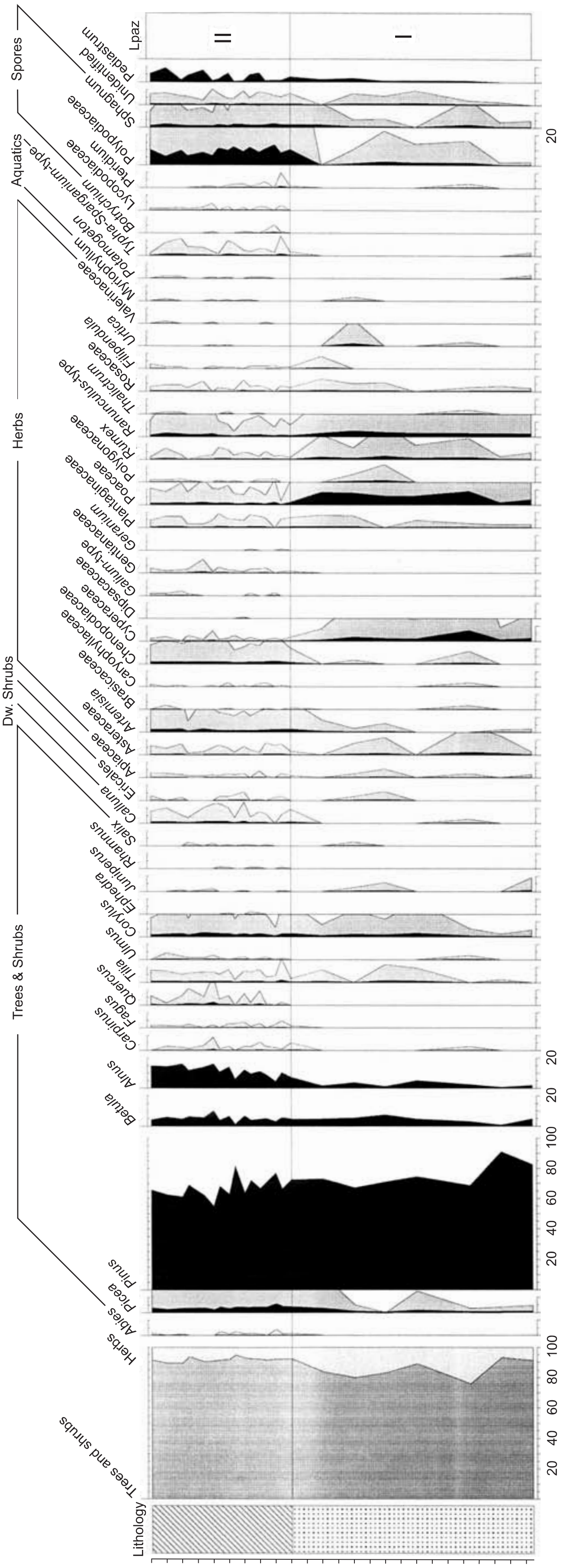

Fig. 7. Pollen diagram of section A

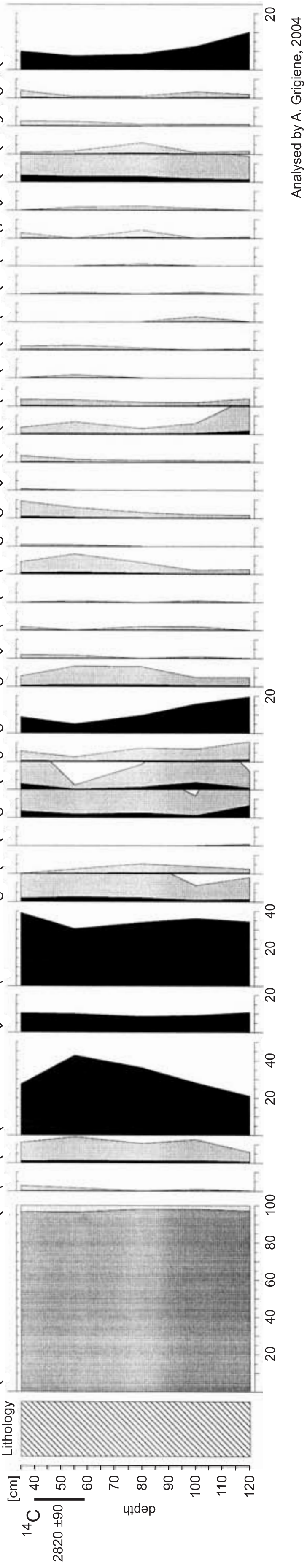

Fig. 8. Pollen diagram of section B

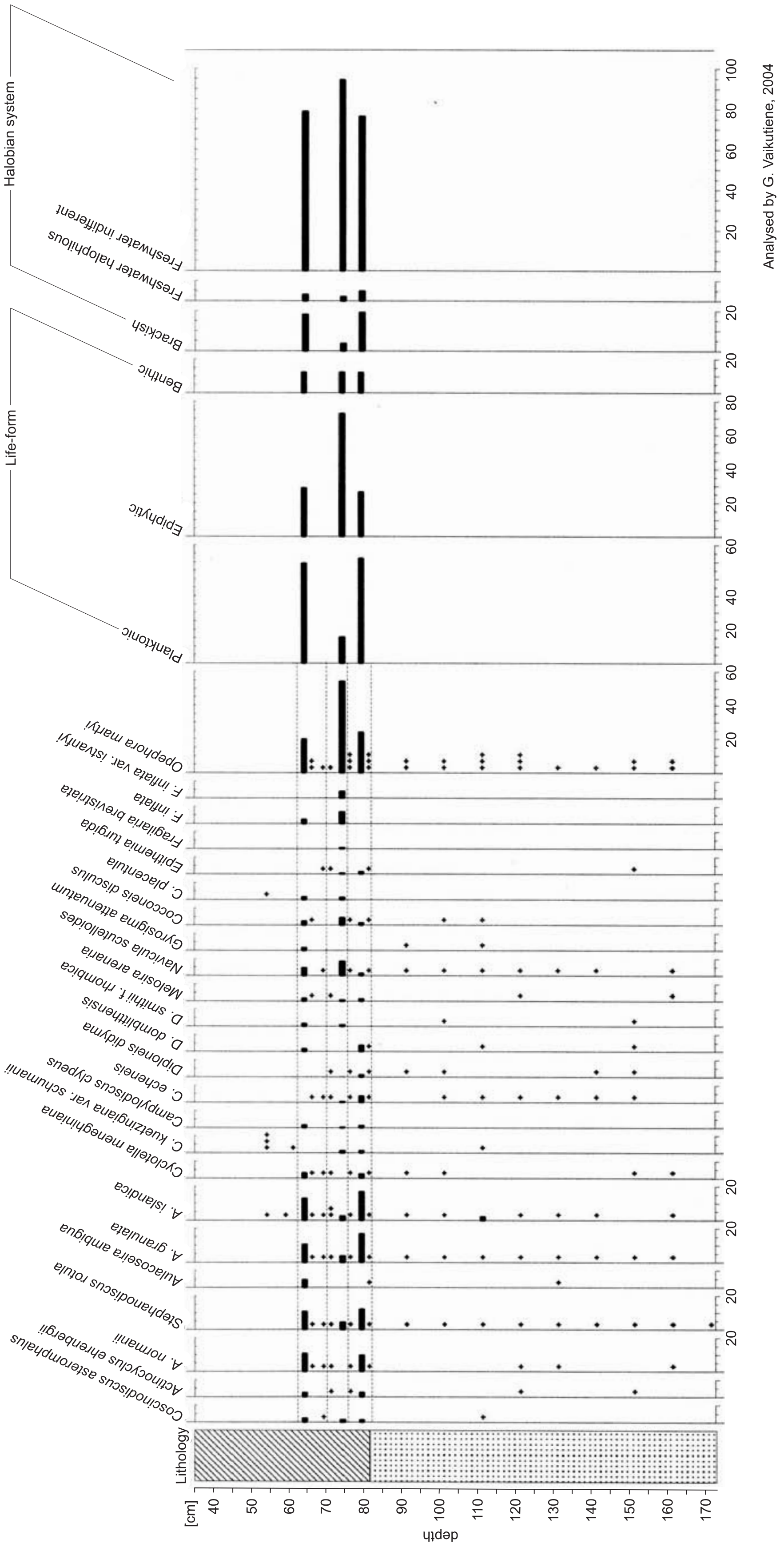

Fig. 9. Diatom diagram of section A

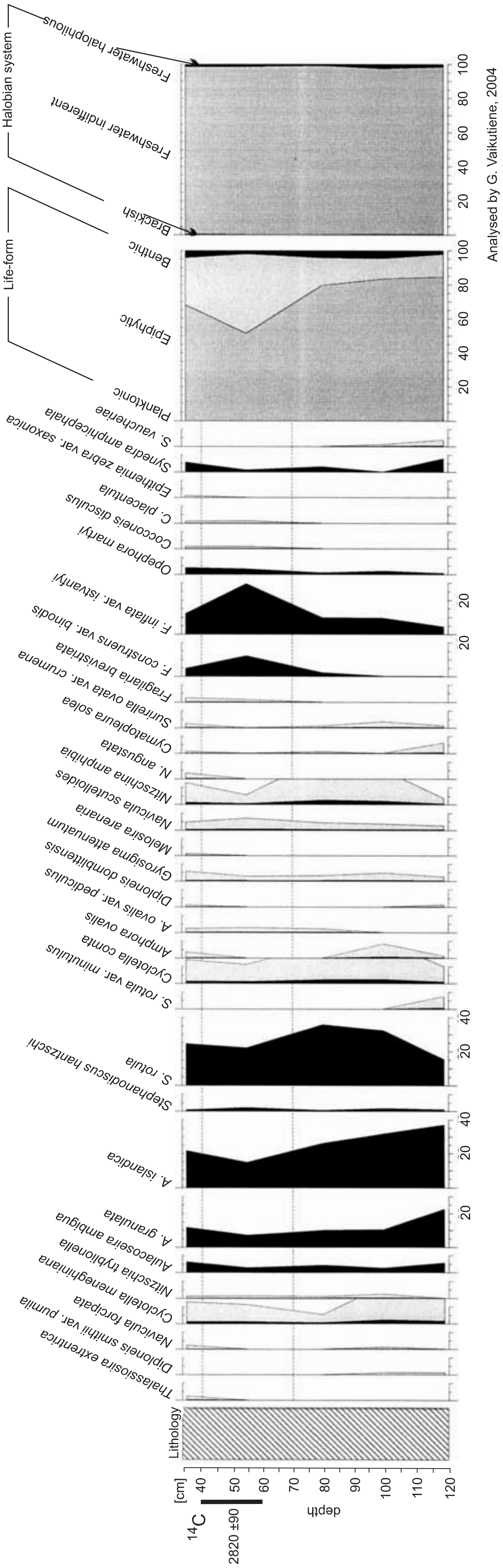

Fig. 10. Diatom diagram of section B

MOLLUSC ANALYSIS

The range of molluscs is very similar in both the investigated sections (Figs. 3 and 4), and suggests that the lagoon sediments were deposited in a shallow, overgrown freshwater basin (*Pisidium personatum* Malm, *Pisidium obtusale* Lamarck) with slack water (*Musculium lacustre* Müller, *Sphaerium corneum* Linnaeus) and slimy bottom (*Valvata piscinalis* Müller, *Valvata naticina* Menke, *Pisidium milium* Held), rich with aquatic plants (*Viviparus viviparus* Linnaeus, *Sphaerium nucleum* Studer). A few land snails (*Eulota fruticum* Müller, *Zonitoides nitidus* Müller, *Cochlicopa lubrica* Müller) characteristic of wet coasts have been found in section A.

POLLEN ANALYSIS

The sandy sediments of section A contain pollen in lower frequency than the overlying gyttja (Fig. 7). The percentage of herbaceous plant pollen is higher (up to 20% of the total pollen sum) in the sand. The percentage of arboreal pollen rises in the gyttja. The pollen diagram is subdivided into two local pollen assemblage zones (LPAZ):

I. *Pinus*–Poaceae LPAZ (depth 0.8–1.6 m): *Pinus* pollen accounts for some 70%, however it reaches up to 90% in the lower part of the zone. Poaceae with its 10% prevails among the herbs. Cyperaceae and Ranunculaceae are also common in this zone.

II. *Pinus–Alnus* LPAZ (depth 0.35–0.8 m): *Pinus* is dominant. The amount of *Alnus*, *Picea* and broad-leaved tree pollen is also increased. Abundant herb pollen flora, but in low percentage, was also noted: e.g. *Artemisia*, Caryophylaceae, Chenopodiaceae, Plantaginaceae, *Thalictrum* and Valerianaceae. Aquatic plant pollen and spores of *Botrychium* and Lycopodiaceae were found, too. The amount of Polypodiaceae spores is increased in the zone.

In section B (Fig. 8), arboreal pollen constitutes 98% of the total pollen sum. *Pinus* and *Alnus* are dominant. Broad-leaved trees reach up to 10%. *Picea* pollen is noted. Poaceae and *Artemisia* are most common among herbaceous plants.

The pollen flora is similar in gyttjas from both the sections, however its percentages are different. The *Pinus* percentage is higher in section A than in B; for *Alnus* and *Corylus* the relation is opposite. The gyttja from section A contains *Ephedra* pollen and *Botrychium* spores. Aquatic plants pollen is observed in higher amounts in sediments from section A.

The pollen flora represented mainly by pine, alder and birch is similar to the Late Subboreal–Early Subatlantic pollen flora from the western part of Lithuania (Kabailienė, 1990). Grass communities covered part of the territory. *Ephedra*, *Juniperus*, *Rumex* and *Botrychium* indicate that also open landscape developed: it could be related to human impact.

DIATOM ANALYSIS

The results of diatom investigations in section A (Fig. 9) show that sand (depth 0.8–1.7 m) contains only single freshwater epiphytic and planktonic diatom frustules. Only the gyttja layer (depth 0.7–0.8 m) overlying the sand is richer in diatoms. Planktonic freshwater (mostly *Stephanodiscus rotula*, *Aulacoseira granulata* and *A. islandica*) and brackish (*Actinocyclus normanii*, 10%) diatoms prevail at the depth of 0.75–0.8 m. Freshwater epiphytic (*Opephora martyi, Cocconeis disculus*) and benthic (*Navicula scutelloides*) diatoms dominate at the depth of 0.70–0.75 m. There are only few brackish-water diatoms. Freshwater and brackish planktonic diatom species dominate in the interval of 0.6–0.7 m. Only a few freshwater diatoms were found at the depth of 0.5–0.6 m. No diatoms are observed at the topmost part (depth 0.35–0.50 m) of the gyttja layer.

Diatoms from the sand layer of section A are characteristic of a shallow freshwater basin with rapid sedimentation. The lower part of the gyttja layer was deposited in a relatively deep freshwater basin with evident brackish water inflow. Later, the water level started to fluctuate: it dropped and the area became a shallow-water or even boggy (high amount of *Opephora martyi* – 55% at the depth of 0.75–0.70 m, characteristic of stagnant eutrophic waters), Subsequently, the water level rose again (freshwater planktonic diatoms dominate at the depth of 0.6–0.7 m). Finally, the area became an almost dry land.

The gyttja layer of section B is very rich in diatoms along the whole section (Fig. 10). Freshwater planktonic diatoms (mainly *Aulacoseira islandica, A. granulata* and *Stephanodiscus rotula*) dominate (85%) at the depth of 0.7–1.2 m. The amount of planktonic diatoms decrease to 48% at the depth of 0.4–0.7 m. Epiphytic freshwater species (*Fragilaria inflata* var. *istvanffyi*, *F. construens* var. *binodis* and *Opephora martyi*) are predominant among the diatoms. The amount of freshwater planktonic diatoms increases to 70% again in the upper interval of the sediments (depth 0.35–0.40 m).

In section B, the lower part of the gyttja layer (depth 0.7–1.2 m) was deposited in a relatively deep freshwater basin, as evidenced by dominant planktonic freshwater diatoms. Small admixture of brackish and halophilous diatoms indicates that there was a small inflow of brackish water. The water level dropped during the deposition of the gyttja layer at the depth of 0.4–0.7 m – the study area became shallow freshwater littoral zone at that time. Diatom composition in the uppermost part of the gyttja layer shows that the water level rose again but to a lesser extent than it did at the previous event. A greater amount of diatoms in section B indicates that the basin was deeper than that for section A.

CONCLUSIONS AND DISCUSSION

All the received research results – from field observations to laboratory analysis – indicate that the lagoon gyttja layers are in situ, as evidenced by undisturbed textures (including bioturbation) of sand underlying the gyttja layer and by the natural sedimentary sequence of gyttja and sand determined from the pollen and diatom diagrams. Thus, some remarks about artificial origin of the gyttja layer have no substance.

According to the mollusc and diatom investigations, the lagoon gyttja of both the sections was deposited in very similar palaeoecological and palaeogeographic conditions – in shallow freshwater overgrown basins with an unstable water level and small inflow of brackish water. Pollen analysis indicates that during the Late Subboreal–Early Subatlantic lagoonal deposition, the area surrounding the basins was covered by a sparse mix forest, but an open landscape also developed there. So, it can be claimed that the similar shapes of water level fluctuations in the basins, as well as very close radiocarbon ages of gyttja and molluscs, indicate that sections A and B were two fragments of the same freshwater basin (a bay of the former Vistula Lagoon). There are some doubts about the existence of a temporary strait between the sea and the lagoon (based on the inflow of brackish water according to data from diatom investigations) in the study area. The periodical inflow of brackish water via the main strait between the sea and the lagoon is the characteristic phenomenon of Baltic Sea lagoons. For example, brackish water diatoms are common for present-day sediments in much of the Curonian Lagoon (Vaikutienė, 2004).

Thus, we have received an answer to one of the questions of our investigation program. But how is it possible to explain the anomalously high position of the investigated lagoon gyttja? There was no significant sea-level rise in the South-Eastern Baltic during the Subboreal or Subatlantic (Kabailienė, 1999). Maybe, the gyttja was formed in a high-altitude lake? It is impossible, because an aquiclude that is the essential condition for existence of such a lake is absent in the sand body of the Vistula Spit. The correlation of the lagoon gyttja with analogous sections in the southern part of the Vistula Spit is also very problematic. For example, sediments of the same lithology (gyttja), but significantly younger (about 1.2 ka BP), occur about 1.0–1.5 m below the present sea level in the adjacent areas of Poland (Dziady environs), about 5 km to the SW of the study area (Uścinowicz, 2003). Thus, according to our opinion, the anomalously high position of the lagoon sediments in the central part of the Vistula Spit could be explained only by neotectonic movements of the Earth’s crust blocks.

THE HYPOTHESIS OF SPIT FORMATION

An assumption that certain blocks of the Earth's crust were tectonically active during the whole Holocene until the recent time is the backbone of the presented hypothesis. The sinking and uplifting of the blocks was of oscillatory nature. The principle scheme of possible formation of the spit is presented in a graphic form (Fig. 11).

When the formation of spit goes in the frame of a single Earth's crust block (despite of sinking or uplifting), the spit formation proceeds more or less equally (i.e. equal sedimentation rate, sediment thickness, spit width, etc.) (Fig. 11, I). The conditions of spit formation are changing when the spit overgrows into another block with opposite sense of neotectonic movement. In our case, for example, if the new block sinks (Fig. 11, II), more sediments (sand) are necessary for spit construction (for compensation of the constantly increasing depth); thus, the spit grows slowly, but becomes wider. After some time, certain parts of the spit (especially that at the lagoon side) can occur below the water level, and lagoon sediments (including gyttja) can start to be deposited above the spit (barrier) sands;

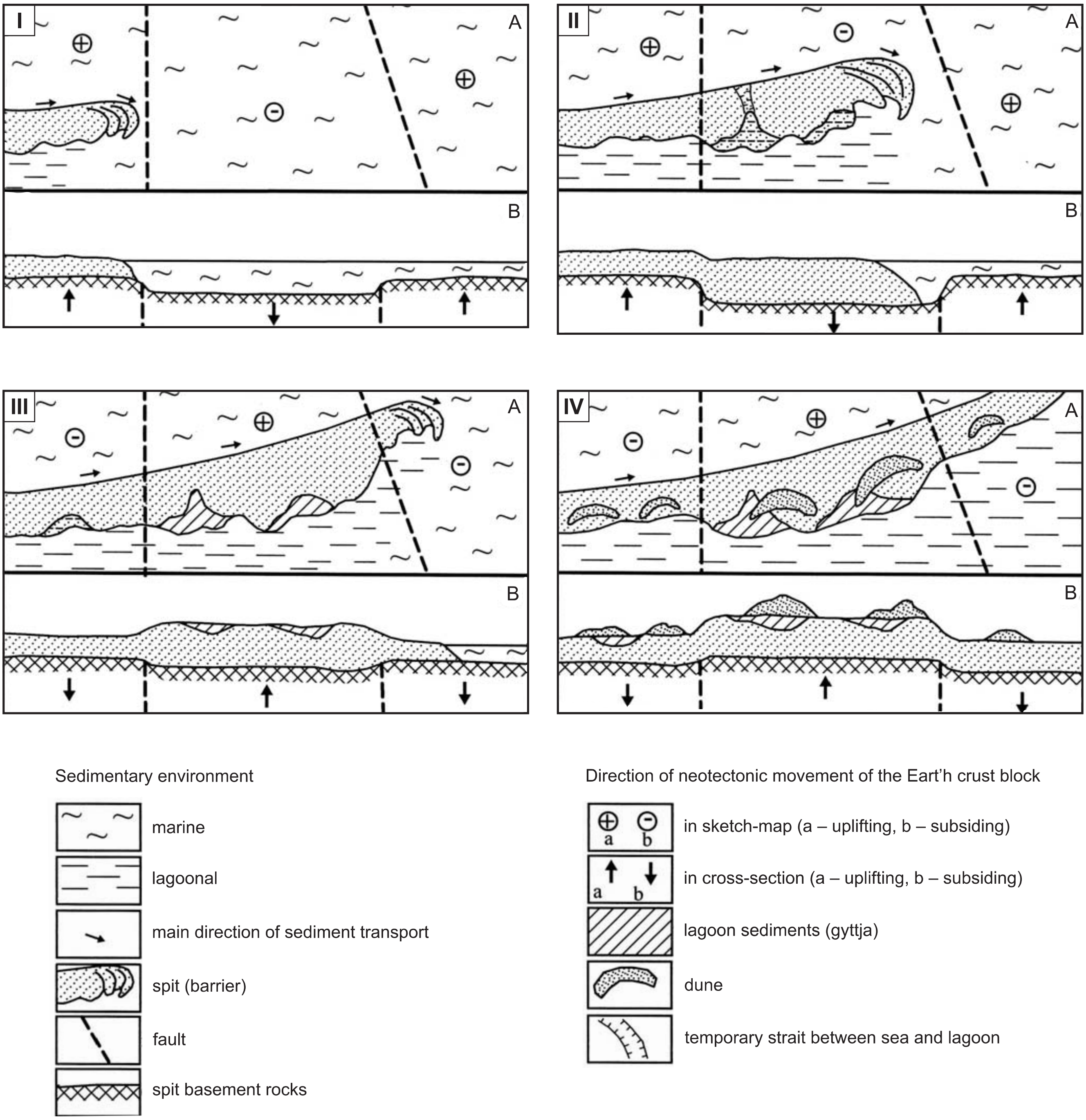

Fig. 11. Hypothetical model of spit formation (A – in sketch-map; B – in cross-section).

a strait between the sea and the lagoon can form in such conditions as well. As mentioned above, neotectonic movements were of oscillatory nature so that the direction of Earth's block movements changed after a certain period (Fig. 11, III). Thus, the formation of gyttja in the uplifting block is finished. Gyttja can appear above the water level after a certain period. Simultaneously, the formation of another gyttja layer can start above the sand barrier sediments in the neighbouring sinking block. The onshore part of the spit, limited by inversion of the uplifting block, becomes significantly wider than in the sinking fragments of the spit; during the subsequent aeolian activity the most powerful dunes were formed in this area (Fig. 11, IV). Finally, the older lagoon gyttja occurs at higher altitude that the younger one in the same spit.

FINAL REMARKS

We think that the presented hypothesis of spit formation could be one of the versions (probably most reliable) explaining the anomalously high level of the investigated lagoon gyttja. Assuming that the neotectonically active Earth's crust block was uplifted about 2 m during the last 1000 years, the average rate of neotectonic uplift would be about 2 mm per year, that is normal for the South-Eastern Baltic region. This is confirmed by data of geodesic high class levelling in the neighbouring territory of Western Lithuania (Šliaupa *et al.*, 2005). Neotectonic activity of the South-Eastern Baltic region is also proved by the 2004 earthquake epicentered close to Kaliningrad, i.e. approximately 50 km to the NE of the study area.

The study area with the lagoon gyttja is located in the widest part of the Vistula Spit (Fig. 2). According to the tectonic map of Lithuania and Kaliningrad region (Suveizdis, 2003), the wider part of the spit is obviously restricted by two sub-latitudinal faults of the Aistmarės graben: such conjunction also makes to suppose that the spit formation was influenced by tectonic factors.

Despite the existing sceptic positions about the role of netoctonics, we are tending to the opinion that neotectonic activity (oscillatory fluctuations) of the Earth's crust blocks should be taken into consideration during the reconstruction of sea-level fluctuations in the South-Eastern Baltic during the Late Glacial and Holocene.

Acknowledgements. We would like to express our gratitude to all the colleagues who supported our investigations in the Vistula Spit: special thanks are due to J. Pociene, who helped to prepare the illustrations. We are keeping warm memory about the driver of our field expedition Zenonas Avlasevičius, who, unfortunately, is not with us any more… Discussions with the colleagues – B. Winterhalter and H.Terry first of all – about the Vistula Spit formation during the BSSC-5 helped us to improve significantly the final version of the manuscript.

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