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Phases of aeolian accumulation on the Vistula Spit (Southern Baltic Sea) in the light of TL dating and analysis of a digital elevation model

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The genesis of the Vistula Spit (Southern Baltic Sea) in the Postlitorina period is regarded as occurring by gradual addition of successive dune ridges along the entire length of the form. Based on the degree of soil profile development and radiocarbon dating of organic sediments three main stages of aeolian processes are usually recognized. GIS analysis of a digital elevation model (DEM) and thermoluminescence dating of dune sand supports the model of progressive development of dune ridges, and has identified four periods of intense aeolian activity. These were established 5860–5400, 1930–1610, 1200–900 years ago from the present, and from 500 years ago.

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Key words: Southern Baltic, Vistula Spit, Holocene, dune ridges, TL dating, DEM.

INTRODUCTION

The Southern Baltic seashore is characterized by a wave-eroded moraine plateau forming cliffed coasts alternating with spits (formed as a result of both marine and aeolian accumulation) that cut off bays and coastal lowlands (Rosa, 1963; Augustowski, 1972; Borówka, 1990; Tomczak, 1995*a*, *b*). Within this, the southern coast of Gdańsk Bay comprises one of the longest spits in the Baltic Sea. The Vistula Spit is a zone of intensive aeolian accumulation, the width of which ranges from 300 m near Gdańsk and Sopot to 3 km near Stegna. Its length is about 115 km (out of which 75 km lies in Polish territory; Fig. 1). Its western part adjoins the Vistula River delta, and its eastern part has the character of a peninsula separating the Vistula Lagoon from Gdańsk Bay. There are two opposing views about the origin of the spit (Fedorowicz *et al*., 2009). The first suggests that the spit accumulated by processes transporting material from two opposing directions (Klautzsch, 1919; Beurlen, 1933), while the second involves gradual addition of successive dune ridges along its whole length (Rosa, 1963; Mojski *et al*., 1995; Tomczak, 1995*a*, *b*; Uścinowicz, 2003). A second problem is the age of accumulation processes, and especially the beginning of spit development. This is determined as during the final stage of the Litorina transgression at 6300 BP – Middle Atlantic (Rosa and Wypych, 1980; Tomczak, 1995*b*) or at the Postlitorina period in the Middle Subboreal (Tomczak *et al.*, 1989; Musielak, 1980). There is general agreement following Klautzsch (1919) that successive dune ridges were formed in phases. Geomorphological survey, supported by radiocarbon dating, has indicated three phases: 3920–3160 BP, 1210–1060 BP and from 900 BP to present (Tomczak *et al.*, 1989; Tomczak, 1995*a*, *b*). Taking into account climate changes, i.e. the cooling periods of Little Ice Age (LIA) type (McDermott *et al*., 2001) and oscillations of water level in the Baltic Sea (Rosa, 1987; Tomczak, 1995*a*; Uścinowicz, 2003; Rotnicki, 2009) in the later Holocene, considering radiocarbon dates (Tomczak, 1990), three series of TL dates (Fedorowicz *et al*., 2009) and also optically stimulated luminescence (OSL) ages of generation foredunes in the Świna Barrier (Reimann *et al*., 2011) and aeolian accumulation within the coastal dunes on the Jutland Peninsula (Murray and Clemmensen, 2001;

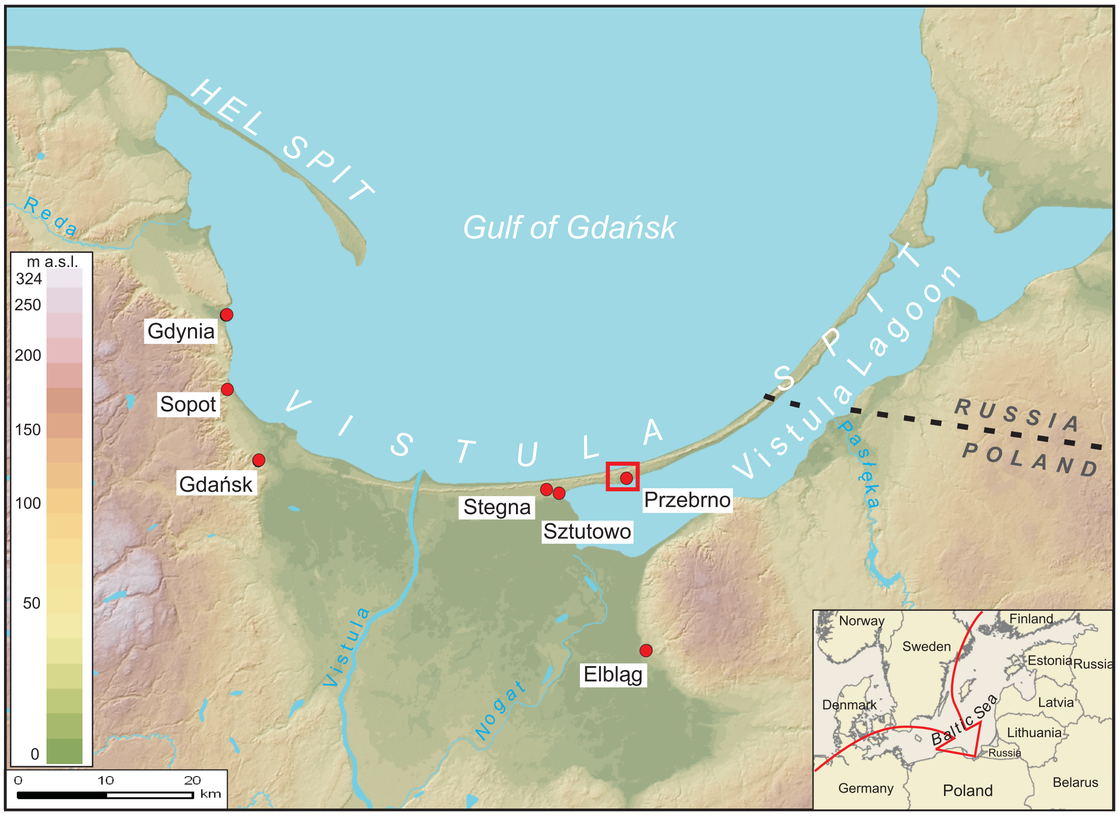

Fig. 1. Location of the Przebrno profile shown on relief map

The red arrow indicates the location of mainly figure

Clemmensen *et al.*, 2009), as many as five aeolian phases have been distinguished in the later Holocene.

In this context, we have carried out detailed dating of aeolian sands in successive cross-sections of the Vistula Spit to constrain the number and age of aeolian phases in which individual dune ridges were formed on the Vistula Spit.

METHODS

The aims of this project need use of advanced analytical methods (as in Osadczuk, 2004). Firstly topographic maps at a scale of 1:10 000 (sheet N-34-51-D-c-4) were calibrated, and then their hypsometric content was digitized. From this, a digital elevation model was created. It functioned as an input layer in further analytical operations, and from it were derived primary topographic attributes, such as land slope, aspect and curvature. A geological layer (vectorized content of the *Detailed Geological Map of Poland* at a scale of 1:50 000, Krynica Morska sheet, Makowska, 1987) and soil layer (vectorized content of the *Soil-Habitat Map*..., 1969) were also included in the analysis. Successive dune ridges can be indicated by the degree of soil podsolization (Keilhack, 1912). Based on this, the extents of white, yellow and brown dunes were determined that enabled us to delineate two research profiles perpendicular to the spit (Fig. 2).

Two cross-sections through the spit (Fig. 3) were compiled based on twelve a hand auger-holes (Eijkelkamp, Netherlands). Two or three samples at different depths were taken from each auger-hole, at up to 5 metres from the dune surface. In total, 29 samples were taken from the profiles for TL dating. At first sample moisture was measured. The dose rate (d_r) was determined for a dried sample with use of the *MAZAR-95* gamma spectrometer. The concentrations of ^{226}Ra, ^{232}Th, ^{40}K in dry mass were measured. One sample was measured 20 times; each measurement lasted 2000 s. The concentrations of radionuclides were converted into dose rates for alpha, beta and gamma radiation. The dose rate was calculated with corrections for deposit moisture, dose of cosmic radiation, grain size, and time of etching with hydrogen fluoride (HF; Aitken and Xie, 1985; Adamiec and Aitken, 1998). Uncertainty of dose rate determination was about 3% (Poręba and Fedorowicz, 2005). The measurement of equivalent dose (d_e) was preceded by preliminary treatment. The 80–100 μm quartz grain fraction, separated by sieving, was treated with 10% HCl for twenty-four hours, and then with 2% NaOH for twenty-four hours. Then grains were etched with 40% HF for 45 minutes (Bluszcz, 2000). After each treatment a sample was washed with distilled water. The equivalent dose (d_e) was measured by the TL multi-

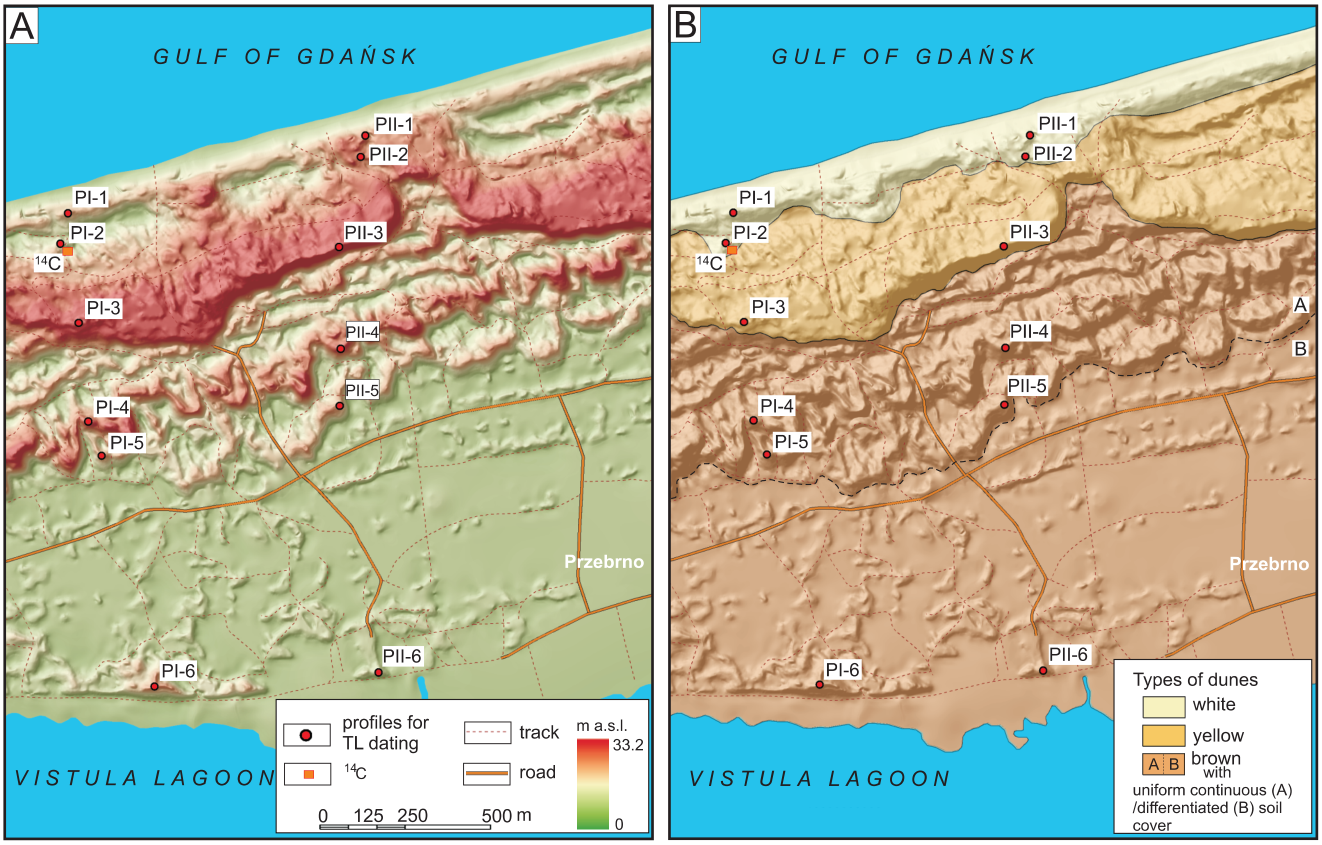

Fig. 2. Location of research sites shown on: A – digital elevation model near Przebrno; B – dune generations, which were marked on the basis of the *Soil-Habitat Map....* (1969)

ple-aliquot regeneration technique (Wintle and Prószyńska, 1983), according to the description published by Fedorowicz (2006). The glow curves were recorded using a TL reader-analyser of *RA'94* type (with an *EMI 9789 QA* photomultiplier) linked with an IBM computer. A sample was heated in argon atmosphere to 400°C with a heating rate of 8°C/s. The *RA'94* reader-analyser was used with a *BG-28* optical filter (Berger *et al*., 1992). The peak analysed occurred at about 250°C. The plateau occurred between 230 and 280°C. Grain sensitivity was tested by additional measurements.

RESULTS

Analysis of the digital elevation model indicates that 10.1% of the area examined is covered by white dunes, 16.1% by yellow, and 73.9% by the brown[1] dunes (Fig. 2). The white dunes form the ridge of the fore-dune reaching a height of slightly over 10 m, being undercut by coastal abrasion in places. Considerable lows to 3.75 m a.s.l. occur in this ridge, and extend, to the south where they from wind-blown depressions up to 600 m long and 150 m wide. A second discontinuous ridge occurs between these depressions. It is composed of forms up to 140 m long and 15 m high. In this zone, 6 samples from white dunes and 4 samples from wind-blown depressions were taken (Table 1). The TL ages obtained for white dunes range from 0.3 ±0.1 to 0.5 ±0.1 ka, and those for depressions range from 0.9 ±0.1 to 1.2 ±0.1 ka. The TL ages were compared with the results of radiocarbon dating of sub-fossil organogenic layers. Two radiocarbon dates were obtained: cal. 295 ±125 BP (Gd-30231) and cal. 500 ±110 BP (Gd-30232) (Fig. 3). The highest train of dunes forms the zone (70–410 m wide) of yellow dunes. These are arch and parabolic forms of different size often occurring in the foreland of the wind-blown depressions described above. The largest of these reach a height of 30 m in the front part, a length of 900 m along the ridge, and their arm-span is up to 400 m. Based on dating of 5 samples (PI-3, PII-3), the age of these dunes was determined at 1.61 ±0.2–1.85 ±0.2 ka (Fig. 3 and Table 1). The next zone of brown dunes is the widest one (1050–1450 m) in the area examined. It is composed of three dune trains: 1) a continuous dune train composed

[1] The dune generations are characterized by the degree of soil development. The brown dunes have complete soil profile developed, the yellow ones are covered by initial soils, and white dunes are active forms without soil cover.

Table 1

Luminescence dates of samples from Przebrno

No. of drilling	Dune ridges	Depth [m]	No. Lab. UG	Radionuclide concentration (Bq kg^{-1})				Water content [%]	Dose rate d_r [Gy/ka]	Equivalent dose d_e [Gy]	TL age [ka]
				^{226}Ra	^{232}Th	^{40}K	d_c				
PI-1	white	1.00	6071	20.8 ±1.1	23.6 ±0.6	452 ±6	0.14	4 ±4	2.42 ±0.10	1.21 ±0.25	0.50 ±0.10
	white	2.00	6072	20.4 ±1.1	22.8 ±0.6	449 ±6	0.11	5 ±4	2.37 ±0.09	1.19 ±0.25	0.51 ±0.11
	white	4.00	6073	21.0 ±1.1	23.0 ±0.6	450 ±6	0.06	4 ±4	2.40 ±0.11	1.20 ±0.25	0.50 ±0.12
PI-2	white/yellow	2.00	6074	20.4 ±1.4	22.2 ±0.7	440 ±6	0.11	4 ±4	2.29 ±0.10	2.30 ±0.24	1.03 ±0.12
	white/yellow	3.80	6075	20.8 ±1.2	23.0 ±0.7	445 ±7	0.06	4 ±4	2.37 ±0.11	2.37 ±0.24	1.03 ±0.10
PI-3	yellow	2.00	6076	24.0 ±1.1	26.0 ±0.6	475 ±7	0.11	4 ±4	2.63 ±0.12	4.81 ±0.48	1.83 ±0.21
	yellow	4.00	6077	21.7 ±0.6	24.7 ±0.6	467 ±5	0.06	4 ±4	2.65 ±0.11	4.90 ±0.49	1.85 ±0.20
	yellow	5.00	6078	20.8 ±0.6	24.4 ±0.7	453 ±6	0.04	4 ±4	2.62 ±0.10	4.72 ±0.50	1.80 ±0.22
PI-4	brown	2.00	6079	21.0 ±0.6	23.8 ±0.6	455 ±7	0.11	4 ±4	2.57 ±0.10	4.65 ±0.47	1.81 ±0.21
	brown	4.00	6080	21.8 ±1.1	25.0 ±0.6	460 ±6	0.11	4 ±4	2.66 ±0.11	4.95 ±0.50	1.86 ±0.22
PI-5	brown	2.00	6081	20.8 ±1.2	22.9 ±0.7	458 ±6	0.11	4 ±4	2.58 ±0.11	4.72 ±0.47	1.83 ±0.20
	brown	4.05	6082	20.9 ±1.0	23.6 ±0.7	459 ±6	0.06	4 ±4	2.58 ±0.10	4.67 ±0.47	1.81 ±0.20
PI-6	brown	1.50	6083	25.8 ±1.0	27.5 ±0.4	548 ±5	0.12	5 ±4	2.88 ±0.11	15.55 ±1.6	5.40 ±0.52
	brown	4.05	6084	21.7 ±1.3	24.0 ±0.7	547 ±5	0.06	4 ±4	2.83 ±0.12	15.71 ±1.6	5.55 ±0.62
	brown	4.40	6085	28.3 ±1.1	27.4 ±0.5	523 ±5	0.05	4 ±4	2.79 ±0.11	15.60 ±1.6	5.59 ±0.63
PII-1	white	2.00	6086	21.0 ±1.2	23.0 ±0.6	250 ±6	0.11	4 ±4	2.39 ±0.10	0.7 ±0.35	0.30 ±0.12
	white	4.00	6087	21.8 ±1.1	22.6 ±0.6	255 ±6	0.06	4 ±4	2.42 ±0.09	1.21 ±0.25	0.52 ±0.11
	white	5.00	6088	20.9 ±1.1	23.6 ±0.6	259 ±7	0.04	4 ±4	2.43 ±0.10	1.22 ±0.25	0.52 ±0.12
PII-2	white/yellow	2.00	6089	21.7 ±1.2	25.5 ±0.7	470 ±7	0.11	4 ±4	2.42 ±0.11	2.18 ±0.24	0.93 ±0.11
	white/yellow	4.00	6090	20.0 ±1.1	21.4 ±0.6	454 ±6	0.06	4 ±4	2.32 ±0.10	2.78 ±0.28	1.20 ±0.10
PII-3	yellow	2.00	6091	23.8 ±0.7	25.9 ±0.7	479 ±7	0.11	5 ±4	2.59 ±0.10	4.17 ±0.42	1.61 ±0.22
	yellow	4.00	6092	23.9 ±0.8	25.8 ±0.6	486 ±7	0.06	4 ±4	2.66 ±0.11	4.92 ±0.50	1.85 ±0.20
PII-4	brown	2.00	6093	20.9 ±0.7	23.6 ±0.7	458 ±7	0.11	4 ±4	2.60 ±0.10	4.21 ±0.44	1.62 ±0.22
	brown	4.00	6094	21.0 ±0.7	23.0 ±0.6	450 ±6	0.06	4 ±4	2.57 ±0.10	4.65 ±0.48	1.81 ±0.21
PII-5	brown	2.00	6095	21.4 ±0.7	24.0 ±0.7	450 ±6	0.11	4 ±4	2.55 ±0.11	4.11 ±0.42	1.61 ±0.20
	brown	4.00	6096	20.9 ±0.7	25.2 ±0.7	461 ±6	0.06	4 ±4	2.63 ±0.11	4.66 ±0.50	1.77 ±0.21
	brown	5.00	6097	21.0 ±0.7	25.5 ±0.7	459 ±7	0.05	4 ±4	2.63 ±0.10	5.08 ±0.52	1.93 ±0.32
PII-6	brown	2.00	6098	19.2 ±1.4	26.6 ±0.7	540 ±6	0.11	4 ±4	2.87 ±0.12	15.67 ±1.6	5.46 ±0.60
	brown	4.00	6099	20.8 ±1.3	27.1 ±0.6	528 ±7	0.06	4 ±4	2.79 ±0.12	16.35 ±1.7	5.86 ±0.62

of medium and small arch and parabolic forms up to 15 m high and 200–300 m long; morphologically this train distinctly resembles yellow dunes but the soil cover and hypsometric conditions are different; 2) a discontinuous train composed of single small arch dunes up to 5 m high and 200 m long, separated by small (50–150 m long) waterlogged wind-blown depressions, and 3) ridge dunes about 10 m high and up to 250 m long occurring near the shore of the Vistula Lagoon and separated by larger wind-blown depressions, that are up to 200 m long and 300 m wide. The TL ages of 14 samples occur in two intervals from 1.62 ±0.22 to 1.93 ±0.32 ka and from 5.40 ±0.52 to 5.86 ±0.62 ka (Fig. 3 and Table 1).

DISCUSSION OF RESULTS

The analysis of a DEM (digital elevation model) and a DTM (digital terrain model) shows the existence of three dune zones (Fig. 2). Dunes occurring in each separate zone are similar in terms of hypsometry and morphology, so probably have a common origin. This is especially clear in the case of the yellow dunes – mostly arch and parabolic forms of considerable size and concentration, with initial soils. The zone of brown dunes is less uniform. Podzolic soils form a continuous cover on the train adjacent to the yellow dune zone. In two other trains podzolic soils occur only on dunes whereas peat and hydrogenic soils are found in the inter-dune depressions. The different arrangement and morphology of forms indicate that the zone is not uniform. We tentatively distinguish two subzones within the zone of brown dunes. The first is characterized by a dense pattern of dunes, which are mostly arch forms. Scattered ridge dunes dominate in the second subzone. It is more difficult to delineate a clear boundary between the white and yellow dunes due to the occurrence of the second discontinuous ridge of white dunes, which is often situated within the wind-blown depressions supplying the yellow dunes (Fig. 2). Therefore, it can be assumed that this dune ridge is a transitional unit between the white and yellow dunes as observed by Fedorowicz *et al*. (2009), and also in papers describing the development of the Vistula Spit (Tomczak, 1990). Two generations of white dunes were also described by Osadczuk (2004) in the Świna Barrier.

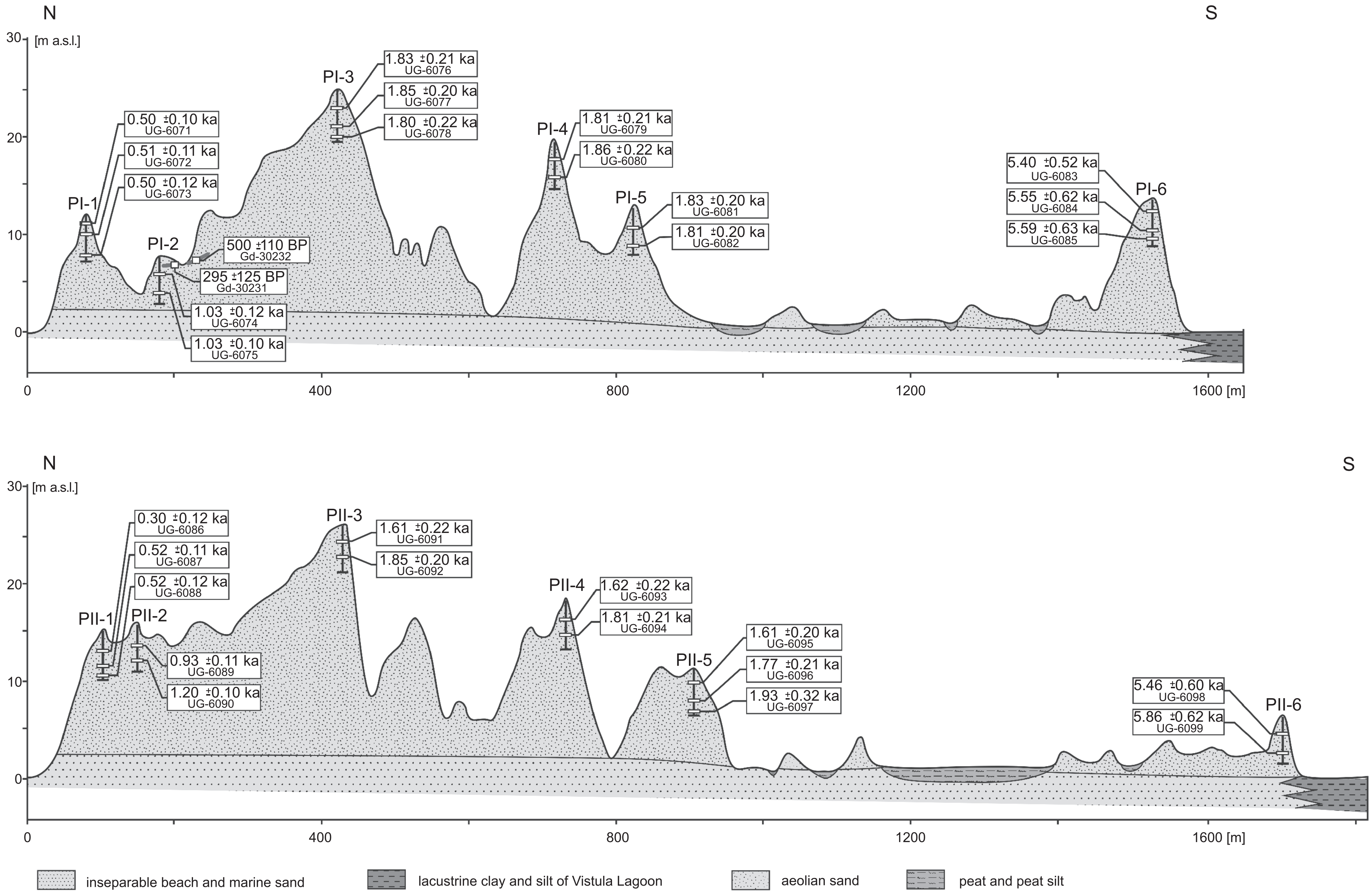

Fig. 3. Simplified geological profiles through the Vistula Spit near Przebrno and results of TL dating

This matter is elucidated by TL dating of separate dune trains. The results obtained in the white, yellow and transitional dune zones clearly indicate their different ages, and are consistent with distinguishing a transitional zone between white and yellow dunes. The dates from the brown dunes form two groups. The first, distinctly younger, with dates ranging from 1.62 to 1.93 ka, in terms of age resembles the yellow dunes. Based on dating of dunes in Stegna, Fedorowicz *et al*. (2009) distinguish also a transitional zone between yellow and brown dunes but the dates obtained, ranging from 4.24 to 5.63 ka, correspond better to the age of brown dunes. Therefore, the younger subzone of brown dunes discussed above cannot be identified with this transitional zone of yellow-brown dunes. It seems reasonable to include the continuous train of brown dunes in the zone of yellow dunes based on their similar morphology, dune orientation, continuous soil cover and TL age. They differ in hypsometric conditions and degree of pedogenesis development. This problem needs further investigation. Similarly distributed ages indicating distinct separation of the OSL dates were obtained by Reimann *et al*. (2011) from brown dunes from the Świna Barrier.

The TL ages obtained are classified into four distinct periods/phases of intensified aeolian accumulation (Fig. 4). The first of these is indicated by the dating results of the oldest train

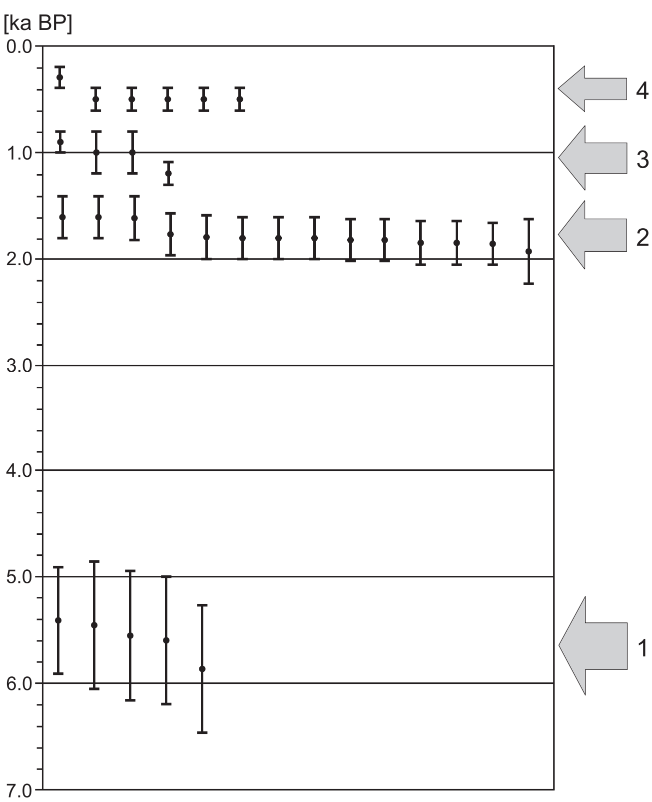

Fig. 4. Phases of intensification of aeolian processes on the basis of TL dates

of brown dunes adjacent to the Vistula Lagoon. The average TL age corresponding to this phase is 5.57 ±0.53 ka, and the whole period is estimated at over 400 years. These results differ considerably from the formerly determined time of the beginning and duration of the first phase of dune accumulation on the Vistula Spit. Based on the results of radiocarbon dating of the bottom peats in the inter-dune depressions, Tomczak (1990) estimated the end of the first phase of the Spit development at 3920–3160 BP (cal. 3380–4360 ^{14}C BP[2]). She also suggested that marine regression initiated this phase i.e. after the Litorina transgression; so the beginning of aeolian transformation of beach ridges occurred about 5000 BP. Analogous radiocarbon dating on the Świna Spit (western part of Polish coast) indicates an age of 4810 BP (cal. 5585 ^{14}C BP; Prusinkiewicz and Noryśkiewicz, 1966) and on the Curonian Spit (Lithuanian coast) of 4630 BP (Gaigalas *et al.*, 1989). These results better correspond to those obtained by us. The increasing number of luminescence dates seems to confirm the existence of a phase of intensified aeolian activity in the coastal dune zone at the turn of the Atlantic and Subboreal periods (Gaigalas *et al.*, 1989; Borówka, 1990, 2001; Murray and Clemmensen, 2001; Osadczuk, 2004; Moe *et al*., 2005; Molodkov and Bitinas, 2006; Clemmensen *et al.*, 2009; Reimann *et al*., 2011). This phase of aeolian accumulation on the Vistula Spit was dated at 7.28–5.12 TL ka by Fedorowicz *et al*. (2009). In the light of OSL dating from the Świna Barrier, aeolian accumulation of the first generation of brown dunes began at 6.62 ±0.42 ka on the Uznam Spit and at 5.39 ±0.37 ka on the Wolin Spit, while its termination is expressed by a date of 2.45 ±0.15 ka (Reimann *et al*., 2011). On the Jutland Peninsula, however, the oldest (4) phase of aeolian sand accumulation occurred at 4.6–4.3 ka (Murray and Clemmensen, 2001; Clemmensen *et al.*, 2009).

The second phase of intensified aeolian processes on the Vistula Spit is represented by the dates ranging from 1.93 to 1.61 ka. They correspond to the end of accumulation of yellow dunes determined by Tomczak (1990) at 1210–1060 BP. However, yellow dunes on the Świna Spit were dated by Prusinkiewicz and Noryśkiewicz (1966) at the 15–17th century. However, the OSL dates of 1.72 ±0.12 ka and 1.65 ±0.11 ka obtained from the second generation of brown dunes by Reimann *et al*. (2011) correspond well with the results described here. The bottom parts of dunes on the Curonian Spit were OSL dated by Bitinas (2004) at cal. 1500 ±100 a. Moe *et al*. (2005) obtained a very similar AMS (Accelerator Mass Spectrometry Radiocarbon Dating) date (cal. 1900 ±40 ^{14}C BP) from subfossil soil covering the aeolian deposits. A slightly younger age (1.2 ±0.1 ka) was obtained for dune sands on the Curonian Spit by Molodkov and Bitinas (2006). Fedorowicz *et al*. (2009) obtained a broad spectrum of TL dates (6.0–1.53 ka) from the Stegna profile (Vistula Spit). Clemmensen *et al.* (2009) determined the age of the dune-forming phase denoted as no. 2 on the Jutland Peninsula at 2.0–1.59 ka.

[2] Dates calibrated on the basis of tables by Reimer *et al*. (2004) included in Walanus and Goslar (2009).

The third phase of aeolian processes took place between 1.2 and 0.9 ka. It resulted in the formation of the discontinuous dune ridge (between the yellow dunes and the foredune) and the wind-blown depressions, and probably in the building of the northern slopes of the yellow dunes. According to Tomczak (1990), a marine ingression on the Vistula delta in the Sztutow region occurred at that time. Similar observations were conducted by Rotnicki (2009) on the Gardno–Łeba Lowland indicating a rapid increase in Baltic sea level between 1.8 and 1.1 ka BP (3.4 mm/year), followed by a stable high water level until 0.7 ka BP. The rise in sea level caused the undercutting of beach ridges that probably narrowed the beach, which was the natural alimentation area for dunes on the spit (Borówka, 1999). Therefore, the material supply for dune formation was considerably reduced. However, the deposits of similar age occur on the Lithuanian coast (Molodkov and Bitinas, 2006), and on the Danish coast where the dune-forming phase denoted as no. 1 is related to this period (Clemmensen *et al.*, 2009). So it seems that the rise in sea level is not a significant impediment to the intensification of dune-forming processes. Borówka (1999) indicates that aeolian deposition in foredunes reaches significant values nowadays, of about 1.5 m/year, though the rise in sea level is a constant trend. Reimann *et al*. (2011), however, reconstruct the rate of the yellow dunes' growth at 1.3–1.1 m/year. One thousand years ago the destruction of beach ridges on the Vistula Spit could have moved a great amount of sand, which was then transported by longshore drift; after storms this sand could have been accessible for aeolian transport. Additionally, the wind-transported material could have originated from the formerly accumulated deposits as is shown by the occurrence of wind-blown depressions between white and yellow dunes.

The youngest phase of intensification of aeolian processes is dated at 0.5–0.3 ka. A similar age was obtained for the Stegna profile by Fedorowicz *et al*. (2009). On the other hand, according to Tomczak (1990) this phase has continued for the last 900 years, with slightly less intense processes from 480 to 340 years ago. This is undoubtedly correct because the processes in the foredune zone are incessantly active though periodically less intense. In the Przebrno profile such weakenings are radiocarbon dated at 295 ±125 BP (Gd-30231) and 500 ±110 BP (Gd-30232); these dates are similar to the age range given by Tomczak (1990). Borówka (1990, 2001) described the reactivation of aeolian processes on the Łeba Spit at about 500 BP, which was influenced by human activity but caused mainly by deteriorating climatic conditions expressed mainly by a decrease in mean temperature and an increase in the number of storms. Similar conclusions about the age and causes of activation of aeolian processes resulted also from the investigations on the Wolin Spit (Reimann *et al*., 2011), on the Curonian Spit (Bitinas, 2004; Moe *et al*., 2005) and on the northern coast of Denmark (Aagaard *et al*., 2007; Clemmensen *et al*., 2009).

The four phases of aeolian accumulation on the Vistula Spit described have their equivalents on other spits of the Southern Baltic as well as in the western and northern parts of the Jutland Peninsula (Gaigalas *et al.*, 1989; Borówka, 1990, 2001; Murray and Clemmensen, 2001; Bitinas, 2004; Osadczuk, 2004; Moe *et al*., 2005; Molodkov and Bitinas, 2006; Aagaard *et al.*, 2007; Clemmensen *et al.*, 2009; Reimann *et al*., 2011). Comparing the age of these phases with the cooling periods of LIA type (McDermott *et al*., 2001) it seems that deposition was triggered by such weather conditions. According to Reimann *et al*. (2011) intensified storms delivered larger amounts of sand material onto the beaches, which was subsequently used in aeolian transport that was accelerated by stronger winds. These phases can also be correlated with relative oscillations of water level in the southern Baltic (Rotnicki, 2009); in general, they correspond with periods of decreased water level. An exception is the second phase, dated by the authors between 1.93 and 1.61 ka (Fig. 4), which corresponds with the Roman Warm Period (RWP; McDermott *et al*., 2001; Reimann *et al*., 2011), and also a relative increase in the water level of the Baltic (Rotnicki, 2001). Reimann *et al*. (2001) interpret the restart of the aeolian transport as due to human activity in the area, mainly deforestation.

FINAL REMARKS

The data presented are a contribution to the discussion on the origin, age and phases of the formation of the Vistula Spit. They enlarge the collection of absolute dating results obtained for this area. Based on the large set of TL ages, global tendencies and local variation of the processes discussed can be indicated. The authors consider that three facts are worth noting.

Based on the degree of soil cover development, only general information about the age and sequence of formation of the dune ridges distinguished can be obtained. This is most evident within the zone of brown dunes where two dune ridges are distinctly different in terms of age, and one of them in terms of age resembles the yellow dunes. Moreover, we should take into account that stable dunes were/could have been transformed to some extent during the addition of successive dune ridges.

Aeolian processes were activated periodically. In the area examined they were intensified in the following periods: 5860–5400, 1930–1610, 1200–900 and from 500 years ago. This intensification was most probably determined by deterioration of climatic conditions of LIA type, which resulted in a decrease in mean annual air temperature, an increase in the number of storms, and lowering of the water level in the Baltic Sea. The exception was the phase occurring 1930–1610 years ago, which corresponded to a warm period (RWP) and a rise of sea level. So, the intensification of aeolian deposition during this phase should be related to anthropogenic factors.

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