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Geological development of the Nemunas River Delta and adjacent areas, West Lithuania

Albertas BITINAS, Aldona DAMUŠYTĖ, Miglė STANČIKAITĖ and Paulius ALEKSA

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Geological mapping at a scale of 1:50 000 of the Lithuanian Maritime region has recently been focused on the delta of the Nemunas River and its surroundings. Pollen, diatom and mollusc analyses, lithological investigations, and radiocarbon and optically stimulated luminescence dates have enabled stratigraphic correlation of the Late Glacial and Holocene deposits which make up this delta. Palaeogeographical reconstructions of the southern part of the Lithuanian Maritime region during the maximum extent of the Baltic Ice Lake (~12 000–11 200 years BP), the Ancylus Lake (~8 700–8 500 years BP), the Litorina Sea (~6 100 years BP) and the Post-Litorina Sea (~4 000 years BP) have been made. A geological and geomorphological model of the Nemunas River Delta and its adjacent areas has been constructed. Our results suggest that that part of Nemunas River Delta in Lithuania is very young, having formed during the last 1 000–1 100 years.

Albertas Bitinas, Aldona Damušytė and Paulius Aleksa, Geological Survey of Lithuania, 35 Konarskio St., 2600 Vilnius, Lithuania, e-mails: albertas.bitinas@lgt.lt, aldona.damusyte@lgt.lt; Miglė Stančikaitė, Institute of Geology and Geography, 13 Ševčenkos St., 2600 Vilnius, Lithuania, e-mail: migle@geologin.lt *(received: December 12, 2001; accepted: April 10, 2002).*

Key words: Lithuanian Maritime region, Nemunas Delta, Late Glacial, Holocene, geochronology, palaeogeography.

INTRODUCTION

The greatest Lithuanian river, the Nemunas, flows into the freshwater Curonian Lagoon and its delta extends into the eastern side of the lagoon (Fig. 1). The Nemunas Delta and its sourrandings have long been studied, as regards geomorphology and hydrology, geology and palaeogeography (Basalykas, 1961; Červinskas and Kunskas, 1982; Gudelis and Klimavičienė, 1990*b*, 1993; Kunskas, 1996; Gudelis, 1997, 1998; *etc*.). A detailed palaeogeographical analysis of the southern Lithuanian Maritime region was made by Gudelis and Klimavičienė (1990*a*), who reconstructed successive shorelines of the Baltic Sea. Žaromskis (2000) noted that a core problem remained the definition of the limits of the Nemunas Delta. Depending on the criteria employed, the extent of the delta itself has been drawn very differently (Basalykas, 1961; Gudelis and Klimavičienė, 1993; *etc*.) and interpretation its geological structure also varies (Basalykas, 1961; Dvareckas and Gaigalas, 1996; Kunskas, 1996). Even larger discrepancies appeared when attempts were made to reconstruct the geological history of the Nemunas Delta and its environs. Some researches date the beginning of its development to the Late Glacial and relate its geological evolution mainly to succesive base level changes of the Baltic Sea (Gudelis, 1998). Others have suggested that the delta dates back to the Pre-Glacial and, in explaining the history of its geological development, ascribe a leading role to local neotectonic movements (Kunskas, 1996). Some authors (Basalykas, 1961; Gudelis, 1998; *etc*.) maintain that deposits of the present Nemunas Delta overlie a buried valley of the Nemunas (Pre-Nemunas) River, filled with alluvial deposits. This Pre-Nemunas River valley prolongation may be locally traced in the underwater slope of the Baltic Sea (Bjerkéus *et al*., 1994; Savukynienė and Ruplėnaitė, 1999).

Most work on the Nemunas Delta has been based on geomorphological and hydrological data or on results from shallow boreholes, mostly drilled to study bog deposits. The contradictory opinions regarding its geological evolution has been due to a lack of reliable data on the geological structure of this region.

In 1996–2000, geological maps at a scale of 1:50 000 were prepared of the northern part of the Nemunas Delta and its surroundings in Lithuania. The geological mapping encompossed the

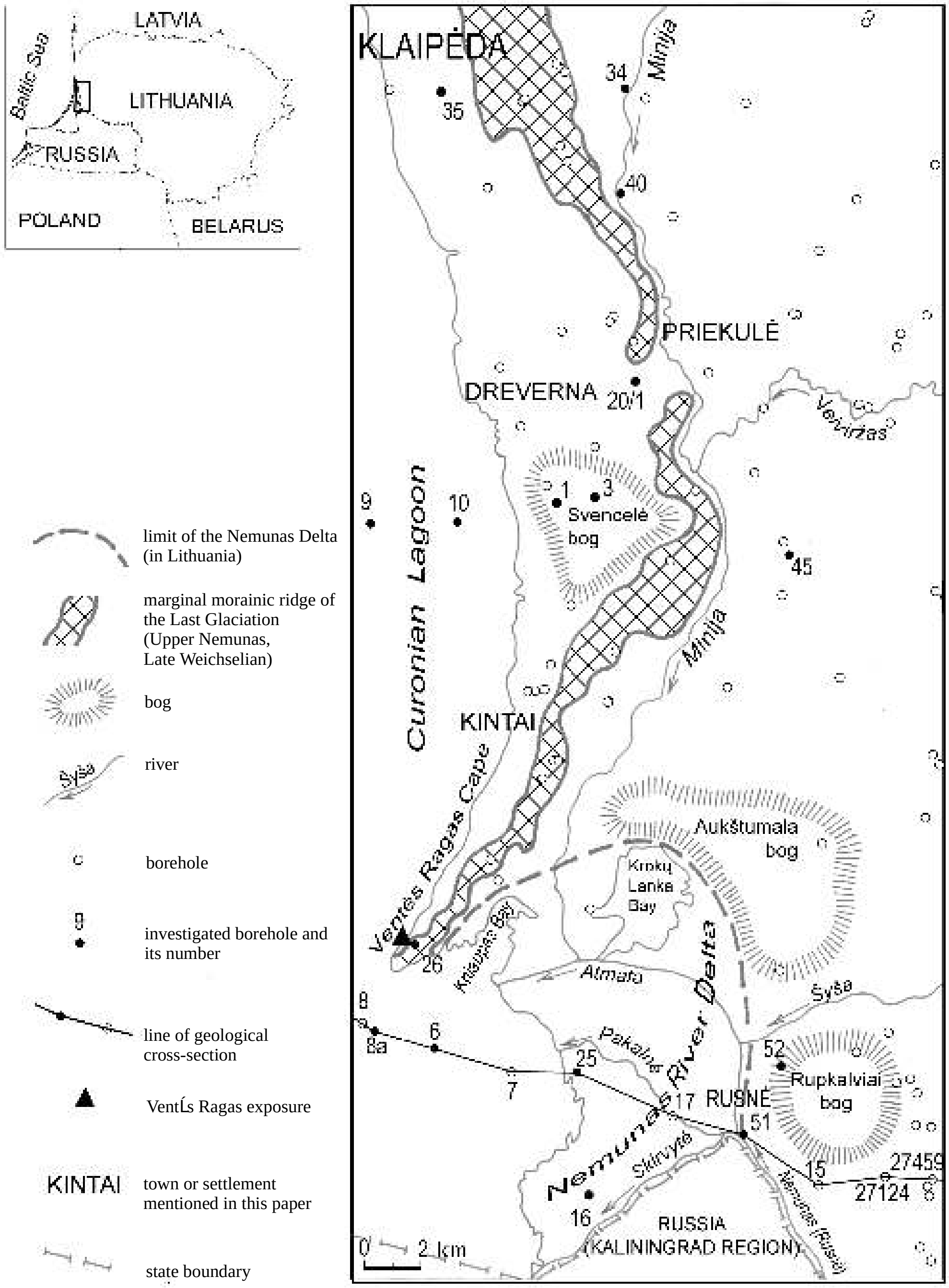

Fig. 1. Scheme of the study area

entire Lithuanian Maritime region and provided new geological information, which allowed a fresh look at the underground structure of this part of Lithuania and its geological development.

METHODS

Geological and geomorphological studies of the Quaternary deposits in the Nemunas Delta and its environs included analyses of space and aerial photographs, topography, exposures and borehole cores. The cores were analysed as regards lithology, spores and pollen, diatom and mollusc analyses and absolute dating.

In order to compile the geological and geomorphological maps aerial photographs taken in 1958 (scale 1:17 000), 1973 (scale 1:18 750) and 1993 (scale 1:21 400) as well as a space panchromatic orthophoto digital map of 1993 (scale 1:50 000) were interpreted. The sedimentation rate on the Nemunas Delta was estimated by comparing topographic maps from different years.

Exposure of the Ventės Ragas organic deposits have yielded considerable geological data on the Nemunas Delta

Table 1

Results of spores and pollen analysis

Borehole	Latitude N; Longitude E	Examined interval		Number of examined samples	Age of deposits
		Depth [cm]	Altitude [cm a.s.l.]		
1	55°29’34” 21°16’16”	25–215 635–1160	275–85 –335– –860	14 28	SB$_2$–SA AL–YD
3	55°29’42” 21°17’33”	47–395	23– –325	51	AT$_2$–SA
8a	55°19’22” 21°10’51”	30–140 240–440	–460– –570 –67 – –870	12 19	BO–SB$_1$ OD–PB
20/1	55°31’56” 21°18’47”	360–1590	–60– –290	23	BO–SB
25	55°18’44” 21°17’43”	40–530	–20– –510	27	AL–SA
26	55°21’02” 21°12’06”	20–300	240– –40	21	AL–AT
45	55°28’44” 21°24’12”	40–530	110– –380	27	AL–SA$_1$

(Gudelis *et al*., 1989–1990). At present, there is only a single exposure of this, which has been used for mollusc analysis and absolute dating.

Boreholes have enabled a model of the geological structure of the Quaternary deposits to be constructed. In the Nemunas Delta region, including the Curonian Lagoon more than 90 boreholes have been drilled, some of them penetrating the entire Quaternary succession.

Spores and pollen from 7 boreholes and diatoms from 5 boreholes have been analysed in detail. Spore and pollen analysis was performed at the Geological Survey of Lithuania (by M. Stančikaitė) and the Institute of Geology (by O. Kondratienė). Diatoms were analysed at Vilnius University (by M. Kabailienė) and the Institute of Geography (by G. Vaikutienė). In 5 boreholes and in the Ventės Ragas exposure mollusc fragments were also found; these were analysed at the Geological Survey of Lithuania (by A. Damušytė). Radiocarbon (^{14}C) analysis of 23 samples from 6 boreholes and the Ventės Ragas exposure was carried out by members of the Radioisotopes Studies Laboratory of the Institute of Geology (J. Mažeika and R. Petrošius) and the Laboratory of Isotopic Studies of Trondheim University, Norway (S. Guliksen). Age determination by optically stimulated luminescence (OSL) of 14 samples from the Ventės Ragas exposure and from 2 boreholes was carried out in the Laboratory of Radiometric Methods of Dating, Institute of Geology, Tallinn Technical University (G. Hütt and A. Molodkov).

RESULTS

Spore and pollen analysis. Spores and pollen from 7 boreholes were analysed (Table 1), and a chronostratigraphic subdivision was based on the results and on ^{14}C dating. The local pollen assemblage zones (LPAZ) singled out in each diagram were correlated with regional ones characteristic of Lithuania (Kabailienė, 1998). The latter correspond to the Late Glacial and Holocene chronozones of North-west Europe (Mangerud *et al*., 1974) and, together with the radiocarbon dates, establish the timing of deposition.

The local pollen zones singled out in the pollen diagrams were inter-correlated and compared to the corresponding chronozones (Fig. 2) (generalised characteristics of each LPAZ is given below).

Older Dryas — LPAZ I (borehole 8a)

A large content of tree pollen (up to 87%) characterises this zone. *Pinus* (up to 93%) or *Picea* (up to 18%) are predominate, while *Betula* (up to 11%) and *Betula nana* (up to 8%) are abundant. *Artemisia* (17%) and Cyperaceae comprise the bulk of herbaceous plants. *Sphagnum* (up to 7%) and Polypodiaceae (16%) are abundant, while spores of *Selaginella selaginoides* have been recognised.

Alleröd — LPAZ II (boreholes 1, 8a, 25, 26, 45)

The total content of tree pollen in this zone is lower and varies from 60–75%. *Pinus* remain the dominant species and yields about 60%. *Betula* in individual profiles amounts to 40% and *Picea* to 14%. The sediments contain abundant herbaceous pollen (20–25%), with *Artemisia* (up to 18%), Poaceae and Cyperaceae predominant.

Younger Dryas — LPAZ III (boreholes 1, 8a, 25, 26, 45)

The *Betula* pollen content increases, reaching up to 80% in some profiles. At the beginning of the zone the content of *Pinus* is reduced, but later on it reaches 70%. Herbaceous plants comprise 65%. *Artemisia* (up to 15%), Cyperaceae (10–15%) and Poaceae (up to 5–6%) pollen is abundant. Spores of *Selaginella selaginoides*, Polypodiaceae, *Botrychium* are numerous.

Pre-Boreal — LPAZ IV (boreholes 8a, 26, 45)

Betula (up to 42%) and *Alnus* (26%) dominate the pollen in this zone. There is up to 80% of tree pollen. Herbaceous pollen is less abundant as compared to the previous chronozone. Poaceae and Cyperaceae are predominant.

Boreal — LPAZ V (boreholes 8a, 20/1, 26, 45)

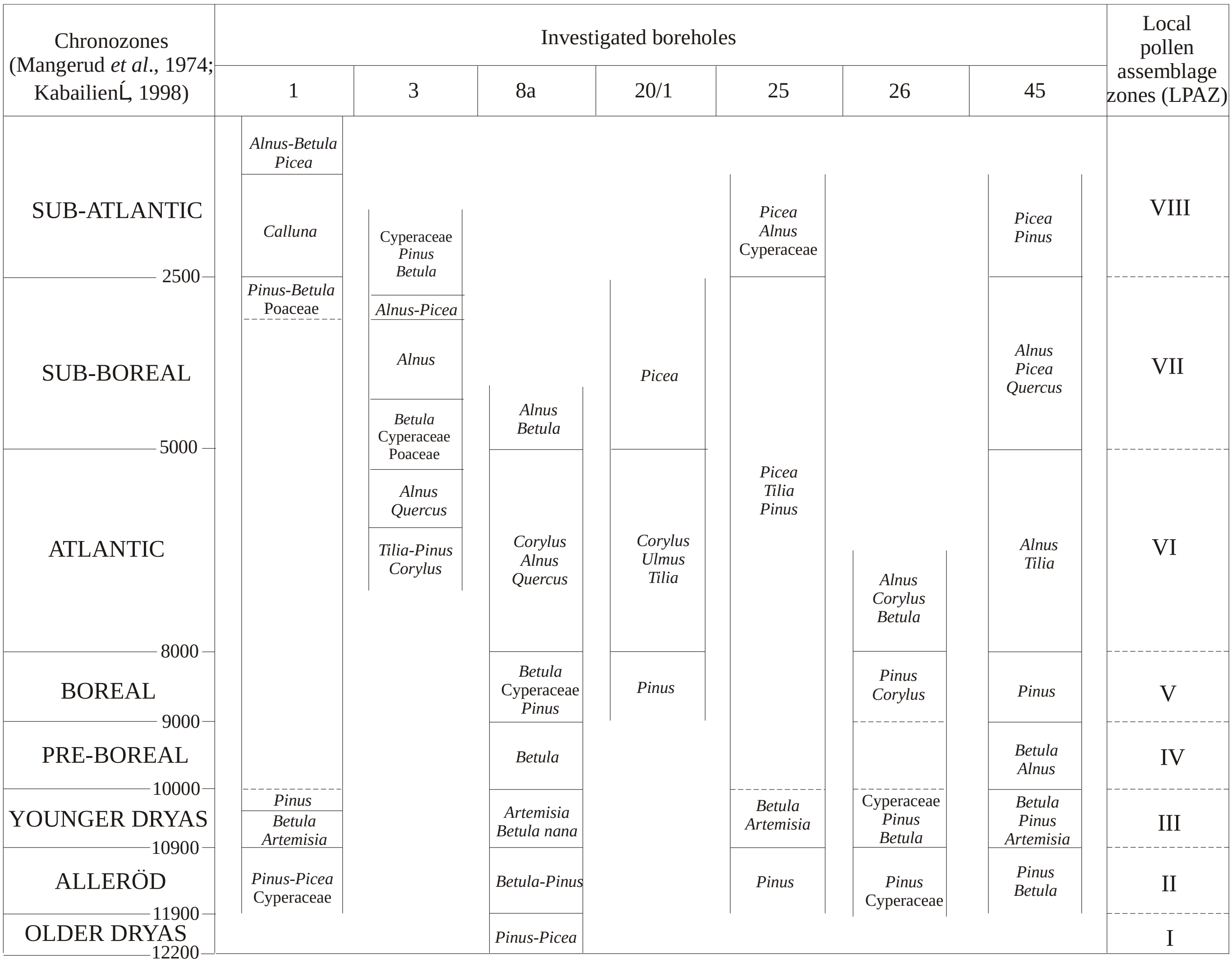

Fig. 2. Time-space correlation of the local pollen assemblage zones

Pinus pollen, which in individual profiles reaches 80%, is the characteristic feature of this zone. *Betula* (up to 23%) may be abundant, and *Betula nana* pollen occurs. The content of *Ulmus*, *Tilia* and *Quercus* pollen gradually increases. Herbaceous pollen makes about 10–15%. Cyperaceae and Poaceae predominate and there are traces of Ericaceae.

Atlantic — LPAZ VI (boreholes 3, 8a, 20/1, 25, 26, 45)

Alnus (up to 43%), *Corylus* (up to 23%) and *Quercus* (7–8%) are abundant in this zone. The deposits contain *Pinus* (up to 40%), *Picea* (up to 22%) and *Tilia* (4–5%). Herbaceous plants are rarely equal to 10%, with Cyperaceae and Poaceae as the predominant species.

Sub-Boreal — LPAZ VII (boreholes 1, 3, 8a, 20/1, 25, 45)

A high content of *Picea* was noted, in some profiles up to 60%. *Pinus* reaches about 45%,while *Betula* and *Quercetum mixtum* occur. Herbaceous plants comprise about 20%, with a prevalence of Poaceae and Cyperaceae. Spores of Polypodiaceae and *Sphagnum* are numerous.

Sub-Atlantic — LPAZ VIII (boreholes 1, 3, 25, 45)

Pinus (about 45%), *Betula* (about 20–25%) and *Alnus* (up to 25%) prevail in most diagrams. In individual profiles the content of *Calluna* increases up to 36%. The total of herbaceous pollen does not exceed 10–15%. Poaceae and Cyperaceae are abundant, while traces of *Cerealia*, *Plantago lanceolata*, *Rumex acetosa/acetosella* occur.

Diatom analysis. To help palaeoecological condition reconstruction of the Nemunas Delta the diatom flora from 5 boreholes was studied (Table 2). The diatom assemblage found in the lower part of boreholes 25 (–450– –970 cm a.s.l.) and 34 (380– –200 cm a.s.l.) is a characterised by a high content of *Opephora martyi* Heriboud and *Fragilaria inflata* var. *istvanfyi* Pantocsek, typical of a shallow freshwater oligotrophic basin. Some profiles contain in their upper part a diatom assemblage with abundant freshwater diatoms — *Fragilaria inflata*, *Aulaciseira italica, etc.* indicating littoral conditions. Deposits with these diatoms were found in boreholes 25 (–50– –210 and –450– –970 cm a.s.l.) and 26 (180 – –40 cm a.s.l.). Freshwater diatoms were found also in borehole 34 (760– –200 cm a.s.l.), though diatom — bearing deposits accumulated in a coastal basin with the Minija River valley over a long interval of the Holocene.

Table 2

Results of diatom analysis

Borehole	Latitude N; Longitude E	Interval with diatoms		Number of examined samples	Palaeoecological conditions
		Depth [cm]	Altitude [cm a.s.l.]		
8a	55°19’22” 21°10’51”	25–40	–455– –470	5	Freshwater basin with influence of brackish water
20/1	55°31’56” 21°18’47”	50–1600	250– –1300	30	Brackish basin
25	55°18’44” 21°17’43”	70–230 230–470 470–990	–50– –210 –210– –450 –450– –970	2 6 18	Freshwater basin Freshwater basin with influence of brackish water Freshwater basin
26	55°21’02” 21°12’06”	80–300	180– –40	12	Freshwater basin
34	55°37’30” 21°18’03”	40–1000	760– –200	11	Freshwater basin

Some intervals of the sections examined contain diatom species typical of brackish basin or suggesting marine influence. The diatom flora of boreholes 8a (–455– –470 cm a.s.l.), 20/1 (250– –1300 cm a.s.l.) and 25 (–210– –450 cm a.s.l.) includes the taxa *Campylodiscus echeneis*, *Campylodiscus clypeus*, *Navicula peregrina*, *Diploneis smithii* f. *rombica*, *Cyclotella meneghiniana*, *Fragilaria inflata* var. *istvanfyi*, *Epithemia turgida*. Mesohalobous diatoms *Navicula forcipata*, *Campylodiscus echeneis* and *Caloneis amphisbaena*, indicating various levels of brackish to marine water influence (Table 2).

Mollusc analysis. Subfossil molluscs have been found and identified in 5 boreholes and the Ventės Ragas exposure (Table 3). That from the Ventės Ragas exposure (*Armiger crista* f. *cristatus*, *Gyraulus albus*, *G. laevis*, *Lymnaea peregra*, *L. stagnalis*, *Musculium lacustre*, *Pisidium* sp., *Sphaerium lacustre*, *S. rivicola*, *S. solidum*) is characteristic of the near-shore zone of a shallow freshwater basin. Similar mollusc faunas have been found in all the boreholes studied. Concentrations of *Bithynia tentaculata*, *Valvata naticina*, *V. piscinalis*, *V. piscinalis* f. *antiqua*, *V. pulchella*, *Viviparus fasciatus*, *V. fluviatilis*, *V. viviparus*, *Musculium lacustre*, *Sphaerium solidum*, *Pisidium amnicum*, *P. henslowanum*, *P. lilljeborgi*, *P. milium*, *P. moitessierianum*, *P. nitidum*, *P. pulchellum*, *P. supinum*, *Unio* sp. indicate that shallow freshwater basins existed around the Nemunas Delta.

Radiocarbon (^{14}C) dating. Deposits from 6 boreholes and the Ventės Ragas exposure have been dated (Table 4), all dates being obtained from bulk samples. The RADIOCARBON CALIBRATION PROGRAM REV 3.0.3 (Stuiver and Reimer, 1993) that includes information from the INTCAL 93. ^{14}C database (Stuiver *et al*., 1991; Stuiver and Becker, 1993) has been used for calibration of the radiocarbon dates. However, in dis-

Table 3

Results of mollusc analysis

Borehole or outcrop	Latitude N Longitude E	Interval with molluscs		Number of examined samples	Palaeoecological conditions
		Depth [cm]	Altitude [cm a.s.l.]		
6	55°19’05” 21°12’54”	160–200 310–360 520–590	–550– –590 –700– –750 –910– –980	1 1 1	Freshwater basin
9	55°29’01” 21°10’01”	20–100	–190– –270	1	Freshwater basin
10	55°29’07” 21°12’57”	0–110	–140– –250	1	Freshwater basin
16	55°16’24” 21°18’16”	160–250 250–350 550–750	–160– –250 250– –350 –550– –750	1 1 1	Freshwater basin
25	55°18’44” 21°17’43”	320–370	–300– –350	1	Freshwater basin
Ventės Ragas exposure	55°21’05” 21°12’05”	268–271	312–309	1	Freshwater basin

Table 4

Results of radiocarbon (^{14}C) dating

Borehole or outcrop	Latitude N; Longitude E	Uncalibrated ^{14}C years BP (calibrated date)	Examined interval		Dated material	Laboratory code
			Depth [cm]	Altitude [cm a.s.l.]		
1	52°29’34” 21°16’16”	2345±70 (BC 445–380)	144–146	156–154	Peat	T-10958
		4005±105 (BC 2650–2440)	204–206	96–94	Peat	T-10957
3	55°29’42” 21°17’33”	3295±50 (BC 1650–1525)	127–129	–57– –59	Peat	T-10961
		4415±45 (BC 3100–2950)	182–184	–112– –114	Peat	T-10962
		5755±100 (BC 4760–4500)	287–289	–217– –219	Peat	T-10963
		6010±125 (BC 5090–4780)	315–317	–245– –247	Peat	T-10960
34	55°37’30” 21°18’03”	1580±65 (AD 420–553)	420–460	380–340	Silty gyttja	Vs-1172
		6400±100 (BC 5389–5262)	700 – 730	100–70	Gyttja	Vs-1170
		7320±105 (BC 6217–6011)	740–770	60–30	Gyttja	Vs-1183
		7635±65 (BC 6483–6379)	800–830	0– –30	Gyttja	Vs-1182
		7000±75 (BC 5844–5761)	850–880	–50– –80	Gyttja	Vs-1184
40	55°35’30” 21°18’02”	7120±90 (BC 6027–5920)	870–890	–240– –260	Gyttja	Vs-1174
		6685±120 (BC 5633–5447)	890–910	–260– –280	Gyttja	Vs-1169
51	55°17’40” 21°23’22”	1220±55 (AD 768–886)	230–250	–130– –150	Gyttja	Vs-1171
		3090±110 (BC 1448–1195)	260–270	–160– –170	Gyttja	Vs-1173
		4570±90 (BC 3244–3101)	360–380	–260– –280	Peat	Vs-1179
		5545±45 (BC 4451–4420)	410–430	–310– –330	Peat	Vs-1175
		5590±45 (BC 4428–4364)	450–470	–350– –370	Peat	Vs-1176
52	55°19’00” 21°24’34”	5260±45 (BC 4086–3992)	250–270	–290– –310	Peat	Vs-1177
		7760±85 (BC 6622–6457)	380–400	–420– –440	Peat with gyttja	Vs-1178
Ventės Ragas exposure	55°21’05” 21°12’05”	10640±160 (BC 10799–10422)	256–260	324–320	Peat	Vs- 1152
		10460±150 (BC 10621–10162)	262–266	318–314	Peat	Vs-1153
		11700±180 (BC 119201–1474)	268–271	312–309	Gyttja with peat	Vs-1161

cussing the age of the dated material and the palaeogeography of the Nemunas Delta uncalibrated dates have been used.

The oldest deposits dated by the ^{14}C method around the Nemunas Delta are from the Ventės Ragas exposure (Fig. 3). Gyttja with peat accumulated in the Late Glacial, during the Alleröd. The overlying peat, despite inversion revealed by the dating (the higher deposits are older) can be dated to the Younger Dryas.

Other ^{14}C data give Holocene ages, relatively good agreement between the dates. A few inverted radiocarbon dates (Fig. 3, boreholes 34 and 40) are probably a result of admixture of older redeposited organic matter into younger strata. In one instance of a very thin organic layer in sand within a zone of active groundwater movement, a radiocarbon date from the upper part of borehole 34 may be significantly rejuvenated (Arslanov, 1987).

Optically stimulated luminescence (OSL) dating. Dating of sediments by the OSL method was carried out on deposits from the Ventės Ragas exposure and from 2 boreholes (Table 5). In the Ventės Ragas exposure and borehole 51 (Fig. 3) OSL dates are consistent and, allowing for significant errors, fit reasonable well with the radiocarbon dates. In the Ventės Ragas exposure three episodes of sand deposition can be distinguished: Early Atlantic, Early Sub-Boreal and Sub-Atlantic. In borehole 51 sandy deposits rich in organic matter and mollusc fragments below gyttja have been dated. The OSL data suggest that deposition began at the end of the Boreal or at the very beginning of the Atlantic and proceeded up to Middle Atlantic. The OSL age of deposits in borehole 35 as well as from other sections of the Lithuanian Maritime region have been published and discussed earlier: inverted dates and a wide variety of ages suggest that the grains sand were incompletely bleached before deposition (Bitinas *et al*., 2001).

A summary of geological, palaeontological and geochronological data from key sections of the Nemunas Delta region are given in Figure 3.

GEOLOGICAL EVOLUTION IN THE LATE GLACIAL AND HOLOCENE

In the Nemunas Delta region the Quaternary deposits mantle an irregular sub-Quaternary surface, cut by palaeoincisions, comprising a monocline in Lower to Upper Cretaceous rocks. The thickness of the Quaternary deposits depends on the topog-

Table 5

Results of optically stimulated luminescence (OSL) dating

Borehole or outcrop	Latitude N; Longitude E	Uncalibrated OSL years BP	Examined interval		Dated material	Laboratory code
			Depth [cm]	Altitude [cm a.s.l.]		
35	55°37’18” 21°11’51”	7200±1500	50–90	460–440	Sand	Tln-1269
		8300±4000	90–110	420–400	Sand	Tln-1270
		7600±1500	120–150	390–360	Sand	Tln-1271
		8100±1600	220–250	290–260	Sand	Tln-1275
		15100±2300	270–300	240–210	Sand	Tln-1276
		10000±2000	330–360	180–150	Sand	Tln-1277
51	55°17’40” 21°23’22”	6000±800	530–550	–430– –450	Sand	Tln-1312
		6900±700	680–700	–580– –600	Sand	Tln-1313
		8000±700	830–850	–730– –750	Sand	Tln-1314
Ventės Ragas exposure	55°21’05” 21°12’05”	980±90	40–45	540–535	Sand	Tln-1373-051
		1320±130	110–115	470–465	Sand	Tln-1375-051
		4840±490	160–165	420–415	Sand	Tln-1376-051
		7060±710	210–215	370–365	Sand	Tln-1377-051
		7160±720	240–245	340–335	Sand	Tln-1378-051

raphy of the sub-Quaternary surface. The Quaternary thickness is less than 20 m at local elevations of this surface just beneath the Nemunas Delta whereas may exceed 80–100 m in the surrounding areas where deep palaeoincisions occur. Generalised thicknesses of the Quaternary deposits reach 30–40 m in the central part of the area and 60–70 m in the northern part. Over most of the region, the Quaternary is represented by tills. Around the Nemunas Delta, though, the upper part of the Quaternary succession was deposited during different stages of the Baltic Sea: the Baltic Ice Lake, Ancylus Lake, Litorina and Post-Litorina Sea (Fig. 4).

The evolution of the Nemunas Delta is best analysed in the context of the geological development of the surrounding region during the Late Glacial and Holocene. Recent geological mapping has elucidated the palaeogeographic evolution of the Baltic Sea (Fig. 5).

The geological evolution of the Nemunas Delta region in the Late Glacial commenced with the Baltic Ice Lake (BIL) stage (Fig. 5A). This lake originated during rapid melting of the ice sheet, and consequent meltwater drainage to the southern part of the present Baltic Sea. In the basin which appeared at the end of the Older Dryas and the beginning of the Alleröd, 12 000 years ago, the first transgression occurred and the water level rose considerably (Björck, 1995). Estimation of the BIL level in the southern part of the Lithuanian Maritime region is problematic. An altitude of 5–7 m (above present sea level) for terrace fragments in the northern part of the area (north of Priekulė) has been attributed to the BIL. The terrace has been dated by OSL analysis of deposits penetrated by borehole 35 (Fig. 3) — the terrace deposits range from 8 to 15 ka BP and are covered by aeolian deposits formed 7–8 ka BP. The BIL terrace elsewhere has been traced using geomorphological features only. These may locally, though indicate not the BIL position, but shorelines of local pre-BIL glaciolacustrine basins. Nevertheless, the whole western part of the study area may have been flooded together with part of the marginal morainic ridge between Priekulė and Ventės Ragas Cape. The major Minija and Veiviržas rivers were flowing into the gulf of the Baltic Ice Lake, on the eastern side of the marginal ridge. Silt and silty fine-grained sand accumulated at the bottom of the BIL. Medium-grained sand (loccaly with admixture of redeposited organic matter) or gyttja were deposited in littoral areas and in lagoons (Fig. 3, Ventės Ragas exposure, boreholes 1, 26, 45). Freshwater diatoms found in the deposits are typical of an oligotrophic basin with predominantly benthic and epiphytic species. Pollen assemblages suggest that the Older Dryas was characterised by flourishing herbaceous communities characteristic for poor soils with scattered pine trees. During the Alleröd, the coast of the Baltic Ice Lake was overgrown with *Artemisia*, Cyperaceae and Poaceae, and sparse pine and birch appeared on richer soils.

A Baltic Ice Lake regression, which occurred in the Late Alleröd, about 11 200 years ago, has been recognised (Björck, 1979; Kessel and Raukas, 1979; Dolukhanov, 1979; Gudelis, 1979). The Baltic Ice Lake drained to the ocean through Billingen in Sweden around 10 500–10 400 or 10 300 years ago (Björck and Digerfeldt, 1984, 1986; Svensson, 1989). In the Nemunas Delta minor basins remained (Fig. 4, borehole 25), together with bogs (Fig. 3, Ventės Ragas exposure). The abudance of *Selaginella selaginoides* spores suggest severe climatic conditions.

During the regression of the Baltic Ice Lake a new sedimentary basin termed the Yoldia Sea appeared in the Pre-Boreal. Sea level than was low, the coastline being to the west of the present Baltic Sea coast, below –30 to –33 m b.s.l. (Gudelis, 1979; Kabailienė, 1999). Terrestrial deposits only of Pre-Boreal age have been found in boreholes around the Nemunas Delta (Fig. 3, borehole 45). The lower sea level enhanced fluvial erosion, with deepening of the Minija River valley. The river then, south of the present Priekulė, drained through an

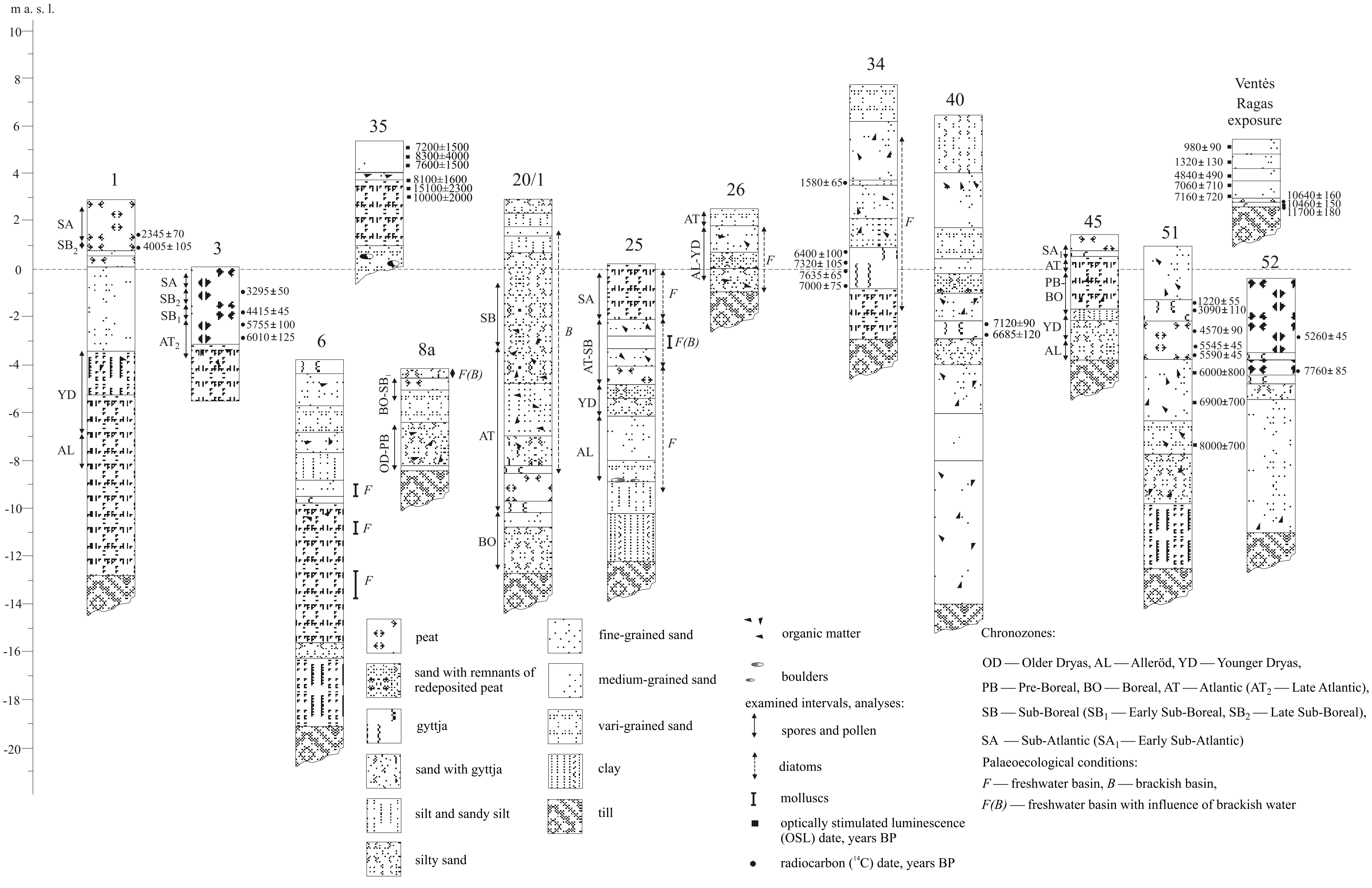

Fig. 3. The geological key sections of Nemunas Delta region

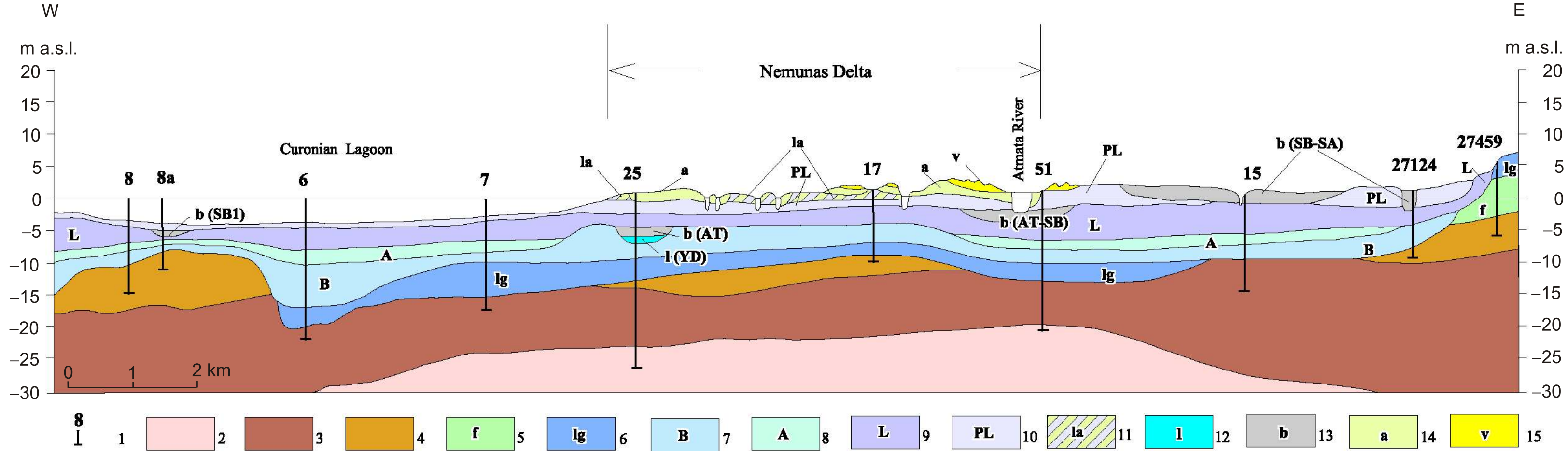

Fig. 4. Geological structure of Quaternary deposits around Nemunas Delta

1 — borehole and its number; 2 — Pre-Quaternary rocks; 3 — Middle Pleistocene sediments (till, gravel, sand of various grain size, *etc.*); **Last Glaciation sediments**: 4 — till, 5 — glaciofluvial coarse and medium-grained sand, 6 — glaciolacustrine sand, silt, clay; **Baltic Sea basins sediments**: 7 — Baltic Ice Lake (fine-grained sand, sandy silt, silt), 8 — Ancylus Lake (fine-grained sand, sandy and clayey silt), 9 — Litorina Sea (medium- and fine-grained sand, silty sand, sand with organic matter and mollusc shells), 10 — Post-Litorina Sea (fine-grained sand, silty sand, gyttja); **other sediments and deposits** (symbols of chronozones see in Fig. 3): 11 — lagoon (gyttja, sandy gyttja), 12 — limnic (gyttja, gyttja with peat, fine-grained sand with organic matter and mollusc shells), 13 — bog (peat, peat with gyttja), 14 — alluvial (vari-grained sand), 15 — aeolian (fine-grained sand); for line of geological cross-section see Fig. 1

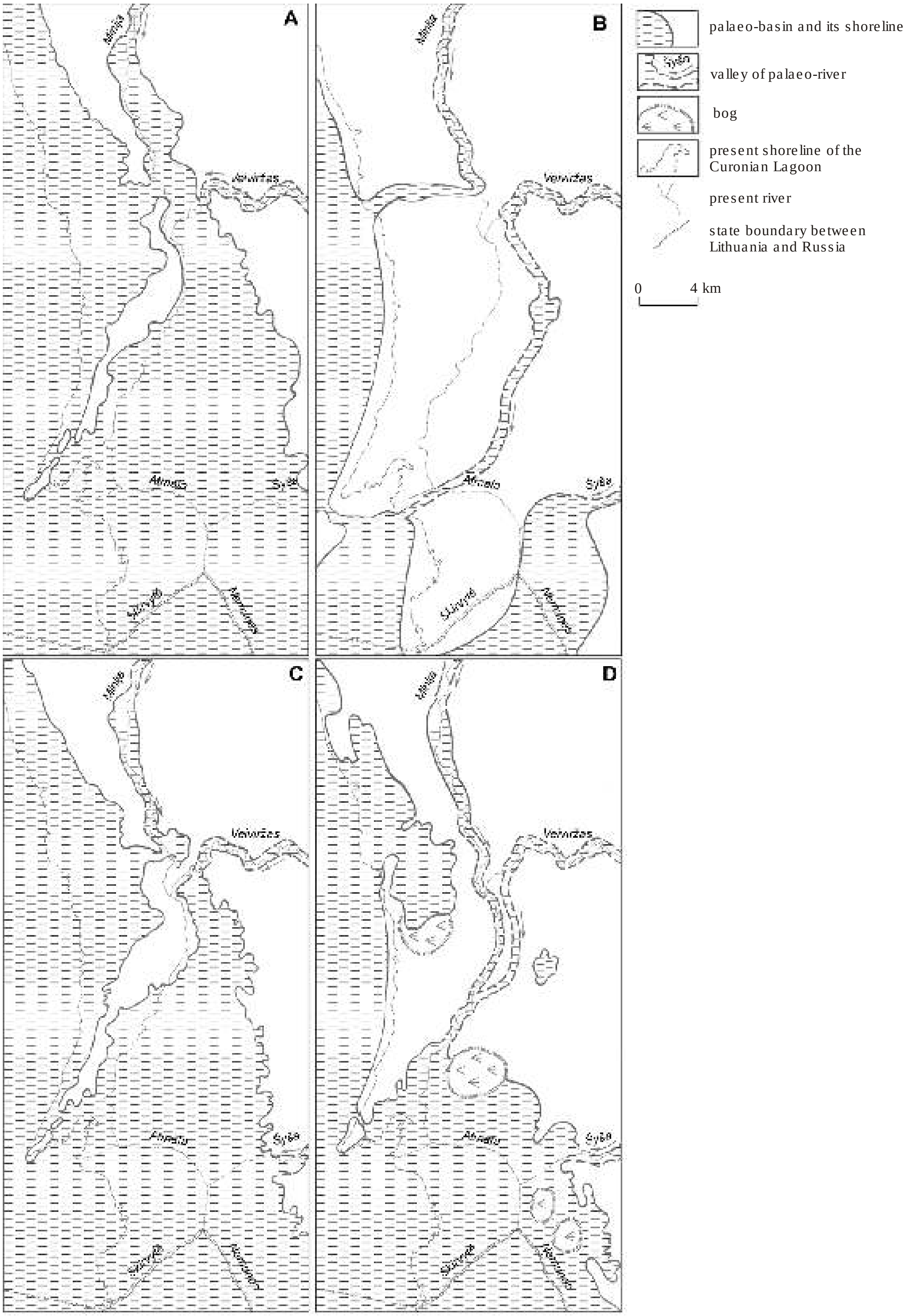

Fig. 5. Palaeogeographic schemes of different palaeo-basins of the Baltic Sea during they maximum transgression

A — Baltic Ice Lake (~12 000–11 200 years BP); **B** — Ancylus Lake (~8 700–8 500 years BP); **C** — Litorina Sea (~6 100 years BP); **D** — Post-Litorina Sea (~ 4 000 years BP) outlet in a marginal ridge, and this incision probably served as a drainage channel for earlier meltwaters which abruptly turned westwards, towards Dreverna. The bottom of the Minija River valley at this locality was 12–15 m below the present sea level. At the same time the Veiviržas River, southward from that outlet, turned to the south.

The Yoldia Sea existed for nearly 800 years (Björck, 1995), but because of glacioisostatic rebound 9 500–9 600 years ago (Fréden, 1967) its connection with the open ocean was broken. De Geer (1890) termed this stage of the Baltic Sea the Ancylus Lake. A considerable transgression of the Ancylus Lake took place 9 500–9 200 years BP (Björck, 1995). During the maximum extent of the Ancylus Lake (about 8 700–8 500 years BP) the coastline nearly reached the present Curonian Lagoon in its northern part (Fig. 5B). The lower part of Minija River valley became its estuary, extending almost as far as Priekulė. Around the Nemunas Delta the level of the Ancylus Lake locally reached about –6 to –4 m a.s.l. (Fig. 3, PB-BO sediments in boreholes 8a, 51). Thus, bays of this basin lay between the Ventės Ragas Cape and the present Nemunas Delta, and through Kaliningrad reached as far as the Rupkalviai bog. The Veiviržas and the Šyša rivers flowed into these bays. Sand deposition was dominant in the Ancylus Lake (Fig. 3, boreholes 8a, 51), when the geology of the region was influenced by glacioisostatic tectonic uplift, directed to the north (Gudelis, 1979). Glacioisostasy probably formed the watershed between the Minija and the Veiviržas rivers. Before the maximum transgression of the Ancylus Lake in the Pre-Boreal, neotectonic activity of crustal blocks led to local uplift of the present Nemunas Delta (Fig. 4).

Around the shores of the Ancylus Lake, new floral communities emerged. The sparse birch groves of the Pre-Boreal become replaced by hazel, elm and alder trees, and later during the Boreal by broad-leaved trees.

In the second half of Ancylus Lake history (Late Boreal) water level dropped, as shown by diatom analysis carried out on marine cores (Kabailienė, 1999). Many isolated basins were left over the Nemunas Delta and on adjacent areas.

The next stage of the Baltic Sea, the Litorina Sea, was initiated by erosion of the outlet as eustatic sea-level rise submerged the Store Belt Strait and the shallower Öresund Strait. Estimates of when this happened range from 8 500–8 000 ^{14}C years BP (Berglund, 1964; Krog, 1979). Kabailienė (1999) suggested that the first Litorina Sea transgression, 8 000–7 800 years ago, was of minor significance, the coastline of that basin in Lithuania lying between –10 to –6 m a.s.l. But, recent geological mapping suggests that it could not have been above –13 m a.s.l. Only small isolated basins existed then in the Nemunas Delta region, and bogs developed in areas such as Rupkalviai (Fig. 3, borehole 52).

Our data suggests that the Litorina transgression in the Nemunas Delta region culminated about 6 100 years ago. Mollusc and diatom analyses indicate (Fig. 3, borehole 25) that it was a freshwater basin, but with inflow of brackish water. Thus, by this time a significant part of the Curonian Spit must have been formed and this separated the southern and central part of the Curonian Lagoon from the open Litorina Sea (the Curonian Spit is a peninsula, 97 km long and 0.4–4 km wide, which makes up the western coast of the Curonian Lagoon; this peninsula is formed of marine and aeolian sand, with dunes up to 65–68 m high). At that time the water level in the sedimentary basin was higher than now, and sandy sediments accumulated there (Fig. 3, borehole 26). The high water level and the easterly shift of the coastline led to considerable changes of coastal relief (Fig. 5C). The level of the Litorina Sea in the northern part of the area (near Priekulė and northward) did not rise above the level of the Baltic Ice Lake, the coastline of which can be traced by the 7 m bench. On the western slope of the marginal ridge the Litorina Sea left a terrace only 3.5–4.5 m above present sea level. But to the south from Priekulė the Baltic Ice Lake terrace was eroded and buried beneath the Litorina Sea deposits. Such an abrupt inversion of the basin coastline suggests laterally varying glacioisostatic uplift. The level of the Litorina Sea changed more than once after the maximum transgression (Kabailienė, 1999), however, few traces of this have been found in the Nemunas Delta area, except for a few recessional terraces close to Kintai.

A significant Litorina Sea regression took place after the short-lived sea level high, climax about 6 000–5 900 years ago, and the water level in the basin then fell to –4– –5 m a.s.l. The former bays turned into lagoons, with bog development in the major marshlands around areas such as Aukštumala, Svencelė and Rupkalviai (Fig. 3, boreholes 3, 51, 52). It was probably then, when the Litorina Sea level fell, that the Minija River turned to the south from Priekulė. This hydrographic adjustment was likely related to glacioisostatic rebound.

The precise timing of the transition from the Litorina to the subsequent Post-Litorina environments has not been determined, though one estimate places it at 4 000 years BP (Fréden, 1967). In the Nemunas Delta region the Post-Litorina Sea stage began with a new transgression, as water level rose up to 1–2 m above the present level (Fig. 5D). This transgression took place about 4 000 years ago: evidence of this date comes from a sand interlayer in the Svencelė bog peat and a layer of buried peat at the Nemunas River branching into the Skirvytė and Atmata rivers (Fig. 3, boreholes 1 and 51). In the former bay of the Curonian Lagoon, occupied by the present Nemunas Delta, accumulation presisted to the 1 100–1 000 years BP (Fig. 3, borehole 51). The bay was surrounded by the Aukštumala, Rupkalviai and Strazdapolis bogs (i.e. in the neighbouring Kaliningrad District indicated in Figure 1) which continued their development during the Sub-Boreal and Sub-Atlantic. Our data suggests that deposition in the present Nemunas Delta started from Rusnė (where the Atmata and Skirvytė rivers branch away) only about 1 100–1 000 years ago i.e. already in historical times. It is this date that should be considered as representing the inception of that part of the Nemunas Delta located in Lithuania.

GEOMORPHOLOGICAL CHARACTERISTICS OF THE DELTA AND ITS FORMATION

The Nemunas River has formed a complex and distinctive geomorphological body at its mouth (Fig. 6). In the same bay a smaller delta, of the Minija River, has developed. At present these two deltas have practically merged into a common delta named the Nemunas Delta. Geomorphologically, this common

Fig. 6. Satellite image of the Nemunas Delta (panchromatic ortophoto digital map, SPOT PAN R © Metria Satellus)

delta of the two rivers can be considered as a lobate type of delta, with some multiple branching (Žaromskis, 1999). The outlines of the delta are easily traceable on aerial photographs and are particularly distinct on the satellite orthophoto map (Fig. 6). The Nemunas Delta is the lowermost part of the Lithuanian Littoral Lowland. The flat surface of the plain, from 1.5 m above sea level at its oldest part (at Rusnė), consistently drops westwards and at the shore of the Curonian Lagoon rises only some dozens of centimetres above water level.

The formation of the delta has been and still is of cyclic character: firstly, on the bottom of the basin, sub-aqueaus deposition forms a fore-delta. This delta, with further deposition, formed a shallow shoal — the delta front which emerged above water level and formed the subaerial delta separating isolated water bodies — lagoons (lakes of the delta plain) from the basin. These lagoons later on became integral parts of the delta structure (Gudelis, 1998; Žaromskis, 1999). This cycle was subsequently repeated: river channels branched off, flowed across the emergent part of the delta, again formed fore-deltas, and so on. At the mouths of the rivers and rivulets the depositional forms — river-mouth islands — appeared and in the course of time joined the mainland. Individual rivulet channels turned into the bog-creeks, river meanders became oxbow lakes, and delta plain surfaces become channelled intermittent floods. Growing delta fans divided the lagoon into smaller closed or semi-closed basins, in which lagoon deposition continued (as in the present Krokų Lanka Bay or Kniaupas Bay). Later some basins, by then entirely enclosed, began to transform into bogs. The uppermost parts of the alluvial deposits were later locally modified by aeolian processes. Thus, five facies have been recognised and mapped across the recent Nemunas Delta: delta front alluvium, flood alluvium, lagoon sediments, bog deposits and aeolian deposits (Fig. 7).

Deposition on the Nemunas Delta was rapid and, as has been noted (Basalykas, 1961; *etc.*), the accumulation rate increased in the Middle Ages. This was associated with intensifying agriculture and associated soil erosion, and hence by increased input of sediment into the rivers. Comparison of the

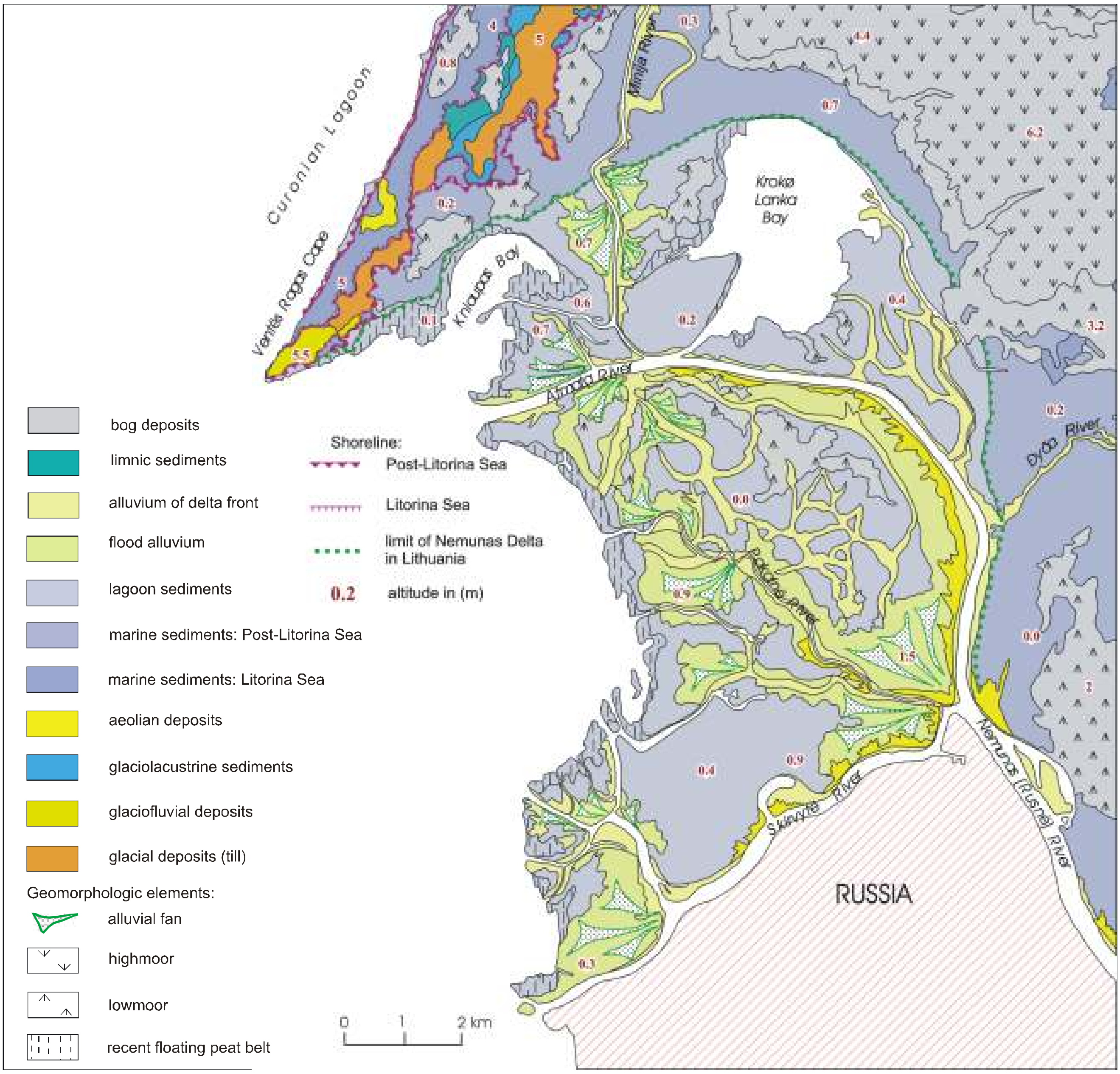

Fig. 7. Geological–geomorphological structure of the Nemunas Delta

two relatively recent topographic maps of the Nemunas Delta (Fig. 8) reveals the rate of delta accretion. In less than a century, the coastline in some places has shifted towards the Curonian Lagoon by more than 1 km. Hence, such a rate of deposition is high enough for the present Nemunas Delta (in Lithuanian) to have formed during the last 1 000–1 100 years.

DEBATABLE QUESTIONS

The history of the geological evolution of the Nemunas Delta given in this paper is based on studies of only the northern, Lithuanian part of the Lower Nemunas region. Some questions can only be addressed when the southern, Russian part of the Lower Nemunas is studied in more detail. One such question could be where the old valley of the Pre-Nemunas, noted by many research cited in this paper, "disappeared". Traces of Nemunas activity (i.e. buried palaeoincisions, alluvial or deltaic deposits, *etc.*) that date to earlier than the Sub-Atlantic have so far not been found either in the Nemunas Delta region or the Curonian Lagoon or under the Curonian Spit. If the Pre-Nemunas had existed around the present Nemunas Delta, it would have cut the morainic ridge extending along the eastern coast of the Curonian Lagoon and ranging on the bottom of the lagoon south-southwestwards from the Ventės Ragas Cape (Fig.1). Shallow buried valleys only cut this ridge in two places. In addition to the previously mentioned outlet cut by glacial meltwater south of Priekulė, another outlet along the same marginal ridge was encountered while drilling boreholes

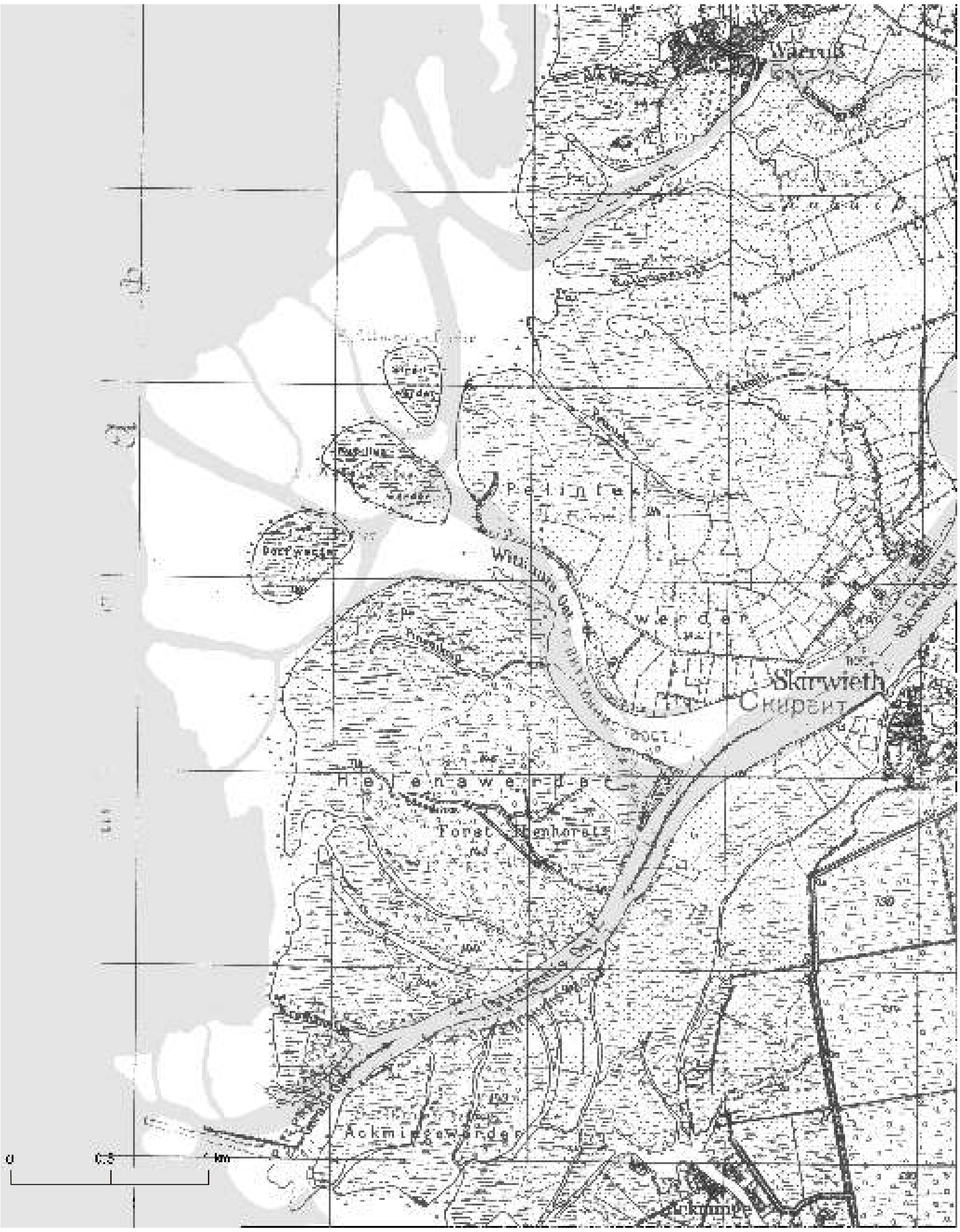

Fig. 8. Changes of the Nemunas Delta during the 20th century (Skirvytė River mouth region)

white — shoreline according to DBK 50 000 topographic background (created in 1997), hatched area — the land according to the Deutsche Reich map at a scale of 1:25 000, compiled on the basis of fieldwork in 1910–1912 and re-published in the Soviet Union in 1939

in the Curonian Lagoon, about 2 km to the south from the Ventės Ragas Cape (Figs. 1 and 3, boreholes 8 and 8a). The relative depth of this outlet barely reaches 5–7 m (to –10 below sea level). The deposits that filled this valley formed in different basins (starting from the Older Dryas). So, it seems that this buried outlet may be related to the erosive action of meltwater in the Late Glacial time, rather than with activity of the Nemunas River. Thus, the question where the Nemunas River entered the Baltic Sea during the Late Glacial, the Early and Middle Holocene is still open. It perhaps flowed *via* Kaliningrad.

Other interesting characteristics of the Nemunas Delta have been noted. In the 70–75 km long section of the Lower Nemunas, river terraces are absent, and no trace of human habitation during the Stone Age has been found (Rimantienė, 1974; 1977). Archaeological finds on the Nemunas Delta are related only to the Bronze Age. They are distributed not along the recent Nemunas River, but at some distance from its present bed, along the shoreline of the former Post-Litorina Sea basin. We consider that this is consistent with a very young age for the Lower Nemunas.

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