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Late Glacial and Holocene environmental changes in the Southern Baltic Sea area based on malacofauna investigations

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Abstract. Climate fluctuations and related crucial environmental changes in the Late Glacial and Holocene in the Southern Baltic Sea area can be reconstructed by mollusc analyses. Lacustrine sediments host an association of molluscs and other fossils, including freshwater species such as: *Armiger crista f. cristatus, Gyraulus laevis, Lymnaea peregra, Pisidium casertanum, Pisidium casertanum f. ponderosa, Pisidium milium, Pisidium nitidum, Pisidium obtusale f. lapponicum, Valvata cristata and Pisidium conventus*, which indicate cold climate. Deposition in freshwater reservoirs continued during the Early Holocene. At that time, species characteristic of cold freshwater environments were accompanied by freshwater mollusc species that require higher temperatures: *Bithynia tentaculata, Physa fontinalis and Pisidium amnicum*. This suggests climate warming in the Preboreal period.

These lacustrine sediments were partly destroyed and covered by marine sands during the Middle and Late Holocene. Good indicators of changing environmental conditions from freshwater to marine are the following marine species found in the sediments: *Hydrobia ulvae, Hydrobia ventrosa, Cerastoderma glaucum, Mytilus edulis* and *Macoma balthica*.

Key words: Late Glacial, Holocene, Southern Baltic Sea, malacofauna.

Abstrakt. Zmiany klimatyczne, a za tym daleko idące zmiany środowiska w późnym glacjale i holocenie na obszarze południowego Bałtyku mogą być wyjaśniane także przez badania fauny mięczaków. Na obszarze południowego Bałtyku w okresie późnego glacjału występowały gatunki słodkowodne wskazujące na klimat zimny, takie jak: *Armiger crista f. cristatus, Gyraulus laevis, Lymnaea peregra, Pisidium casertanum, Pisidium casertanum f. ponderosa, Pisidium milium, Pisidium nitidum, Pisidium obtusale f. lapponicum, Valvata cristata, Pisidium conventus*. Akumulacja jeziorna w słodkowodnych zbiornikach strefy przybrzeżnej kontynuowała się w okresie wczesnego holocenu. W tym czasie oprócz gatunków słodkowodnych, zimnolubnych pojawiły się gatunki mięczaków i małżoraczków słodkowodnych, o wyższych wymogach termicznych (*Bithynia tentaculata*, *Physa fontinalis*, *Pisidium amnicum*). Świadczy to o ociepleniu się klimatu w okresie preborealnym.

Zarastanie przybrzeżnych zbiorników rozpoczęło się w okresie borealnym i trwało również w okresie atlantyckim. W tym czasie miały miejsce wlewy wód morskich do zbiorników. Wskaźnikiem tego jest liczne występowanie morskich gatunków takich jak: *Hydrobia ulvae, Hydrobia ventrosa, Cerastoderma glaucum, Mytilus edulis, Macoma balthica*. W osadach piaszczystych w okresie subborealnym i subatlantyckim zdecydowanie przeważała fauna morska.

Słowa kluczowe: późny glaciał, holocen, południowy Bałtyk, malakofauna.

INTRODUCTION

The monograph provides the state-of-the-art of knowledge on molluscs from Quaternary deposits of the Southern Baltic Sea. Mollusc successions have allowed characterizing individual stages of evolution of the Southern Baltic area during the Late Glacial and Holocene. Major phases of climatically controlled environmental changes have been identified.

Late Pleistocene and Holocene mollusc associations include characteristic species that can serve as indicators enabling correlation to the existing research results on palaeogeography and palaeoenvironmental changes in this area. However, it is important to consider the entire faunal assemblage that fully allows concluding about climatic and hydrological conditions. Each environmental change is reflected in the variation of frequency of occurrence of individual mollusc species forming specific associations. Therefore, analysis of changes in the mollusc species composition during the Late Glacial and Holocene was the main research task.

Since temporal changes in the natural environment are manifested by variations in the quantitative and qualitative composition of faunas along the vertical section. The study results have allowed reconstructing environmental changes, especially determining climatic and trophic conditions existing at the end of the glacial period in the Southern Baltic area, and the conditions that accompanied the environmental change from the freshwater to marine regime in the Middle and Late Holocene.

Taking into account the specific ecological relationships between the individual species, errorless identification of remains of these animals, i.e. their carbonate shells, to the rank of species has appeared to be the basic condition for using *Mollusca* for reconstructions of ancient environments. The degree of preservation of shells is variable depending on the sediment type (sand, mud, gyttja, lake marl). Unfortunately, Polish literature provides no modern and up-to-date studies of subfossil molluscs from sites linked with the Late Quaternary history of the Polish sector of the Baltic Sea.

Nowadays, there are only three monographs that support identification of mollusc shells preserved in Quaternary deposits of Poland: a) key to identification of contemporary freshwater species (Piechocki, 1979; Piechocki, Dyduch-Falniowska, 1993), b) chapter on *Mollusca* in the Atlas of Quaternary Fossils (Skompski, Makowska, 1989), c) Quaternary fauna of Poland (Skompski, 1991), and an overview study of Quaternary geological stands – Standard assemblages of malacofauna in different Quaternary stratigraphic units (Skompski, 1996).

All of these studies apply primarily to species occurring at geological stands that represent modern or Quaternary environments of inland waters, while the area of the Polish sector of the Baltic Sea has been so far treated very briefly.

As regards malacological sites studied before the 1990s, the Southern Baltic Sea was a blank area. For purposes of establishing stratigraphic schemes, an important role was played by palynological and diatom investigations (Zaborowska, Zachowicz, 1982; Bogaczewicz-Adamczak, 1982; Zaborowska, 1985; Bogaczewicz-Adamczak, Miotk, 1985; Witkowski, Witak, 1993; Witkowski, 1994; Miotk-Szpiganowicz, 1997; Latałowa, Badura 1998; Bogaczewicz-Adamczak *et al.*, 1999; Uścinowicz, Miotk-Szpiganowicz, 2003; Witak, 2000, 2002, 2006, 2013).

The early studies of subfossil (both freshwater and marine) molluscs are known from the late 20[th] century and were carried out on a cliff located between Ustka and the Potok Orzechowski Stream (Brodniewicz, 1979) and on a cliff situated near Niechorze (Kopczyńska-Lamparska *et al.*, 1984). Holocene fauna is known from the Gardno-Łeba Lowland (Brodniewicz, Rosa, 1967). In subsequent years, geological and malacological investigations were carried out in the Gardno-Łeba Lowland by Wojciechowski (1995, 1998, 2008, 2013).

Littorina and Post-Littorina malacofauna is also known from the Gulf of Gdańsk (Janiszewska-Pactwa, 1976), Vistula Lagoon and Vistula Spit (Dmoch *et al.*, 1975; Tomczak *et al.*, 1989), and from the Czołpin area near Łeba (Brodniewicz, Rosa, 1967).

In the late 1980s, Krzymińska initiated malacological studies in offshore areas (1986, 1990; Krzymińska, Wołowicz, 1991; Krzymińska, 1993, 1995; Krzymińska, Wołowicz, 1996; Krzymińska, 2001; Krzymińska, Przezdziecki, 2001; Krzymińska *et al.*, 2004). These studies have been continued along the Southern Baltic Sea coast until today (Krzymińska *et al.*, 2003; Krzymińska, Dobracki, 2004; Krzymińska *et al.*, 2011; Krzymińska, Cedro, 2011, 2012; Sydor *et al.*, 2015; Krzymińska *et al.*, 2016).

GEOLOGICAL STRUCTURE OF THE BALTIC SEA BOTTOM IN THE QUATERNARY

The Quaternary sedimentary cover of the Southern Baltic area is represented by Pleistocene glacial and glaciofluvial and Holocene marine deposits. In regions of sub-Quaternary sedimentary rocks and smooth relief, the post-glacial sedimentary cover and its stratigraphic units are unvarying over large areas (Uścinowicz *et al.*, 2011). Thickness of the Quaternary deposits is highly variable: the lowest thickness is observed in the margins of the present-day deep-water basins, where glacial erosion (exaration) processes dominated during Pleistocene times. In the southern part of the Baltic Sea, such areas are represented by, e.g., the bottom of the Słupsk Channel and the southern outskirts of the Gotland Basin (Pikies, 2005). Greater thicknesses of Quaternary deposits (mainly of the Pleistocene) are found locally within deep incisions in the sub-Quaternary basement, which show features of subglacial channels. Higher thicknesses of the Pleistocene are also locally observed on the southern slope of the Southern Middle Bank. This results from more intense deposition of glacial material on the distal side of a mega-obstacle on the way of invading ice sheet, which was initiated on Gotland Island and terminated in the Southern Middle Bank area (Pikies, 2005). Generally, the Pleistocene glacial deposits of extensive Baltic Sea areas, in both deep-water basins (excluding the fills of subglacial channels) and their outskirts, are represented by a single till bed of the last glaciation. The most complex geological structure of the Pleistocene succession is observed in the shallow-water southern region of the Baltic Sea, where older tills and glaciofluvial, ice-dammed lake and interstadial deposits have been locally encountered (Uścinowicz *et al.*, 2011). In the southern part of the Baltic Sea, glacial and glaciofluvial deposits were eroded during the Early and Middle Holocene. Thicker packages of glacial and glaciofluvial deposits, assigned to the undivided Pleistocene, have been preserved predominantly in deep subglacial channels.

Post-glacial clay-mud deposits found at the bottom of deep-water sedimentary basins are represented by three major lithostratigraphic units: Baltic brown clays of limnoglacial origin (Baltic Ice Lake), limnoglacial and limnic Baltic grey clays (Yoldia Sea and Ancylus Lake), and marine Baltic olive-grey muds (Littorina Sea and Post-Littorina Sea; Harff *et al.*, 2001).

The Baltic brown clays consist of three lower-order units: varved clay-mud deposits passing upward into microlaminated (cryptolaminated) clays and then into homogeneous clays (Uścinowicz *et al.*, 2011). In the Southern Baltic Sea, deposition of the Baltic brown clays commenced in the Bølling period, and occurred close to the melting ice sheet. As the deglaciation continued, further from the ice sheet front, deposition of microlaminated clays was followed by sedimentation of homogeneous clays. These deposits accumulated at different stages of the Baltic Ice Lake evolution.

The Baltic grey clays overlie concordantly the brown clays. There is sedimentary continuity between them and therefore the lower boundary is poorly marked. The distinctive feature of these deposits is the lack or very small content of calcium carbonate and the presence of black laminae or point accumulations of iron sulphides. The colour of these clays varies from grey-brown at the base to light grey with a bluish hue at the top. The deposition age of the Baltic grey clay layer was palynologically determined as the Preboreal – early Boreal. They represent the Yoldia Sea and Ancylus Lake phase.

In the Middle and Late Holocene, the Baltic olive-grey muds were deposited in deep-water sedimentary basins. They overlie discordantly the deposits of the Baltic Ice Lake, Yoldia Sea and Ancylus Lake.

The Baltic olive-grey muds compose two lower-order lithological units: laminated grey-olive muds, and dark grey homogeneous muddy-clay deposits. Both are enriched in organic matter whose content can reach a level of 10–15% (Uścinowicz *et al.*, 2011). Palynological and radiocarbon studies indicate that the lower layer was deposited in the late Boreal and early Atlantic periods. Deposition of the upper layer started at the end of the early Atlantic period and has continued until the present (Uścinowicz *et al.*, 2011).

Deposits forming the Baltic olive-grey mud layer were accumulated during marine phases of the Baltic Sea, namely in the Mastogloia Sea (transition phase from a freshwater to marine basin), in the Littorina Sea and in the Post-Littorina Sea. In the shallow-water part of the Southern Baltic Sea, sandy sediments were accumulated during the Baltic Ice Lake period and during the Yoldia Sea and Ancylus Lake phases. Deposits of terrestrial environments, (represented by peats, bog-lacustrine gyttjas and muds), and fluvial-deltaic sands, are preserved locally on the sea bottom.

Sand and gravel facies, coeval with the Baltic muds of the Littorina Sea and Post-Littorina Sea, occur on slopes of sedimentary basins in the shallow-water area. Over most of the area, the thickness of the deposits is commonly below 2 m. However, the thickness of marine sands locally exceeds 3 m, being the greatest within the spit structures that developed during the transgression of the Littorina Sea (Uścinowicz *et al.*, 2011).

ENVIRONMENTAL CHARACTERISTICS OF THE BALTIC SEA

The Baltic Sea is a shallow, semi-enclosed intracontinental sea, practically endorheic, which has shallow and narrow connections with the Atlantic Ocean through the Danish Straits. In accordance with the subdivision proposed by the Helsinki Commission the following regions are distinguished within the Baltic Sea with respect to hydrogeological conditions and sea-floor and coastal relief: Bothnian Bay, Bothnian Sea, Archipelago Sea, Gulf of Finland, Gulf of Riga, Baltic Proper, Western Baltic and Belt Sea, Sound and Kattegat (Fig. 1).

For the purpose of our considerations, the subdivision of the Baltic Proper is important. In the northern part it encompasses the North Central Basin, the Western Gotland Basin and the Eastern Gotland Basin. The southern part consists of the following units: Arkona Basin, Bornholm Basin and Gdańsk Basin.

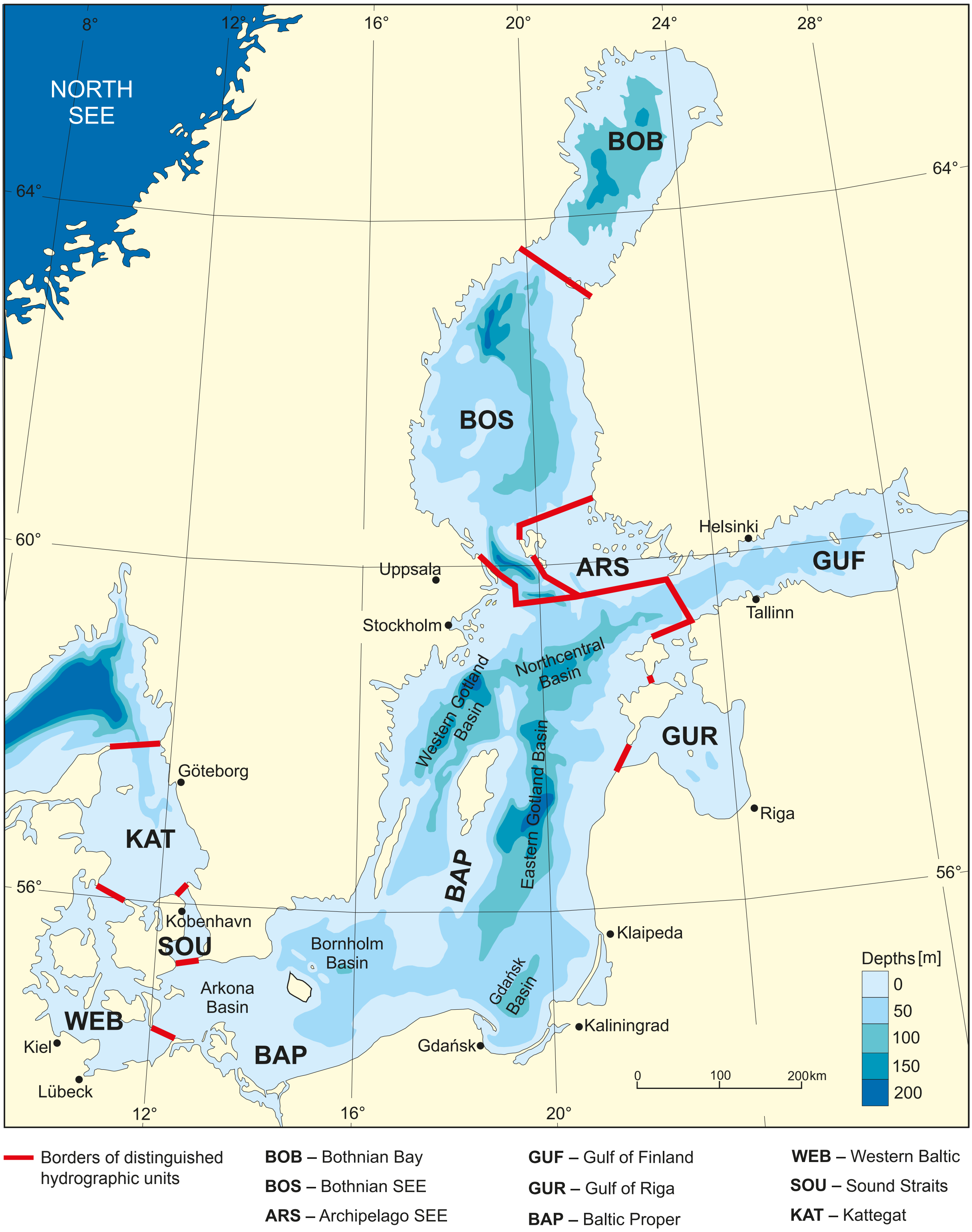


Fig. 1. Division of the Baltic Sea area into hydrographic units and main accumulative basins

The Polish Economic Exclusive Zone (EEZ) of the Baltic Sea consists of the southern part of the Bornholm Basin, southern end of the Gotland Basin, western part of the Gdańsk Basin, and the longitudinally oriented Słupsk Furrow, connecting the Bornholm, Gdańsk and Eastern Gotland basins (Fig. 1).

The sea depth in the Bornholm Basin reaches 95 m, in the Słupsk Channel – 90 m, in the southern part of the Gotland Basin – 120 m, and in the Gdańsk Basin – 107 m. Deeper areas (basins) of the Baltic Proper are separated by gentle sea-floor elevations. However, farther to the south, between the coast and slopes of deep-water basins (up to

40 m depth), there are sea bottom rises called banks, among which the most important are: the Odra Bank (6 m b.s.l.), the Słupsk Bank (8 m b.s.l.) and the Stilo Bank (20 m b.s.l.). Besides, to the north of the Słupsk Furrow, the southern part of the Southern Middle Bank is situated within Polish EEZ, where the smallest depths do not exceed 15 m b.s.l. (Fig. 1).

The Baltic Sea is an intracontinental basin with a limited connection with the ocean, and therefore is characterized by a two-layer salinity stratification of the water column. Thus, there are the isohaline upper layer that is less saline and of constant salinity, and the lower layer with more saline water. These two layers are separated by the so-called halocline characterized by a high salinity gradient. This vertical stratification is highly varied spatially. It is controlled by the influx of river waters into the marine basin, and by the near-bottom influx of oceanic waters, and is modified by temporal, seasonal and climatic variations due to atmospheric and hydrological factors. In the Kattegat, the halocline occurs at a depth of merely 20 m, in the Arkona Basin at 30–40 m, in the Bornholm Basin at about 55–65 m, and in the East Gotland Basin at 70–90 m (Cyberski, 2011). In the Gulf of Bothnia, it is much less pronounced.

The depth, at which the halocline forms, and the vertical salinity profile are not constant at all. The salinity of surface waters along a longitudinal profile of the Baltic Sea generally decreases northward as moving from the Kattegat toward the eastern end of the Gulf of Finland and in the Gulf of Bothnia. High values are recorded in the Kattegat, ranging from 18 to 28 psu (Practical Salinity Unit). In the Danish Straits the values are 10–22 psu, in the Baltic Proper – 6–10 psu, and in the eastern part of the Gulf of Finland and in the Gulf of Bothnia – around 4 psu (Cyberska, 1994). However, in the southern part of the Baltic Proper, the waters are characterized by a relatively constant salinity level.

For example, the average salinity of the surface layer in the Bornholm Basin is in the range of 7.5–8.0 psu, while in the Gdańsk Basin it is approximately 7 psu. Waters of shallow-marine areas in the southern part of the Baltic Proper has salinity similar to that of surface waters of deep-water areas (sea depths, basins). Only locally, near river mouths, considerable salinity variations are observed, ranging from 2 to 7 psu. The range of river water penetration into the sea depends on the amount of river runoff and current atmospheric conditions (winds, air pressure).

At greater depths, below the halocline, the salinity is sometimes by 30–100% higher than at the surface (Cyberski, 2011). Depending on the distance of the given area of the Southern Baltic Sea from the straits, the salinity of this layer varies between 12 and 17 psu. In the Bornholm Basin, the value is about 15 psu. The salinity and water oxygenation levels in sea depths of the Southern Baltic Sea depend on the abundance and frequency of saline water intrusions from the North Sea. Influx of saltier, well-oxygenated waters reaches the Baltic depths and affects the oxygen conditions in these zones, which can contribute to temporal reduction of hydrogen sulphide in the deep sea zones (Cyberski, 2011). Due to the events of massive intrusions and impediment for their migration over sea-floor ridges that separate individual basins they rarely reach far-away sea depths in the eastern and northern parts of the Baltic Proper. This results in seasonal (Bornholm Basin) and even long-term (Gdańsk Basin, East and West Gotland basins, etc.) hypoxia conditions in deep waters.

Water temperature fluctuations in the shallow-water zone show seasonal variations throughout the year from *ca*. 0ºC to over 22ºC, with a minimum in February and a maximum usually in August. The range of these fluctuations decreases with depth. While moving from the surface layer into the deeper one the range of fluctuations rapidly decreases and their seasonality vanishes (Cyberska, 1994). In the bottom layer of areas with the sea depth below 60 m the water temperature varies within a small range from 3 to 4ºC. In shallow-water zones, temperature variations are much greater and commonly reach the sea-floor. The main reason for these fluctuations is wind action and the occurrence of autumn convection processes, which result in the mixing of waters and temperature equalization in the water column, down to a depth of 60–70 m.

SCOPE AND METHODS OF STUDY

The scope of the study included collecting, analyzing and selecting archival materials, among others, (Pleistocene and Holocene) drill cores of Quaternary deposits, acquired from the sea bottom of the Polish part of the Baltic Sea and its coastal zone using vibratory samplers, in which mollusc specimens (gastropods and bivalves) were found. The drill core and data acquisition was carried out within the framework of various research projects performed in the Southern Baltic area by the Marine Geology Branch of PGI-NRI in the period of 1985–1997. The material was also extended based on new data derived from drill cores acquired in the period of 2000–2013. Seismo-acoustic profiles and radiocarbon dates from the study area, archived at the Marine Geology Branch of PGI-NRI, were also analyzed.

The drill core acquisition sites (167 drill cores in total – Fig. 2) were located primarily in the south-eastern part of the Pomeranian Bay (51 drill cores), Gulf of Gdańsk (64 drill cores), Vistula Lagoon (13 drill cores), Vistula Spit (11 drill cores), and along the remaining part of the Polish coastal zone (28 drill cores). Of the total number of 167 drill cores, research results have been published for 96 profiles; for the remaining 71 profiles, no published results of malacological investigations are available so far.

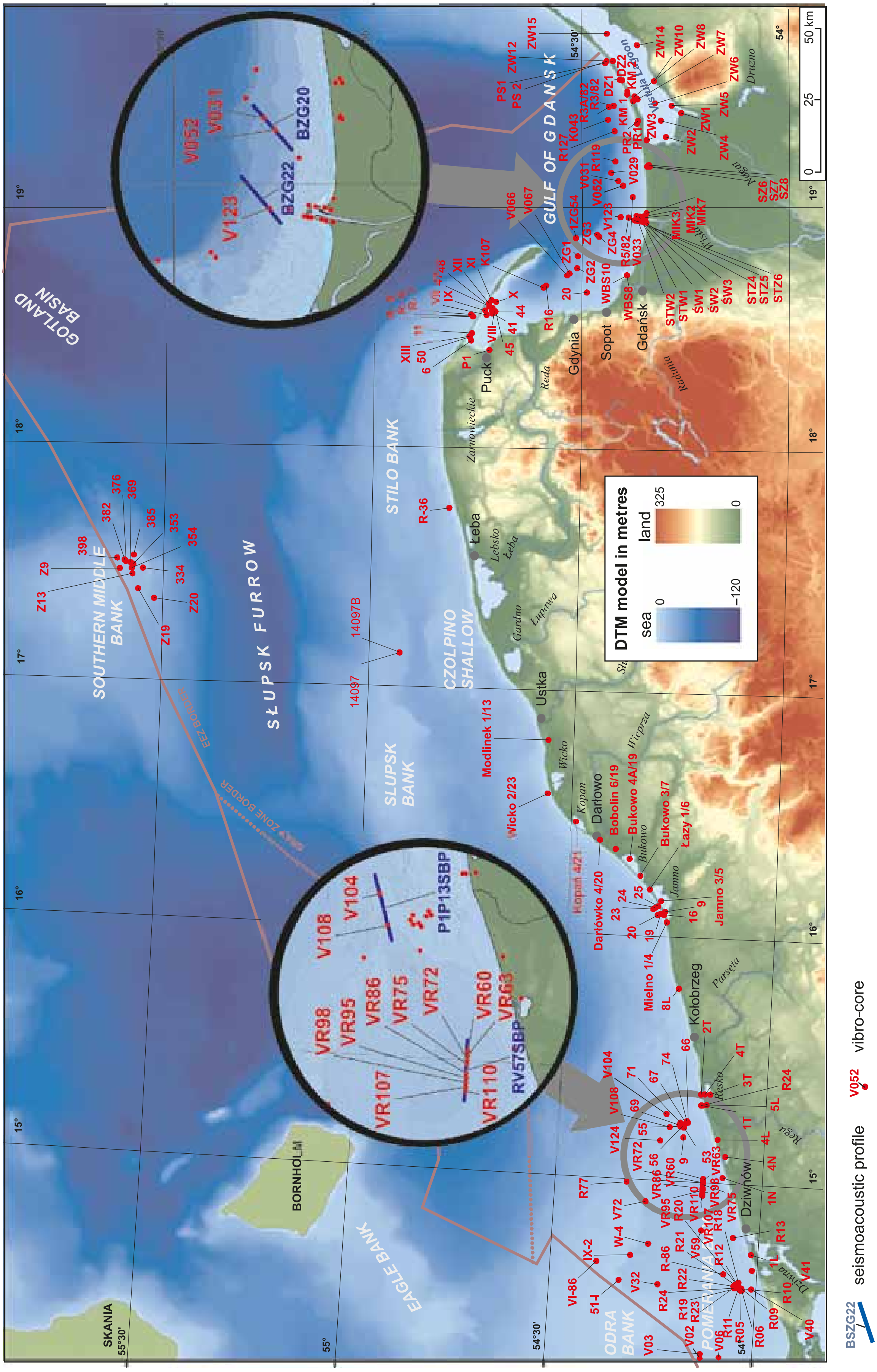


Fig. 2. Location of sampling sites – vibro-core type, areas within circles show places with reference sites, where geological structure is recognized by seismoacoustic method

The monograph depicts 64 mollusc taxa (42 freshwater and 22 marine taxa) out of *ca*. 125,000 species currently occurring in Poland, based on author's own unpublished data (basic material) and verified data coming from the literature.

For the malacological analysis, sediment samples of some strata were preliminarily macerated using a solution of hydrogen peroxide (H_2O_2), and washed on a 0.1-mm sieve. Then, the mollusc shells were selected according to standard methods. After determination of mollusc shells to the species rank, according to available keys and guides (Piechocki, 1979; Jagnow, Gosselck, 1987; Piechocki, Dyduch-Falniowska, 1993; Glöer, Meier-Brook, 1994) as well as based on both own observations and gathered collections (unpubl.), the best-preserved shells with distinct diagnostic features were thoroughly described and illustrated based on a set of scanning electron microscope (SEM) photographs (the work carried out at the Roman Kozłowski Institute of Palaeobiology PAS in Warsaw).

LATE GLACIAL AND EARLY HOLOCENE FAUNA

In the Southern Baltic area, conditions favouring development of abundant associations of gastropods and bivalves existed in the interglacials and interstadials. The present stratigraphical and palaeogeographical interpretation is based on the identified molluscan associations. Age determinations of the deposits have enabled placing the freshwater molluscan associations within the Late Glacial and Early Holocene. The Late Glacial and Early Holocene depositional sequences with faunal evidence were represented by lacustrine-bog deposits (peats and muds), and deltaic and lagoonal sands, which currently occur on the sea-floor in different regions of the Southern Baltic Sea.

In the Pomeranian Bay and it's nearest vicinity, the bog-lacustrine deposits of the W4, R74, R86, 82/VI, 89/VI, S63 and IX-2 profiles, contain an association represented by freshwater gastropods: *Armiger crista f. cristaus* Draparnaud, *Bithynia tentaculata* (Linnaeus), *Gyraulus laevis* (Alder), *Lymnaea peregra* (Müller), *Valvata pulchella Studer* and *Valvata piscinalis* (Müller), as well as freshwater bivalves: *Pisidium amnicum* (Müller), *Pisidium casertanum* (Poli), *Pisidium milium* Held, *Pisidium moitessierianum* Paladilhe, *Pisidium nitidum* Jenyns and *Pisidium obtusale f. lapponicum* (Lamarck). The association indicates a nearshore zone of lakes and rivers (Krzymińska, 2001; Krzymińska, Przezdziecki, 2001). The age of these deposits determined by the ^{14}C method is estimated at 14,060–13,350 years BP (Kramarska, Jurowska, 1991).

The sandy muds (R-5, R-6, R-9, R-11 and R-18 profiles) contained abundant molluscan fauna dominated by such species as: *Pisidium amnicum* (Müller), *Pisidium casertanum* (Poli), *Pisidium casertanum f. ponderosa* Stelfox, *Pisidium milium* Held, *Pisidium nitidum* Jenyns and *Pisidium conventus* Clessin. Deposits of R-24 profile have yielded the gastropods *Valvata piscinalis*, and opercula of *Bithynia tentaculata* (Linnaeus) and *Bithynia leachi* (Sheppard), accompanied by the bivalves *Pisidium amnicum* (Müller), *Pisidium casertanum* (Poli), *Pisidium casertanum f. ponderosa* Stelfox, *Pisidium milium* Held, *Pisidium nitidum* Jenyns and *Pisidium conventus* Clessin. *Gyraulus laevis* (Alder), *Valvata piscinalis f. antiqua* Sowerby, *Sphaerium corneum* and *Pisidium moitessierianum* Paladilhe occurred sporadically.

This malacofauna indicates a shallow, overgrown basin. The presence of *Valvata piscinalis f. antiqua* Sowerby and *Pisidium conventus* Clessin suggests a typical lacustrine basin.

Sandy muds and gyttjas occurring north of Rewal (Fig. 3) in profiles VR 041, VR 072, VR 086 and VR 138) contained abundant molluscan fauna dominated by the following species: *Pisidium amnicum* (Müller), *Pisidium casertanum* (Poli), *Pisidium casertanum f. ponderosa* Stelfox, *Pisidium milium* Held, *Pisidium nitidum* Jenyns and *Pisidium conventus* Clessin. This type of association can also prove the presence of a shallow-water basin with stable depositional conditions.

Similar assemblages were found in muds from offshore profiles north of Mrzeżyno (71, 74, 69, 67, 66, 56, 55, 53 and 9). They have yielded specimens typical of the Preboreal period: *Pisidium casertanum f. ponderosa* Stelfox, *Pisidium milium* Held, *Pisidium nitidum* Jenyns and *Pisidium conventus* Clessin. The overlying, younger deposits contained species exhibiting higher thermal requirements, represented by the gastropods *Bithynia tentaculata* (Linnaeus), *Bithynia leachi* (Sheppard) and *Valvata piscinalis f. antiqua* Sowerby, and accompanied by the bivalves *Pisidium amnicum* (Müller), *Pisidium casertanum* (Poli), *Pisidium moitessierianum* Paladilhe and *Sphaerium corneum* f. *mamillanum* (Westerlund), which may indicate a climate warming in the Early Holocene.

Along the western coast, lacustrine and alluvial organic muds (5L-Mrzeżyno and 8L-Ustronie Morskie profiles) have yielded similar associations of freshwater molluscs represented by the following gastropods: *Acroloxus lacustris* (Linnaeus), *Anisus spirorbis* (Linnaeus), *Armiger crista f. cristatus* Draparnaud, *Bithynia tentaculata* (Linnaeus), *B. leachi* (Sheppard), *Gyraulus laevis* (Alder), *Lymnaea glutinosa* (Müller), *Segmentina nitida* (Müller), and *Valvata piscinalis* (Müller), as well as the bivalves *Pisidium amnicum* (Müller), *P. casertanum f. ponderosa* Stelfox, *P. milium* Held, *P. moitessierianum* Paladilhe, *P. nitidum* Jenyns and *Sphaerium* sp. They are typical of lakes, stagnant water bodies and oxbow ponds. Mollusc species of *Pisidium amnicum, P. casertanum f. ponderosa* and *P. moitessierianum*, and species of the *Sphaerium* genus occur also in rivers. These

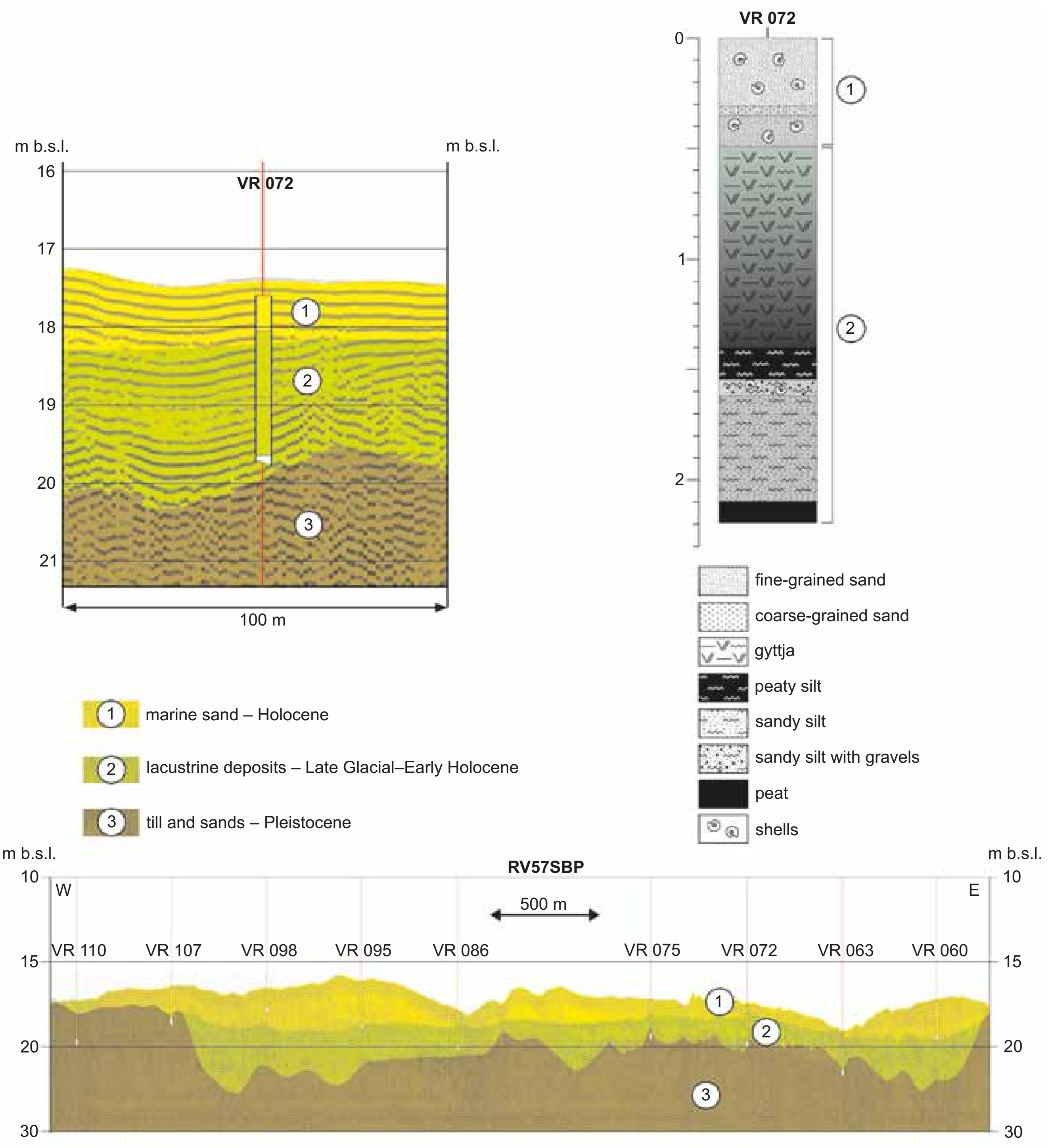


Fig. 3. Palaeolake structure (Late Glacial–Early Holocene age of deposits) within the roof of till horizon, covered by series of Holocene marine sand, geological succession documented by malacological investigation in core profile VR 072 (Pomeranian Bay, fragment of boomer profile RV57SBP)

molluscan associations prove that the lakes were shallow and becoming overgrown. Periodically, they could be flow-through lakes.

Sandy muds from five offshore boreholes (1T-Mrzeżyno, 2T-Dźwirzyno, 1N-Rewal, R13-Dziwnów and R24-Mrzeżyno), the 3T and 4T boreholes (Lake Resko and its spit) and the 4N borehole (spit of Lake Liwia Łuża) contain numerous mollusc species, predominantly *Pisidium amnicum* (Müller), *Pisidium casertanum* (Poli), *Pisidium casertanum f. ponderosa* Stelfox, *Pisidium milium* Held, *Pisidium nitidum* Jenyns and *Pisidium conventus* Clessin. This type of association can indicate that a shallow freshwater lake with stable depositional conditions occurred in this area (Krzymińska *et al.*, 2003).

In the Słupsk Bank area, lacustrine sands from two drill cores (14097 and 14097B) have yielded the following freshwater gastropod species: *Bithynia tentaculata* (Linnaeus), *Physa fontinalis* (Linnaeus) and *Valvata cristata* Müller, as well as the bivalve species *Pisidium amnicum* (Müller), *Pisidium casertanum f. ponderosa* Stelfox, *Pisidium milium* Held and *Pisidium nitidum* Jenyns (Krzymińska, 2001). The molluscan association points to an overgrowing shallow-water basin. The peats, dated by ^{14}C and palynological methods, accumulated in a period of 10,150–8,950 years BP (Uścinowicz, Zachowicz, 1991), which corresponds to the latemost Glacial through the early Boreal.

In the Southern Middle Bank, fine-grained sands (376, 354, Z 20 and 382) contained the freshwater gastropod *Lymnaea peregra* (Müller), and the bivalve species *Pisidium amnicum* (Müller) and *Pisidium milium* Held (Krzymińska, 2001). Malacological investigations allow suggesting that the deposits containing bivalve shells of *Pisidium milium* Held (a species tolerant to cold climates) might have been deposited in the Late Glacial, while the deposits with *Pisidium amnicum* (Müller) (a species that requires better thermal conditions) were accumulated at the Pleistocene/Holocene transition.

Western part of the Gulf of Gdańsk, spanning also the Puck Bay and submarine slopes of the Hel Peninsula, differs from the eastern part, encompassing the foreland of the Vistula Spit, in terms of lithology (Uścinowicz, Zachowicz, 1994). In the south-western part of the Gulf of Gdańsk (1ZG54, ZG4, ZG3, ZG2, ZG1 and V067), where pra-Vistula deltaic deposits are found, the deposits contained the gastropods *Bithynia tentaculata* (Linnaeus), *Bithynia leachi* (Sheppard), *Gyraulus laevis* (Alder) and *Valvata piscinalis* (Müller), as well as the bivalves *Pisidium amnicum* (Müller), *Pisidium milium* Held, *Pisidium moitessierianum* Paladilhe and *Pisidium nitidum* Jenyns (Krzymińska, 2001). This freshwater molluscan association points to a calm and shallow flood-basin lake, periodically incorporated into a flowing river. Dark grey muddy sands and sandy muds with abundant plant detritus, dated in this area at 12,200 ±240 years BP by the radiocarbon method (Uścinowicz, Zachowicz, 1994), contained also freshwater ostracod species (Krzymińska, Namiotko, 2012, 2013).

Eastern part of the Gulf of Gdańsk, spanning the foreland of the Vistula Spit (R3a/82, R3, El 1, R125, R127 and R119), is composed of lagoonal deposits containing abundant molluscan fauna represented by the following gastropods: *Gyraulus laevis* (Alder), *Lymnaea peregra* (Müller), *Lymnaea glutinosa* (Müller) and *Valvata piscinalis* (Müller), as well as the bivalves *Anodonta cygnea* (Linnaeus) – a glochidium, *Pisidium amnicum* (Müller), *Pisidium milium* Held, *Pisidium nitidum* Jenyns and *Pisidium moitessierianum* Paladilhe (Krzymińska, 2001). The malacofauna indicates a shallow overgrowing lake with lush vegetation. The freshwater nature of the sedimentation is substantiated by the presence of freshwater ostracods (profile El 1; Krzymińska, Przezdziecki, 2010; Krzymińska, Namiotko, 2012, 2013). These deposits were also dated at 10,650 ±160 years BP and 9,000 ±260 years BP using the ^{14}C method (Uścinowicz, Zachowicz, 1994; Uscinowicz, 2003). It should be noted that the above-mentioned lagoonal deposits represent a sedimentary environment of small shallow and quickly disappearing water bodies that developed at the top of a thick delta front complex. Thus, those are not such lagoonal deposits as these of the modern Vistula Lagoon or the inner (northern) part of the Puck Bay.

A similar type of sedimentation was recognized in profiles K043 and VR 052 (Fig. 4), predominantly represented by muddy sands, containing exclusively freshwater fauna of gastropods *Bithynia tentaculata* (Linnaeus) and *Valvata piscinalis* (Müller), and molluscs Pisidium casertanum (Poli), *Pisidium casertanum f. ponderosa* Stelfox, glochidia *of Anodonta* and *Pisidium supinum* Schmidt. These species are characteristic of lakes where they inhabit both various littoral and profundal environments.

Based on the above investigations, it can be claimed that the molluscan association from the deposits in the Pomeranian Bay, Słupsk Bank and Gulf of Gdańsk represent aquatic assemblages typical of the nearshore zone of lakes and rivers, with periodic water flow. The results of malacofauna investigations correlated with ^{14}C datings show that the occurrence of molluscs, such as *Gyraulus laevis* (Alder), *Valvata piscinalis* (Müller), *Pisidium casertanum* Poli, *Pisidium obtusale f. lapponicum* (Lamarck), *Pisidium nitidum* Jenyns and *Pisidium milium* Held, which are tolerant to cold climate, points to their Late Glacial age. Whereas, the presence of species that require higher thermal conditions, including *Bithynia tentaculata* (Linnaeus), as well as *Bithynia leachi* (Sheppard), *Physa fontinalis* (Linnaeus), *Anodonta cygnea* (Linnaeus) – a glochidium, *Pisidium amnicum* (Müller), *Pisidium moitessierianum* Paladilhe and *Pisidium supinum* Schmidt, indicates that the deposits were accumulated probably only in the Early Holocene.

MIDDLE AND UPPER HOLOCENE FAUNA

In the Southern Baltic area, deposits that represent the Middle and Late Holocene climatic optimum contained marine fauna typical of low-salinity basins. Molluscan associations that indicate such environment were found in various areas of the Southern Baltic Sea. They included species with different ecological requirements and different geographical ranges. The described faunal species live at present in the seas surrounding Europe, and some of them show greater geographical ranges. This can be the basis for assigning them to specified climatic and zoogeographical regions. The Venice system for the classification of marine waters according to salinity divides the waters into euhaline, typically ma-

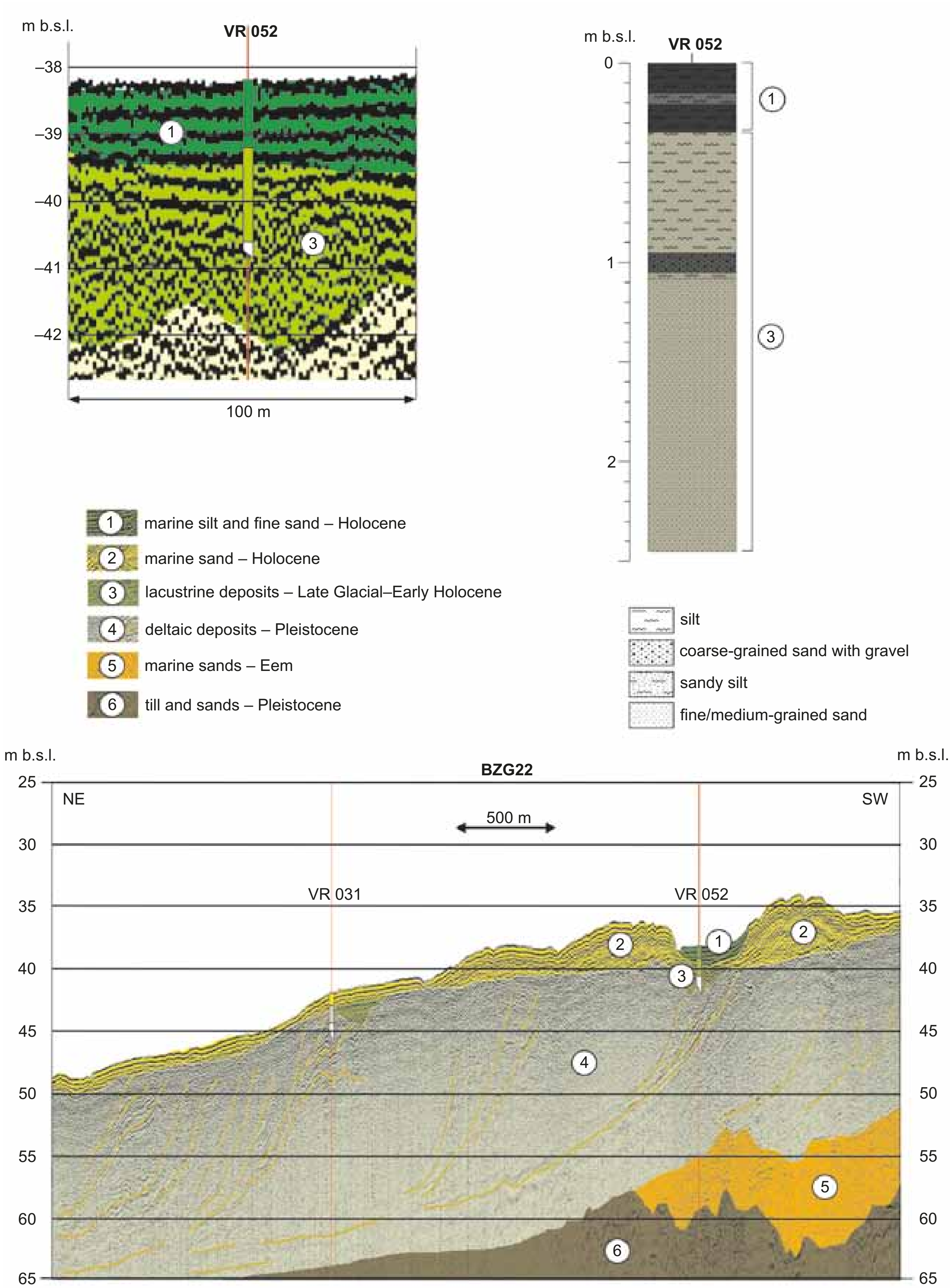


Fig. 4. Palaeolake structure (Late Glacial–Early Holocene age of deposits) within the local depression in the roof of front delta deposits (pra-Vistula River), covered by series of Holocene marine silts (dark green colour) and sands (yellow colour), geological succession documented by malacological investigation in core profile VR 052 (Gulf of Gdańsk, fragment of boomer profile BZG22)

rine (30–40 psu), hyperhaline, with salinity higher than that of oceanic waters (>50 psu), and mixohaline (0.5–30 psu) with lowered salinity (Wiktor *et al.*, 1997). Equally important is the criterion of changes in the salinity tolerance range of organisms. In this respect we distinguish euryhaline organisms, which can exist in a wide range of salinity changes, and stenohaline species with a narrow tolerance range for salinity changes. Euhaline waters are inhabited by typical marine species, including a large number of stenohaline species. Mixohaline waters are inhabited by stenohaline marine species, euryhaline brackish species, as well as freshwater species. With the increasing proportion of fresh waters, which results in the lowering of total salinity, the number of stenohaline marine species decreases, and euryhaline species become dominant. Although different marine organisms prefer different temperatures, and their ranges of thermal tolerance are also different, it is possible to characterize the paleaogeographic and palaeoclimatic conditions of the environment in which the fauna lived at that time. Stenothermal organisms show little tolerance to water temperature changes. These include cold- and warm-loving stenotherms living exclusively in cold waters or only in warm waters, respectively. Another group is represented by species with a wide tolerance range – eurythermal species that tolerate a considerable range of temperatures (Wiktor *et al.*, 1997).

The specific nature of the Baltic Sea as a living environment is related to the influx of both fully saline waters from the North Sea and fresh waters carried into the sea by rivers. This gives a brackish character to the waters of the Southern Baltic Sea. The Southern Baltic biocoenose comprises euryhaline marine species (most numerous in this area), brackish species, and freshwater species. In contrast, the marine fauna during the transgression of the Littorina Sea, whose water salinity was above 15 psu, was represented by stenohaline and euryhaline species. Therefore, due to a drop in water salinity to 7–8 psu in the Southern Baltic Sea in the Late Holocene, stenohaline species retreated westwards to the Western Baltic and Belt Sea (WEB), and Sound Straits (SOU) (Fig. 1).

While presenting the conditions, under which the marine fauna of the Middle and Late Holocene evolved, it should be born in mind that the shallow-water area of the Southern Baltic Sea was affected by the Littorina transgression relatively late, only at the beginning of the Atlantic period. That is why the deposits containing also freshwater fauna, which accumulated before the transgression event, have been found in numerous sites of this area beneath those with marine fauna.

In the Pomeranian Bay the Littorina Sea phase was marked by deposition of marine sands (95/VII, 88/VIII, W-4, R86, 51/I, 89/VI, 124/IV and 160/IV) which contain euryhaline species of marine molluscs, such as: *Hydrobia ulvae* (Pennant), *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Mytilus edulis* (Linnaeus) and *Macoma balthica* (Linnaeus), as well as rarer stenohaline marine gastropods, including: *Rissoa membranacea* (Adams), *Retusa truncatula* (Bruguière) and *Turboella parva* (Da Costa), and bivalves *Scrobicularia plana* (Da Costa), *Cardium edule* Linnaeus, *Mya truncata* Linnaeus, *Mysella bidentata* (Montagu) and *Thracia papyracea* (Poli). In addition to marine species, freshwater gastropods were also found at the bottom of the marine series, including *Theodoxus fluviatilis* (Linnaeus) and *Valvata piscinalis* (Müller), and freshwater ostracods. It can suggest the existence of a lagoon periodically recharged by salt waters (Krzymińska, 2001; Krzymińska, Przezdziecki, 2001).

Marine sands of the southern part of the Pomeranian Bay (profiles: R-10, R-13, R-20, R-22 and R-23) contain predominantly *Hydrobia ulvae* (Pennant), *Hydrobia neglecta* Muus, *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Mytilus edulis* Linnaeus and *Macoma balthica* (Linnaeus), with sporadic gastropods of *Littorina obtusata* (Linnaeus), *Rissoa membranacea* (Adams) and *Theodoxus fluviatilis* (Linnaeus), and the bivalve *Mysella bidentata* (Montagu). This assemblage is conspicuous by high ecological tolerance and represented by euryhaline species that inhabit sea-floors overgrown by algae. Worth noting are the gastropod *Littorina obtusata* (Linnaeus) and the bivalve *Mysella bidentata* (Montagu), because these species presently do not inhabit the Southern Baltic Sea, but they occur in the Western Baltic waters with the salinity exceeding 12 psu.

Similar situation is observed in the eastern part of the Pomeranian Bay, North of Mrzeżyno (P1V 104 and V124 profiles). The upper part of the profiles are composed of marine sands, while the lower part is represented locally by lacustrine deposits (P1V 104, Fig. 5). Generally, the marine sands of the Pomeranian Bay area are commonly underlain by sands and silts, sporadically also by peats. In many situations the lacustrine origin is confirmed by an assemblage of freshwater ostracods (Krzymińska, Przezdziecki, 2011).

Along the western coast, in the 4T and 3T boreholes (Lake Resko and its spit), numerous freshwater bivalve species were found, including *Pisidium milium* Held, *Pisidium nitidum* Jenyns and glochidia *of Anodonta cygnaea* (Linnaeus). The presence of *Anodonta cygnea glochidia* in the deposits glochidia are larval forms attached to the gills until the springtime (April-May) and then detached to fall into the water at specified depths can suggest that the basin depth could be approximately 7 m (Aldridge, Horne, 1998; Piechocki, Dyduch-Falniowska, 1993). Apart from mentioned bivalve species, several mollusc species were found: *Pisidium milium* Held, *Pisidium nitidum* Jenyns, *Valvata piscinalis f. antiqua* Sowerby, *Theodoxus fluviatilis* (Linnaeus) and *Rissoa membranacea* (Adams). The above-described type of association can indicate a shallow-water basin with stable depositional conditions in this area, but the presence of the last two representatives can indicate a temporary connection with an open sea. The lacustrine silts are underlain (profile 4T) by a thin peat layer dated by the ^{14}C method at 6480 ±60–6210 ±60 years BP (Krzymińska *et al.*, 2003). It can be assumed that the lacustrine deposits were probably accumulated in the late Atlantic and Subboreal freshwater basin, which was periodically connected with the open sea.

In the Jamno 3/5 borehole (Fig. 2), a series of lacustrine deposits, 6.80 m in thickness, is composed of sandy muds

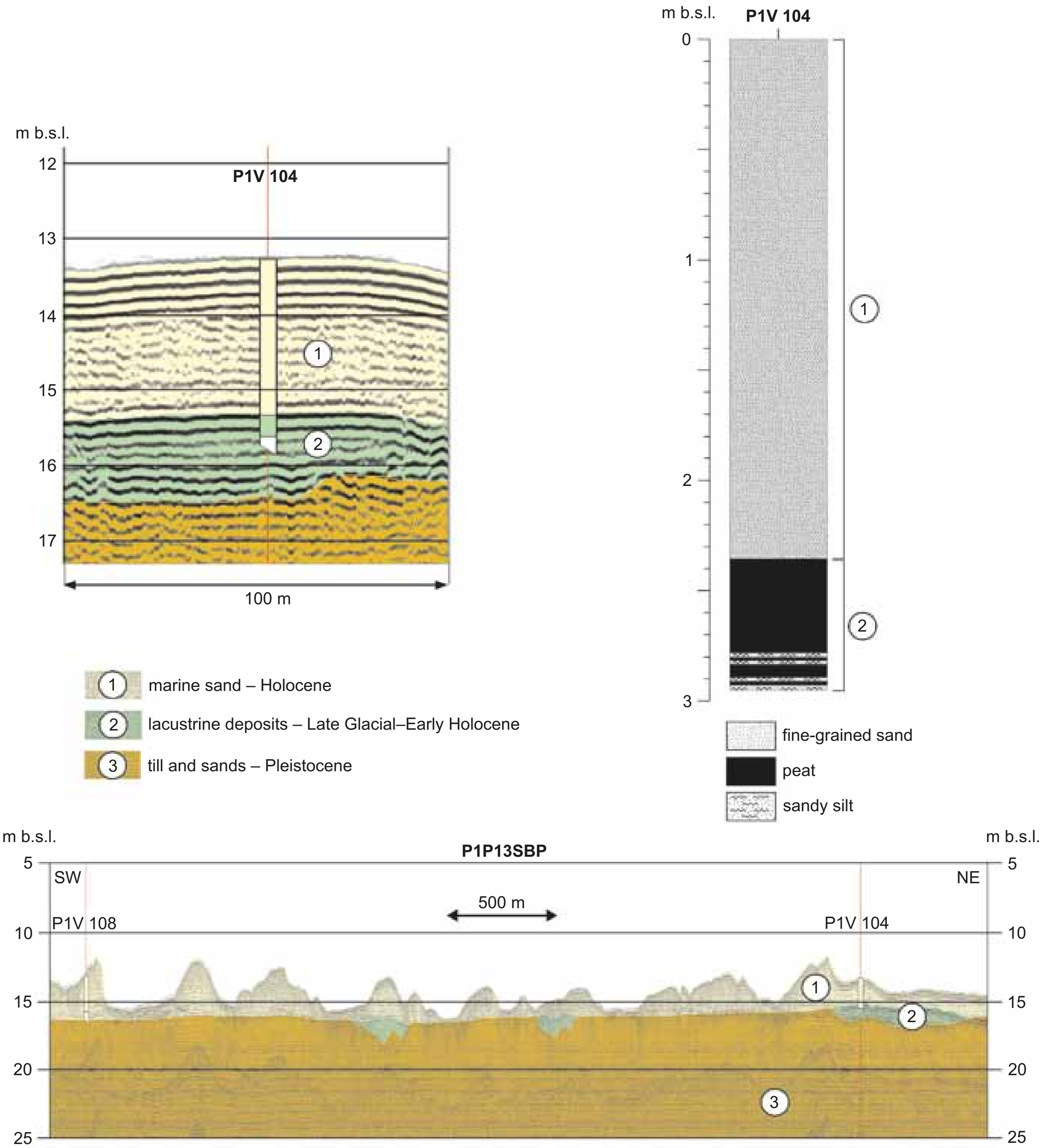


Fig. 5. Leveled, palaeo-relief of Late Glacial–Early Holocene age with lacustrine infillings, overbuilt by series of Holocene marine sands (slightly hummocky relief), presence of Middle and Upper Holocene age of marine sands is documented by malacological investigations in core profile P1V 104 (Pomeranian Bay, fragment of boomer profile P1P13SBP)

passing upwards into clayey gyttjas. The radiocarbon date acquired for the base of these deposits is 8,655 ±230 years BP (Dobracki, Zachowicz, 1997). The base of lacustrine deposits occurs at a depth of 9 m b.s.l. In the lower part of the section there are freshwater basin deposits with *Bithynia tentaculata* (Linnaeus), *Valvata piscinalis* (Müller), and *Pisidium casertanum* (Poli). Only in the upper part (above the fine-grained sand layer of the Atlantic transgression, found at a depth of 5–6 m) the marine species *Cerastoderma glaucum* (Poiret) appears, indicating periodic contacts of marine salt waters with waters of a coastal lake (Krzymińska, Dobracki, 2004).

In Mielno (sites 23/8 m and 25/7.5 m; Fig. 2) there was a peat layer dated by the radiocarbon method at 7,370 ±50 and 7,090 ±40 years BP (Dobracki, Zachowicz, 1997). Above the peat layer, abundant ostracod fauna (*Cyprideis torosa*) and marine molluscs (*Cerastoderma glaucum*) were found (Krzymińska, Dobracki, 2004).

In the middle coast, in the 4/21 borehole drilled in the floor of Kopań Lake (Fig. 2), there is a series of bottom organic peaty muds and clays (5 m thick) with laminae rich in freshwater mollusc shells, underlain by a 2.4 m thick bed of limnic deposits (silty sands and muds with fine gravel at the base). The 5 m thick mud series contains malacofauna and ostracod associations typical of freshwater environment, although the presence of some taxa may prove variable conditions during deposition. Such palaeoenvironmental interpretation is suggested by the species composition of the malacofauna represented by *Pisidium amnicum* (Müller), *Pisidium casertanum* (Poli), *Pisidium casertanum f. ponderosa* Stelfox and *Pisidium conventus* Clessin.

In the 4/20 profile located in the Darłówko region (Fig. 2), a till horizon is covered by about 4 m thick layer of silty clayey deposits of lacustrine origin, containing freshwater bivalves: *Pisidium casertanum* (Poli), *Pisidium conventus* Clessin, and the gastropod *Valvata piscinalis f. antiqua* Sowerby. The limnic deposits are overlain by athin horizon of peat dated by the ^{14}C method at 5,415 ±110 years BP (Dobracki, Zachowicz, 1997). Similar situation is observed in the 3/19 borehole, drilled on the spit of Bukowo Lake, where the top of the till horizon (14 m b.s.l.) is overlain by a 3.8 m thick series of lacustrine deposits represented by silts and silty sands. These lacustrine deposits are capped by a 4 m series of fine sands rich in detritus of coalified plants and shells. The presence of wood fragments, bog iron nodules, and vivianite grains proves shallowing of the basin and its decline. Above, up to a depth of 4.7 m, below the water table, there are peaty muds with peat interbeds, which were dated at 5,912 ±85 years BP. The Preboreal deep lake basin was rapidly shallowing northwards, and the uppermost organic series ending the lacustrine succession is overlain by marine sands of the Bukowo Lake spit (Dobracki, Zachowicz, 1997).

Lacustrine deposits, 6.75 m in thickness, were also found in the 6/19 borehole, situated near Bobolin (between the town of Darłowo and Bukowo Lake). The lowermost part of these deposits, represented by humic sands with interbeds of woody peat, is dated at 9,885 ±450 years BP. The top of the lacustrine deposits, consisting of a 0.9 m peat layer, whos base is dated at at 4,280 ±55 years BP (Dobracki, Zachowicz, 1997). The lacustrine series of the 6/19 profile overlies glacial tills and is covered by sands containing marine fauna with *Macoma balthica* (Linnaeus) and *Hydrobia ulvae* (Pennant).

In the 1/12 section from Wicko Lake (Fig. 1) there were accessory marine mollusc species, such as: *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus) and *Mya arenaria* Linnaeus. This may indicate a periodic contact with the sea. All of the abovementioned species are currently common in the Southern Baltic Sea. The deposits of the Modlinek 1/13 section (Fig. 2) contained a marine association of molluscs that today inhabit the Southern Baltic area.

In the Southern Middle Bank area (Fig. 2), the sections of R334, R353, R369, R376, R382, R385, R398, Z13, Z19 and Z20 have yielded typical euryhaline marine species, such as: *Hydrobia ulvae* (Pennant), *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus) and *Mytilus edulis* Linnaeus.

In the southern part of the Gulf of Gdańsk, the Atlantic period was marked by the influence of the Littorina Sea. Euryhaline and stenohaline marine species appeared at that time, including: *Hydrobia ulvae* (Pennant), *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Mytilus edulis* Linnaeus, *Retusa obtusa* Montagu, *Retusa truncatula* (Bruguière), *Rissoa membranacea* (Adams), *Cardium edule* Linnaeus, *Mya truncata* Linnaeus and *Scrobicularia plana* (Da Costa) (Krzymińska, 2001; Krzymińska, 2004). They were found in deposits of the following drill cores: R5/82, ZG3, ZG4, V123, Nr5, Nr10, Nr16 and Nr23. Muds in the WSB8 and WSB10 profiles near the North Port area (Gdańsk harbour) have yielded the marine bivalves *Scrobicularia plana* (Da Costa) and *Cerastoderma glaucum* (Poiret). *Scrobicularia plana* (Da Costa) is a euryhaline species typical of Boreal and Lusitanian zones. It inhabits highly muddy (clayey and argillaceous) as well as sandy and muddy bottoms of deeper nearshore areas (Jagnow, Gosselck, 1987). At present, it occurs in the Bay of Kiel and the Bay of Mecklenburg (Western Baltic Sea), and in the Danish Straits and the North Sea, but does not inhabit the Southern Baltic Sea. Therefore, it can serve as a water salinity indicator of the then-existing basin, because it lives in waters with salinity above 14 psu. According to Brodniewicz (1967, 1974), this is a guide species for Littorina Sea deposits in the Polish coast. The species was also found in Eemian Interglacial deposits at Brachlewo (Lower Vistula Valley) (Brodniewicz, 1960), in Littorina Sea deposits of the Gardno-Łebsko Lowland (Brodniewicz, Rosa 1967; Brodniewicz, 1974; Wojciechowski, 1995; Wojciechowski, 2008, 2013), in sandy muds with admixture of organic matter in the Vistula Spit (Stegna) (Krzymińska, 2003), and in deposits of the Śmiała Vistula mouth (Jegliński, 2013).

In the Puck Bay, during the period from 6,660 to 3,200 years BP (Kramarska, Uścinowicz, Zachowicz, 1994), the influence of the Littorina and Post-Littorina transgression was marked by the appearance of the following gastropod and bivalve species: *Potamopyrgus antipodarum* (Gray), *Theodoxus fluviatilis* (Linnaeus), *Hydrobia ulvae* (Pennant), *Hydrobia ventrosa* (Montagu), *Rissoa membranacea* (Adams), *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus), *Mya truncata* Linnaeus, *Mytilus edulis* Linnaeus and *Parvicardium hauniense* (Petersen et Russell) in the following sections: VII, VIII, IX, X, XI, XII, XIII, 6, 11, 41, 44, 45, 47, 48 and 50. This association contains also the freshwater species *Potamopyrgus antipodarum* (Gray) and *Theodoxus fluviatilis* (Linnaeus), which are tolerant to water salinity ranging up to 16–19 psu. The exception is *Mya truncata* that requires different ecological conditions, showing an arctic-boreal nature (Krzymińska, 2001).

Four boreholes (Hel, Bór, Kuźnica and Chałupy) drilled in the Hel Peninsula have also proved the presence of marine molluscs, such as: *Hydrobia ulvae* (Pennant), *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus) and *Mytilus edulis* Linnaeus, which currently live in the Southern Baltic Sea (Tomczak *et al.*, 1989; Krzymińska, 2001).

As regards the shallow-water zone of the Gulf of Gdańsk, it is worth to pay attention to the currently active part of the youngest delta of the Vistula: the river mouth fan (delta front) and its foreland (prodelta). It is the most diversified area in terms of frequency of environmental changes, because there is a natural zone of interfingering of layers, and thus either mixing of river and marine waters, or intrusion of seawater into the river. The delta itself is a very young feature formed as a result of the construction of the Vistula dug-through to the Gulf of Gdańsk in 1891–1895.

The deltaic medium- and coarse-grained sands of all analyzed sections (Świb3, Świb2, Świb1, STZ4, STZ5, STZ6, Mik7, Mik3, Mik2, STW1 and STW2) contained freshwater mollusc species that inhabit both lakes and rivers. The species typical of lakes include *Valvata piscinalis f. antiqua* Sowerby, *Gyraulus rossmaessleri* (Auerswald), *Pisidium conventus* Clessin and *Pisidium lilljeborgii* Clessin. They inhabit oligotrophic and mesotrophic lakes, and probably represent relics of the early Postglacial period (Piechocki, Dyduch-Falniowska, 1993). The typical riverine faunal components are gastropods, including: *Lithoglyphus naticoides* (Pfeiffer), *Theodoxus fluviatilis* (Linnaeus) and *Viviparus viviparus* (Linnaeus), as well as the bivalves *Pisidium amnicum* (Müller), *Pisidium casertanum f. ponderosa* Stelfox, *Pisidium supinum* Schmidt, *Unio pictorum* (Linnaeus), *Unio crassus* Philipsson, *Dreissena polymorpha* (Pallas), *Sphaerium solidum* (Normand) and *Sphaerium rivicola* (Lamarck). *Lithoglyphus naticoides* (Pfeiffer) occurs on muddy bottoms of large rivers, whereas *Theodoxus fluviatilis* (Linnaeus) and *Viviparus viviparus* (Linnaeus) inhabit stony bottoms of rivers and lakes. *Dreissena polymorpha* (Pallas) is a bivalve that prefers hard bottoms, adhering to the surface by the byssus. It occurs in fresh and brackish waters up to 5 psu. *Sphaerium solidum* (Normand) and *Sphaerium rivicola* (Lamarck) are typical riverine species; however, they occur predominantly in large rivers. They are also found to inhabit sandy and gravelly bottoms. The bivalves *Pisidium amnicum* (Müller), *Pisidium casertanum f. ponderosa* Stelfox, *Pisidium supinum* Schmidt, *Unio pictorum* (Linnaeus) and *Unio crassus* Philipsson inhabit sandy and sand-gravelly bottoms of both rivers and lakes (Piechocki, Dyduch-Falniowska, 1993).

The deltaic fine- and coarse-grained sands, locally also muds, reveal the presence of the gastropods *Hydrobia ulvae* (Pennant) and *Hydrobia ventrosa* (Montagu), and the bivalves *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus), *Mytilus edulis* Linnaeus and *Mya arenaria* Linnaeus. These shallow-water euryhaline species are typical of low salinity basins and show high tolerance to salinity changes characteristic of the boreal climate. They represent elements of the present-day fauna of the Southern Baltic Sea and are widespread throughout the Baltic Sea (Krzymińska, 2000).

Beside the above-mentioned species, the fine- and coarse-grained sands have also yielded species showing specific ecological requirements. Their presence in the analyzed deposits can prove their origin in a sea with different hydrological conditions than the ones that currently exist in the Southern Baltic area. These are the following species: *Bittium reticulatum* (Da Costa), *Eulimella nitidissima* (Montagu), *Rissoa membranacea* (Adams), *Nassarius reticulatus* (Linnaeus), *Littorina littorea* (Linnaeus), *Cardium edule* Linnaeus, *Corbula gibba* (Olivi), *Mya truncata* Linnaeus, *Mysella bidentata* (Montagu) and *Thracia papyracea* (Poli). The above-described molluscs currently live in the highly saline seas that surround Europe (16–35 psu). All of them can serve as water salinity indicators. Thus, these species can document the fauna from the Atlantic period of the Littorina Sea transgression. Taking into account the young age of the Vistula dug-through, this fauna is redeposited. The analyzed malacofauna of the present-day mouth fan of the Vistula River contained a mixed assemblage of both freshwater and marine species, which is typical of prograding deltaic deposits.

In the fine- and coarse-grained sands (locally muds) from the V033, V029 and V123 profiles on the submarine slope of the Vistula Spit (Fig. 6), the following molluscan species have been found: *Hydrobia ulvae* (Pennant), *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus) and *Mytilus edulis* Linnaeus. These are shallow-water euryhaline species highly tolerant to salinity changes and typical of the boreal climate. They are widespread in the Baltic Sea.

Holocene deposits of the Vistula Spit, in the Sztutowo (SZ1), Przebrno (PR1, PR2), Krynica Morska (KM1, KM2), Dziady (DZ1, DZ2) and Piaski (PS1, PS2) profiles between Stegna and Piaski contain mainly marine faunal association represented by the bivalves *Cerastoderma glaucum* (Poiret) and *Macoma balthica* (Linnaeus). In the north-eastern part of the spit, a set of freshwater species was recognized in the lower part of profile KM3. Fine-grained sands of this area reveal the presence of the gastropod *Valvata piscinalis* (Müller) and the ostracod *Cyprideis torosa* (Jones). Freshwater faunas, occasionally accompanied by marine and mixed assemblages, are also known from profiles of the Sztutowo region (SZ6, SZ7 and SZ8). The Sztutowo 6 section provides an abundant association of freshwater fauna represented mainly by riverine bivalves, such as: *Pisidium moitessierianum* Paladilhe, *Pisidium casertanum* (Poli), *Pisidium casertanum f. ponderosa* Stelfox and *Sphaerium rivicola* (Lamarck), and *glochidia of Anodonta cygnaea* Lamarck. The Sztutowo 7 section revealed only a freshwater fauna with the riverine species *Theodoxus fluviatilis* (Linnaeus), *Bithynia tentaculata* (Linnaeus), *Valvata piscinalis* (Müller), *Pisidium moitessierianum* Paladilhe, *Pisidium amnicum* (Müller) and *Pisidium casertanum f. ponderosa* Stelfox. The Sztutowo 8 section contained a marine mollusc association, including: *Hydrobia ulvae* (Pennant), *Rissoa membranacea* (Adams), *Cardium edule* Linnaeus, *Cerastoderma glaucum* Poiret, *Mytilus edulis* Linnaeus and *Mysella bidentata* (Mon-

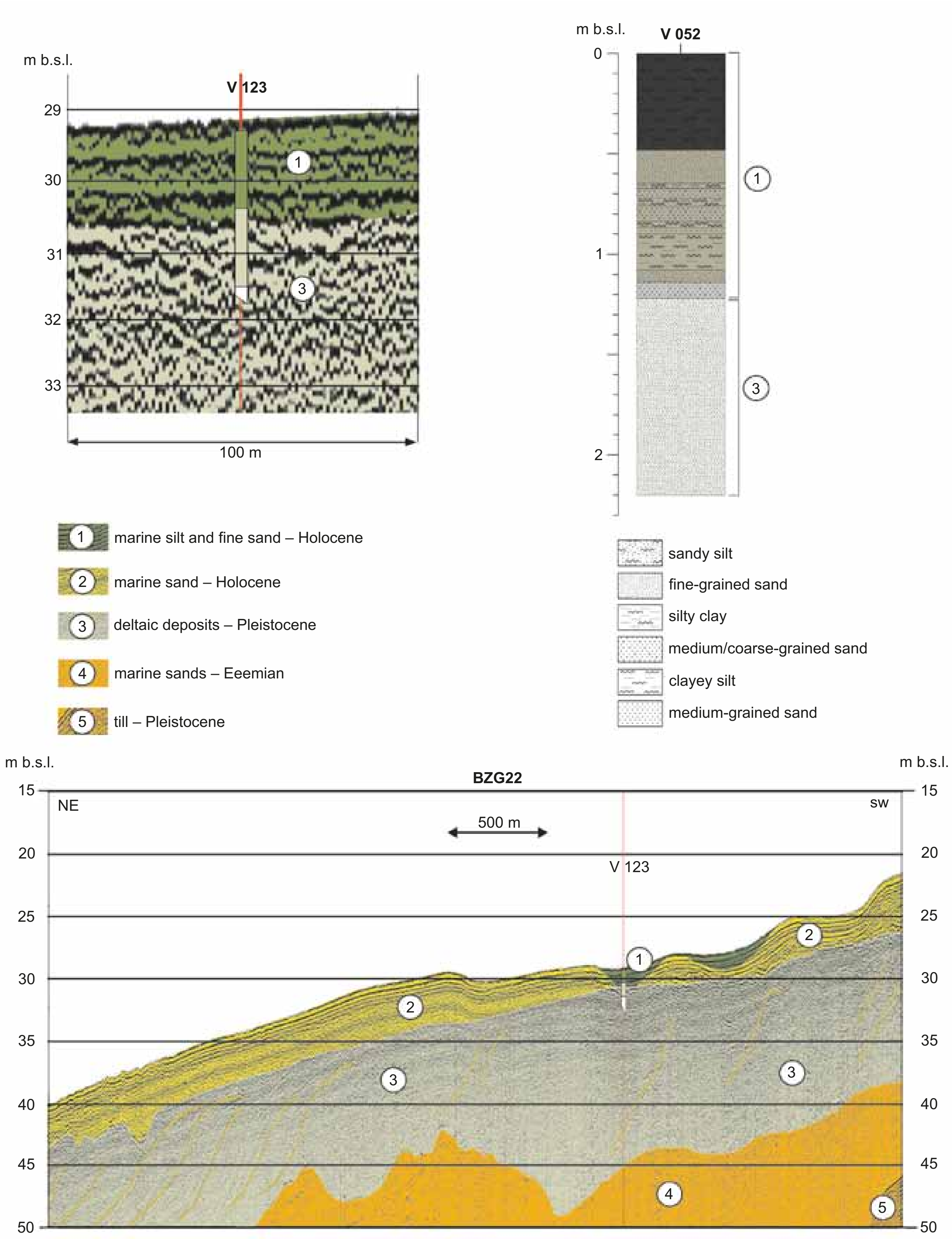


Fig. 6. Examples with different type of young, marine accumulation, which covers older (Late Glacial) accumulation of front-delta deposits. In site V123 is seen local depression infill by silts and fine sands, while neighbouring parts are built by marine sands, presence of Middle and Upper Holocene age of marine deposits is documented by malacological investigations in core profile V 123 (Gulf of Gdańsk, fragment of boomer profile BZG22)

tagu). This association contains the bivalve species *Cardium edule* Linnaeus and *Mysella bidentata* (Montagu) which currently do not inhabit the Southern Baltic area, but are found in the Western Baltic Sea, and can be indicators of higher water salinity above 10 psu.

The upper part of profiles DZ2 and KM2, located in the north-eastern part of the Vistula Spit, includes a ca. 2 m thick series of coarse sands and sandy gravels with band accumulations of bivalves, mainly *Cerastoderma glaucum*. Such sediments developed as a result of episodic shallowing, and regression of the sea. The ^{14}C data show that these deposits accumulated about 2920 ±50 (GD 12369) and 2760 ±60 years BP (GD 12359), (Pikies *et al.*, 2008).

Based on the differences between the individual molluscan associations, related to different habitats (freshwater and marine), cyclic intrusions of saline waters into the Vistula Lagoon area have been indicated in deposits of the lagoon. This resulted in the occurrence of both freshwater and mixed faunas.

In the ZW 12 drill core we have found the gastropod *Viviparus viviparus* (Linnaeus). This species lives in rivers, inhabiting sandy, muddy and stony bottoms. It can migrate into brackish waters. In the ZW 10 drill core, a single shell of the gastropod *Ancylus fluviatilis* (Müller) was encountered. This snail also lives in lakes. Bivalves were represented by the following species: *Pisidium amnicum* (Müller), *Pisidium supinum* Schmidt, *Pisidium moitessierianum* Paladilhe, *Sphaerium rivicola* (Lamarck) and *Sphaerium solidum* (Normand). They inhabit predominantly riverine environments, but can also live in nearshore zones of lakes. In the ZW 5 drill core, *Pisidium henslovanum* (Sheppard), *P. casertanum* (Poli), *P. casertanum f. ponderosa* Stelfox, *P. conventus* Clessin, *P. milium* Held, *P. nitidum* Jenyns, *P. pseudosphaerium* Schlesch and *P. subtruncatum* Malm were found. The species *P. henslovanum* and *P. conventus* are typical of lakes. The bivalve *Dreissena polymorpha* Pallas, reported from the ZW 2, ZW5, ZW 6, ZW 8, ZW 10 and ZW 12 drill cores, inhabits slack-water rivers, lakes and ponds, preferring hard bottoms. It also occurs in brackish environments. The species *Unio pictorum* (Linnaeus) was found in drill cores of the ZW 2, ZW 3, ZW 4, ZW 7 and ZW 14 sections. This bivalve inhabits lakes, ponds and rivers. In the drill core ZW 3, sandy muds, dated at 10,200 years BP (Uścinowicz, Zachowicz, 1997), were accumulated in total isolation from marine influences. They contain exclusively freshwater fauna. Peats from the ZW 7 and ZW 10 sections were dated at 7,820–7,240 years BP. The overlying clayey muds contain exclusively marine bivalves, single shells of *Cerastoderma* sp., and one shell of juvenile *Corbula gibba* (Olivi), which indicates an old contact of marine transgression in this area of the lagoon (Uścinowicz, Zachowicz, 1997).

SYSTEMATIC RECORDS AND BRIEF DESCRIPTION OF SPECIES

This chapter presents the variability of species composition in the Late Glacial and Holocene sediments of the Southern Baltic Sea. The description of 64 mollusc taxa (42 freshwater and 22 marine taxa) refers to Quaternary deposits from the mentioned part of the Baltic Sea (Fig. 7). All specimens from the collection of the Marine Geology Branch of PGI-NRI in Gdańsk were determined according to available keys and guides (Piechocki, 1979; Jagnow, Gosselck, 1987; Skompski, Makowska, 1989, 1994; Piechocki, Dyduch-Falniowska, 1993; Glöer, Meier-Brook, 1994).

TYPE MOLLUSCA
Class GASTROPODA

Order **Archaeogastropoda** Thiele, 1925
Family **Neritidae** Rafinesque, 1815
Genus *Theodoxus* Montfort, 1910

Family **Viviparidae** Gray, 1840
Genus *Viviparus* Montfort, 1810

Family **Valvatidae** Thompson, 1840
Genus *Valvata* O.F. Müller, 1774

Family **Littorinidae** Gray, 1840
Genus *Littorina* Férussac, 1821

Family **Rissoidae** Adams, 1854
Genus *Rissoa* Freminville, 1813
Genus *Turboella* Leach, 1847

Family **Hydrobiidae** Troschel, 1857
Genus *Hydrobia* Hartmann, 1821

Family **Bithyniidae** Fischer, 1885
Genus *Bithynia* Leach, 1818

Family **Cerithiidae** Cossman, 1906
Genus *Bittium* Gray, 1847

Family **Nassariidae** Swainson, 1840
Genus *Nassarius* Dumèril, 1805

Family **Retusidae**
Genus *Retusa* T. Brown, 1827

Family **Pyramidellidae**
Genus *Eulimella* Forbes et M`Andrew, 1846

Family **Physidae** Fitzinger, 1833
Genus *Aplexa* Fleming, 1820
Genus *Physa* Draparnaud, 1801

Family **Lymnaeidae**
Genus *Lymnaea* Lamarck, 1799
Genus *Galba* Schrank, 1803
Genus *Radix* Montfort, 1810

Family **Planorbidae**
Genus *Anisus* Studer, 1820
Genus *Gyraulus* Charpentier, 1837
Genus *Armiger* Hartmann, 1843
Genus *Segmentina* Fleming, 1817

Family **Ancylidae**
Genus *Ancylus* O.F. Müller, 1774
Genus *Acroloxus* Beck, 1837

Class BIVALVIA

Order Mytiloida Férussac, 1822
Family **Mytilidae** Rafinesque, 1815
Genus *Mytilus* Linnaeus, 1758

Order Unionoida Stoliczka, 1871
Family **Unionidae** Rafinesque, 1820
Genus *Unio* Philipsson, 1788

Order Veneroida H. Adams et A. Adams, 1856
Family **Montacutidae** Clark, 1855
Genus *Mysella* Angas, 1877

Family **Cardiidae** Lamarck, 1809
Genus *Cardium* Linnaeus, 1758

Family **Mactridae** Lamarck, 1809
Genus *Spisula* Gray, 1837

Family **Tellininidae** de Blainville, 1814
Genus *Macoma* Leach, 1819

Family **Scrobiculariidae** H. Adams et A. Adams, 1856
Genus *Scrobicularia* Schumacher, 1815

Family **Dreissenidae** Gray in Turton, 1840
Genus *Dreissena* van Beneden, 1835

Family **Sphaeriidae**
Genus *Sphaerium* Scopoli, 1777
Genus *Pisidium* Pfeiffer, 1821

Order Myoida Stoliczka, 1870
Family **Corbulidae** Lamarck, 1818
Genus *Corbula* Bruguière, 1797

Family **Thraciidae**
Genus *Thracia* Blainville, 1824

Family **Myidae,**
Genus *Mya* Linnaeus, 1758

DESCRIPTION OF SPECIES

Theodoxus fluviatilis (Linnaeus, 1758)

Pl. I, Fig. 1

Size. – L = 6–14 mm, W = 4–8 mm, H = 3–6 mm.

Habitat. **–** Rivers, lakes and the nearshore zone of the Baltic Sea.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank (Holocene), Puck Bay (Holocene), Czołpino (Holocene), vicinity of Dobrzyń upon Vistula River (Holocene), Vistula Lagoon and Vistula Spit (Holocene), Resko Lake (Holocene), Slovincian Coast seacoast, Polish Lowlands.

Viviparus viviparus (Linnaeus, 1758)

Pl. I, Figs. 2, 3

Size. – H = 25–40 mm, W = 18–28 mm.

Habitat. – Major rivers with moderate velocity currents and lakes of Europe.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Gulf of Gdańsk (Holocene), Vistula Lagoon (Holocene), vicinity of Dobrzyń upon Vistula River (Holocene).

Valvata (Valvata) cristata Müller, 1774

Pl. I, Fig. 4

Size. – H = 1–1.3 mm, W = 2–3.5 mm.

Habitat. – Stagnant water reservoirs with rich vegetation or completely overgrown, or even swamps and trenches.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank (Late Glacial), Słupsk Bank (Late Glacial), Lower Vistula River area of Elbląg, Nadbrzeże (Eemian Interglacial), Poznań-Winiary and Szeląg (Eemian Interglacial), Pomerania and Wielkopolska regions (Holocene).

Valvata piscinalis f. antiqua Sowerby, 1838

Pl. I, Fig. 6

Size. – H = 5–7 mm, W = 4.8–7 mm.

Habitat. – A lacustrine form of the species *V. piscinalis*, known from almost all lakes of Poland and the Vistula Lagoon.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Gulf of Gdańsk (Late Glacial, Holocene), Resko Lake (Holocene), Czołpino (Holocene), Boże Pole (Late Glacial and Early Holocene), Vistula Lagoon (Holocene), vicinity of Przasnysz (Mazovian Interglacial), Poznań-Szeląg, Warsaw, vicinity of Wrocław, Polesie Lubelskie region, and vicinities of Lipno and Łomża (Holocene).

Valvata (Cincinna) piscinalis (Müller, 1774)

Pl. I, Fig. 5

Size. – H = 5–7 mm, W = 4.8–7 mm.

Habitat. – Rivers, lakes, ponds and lakes of the coastal zone, muddy or sandy-muddy bottoms.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Gulf of Gdańsk (Late Glacial and Holocene), Czołpino (Holocene), Jamno and Bukowo lakes (Holocene), Boże Pole (Late Glacial and Early Holocene), Vistula Lagoon (Holocene).

Littorina littorea (Linnaeus, 1758)

Pl. II, Figs. 1, 2

Size. – H = 24 mm, W = 17.5 mm.

Habitat. – Intertidal zone, abundant on rocky shores, can be found to a depth of 60 m.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay (Holocene), Gulf of Gdańsk (Holocene), Czołpino (Holocene), Lower Vistula River (Eemian Interglacial).

Littorina obtusata (Linnaeus, 1758)

Pl. II, Fig. 1

Size. – H = 10 mm, W = 10 mm.

Habitat. – Intertidal zone, lives on weeds.

Stratigraphical range. – Miocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay (Holocene).

Rissoa membranacea (Adams, 1800)

Pl. II, Fig. 3

Size. – H = 11 mm, W = 3 mm.

Habitat. – From the tidal zone sublittorally to about 15 m, associated with Zostera or on weeds with the same habit, extending into brackish water.

Stratigraphical range. – Miocene to Recent.

Quaternary inland records in Poland. – Southern Baltic – Pomorska Bay, Gulf of Gdańsk and Puck Bay (Holocene), Hel (Holocene), Czołpino (Holocene), Vistula Spit (Holocene), Lower Vistula River (Eemian Interglacial).

Turboella parva (Da Costa, 1779)

Pl. II, Fig. 4

Size. – H = 4.3 mm.

Habitat. – From the tidal zone to about 25 m, on fronds, smaller weeds and under stones.

Stratigraphical range. – Miocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay (Holocene).

Hydrobia ulvae (Pennant, 1777)

Pl. II, Figs. 5, 6

Size. – H = 8 mm, W = 3 mm.

Habitat. – Intertidal zone, but also found as deep as 20 m, on soft substrate, most often on intertidal banks of firm mud or muddy sand.

Stratigraphical range. – Miocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank, Southern Middle Bank (Holocene), Gulf of Gdańsk (Holocene), Puck Bay (Holocene), Czołpino (Holocene), Łebsko Lake (Holocene), Vistula Lagoon (Holocene), Vistula Spit (Holocene), Lower Vistula River (Eemian Interglacial).

Hydrobia ventrosa (Montagu, 1803)

Pl. II, Figs. 7, 8

Size. – H = 4 mm, W = 2.2 mm.

Habitat. – Intertidal zone, prefers lower salinities.

Stratigraphical range. – Miocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank, Southern Middle Bank (Holocene), Gulf of Gdańsk (Holocene), Puck Bay (Holocene), Lake Wicko (Holocene), Czołpino (Holocene), Lake Łebsko (Holocene), Vistula Lagoon (Holocene), Vistula Bar (Holocene).

Bithynia tentaculata (Linnaeus, 1758)

Pl. III, Figs. 1, 2, 3, 4

Size. – H = 9–12 mm, W = 6–8 mm.

Habitat. – Stagnant water and rivers, except for river sections with high velocity currents and acidic water. Also known from the Baltic Sea nearshore zone.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank (Holocene), Słupsk Bank (Holocene), Gulf of Gdańsk (Holocene), Jamno and Bukowo lakes (Holocene), Vistula Lagoon (Holocene), Vistula Spit (Holocene), Polish Lowlands (Mazovian and Eemian interglacials, and Holocene), Grabowa Valley (Early Holocene).

Bithynia leachi (Sheppard, 1823)

Pl. III, Figs. 5, 6

Size. – H = 5–7 mm, W = 4–4.5 mm.

Ecological notes. – Near shore zones of lakes and rivers, oxbows, draining trenches and other overgrown water reservoirs including intermittent lakes.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Gulf of Gdańsk (Holocene), Vistula Spit (Holocene), Vistula Lagoon (Holocene), Lake Resko (Holocene), vicinities of Elbląg and Łowicz (Eemian Interglacial), and Koszalin and Pyrzyce (Holocene).

Bittium reticulatum (Da Costa, 1778)

Pl. IV, Figs. 1, 2

Size. – H = 11 mm, W = 3 mm.

Habitat. – Common in shallow sublittoral water, but recorded to 250 m depth. Found on soft bottoms in association with weeds.

Stratigraphical range. – Neogene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula outlet cone (Holocene), Lower Vistula River area (Eemian Interglacial).

Nassarius reticulatus (Linnaeus, 1758)

Pl. IV, Figs. 3, 4

Size. – H = 21.5 mm, W = 12 mm.

Habitat. – From the tidal zone to about 15 m deep on soft bottoms.

Stratigraphical range. – Neogene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula outlet cone (Holocene), Lower Vistula River area (Eemian Interglacial).

Retusa obtusa (Montagu, 1803)

Pl. IV, Fig. 5

Size. – H = 7 mm, W = 3 mm.

Habitat. – From the intertidal zone down to 300 m deep in mud or fine sand, in the Kattegat region to around 20 m and in the Baltic Sea to 60 m deep.

Stratigraphical range. – Neogene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Gulf of Gdańsk (Holocene).

Retusa truncatula (Bruguière, 1792)

Pl. IV, Fig. 6

Size. – H = 4.5 mm.

Habitat. – In general, the species lives from the tidal zone down to a depth of 200 m. However, in the Danish area it lives in shallow waters down to only 20 m deep on sandy bottoms with Zostera.

Stratigraphical range. – Neogene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay (Holocene), Gulf of Gdańsk (Holocene).

Eulimella nitidissima (Montagu, 1803)

Pl. IV, Fig. 7

Size. – H = 2.5 mm, W = 0.7 mm.

Habitat. – From 5 to 50 m deep on muddy sand or shelly bottoms.

Stratigraphical range. – Neogene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula outlet cone (Holocene), Lower Vistula River (Eemian Interglacial).

Aplexa hypnorum (Linnaeus, 1758)

Pl. IV, Fig. 8

Size. – H = 8–15 mm, W = 3–5 mm.

Habitat. – Small stagnant water reservoirs such as clay pits, peatbogs and intermittent swamps.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Southern Middle Bank (Holocene), Gulf of Gdańsk (Holocene), Vistula Spit (Holocene), Vistula Lagoon (Holocene).

Physa fontinalis (Linnaeus, 1758)

Pl. IV, Figs. 9, 10

Size. – H = 7–11 mm, W = 5–8 mm.

Habitat. – Rivers, ponds, lakes, springs, canals and irrigation ditches. It occurs in both nutrient-poor and richly vegetated habitats.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Słupsk Bank (Early Holocene), Grabowa River valley (Early Holocene).

Lymnaea (Radix) peregra (Müller, 1774)

Pl. V, Fig. 5

Size. – H = 7–40 mm, W = 5–40 mm.

Habitat. – Small stagnant water reservoirs.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Southern Middle Bank (Holocene), Gulf of Gdańsk (Holocene), Vistula Spit (Holocene), Vistula Lagoon (Holocene), vicinity of Bełchatów, Poznań-Winiary and Szeląg (Eemian Interglacial), Mazury Lake District and surroundings of Krościenko (North-Polish Glaciation), vicinities of Dobrzyń upon Vistula River and Lipno, and eastern Pomerania (Holocene).

Lymnaea (Myxas) glutinosa (Müller, 1774)

Pl. V, Fig. 2

Size. – H = 10–19 mm, W = 8–14 mm.

Habitat. – Stable stagnant water reservoirs with rich vegetation, lakes, ponds, oxbows, quiet zones in rivers, peatbogs.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank (Holocene), Puck Bay (Holocene), Boże Pole (Early Holocene), Vistula Lagoon (Holocene).

Lymnaea (Galba) truncatula (Müller, 1774)

Pl. V, Figs. 3, 4

Size. – H = 5–10 mm, W = 3–6 mm.

Habitat. – Small shallow-water reservoirs of stagnant to slowly flowing water, but also known from wet shore zones.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Puck Bay (Holocene), Vistula Lagoon (Holocene), Poznań-Winiary, Warszawa-Żoliborz, and vicinity of Wrocław (Eemian Interglacial), Kraków-Częstochowa Upland (North-Polish Glaciation), Nida drainage basin, Pomerania, vicinities of Dobrzyń upon Vistula River and Fordon (Holocene).

Lymnaea stagnalis (Linnaeus, 1758)

Pl. V, Fig. 6

Size. – H = 25–60 mm, W = 11–30 mm.

Habitat. – Nearshore zones of reservoirs of stagnant or slowly flowing water, but sometimes also in drying-up reservoirs.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula Lagoon (Holocene), Warszawa-Żoliborz, Żmigród Basin (Eemian Interglacial), Wielkopolska region, and vicinity of Dobrzyń upon Vistula River (Holocene).

Anisus spirorbis (Linnaeus, 1758)

Pl. VI, Fig. 1, 2

Size. – H = 1.2–1.8 mm, W = 5–7 mm.

Habitat. – Small stagnant water reservoirs and even intermittent swamps.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula Lagoon (Holocene). Lower Silesia, western Pomerania, and Nida River drainage basin (Holocene).

Gyraulus albus (Müller, 1774)

Pl. VI, Fig. 3, 4

Size. – H = 1.2–1.9 mm, W = 4–7 mm.

Habitat. – Stagnant and slowly flowing waters.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula Lagoon (Holocene), Central Lublin region (Ferdynandów Interglacial), Wielkopolska Lake District, vicinity of Bełchatów, and Mazovian Lowland (Eemian Interglacial), western Pomerania, Bobrówka River valley, and Mazury Lake District (Holocene).

Gyraulus laevis (Alder, 1838)

Pl. VI, Fig. 5

Size. – H = 1.3–1.5 mm, W = 4–6 mm.

Habitat. – Clear stagnant waters of ponds, lakes and other not very strongly overgrown reservoirs.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank (Late Glacial), Gulf of Gdańsk (Late Glacial), Boże Pole (Late Glacial and Early Holocene), Vistula Lagoon (Holocene), Lublin Upland (Mid-Polish Glaciation), vicinity of Bełchatów (Eemian Interglacial), Łomża in the Narew River valley, and Szczecin Lowland (Holocene).

Armiger crista (Linnaeus, 1758)

Pl. VI, Fig. 6, PL. VII, Fig. 1

Size. – H = 0.5–0.85 mm, W = 2–3.5 mm.

Habitat. – Small shallow stagnant water reservoirs with rich vegetation.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank (Late Glacial), Pomeranian Bay (Late Glacial), Gulf of Gdańsk (Late Glacial), Vistula Lagoon (Holocene), Middle Odra River drainage basin – Boczów (Mazovian Interglacial), vicinity of Bełchatów (Eemian Interglacial), western Pomerania (end of North-Polish Glaciation), drainage basins of the Skrwa and Drwęca rivers (Holocene).

Segmentina nitida (Müller, 1774)

Pl. VII, Figs. 2, 3

Size. – H = 1.5–2 mm, W = 4–7 mm.

Habitat. – Small stagnant water reservoirs with rich vegetation.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula Lagoon (Holocene), Poznań-Winiary, Szeląg and Warszawa-Żoliborz (Eemian Interglacial), vicinity of Dobrzyń upon Vistula River, western Pomerania. Wielkopolska and Polesie Lubelskie regions (Holocene).

Acroloxus lacustris (Linnaeus, 1758)

Pl. VII, Figs. 4–7

Size. – H = 1.5–2 mm, W = 3.2–5 mm, L = 6–9 mm.

Habitat. – Overgrown stagnant water bodies, sometimes also flowing water with low current velocity.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay (Holocene), Vistula Lagoon (Holocene). Pomeranian Lake District and Wielkopolska – Kujawy region (Holocene), vicinity of Bełchatów (Eemian Interglacial).

Mytilus edulis Linnaeus, 1758

Pl. VIII, Fig. 1

Size. – L = 30–110 mm.

Habitat. – It inhabits lakes, ponds and rivers, lives on the sandy, stony, rocky and silty bottom.

Stratigraphical range. – Neogene to Recent.

Quaternary inland records in Poland. – Southern Baltic – Odra Bank, Southern Middle Bank, Słupsk Bank and Gulf of Gdańsk (Holocene), Lower Vistula River area (Eemian Interglacial), Czołpino (Holocene), Vistula Bar (Holocene).

Unio pictorum (Linnaeus, 1758)

Pl. VIII, Figs. 2, 3

Size. – L = 67–70 mm, H = 31 mm, W = 21–23 mm.

Habitat. – Rivers with variable current velocity, and lakes.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic – Gulf of Gdańsk (Late Glacial), Vistula Lagoon (Holocene), Vistula Bar (Holocene), Boże Pole (Early Holocene), Poznań-Szeląg and Elbląg (Eemian Interglacial), Mazury Lake District (North-Polish Glaciation) and vicinity of Dobrzyń upon Vistula River (Holocene).

Anodonta cygnaea – glochidium (Linnaeus, 1758)

Pl. VIII, Figs. 5–8

Size. – L = above 300 µm, H = above 300 µm,

Habitat. – The glochidium is a microscopic larval stage of some freshwater mussels, aquatic bivalve molluscs of the families Unionidae and Margaritiferidae, river mussels, and European freshwater pearl mussels. This larval form has hooks that enable it to attach itself to fish.

Stratigraphical range. – Pleistocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Gulf of Gdańsk (Holocene), Vistula Lagoon (Holocene), Resko Lake (Holocene), Czołpino, Elbląg, Poznań (Holocene), vicinity of Bełchatów (Eemian Interglacial).

Mysella bidentata (Montagu, 1803)

Pl. VIII, Fig. 8

Size. – L = 3.7 mm, W = 2 mm, H = 3 mm.

Habitat. – Intertidal zone down to 2500 m depth, often in commensal association with other animals.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay and Gulf of Gdańsk (Holocene), Vistula Spit and Lower Vistula River (Eemian Interglacial).

Cardium edule (Linnaeus)

Pl. IX, Figs. 1, 2

Size. – L = 28 mm, W = 17 mm, H = 23 mm.

Habitat. – A shallow-water infaunal species, intertidal to a few metres deep, but in the Baltic Sea occurring also at 20–30 m.

Stratigraphical range. – Neogene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Ławica Odrzana (Holocene), Pomeranian Bay and Gulf of Gdańsk (Holocene), Vistula Spit (Eemian Interglacial and Holocene), Czołpino (Holocene).

Cerastoderma glaucum (Poiret)

Pl. IX, Figs. 3, 4

Size. – L = 27 mm, W = 18 mm, H = 22 mm.

Habitat. – This is a shallow-water species on sand and mud bottoms, the associated fauna indicates a tidal estuarine environment.

Stratigraphical range. – Neogene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank, Southern Middle Bank, Gulf of Gdańsk and Puck Bay (Holocene), Vistula Spit (Holocene), Bukowo and Wicko Lakes (Holocene), Czołpino (Holocene), Lower Vistula River (Eemian Interglacial).

Parvicardium hauniense (Petersen et Russell, 1971)

Pl. IX, Figs. 5, 6

Size. – L = 8 mm, W = mm, H = mm.

Habitat. – Bottoms lined with vascular plants or algae.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay (Holocene), Puck Bay (Holocene).

Spisula subtruncata (Da Costa, 1778)

Pl. X, Figs. 1, 2

Size. – L = 8 mm, H = 5 mm, W = 3 mm.

Habitat. – From the intertidal zone down to 20–30 m deep in mud and sand.

Stratigraphical range. – Miocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula outlet cone (Holocene), Lower Vistula River area (Eemian Interglacial).

Macoma balthica (Linnaeus, 1758)

Pl. X, Figs. 3, 4

Size. – L = 23 mm, H = 17 mm, W = 9 mm.

Habitat. – A shallow water-species, but in the Baltic Sea it occurs also at depths of more than 50 m on soft bottoms.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay, Southern Middle Bank, Gulf of Gdańsk, Puck Bay and Vistula Spit (Holocene), Czołpino (Holocene), Lower Vistula River and Vistula Spit (Eemian Interglacial).

Scrobicularia plana (Da Costa, 1778)

Pl. X, Figs. 5–8

Size. – L = 50 mm, H = 40 mm, W = 10 mm.

Habitat. – From the intertidal zone to about 30 m depth in clay or muddy bottoms, often in estuaries.

Occurrence. – The Boreal and Lusitanian regions.

Quaternary inland records in Poland. – Southern Baltic Sea – Gulf of Gdańsk (Holocene), Vistula Bar (Holocene), Czołpino (Holocene) Lower Vistula River (Eemian Interglacial).

Dreissena polymorpha (Pallas, 1771)

Pl. XI, Fig. 1

Size. – L = 25–40 mm, H = 13–18 mm, W = 17–23 mm.

Habitat. – Slowly flowing rivers, canals, lakes and ponds. It prefers hard substrate.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Szczecin Lagoon and Vistula Lagoon (Late Holocene).

Sphaerium corneum (Linnaeus, 1758)

Pl. XI, Figs. 4, 5

Size. – L = 8–16 mm, H = 7–11.5 mm, W = 6–9.5 mm.

Habitat. – Lakes and rivers, also known from the Vistula Lagoon.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula Lagoon (Holocene).

Sphaerium solidum (Normand, 1844)

Pl. XI, Figs. 2, 3

Size. – L = 7–12.5 mm, H = 5–10.5 mm, W = 5–8.5 mm.

Habitat. – Sandy bottoms of major rivers, but also known from the Vistula Lagoon.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula Lagoon (Holocene).

Sphaerium rivicola (Lamarck, 1818)

Pl. XI, Figs. 6, 7

Size. – L = 18–30 mm, H = 15–18 mm, W = 10–14 mm.

Habitat. – Mainly rivers, but also in large reservoirs of stagnant water.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula Lagoon (Holocene).

Pisidium amnicum (Müller, 1774)

Pl. XII, Figs. 1, 2, 3

Size. – L = 7–11 mm, H = 5–9 mm, W = 4–6.5 mm.

Habitat. – It lives mainly in flowing waters, it occurs in large lakes and ponds.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank (Late Glacial), Słupsk Bank (Early Holocene), Southern Middle Bank (Holocene), Kopań Lake (Holocene), Gulf of Gdańsk (Early Holocene and Holocene), Vistula Lagoon (Holocene), Vistula Spit (Holocene), vicinities of Wrocław and Chełmno upon the Lower Vistula River (Eemian Interglacial), eastern Lublin region (Brörup Interglacial), Boże Pole, vicinity of Wierzyca (Early Holocene).

Pisidium supinum Schmidt, 1851

Pl. XII, Figs. 4, 5

Size. – L = 3.3–5.2 mm, H = 2.8–4.9 mm, W = 2–3.8 mm.

Habitat. – Rivers with sandy to somewhat clayey bottoms and occasionally stagnant water basins.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Gulf of Gdańsk (Holocene), Vistula Lagoon (Holocene), Vistula Spit (Holocene), drainage basin of the Middle Odra River (Mazovian Interglacial), and vicinities of Poznań and Wrocław (Eemian Interglacial).

Pisidium milium Held, 1836

Pl. XIII, Figs. 1, 2

Size. – L = 1.8–3.75 mm, H = 1.6–3.0 mm, W = 1.5–2.75 mm.

Habitat. – Stagnant and slowly flowing water with muddy bottom, but mainly related to shallow muddy reservoirs of stagnant water, overgrown with aquatic plants.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank, Słupsk Bank, Southern Middle Bank, Resko Lake (Holocene), Gulf of Gdańsk (Late Glacial), Poznań-Winiary and vicinity of Bełchatów (Eemian Interglacial), western Pomerania, vicinities of Lipno and Łomża (Holocene), Boże Pole, vicinity of Wierzyca (Late Glacial and Early Holocene), Grabowa River valley (Early Holocene).

Pisidium subtruncatum Malm, 1855

Pl. XIII, Figs. 3, 4

Size. – L = 2.5–4.5 mm, H = 2–3.7 mm, W = 1.3–3 mm.

Habitat. – Rivers, lakes and even swamps.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Vistula Lagoon (Holocene).

Pisidium nitidum Jenyns, 1832

Pl. XIII, Figs. 5, 6

Size. – L = 2.6–4.3 mm, H = 2.1–3.5 mm, W = 1.4–2.7 mm.

Habitat. – An eurytopic species living in stagnant and flowing water, but avoiding strong current zones.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank, Słupsk Bank Southern Middle Bank, and Gulf of Gdańsk (Late Glacial), Resko Lake (Holocene), Vistula Lagoon (Holocene), Vistula Spit (Holocene), Boże Pole, vicinity of Wierzyca (Late Glacial and Early Holocene), Grabowa Valley (Early Holocene), Poznań-Winiary and vicinity of Bełchatów (Eemian Interglacial), western Pomerania, vicinities of Lipno and Łomża (Holocene).

Pisidium obtusale (Lamarck, 1818)

Pl. XIV, Fig. 1

Size. – L = 2.4–3.5 mm, H = 1.9–2.9 mm, W = 1.5–2.7 mm.

Habitat. – Small stagnant water reservoirs, such as swampy lakes, oxbows, trenches, ponds, and peatbogs.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank (Late Glacial), Poznań-Winiary and vicinity of Bełchatów (Eemian Interglacial), western Pomerania (end of the North-Polish Glaciation), drainage basin of the lower Drwęca River (Holocene).

Pisidium casertanum (Poli, 1791)

Pl. XIV, Figs. 2–6

Size. – L = 3.5–6.5 mm, H = 3–5.5 mm, W = 2–4 mm.

Habitat. – Various aquatic environments, from flowing to stagnant water and even swamps and springs.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank, Słupsk Bank, Southern Middle Bank, Jamno, Bukowo and Kopań lakes (Holocene), Gulf of Gdańsk (Late Glacial), Kopań Lake (Holocene), Vistula Lagoon (Holocene), Vistula Spit (Holocene), drainage basin of the Middle Odra River (Mazovian Interglacial), Poznań-Winiary, Warszawa-Żoliborz, and Bełchatów area (Eemian Interglacial), western Pomerania, Warsaw-Żoliborz, vicinity of Bełchatów (Eemian Interglacial), Mazury Lake District (North-Polish Glaciation), Wielkopolska, and drainage basins of Kamienna River and lower Drwęca River (Holocene).

Pisidium conventus Clessin, 1877

Pl. XV, Figs. 1, 2

Size. – L = 2.2–3 mm, H = 1.7–2.2 mm, W = 1.2–1.5 mm.

Habitat. – A relic of colder climatic periods, found only in deep, cold upland lakes.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank (Late Glacial), Pomeranian Bay (Late Glacial), Kopań Lake (Late Glacial), Gulf of Gdańsk (Late Glacial).

Pisidium moitessierianum Paladilhe, 1866

Pl. XV, Figs. 3, 4

Size. – L = 1.5–2.2 mm, H = 1.4–2.1 mm, W = 1–1.8 mm.

Habitat. – Living in lakes and rivers, but avoiding environments of quick currents and those of minor stagnant water reservoirs.

Stratigraphical range. – Pliocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank, Słupsk Bank and Gulf of Gdańsk (Early Holocene), Resko Lake (Holocene), Vistula Lagoon (Holocene), Vistula Spit (Holocene), drainage basin of the Middle Odra River (Mazovian Interglacial), Poznań-Szeląg, vicinities of Piotrków Trybunalski and Wrocław (Eemian Interglacial), and Kaszuby Lake District and vicinity of Łomża (Holocene).

Corbula gibba (Olivi, 1792)

Pl. XV, Figs. 5, 6

Size. – L = 9 mm, H = 6.5 mm.

Habitat. – From the low intertidal zone to 250 m, anchored by a byssus on silty sand and muddy gravel bottoms, however, in Danish waters, rarely at depths of more than *ca.* 50 m, in the North Sea sampled at 35–50 m depths on mixed bottoms.

Stratigraphical range. – Miocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Odra Bank, Gulf of Gdańsk (Holocene), Vistula Bar (Eemian Interglacial).

Thracia papyracea (Poli, 1795)

Pl. XVI, Fig. 1

Size. – L = 30 mm.

Habitat. – Clayey sand and sandy clay bottoms of low-temperature waters.

Stratigraphical range. – Miocene to Recent.

Quaternary inland records in Poland. – Southern Baltic – Pomeranian Bay and Gulf of Gdańsk (Holocene), Vistula outlet coin (Holocene).

Mya arenaria Linnaeus, 1758

Pl. XVI, Fig. 2

Size. – L = 100 mm, H = 60 mm, W = 40 mm.

Habitat. – Living buried deeply in sandy or silty-sandy bottoms.

Stratigraphical range. – Late Holocene to Recent.

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay, Wicko Lake (Late Holocene), Gulf of Gdańsk (Late Holocene), Vistula outlet cone (Late Holocene).

Mya truncata Linnaeus, 1758

Pl. XVI, Figs. 3, 4

Size. – L = 52 mm, H = 38 mm, W = 22 mm.

Habitat. – From the intertidal zone down to *ca.* 75 m deep, in the North Sea found at depths of 37–70 m on soft mixed bottoms.

Stratigraphical range. – Neogene to Recent

Quaternary inland records in Poland. – Southern Baltic Sea – Pomeranian Bay and Gulf of Gdańsk (Holocene).

LATE GLACIAL AND HOLOCENE ENVIRONMENT CHANGES IN THE LIGHT OF DIVERSIFIED INVESTIGATIONS

Much of the Southern Baltic area was a lakeland during the Late Glacial and at the beginning of the Holocene. This is substantiated by geophysical and biostratigraphic investigations which reveal that the lakes, accompanied by peat bogs, were forming in depressions. Lakes that developed within melt-out kettles were later filled with clay-mud and mud-sand sediments. The presence of remnants of such lakes has been evidenced in the shallow-water area of the Southern Baltic Sea and in many sites of the Polish coast, e.g. in the Gulf of Gdańsk and along the middle coast.

These were oligotrophic water bodies with highly stable depositional conditions, recharged by rain and ground waters as well as by surface watercourses draining the moraine upland. In many areas, sediments of these lakes have survived the marine transgression and are identifiable by seismo-acoustic images and lithological and biostratigraphical investigations.

The occurrence of any species in deposits is directly dependent on the change of climate (there are both warm and cold taxa) and environment (marine, brackish and freshwater) (Fig. 7). Figure 7 summarizes the palaeoclimate and palaeoenvironmental constraints on the occurrence of species presented in this contribution.

Results of investigations of sediment samples collected in the Pomeranian Bay show that the bog-lacustrine sediments with freshwater molluscs were deposited during the Late Glacial period (Kramarska, 1998; Krzymińska, 2001; Krzymińska, Przezdziecki, 2001). Detailed mapping of the Pomeranian Bay, carried out in 2010–2013 (Kramarska *et al.*, 2013), has allowed developing a model of the lakeland that had existed in that area prior to the marine transgression. Geophysical records from that region indicate high variability in the size and depth of the lakes, as well as in the sedimentary structures of the lake infills (Krzymińska *et al.*, 2016).

Species	Palaeoclimatic characteristic lacustrine marine				Palaeoenvironmental characteristic			
	warm	cold	boreal	subarctic	marine	marine-brackish	brackish-freshwater	freshwater
Acroloxus lacustris	•							•
Aplexa hypnorum	•							
Armiger crista f. cristatus		•						•
Bithynia tentaculata	•							•
Bithynia leachi	•							•
Gyraulus laevis		•						•
Gyraulus albus	•							•
Gyraulus rossmaessleri	•							
Lithoglyphus naticoides	•							•
Lymnaea auricularia	•							
Lymnaea peregra		•						•
Lymnaea glutinosa	•							•
Lymnaea truncatula		•						•
Physa fontinalis	•							•
Planorbarius corneus	•							•
Potamopyrgus antipodarum	•						•	
Segmentina nitida	•							•
Theodoxus fluviatilis	•						•	
Valvata cristata	•							•
Valvata piscinalis	•							•
Valvata piscinalis f. antiqua	•							•
Valvata pulchella	•							•
Viviparus viviparus	•						•	
Anodonta cygnea-glochidium	•							•
Unio crassus	•							•
Unio pictorum	•							
Dreissena polymorpha	•						•	
Pisidium amnicum	•							•
Pisidium casertanum		•						•
Pisidium casertanum f. ponderosa		•						•
Pisidium conventus		•						•
Pisidium lilljeborgii								
Pisidium milium		•						•
Pisidium moitessierianum	•							•
Pisidium nitidum		•						•
Pisidium subtruncatum	•							•
Pisidium supinum	•							•
Pisidium lapponicum f.obtusale		•						•
Sphaerium corneum	•							•
Sphaerium corneum f. *mamillanum*	•							•
Sphaerium rivicola	•							•
Sphaerium solidum	•							•
Bittium reticulatum			•		•			
Hydrobia ulvae			•			•		
Hydrobia ventrosa			•			•		
Littorina littorea			•		•			
Littorina obtusata			•		•			
Nassarius reticulatus			•		•			
Retusa truncatula			•		•			
Retusa obtusa				•	•			
Rissoa membranacea			•		•			
Turboella parva			•		•			
Cerastoderma glaucum			•			•		
Cardium edule			•		•			
Corbula gibba			•		•			
Macoma balthica				•		•		
Mya truncata				•	•			
Mya arenaria			•			•		
Mysella bidentata			•		•			
Mytilus edulis			•			•		
Parvicardium hauniense			•		•			
Scrobicularia plana			•		•			
Spisula subtruncata			•		•			
Thracia papyracea			•		•			

Fig. 7. Palaeoenvironmental and palaeoclimatic characteristics of studied molluscs from the Late Glacial and the Holocene sediments of the Southern Baltic Sea

Malacofaunal studies in the Gulf of Gdańsk showed that the fossiliferous bog-lacustrine sequences were accumulated in the Late Glacial and Early Holocene (Uścinowicz, Zachowicz, 1994; Krzymińska 2001; Krzymińska, Przezdziecki 2010; Krzymińska, Namiotko, 2012). Remains of trees, rooted in the present-day sea-floor, were found in a shallow-water area (about 20 m b.s.l.) north of Ustka. Analysis of seismo-acoustic materials from that region demonstrates that the trees once grew on a promontory surrounded by lakes. Remains of water bodies, filled with lacustrine sediments, were also found in the Southern Middle Bank (Miotk-Szpiganowicz *et al.*, 2009; Krzymińska *et al.*, 2016).

More evidence of Late Glacial freshwater basins comes from some sites of the present-day coastal zone (Dobracki, Zachowicz, 1997; Krzymińska *et al.*, 2003; Krzymińska, Dobracki, 2004; Krzymińska *et al.*, 2011). However, modern coastal lakes were initially located on a much wider terriestal area surrounding the Baltic Ice Lake from the south, which functioned for about 10.3 ka of BP (Swenson, 1991). The eustatic sea-level fall in the Early Holocene Yoldia Sea basin and the freshwater Ancylus Lake (10.3–8.5 ka BP) remain unaffected by the palaeoecological changes of these lakes. Within them, the continuous accumulation of terrigenic material originating from erosion and denudation of the upland as well as from fluvial sedimentation continues, they do not affect the palaeoecological changes of these lakes. Intense sedimentation in these lakes caused their rapid shallowing. The mollusc and ostracod faunas are represented exclusively by freshwater species.

Palaeogeographic situation of the Baltic Sea dramatically changed as a result of marine transgression in the Atlantic period of the Littorina Sea. In the wake of renewed connection with the world ocean through the Danish Straits at about 8.5 ka BP, the present-day shape of the Baltic Sea-floor started to be formed (Uścinowicz, 2003). Initially, the transgression was very fast and, during the time interval of 8.5–7.5 ka BP (Mastogloia Sea phase), the sea-level rose by approximately 13 m. Then, the transgression rate decreased and, in the period from 7.5 to 5.0 ka BP (Littorina Sea phase), the sea-level rose by only 12 m (Uścinowicz, 2003). It should be borne in mind that the shoreline significantly shifted southwards at that time. In contrast, no distinct changes in the shoreline took place in the post-Atlantic period (after 5.0 ka BP), and it became very similar to the present one.

Due to the connection with the world ocean, namely with the North Sea, there was also a change in the hydrographical structure of the Baltic waters. The Baltic Sea is characterized by two-layer salinity stratification of the water column, including the isohaline upper layer which is less saline and withrelatively constant salinity, and the higher-salinity lower layer. These two layers are separated by a zone of rapid salinity increase, referred to as the halocline. Vertical stratification of the Baltic Sea is changeable and depends predominantly on the influx of river waters into the marine basin, and on the bottom intrusions of oceanic waters.

These hydrological changes, associated with the transgression of the Littorina Sea and Post-Littorina Sea (Atlantic – Subatlantic period) and resulting in the present-day spatial pattern of the Baltic Sea, strongly affected the southern coast of the marine basin. Individual lake basins were transformed as a result of the abrasion-driven southward shift of the shoreline into shallow-marine embayments or isolated water bodies that had periodic connections with the marine basin. The nature of the fauna and flora was changing, depending on the type of connection with the open sea, which is well-reflected in the changes in malacofauna associations from the spit areas of Jamno and Bukowo Lakes (Krzymińska *et al.*, 2016).

SUMMARY

The study of molluscs has allowed determination of relationships between the faunal sequence and the changes in ecological, hydrological and climatic conditions. The presence of subfossil mollusc associations in the deposits has been linked to the geological history of the Southern Baltic Sea. This provides the basis for a fairly clear outline of the evolutionary stages of this area that was subjected to transformation from the areal deglaciation and the existence of lakes during the Late Glacial and earliest Holocene, through the saline basin of the climatic optimum (Littorina Sea phase), to the brackish basin similar to the present-day one (Fig. 8).

In the Late Glacial and Preboreal periods, mineral-organic accumulation started in cold tundra lakes that had been formed in melt-out kettles. The malacofauna associations were represented by freshwater species indicating cold climate, such as: *Armiger crista f. cristatus* Draparnaud, *Gyraulus laevis* (Alder), *Lymnaea peregra* (Müller), *Valvata cristata* Müller, *Pisidium conventus* Clessin, *Pisidium milium* Held and *Pisidium nitidum* Jenyns (Fig. 9).

Gyttjas, peats and peaty muds were accumulated in shallow lakes overgrown by alder woods and rushes. In contrast, lacustrine deposits of the Boreal period have yielded molluscs with higher thermal requirements: *Bithynia tentaculata* (Linnaeus), *Bithynia leachi* Sheppard, *Theodoxus fluviatilis* (Linnaeus), *Physa fontinalis* (Linnaeus), *Pisidium amnicum* (Müller) and *Pisidium moitessierianum* Paladilhe (Fig. 8).

The Littorina Sea transgression (Atlantic period) shaped the basin of the Baltic Sea, having a particularly strong effect on its southern coast. Individual lake basins were transformed as a result of the abrasion-driven southward shift of the shoreline into shallow-marine embayments or isolated water bodies that had periodic connections with the marine basin.

At the initial stage of marine deposition, steno- and euryhaline mollusc species dominated, including: *Hydrobia ul-*

vae (Pennant), *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Mytilus edulis* Linnaeus, *Retusa obtusa* Montagu, *Retusa truncatula* (Bruguière), *Rissoa membranacea* (Adams), *Cardium edule* (Linnaeus), *Mya truncata* Linnaeus, *Mysella bidentata* (Montagu), *Thracia papyracea* (Poli), *Turboella parva* (Da Costa), *Parvicardium hauniense* (Petersen et Russell) and *Scrobicularia plana* (Da Costa). The presence of these gastropods and bivalves indicates that the water salinity during the first stage of the transgression was higher than at present, and exceeded 20 psu.

The above-mentioned mollusc species have different ecological requirements and different ranges of distribution. Most of them currently inhabit the Bay of Kiel, where the salinity is ca. 20–22 psu, and the Danish Straits, the North Sea and the Arctic Ocean (35 psu). Such species as *Bittium reticulatum* (Da Costa), *Nassarius reticulatus* (Linnaeus), *Abra nitida* (Müller), *Corbula gibba* (Olivi) and *Mya truncata* Linnaeus live in highly saline waters (16–35 psu). Only *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus) and *Mytilus edulis* Linnaeus presently inhabit the Southern Baltic Sea.

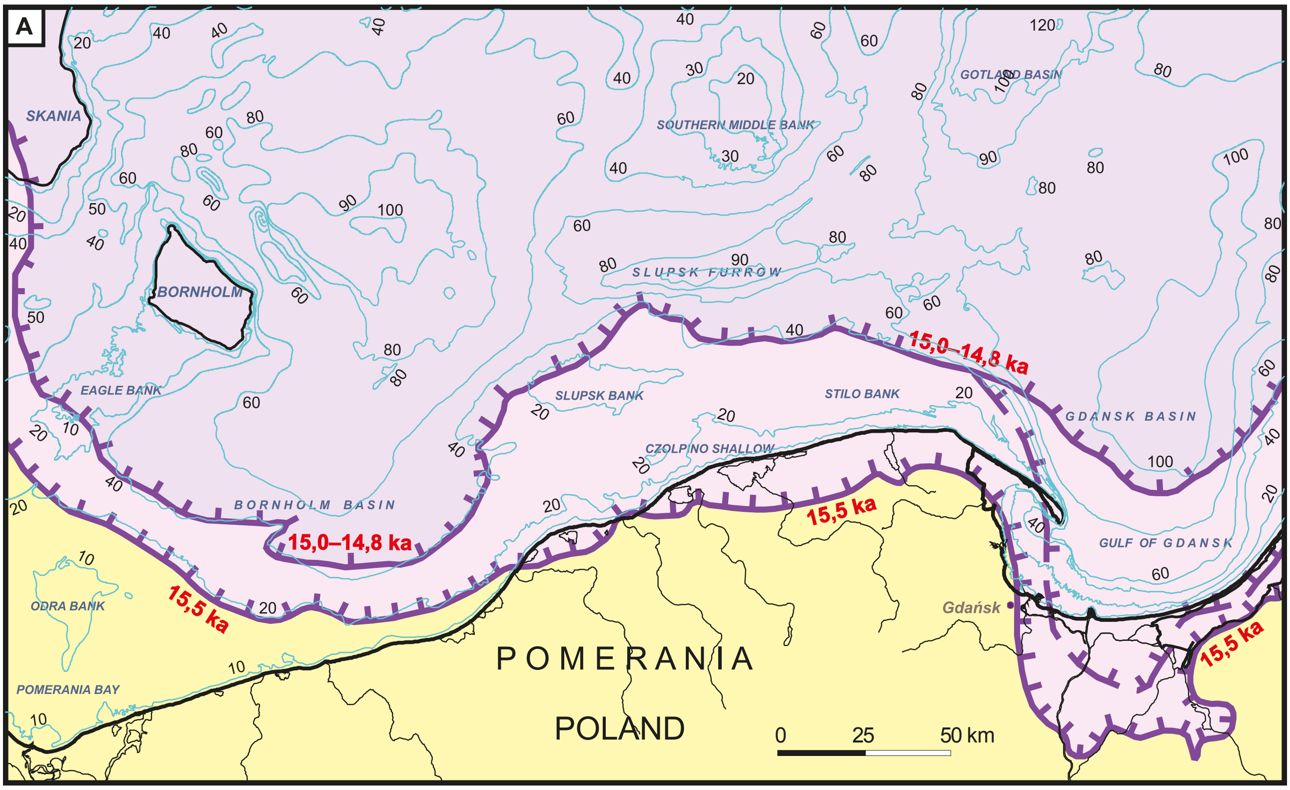
Euryhaline species survived the later stage of the Litorina transgression and they are today the elements of modern faunas of the Southern Baltic Sea: *Hydrobia ulvae* (Pennant), *Hydrobia ventrosa* (Montagu), *Cerastoderma*

Explanations to Figure 8 A–C

- Land area (free of Continental Ice Sheet)
- Hypothetical location od lakes, mainly within Bay of Pomerania (the start of forming of lakeland area – Late Glacial)
- Fig. 4 – Location of Figure 3 and 4 (see Fig. 8B) and Figure 5 and 6 (see Fig. 8C)
- Area of displacement of shore line of Baltic Ice Lake (general rising of water level and retreating of coast line towards the land)
- Area of displacement of shore line of Baltic Ice Lake (rate of agraddation of bottom sediments greater then rate of waterrising and progression of coast line towards the water basin)
- Hypothetical location od lakes, mainly within Bay of Pomerania (different stages of development of former lakeland area during Holocene: Yoldia Sea, Ancylus Lake), Litorina Sea?)
- ~15,5 ka – Ice sheet extent during Gardno phase (about 15,5 ka), last glacial standing partly within land area (Northern Poland)
- 15,0–14,8 ka – Ice sheet extent during Słupsk Bank phase (about 15,0–14,8 ka), glacial standing within southern part of Central Baltic area – deglaciation mainly in land condictions
- ~14,5 ka – Ice sheet extent during Southern Middle Bank phase (about 14,5 ka), glacial standing within northern part of Central Baltic area – beginning of origin of Baltic Ice Lake
- ~14,5 ka – Extent of water basin at the beginning of Baltic Ice Lake (about 14,5 ka)
- ~11,7 ka – Extent of water basin of Baltic Ice Lake before final drenage (about 11,75 ka)
- 20 – Isobathes every 20 m, locally 10 m too (according to recent topography of Baltic Sea)

Extent of water basin during:

- 11,5–11,3ka – Phase of Yoldia Sea
- ~10,5 ka – Phase of Ancylus Lake
- ~8,0 ka – Phase of Litorina Sea (beginning)
- ~7,0 ka – Phase of Litorina Sea
- ~3,0 ka – Phase of Post Litorina Sea



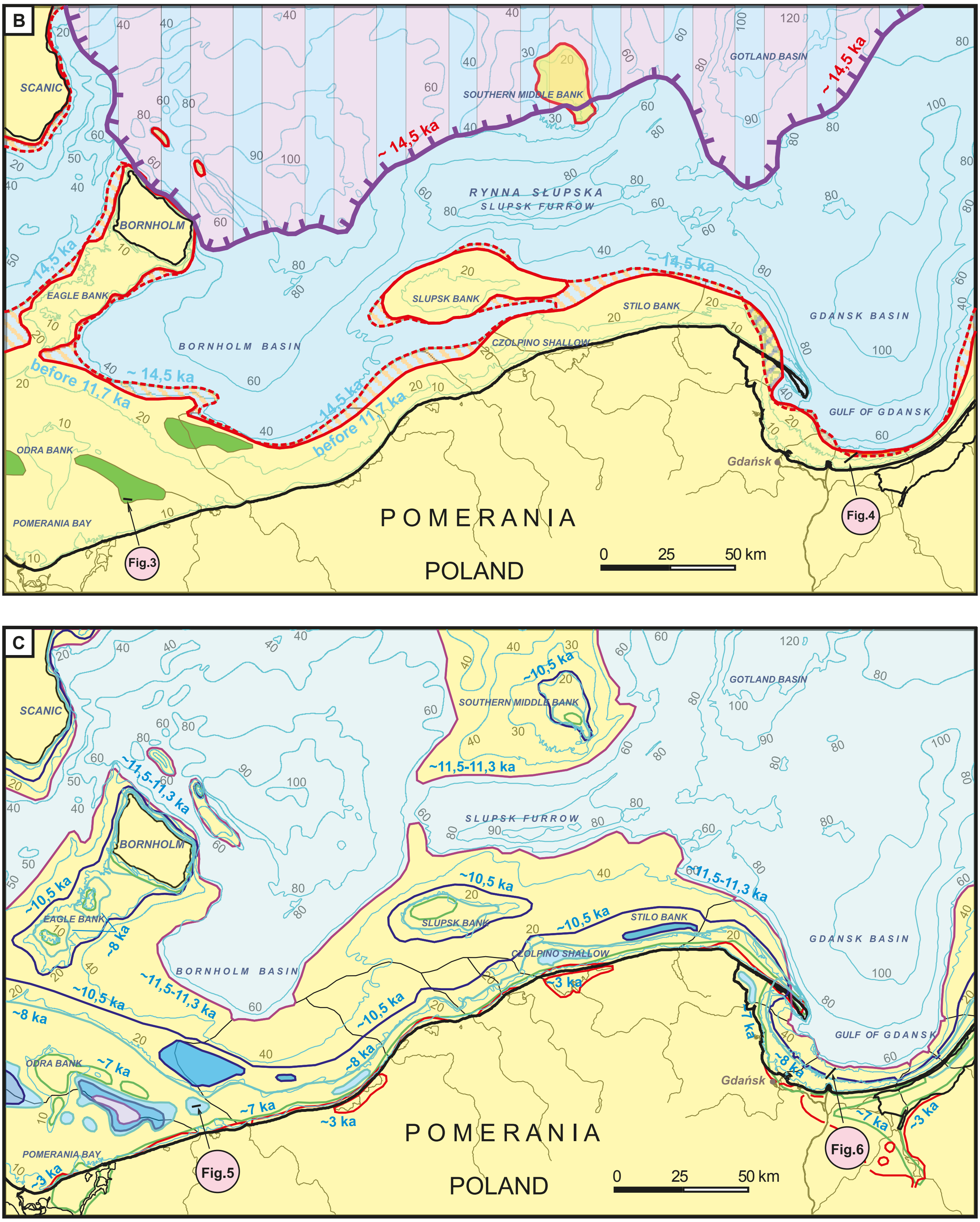


Fig. 8. Palaeogeography of the southern part of Central Baltic during:
A– Late Glacial (15,5–14,8 ka BP); B – Late Glacial (14,5–11,7 ka BP); C – Holocene (11,7 ka BP – up to present).
Palaeogeographical data (evolution of the Southern Baltic during Late Glacial and Holocene)
according to (Uścinowicz, 1995, 2015)

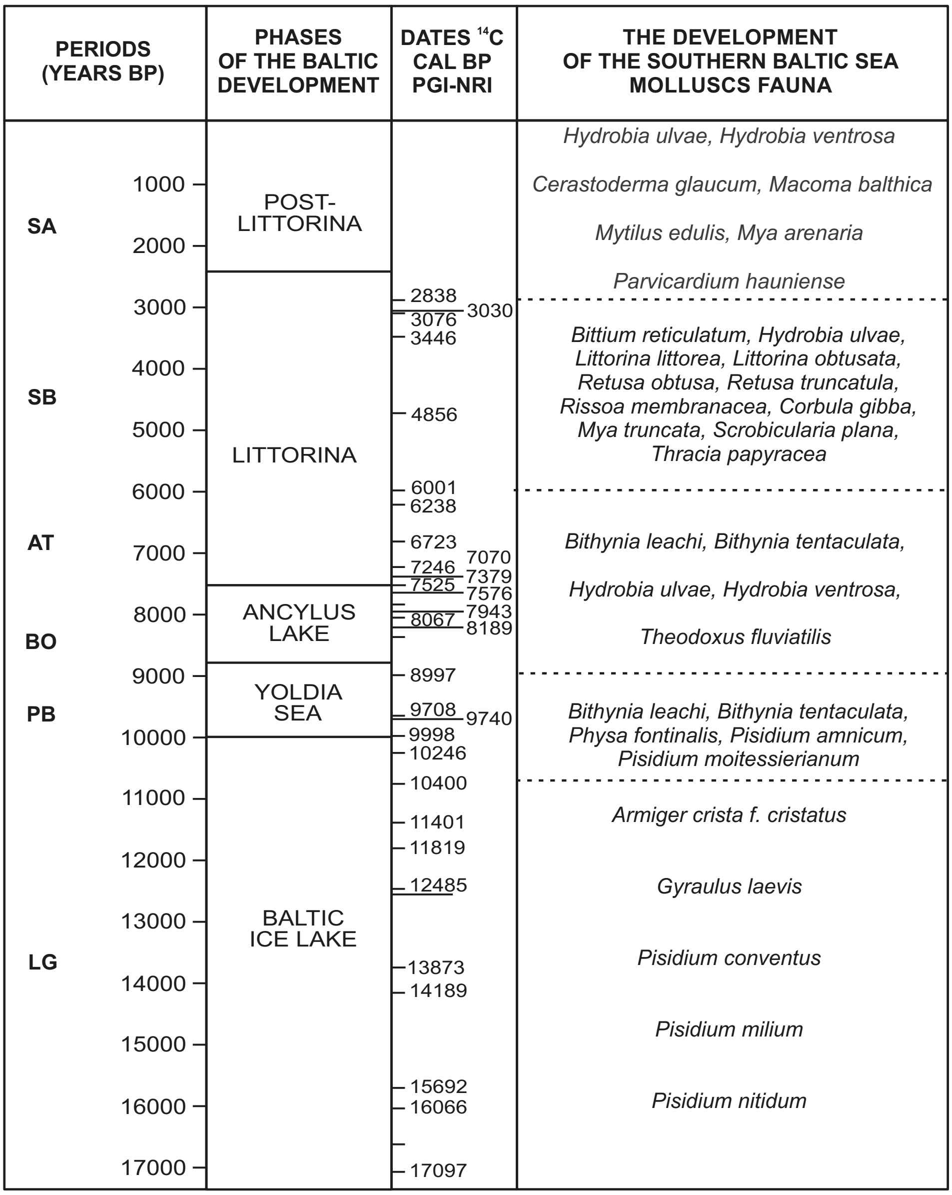


Fig. 9. Correlation between the succession of the molluscs of the Southern Baltic Sea (radiocarbon dates according to the Marine Geology Branch of the mollusc palaeoassemblages of the Polish Geological Institute – National Researche Institute) and phases of the Baltic development (Bjorck, Svensson 1994; Bjorck, 1995; Eronen, 1998; Uścinowicz, 2003)

SA – Subatlantic, SB – Subboreal, AT – Atlantic, BO – Boreal, PB – Preboreal, LG – Late Glacial

glaucum (Poiret), *Macoma balthica* (Linnaeus), *Mytilus edulis* Linnaeus, *Mya arenaria* Linnaeus and *Parvicardium hauniense* (Petersen et Russell). Water salinity in the basin reached a level similar to that observed today, decreasing to ca. 7–8 psu. The faunal and floral succession changed significantly at that time. Faunas of marine and open lagoons, showing variable intensity of contact with saline marine waters, appear in the deposits overlying the peat layer in the analyzed sections of Jamno, Bukowo Lakes and other lakes. This is manifested by the presence of the bivalves *Cerastoderma glaucum* (Poiret) and *Macoma balthica* (Linnaeus).

After the Littorina transgression peak, the process of gradual water freshening was marked in the lakes (Jamno, Bukowo and Kopań lakes). An increase in the proportion of freshwater species *Valvata piscinalis f. antiqua* (Morris), *Pisidium casertanum* Poli and *Pisidium conventus* Clessin is observed in the molluscan associations, with a simultaneous decrease in the number of index species for the Littorina Sea. A change in the species composition of forest communities inhabiting the land close to the shore occurred at that time due to a change in climatic conditions (Krzymińska, Dobracki, 2004; Krzymińska *et al.*, 2011; Krzymińska *et al.*, 2016). In offshore shallow-water areas, the Post-Littorina Sea fauna was represented by euryhaline marine species, such as: *Hydrobia ulvae* (Pennant), *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus), *Mya arenaria* Linnaeus, *Mytilus edulis* Linnaeus and *Parvicardium hauniense* (Petersen et Russell) (Krzymińska, 2000; Krzymińska, 2001; Krzymińska, Przezdziecki, 2001; Krzymińska *et al.*, 2016).

CONCLUSIONS

1. During the Late Glacial and Preboreal periods, freshwater fauna inhabited the areas of the Pomeranian Bay, Słupsk Bank and Gulf of Gdańsk, including: *Armiger crista f. cristatus* Draparnaud, *Gyraulus laevis* (Alder), *Lymnaea peregra* (Müller), *Pisidium amnicum* (Müller), *Pisidium milium* Held and *Pisidium nitidum* Jenyns, indicating lacustrine sedimentary environments.

2. In the Boreal period, terrestrial conditions continued in the Odra Bank region, as evidenced by the occurrence of freshwater species: *Bithynia tentaculata* (Linnaeus), *Bithynia leachi* Sheppard, *Theodoxus fluviatilis* (Linnaeus) and *Pisidium moitessierianum* Paladilhe.

3. By early Atlantic times, the shallow-water part of the Southern Baltic area was covered by lakes. The Littorina transgression proceeded gradually, inundating successively the whole Southern Baltic area. This is evidenced by the co-occurrence of freshwater and marine species in the deposits.

4. *Littorina littorea, Retusa obtusa* (Montagu), *Retusa truncatula* (Bruguière), *Cardium edule* (Linnaeus), *Bittium reticulatum* (Da Costa), *Nassarius reticulatus* (Linnaeus), *Corbula gibba* (Olivi), *Mya truncata* Linnaeus, *Mysella bidentata* (Montagu), *Thracia papyracea* (Poli), *Turboella parva* (Da Costa) and *Scrobicularia plana* (Da Costa) are the species found for the first time in Holocene deposits of the Southern Baltic Sea. Their occurrence may indicate higher water salinity than it is today.

5. Mollusc species, such as: *Hydrobia ulvae* (Pennant), *Hydrobia ventrosa* (Montagu), *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus) and *Mytilus edulis* Linnaeus are characteristic of the Post-Littorina Sea deposits.

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PLATES

PLATE I

Fig. 1. *Theodoxus fluviatilis* (LINNAEUS), × 13

Fig. 2. *Viviparus viviparus* (LINNEAUS), × 3

Fig. 3. *Viviparus viviparus* (LINNEAUS), × 3

Fig. 4. *Valvata cristata* MÜLLER, × 98

Fig. 5. *Valvata piscinalis* MÜLLER, × 36

Fig. 6. *Valvata piscinalis f. antiqua* SOWERBY, × 21

Fig. 7. *Littorina obtusata* (LINNAEUS), × 29

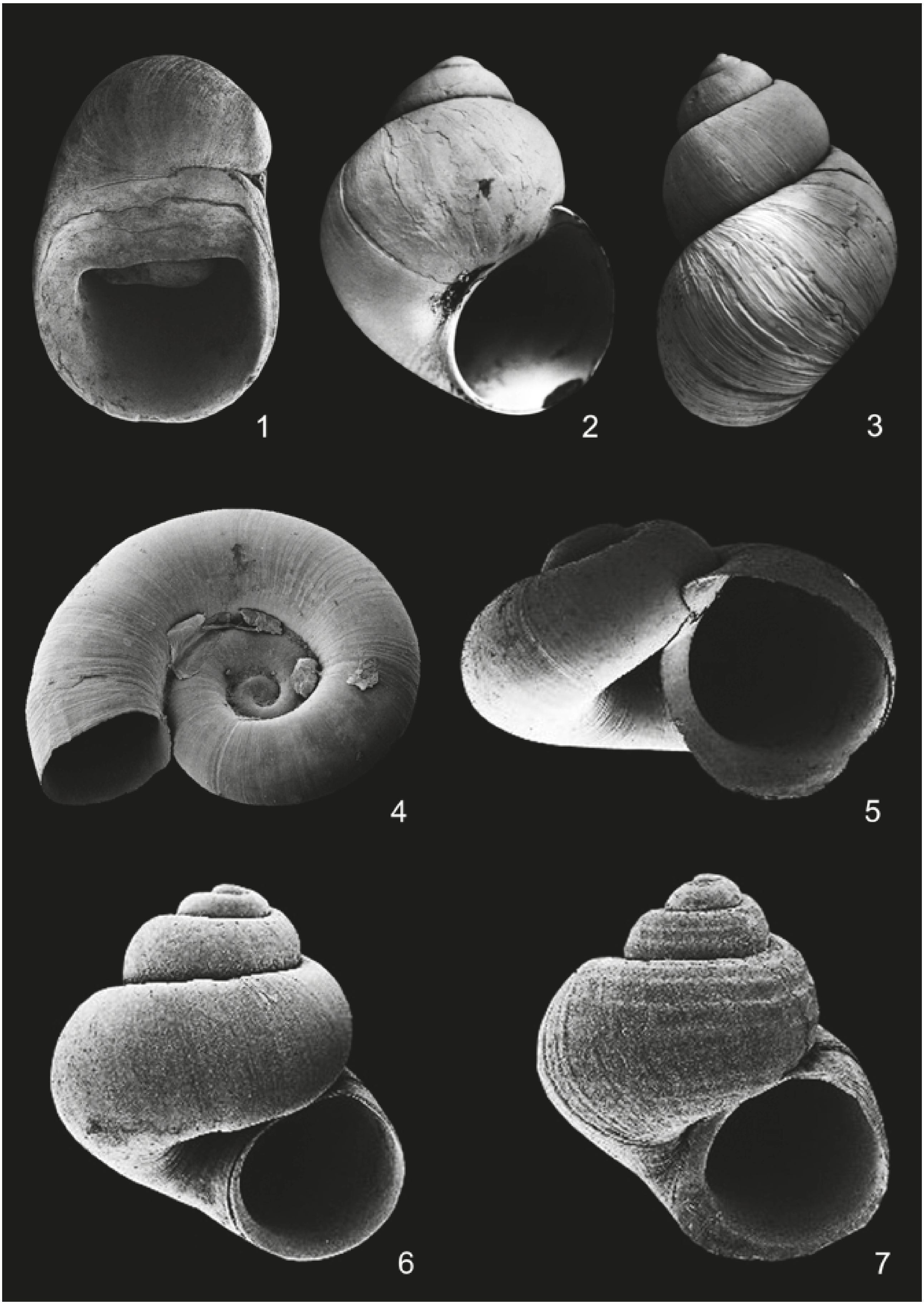
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PLATE II

Fig. 1. *Littorina littorea* (LINNAEUS), × 37

Fig. 2. *Littorina littorea* (LINNAEUS), × 37

Fig. 3. *Rissoa membranacea* (ADAMS), × 45

Fig. 4. *Turboella parva* (DA COSTA), × 45

Fig. 5. *Hydrobia ulvae* (PENNANT), × 40

Fig. 6. *Hydrobia ulvae* (PENNANT), × 40

Fig. 7. *Hydrobia ventrosa* (MONTAGU), × 17

Fig. 8. *Hydrobia ventrosa* (MONTAGU), × 17

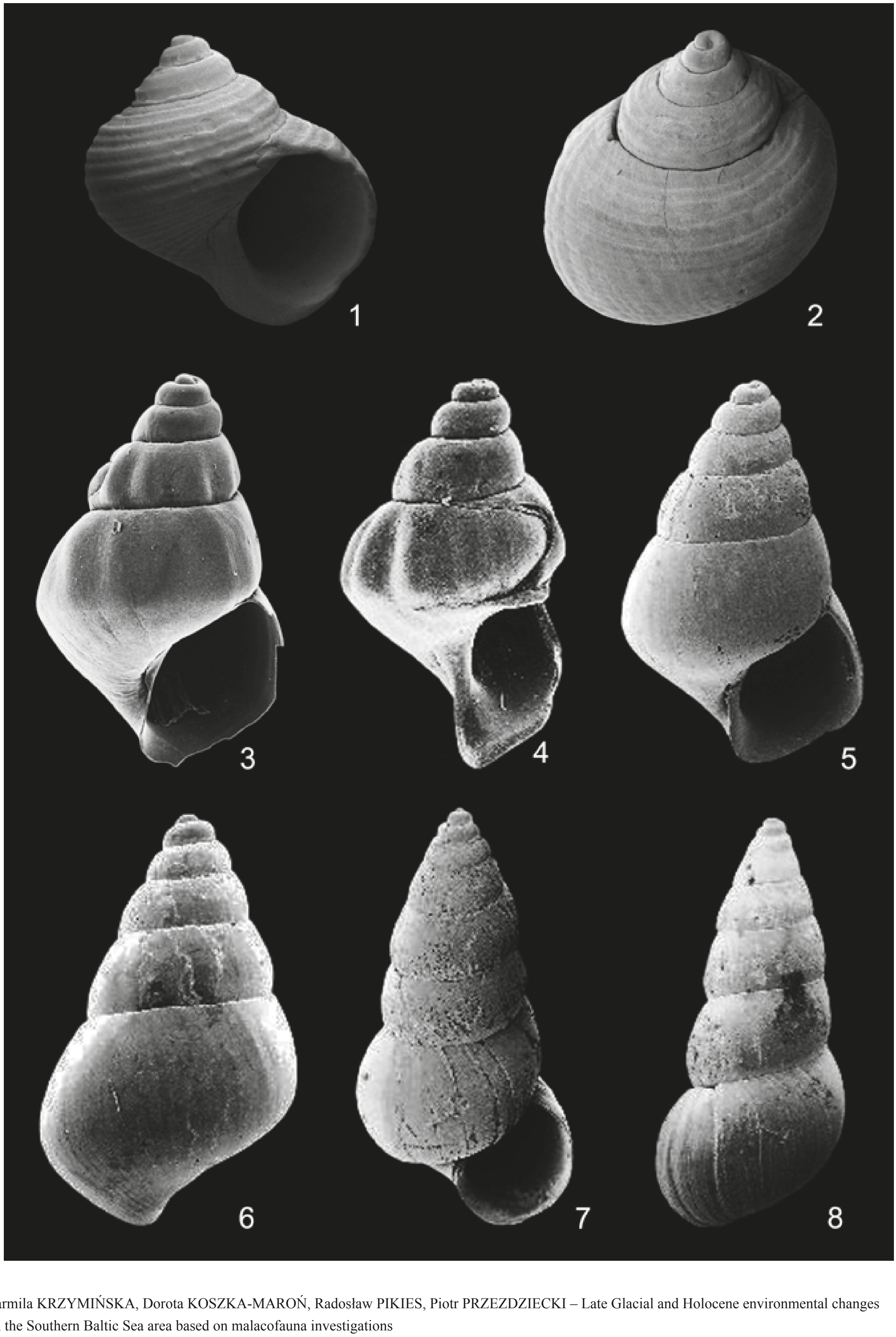

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PLATE III

Fig. 1. *Bithynia tentaculata* (LINNAEUS), × 12

Fig. 2. *Bithynia tentaculata* (LINNAEUS), × 12

Fig. 3. *Bithynia tentaculata* (LINNAEUS) (opercula), × 23

Fig. 4. *Bithynia tentaculata* (LINNAEUS) (opercula), × 21

Fig. 5. *Bithynia leachi* (SHEPPARD) (opercula), × 44

Fig. 6. *Bithynia leachi* (SHEPPARD) (opercula), × 75

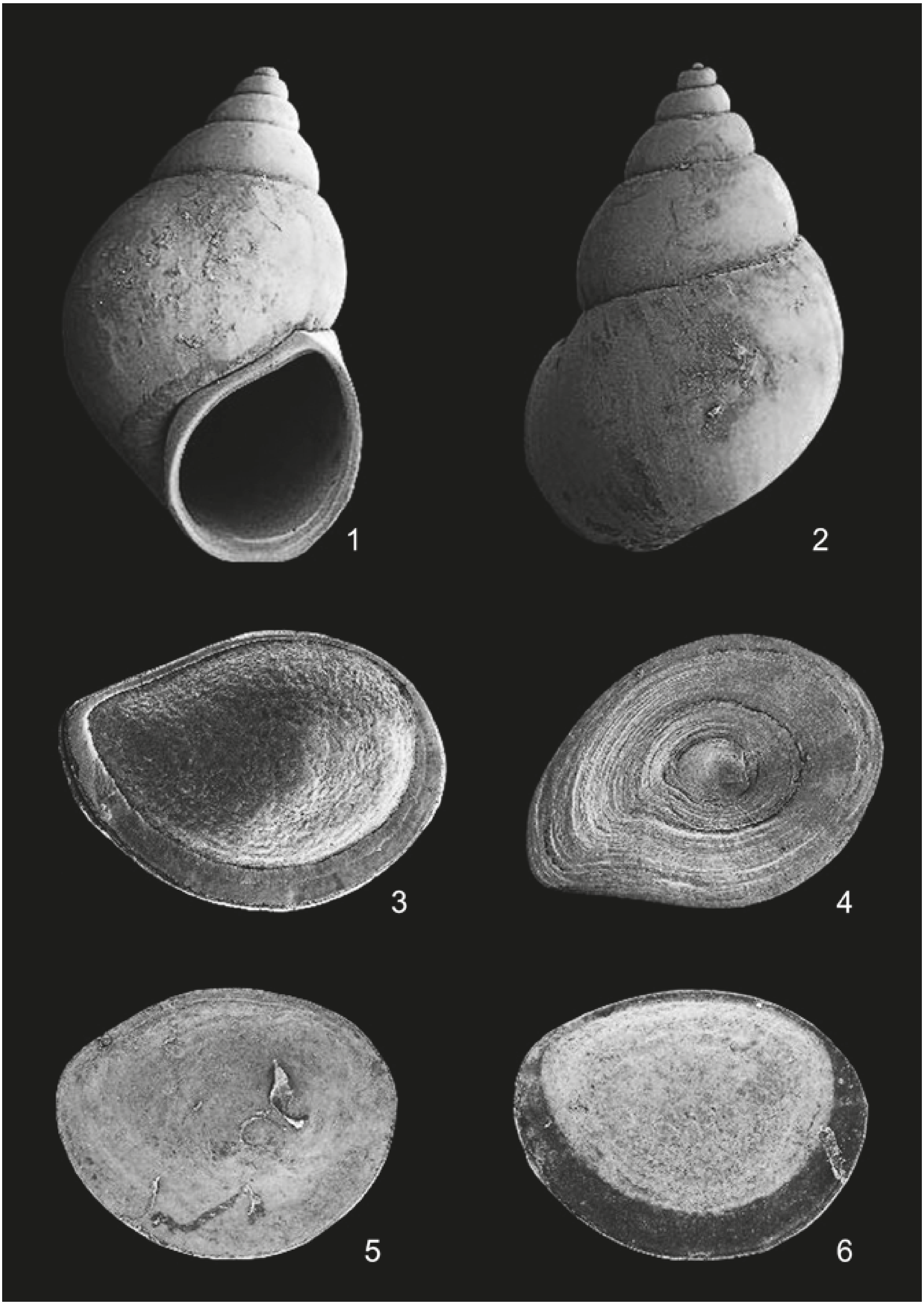
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PLATE IV

Fig. 1. *Bittium reticulatum* (DA COSTA), × 13

Fig. 2. *Bittium reticulatum* (DA COSTA), × 13

Fig. 3. *Nassarius reticulatus* (LINNAEUS), × 30

Fig. 4. *Nassarius reticulatus* (LINNAEUS), × 30

Fig. 5. *Retusa obtusa* (MONTAGU), × 32

Fig. 6. *Retusa truncatula* (BRUGUIÈRE), × 23

Fig. 7. *Eulimella nitidissima* (MONTAGU), × 90

Fig. 8. *Aplexa hypnorum* (LINNAEUS), × 43

Fig. 9. *Physa fontinalis* (LINNAEUS), × 22

Fig. 10. *Physa fontinalis* (LINNAEUS), × 22

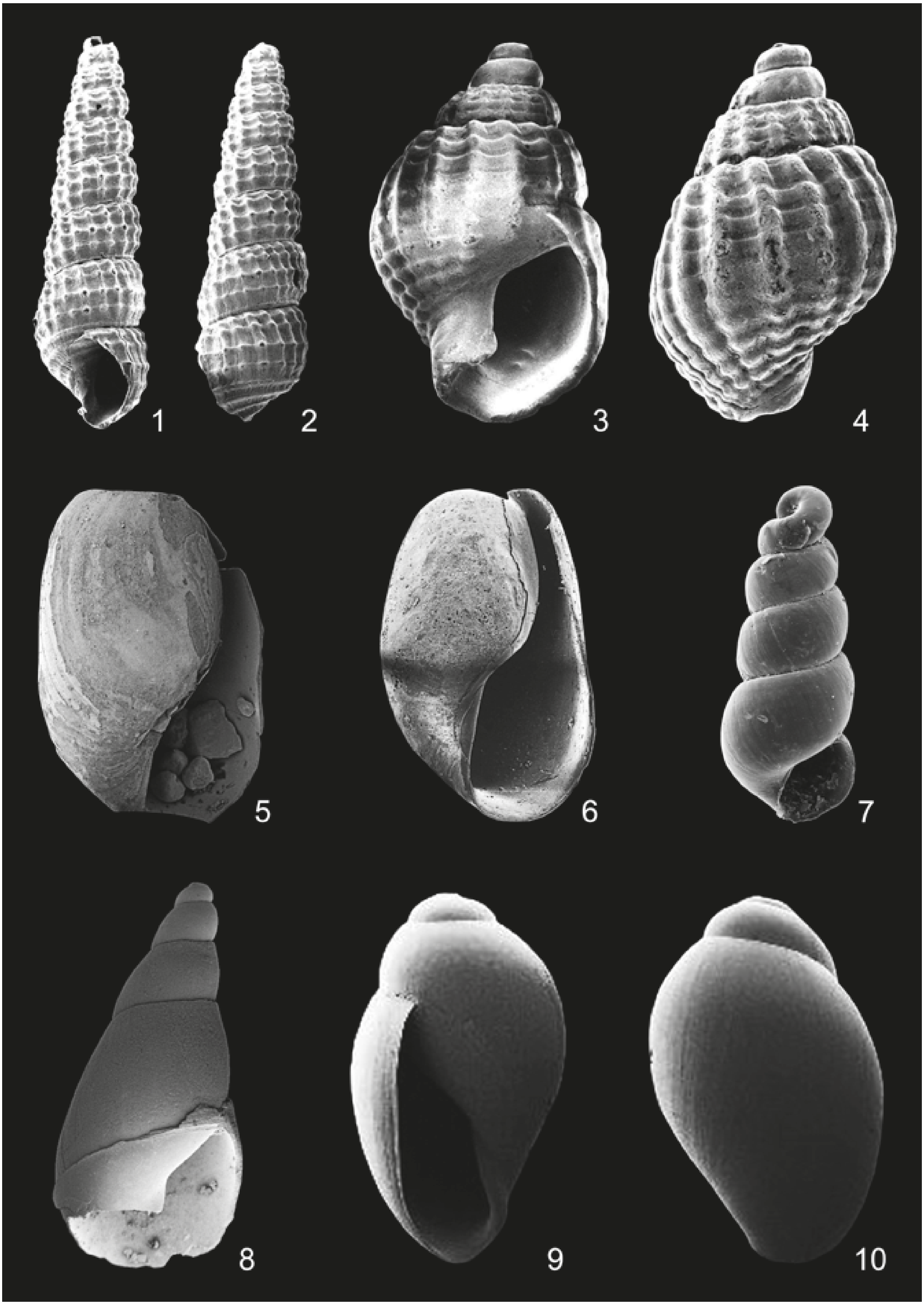
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PLATE V

Fig. 1. *Lymnaea auricularia* (LINNAEUS), × 11

Fig. 2. *Lymnaea glutinosa* (MÜLLER), × 14

Fig. 3. *Lymnaea truncatula* (MÜLLER), × 27

Fig. 4. *Lymnaea truncatula* (MÜLLER), × 29

Fig. 5. *Lymnaea peregra f. ovata* (DRAPARNAUD), × 33

Fig. 6. *Lymnaea stagnalis* (LINNAEUS), × 11

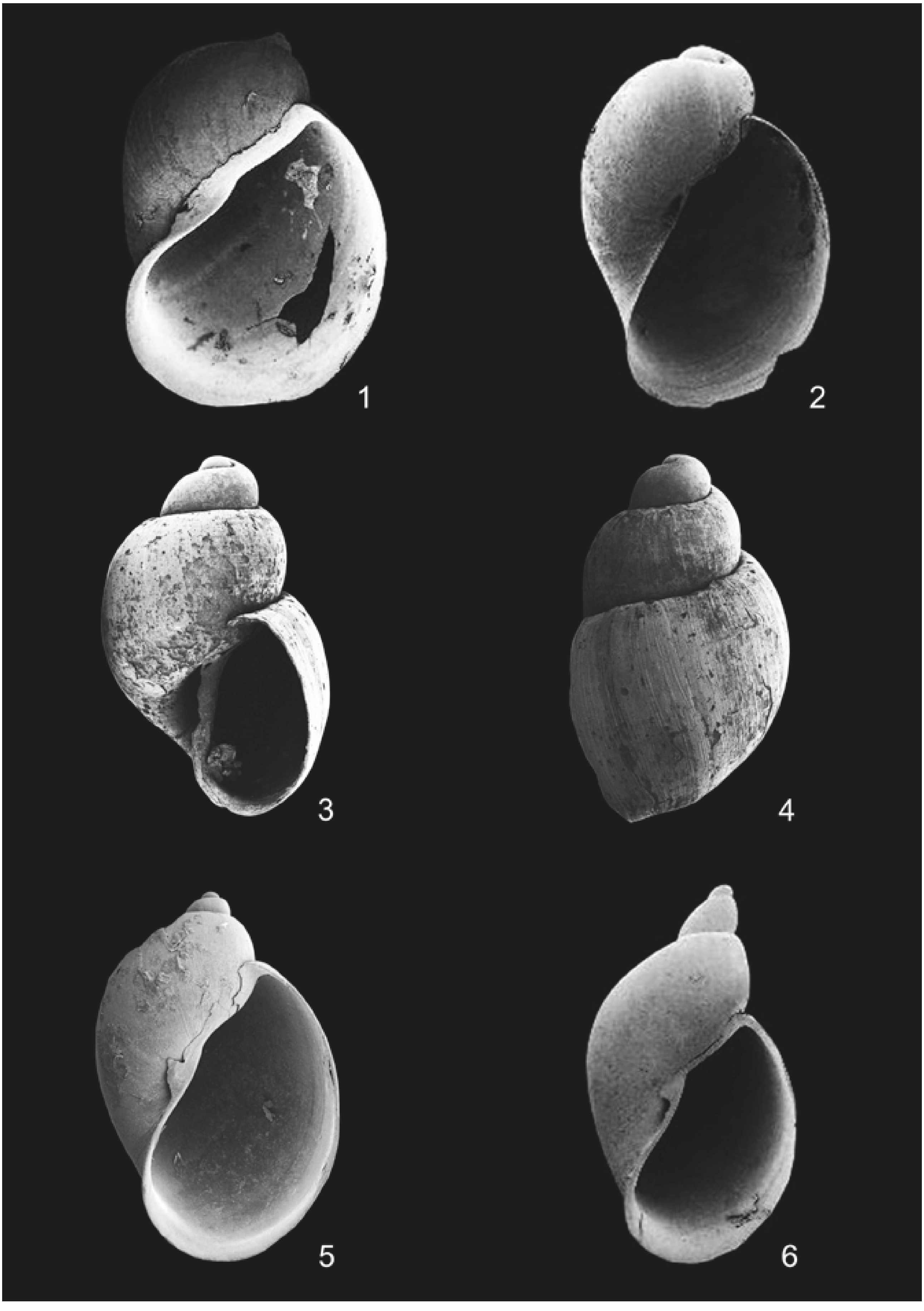

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PLATE VI

Fig. 1. *Anisus spirorbis* (LINNAEUS), × 18

Fig. 2. *Anisus spirorbis* (LINNAEUS), × 18

Fig. 3. *Gyraulus albus* (MÜLLER), × 18

Fig. 4. *Gyraulus albus* (MÜLLER), × 18

Fig. 5. *Gyraulus laevis* (ALDER), × 109

Fig. 6. *Armiger crista f. cristatus* DRAPARNAUD, × 40

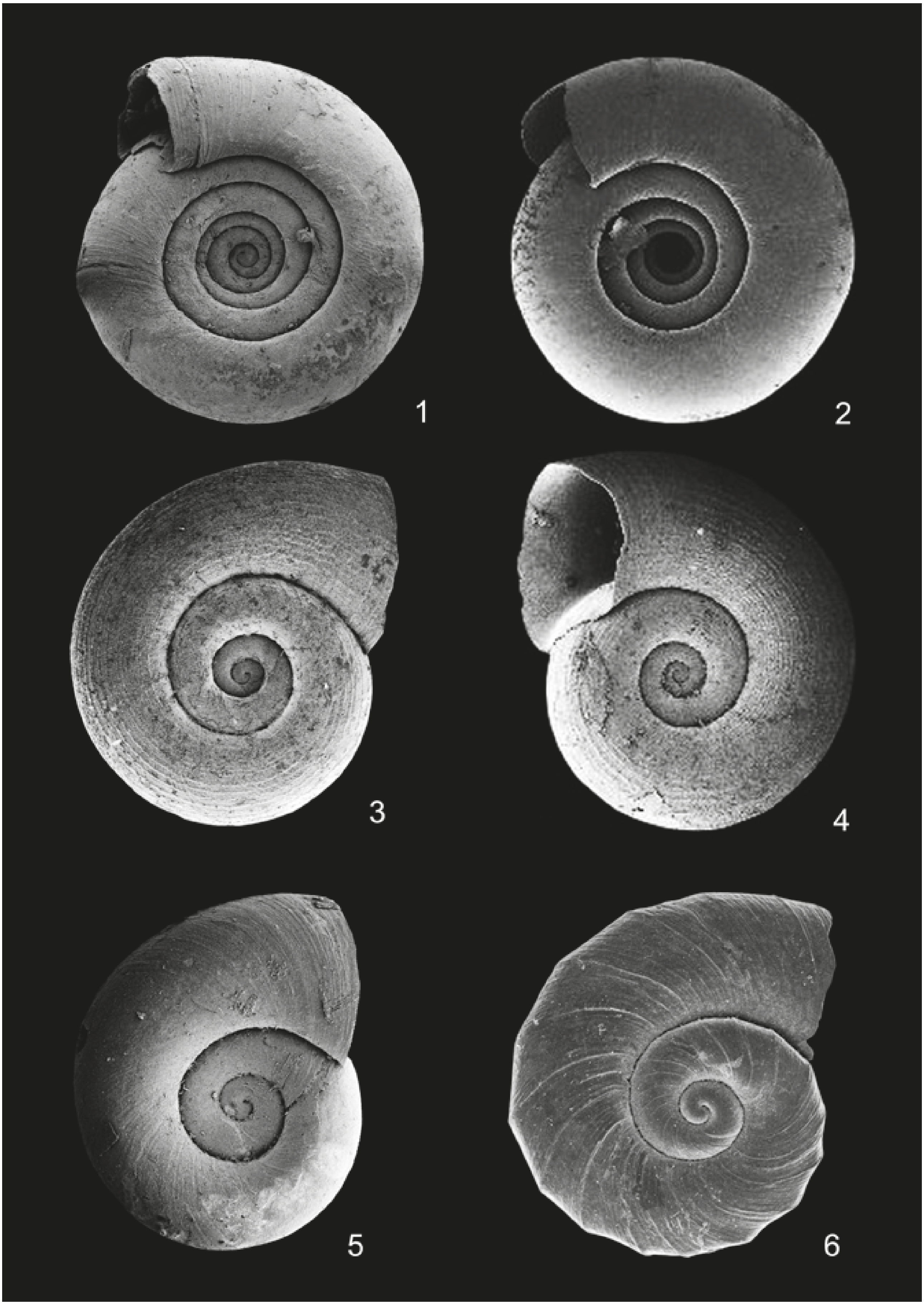
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PLATE VII

Fig. 1. *Armiger crista f. cristatus* DRAPARNAUD, × 40

Fig. 2. *Segmentina nitida* (MÜLLER), × 138

Fig. 3. *Segmentina nitida* (MÜLLER), × 136

Fig. 4. *Acroloxus lacustris* (LINNAEUS), × 70

Fig. 5. *Acroloxus lacustris* (LINNAEUS), × 60

Fig. 6. *Acroloxus lacustris* (LINNAEUS), × 53

Fig. 7. *Acroloxus lacustris* (LINNAEUS), × 51

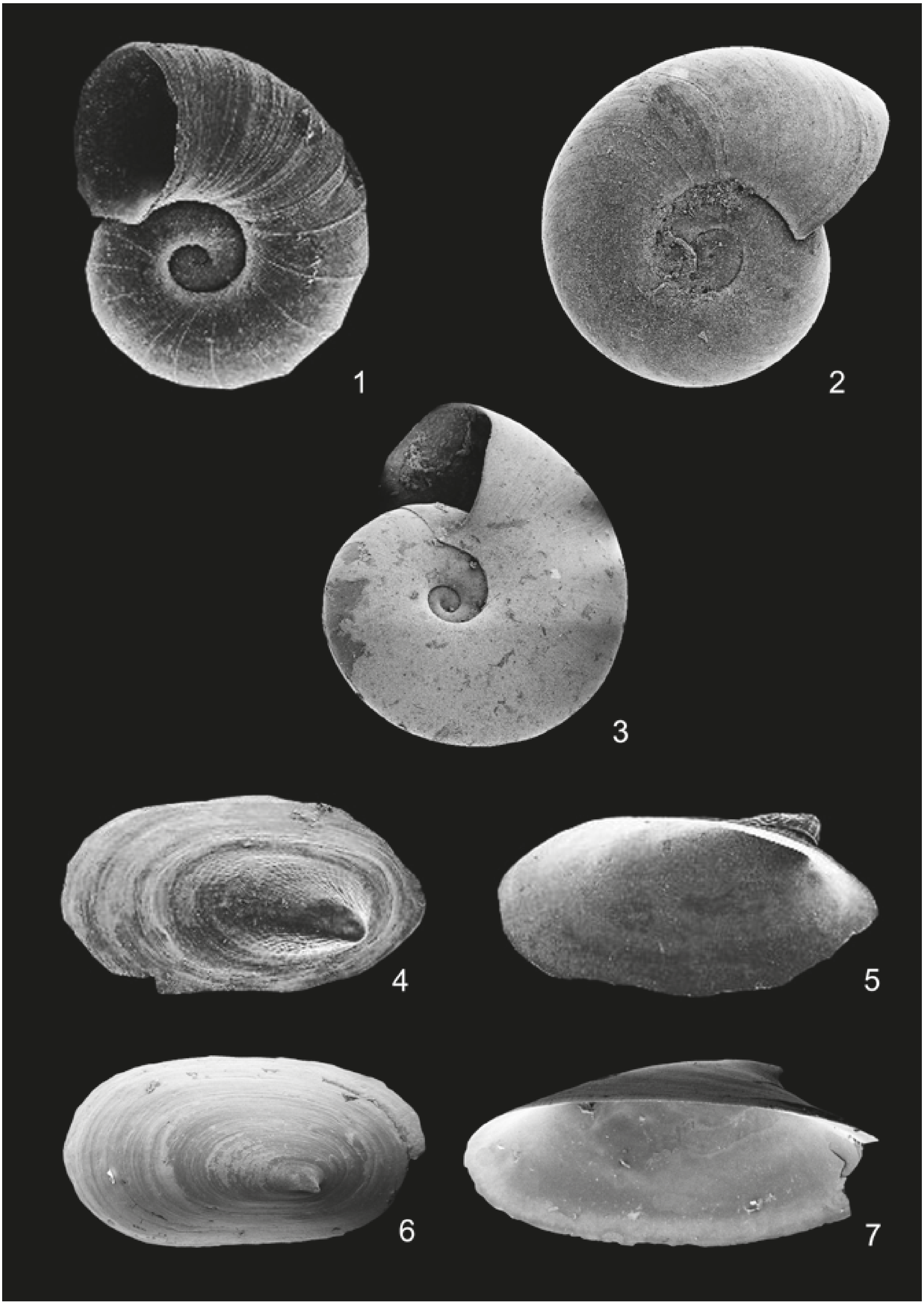

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PLATE VIII

Fig. 1. *Mytilus edulis* LINNAEUS, × 11

Fig. 2. *Mytilus edulis* LINNAEUS, × 2

Fig. 3–4. *Unio pictorum* (LINNAEUS), × 2

Fig. 5. *Anodonta cygnea* (LINNAEUS) – glochidium, × 220

Fig. 6–8. *Anodonta cygnea* (LINNAEUS) – glochidium, × 680

Fig. 9. *Mysella bidentata* (MONTAGU), × 112

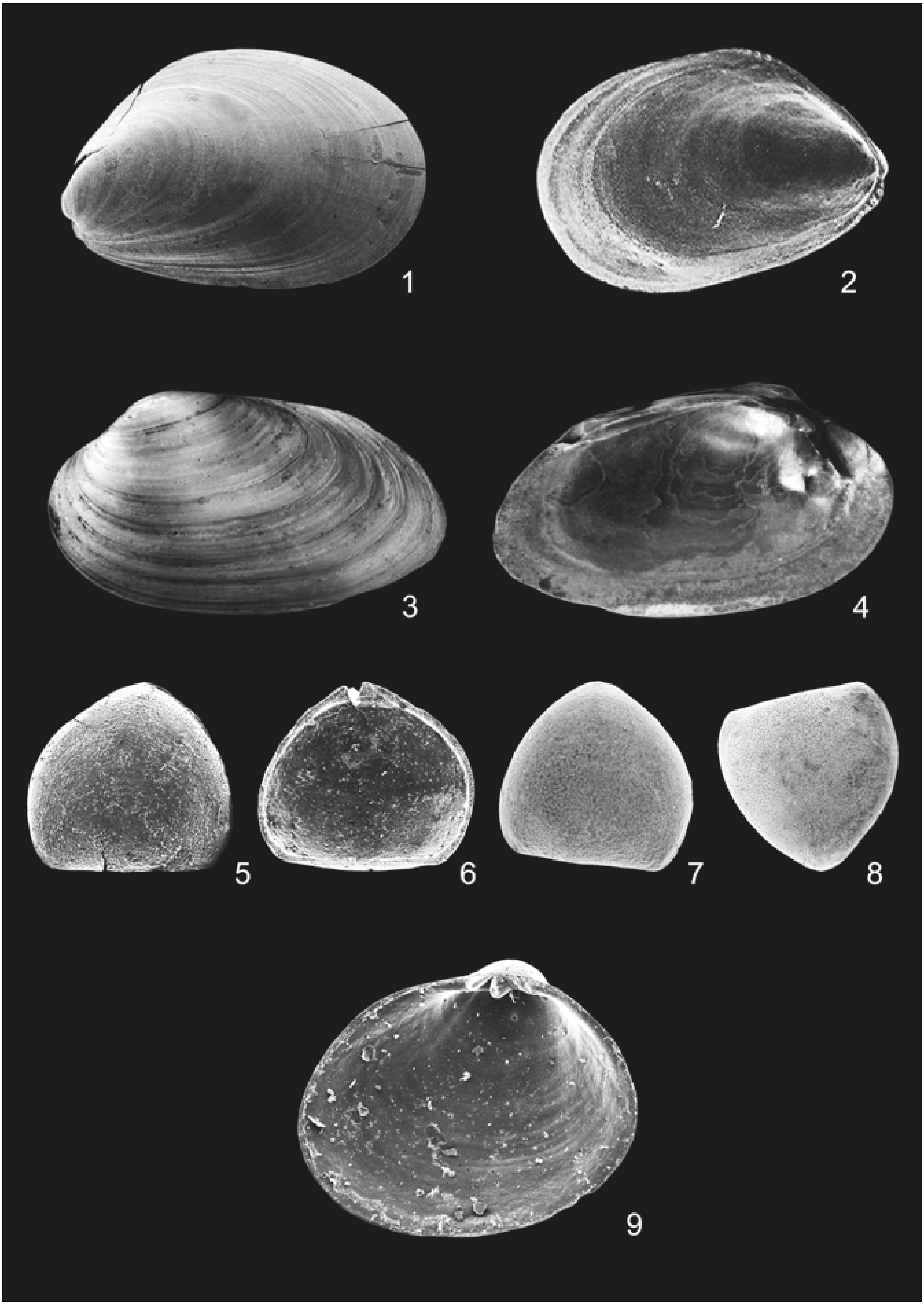
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PLATE IX

Fig. 1. *Cardium edule* (LINNAEUS), × 7.2

Fig. 2. *Cardium edule* (LINNAEUS), × 7.2

Fig. 3. *Cerastoderma glaucum* (POIRET), × 7.2

Fig. 4. *Cerastoderma glaucum* (POIRET), × 7.2

Fig. 5. *Parvicardium hauniense* (PETERSEN et RUSSELL), × 20

Fig. 6. *Parvicardium hauniense* (PETERSEN et RUSSELL), × 24

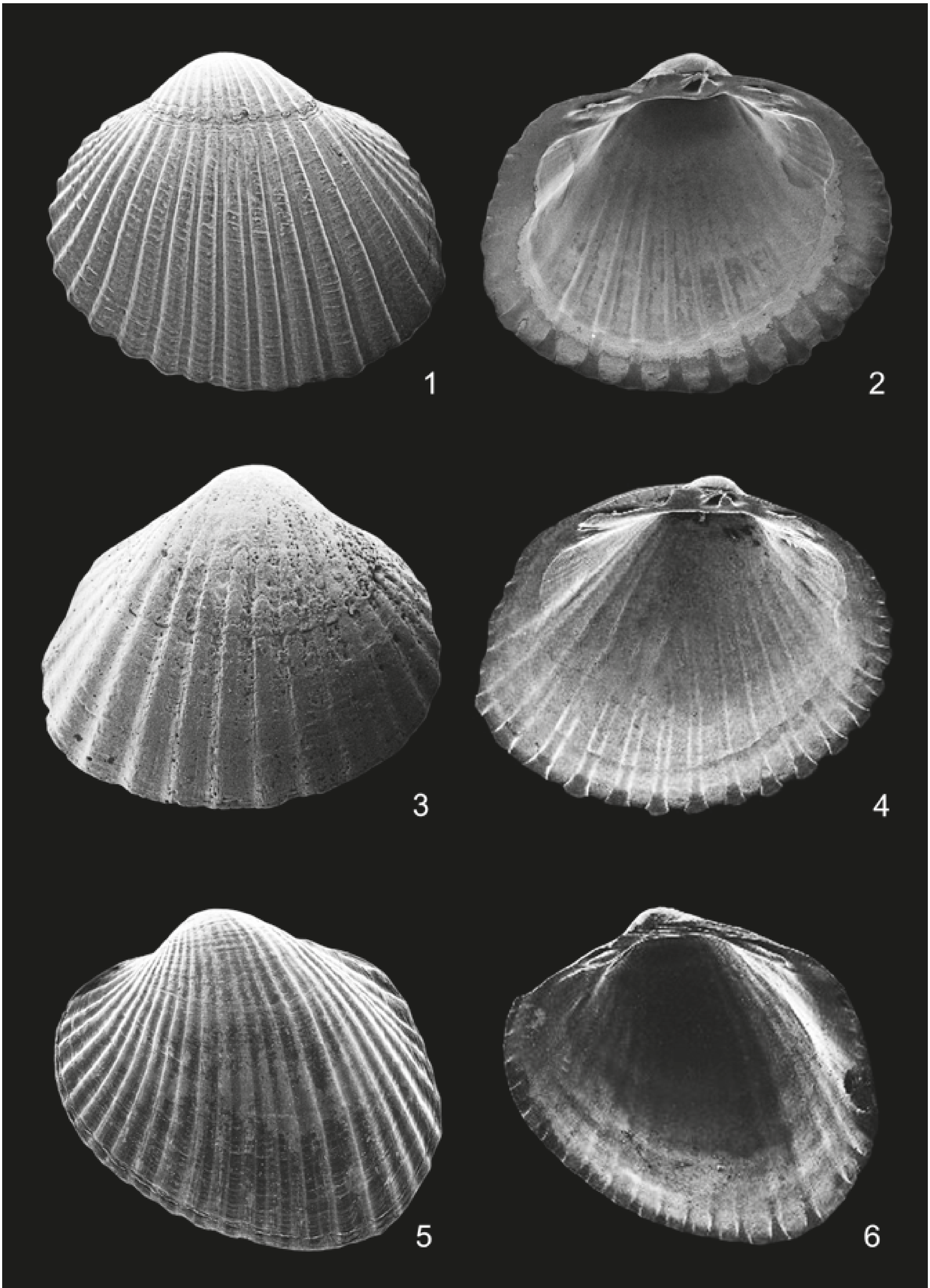

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PLATE X

Fig. 1. *Spisula subtruncata* (DA COSTA), × 36

Fig. 2. *Spisula subtruncata* (DA COSTA), × 36

Fig. 3. *Macoma balthica* (LINNAEUS), × 3.2

Fig. 4. *Macoma balthica* (LINNAEUS), × 3.2

Fig. 5. *Scrobicularia plana* (DA COSTA), × 1

Fig. 6. *Scrobicularia plana* (DA COSTA), × 1

Fig. 7. *Scrobicularia plana* (DA COSTA), × 1

Fig. 8. *Scrobicularia plana* (DA COSTA), × 1

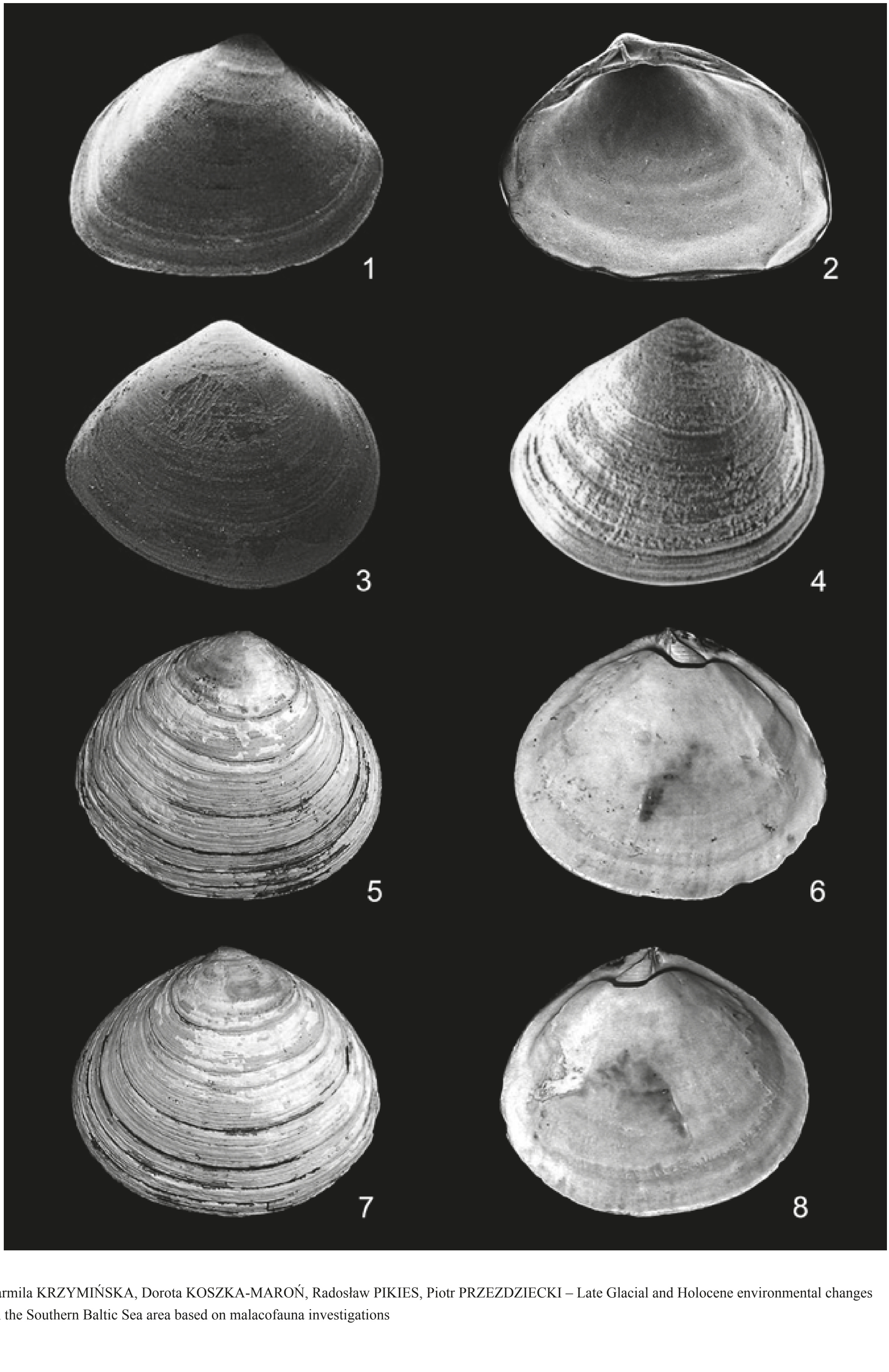

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PLATE XI

Fig. 1. *Dreissena polymorpha* (PALLAS), × 10

Fig. 2. *Sphaerium solidum* (NORMAND), × 12

Fig. 3. *Sphaerium solidum* (NORMAND), 12

Fig. 4. *Sphaerium corneum* f. *mamillanum* (WESTERLUND), × 10

Fig. 5. *Sphaerium corneum* f. *mamillanum* (WESTERLUND), × 11

Fig. 6. *Sphaerium rivicola* (LAMARCK), × 20

Fig. 7. *Sphaerium rivicola* (LAMARCK), × 20

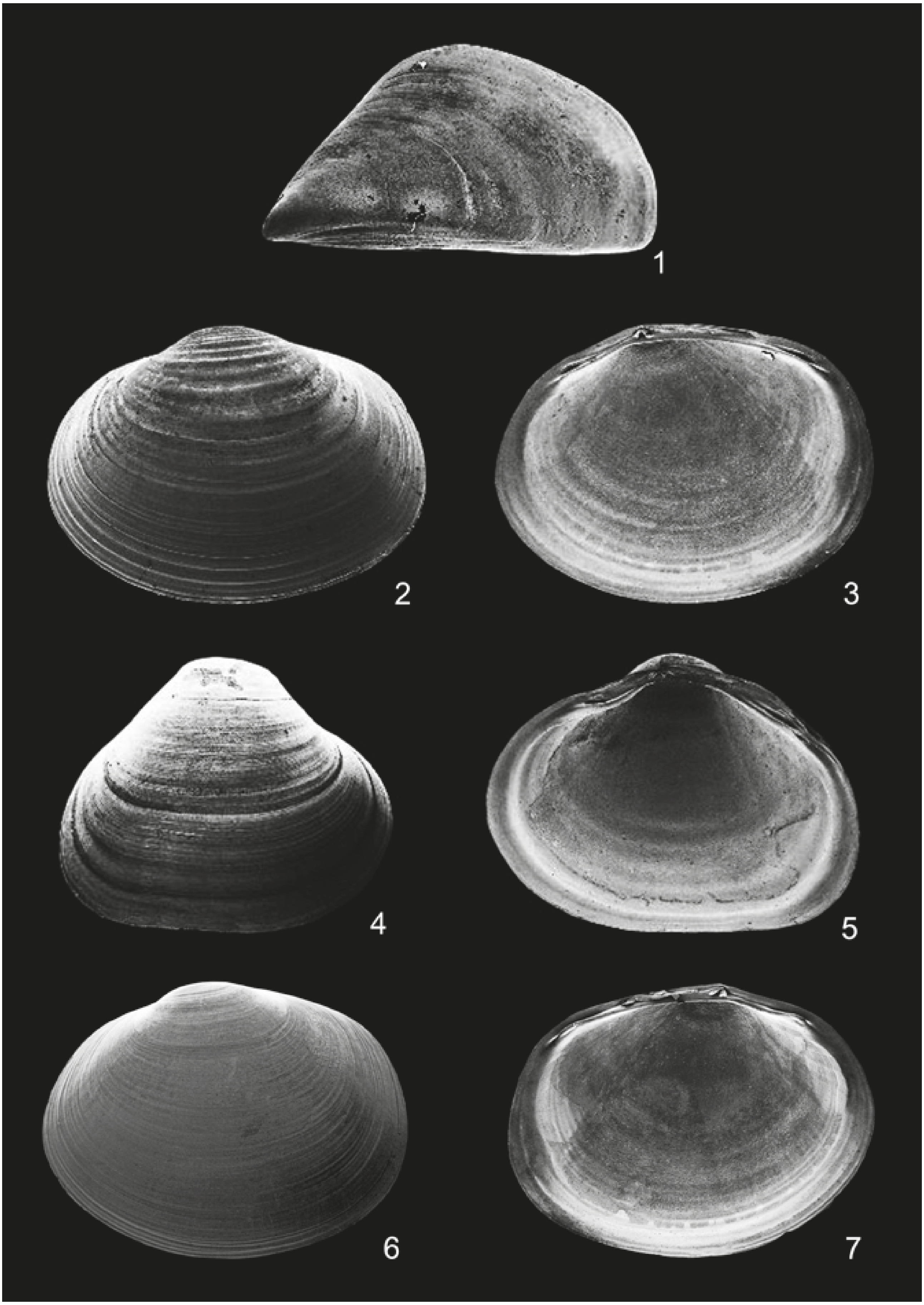
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PLATE XII

Fig. 1. *Pisidium amnicum* (MŰLLER), × 15

Fig. 2. *Pisidium amnicum* (MŰLLER), × 15

Fig. 3. *Pisidium amnicum* (MŰLLER), × 15

Fig. 4. *Pisidium supinum* SCHMIDT, × 30

Fig. 5. *Pisidium supinum* SCHMIDT, × 30

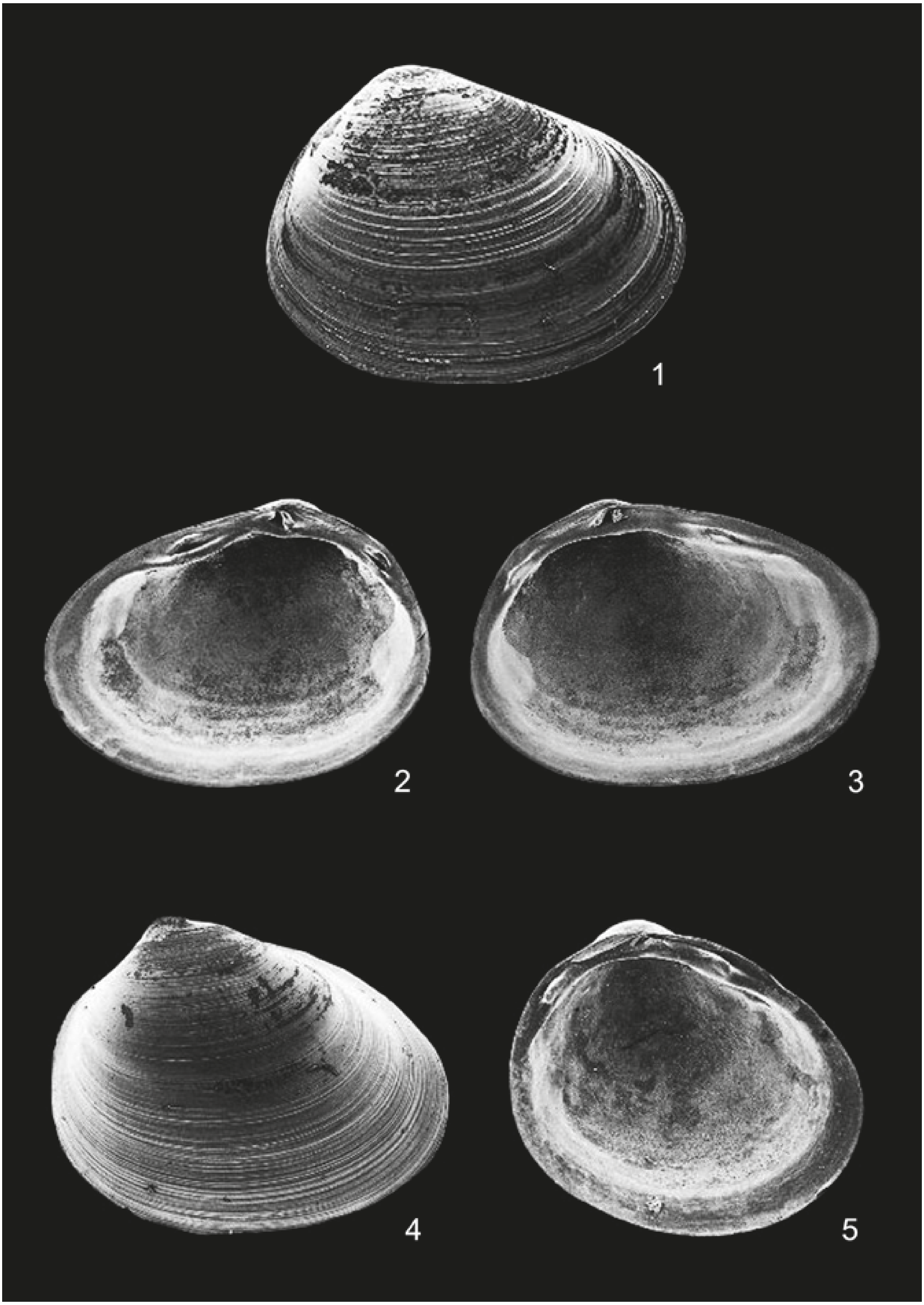

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PLATE XIII

Fig. 1. *Pisidium milium* HELD, × 56

Fig. 2. *Pisidium milium* HELD, × 50

Fig. 3. *Pisidium subtruncatum* MALM, × 33

Fig. 4. *Pisidium subtruncatum* MALM, × 45

Fig. 5. *Pisidium nitidum* JENYNS, × 50

Fig. 6. *Pisidium nitidum* JENYNS, × 45

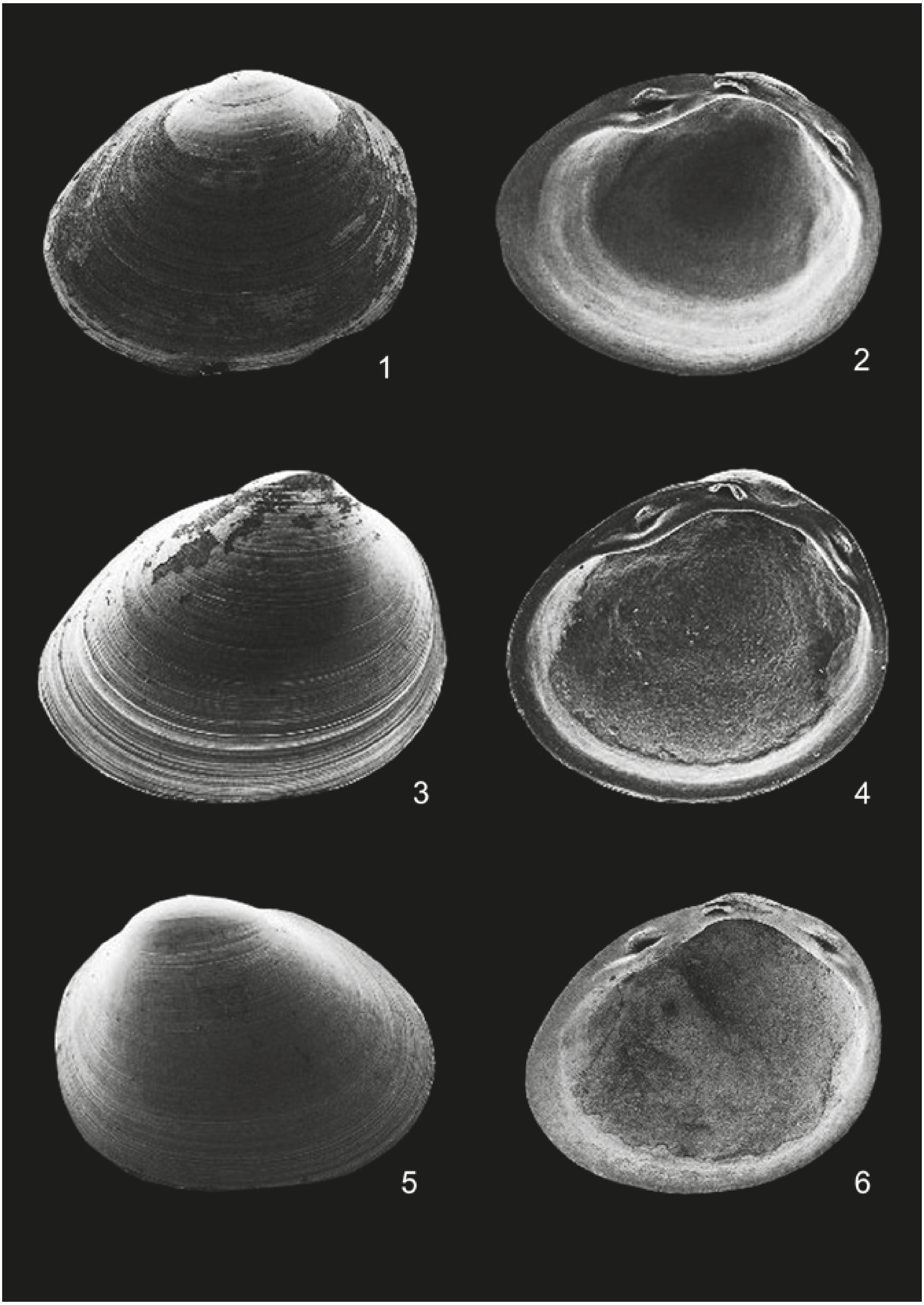
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PLATE XIV

Fig. 1. *Pisidium obtusale* (LAMARCK), × 132

Fig. 2. *Pisidium casertanum* (POLI), × 30

Fig. 3. *Pisidium casertanum* (POLI), × 30

Fig. 4. *Pisidium casertanum* (POLI), × 30

Fig. 5. *Pisidium casertanum f. ponderosa* STELFOX, × 15

Fig. 6. *Pisidium casertanum f. ponderosa* STELFOX, × 15

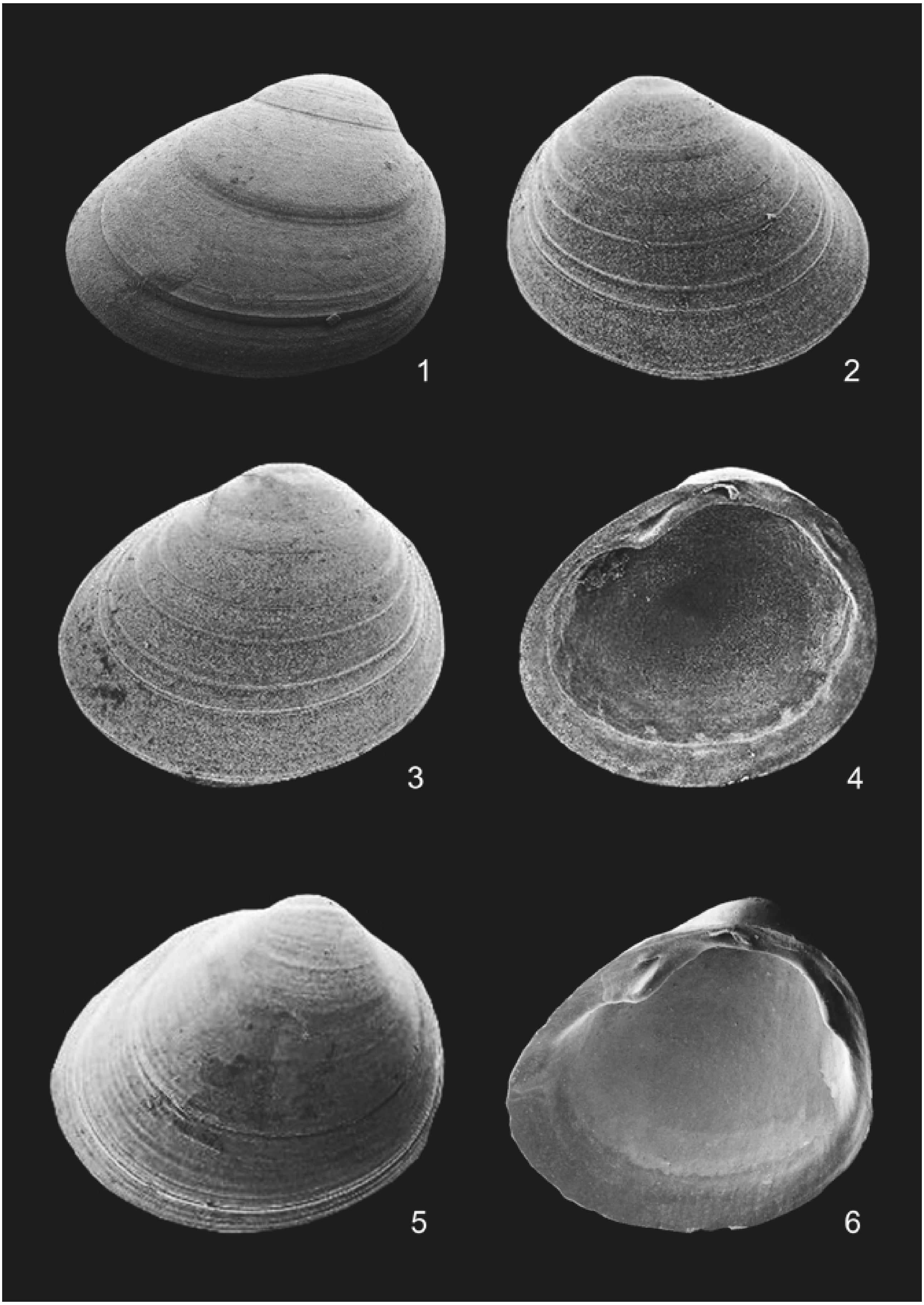

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PLATE XV

Fig. 1. *Pisidium conventus* CLESSIN, × 70

Fig. 2. *Pisidium conventus* CLESSIN, × 60

Fig. 3. *Pisidium moitessierianum* PALADILHE, × 56

Fig. 4. *Pisidium moitessierianum* PALADILHE, × 56

Fig. 5. *Corbula gibba* (OLIVI), × 12

Fig. 6. *Corbula gibba* (OLIVI), × 12

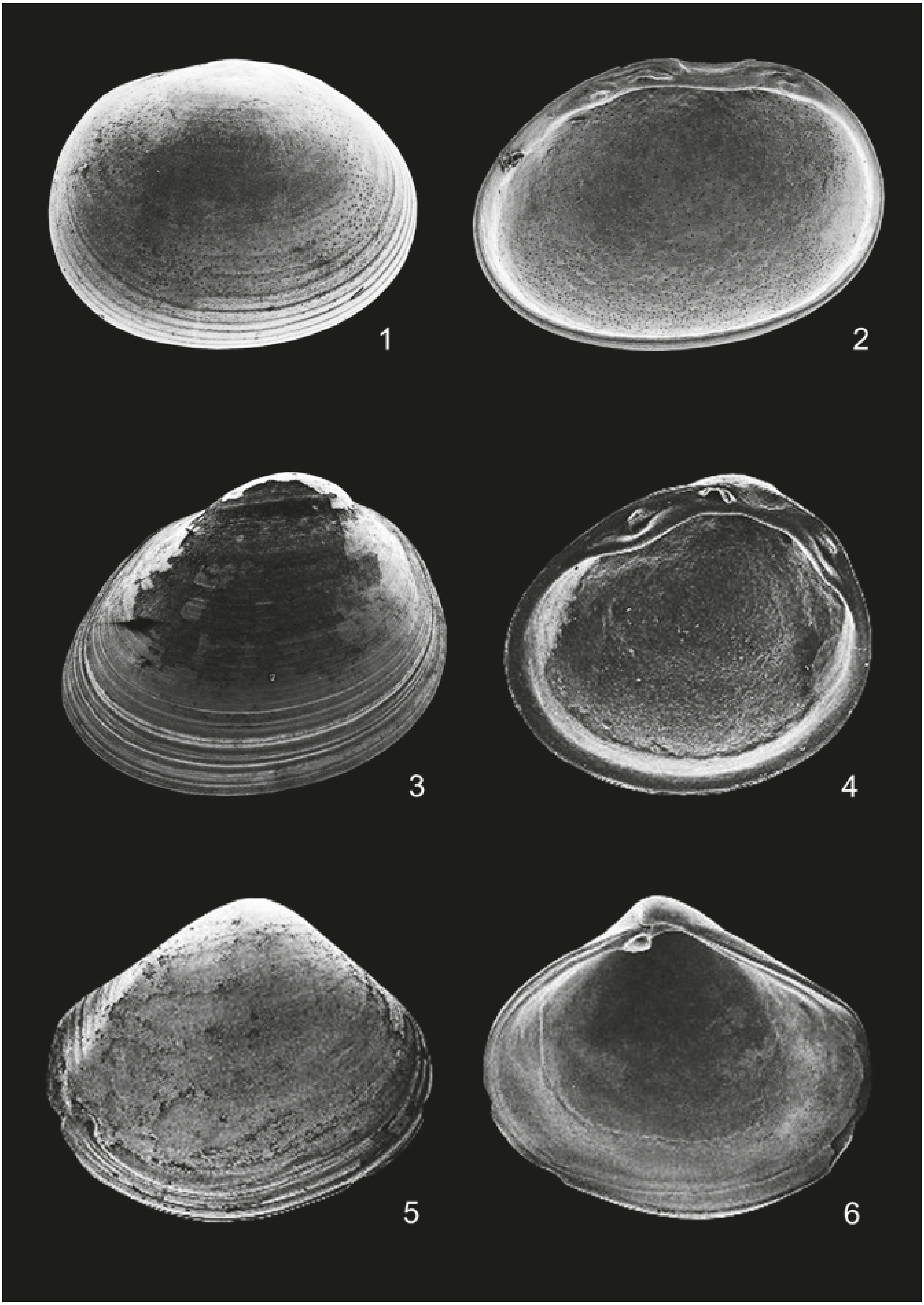

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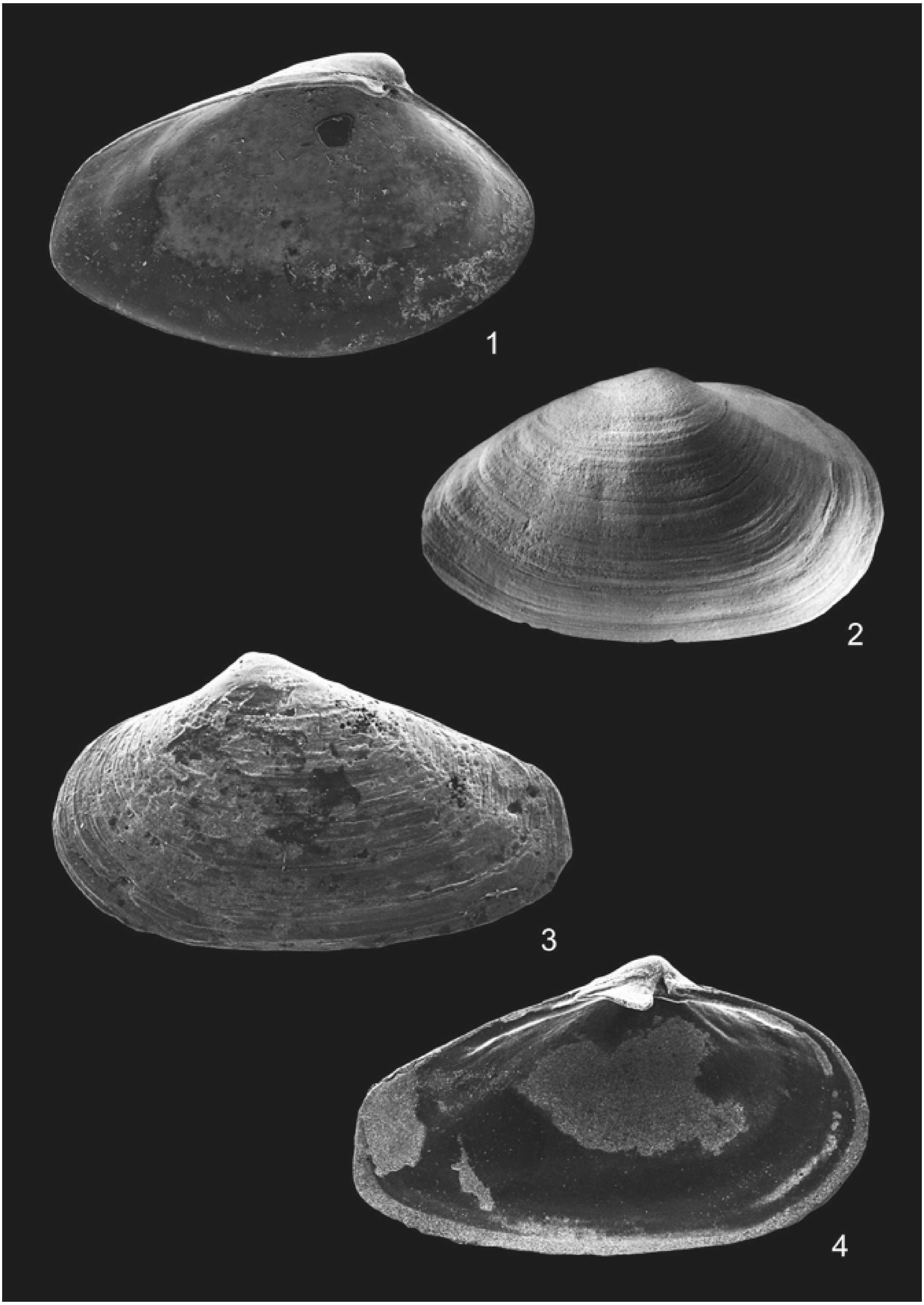
PLATE XVI

Fig. 1. *Thracia papyracea* (POLI), × 50

Fig. 2. *Mya arenaria* LINNAEUS, × 1.6

Fig. 3. *Mya truncata* LINNAEUS, × 24

Fig. 4. *Mya truncata* LINNAEUS, × 24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