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STAGES OF THE FORMATION OF THE ŁEBA BARRIER-LAGOON SYSTEM ON THE BASIS OF THE GEOLOGICAL CROSS-SECTION NEAR RĄBKA (SOUTHERN BALTIC COAST, POLAND)

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Abstract
The article presents the results of a detailed study of the geological structure of the Łeba Barrier in the Rąbka cross-section (Southern Baltic, Poland). The barrier separates Lake Łebsko from the Baltic. Five sedimentary complexes were distinguished there (M2–M6). The spatial variability of the grain-size distribution was examined and succession stages of the mollusc fauna occurring in the individual sedimentary complexes were distinguished. Radiocarbon dating was used to establish the age of the most important events during the process of formation of the barrier, which took place in the course of several relative sea-level changes. The first sedimentary complex (M2) at Rąbka is connected with the second ingression (i2) of the Baltic Sea (ca. 6,700–6,000 ^{14}C years BP), sea-level stabilization (6,000–5,500 ^{14}C years BP), and at last sea-level lowering (5,500–5,000 ^{14}C years BP) in the region of the Gardno-Łeba Coastal Plain. The sedimentary complex M3 developed in a lagoonal environment when the barrier was situated north of its present position (5,000–3,000 ^{14}C BP). The next lowering of the sea-level made the lagoon shallower and caused the emergence of small but already subaerial stretches of barrier land with a freshwater fauna in the north (4,880±40 ^{14}C BP). With the next ingression stage (i3), which took place between 4,500 and 3,000 BP, the barrier shifted to its present-day position and the lagoon changed into a freshwater lake. From 3,000 to 1,700 ^{14}C BP fossil soil and peats developed on the barrier surface as a result of another sea-level lowering. The last ingression stages (i4 and i5), younger than 1,700 BP, built up the barrier, practically in its today's location (sedimentary complexes M4 and M5). The youngest sedimentary complex (M-6) is represented by present-day beach sands.

Key words: sand barriers, lagoons, Holocene barrier-lagoon system, Poland, southern Baltic coast

INTRODUCTION

Relative changes in the sea level during the Holocene are among the major issues of research of the southern Baltic shore. It has been the focus of a considerable number of studies, the most important including: Bülow (1928, 1933, 1937), Rosa (1958, 1959, 1963, 1968, 1987, 1991), Kliwe and Jahnke (1982), Kolp (1979, 1981, 1983), Tobolski (1987, 1989, 1997, 2001), Wojciechowski (1988, 1990, 1995), Mojski (1995), Tomczak (1993, 1995a, b), Kramarska *et al.* (1995), Rotnicki (1999, 2001), Rotnicki *et al.* (1999a), Rotnicki and Pazdur (2003), Uścinowicz (1999, 2000, 2001, 2003), Uścinowicz and Miotk-Szpiganowicz (2003), and Zachowicz *et al.* (1992). Only few studies comprise the transformation of bays of the open southern Baltic sea into lagoons and lakes, and especially with the connection between changes in the sedimentary environment of this coastal zone and the development of a barrier system and sea-level fluctuations (Berglund 1964, 1971; Wypych 1973, 1980; Przybyłowska-Lange 1979; Bogaczewicz-Adamczak, Miotk 1985; Wojciechowski 1994a, b, 1995; Hadenström, Risberg 1999; Rotnicki *et al.* 1999a; Borówka *et al.* 2001a, b; Janczak-Kostecka, Kostecki 2008). They are often based on an analysis of single geological profiles.

The present article seeks to bridge this gap. It describes the results of detailed lithostratigraphic studies, some sedimentological and malacological ones, radiocarbon dating of chief deposit series, and the age of the definite closure of the Łeba lagoon and its transformation into a freshwater lake. The entire research, with the exception of drilling the boreholes L-001, L-002 and L-002C, was financed by the Committee for Scientific Research Project No 3 P04E 028 23.

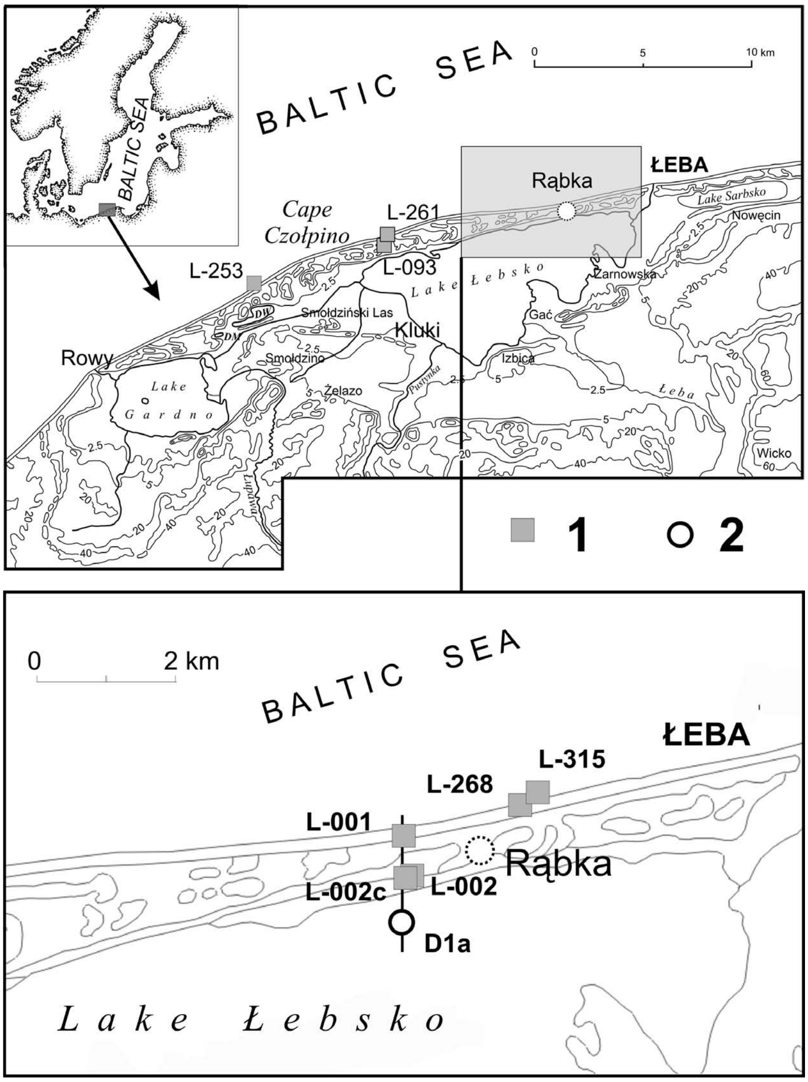

Fig. 1. Study area and the location of the analysed profiles. *1* – profiles obtained using MERES drilling rig, *2* – Instorf sounding (after Wojciechowski 1994b, 1995).

To start with, a terminological question has to be settled: is the rising sea-level in the southern Baltic zone a regional transgression or series of local ingressions? In the opinion of Alexandrowicz (1999), with reference to the Baltic as a whole, the term 'Littorina Transgression' should be replaced with 'Cardium Transgression'. He believes that in the Holocene climatic optimum there were periodic inundations of some lower-lying areas situated south of today's coastline. He terms them a 'Pomeranian Ingression'. It follows from his definition of this notion that it embraces events more or less local in range. Because of the spatial scale of the issues analysed in the present article, the sea-level changes discussed can only be considered relatively. That is why periods of elevated sea-levels are termed ingressions, which has been justified elsewhere (Rotnicki 2001). They are covered by the notion 'Pomeranian ingression' or 'ingressions'.

RESEARCH AREA, SCOPE AND METHODS

The analysed profiles are situated on the Łeba Barrier near a locality of Rąbka, which lies 2.5 km west of the town of Łeba (Fig. 1). Drilling was performed using a MERES hydraulic-mechanical drilling rig (Rotnicki *et al.* 1999b). Bore-holes L-001 (1.9 m a.s.l.) and L-002 (1.0 m a.s.l.), reaching down to a depth of 10-12 m and drilled in 1986, are situated on the meridional cross-section of the barrier located in the area of an old V-1 rocket launching pad 3 km west of Rąbka. The Łeba Barrier is 900 m wide here. The presence of a mollusc fauna in the profile of the L-002 bore-hole at a depth of 3.0 to 9.5 m in the Holocene marine deposits, both lagoon and lacustrine, prompted the drilling of another bore-hole (L-002c) a few metres away in order to take 39 samples for malacological studies from a depth of 2.90 to 9.40 m. The L-001 profile lies in the northern part of the barrier, at the southern foot of a foredune, while bore-holes L-002 and L-002c are situated 25 m from the northern shore of Lake Łebsko. Somewhat later, under the same project of the AMU Department of Quaternary Geology and Paleogeography on the so-called Holocene transgression of the southern Baltic, Wojciechowski (1994a, b, 1995) took five cores through the ice along the meridional cross-section embracing the eastern part of Lake Łebsko. A standard Russian peat corer was used. It is an extension of the cross-section marked by the profiles L001-L002-L002c (Fig. 1). The profile of Wojciechowski's D1a sounding has been used in a simplified form in geological cross-section of the Łeba Barrier. Much later, in 1998, the first author of this article made the L-268 bore-hole (0.5 m a.s.l.) on the beach, 2 km east of the cross-section above (Fig. 1). The abundance of the mollusc fauna found in the cross-section at a depth of 5.35 to 8.80 m caused the drilling to be repeated twice in 2002. The samples taken were then used for the study of the mollusc fauna. To obtain material for sedimentological studies and for radiocarbon analysis of shells of *Cardium* sp., in 2002 three further bore-holes were drilled, L314, L315 and L316 (0.5 m a.s.l.), all located in the immediate vicinity of L-268. The type and order of marine, lagoon and lake deposits are similar in all of them, taking into consideration their spatial facies variability.

To characterise the lithostratigraphic profile, grain-size analysis was performed for 102 samples from the L-002 profile and 93 samples from L-315. The samples were taken in a continuous sequence. The analysis was carried out in the Laboratory of the Department of Quaternary Geology and Paleogeography of the Adam Mickiewicz University in a way described elsewhere (Rotnicki, Młynarczyk 1990). Statistical moment measures of the grain-size distribution were calculated using an originally designed computer program.

The same laboratory analysed selected geochemical properties of sediments sampled from the L-002 profile. The properties included: loss on ignition, per cent content of calcium carbonate, biogenic and terrigenous silica, as well as

Na, K, Ca, Mg, Mn and Fe. The analyses were made using methods described earlier by Borówka (1988). Fresh sediment samples were dried at 105°C and then mineralised by roasting at 550°C. The remaining ash (mineral matter) was solubilised first in aqua regia and then in hydrochloric acid (Januszkiewicz 1978; Borówka 1992). The solution was used to determine the levels of the elements listed, with sodium and potassium being determined by flame spectrometry while calcium, magnesium and iron, by atomic absorption spectrometry. To avoid interaction among the elements, a lanthanum solution was used in concentrations proposed by Pinta (1977).

Malacological analysis encompassed 114 samples taken in two profiles: 41 from L-002c and 73 from L-268. In the former, all the samples (1 to 41) contained mollusc shells; in the latter, some fauna was found in samples 17–71 and 73–77, while in the rest (1–16, 72 and 78–88) no remains of bivalves or snails were found. The analysis was performed using the standard procedure described in Ložek (1964) and Alexandrowicz (1988). The occurrence of shell banks rich in detritus of bivalve shells but only sporadically complete specimens, forced us to estimate the number of remains found and to accommodate semi-quantitative symbols (Alexandrowicz 1988). In the malacological spectra *Bithynia opercula* were not included.

To determine the age of peat layers found in the analysed profiles as well as of shells from the levels of their exceptional abundance, a total of 5 peat samples and 6 samples from the shell-bank levels were taken in the L-314 bore-hole, situated 1 m from L-315, both profiles revealing the same succession of layers. Besides, we used the date of the lowermost peat layer in the D1a sediment profile from the northern part of Lake Łebsko (Wojciechowski 1995). Samples of *Cardium* shells were taken from layers 5 cm thick. Owing to the minimum mass requirement for the conventional radiocarbon dating, in two cases two successive samples were combined into one; thus, each of them represented a layer 10 cm thick. In one case, a 10-cm thick layer yielded not only *Cardium* sp. shells but also those of *Hydrobia* sp. Most ^{14}C dates were obtained in the GADAM Centre, Institute of Physics, the Silesian University of Technology in Gliwice, using the traditional technique with gas proportional counters filled with CO_2 (Pazdur *et al.* 2000). ^{14}C age of four shell samples from the L-002C profile and one from L-268 was measured using the AMS technique in the Poznań Radiocarbon Laboratory (Goslar *et al.* 2004).

LITHOSTRATIGRAPHY OF SEDIMENTS BUILDING THE ŁEBA BARRIER BETWEEN ACTIVE DUNES AND RĄBKA

Characteristics of selected profiles

Profile L-002. It starts with gravelly sands (at a depth of 12.0–10.3 m) which underlie medium sands (10.3–9.8 m) followed by coarse sands (9.8–9.4 m), in the topmost part visibly enriched with fine gravel forming a thin layer of erosion pavement (Fig. 2). These are sediments deposited in an environment of running waters, both riverine and glaciofluvial, at the close of the Upper Pleni-Vistulian (Rotnicki 2001). Above the pavement starts a fine-grained series of intercalated marine, lagoon and lacustrine sediments. It reaches up to the present-day surface of the southern part of the barrier.

The series starts with marine sands, medium and fine (9.4–9.25 m), containing sparse plant macro-remains. At a depth of 9.25 to 5.25 m there is a 4-metre-thick lagoon-lake series composed of the following layers:

(a) two layers of dark olive-grey brackish silts with a small admixture of sand (8.9–8.0 m and 5.6–5.25 m),

(b) fine light-grey sands intercalated with thin stripes of olive-grey silts (6.9–5.8 m),

(c) gyttja of beige colour, also containing a slight admixture of fine sand, and found in three layers (9.25–8.9; 8.0–6.9; and 5.8–5.6 m).

In the profile of this series shells and their fragments occur in varying amounts. They are rare in the beige gyttja, but more abundant in the olive-grey silts and sands with intercalations of silts (Fig. 2).

The top series of marine sands is 5.25 m thick. These are fine sands, at places with an admixture of medium sands light-grey in colour. Near the bottom (5.25–4.75 m) and at a depth of 4.25–3.80 m a few thin intercalations of olive-grey silt still appear. Between 1.5–2.5 m the sands appear dirty-grey in colour, resulting from the presence of scattered humus. There is also an admixture of small plant macro-remains. Considering that the discussed profile lies some 25 m from the today's northern shore of Lake Łebsko, one can conclude that this layer is a remnant of a fossil soil horizon associated with a once higher level of Lake Łebsko.

Profile L-315 (next to profile L-268). Like profile L-002, it starts with gravelly sands penetrated at a depth of 9.5–8.75 m (Fig. 3). They are covered by a thin layer of well decomposed black peat (8.75–8.68 m) on which lies a complex of fine-grained sediments representing various facies of littoral marine environment reaching up to the surface of the present-day Baltic beach. From the bottom upwards, the following sediments can be distinguished in it:

(1) Bottom sands, very fine and fine, grey and dark-grey (8.68–7.95 m), containing shells of *Cardium* sp. at a depth of 7.95 to 7.40 m.

(2) A series of silt and silt-sand sediments (7.95–6.15 m). It consists of: (a) rather thin layers of olive-grey silt, usually sandy (7.95–7.4 m; 6.4–6.15 m), and (b) very fine sands, grey or sometimes dark-grey, with occasional intercalations of olive-grey silt (7.4–6.4 m; 6.15–5.65 m). In both, silts and sands, there occur shells and shell detritus, but the frequency of those admixtures is low. It is only in the upper sandy layer, at a depth of 5.70–5.65 m, that there is a distinct shell level from which two shell samples were taken to determine their radiocarbon age. One contained the shells of *Cardium* sp., the other of *Hydrobia* sp.

(3) A lamina of fine and very fine sand, dark-grey in colour with a clear admixture of humus and fine plant macro-remains, occurring at a depth of 5.65 to 5.50 m. It probably corresponds to the lamina of fine, olive-grey sand with thin peaty intercalations found at a depth of 5.85–5.92 cm in the profile L-268, for which studies of the mollusc fauna were made. This lamina might have formed in a terrestrial environment.

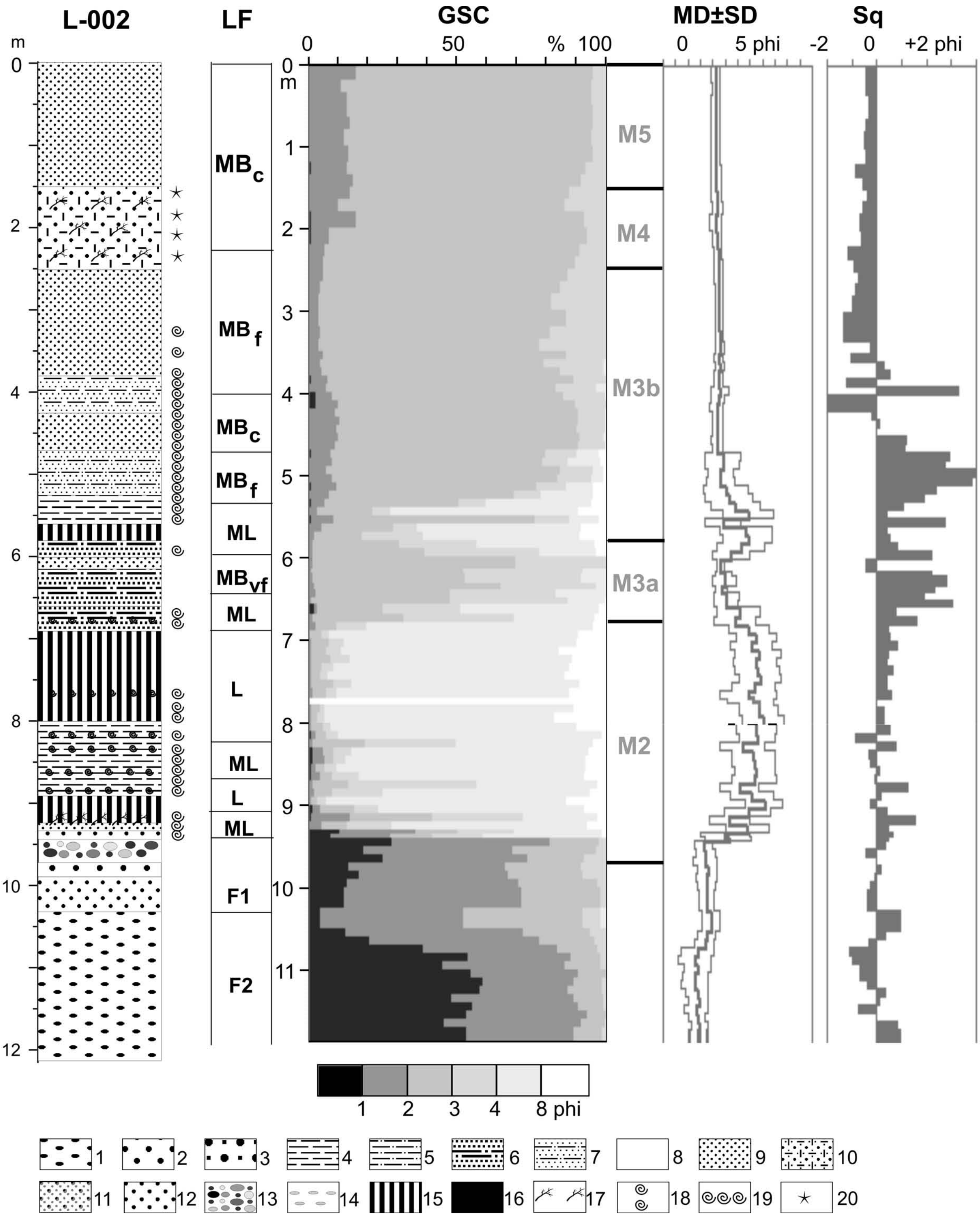

Fig. 2. Lithostratigraphic profile of the L-002 bore-hole and the variability of its grain-size distribution and main statistical measures. LF – lithofacies: M-B$_F$ – sub-lithofacies of finer variety of fine marine sands; M-B$_C$ – sub-lithofacies of coarser variety of fine marine sands; M-B$_{VF}$ – very fine marine and marine-lagoonal sands; M-L – silty lagoonal sands; L – lagoonal silts and sandy silts; F$_1$ and F$_2$ – riverine and glaciofluvial varigrained and gravelly sands, in top part of F$_1$ lithofacies base pavement of sea ingression; GSC – grain-size distribution; MD±SD – mean diameter ± standard deviation; Sq – skewness. *1* – varigrained sands, *2* – coarse sands, *3* – gravelly sands, *4* – silts, *5* – sandy silts, *6* – sands intercalated with silts, *7* – fine silty sands, *8* – very fine sands, *9* – fine sands, *10* – fine humic sands, *11* – fine and medium sands, *12* – medium sands, *13* – lag deposit (pavement), *14* – beach pavements, *15* – gyttjas, *16* – peats, *17* – plant macro-remains, *18* – presence of mollusc fauna in profile, *19* – levels of shell banks, *20* – occurrence of humus.

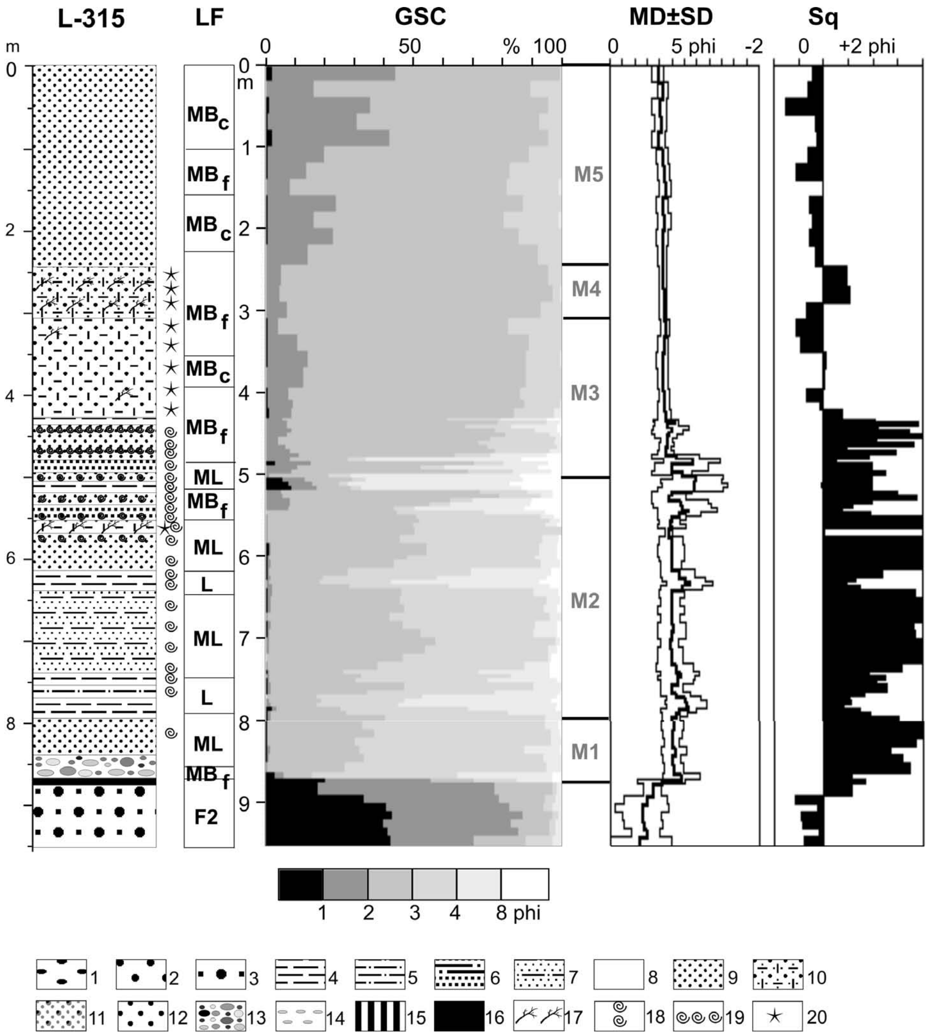

Fig. 3. Lithostratigraphic profile of the L-315 bore-hole and the variability of its grain-size distribution and main statistical measures. Explanations as in Fig. 2.

(4) A complex of sandy and silty-sandy layers more than 1 meter thick, containing several abundant shell levels (5.50–4.32 m). From the depths of 5.5–5.55 m, 5.2–5.17 m and 5.0–4.96 m, *Cardium* sp. samples were taken for radiocarbon dating.

(5) Fine, humic and humic-ferruginous sands, beige-brown and sometimes brown in colour, with numerous fine orange and brown plant macro-remains (4.32–2.45 m).

(6) Fine light-grey sands, in the top part whitish-yellow, being the youngest marine deposit of the barrier (2.45–0.0 m).

Lithofacies

To distinguish the lithofacies of sediments building the Łeba Barrier in the Rąbka region, we used the method of similarity of the grain-size distribution employing the non-parametric Kolmogorov-Smirnov test and the *U* test of two means. Next, grain-size distribution means were calculated (Fig. 4) as well as means of the chief moment measures characterising this distribution and their standard deviations in each of the lithofacies (Table 1). In this way the following lithofacies were distinguished:

Lithofacies of fine sands (M-B). This is a lithofacies of marine barrier sands. Its mean diameter (*M*) is +2.41 phi (Fig. 5). It is fairly homogeneous, as proved by a very low standard deviation of the mean (0.26 phi). It is best sorted of all the lithofacies (*SD* = 0.92 phi). The grain-size distribution is slightly positively skewed (*Sq* = 0.53), and the distribution in this lithofacies is closest to symmetry. There is a slight spatial variability: the material found in the northern part of the barrier is somewhat coarser (*M* = 2.38±0.30, *SD* = 0.64±0.39 phi) than in the southern part (*M* = 2.43±0.22, *SD* = 0.55±0.41 phi). The modal fraction (2.25–2.50 phi) is more defined in the southern part is where it attains 30%, against 20% in the northern part (Figs 5, 6; lithofacies M-B).

Two sub-lithofacies can be distinguished in the lithofacies M-B: M-B_C, built of somewhat coarser material, and M-B_F, composed of finer material. They occur in similar proportions in both the northern and southern parts of the barrier (Fig. 6).

Coarser sub-lithofacies M-B_C shows a negative skewness of its grain-size distribution visible in both the northern and southern parts of the barrier. Distribution of the finer sub-lithofacies, in turn, is clearly positively skewed (Table 1). The former one is better sorted (*SD* = 0.41–0.52) than the

Table 1

Statistical measures of grain-size distribution of lilthofacies building the Łeba Barrier system at Rąbka

	Lagoonward part of the barrier	Mean measures for the Łeba Barrier at Rąbka	Seaward part of the barrier
		Mean measure for the whole lithofacies	
MB	MD = 2.43 ± 0.22 SD = 0.55 ± 0.41 Sq = 0.06 ± 1.64	MD = 2.41 ± 0.26 SD = 0.92 ± 0.83 Sq = 0.53 ± 1.64	MD = 2.38 ± 0.30 SD = 0.64 ± 0.39 Sq = 0.61 ± 1.60
		Sub-lithofacies MB_F	
	MD = 2.54 ± 0.22 SD = 0.67 ± 0.49 Sq = 0.43 ± 1.96	MD = 2.52 ± 0.26 SD = 0.69 ± 0.48 Sq = 0.81 ± 1.81	MD = 2.48 ± 0.28 SD = 0.69 ± 0.45 Sq = 1.06 ± 1.66
		Sub-lithofacies MB_C	
	MD = 2.28 ± 0.06 SD = 0.41 ± 0.06 Sq = -0.51 ± 0.94	MD = 2.23 ± 0.14 SD = 0.44 ± 0.07 Sq = -0.51 ± 0.82	MD = 2.05 ± 0.16 SD = 0.52 ± 0.04 Sq = - 0.52 ± 0.45
MB_{VF}	MD = 2.95 ± 0.24 SD = 0.83 ± 0.37 Sq = 2.01 ± 1.06	---------------	---------------
ML	MD = 4.40 ± 0.61 SD = 1.86 ± 0.15 Sq = 0.58 ± 0.46	MD = 3.42 ± 0.71 SD = 1.24 ± 0.46 Sq = 2.66 ± 1.73	MD = 3.10 ± 0.36 SD = 1.03 ± 0.31 Sq = 3.36 ± 1.41
L	MD = 5.12 ± 0.77 SD = 1.73 ± 0.17 Sq = 0.40 ± 0.48	MD = 4.62 ± 0.93 SD = 1.82 ± 0.34 Sq = 0.82 ± 0.92	MD = 3.93 ± 0.64 SD = 1.95 ± 0.45 Sq = 1.39 ± 1.05
F	---------------	MD = 1.10 ± 0.64 SD = 1.10 ± 0.49 Sq = -0.06 ± 0.72	---------------

Lithofacies: MB – marine fine sands, sub-lithofacies MB_F – finer fractions of fine sands, sub-lithofacies MB_C – coarser fractions of fine sands, MB_{VF} – very fine sands, ML – lagoon silty sands, L – lagoon silts and sandy silts, F – varied grained sands and gravelly sands, fluvial and glacio-fluvial; MD – mean diameter ± standard deviation, SD – standard deviation as a measure of sorting ± standard deviation, Sq – skewness of grain size distribution ± standard deviation

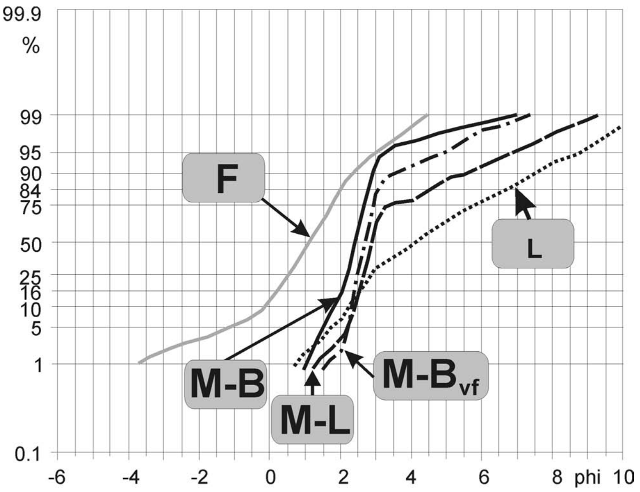

Fig. 4. Curves of mean grain-size distributions of the lithofacies distinguished. Lithofacies symbols as in Fig. 2

latter (0.67–0.69). Like the entire lithofacies, they both display similar character of meridional dependence of the mean diameter and sorting, although in numerical terms these parameters span a small interval. In general the sands are finer and better sorted in the lagoon-ward than in the seaward part of the barrier (Table 1).

Lithofacies of fine and very fine sands (M-B_{VF}). Its mean grain diameter is a midway between fine and very fine sands (M = 2.95±0.24 phi), and sorting is slightly better than that of lithofacies M-B as a whole. Its positive skewness is definitely more pronounced than in the first of the discussed lithofacies and its variants (Sq = 2.01±1.06), which results from remarkable admixture of very fine sand and coarse silt. This lithofacies occurs only in the bottom of the lagoon-ward part of the barrier, in a stratigraphic position indicative of appearance of a transitional environment between the lagoon and the barrier (Figs 4, 5).

Lithofacies of silty sands (M-L). In the lithostratigraphic profiles of the barrier, this lithofacies forms the fundamental part of sediments of the lagoon environment (Figs 2, 3, 4, 5). While its mean grain diameter occupies a mid-position in the interval of very fine sands, the lithofacies shows considerable non-homogeneity (M = 3.42±0.71 phi) resulting primarily from its very distinct spatial variability (Table 1). The high standard deviation of the grain-size distribution (SD = 1.24±0.46 phi) shows it to contain a wide range of fractions. The clear bimodality of the grain-size distribution indicates contribution of two sedimentary environments: lagoon and marine to the formation of this lithofacies. The sandy part of the lithofacies is probably the distal section of ingression cones deposited in places of temporary breaches in the barrier between the lagoon and the open sea, or deposited as a result of inflows of sea water over the low barrier during high storm surges. The very high positive skewness of the grain-size distribution, the highest among the lithofacies distinguished (Sq = 2.66±1.73), is also widely variable spatially.

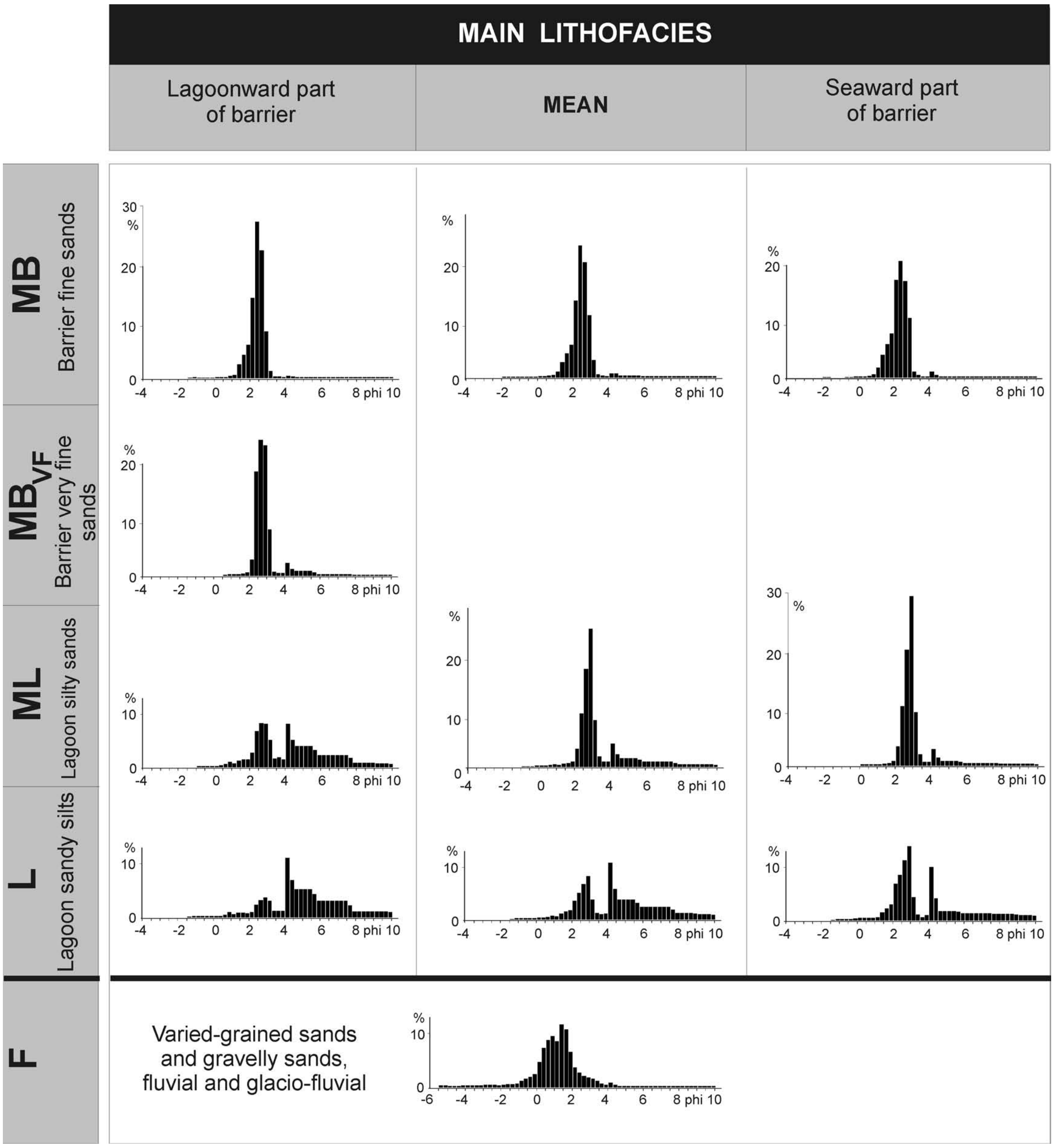

Fig. 5. Histograms of mean grain-size distributions of the lithofacies building the Łeba Barrier near Rąbka and averages for the lagoonward and seaward parts of the barrier. Lithofacies symbols as in Fig. 2.

The regularities of the spatial variability of the silty sands (M-L) include (Table 1, Fig. 5):

(1) A shift in the mean diameter, from the borderland between fine and very fine sands in the seaward zone of the barrier (M = 3.10±0.36 phi) to coarse-grained silts in the lagoonward part (M = 4.40±0.61 phi), with a simultaneous increase in the non-homogeneity of the mean diameter.

(2) A shift in the grain-size distribution from the category of fine and very fine sands in the seaward zone of the barrier – where those sands (+2 – +4 phi) contribute as much as 85.7% – to the category of typical silty sands in which the mentioned sands are as abundant (35.5% each) as the coarse and medium silts (+4 to +6 phi). It needs no explanation why the proportion of the sandy fraction declines towards the middle of the lagoon basin while that of silts increases. As to the coarsest (+2 phi) and the finest (+6 phi) fractions, there is a clear asymmetry in favour of fine silts and the clay fraction (from +6 to +10 phi), which make up 21.3%, against 7.7% of fractions coarser than +2 phi. This is indicative of the growing dominance of the lagoon environment over the temporary influence of the marine environment towards the middle part of the lagoon.

(3) A markedly lower skewness of the grain-size distribution in the lagoon-ward area (Sq = 0.58±0.46) than that characterising the seaward side of the barrier (Sq = 3.36±1.41), in accordance with the facts discussed in points (1) and (2).

Lithofacies of sandy silts (L). This is the finest lithofacies among those distinguished (Figs 4, 5, Table 1). It is composed of both, dark olive-grey brackish silts and mineral admixtures contained in beige and beige-brown gyttja. Thus, its formation took place in the middle part of the basin (far from the shores) when the lagoon was changing into a closed freshwater lake.

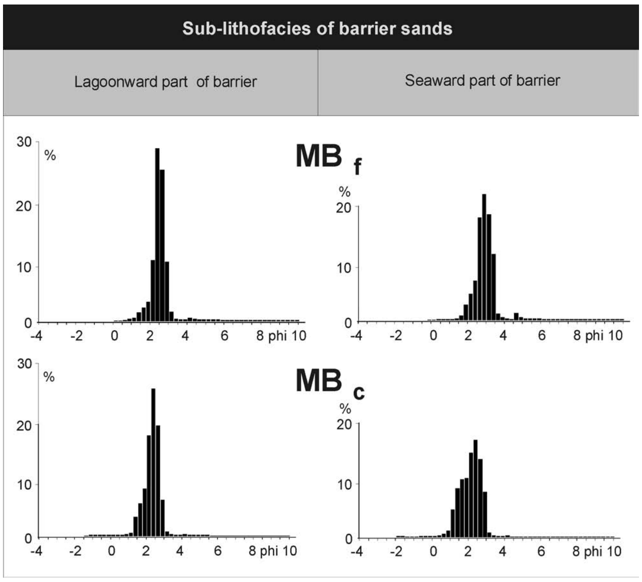

Fig. 6. Histograms of mean grain-size distributions for the sub-lithofacies of fine marine sands (M-B) for the lagoonward and seaward zones of the Łeba Barrier near Rąbka.

The mean grain diameter of this lithofacies falls into the fraction of coarse-grained silts (*M* = 4.62±0.93 phi). In fraction terms, this is the most diversified lithofacies among those distinguished, which is indicative of the poorest sorting (*SD* = 1.82±0.34 phi). However, the positive skewness of its grain-size distribution is less pronounced than in the lithofacies of silty sands (M-L). The regularities of its spatial diversity are similar to those found in the lithofacies discussed earlier: (a) the mean grain diameter diminishes from the seaward side of the barrier towards its lagoon-ward side, while non-homogeneity of sandy silts in the lagoon-ward zone increases (Table 1), and (b) there is a distinct bimodality in the grain-size distribution caused by similar factors as in the case of the silty sand lithofacies (M-L). In the seaward zone there is a slight predominance of sandy fractions, while in the lagoon-ward zone silty fractions clearly prevail.

Lithofacies of varigrained and gravelly sands (F). Sandy deposits with admixture of gravels, found in the substratum of the four lithofacies above, and connected with marine, lagoon and lake environments, were treated as one class (Table 1, Figs 4, 5). Also, no analysis of their spatial variability was made. Being deposits of running-water environment, their variability obeys different rules and its scale is different too. The mean grain diameter of those deposits is in the lower limit of coarse-grained sand (*M* = 1.10±0.64 phi). The high standard deviation of the *M* values indicates that the deposits are composed of both, coarse-grained gravelly sands with a mean diameter of 0.46 phi as well as medium and fine sands (*M* = 1.74 phi). Their grain-size distribution is close to normal with a minimum negative skewness (*Sq* = –0.06). Sorting is fairly good (*SD* = 1.10±0.49 phi). Modal classes include the fractions of coarse and medium sand. This lithofacies also contains 7.1% of very coarse sand and 5.2% of gravels with a diameter from –6 to –1 phi.

SELECTED GEOCHEMICAL CHARACTERISTICS OF THE SERIES OF LAGOON AND MARINE SEDIMENTS

The variability in the content of individual geochemical elements in the deposits of the Łeba Barrier at Rąbka is illustrated on the example of bore-hole L-002 (Fig. 7). Each lithofacies is clearly distinct from the others, and they all correspond to specific sedimentary environments.

The geochemical features divide the profile into three sections: (1) deposits of the substratum, (2) lagoon-lake deposits, and (3) littoral marine sands.

Fluvial and glaciofluvial varigrained and gravelly sands of the substratum. Practically the only component of glaciofluvial and fluvial deposits is terrigenous silica, whose proportion reaches 96–99%. Carbonates come second, but their share does not exceed 3.4%. Organic matter and biogenic silica appear in trace amounts: 0.3–0.6% and 0.5–0.7%, respectively.

Lagoon silty sands. They are characterised by a great variability of geochemical properties. In the bottom layers of the lagoon-lake series (9.4–9.2 m) the content of organic matter ranges from 4% to 27% (17.5% on average), carbonates from 45% to 71% (61.7% on average), terrigenous silica 10.1–26.4% (20.3% on average), and biogenic silica merely 0.4–1.1% (0.5% on average). In the middle, thickest layer of the silty sands (6.8–5.8 m) the proportions of organic matter and carbonates are much lower, 0.2–3.8% (2.1% on average) and 0.9–6.6% (3.4% on average), respectively. The content of biogenic silica is low too (2.3% on average). Finally, the top layer of the silty sands lying directly under marine barrier sands (5.2 to 4.7 m) shows a decrease in the content of organic matter from 5.7% at the bottom to 2.6% at the top, of carbonates from 6.6% to 3.9%, and of biogenic silica from 2.6% to 1.7% (Fig. 7).

Lagoon sandy silts. Their lower, thickest, layer situated at a depth of 8.8 to 8.0 m contains from 5% to 10.1% organic matter (8.0% on average), 11.7% to 20.7% carbonates (18.1% on average), and 4.3% to 9.8% biogenic silica (7.0% on average). The proportions of carbonates and biogenic silica grow upwards, from 11.7% to 22.7% ($CaCO_3$) and from 4.3% to 9.1% (biogenic silica). The upper layer of brackish silts situated at a depth of 5.6 to 5.2 m contains on average 9.9% organic matter (a maximum of 22.9%), 13.6% carbonates (a maximum of 25.3%) and 7.6% biogenic silica (a maximum of 15.7%). The proportions of those components are the highest in the middle laminae of this section.

Beige lacustrine gyttjas. They occur in three layers. The content of organic matter in the bottom (9.2–8.8 m) and top layers (5.6–5.8 m) is similar (13.0% and 13.8%, respectively), and it is the highest in the middle layer (8.2–6.8 m) where it averages 17.7%. The carbonate content is the highest in the bottom layer where it varies from 52% to 80% (64.2% on average). In the middle layer, carbonate levels are lower, between 22% and 53% (39.6% on average). Finally, in the top layer there are only 18–21% of carbonates, with a mean of 19.7%. The proportion of biogenic silica is also the highest in the middle layer, 12.3% on average. In the top layer its content is only a bit lower (it averages 10.5%), while the bottom layer shows a mere 1.1% of this component.

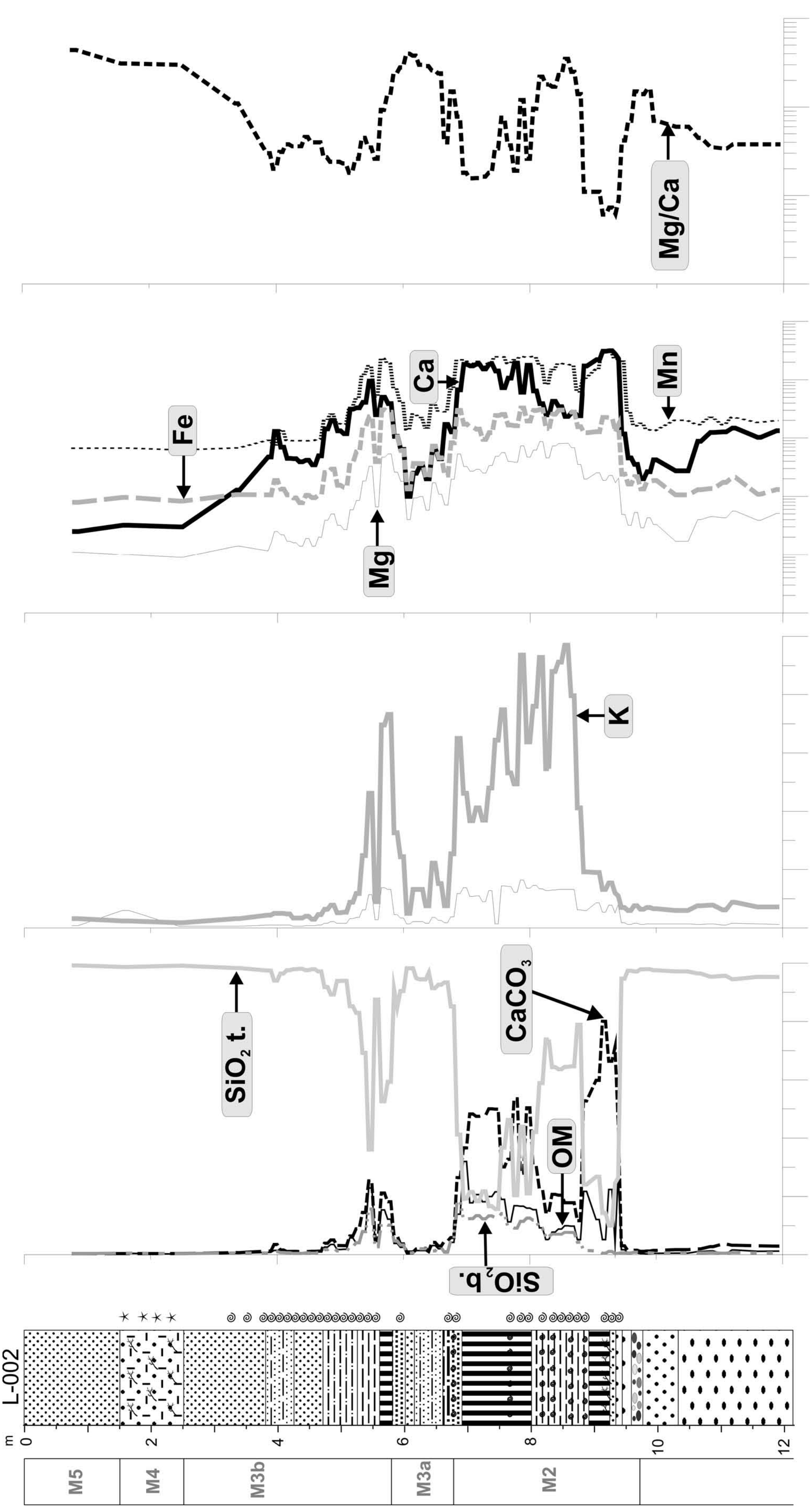

Fig. 7. Variability of selected geochemical parameters of deposits in the L-002 profile situated in the lagoonward part of the Łeba Barrier near Rąbka. Explanation for geological profile as in Fig. 2.

Table 2

Molluscan assemblages in the lagoon-side profile L-002C at Rąbka (sample numbers from the top to the bottom)

	Species	Samples									
		1–2	3–13	4–19	20–21	22–24	25	26–29	30–37	38–39	40–41
V	*Theodoxus fluviatilis*		I		I	I			I	II	I
V	*Valvata piscinalis*	III	V	III	III	I				III	III
V	*Valvata cristata*										II
V	*Bithynia tentaculata*		III	II	II	I				I	II
V	*Bithynia - operculum*	II	IV	II	II					IV	IV
V	*Lymnaea ovata*		I								I
V	*Gyraulus laevis*										III
P	*Unionidae*	I									
P	*Sphaerium corneum*										I
P	*Pisidium henslovanum*	I	II	I							III
P	*Pisidium milium*										II
P	*Pisidium subtruncatum*		I	I							
P	*Pisidium nitidum*		II	I							III
P	*Pisidium crassum*	I	I								
P	*Pisidium casertanum*		I							I	II
P	*Pisidium ponderosum*		II	I						I	I
P	*Pisidium moitessierianum*	I	II	I							II
H	*Hydrobia ulvae*					I	II	I	III	I	
H	*Hydrobia ventrosa*				I	II	I	I	III	III	I
H	*Rissoa*							I	II		
C	*Cardium glaucum*				II	III	IV	II	VI	III	
C	*Macoma baltica*					I	I	I	II	II	
C	*Mytilus edulis*					I	I	I	II	II	
C	*Scrobicularia plana*								II	I	

V – freshwater snails, P – freshwater bivalves, H – snails typical of a brackish environment, C – marine bivalves. Roman numerals denote the following numbers of analysed shells: I – 1–3; II – 4–9; III – 10–31; IV – 32–99; V – 100–316; VI – 317–999.

Summing up the variability of the mentioned components of the lagoon-lake sediments, it is worth noting that generally, from the bottom of the lower layer of beige gyttja to the top of the middle, thickest, layer of this gyttja, we can observe a non-uniform increase in the content of organic matter from 5.1% to 32.0% and of biogenic silica from 0.5% to 18.4%, with a concomitant decline in carbonates and terrigenous silica.

Fine marine sands. These sands contain only traces of organic matter (0.1–0.5%), carbonates (0.30–0.7%) and biogenic silica (0.3–0.7%), against as much as 98–99% of terrigenous silica (Fig. 7).

The curve of the magnesium/calcium ratio, indicating some trends in salinity, is very interesting. The ratio grows markedly just above the layer of the base pavement of the first ingression of the Holocene Baltic situated at the bottom of the lagoon-marine series (Rotnicki 2001). Then, the figure drops in the stages where gyttjas appear, and rises again where the gyttjas are covered with lagoon silts and sands, with the exception of layers of lagoon silts and sands lying on the shallowest layer of beige gyttja (Fig. 7). In this layer and the two lower layers of the beige gyttja the Mg/Ca ratio is low; it is also low in the top lagoon silts and silty sands situated at a depth of 5.6 to 5.2 m. In the bottom layers of marine sands lying at a depth of 4.8–4.2 m the Mg/Ca ratio grows slightly but generally remains low up to the shallowest layer of silty sands at a depth of 4.20–3.80 m. From a depth of 3.80 m up to the surface the Mg/Ca ratio rises markedly to attain a maximum in the last, shallowest-lying sample.

Obviously, the Mg/Ca ratio does not correspond directly to actual salinity levels because it is also affected by diagenetic processes in the sediment and by migration of ions in the groundwater. Generally, however, the curve may correctly indicate relative directions of change in salinity, first in the lagoon-lake and then the marine environment.

THE MOLLUSC FAUNA

In two profiles of sediments consisting of fine-grained sands, silts and gyttjas, malacological analysis was made. It allowed for separation of markedly different mollusc associations, characterising changes in the ecological and sedimentary conditions. The associations are composed of freshwater snails (V), freshwater bivalves (P), snails typical of a brackish environment (H), and marine bivalves adapted to living in water bodies with reduced salinity levels (C).

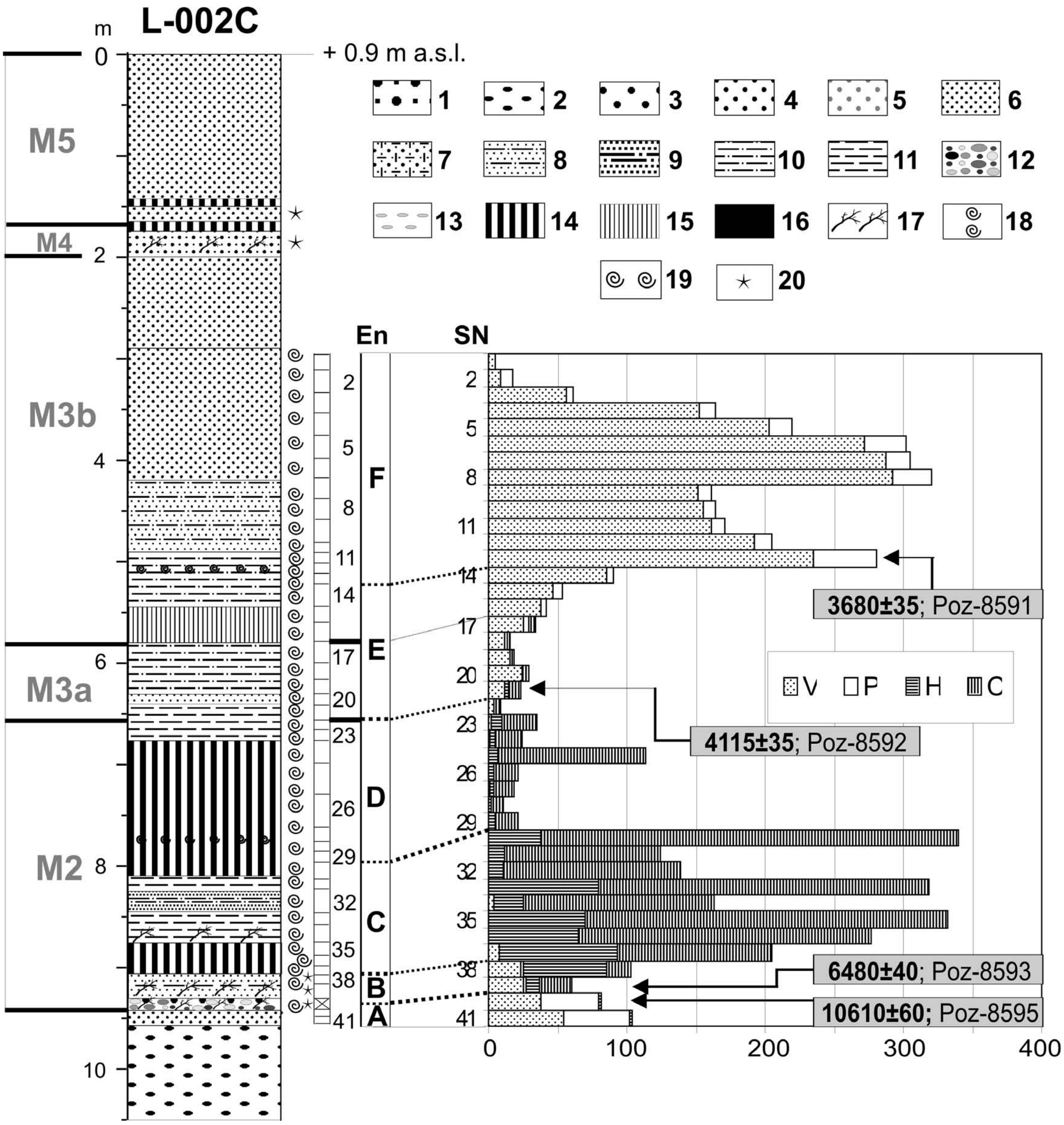

Fig. 8. Changes in the mollusc fauna in the lagoon-ward/lake-ward part of the Łeba Barrier (L-002C profile). En – stages of malacological succession, SN – sample number, V – freshwater snails, P – freshwater bivalves, H – snails typical of a brackish environment, C – marine bivalves adopted to living in water bodies with reduced salinity level; explanation for geological profile as in Fig. 2.

Profile L-002c. The malacological succession embraces 10 faunal associations described in stratigraphic order and identified by sample numbers marked in Table 2 and Fig. 8.

Samples 41–40: an association of freshwater molluscs characterised by a considerable number of snail and bivalve species, with abundant shells of *Valvata piscinalis, Gyraulus laevis, Pisidium henslovanum, P. nitidum*, and *P. casertanum*. There are large amounts of *Bithynia opercula*, greatly exceeding the number of shells of this snail.

Samples 39–38: an association of mixed composition, embracing several freshwater species, including abundant *Valvata piscinalis* shells and *Bithynia opercula*, as well as snails of the genus *Hydrobia* and four species of marine bivalves.

Samples 37–30: a shell bank composed of bivalves and marine snails, with a mass contribution of *Cardium glaucum*, represented by a detritus of easily identifiable shells and sparse, completely preserved specimens; readily visible is the presence of *Scrobicularia plana*.

Samples 29–26: a very poor fauna represented only by sparse shell fragments of marine molluscs.

Sample 25: abundant shell fragments of *Cardium glaucum* and sparse ones of several other species of marine molluscs.

Samples 24–22: a fauna represented by fairly abundant fragments of *Cardium* shells, single specimens of other marine species, and three species of freshwater snails.

Samples 21–20: a poor association of freshwater snails with an admixture of marine molluscs.

Samples 19–14: an association of freshwater molluscs with fairly numerous shells of *Valvata piscinalis*.

Samples 13–3: a rich fauna of freshwater molluscs dominated by *Valvata piscinalis*, with an abundant contribution of shells and opercula of *Bithynia tentaculata*.

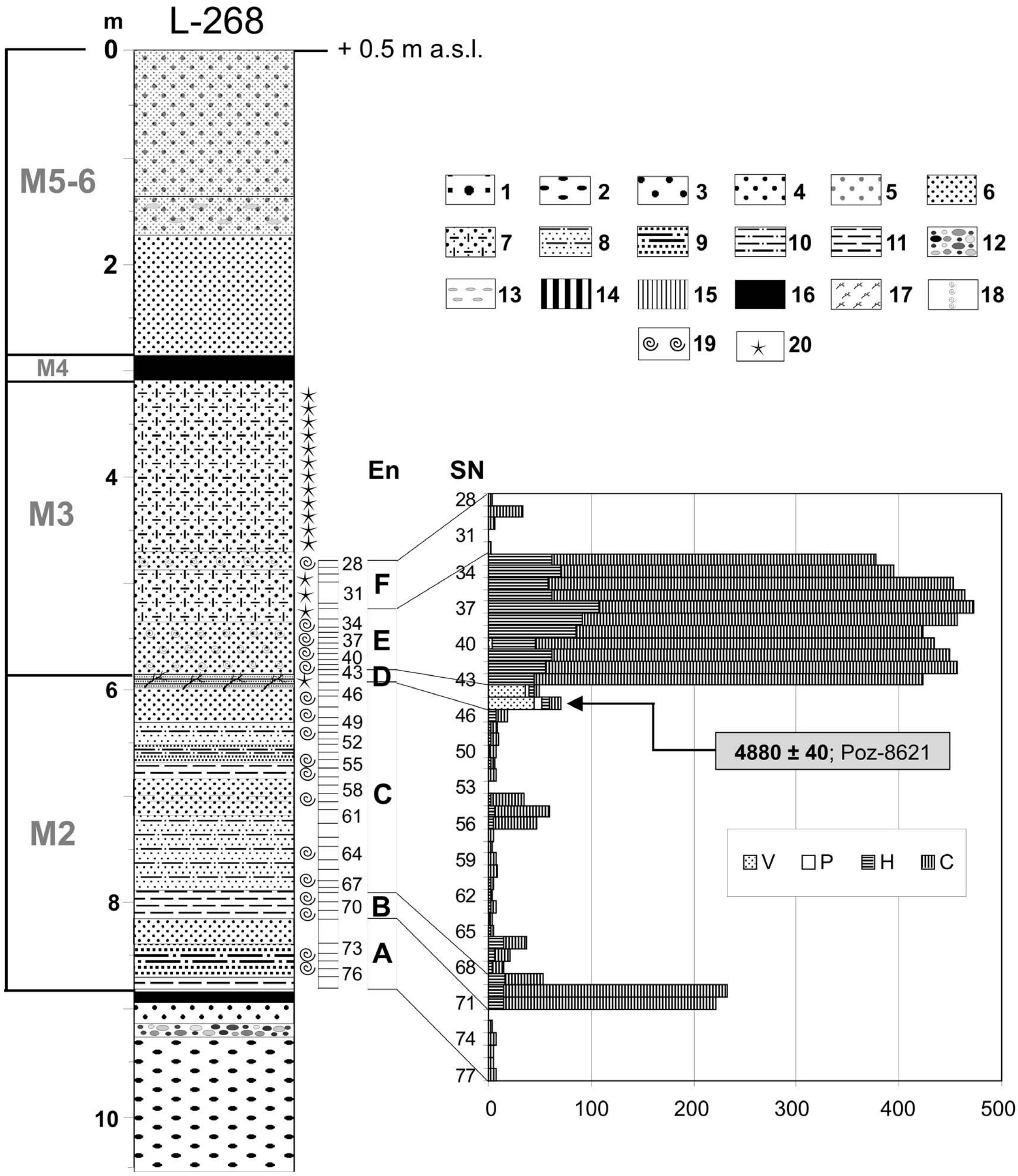

Fig. 9. Changes in the mollusc fauna in the seaward part of the Łeba Barrier in the L-268 profile. En – stages of malacological succession, SN – sample number, V – freshwater snails, P – freshwater bivalves, H – snails typical of a brackish environment, C – marine bivalves adopted to living in water bodies with reduced salinity level; explanation for geological profile as in Fig. 2.

Samples 2–1: a poor freshwater fauna with *Valvata piscinalis*.

The described sequence of mollusc associations is a good reflection of changes that occurred in the environment during the formation of the discussed sediment series (Fig. 8). In the first stage of deposition (A), it was a body of fresh water with an inlet and outlet, *i.e.* a lake. The high values of the '*Bithynia* index' (Alexandrowicz 1999a) corresponding to a very abundant occurrence of *Bithynia* opercula suggest that the littoral zone of this body was overgrown with reeds. Worth noting is the presence of *Gyraulus laevis*, a species typical of the boreal climate recorded in many profiles of Early Holocene lake sediments in northern Poland (Alexandrowicz 1995).

The appearance, beside freshwater molluscs, of a fauna typical of the Baltic (*Cardium, Hydrobia*) means the onset of a sea ingression marking the second stage (B), while the next stage (C) corresponds to the ingression at its height. This is marked by the appearance of a rich Baltic fauna which soon became the only component of a subfossil malacocenosis. A characteristic feature of this association is the presence of *Scrobicularia plana*, a species requiring elevated salinity (of at least 10–12‰). The next stage (D) is reflected in the association getting poorer, and scarce faunal remains, with one episode distinguished by abundant accumulation of fragments of *Cardium* shells. The two last stages (E and F) correspond to the development of the lacustrine fauna with especially abundant shells of *Valvata piscinalis* (Table 2, Fig. 8).

Table 3

Molluscan assemblages in the sea-side profile L-268 at Rąbka (sample numbers from the top to the bottom)

	Species	Samples									
		29	30–32	33–43	44–45	46–53	54–56	57–65	66–69	70–71	72–77
V	*Theodoxus fluviatilis*				IV					I	
V	*Valvata piscinalis*				III						
P	*Unionidae*				II						
P	*Pisidium henslovanum*				I						
P	*Pisidium nitidum*				I						
H	*Hydrobia ulvae*			III	I				II	I	
H	*Hydrobia ventrosa*			V	I				I	I	
H	*Rissoa*						II		I	II	
C	*Cardium glaucum*	IV	I	VI	II	II	IV	II	II	V	II
C	*Macoma baltica*								II	III	
C	*Mytilus edulis*						II	I	III	II	
C	*Scrobicularia plana*						III	I	II	III	I

V – freshwater snails, P – freshwater bivalves, H – snails typical of a brackish environment, C – marine bivalves Roman numerals denote the following numbers of analysed shells: I – 1–3; II – 4–9; III – 10–31; IV – 32–99; V – 100–316; VI – 317–999

Profile L-268. As in the profile described above, the malacological succession also embraces 10 faunal associations (Table 3, Fig. 9). It is striking, however that the molluscs in this profile are almost exclusively marine.

Samples 77–72: single fragments of shells of marine bivalves of the species *Cardium edule* and *Scrobicularia plana*.

Samples 71–70: a rich fauna embracing 7 species dominated by *Cardium glaucum*, with a fairly high proportion of *Scrobicularia plana* and *Macoma baltica*.

Samples 69–66: an association composed of the same species represented by rare specimens or shell fragments among which *Mytilus edulis* predominates.

Samples 65–57: scant remains of shells of three bivalve species.

Samples 56–54: abundant fragments of *Cardium* and *Scrobicularia* shells and sparse ones of two other species.

Samples 53–46: sporadic remains of bivalves.

Samples 45–44: an association of freshwater molluscs marked by an abundant occurrence of *Theodoxus fluviatilis* and fairly numerous *Valvata piscinalis*, with a slight admixture of marine species (*Cardium, Hydrobia*).

Samples 43–33: a shell bank consisting almost exclusively of shells or shell fragments of *Cardium edule*, accompanied by abundant specimens of *Hydrobia ulvae* and *H. ventrosa* (Fig. 10).

Samples 32–28: fragments of *Cardium* shells occurring in fair abundance only in sample 29, and in the remaining samples only sporadically.

The presented sequence of mollusc associations shows that the sediments containing them, formed all the time in a marine environment or under its direct influence (Figs 8, 9). Its first stage (A) corresponds to the conditions of a marine littoral environment outside the zone of concentration of shell material. In the second stage (B) there developed shell thanatocenosis composed almost exclusively of shells of four bivalve species, with a considerable share of *Scrobicularia plana*. The next stage of the malacological succession (C) shows that rather stable conditions of sedimentation persisted for a longer time. The next stage (D) is a short episode with the appearance of freshwater fauna. The substantial proportion of rheophilous species *Theodoxus fluviatilis* and an admixture of marine molluscs indicate that sediments containing this fauna were deposited in the littoral zone at a mouth of river or brook. The most characteristic element of

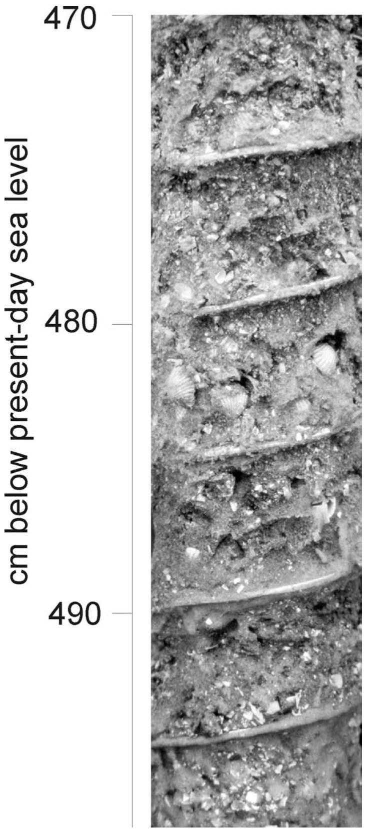

Fig. 10. Marine mollusc shells in the L-268 profile, 470–498 cm below sea-level.

Table 4

Radiocarbon dates of the samples taken from the geological cross-section at Rąbka
(Łeba Barrier, southern Baltic coast, Poland)
Right to conventional ^{14}C ages (in years BP), 68% confidence intervals of calibrated dates are given (in BC or AD)

Bore-hole number	Sample number	Depth (m)	Meters below sea level	Material dated	Lab. code	^{14}C age BP	Year AD/BC
L-001	015	2.80–2.90	0.9–1.0	Peat	Gd-5068	1730 ± 60	240-390 AD
L-001	018A	3.15–3.25	1.25–1.35	Peat	Gd-5066	2910 ± 70	1260-1000 BC
L-001	072	10.60–10.64	8.30–8.34	Peat	Gd-5067	9840 ±110	9650-9180 BC
L-002C	013	5.10–5.20	3.90–3.92	Shells	Poz-8591	3680±35	1910-1620 BC
L-002C	021	6.40–6.50	5.20–5.25	Shells	Poz-8592	4115±35	2490-2190 BC
L-002C	039	9.30–9.40	7.70–7.75	Shells	Poz-8593	6480±40	5280-5020 BC
L-002C	040	9.40–9.50	8.20–8.30	Shells	Poz-8395	10,610± 60	10410-9910 BC
L-265	007	0.80–0.90	1.30–1.40	Peat	Gd-12682	1720±50	250-390 AD
L-268	014	2.60–2.75	2.10–2.25	Peat	Gd-12142	1770±50	170-350 AD
L-268	044	5.85–5.88	5.35–5.45	Shells	Poz-8621	4880±40	3530-3180 BC
L-268	079	8.86–8.89	8.36–8.39	Peat	Gd-11463	8350±110	7540-7190 BC
L-315	035	4.96–5.00	4.46–4.50	Shells	Gd-12204	4980±60	3620-3360 BC
L-315	039	5.15–5.20	4.65–4.70	Shells	Gd-12202	5210±60	3880-3620 BC
L-315	046, 047	5.55–5.60	5.05–5.10	Shells	Gd-12205	4970 ±80	3620-3340 BC
L-315	048, 049	5.75–5.80	5.25–5.30	Shells	Gd-15077	5760±110	4500-4150 BC
L-315	048, 049	5.75–5.80	5.25–5.30	Shells	Gd-16014	5510±250	4350-3750 BC
D1a*	Łe-D1a	8.50–8.60	8.70–8.80	Peat	Gd-4784	9700±110	9290-8850 BC

* Profile Le-D1a and dating the peat according to Wojciechowski (1994, 1995).

the succession is a bank with *Cardium edule* (stage E), formed as a shell bank in the eulittoral or supralittoral zone. The sequence ends with the section of poor, single-species fauna with *Cardium* (stage F).

The composition of the discussed mollusc associations and the nature of the malacological succession, show more or less abundant aggregations of shells, their fragments or even detritus, better reflecting dynamics of the environment than its ecological conditions. Worth noting is the occurrence of *Scrobicularia plana*, a bivalve indicating sea salinity higher than recorded today in the southern and central Baltic. Its presence in the sediments of Lake Łebsko was reported by Wojciechowski (1995), according to whom the species is characteristic of the early stage of the *Littorina* transgression at the southern Baltic coast.

RESULTS OF RADIOCARBON DATING

To determine the age of the chief sedimentary series and some levels of the mollusc fauna, initially 11 samples: six of peats and five of shells were taken for ^{14}C dating. Two peat samples were taken from layers lying directly under the entire sequence of lagoon and marine sediments in bore-holes L-001 and L-268, and four from the peat layer separating the upper series of marine sands in the same bore-holes. The shell samples were taken from the levels of profile L-315 containing fairly abundant shell material allowing for radiocarbon dating with the conventional technique (Pazdur et al. 2000). These levels occur in the lower and middle parts of the upper series of marine sands. After the malacological analysis had been performed, the Poznań Radiocarbon Laboratory (AMS) dated additional 5 shell samples, coming from levels of crucial significance for changes in the mollusc fauna and its environment. Unfortunately, the lagoon-lake series was not sampled because of its paucity of shell material. The lagoon silts and gyttjas themselves were unsuitable for radiocarbon dating owing to their high carbonate content.

Radiocarbon dates of the analysed samples are listed in Table 4. Besides conventional ^{14}C dates, Table 4 shows also calibrated ages, calculated using the program OxCal ver. 3.10 (Bronk Ramsey 2001). For ^{14}C dates of marine shells, correction for reservoir effect had to be applied. As the international database of marine reservoir correction (Hughen et al. 2004, www.calib.org/marine) does not contain any data on local reservoir age on the Polish Baltic coast, we used the average value of DR at the southern Swedish coast, with uncertainty arbitrarily set as high as ±100 yr. Having in mind this obvious drawback of the calibration, in the further discussion we preferred still to use conventional radiocarbon ages (in ^{14}C years BP).

MAIN SERIES OF MARINE, LAGOON AND LAKE SEDIMENTS AND RELATIVE CHANGES IN THE LEVEL OF THE HOLOCENE SOUTHERN BALTIC IN THE REGION OF THE ŁEBA BARRIER

The above results of analyses of lithostratigraphy, selected geochemical properties, mollusc fauna, and radiocarbon dating of the Łeba Barrier in the region of Rąbka allowed for identification of sedimentary series, malacological levels and erosion surfaces. On this basis it was possible not only to

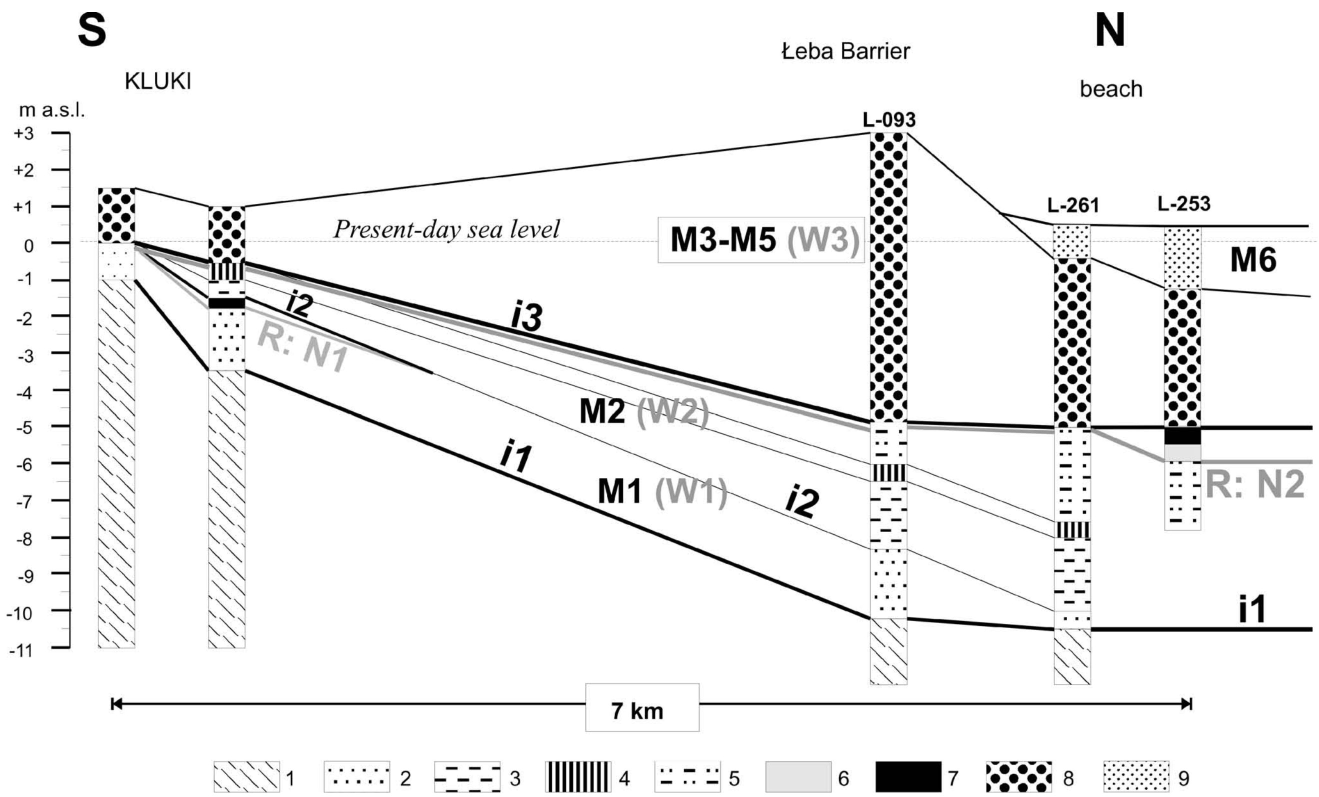

Fig. 11. Correlation of marine, lagoon and lacustrine deposits in the Kluki cross-section, the middle part of the Łeba Barrier and near Rąbka (after Rotnicki, 2001). Upper Pleni-Vistulian and Late Vistulian: *1* – glacio-fluvial and fluvial sands; Holocene: *2* – marine sands, *3* – lagoonalsilts and sandy silts, *4* – gyttjas, *5* – lagoonal sandy silts intebedded with marine sands, *6* – gyttjas and humus sands, *7* – peats, *8* – marine sands (Subboreal and Subatlantic), *9* – present-day marine sands; i1 – basal surface of of the Early Atlantic sea ingression; i2 – basal surface of the Mid-Atlantic sea ingression; i3 – basal surface of the Subboreal and Subatlantic ingressions; R:N1 – surface and extent of the Mid-Atlantic sea regression; R:N2 – surface of the Post-Atlantic sea regressions; W1, W2, W3 – sedimentary complexes recognised in the Kluki cross-section; M2–M6 – sedimentary complexes in the Rąbka cross-section.

determine the structure of the barrier but also to distinguish three periods: (1) appearance and persistence of a marine environment, (2) its transformation into lagoon and lake environment, and (3) relative changes in the level of the southern Baltic Sea in this area.

Five complexes of marine and lagoonal sediments (M2–M6) were distinguished near Rąbka, *i.e.* more than had been identified previously in the Kluki cross-section (Rotnicki 2001) situated some 8 km west of the Rąbka cross-section (Fig. 11). The oldest ingression (i1) and marine sedimentary complex (M1: 7800–7300 ^{14}C years BP), known from Kluki as W-1, has not been found at Rąbka. Most probably, the marine complex M1 has been eroded in Rąbka during the second marine ingression. There is a correspondence between the Kluki complex W-2 (Rotnicki 2001) and the Rąbka complex M2, and between W-3 and the three Rąbka complexes: M4–M6. The sedimentary complexes in Rąbka record stages characterised below (Fig. 12).

Deposits of the substratum

In the substratum of the Holocene marine littoral deposits there are varigrained fluvial sands from the end of the Late Vistulian. Their top lies between 8.40 m and 10.0 m b.s.l. What indicates their riverine origin is the presence of several levels of upward-fining sequences of sands, from medium and coarse to fine and very fine (Fig. 12). In profile L-002C, the fluvial sands are overlain by a 10-cm-thick layer of humic sands of the littoral facies of a freshwater lake that existed here in the Younger Dryas with an association of freshwater molluscs (Fig. 8). ^{14}C age of the dated shells was determined at 10,610±60 years BP (Poz-8595). No other traces of this water body were found, as most probably they were destroyed by the first (i1) and second (i2) ingressions of the Holocene Baltic. It was not a deep basin because at the level of the ordinates between which it was situated only thin layers of Early-Holocene peats were found in the vicinity. Their age was determined at 9,840±110 years BP (Gd-5067) in profile L001 and 9,700±110 years BP (Gd-4784) in profile D1a (Wojciechowski 1994a, 1995).

Sedimentary complex M2

Stage 1: sea ingression i2 (6,700–6,000 ^{14}C years BP) (Rotnicki, Pazdur 2003)

It is recorded in several profiles of the Rąbka cross-section as an erosion pavement taking the form of varigrained sands with admixture of gravel 0.2–3.0 cm in diameter (Fig. 12). The pavement is overlain by a layer of coarse, medium and fine sands containing sparse shells of *Cardium* sp. and their fragments. The total thickness of the erosion pavement and the sand layer ranges from 30 cm near the southern limit of the ingression to 180 cm under the today’s beach of the

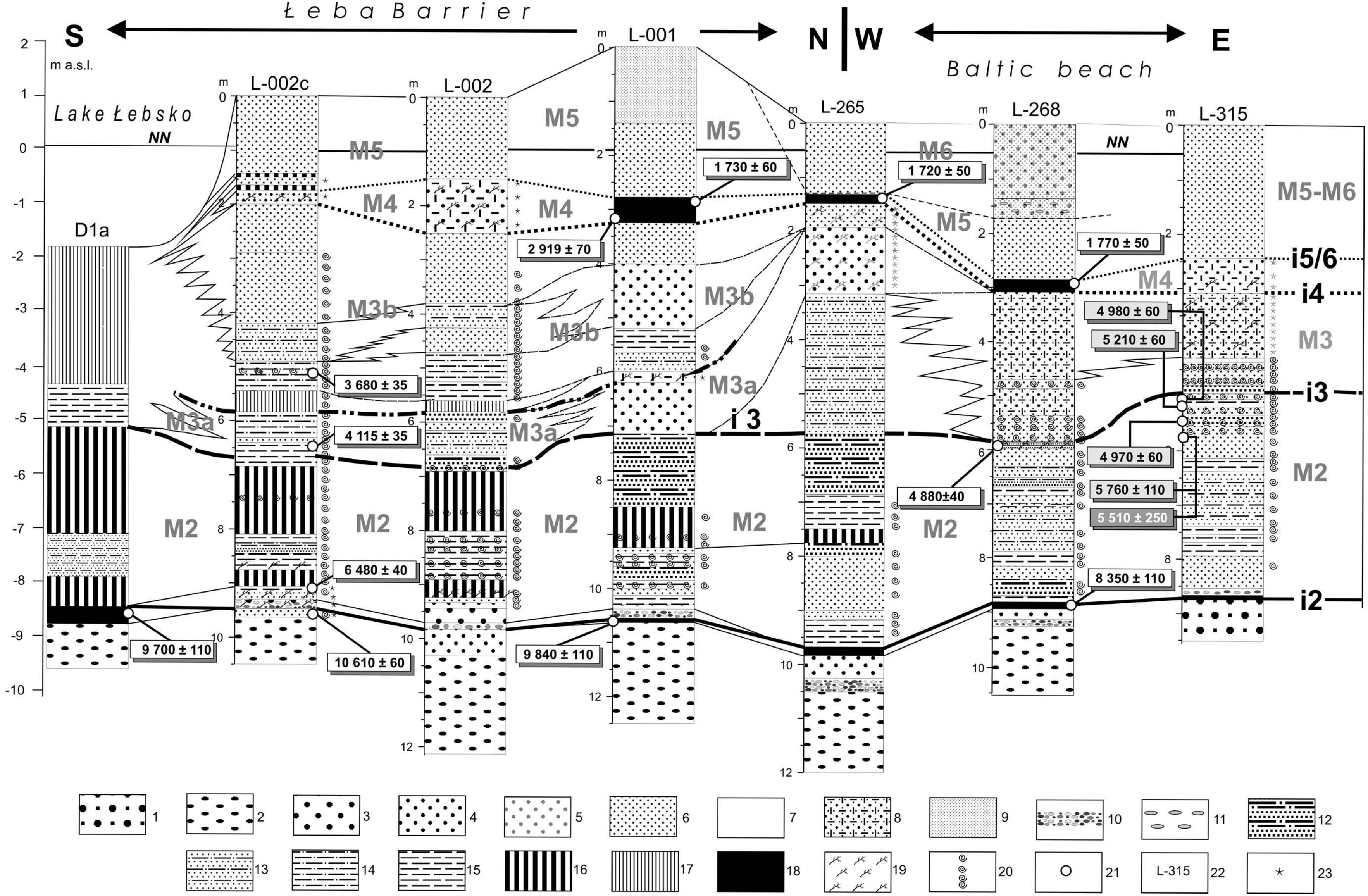

Fig. 12. Correlation of marine, lagoonal and lacustrine deposits near Rąbka, main sedimentary complexes: M1–M5 and main ingression surfaces: i2, i3 and i4. *1* – gravelly sands, *2* – varigrained sands, *3* – coarse sands, *4* – medium sands, *5* – fine and medium sands, *6* – fine sands, *7* – very fine sands, *8* – fine humic sands, *9* – eolian sands, *10* – lag deposit (pavement), *11* – beach pavement, *12* – sands intercalated with silts, *13* – fine silty sands, *14* – sandy silts, *15* – silts, *16* – lagoon gyttjas, *17* – lake gyttjas, *18* – peats, *19* – plant macro-remains, *20* – presence of mollusc fauna in profile, *21* – sampling sites for radiocarbon dating, *22* – bore-hole number, *23* – occurrence of humus.

barrier (L-265). It can be seen in the cross-section that the first ingression merely reached the southern coastal zone of the future barrier. In some places the sands and erosion pavement contain an admixture of humus and plant macro-remains coming probably from older orga- nogenic deposits destroyed by the ingression. In profile L-002C such layers contain associations of mollusc fauna of mixed composition embracing several species of freshwater snails as well as marine snails and bivalves (samples 38–39 in Fig. 8). It is probable that the freshwater fauna was redeposited at this site from the mentioned Late Glacial water body by the sea ingression. The appearance of the first marine species was determined in the Rąbka cross-section at 6,480±40 ^{14}C years BP (Poz-8593). It cannot be excluded, however, that the marine sediments of an earlier ingression, which is estimated to have taken place on the Gardno-Łeba Coastal Plain between the 7,800–7,300 ^{14}C years BP (i1; Rotnicki 2001, Rotnicki, Pazdur 2003), later underwent destruction at Rąbka (Figs 10 and 11).

On the seaward side of the barrier, in profile L-268 (Figs 9 and 10), M2 layers (samples 72–77) contain single fragments of shells of marine bivalves (*Cardium edule* and *Scrobicularia plana*). In the geochemical profile L-002, in the middle part of the bottom marine sands, remarkable increase of carbonates content occurs. It is probably caused by the presence of shells and their fragments. An elevated content of organic matter results from the presence of the mentioned plant macro-remains. Besides, above the pavement, there is a clear increase in the Mg/Ca ratio (Fig. 7). These facts are indicative of marine origin of the sands. There were first some local depressions, where shallow water bodies appeared in periodic contact with the sea. The oldest sediments formed there, were silts and silty sands of a lagoonal environment. Only then they were overlain by layers of light-grey marine sands (L-265 and L-268).

Stage 2a: lagoon (6,000–5,500^{14}C years BP), sea-level stabilisation

The sedimentary environments of this stage are diversified spatially (Fig. 12). In the northern, seaward part of the barrier, it is represented by 2–3 layers of brackish silts dark olive-grey in colour; definitely predominant in this part are light-grey sands and silty sands intercalated with thin stripes of olive-grey silts. In the profiles of those deposits with a total thickness of 2.10 m to 2.80 m, marine bivalves and snails occur practically continuously but usually in small numbers (association C, Fig. 9). Exceptions are the bottom layer of silts in profile L-268 containing a very abundant marine mollusc fauna (association B, Fig. 9) and the layer of sands, silts and sandy silts at a depth of 6.75–6.55 m (samples 54–56).

In the southern, lagoon-ward, part of the barrier the number of layers of light-grey fine sands with stripes of olive-grey silts is very small. Instead, there appear dark olive-grey silts in greater amounts as well as three layers of beige gyttjas with variable carbonate content. The total thickness of the gyttja layers increases southwards. Such spatial differences indicate that: (1) at the time of formation of the sedimentary complex M2, the barrier was situated north of the cross-section discussed, (2) the deposits building the northern part of the sedimentary complex M2, which were closer to the barrier of that time, are more sandy because overflows of marine waters during storm surges, deposited overwash fans there, and (3) during some periods the lagoon was more open to the sea, during others more isolated from it, depending on the degree of compactness of the barrier. This is indicated by variations in the Mg/Ca ratio (Fig. 7), which is especially low during the sedimentation of gyttjas and grows at the times of sedimentation of lagoon silts and sands. However, this lagoon had never turned into a freshwater body, even for the short time of deposition of the sedimentary complex M2, as indicated by the continuous presence of the marine mollusc fauna in it (Figs 8, 9). It is also understandable that this fauna could find better living conditions in the more quiet, southern part of the lagoon than in its near-barrier part, more exposed to inflows of water and sand masses. That is why the frequency of the mollusc fauna in the 'lagoon-ward' profile L-002C (Fig. 8) is several times higher than in the 'seaward' profile L-268 (Fig. 9). The occurrence of *Scrobicularia plana* in the succession stage C (Figs 8, 9) is indicative of elevated salinity (10–12‰) of the lagoon waters and of its still broad contact with the sea during the first stage of formation of the complex M2.

Stage 2b: considerable shallowing of the lagoon and regression of the sea (5,500–ca. 4,800 ^{14}C years BP)

The age at which the sea dropped to its lowest level is not well known; in earlier studies it used to be determined at about 5,000 ^{14}C years BP (Rotnicki 1999, 2001, Rotnicki, Pazdur 2003), but in the light of the new radiocarbon dates obtained for the cross-section discussed, it should rather be shifted to 4,900– 4,500 radiocarbon years BP. In the southern part of the lagoon, this stage is very indistinct due to the fact that lagoon sedimentation did not cease at that time. This stage is perhaps reflected by the middle gyttja layer in today's Lake Łebsko (profile D1A, Wojciechowski 1995) and the upper gyttja of the sedimentary complex M2 in the southern part the barrier (in profiles L-002C and L-002) and farther north by the top of sand-intercalated silts lying on the gyttja (L-001 and L-265). In the succession stage D (Fig. 8) there is a clear decline in the abundance of the mollusc fauna, which may reflect lowering sea-level and hence growing isolation and shallowing of the lagoon.

In turn, in the northern part of the barrier, in the zone of the today's beach, the period of the marine regression is recorded in a layer of fine, humic, olive-grey sand with thin peat intercalations, situated between the ordinates of –5.45 and –5.35 m measured with reference to the present-day sea-level (profile L-268). This layers also occurs in profiles L-315 and L-314 (the latter not included in the cross-section) where it is built of fine and very fine sand dark-grey in colour rich in humus and small plant macro-remains. The layer may be a remnant of a small coastal marshy plain which existed for a short time at this ordinate. Some of the discussed area might have protruded slightly above the lowered sea-level at its quiet and low stages. In this layer in profile L-268, beside small numbers of the marine mollusc fauna, a freshwater fauna appears with a considerable share of the rheophilous species *Theodoxus fluviatilis* (samples 44 and 45 in Fig. 9), indicating that the fauna was deposited at a mouth of river or brook, but in a direct vicinity of the sea shore. The paleomorphological situation of this layer and the underlying deposits rule out the presence of river or brook in this place. It could only have been a small, short creek running on one of the islets which elevated from the shallow water and formed the outline of the future barrier, and flowing south to the Łeba Lagoon. The age of shells from the upper sample of this layer (no. 44; Figs 9, 10) was determined at 4,880±40 BP (Poz-8621) ^{14}C years BP. In profiles L-315 and L-314 the layer occurs between two groups of shell banks. The age of the lower banks is in the interval of 5,760±110 ^{14}C years BP (Gd-15077) to 4,970±80 ^{14}C years BP (Gd-12205). Hence the age of this layer can be assumed a bit younger than 5,000 BP, probably between 5,000 and 4,800 radiocarbon years BP.

As shown by the earlier studies carried out between Cape Czołpino and Rowy, the peats formed during this phase of sea-level lowering lie at an ordinate of about –4 m (Rotnicki 1999, 2001, Rotnicki, Pazdur 2003). In the light of new results that take into account the compaction of lagoon silts, lacustrine gyttjas and peats, the lowering was 1 to 2 m less (Rotnicki 2008).

Sedimentary complex M3

Stage 3: ingression (i3); shift of the barrier to the present-day position and transformation of the lagoon into a freshwater lake (4,800–3,000 ^{14}C years BP)

The record of this ingression is contained in the sedimentary complex M3. It shows clear spatial differences in the north-south cross- section. In the seaward part of the barrier (L-268, L-315) the ingression is recorded in the form of sandy layers 2.5 m thick (L-315); to the south the thickness increases to 4 m in the middle part of the barrier (L-001; Fig. 12) to reach 5.5 m in its southern part (L-002, L-002C, Fig. 12). This sedimentary complex represents the barrier shifting to the position it occupies today and demonstrates that the barrier bordered first a lagoon, and then a freshwater lake. The barrier‘s movement to the present-day area is evidenced by numerous shell banks belonging to the succession stage E and situated in the bottom of complex M3 in profiles L-268 and L-315 (Figs 9, 10, 11). They were formed in the eulittoral zone; periodically they might have been in a supralittoral situation in areas featuring overwash fans on the southern side of the lagoon’s barrier. While the southern shoreline of the barrier moved southwards, passing through the northern zone of today’s Łeba Barrier and leaving there the above-mentioned sands with shell banks, there was a lagoon south of it. In the southern, lagoon-ward part of the barrier, in the bottom of the sedimentary complex M-2, there are brackish dark olive-grey silts and sandy silts passing upwards into fine, light-grey sands with intercalations of olive-grey silts and in the top part of the complex into fine, light-grey sands. This sequence of deposits shows that the south-moving barrier sedimentation had reached the southern edge of the barrier in its present-day location.

Changes in the mollusc fauna in the lagoonward part of the sedimentary complex, provide a basis for distinguishing two sub-complexes (Figs 2, 8, 10). The lower, lagoon one (M3a) starts in the lagoon silts resting on a thick gyttja layer of complex M2, together with the malacological succession stage E, at a depth of 6.55 m (the ordinate of –5.65 m; sample 21). It marks the start of development of a freshwater-lake mollusc fauna dated at 4,115±35 ^{14}C years BP (Poz-8592). Single specimens of freshwater molluscs appear already 10 cm lower. Stage E passed into F with a stepwise increase in numbers of the freshwater fauna, which took place around 3,680±35 ^{14}C years BP (Poz-8591). The deposition of the sedimentary complex M3a ended somewhat earlier, namely when the marine mollusc fauna disappeared from the lagoon. This occurred probably about 3,900 radiocarbon years BP. Between 3,900–3,000 years BP there developed the upper sub-complex M3b embracing the stage when the southern part of the today’s barrier still remained under water level (stage F). The end of this stage is marked by a growing sand content of the lacustrine littoral sediments. The deposition of the sedimentary sub-complex M3b ends with the appearance of subaerial parts of the barrier, indicating sea regression. It was probably the time when the first dunes began to form on the bare sandy surfaces, while peatbogs developed in inter-dune depressions.

Sedimentary complex M4

Stage 4: regression (3,000–1,700 ^{14}C years BP).

During the regression of the sea and the lowering of sea level, formation of peat started in shallow depressions of the already terrestrial surface of the barrier while soils developed on higher- lying land; what remained of them are humic sands. Basing on ^{14}C dates of peat, the period of sea-level lowering can determined to 3,000–1,700 radiocarbon years BP (Fig. 12). Dune fields kept developing throughout the whole stage 4.

Sedimentary complexes M5 and M6

Stage 5: ingression (i4); terrestrial-lacustrine (younger than 1,700 ^{14}C years BP) and present-day beach formation).

t is represented by layers of fine and medium sands with a thickness of 1.3 m to 2.9 m. It is associated with the tendency of sea-level to rise to its present-day ordinate. There were also periodic rises of the level of Lake Łebsko, as evidenced by two laminae of gyttja intercalating sands of this sedimentary complex in the southern part of the barrier. Considering the fact that west of Rąbka, within the field of moving dunes, old fossil soils occur on top of older dunes (now also fossil), dated at 2,900–3,000 14C years BP (Tobolski 1975, To- bolski 2001), it must be stated that the Łeba Barrier took quite a long time (the last 4,000–4,500 radiocarbon years) to develop its present form. Initially it was a chain of islands and islets on which the wind already formed the first generations of dunes, while the younger parts of the barrier developed as overwash fans at a later time, e.g. as the sedimentary complex M5.

Finally, it is worth noting that the complexes M3–M5 correspond to the sedimentary complex W3 in the Kluki cross-section in the middle part of the Łeba Barrier (Rotnicki 2001). In both cases the series are younger than the Middle-Holocene regression of the southern Baltic on the middle coast caused by a marked relative lowering of sea-level (Rotnicki 1999, 2001, Rotnicki and Pazdur 2003).

The youngest sedimentary complex (M-6) is represented by present-day beach sands reaching the thickness of 0.5–3.5 m

SUMMING UP

The lithofacies, sediment-texture, paleomorphological and malacological analyses as well as radiocarbon dating of the sediments forming the Łeba Barrier made it possible to establish the following facts:

1. Traces of the oldest, very shallow freshwater body of Younger Dryas age can be found under the southern part of the barrier. Its presence is documented in humic sands by shells of freshwater bivalves and snails.

2. There are five sedimentary complexes (M2–M6) in the structure of the barrier. The first one (M2) developed between 6,700 and 4,500 ^{14}C years BP. There are erosion pavements and marine sands in their bottom, while their main body consists of the lagoon deposits of the M2 complex: in the southern part these are gyttjas, silts and sandy silts with the marine mollusc fauna, while in the northern part the complex is built primarily of silty sands intercalated with marine sands, also with the marine mollusc fauna. The barrier was then still situated north of today's sea coast. A characteristic feature of this succession stage of the mollusc fauna is the presence of *Scrobicularia piperata* indicating salinity higher than the present level (10–12‰). The final stage of the M2 complex formation is the period of a marked sea-level lowering registered in a sand-peat layer (L-268) with the freshwater mollusc fauna dated at 4,880±40 ^{14}C years BP. The layer shows that at that time there appeared small land surfaces in the zone of shallows and islets outlining the future shape of a solid barrier. Between 4,500 and 3,000 ^{14}C years BP the barrier shifted to its present location (sedimentary complex M3). The first dune fields started to develop. At the same time this is the stage of transformation of the lagoon into a freshwater lake, which took place between 4,200 and 3,900 years BP. At its start the freshwater mollusc fauna appeared in the lake, and by its end (3,900 years BP) the marine fauna had disappeared. Another lowering of sea-level took place between 3,000 and 1,700 ^{14}C years BP. At that time soil developed on the barrier and peatbogs appeared in lower-lying places. During the last ingression, younger than 1,700 years BP, the barrier remained in its present-day position and accreted more sediment. The youngest sedimentary complex (M-6) builds up the present-day beach.

3. Analysis of the grain-size distribution of sediments building the mentioned sedimentary complexes and their spatial situation prove that the Łeba Barrier belongs to the type of transgression barriers (Roy *et al.* 1997). It is only in the final stage of formation that it was a stationary barrier.

4. The complicated sedimentary system in the study area is the result of several relative sea-level changes amplitudes of which, however, could not be studied in the two-dimensional space of a single geological cross-section.

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