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ORIGINAL ARTICLE

From wetland to commercial centre: the natural history of Wyspa Spichrzów ("Granary Island") in medieval Gdańsk, northern Poland

Joanna Święta-Musznicka[1] · Małgorzata Latałowa[1]

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Abstract This paper describes the analyses of pollen, non-pollen palynomorphs, macroremains and geochemistry in sediments from archaeological excavations at Wyspa Spichrzów ("Granary Island") in Gdańsk, northern Poland. The aim of this study was to reconstruct the environmental conditions in this part of the town in the period preceding its occupation and during its transformation with the establishment of a trade centre and an increasing number of granaries, warehouses and workshops. The results show that this area was originally covered by wetlands typical of river oxbows, with a landscape formed by alder woods, shallow pools of water, fens and patches of wet meadows. Around the 9th–10th centuries, a distinct lowering of the groundwater table reduced the pools, and the alder stands also reduced. These changes coincided with the Medieval Climatic Anomaly. Drying of the ground could have been an important factor enabling expansion of settlement in the Gdańsk area. Between the 10th and 13th–14th centuries, the area around the investigated sites was probably used as pasture, as shown by high frequencies of coprophilous fungal spores. A large representation of cereal pollen and pollen and macroremains of field weeds reflects crop transport and storage on the island from ca. the 13th/14th centuries in the northern part of the area and the 15th/16th centuries in its southern part. The increasing human impact caused development of a rich flora associated with human activities, habitat enrichment by nitrogen and phosphorus, and heavy metal pollution from the beginning of the 13th century.

Keywords Archaeobotany · Multi-proxy palaeoenvironmental reconstruction · Wetland occupation · Urban development · Medieval climatic anomaly

Introduction

Through the centuries, Wyspa Spichrzów ("Granary Island") in Gdańsk was one of the most important European locations for the storage and trade of goods. Situated at the mouth of a large river, the Wisła (Vistula) and in the immediate vicinity of the Baltic Sea coast, it played the role of a centre which joined eastern and western Europe, and central Europe with the north (Samsonowicz 1982; Paner 1999a; Litwin 2014). Ruined by 1945, it became a subject of new investment only recently. This new situation enabled large-scale archaeological excavations to be done, opening access to the historical cultural layers and geological strata beneath them (Paner 1993; Kaczyńska et al. 2005). The framework of the palaeoecological and archaeobotanical studies in Wyspa Spichrzów concerned both aspects of the history of useful plants being stored and traded in this area (Latałowa et al. 2007; Badura 2011) and the natural history of this place. The present paper is focused on palaeoenvironmental reconstruction.

In recent years, an increasing number of studies have used the potential of archaeological sites as sources of information about the past environment. Two major issues are usually discussed: (1) the natural context of settlement

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✉ Joanna Święta-Musznicka
j.musznicka@ug.edu.pl

[1] Laboratory of Palaeoecology and Archaeobotany, Department of Plant Ecology, University of Gdańsk, ul. Wita Stwosza 59, 80-308 Gdańsk, Poland

establishment and its further development and (2) the role of human activity in environmental changes (Hall and Kenward 2004; Stančikaitė et al. 2008; Sadori et al. 2015). The first issue concerns decisions made by people to settle in the area, according to their economic and political needs at that time and the possibility of making it habitable. It is important to know about the socio-economic and political background for such decisions and about local natural conditions so as to understand why so much effort and sometimes amazing technical solutions were used for land reclamation in a period of settlement establishment and later development (Behre 2004; Rippon 2005; Bazelmans et al. 2012). The second issue concerns the fact that research carried out directly on archaeological sites offers a unique opportunity to link the environmental effects of human impact with the activity of a specific population described by cultural artefacts or historical sources. It enables assessment of causal links between the rate and range of the local clearance of woodland and the spatial development of settlement (Greig 1992; Latałowa 1999; Kozáková and Pokorný 2007), as well as other ecological processes arising from human pressure. Long-term changes in biodiversity (Kozáková et al. 2009; Ledger et al. 2015), the effects of human activities upon flora and vegetation (Trzcińska-Tacik and Wasylikowa 1982; Willerding 1986), eutrophication of aquatic habitats (Pokorný et al. 2006), and atmospheric and soil pollution (Cook et al. 2005; Oonk et al. 2009a) are all among the important topics studied more and more frequently with the help of materials from archaeological sites.

The major aim of this study was to reconstruct the natural conditions of the island immediately prior to its occupation in the medieval period and then during the early stages of its commercial development. However, because this area lies in the heart of the historical city of Gdańsk, the data obtained here also shed some light on more general aspects of the natural history of settlement development and the process of urbanization of the city. Our study is based on multiproxy palaeoecological data, which offer superior insight into ecological processes. The pollen analysis includes a large spectrum of non-pollen palynomorphs (NPPs), which have become a very useful tool for reconstructing local ecological conditions and various kinds of human activities at archaeological sites (van Geel et al. 1983; Kvavadze and Kakhiani 2010; Florenzano et al. 2013; van den Bos et al. 2014). Also, the results of macrofossil analysis include both plant remains and some faunal taxa, which help towards a more complete characterization of the local ecosystems. The geochemistry of the sediments was analyzed to define the interactions between abiotic and biotic factors as the drivers of change in aquatic and wetland habitats (van Tongeren et al. 1992) and to assess the level of human-induced pollution, especially by heavy metals. Our basic assumption was that the natural circumstances of the settlement development can serve as a source of information about the living conditions of the inhabitants of Gdańsk in medieval times.

Study area and sites

Gdańsk developed at the mouth of the river Wisła (Vistula) in the vicinity of the Gulf of Gdańsk, a part of the southern Baltic Sea (Fig. 1a). The earliest well-dated traces of medieval settlement so far go back to the end of the 10th or beginning of the 11th century. In the 11th century, a stronghold, the seat of a duke, was constructed. In the oldest archaeological layers, finds of imported objects have already confirmed long-distance commercial contacts with most of Europe and Byzantium (Paner 2004). The location at the mouth of a large river and the intersection of numerous overland and maritime routes enabled fast development of the city as an important trade centre. In the period between the mid 15th and 17th centuries, Gdańsk was among the largest and richest European cities (Samsonowicz 1982).

A floodplain covered by wetlands is not a good place for a settlement. Small patches of slightly higher ground were used to establish the first three or four settlements, but after that the city also expanded onto wet land. Large-scale drainage works and thick levelling layers were used to establish new areas for the growing town. The island, with an area of approximately 30 ha, is located in the centre of the city of Gdańsk (Fig. 1b). From the very beginning, it was designated for commercial purposes. Gradual development of the island began in the 13th century, from the north to the south (Paner 1999b). The wet land, on which the granaries were built first, was covered with brushwood fascines and levelling material up to 2 m thick, preventing the buildings from collapsing (Kaczyńska et al. 2005). By the end of the 14th century, 120–130 granaries were built on the island. In the 14th and 15th centuries, the southern and eastern parts of the island were developed for storage spaces, warehouses and workshops because of the ongoing development of the port and its base. At the beginning of the 15th century, several large fires and floods resulted in a temporary slowdown of the infrastructure development; however, by the mid-15th century, the area had been rebuilt and the port developed, and the intensity of trade increased again. By the early 16th century, the number of granaries increased to 340. Also in the 16th century, the former moat was widened and deepened to create a new arm of the river, Nowa Motława ("New Motława"), finally separating this area from the mainland and extending access to the wharfs and improving the flow of traffic within the port. In subsequent centuries, fire and floods recurrently affected the

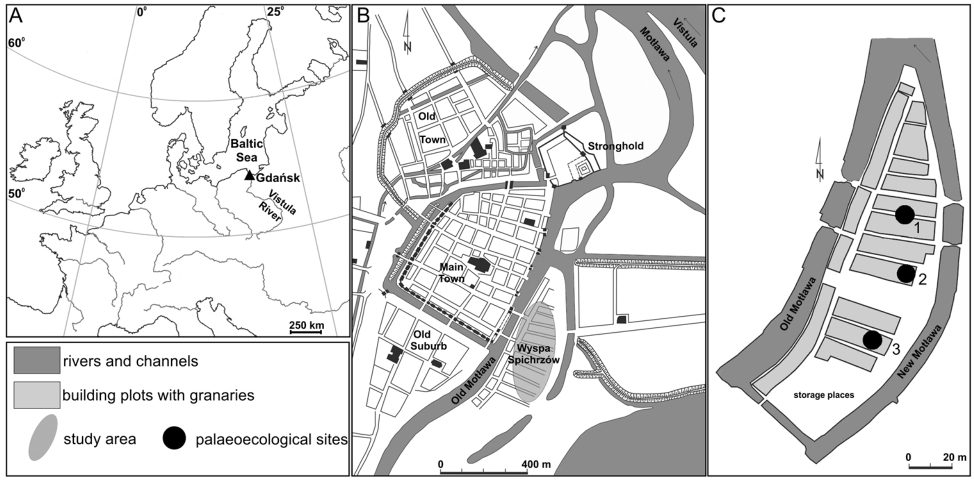

Fig. 1 **a** Location of Gdańsk; **b** location of Wyspa Spichrzów, from map of Gdańsk in the mid-16th century, from Paner (1999b), modified; **c** location of palaeoecological sites in the study area; *1*, ul. Żytnia, *2*, ul. Pszenna, *3* ul. Jaglana (map of Wyspa Spichrzów based on Bushe plan from 1866 to 1869, modified after Paner (1993)

island; however, it showed some recovery after these events and was functioning up to 1945, when this area was completely destroyed during the battle for Gdańsk (Paner 1993).

Two of the investigated sites are situated in ul. Pszenna (”wheat street”) and ul. Żytnia (“rye street”), in the north-eastern part of the island (Fig. 1c), which was the earliest settled area that started to develop into a commercial centre in the 13th–14th centuries. Numerous granaries, workshops and warehouses were active here for trade through the centuries. The third site lies in ul. Jaglana (“millet street”) in the southern part of the island, which started to be developed as late as the 15th century. In this part of the island, there were mainly workshops and storage places for various products other than grain (Paner 1993).

Materials and methods

Sampling

Samples for palaeoecological analyses were collected in vertical series directly from the sides of the archaeological trenches; at two sites, ul. Jaglana and Żytnia, supplementary material was taken from beneath the trench bottoms with an Instorf corer, 5 cm in diameter. There were technical gaps, each approximately 10 cm, between both sequence types to avoid the risk of contamination. Sampling was continued from the bottoms of the profiles up to the levelling layers which separated the peat deposits from destruction layers composed of fragments of bricks, wood, matted straw and charcoal. For pollen sampling, syringes were inserted into every 2 cm of sediment along the profiles, after careful cleaning of the wall and description of the lithostratigraphy. Blocks 4–5 cm thick were cut from the sediments for macrofossil and geochemical analyses. Sections taken by means of the Instorf corer were subsampled in the laboratory.

Pollen analysis

In the laboratory, subsamples with 1 cm^3 of sediment were retrieved from the inner parts of the syringes. Samples were first processed with HF to remove silica and then boiled in 10 % KOH and acetolysed in the normal preparation procedure (Fægri and Iversen 1989). In the resulting prepared slides, NPPs (van Geel 2001) and microcharcoal particles >20 μ were counted along with pollen. In natural sediments, at least 1,000 AP plus all other pollen and microfossils were counted in each sample; 200–600 AP + 600–1,400 NAP were usually counted in samples from cultural layers. In a few topmost samples from ul. Pszenna and ul. Jaglana where the pollen concentration was very poor, counting was stopped at 300–700 AP + NAP. The percentage calculations for dry land taxa are based on the AP + NAP = 100 %. The calculation base for the proportion of wetland and aquatic plants (local taxa) is AP + NAP + local taxa; for algae and cyanobacteria, it was AP + NAP + algae; and for coprophilous fungi, it was the sum of AP + NAP + fungi. The pollen diagrams are divided into local pollen assemblage zones (LPAZ) and named according to the specific composition of the pollen spectra.

Macrofossil analysis

For macrofossil analysis, 300 cm^3 sub-samples taken from the trench walls and 20–120 cm^3 sub-samples from the Instorf corer were immersed in water with a small amount of KOH for 24–28 h and then wet-sieved using a column of sieves of 0.2 and 0.5 mm meshes. The whole sample content was sorted using a stereoscopic microscope under

16× magnification, and then specimens were identified under 20–120× magnifications. Both plant and animal remains were considered. Numerous keys and atlases were used for macrofossil identification. Specifically, *Potamogeton* fruits have been distinguished according to the characteristics given by Aalto (1970) and Cappers (1994), *Chenopodium* determination is based on Kowal (1953) and Berggren (1981), *Juncus* on Körber-Grohne (1964), *Mentha* on Jacquat (1988), while determination of *Carex* was performed with the help of Berggren (1969). Identifications were systematically checked against the reference collection in the Laboratory of Palaeoecology and Archaeobotany, University of Gdańsk. The results are expressed as numbers of specimens per 300 cm^3 of sediment. The diagrams are divided into macrofossil assemblage zones (MAZ) based on the visually distinctive changes in the composition and abundance of the taxa. Each MAZ is named after the dominant taxa or a characteristic of a given section of the diagram. Taxa determined to species level were arranged in defined ecosociological groups according to their occurrence in present-day plant communities in Poland (Matuszkiewicz 2002).

Geochemistry

For geochemical analysis, the longest sequence of sediments from the ul. Pszenna site, with 29 sub-samples was used for this study. Loss on ignition, nitrogen (N), sulphur (S), carbon (C), phosphorus (P), and main and trace metal lead (Pb), zinc (Zn), copper (Cu), iron (Fe), magnesium (Mg) and manganese (Mn) content were analysed. This was carried out in the Instrumental Laboratory of the Geology and Paleogeography Unit, Faculty of Geoscience, University of Szczecin. A Vario MAX CNS elementary particle analyzer and a SOLAR 969 spectrophotometer by Unicam were used.

Age determination

The chronology of the palaeoecological events is based on both the archaeological cultural layers and radiometric dating. Eighteen samples of selected fruits and seeds of terrestrial plants were radiocarbon dated using the accelerator mass spectrometry (AMS) method at the Poznań Radiocarbon Laboratory (Table 1). To obtain calendar years, the conventional radiocarbon dates were calibrated using OxCal 4.2.4, based on the calibration curves IntCal13 and Marine13 (Reimer et al. 2013).

Statistical analyses

Redundancy analysis (RDA) in CANOCO 4.5 for Windows was performed for palaeobotanical data to illustrate the taxa and samples, as well as the relationships of sample and environmental variables (Lepš and Šmilauer 2003).

Results and interpretation

Sediments and their age

The sediments were quite diversified in respect to proportions mineral and organic matter (ESM Tables 1–3). Silty sediments with fine sand and traces of detritus gyttja mud prevailed in the lower parts of the profiles, while in their upper parts peat deposits and coarse detritus gyttja with an admixture of minerogenic matter were identified. The composition of these deposits was typical of oxbow ponds with a variable water table. The tops of the profiles consisted of cultural layers connected with levelling which contained matted straw, pieces of wood, gravel and fragments of bricks.

The AMS dating indicates that the ages of the sediments range from the 5th to the beginning of the 16th centuries AD (Table 1). The oldest sediments dated to the 5th century and they occurred in the profile from ul. Pszenna; however, the two other profiles were only a little younger, ul. Żytnia was 6th century and ul. Jaglana was 7th century. The topmost parts of the profiles, below the levelling layers, represent around the 14th century at ul. Żytnia, the 15th at ul. Pszenna and the 16th century at ul. Jaglana. According to archaeological data, in ul. Żytnia the layer above the levelling belonged to the 17th century; in ul. Pszenna, it was dated to the 17th/18th centuries and in ul. Jaglana, it was dated to the 16th century. The results of radiocarbon dating and comparison of pollen records among the profiles indicate that the technical gaps established in two sites between sampling of the exposure wall and the section taken by means of the Instorf corer do not restrict the interpretation. In ul. Jaglana, the gap is negligible, and in ul. Żytnia, it probably spans around 100 years.

Considering the sediment types and structure and the results of radiocarbon dating, it is evident that particular sequences of the investigated profiles accumulated in environments of different hydrological conditions, which potentially could result in natural hiatuses. On the other hand, construction work could have resulted in the destruction of sediment layers. First of all, we suggest a hiatus in ul. Jaglana at the depth of ca. 55 cm which covers most of the medieval period, from the 7th to the 15th century. This hiatus was already suspected during the field work. At this site, the silty sediments were covered with an organic deposit with a mixture of sand, wood and fragments of bricks. The lithological limit was rather sharp, but

Table 1 Radiometric dating

Lab. no.	Depth (cm)	^{14}C age BP	Age cal AD (2σ)	Median cal AD	Material dated
ul. Pszenna					
Poz-50059	92–97	540 ± 30	1389–1437	1404	*Humulus lupulus* fruits, *Agrostemma githago* seeds
Poz-31661	114–118	840 ± 35	1152–1267	1202	*Ranunculus sceleratus*, *Fragaria vesca*, *Potentilla anserina*, *Carex distans* fruits
Poz-45048	138–142	1,155 ± 30	775–969	881	*C. distans* fruits
Poz-31662	146–151	1,510 ± 30	529–622	559	*Alnus glutinosa* fruits
Poz-45049	179–182	1,830 ± 50	71–264	186	*A. glutinosa*, *Urtica dioica*, *Lycopus europaeus*, *Betula* sect. *albae* fruits
Poz-58959	182–186	1,585 ± 30	406–544	481	*A. glutinosa, B.* sect. *albae, Oenanthe aquatica, U. dioica, Ranunculus repens, Mentha aquatica* fruits
Poz-31663	195–200	1,615 ± 30	387–538	454	*A. glutinosa* fruits
Poz-58958	200–205	1,640 ± 40	332–538	410	*A. glutinosa, B.* sect. *albae, Oe. aquatica, Conium maculatum* fruits
ul. Żytnia					
Poz-50056	6–12	675 ± 30	1271–1319	1304	*Polygonum aviculare, Prunella vulgaris* fruits
Poz-31656	22–26	640 ± 30	1340–1397	1353	*Ranunculus repens* fruits
Poz-31657	44–50	1,110 ± 30	879–1013	937	*A. glutinosa, C. distans* fruits
Poz-31658	65–70	1,215 ± 30	763–889	812	*A. glutinosa, U. dioica* fruits
Poz-31659	90–95	1,520 ± 30	505–609	547	*A. glutinosa* fruits
ul. Jaglana					
Poz-25984	5–15	365 ± 30	1449–1529	1522	*R. sceleratus* fruits
Poz-25992	35–45	395 ± 30	1439–1523	1483	*R. sceleratus* fruits
Poz-70482	45–55	430 ± 30	1421–1499	1453	*R. sceleratus* fruits
Poz-50058	69–77	1,415 ± 30	585–663	631	*R. sceleratus, B.* sect. *albae, A. glutinosa, Lycopus europaeus, Mentha aquatica, Cicuta virosa, U. dioica* fruits
Poz-25983	87–92	1,405 ± 30	595–668	638	*A. glutinosa, R. sceleratus, Schoenoplectus lacustris, S. tabernaemontani* fruits

its line was very irregular across the trench wall, suggesting earlier earthworks on the site.

Environmental changes according to the biotic and abiotic proxies

Pollen frequency and preservation distinctly differed between particular profiles and sediment layers. Well-preserved pollen and good concentration was found in almost all samples from ul. Żytnia. More pollen corrosion and very poor concentration were characteristic of the topmost parts of the ul. Pszenna and ul. Jaglana profiles, which were built of cultural layers containing a significant admixture of mineral matter. In general, the pollen material was rather rich, which enabled identification of 161 plant and 63 NPP taxa. The profile from ul. Pszenna (P) is the most complete one. It has been divided into four LPAZ (Fig. 2a; ESM Table 1). The profile from ul. Żytnia (Z) is very similar; however, it does not contain the oldest zone (Fig. 3a; ESM Table 2). The pollen diagram from ul. Jaglana (J) is similar in its bottom part but distinctly differs in the upper part with respect to the *Alnus* and *Pinus* pollen curves (Fig. 4a; ESM Table 3).

The macroscopic material is characterized by high taxonomic richness and abundance of remains. Among 22,766 specimens of seeds and fruits, 234 taxa were identified. A total of 17,100 specimens represent 17 animal taxa. The ecological spectrum of macrofossils is similar in all three profiles. Wetland taxa dominate, reaching up to 38 % in ul. Pszenna, 40 % in Żytnia and 87 % in Jaglana. Field and ruderal weeds appear exclusively in the upper parts of the profiles and remains of useful plants are scarce. The macrofossil assemblage zones follow the divisions into pollen zones (Figs. 2b, 3b, 4b; ESM Tables 1–3).

The geochemistry results from the ul. Pszenna profile supplement the information on ecological conditions during formation of the sediments on the island (Fig. 5, ESM Table 1). The chemical content of these sediments follows the main lithological units: mineral and mineral-organic sediments accumulated in a water body (Psz-A GchZ), a

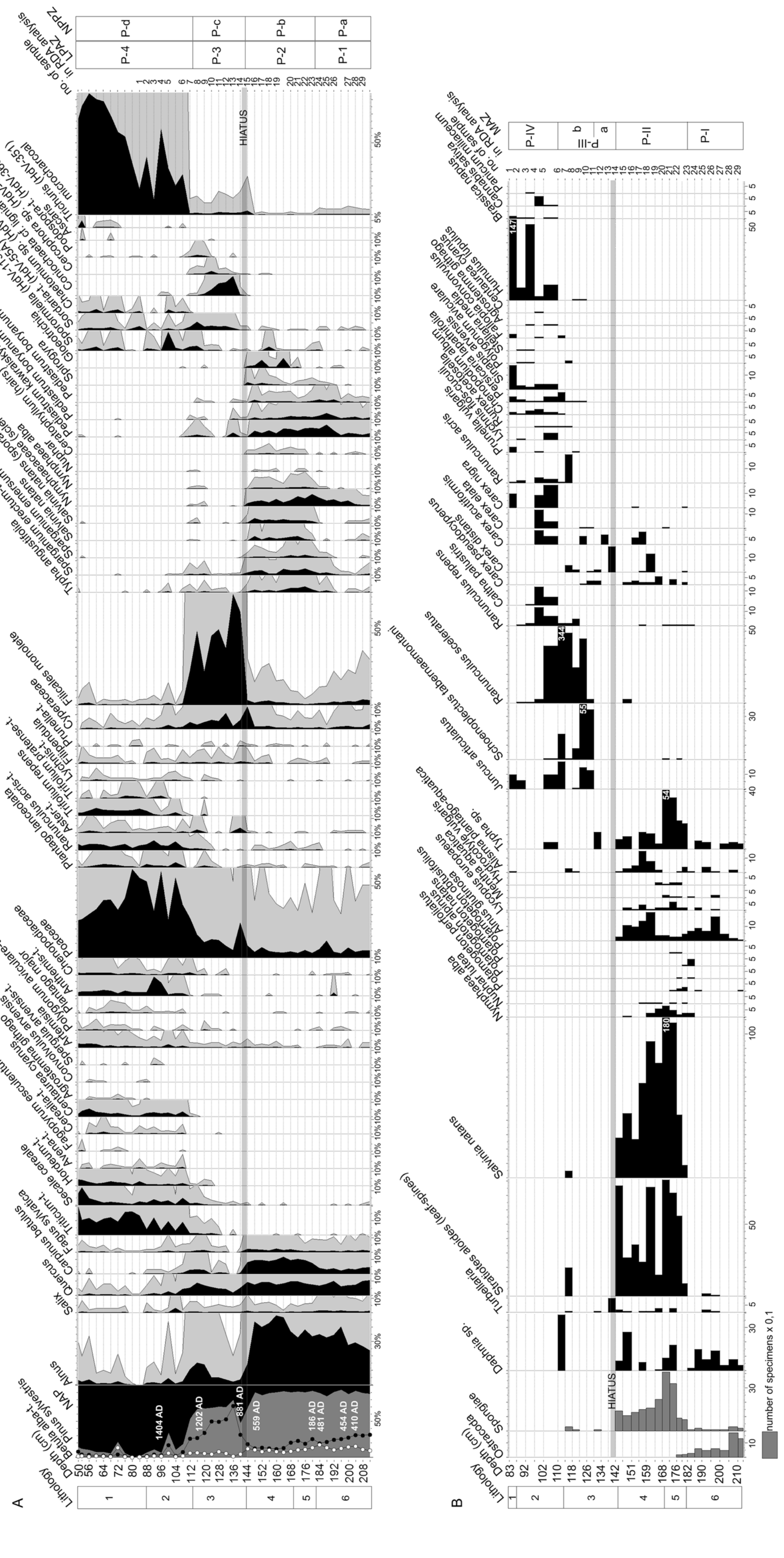

Fig. 2 **a** Pollen, non-pollen palynomorphs; **b** macrofossil diagram from the ul. Pszenna site with selected curves of trees, herbs, local taxa and non-pollen palynomorphs. Lithological units; *1*, cultural layer; 2, matted straw; *3*, *4*, herbaceous peat with various proportions of sand and silt; *5*, *6*, silt with various mixtures of sand and gyttja; for detailed description of the lithological units, LPAZ, NPPZ and MAZ, see ESM Table 1; a *grey horizontal band marks* a hiatus

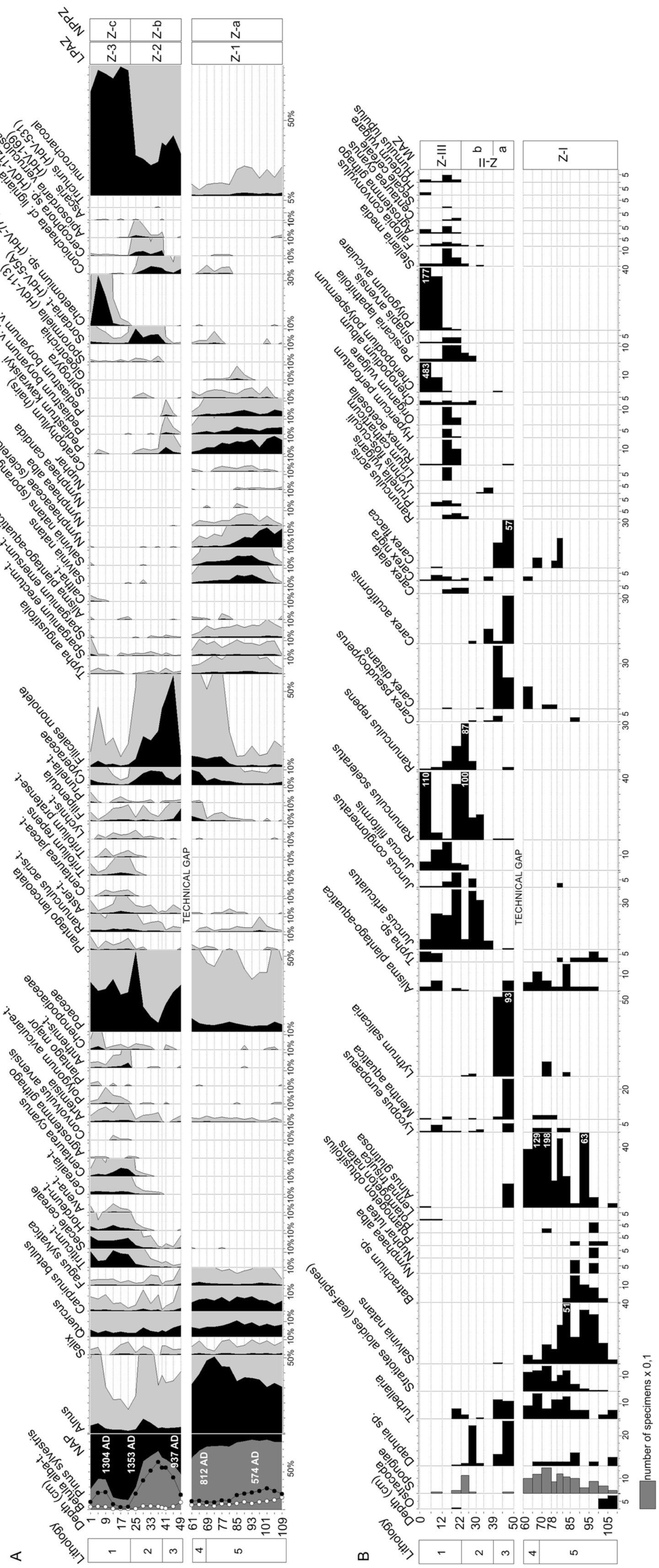

Fig. 3 **a** Pollen, non-pollen palynomorphs; **b** macrofossil diagram from the ul. Żytnia site with selected curves of trees, herbs, local taxa and non-pollen palynomorphs. Lithological units; *1*, sand with silt and coarse detritus; *2–4*, peat with various proportions of gyttja or silt; *5*, silt with sand; for detailed description of the lithological units, LPAZ, NPPZ and MAZ, see ESM Table 2

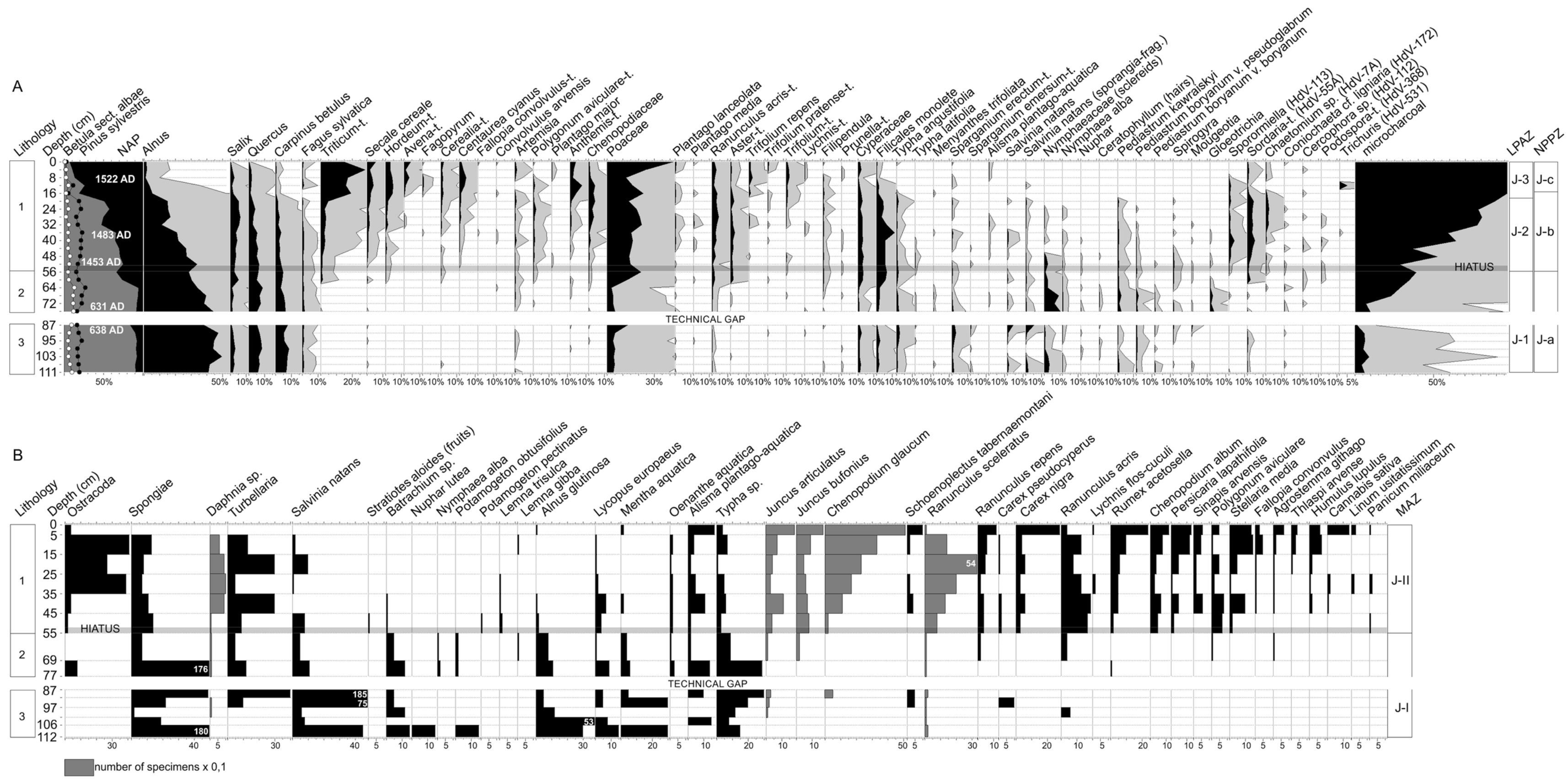

Fig. 4 **a** Pollen, non-pollen palynomorphs; **b** macrofossil diagram from the ul. Jaglana site with selected curves of trees, herbs, local taxa and non-pollen palynomorphs. Lithological units: *1*, cultural layer; *2*, *3*, silt with various proportions of sand and coarse detritus; for detailed description of the lithological units, LPAZ, NPPZ and MAZ, see ESM Table 3; a *grey horizontal band marks* a hiatus

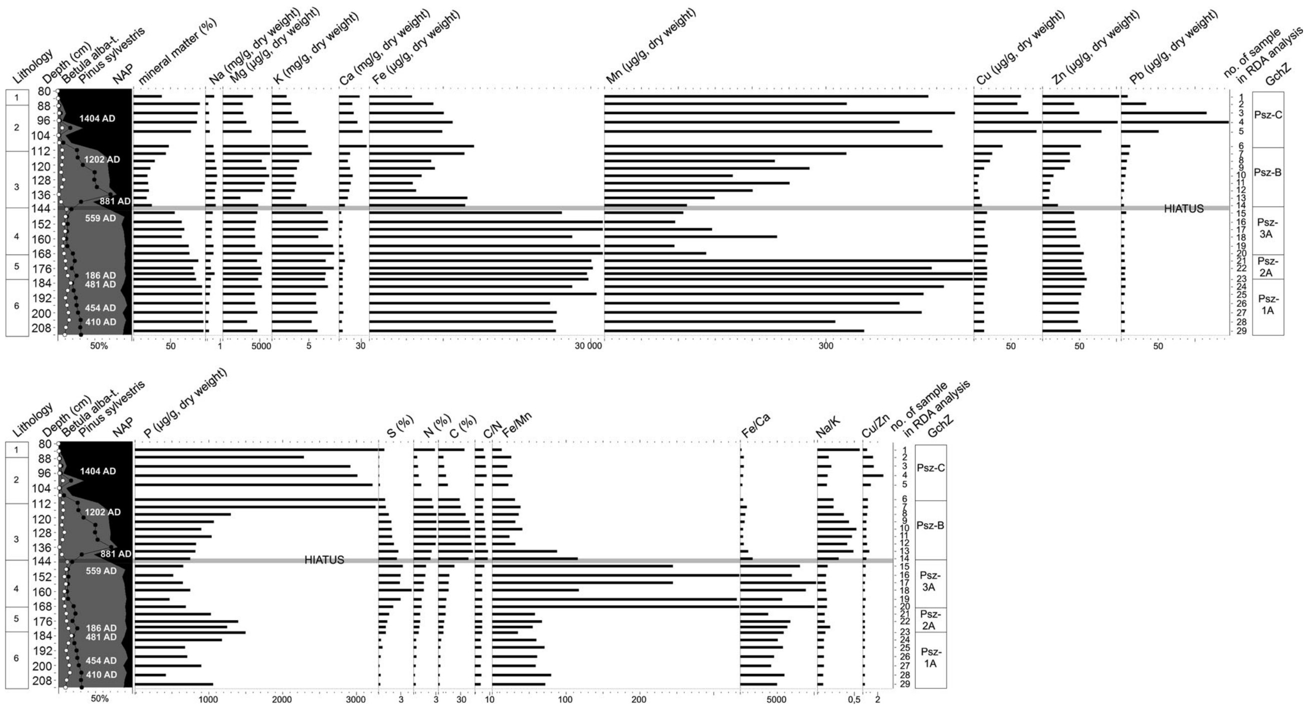

Fig. 5 Geochemical data from the ul. Pszenna site. Lithological units: **1**, cultural layer; **2**, matted straw; **3**, **4**, herbaceous peat with various proportions of sand and silt; **5**, **6**, silt with various mixtures of sand and gyttja; for detailed description of the lithological units and GchZ, see ESM Table 1; *a grey horizontal band marks* a hiatus

peat deposit (Psz-B GchZ) and organic-mineral matter (Psz-C GchZ) in the uppermost section of the profile. Distinct differentiation of the lowest section (Psz-A, 213–144 cm), reflecting the aquatic episode in the history of the site, is the basis for its further division into three subzones, Psz-A (1–3). A strong relationship between the geochemistry of sediments and the composition of palaeoecological samples is confirmed by redundancy analysis (RDA) (Fig. 6). Mineral and mineral-organic sediments at the bottom of the profile are characterized by the highest proportion of aquatic remains, thus confirming that the sediments accumulated in water bodies. These samples are strongly correlated with high iron, potassium, sulphur and mineral matter content, as well as high Fe:Mn and Fe:Ca ratios. Samples from the peat deposit correlate with high sodium, nitrogen and carbon content. Samples from the uppermost section, the cultural layer, were positively correlated with phosphorus, copper, zinc, lead and calcium.

Despite the different thicknesses and amounts of disturbance to the sediments, the palaeoecological data from all three sites confirm and complement each other. This allows us to present a common description of the palaeoecological events which cover four stages of environmental development of the island in the period from the 5th to the 16th century.

The 5th century

The oldest strata, dated to the 5th century AD, have been recovered exclusively from the ul. Pszenna profile. They are characterised by the *Alnus*-*Quercus*-*Pinus* LPAZ, by the Nymphaeaceae-*Pediastrum kawraiskyi* NPPZ, by the Ostracoda-*Daphnia*-*Alnus* MAZ and by the Psz-A1 GchZ. The decrease in *Pinus* and increase of *Alnus* pollen characteristic of this pollen zone might be the result of gradual reduction of pine pollen deposition at the site because of increasing density of the local alder woods; the presence of the latter is confirmed by macrofossils. Traces of primary indicators of human activity such as *Secale*, *Triticum*-t. and scattered *P. lanceolata* pollen reflect this, but at some distance from the site.

Apart from the alder groves, shallow water pools were locally present. The aquatic macroflora was rather poor and consisted of *Potamogeton perfoliatus*, *Stratiotes aloides*, *Alisma plantago-aquatica* and Nymphaeaceae. Several *Pediastrum* taxa (*P. kawraiskyi*, *P. boryanum* v. *pseudoglabrum* and *P. boryanum* v. *boryanum*) were living among phytoplankton, while ostracods, *Daphnia* sp. (ephippia) and Porifera (gemmulae) represented the local fauna. According to the geochemistry data, in this period the water body was mesotrophic according to the rather

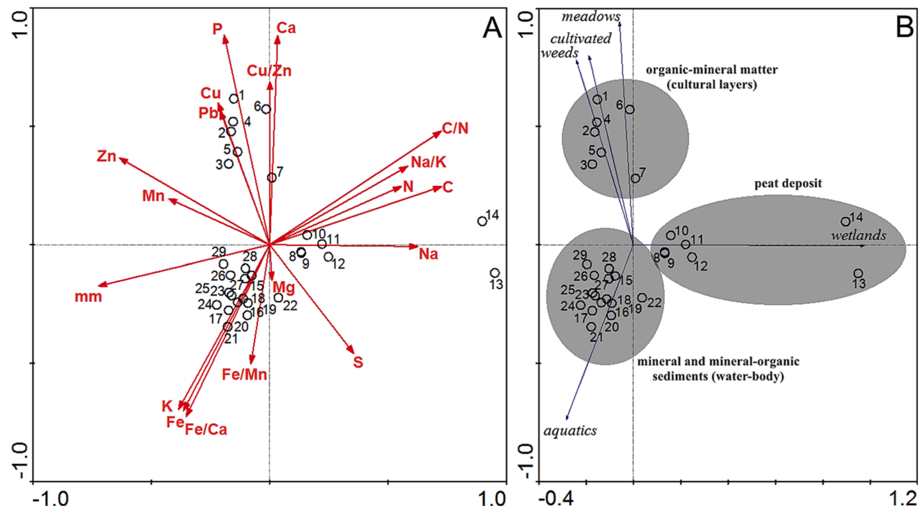

Fig. 6 ul. Pszenna site. **a** RDA biplot of the palaeoecological samples (*open circles*) and environmental variables; **b** RDA biplot of the palaeoecological sample data set including samples (*open circles*) and five taxa groups, samples from the same lithological units are encircled; numbers of palaeoecological and geochemical samples according to Figs. 2 and 5

low Fe:Ca ratio, with a relatively good water oxygenation shown by the low Fe:Mn ratio.

The 6th–8th centuries

According to the data from all three sites, distinct environmental changes took place between the end of the 5th century (ca. AD 480 in ul. Pszenna) and the beginning of the 9th century (ca. AD 810 in the profile from ul. Żytnia). This is shown by the *Alnus*-*Carpinus*-*Quercus* LPAZ, by the Nymphaeaceae-*Pediastrum kawraiskyi*-*Gloeotrichia* NPPZ, by the *Salvinia natans*-*Stratiotes aloides*-*Alnus glutinosa* MAZ and by the Psz-A2-3 GchZ. In this period, *Quercus*-*Carpinus* woods spread on dry land around the wetland, probably regenerating after an earlier human occupation phase. *Fagus* also became slightly more frequent. Scattered pollen grains of *Secale* and other cereals, as well as *P. lanceolata*, may suggest that the area was not totally unoccupied at that time. However, our pollen data poorly reflect these processes because of the strong over-representation of *Alnus* pollen from the local alder woods and the distance of some kilometres to the nearest places where larger patches of other woodland types could develop.

In that period, local oxbow lakes became overgrown by plants, mainly *Salvinia natans* and *Stratiotes aloides*, of which numerous leaf-spines and fruits were found (Fig. 7). High abundances and taxonomic diversity of aquatics were characteristic features of the wetland ecosystem. *Nuphar lutea*, *Nymphaea alba*, *Batrachium* sp., *Potamogeton obtusifolius*, *P. natans* and *Lemna trisulca* frequently appeared, especially in the earlier part of that period; ostracods disappeared while Porifera were frequent among the local micro-fauna. In all three profiles, *Pediastrum kawraiskyi* was the most common of the green algae. In the later part of that period, some aquatics started to be gradually replaced by plants typical of very shallow water or muddy ground such as *Alisma plantago-aquatica*; however, *Salvinia natans* and *Stratiotes aloides* were still very common. *Gloeotrichia* blooms appeared.

The character of the local conditions was well reflected by the sediment geochemistry and in the ul. Pszenna profile it clearly separated the earlier from the later part of the period in question. The mineral matter tended to decrease toward the top of this zone, and among the mineral particles, the fine-grained fraction of silt was more important in the latter stage of the water body development, as indicated by an increase in components connected with minerals such as potassium. Causes of an increase in phosphorus content, which is the main feature which defines the Psz-A2 subzone, might be complex. One possible external source involves the presence of animal dung on the site, as suggested by the presence of *Sporormiella*, a typical coprophilous fungus. The rising Fe:Ca ratio indicates an increasing trophic state and the high Fe:Mn ratio illustrates poor oxygenation of the aquatic habitats throughout the Psz-A3 subzone. A distinct increase in sulphur is another feature of this sub-zone, which confirms strongly reducing conditions. This is in agreement with palynological and macrofossil data indicating vigorous expansion of both micro- and macroflora over the water body and its gradual overgrowing during the 6th–8th centuries.

The 9th–13th centuries

This period is not reflected in the ul. Jaglana site because of an evident hiatus in the sediments (see chronology section). The data from ul. Pszenna and ul. Żytnia show that in the second half of the 9th and during the 10th century, distinct environmental changes took place both locally and regionally. The zones are *Pinus*-Poaceae-Filicales LPAZ,

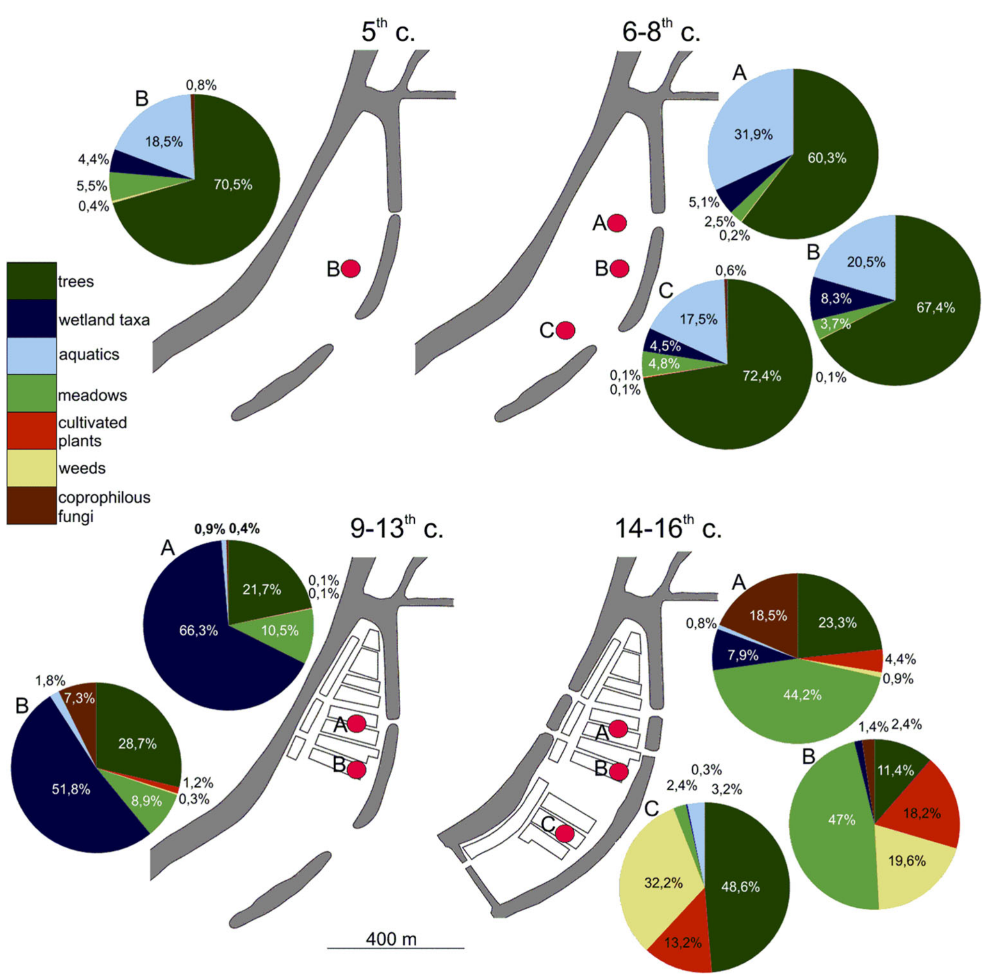

Fig. 7 Wyspa Spichrzów ("Granary Island"), landscape differentiation in the period from the 5th to 16th c. based on palynological data; **a** ul. Żytnia; **b** ul. Pszenna; **c** ul. Jaglana

the *Coniochaeta-Sordaria-Cercophora* NNPZ, the *Carex distans-Ranunculus sceleratus* MAZ and the Psz-B GchZ. A sharp *Alnus* pollen decrease suggests a decline in wetland alder carr woodland. A large amount of decaying wood would have been a substrate for *Coniochaeta* cf. *ligniaria*, spores of which appeared abundantly in the pollen samples. At the same time, a distinct drop in the groundwater table resulted in a reduction in the local water pools and the spread of open-fen vegetation with Cyperaceae (*Carex acutiformis*, *C. nigra*, *C. elata*, *C. distans*, *Schoenoplectus tabernaemontani*), Filicales (*Thelypteris palustris*), *Ranunculus sceleratus* and *Juncus articulatus*; there were also wet meadows with *Filipendula ulmaria*, *Lythrum salicaria*, *Ranunculus repens*, *Lychnis flos-cuculi* and *Carex flacca* (Fig. 7). These areas were probably used for pastures, as suggested by high frequencies of the coprophilous fungal spores *Sordaria*, *Sporormiella*, *Chaetomium*, *Apiosordaria verruculosa* and *Cercophora*. Changes in vegetation caused transformation of the local habitats and their enrichment with organic matter, magnesium and sodium. The presence of animal dung could be a reason for the increasing phosphorus content. Reduction in other broad-leaved tree pollen types, especially of *Carpinus* and *Quercus*, indicates concurrent thinning of woodland on dry land. A strong rise in *Pinus* pollen may partly reflect opening of the woodland which increased pollen transport, but it also illustrates pine expansion on the disturbed parts of the dry land. A still low but systematically increasing frequency of *Secale* and *Triticum*-t. pollen, as well as of other indicators of human activity, reflects the development of settlements and fields at some distance from the investigated sites. A new small peak of *Alnus* and most other tree pollen dated to ca. AD 1200 is worthy of note, as it suggests a short-lived human population crisis that allowed the trees to grow back again.

The 14th–16th centuries

Our data illustrate different histories for the northern and southern parts of the area in that period (Fig. 7). The northern part, with ul. Pszenna and ul. Żytnia, must have been directly occupied by settlement structures since at least the 13th–14th centuries, as shown by high proportions of both pollen and some macrofossils of crops (*S. cereale*, *Triticum*-t., *P. miliaceum*, *Cannabis sativa*, *Humulus lupulus*), field weeds (such as *Centaurea cyanus*, *Agrostemma githago*, *Fallopia convolvulus*, *Sinapis arvensis*) and various ruderal plants (such as *Artemisia*, *Chenopodium* spp., *Stellaria media*), including those typical of trampled places and paths (*Polygonum aviculare*, *Plantago major*), as shown by the Poaceae-Cerealia LPAZ and the *Juncus articulatus*-*Chenopodium* spp. MAZ. It is interesting that in the profile from ul. Pszenna ("wheat street"), *Triticum*-t. (wheat) pollen distinctly dominates over *Secale*, while in ul. Żytnia ("rye street"), both cereals are represented in similar proportions. *Hordeum* and *Avena* pollen types are present in much lower but similar frequencies in both profiles, and *Fagopyrum* appears exclusively at ul. Pszenna. Because of the widespread wetlands, we assume that cultivated fields were not situated directly in this area, so the strong representation of cereals and field weeds may reflect crops which were transported to and stored on the site. Occurrence of wetland taxa (*Juncus* spp., *Carex* spp., *R. sceleratus*, *R. repens*, *Caltha palustris*, *A. plantago-aquatica*) confirms that at least a part of the area was still covered by muddy ground. In the 13th and 14th centuries, patches of wet meadows could still serve as pastures. However large proportions of pollen of *Trifolium pratense*-t. and *T. repens*, typical rather of only moderately wet habitats, together with a high frequency of coprophilous fungal spores, the presence of *Trichuris* and *Ascaris* intestinal parasite ova and a very high level of phosphorus, reflect the presence of dung directly on the sites; this might have come from draught animals used for transporting goods to this area.

In the 15th century, the southern part of the area with ul. Jaglana was still covered by wetland, with patches of *Alnus* stands and a mosaic of water pools, rushes and wet meadows (*Alnus*-Poaceae-Filicales LPAZ). This area was most probably used as a pasture, as shown by high frequencies of *Sporormiella*, *Sordaria* and *Chaetomium* spores. Macrofossils of weeds and some useful plants indicate that the area could also have served other purposes. However, a distinct rise in cereal and field weed pollen (Poaceae-Cerealia LPAZ) is dated to the 16th century only, around AD 1520.

A strong increase in copper, zinc and lead content in the profile from ul. Pszenna indicates increasing atmospheric pollution by heavy metals from around AD 1200.

Discussion

Combining different proxies for a better understanding of palaeoenvironmental changes on archaeological sites

In recent years, along with pollen and macrofossils, NPPs and geochemistry of sediments have also been used to reconstruct long-term environmental changes. However, in the case of research carried out directly on archaeological sites, this type of comprehensive study is still rare because of the usually limited possibilities of obtaining adequate sequences of undisturbed sediments. The same problem concerns ecological studies on the natural history of old urban centres. In this respect, the study carried out on Wyspa Spichrzów in Gdańsk increases the so far relatively small number of early urban archaeological sites providing multi-proxy continuous records of environmental data covering the period before settlement, establishment of the settlement and the continuation for some centuries of urban development (Beneš et al. 2002; Sadori et al. 2010; Kisielienė et al. 2012; Pepe et al. 2013; Bosi et al. 2015).

The palaeoecological material from the island represents three distinct sediment series that are well characterized by all proxies used in this study. It should be stressed that the variable character of the sediments has to be considered when interpreting particular elements of the data. Especially, the geochemistry data are strongly dependent on the origin and specific properties of sediments with respect to their abilities of retention and sequestration of various elements (Oonk et al. 2009a).

The lowest parts of the profiles, dating back to the 5th–8th centuries AD, accumulated in natural conditions with shallow mesotrophic and then eutrophic water bodies surrounded by wetlands covered by alder woods, typical of alluvial areas. The pollen data indicate a lack of local human activity over that period, and macrofossils, NPPs, geochemistry and lithostratigraphy show the gradual shallowing of the water pools, a strong rise in the trophic state and decreasing oxygenation of the aquatic habitats, as well as decreasing mineral matter input, suggesting decreasing water flow energy. The distinct negative correlation between phosphorus and sulphur content in the sediments in the ul. Pszenna site reflects a known relationship between sulphide production and phosphorus release from the sediments as a mechanism which enhances lake eutrophication (Holmer and Storkholm 2001). These changes which occur together with the expansion of thermophilous *Salvinia natans*, especially in the period of the 7th–8th centuries, seem to reflect the beginnings of the medieval climate warming (Büntgen et al. 2011; Święta-Musznicka et al. 2011). The occurrence of coprophilous *Sporormiella* spores in ul. Pszenna indicates herbivore dung at the site (van Geel et al. 2003; Davis and Shafer 2006), which in turn might at least partly be responsible for the increased phosphorus content in the sediments (Oonk et al. 2009a). Because of the weak presence of primary indicators of human activity, we suspect that this evidence of dung represents grazing by wild rather than domestic animals in that period.

The second sediment series dating to the 9th–13th centuries represents peat formed under an open fen, and a distinct hiatus separates it from the earlier series. The long-lasting drier conditions that characterized the period of the Medieval Climatic Anomaly (MCA) (Büntgen et al. 2011) caused lowering of the groundwater. This series was deposited during the early stage of establishment and development of the town of Gdańsk, but at that time the island was not yet built upon. The increasing frequency of *Sordaria*-t., *Sporormiella*, *Podospora*-t. and *Cercophora* sp. spores, all considered as indicators of grazing (van Geel et al. 1983; Davis and Shafer 2006; Florenzano et al. 2013), together with the increase in indicators of human activity, show that the area most probably served as a pasture. Here again, the increasing phosphorus content is an additional indicator of the local presence of dung directly on the site.

The cultural layers lying as a top series in all three profiles were formed when granaries and other commercial structures already operated on the Wyspa Spichrzów. These cultural deposits are distinguished by a dominance of a flora connected with people, initially the pollen and macrofossils of cultivated plants and weeds. Huge phosphorus values and a high frequency of coprophilous fungal spores, as well as ova of *Trichuris* and *Ascaris*, indicate strong pollution with faecal material (van Geel et al. 2003; Oonk et al. 2009b; Bosi et al. 2011; Brinkkemper and Van Haaster 2012), which could have partly originated from draught animals used for transportation of goods. It is, however, worth noting that on archaeological sites, phosphorus is one of the most important human indicators, not only associated with animal husbandry but also considered a good sign of the processing and storage of food, waste deposits, burning of organic matter, and the presence of human faeces (Wilson et al. 2008; Cook et al. 2014; Stivrins et al. 2015).

Our data show atmospheric pollution by the heavy metals copper, zinc and lead accelerating at around AD 1200. As at other archaeological sites, these elements can be associated with metal working and various crafts, as well as with burning (Wilson et al. 2008; Cook et al. 2014; Stivrins et al. 2015). Increasing values indicate that human-induced atmospheric pollution by heavy metals had begun already in prehistory (Hong et al. 1994; de Vleeschouwer et al. 2010). In Europe, the earliest strong pollution going back to the Bronze and Roman Iron ages occurred in the Mediterranean area (Garcia-Alix et al. 2013). In central and north-western Europe, the first distinct signals dating to the Bronze Age and then the Roman Iron Age occur rather locally and concern sites situated in areas of mining activity (Mighall and Chambers 1993; Veselý 2000). A strong increase in heavy metal pollution became a common feature from the medieval period (Garbe-Schönberg et al. 1988; de Vleeschouwer et al. 2010), but the more detailed chronology of this process depends on the timing of the development of local and regional medieval settlement (Hudson-Edwards and Macklin 1999).

Did the beginnings of Gdańsk follow the medieval climate change with the occupation of wetlands?

One of the most interesting questions in studies of prehistoric and historic populations concerns decisions about settlement location, the reasons why people settled in certain areas and avoided others. The perspective on the natural attractiveness of an area as being suitable for settlement varied according to the political and economic needs of the times in question and the technological potential for land reclamation. However, proximity to water was always a priority, as may be observed on maps illustrating the concentration of settlements along river valleys, sea shores and large lake shores in all prehistoric and historic periods and on all continents. Location at the mouth of a large river, close to the sea shore, is typical of a large number of medieval cities such as Rouen, Bremen, Hamburg, Lübeck, Szczecin and Amsterdam because access to water routes was important for shipping and long-distance trade as a basis for their economic success. In fact, these cities were established or re-established in the case of the towns earlier settled in the Roman period, on floodplain wetlands.

Floodplain wetlands and marshes have been occupied for settlement from the earliest prehistory. In many European regions, specific adaptations to this very special environment have been developed, such as settlements on terps or built-up occupation mounds, which were widespread along the North Sea coast (Meier 2004; Behre 2012; Bazelmans et al. 2012). The main attractiveness of wetlands was easy access to water and high productivity of the ecosystem. They were particularly suited to meadow and pasture, but if drained, they also provided fertile arable land (Brinkkemper 1991; Rippon 2005). Difficult to reach, wetlands played an important role as a natural element in defence (Marzo 2012). However, living in wetlands carried several constraints. Wetland topography is totally dependent upon hydrological events, especially floods. In many periods, prolonged changes to wetter conditions forced people to move their settlements to higher ground, while dry periods caused settlements to migrate towards the lower parts of river valleys (Jasiewicz and Hildebrandt-Radke 2009; Vandenberghe 2015). Therefore, we may assume that occupation of this kind of environment involved consideration of current hydroclimatic conditions, water levels and the dynamics of a river system. Living in wetlands demanded great care in site preparation, especially keeping dry enough. The living areas needed to be raised, as shown by dwelling mounds such as terps

(Bazelmans et al. 2012) and drained. Some coastal marshes appear to have already been reclaimed in the late Iron Age and the Roman period, as shown by the archaeological data from, for example, Friesland (Bazelmans et al. 2012; Behre 2012) or Britain (Rippon 2005). In the early Middle Ages, wetland reclamation was already a common practice in many areas of north-western Europe (van de Noort 2000; Meier 2004). In the delta of the river Wisła (Vistula), regular land reclamation and a polder system started to be established in the 14th century when Dutch farmers settled in this area (Cyberski et al. 2006).

Gdańsk started to develop on small patches of higher ground within the wetlands dissected by rivers, where three or four settlements were established (Paner 1999a). The so far earliest traces of the medieval settlements from the late 10th and 11th centuries are relatively late compared to the timing of the medieval occupation in the region in the 8th–9th centuries (Łosiński 1982; Śliwiński 2009). Therefore, it may be assumed that until the end of the 10th century, the area was unsuitable for settlement. Our results direct us to a similar conclusion, with the presence of a wetland covered by alder woods and open water pools up to the 9th–10th centuries. In the 10th century, the water table dropped, as shown by a hiatus and decline in aquatic taxa in the subsequent sections of the profiles. We suggest prolonged drought as a factor responsible for this change. These data conform with the climate reconstructions indicating dry conditions between ca. AD 1000–1200, during the Medieval Climatic Anomaly (Helama et al. 2009; Büntgen et al. 2010).

According to our interpretation, the primary cause for the strong *Alnus* decline in the 10th century could also have been drought rather than clearance of the woodland due to settlement activity. This conclusion seems to be confirmed by (1) a still rather weak presence of human indicators and (2) a drop in the water table instead of its temporary rise, as could be expected in the case of sudden clearance of woodland caused by reduced water take-up and evapotranspiration. *A. glutinosa* is sensitive to long-lasting droughts because its roots are strikingly vulnerable to cavitation when exposed to drier conditions (Hacke and Sauter 1996), and its stands then may sharply decline when riverside habitats become dried out (Rejewski 1971). The *Alnus* decrease around the 10th century caused by climatic factors seems to have been a widespread phenomenon (Noryśkiewicz 2013).

Considering all of the above arguments, we postulate a strict relationship between development of the early medieval settlement in Gdańsk and lowering of the water table in the wetland due to the long-lasting drier conditions. This resulted in less space being occupied by water bodies and the emergence of patches of dry land. Dying alder woods were gradually replaced by open herbaceous vegetation which was used for pasture, while *Alnus* timber served as building material. According to the archaeological data, it constituted about 20 % of the wood used in 10th–11th century buildings (Zbierski 1978). Such a scenario is in agreement with the observed tendencies of early medieval settlement location in river valley bottoms, characteristic of drier periods with low flood activity (Jasiewicz and Hildenbrandt-Radke 2009).

Our palaeoecological data strictly correspond with the archaeological findings on the spatial development of the area of Wyspa Spichrzów as a commercial centre (Paner 1993; Kaczyńska et al. 2005). The northern part of the area, after the decline of the *Alnus* woods in the 10th century, stayed as an open wetland covered by wet meadows up to the 13th–14th centuries. In the south, wetland partly covered by the alder wood was declining more steadily and this was built upon only in the 15th century. Thick layers of material were used to raise the buildings from the muddy ground (Kaczyńska et al. 2005). Even so, in some periods, the conditions for storage of grain and other food products were certainly not perfect, especially because the area was flood-prone (Cyberski et al. 2006). Dampness could result in grain decay or sprouting, as shown in some archaeobotanical samples dated to various centuries, which contained sprouted and then charred rye grain (Badura 2011).

Conclusions

This study, based on multi-proxy data from three archaeological sites on Wyspa Spichrzów ("Granary Island") which lies in the heart of the historical city of Gdańsk, has allowed us to reconstruct natural conditions before occupation of this area in the early medieval period and then during its development into a commercial centre. The results show that Gdańsk was established on floodplain wetlands following lowering of the water table in the 10th century, which caused a reduction in the local alder woodland and areas of open water. We suggest a causal link between town development and the water table lowering, most probably caused by the long-lasting dry conditions of the Medieval Climatic Anomaly.

Our palaeoecological reconstruction of the history of occupation on the island conforms well with the archaeological and historical data and shows it in an environmental context. In the period between the 10th and 13th–14th centuries, the area was used primarily for meadows and pastures. Significant changes of the environment due to commercial development of the area began in the 13th–14th centuries on the northern side, while the southern part remained in a semi-natural state until the 16th century. The large values of cereal pollen indicate transport of grain to granaries on the island.

Our results clearly benefit from the inclusion of the analyses of NPPs and geochemistry in the study. These data have allowed us to refine the palaeohydrological reconstruction, detect changes in the trophic state of the local water pools and date the strong increase in atmospheric pollution by heavy metals from the 13th century. The presence of coprophilous fungal spores together with an increase in phosphorus and nitrogen content have confirmed the presence of animals directly on the site. The multi-proxy approach has certainly helped to better understand the processes of environmental changes as shown by the results from the sediments and cultural layers at these archaeological sites.

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