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Chronology of the last ice sheet decay on the southern Baltic area based on dating of glaciofluvial and ice-dammed lake deposits

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The paper presents the results of the first OSL dating of glaciofluvial and ice-marginal lake sediments which occur between end moraines of the Słupsk Bank and the Polish coast. The sand and gravel of glaciofluvial deltas on the Słupsk Bank were deposited most likely during a period from 14.3 ±1.2 to 16.6 ±1.4 ka ago. The deposition of silty-sandy sediments of the ice-marginal lake is dated at 14.51 ±0.81 and 14.6 ±1.4 ka years. Likewise, dates ranging from 13.74 ±0.84 to 16.70 ±1.1 ka obtained from low sandy ridges, related to the southern range of the ice-marginal lake in the Gardno-Łeba Lowland, indicate the most likely timing of their deposition. It can be concluded that a short stop of the ice sheet on the Słupsk Bank took place approximately 15.2 ka ago, which could be correlated with the position of the ice sheet front in central Skåne and in northern Lithuania at that time. Older and younger results were also obtained, except the dates mentioned above. The older ages show little sunlight exposure of sediments during their deposition. The younger dates indicate a marine origin of the sediments and show that some parts of glaciofluvial sediments were redeposited and exposed to sunlight at a later stage, most probably when dead-ice blocks were melting.

Key words: southern Baltic area, deglaciation, Late Glacial, Słupsk Bank Phase, OSL dating.

INTRODUCTION

Location of the various deglaciation phases on the bottom of the Baltic Sea were previously determined indicatively by the spatial correlations of marginal forms on the Baltic Sea coast (e.g., Mörner et al., 1977; Ignatius et al., 1981; Lundqvist, 1986; Mojski, 1995). Space-time correlations that are based on remains of sediments and forms of marginal zones on the Baltic seabed are scarce, and ages were determined indirectly *via* the link to the dated form onshore (Södeberg, 1988; Uścinowicz, 1999). Until recently, inland ice sheet recession phases have been dated indirectly by varve chronology or by radiocarbon dating of organic deposits from sites close to marginal zones (e.g., Lundqvist, 1986; Lagerlund and Houmark-Nielsen, 1993; Raukas et al., 2004). The dating of glaciofluvial sediments using OSL resulted in significant progress in determining the time of the last deglaciation (e.g., Houmark-Nielsen, 2008; Thrasher et al., 2009; Raukas et al., 2010). Great contribution is also dating of erratic boulders exposures using ^{10}Be (e.g., Rinterknecht et al., 2004, 2006; Johnsen et al., 2009; Anjar et al., 2014; Cuzzone et al., 2016). Data sets on the last deglaciation timing of Scandinavia based on OSL ages and ^{10}Be cosmogenic ages are being developed. Very few ages originate from northern Poland and there are no data related to phases younger than the Pomeranian (e.g., Rinterknecht et al., 2006; Marks, 2010). Timing of the last Scandinavian Ice Sheet (SIS) recession from the Polish coast have been estimated until now based on a very few conventional radiocarbon ages of bulk samples of ice-marginal lake silty clay and silty peat (Rotnicki and Borówka, 1995a, b; Kramarska, 1998). Therefore, reconstructions of deglaciation patterns of the Polish coast and the present southern Baltic area should be verified by OSL dating of sediments related to the remains of ice-marginal landforms present on both the seabed and the coast.

The aim of the paper is to present OSL dating of glaciofluvial and ice-dammed lake deposits from the southern Baltic area situated between the Słupsk Bank and the Polish coast, which could allow gaining insight on timing of the last deglaciation of the southern Baltic area.

Considering that the Pomeranian Phase took place 17–16 ka ago (Wysota, 2002; Marks, 2010) and the deglaciation of

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southernmost Sweden (eastern Skåne, Blekinge, southern Småland) occurred between 15.5 and 13.5 ka ago (e.g., Lundqvist and Wohlfarth, 2001, Houmark-Nielsen, 2008; Johnsen et al., 2009; Anjar et al., 2014) the expected (i.e. most likely) time of icesheet decay in the southern Baltic Basin falls in a period between 16,000 and 14,000 years ago. This hypothesis is also supported by the radiocarbon ages of peat from the Vistula Lagoon (core ZW 3) dated to 14,639–13,888 (Gd-10246) (Zachowicz and Uścinowicz, 1997), and from the Pomeranian Bay (profile VR 072), dated to 14,003–13,753 cal. years BP (Poz--43787). The last one is supported also by pollen analyses (Kramarska et al., 2013).

However, when considering the timing of ice sheet decay on the Polish coast, we must refer also to the oldest radiocarbon dates published by Rotnicki and Borówka (1995a, b) and Kramarska (1998). The oldest known organic deposits recognized in the borehole W-4 in the Odra Bank (Pomeranian Bay) region were described by Kramarska (1998) as a peat and dated to a period between 14,060 ±220 (Gd-2928) and 13,100 ±300 (Gd-4336) years BP (i.e. 17,430–16,765 and 16,130–15,250 cal. years BP). Later, the lithology of core W-4 was reanalysed and the dataset was completed by pollen analyses (Kramarska et al., 2007). The sediments described earlier as peat had been classified as silty clay with organic remains. The results of pollen analyses (Kramarska, 2007) prove that the investigated sediments were accumulated in cold, sub-arctic climate, characteristic for the Late Glacial. However, large amounts of pollen grains of spruce (*Picea abies*) and alder (*Alnus*), species which did not occur at that time in this area, indicate the sediments contain an admixture of redeposited organic matter. The source of it could be sediments of the Grudziądz Interstadial (MIS 3), whose presence is documented close to this area (Kramarska, 1998). The admixture of older sediments could be the reason of uncertainty of the discussed radiocarbon ages.

A similar case could be with radiocarbon dates from the Gardno-Łeba Lowland (Rotnicki and Borówka, 1995a, b). The age of 14,310 ±150 (Gd-4476) (17,630–17,205 cal. years BP) comes from varved silt and clay of an ice-dammed lake in the borehole 101. The second age, 13,800 ±270 (Gd-6117) (17,085–16 295 cal. years BP), has been derived from a thin peat interbed in sands of a fossil channel within a river's alluvial fan. Very close to the discussed sediment layers are fine and very find sands with admixture of organic matter, dated for a period >42,000–22,300 years BP, i.e. MIS 3 (Rotnicki and Borówka, 1995a, b). The top of these sediments is an erosional surface, so it is probable that an admixture of MIS 3 sediments could occur within younger deposits. In such a case, the oldest radiocarbon ages from cores W-4 in the Pomeranian Bay (Kramarska 1998), as well as in 101 and 35 from the Gardno--Łeba Lowland (Rotnicki and Borówka, 1995a, b), indicate neither the beginning of peat formation nor the timing of ice sheet decay on the southern Baltic coast.

AREA OF INVESTIGATION (GEOLOGICAL SETTING)

The investigations were carried out in the southern part of the Baltic Sea; on the Słupsk Bank and in area between the Słupsk Bank and the Gardno-Łeba Lowland, as well as on the Lowland itself (Fig. 1).

The Słupsk Bank is a sea-floor elevation located about 30 km from the middle part of the Polish coast. The water depth in the Słupsk Bank ranges from 8 to 25 m. The southern slopes

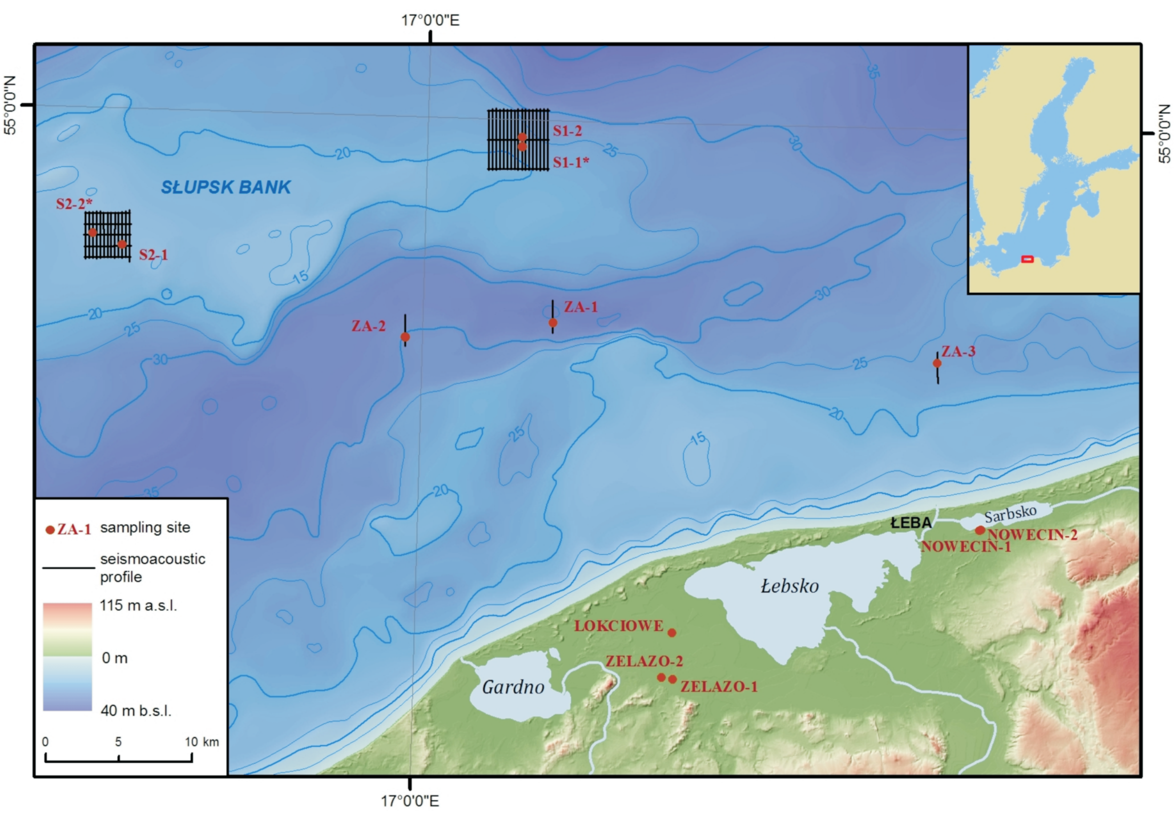

Fig. 1. Location of the research area and sampling sites

of the Słupsk Bank are relatively steep, lowering to a W–E elongated seabed depression that separates the bank from the coast. The water depth in the depression is 30–35 m. From these depths, the sea bottom gently rises towards the Polish coast (Fig. 1).

The pre-Quaternary sedimentary bedrock in the study area is composed of Eocene-Oligocene marine silty-clayey and silty-sandy deposits, and local silty-sandy Miocene deposits (Kramarska et al., 1999). Their top is at a depth of 30–50 m b.s.l. The Pleistocene sediments consist mainly of one, locally two beds of glacial till with a thickness ranging between a few and 20 m. Glaciofluvial sand and gravel also occur locally on the Słupsk Bank. On the large areas south of the Słupsk Bank towards the Polish coast, glacial till is covered by silty-sandy and silty-clayey deposits of ice-marginal lake. Seabed sediments consist of Middle to Late Holocene marine sand with a thickness varying from a few cm up to 3–4 m (Kramarska, 1991; Uścinowicz and Zachowicz, 1991). In the northern part of the Słupsk Bank, remains of end moraine ridges and De Geer moraines occur marking the Słupsk Bank Phase of the last deglaciation. The ridges are covered by lag deposits – boulders and cobbles situated on till. In front of the ridges, in the south, glaciofluvial deltaic sediments occur locally. The top of all Pleistocene landforms and sediments is eroded by the Holocene transgression (Uścinowicz, 1995, 1999, 2010).

The Gardno-Łeba Lowland extends in the southern coast of the Baltic Sea, from the Gardno Lake in the west to the Sarbsko Lake in the east in northern Poland. The W–E extent of the lowland is ~45 km and the width between the morainic upland and the coast is ~3 km in both the west and east, up to ~10 km in the middle part. Łebsko Lake occupies the middle part of the Gardno-Łeba Lowland.

The lowland surface is almost completely flat and elevated only ~0.5–3 m a.s.l. Only locally, there are very low and gentle ridges in the vicinity of Żelazo, Łokciowe and Kluki in the western part of the Lowland, and near Nowęcin east of Łeba in the eastern part (Fig. 2). The highest elevations in the Lowland, up to 18 m (except the dunes on the Łeba Barrier), are in the area of inland dunes located west of Łokciowe village and south of the lakes of Łebsko and Sarbsko

The thickness of Quaternary deposits, mainly till and glaciofluvial sand and gravel, is between 80 and 120 m, reaching a maximum of 260 m (Morawski, 1987; Petelski 2007, Rotnicki and Borówka, 2000). The Gardno-Łeba Lowland is the area of Poland's youngest Pleistocene deposits (Gardno Phase). Pleistocene deposits are covered by Late Glacial and Holocene deposits of various origins and thicknesses. Ice-marginal lake sediments occupy a large area and their thickness varies from a few up to 18 m. Uppermost, Holocene sediments: fluvial, limnic and aeolian sands as well as peats occur in patches. Marine, littoral and aeolian sands forming the inland and barrier dunes are found only in the northern part of the lowland (Morawski, 1987; Rotnicki and Borówka, 2000; Petelski, 2007; Rotnicki, 2009).

The ridge north of Żelazo village is ~4 km long, and ~50–100 m wide, with an elevation of 3–5 m a.s.l. and a height of ~1.5–0.5 m above the surrounding area. The second ridge, in Łokciowe, is ~5 km long, ~30–100 m wide, and 2.5–5 m a.s.l. high, rising ~1–3 m above the surrounding area. The third ridge, east of Nowęcin is ~3 km long, ~80–150 m wide, and 2–3.5 m a.s.l. high, rising ~1.0–2.5 m above the surrounding terrain.

The ridges in Łokciowe and Kluki, located between Gardno and Łebsko lakes, were considered in the earlier papers as beach ridges marking the maximum extent of the Holocene Baltic Sea (Littorina Sea) (Rosa, 1963; Rotnicki and Borówka, 2005c; Rotnicki, 2009). The ridge in Żelazo has not been described in the papers until now. The Nowęcin ridge, south of Sarbsko Lake, was described by Bülow (1928, 1937) and Rosa (1963) as a beach ridge also marking the maximum extent of the Baltic Sea. Later, based on TL ages (12.8 and 13.2 ka), it was regarded as a coastal ridge of a Late Glacial ice-marginal lake (Rosa, 1987).

MATERIALS AND METHODS

FIELD WORK

All measurements at sea were carried out on board of the R/V „IMOR". The investigated sites were selected on the basis

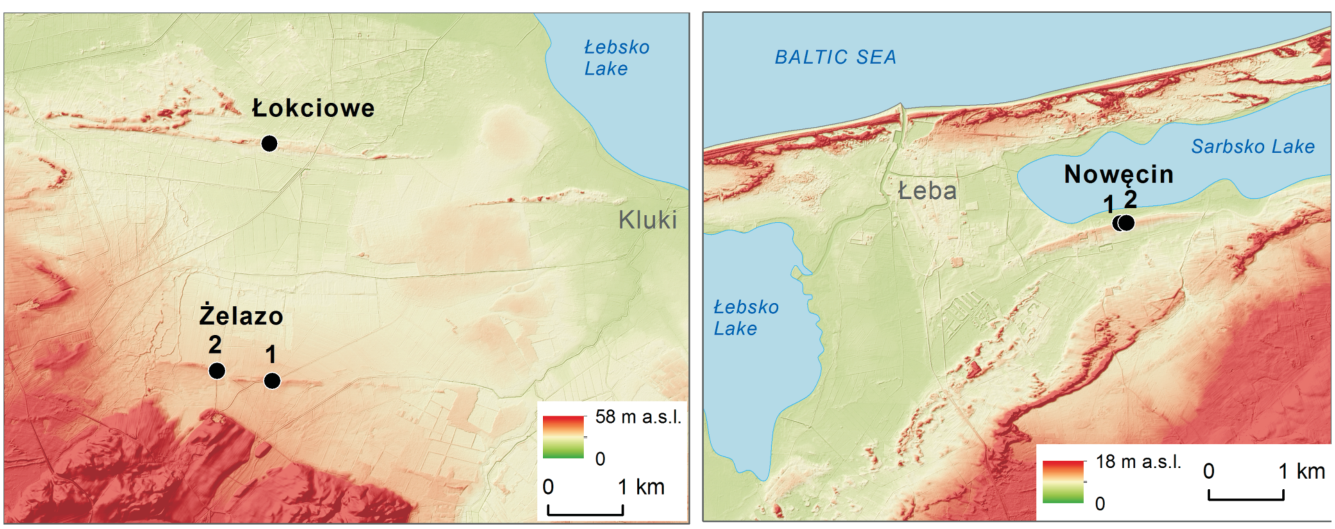

Fig. 2. Digital Terrain Model and location of sampling sites at Żelazo, Łokciowe and Nowęcin in Gardno-Łeba Lowland

of previous seismoacoustic surveys and coring (i.e. Uścinowicz and Zachowicz, 1991; Kramarska, 1991). The two known glaciofluvial deltas on the Słupsk Bank and three selected sites of ice-marginal lake deposits were surveyed in detail. In the glaciofluvial deltas, 124 km of bathymetric, side-scan sonar and seismoacoustic profiles were performed and sediment cores were taken from two sites on each delta. For ice-marginal lake deposits, 6 km of seismoacoustic profiles (2 km for each site) were carried out and sediment cores were taken at three sites (Fig. 1). Two parallel cores (duplicate) were taken from each site (duplicates are marked by asterisk). Altogether, 14 sediment cores were taken at seven sites offshore. Water depth measurements were carried out with an *SBES DESO 15* single beam echosounder. Obtained bathymetric data were corrected for the actual sea level and sound velocity in the water, measured with a *Reson SVP 15* sound velocity metre. Side scan sonar profiling was carried out with the *EdgeTech MS-4200* side sonar with side scan range of 150 m for each receiving channel.

For seismoacoustic measurements, a boomer of 250 Hz – 1.5 kHz frequency, 300 J impulse energy, and 80 ms sweep time was used. Geophysical records were processed using the *MDPS MERIDATA* software with the sound velocity of 1.45 m/ms in water and 1.6 m/ms in sediment. The bathymetric sonar and seismoacoustic profiling was carried out at the sea level not exceeding 2^{o}B and at the vessel speed not exceeding 4 knots. The CODA data acquisition system was used for registration and numerical recording of acoustic signals.

Coring sites were selected after detailed analyses of seismoacoustic records. A vibro-corer with the coring tube length of 6 m and with a PCV liner (internal diameter of 0.08 m) was used.

During the research cruise, positioning was carried out using the *DGPS AG-132 Trimble* navigation system with RTCM correction transmitted from the Rozewie station, resulting in horizontal accuracy better than 0.5 m.

Samples were also taken from coastal ridges of the ice-marginal lake on the Gardno-Łebsko Lowland (Fig. 2). The sampling sites were selected after analyses of DTM based on airborne laser scanning. Ten samples of sand and gravelly sand were taken from 5 sites: site Żelazo – 4 samples from two excavations, site Łokciowe – 2 samples from a single excavation, and site Nowęcin – 4 samples from two excavations. Samples were taken from the excavations at a depth between 0.85 and 1.8 m (Table 1), directly to stainless steel tubes. The ridge in Kluki village was not sampled because its aeolian origin and young age was evident (the peat base at 0.5 and 0.7 m b.s.l. dated to 1360 and 1600 AD) (Rotnicki, 2009).

LABORATORY ANALYSES

Macroscopic description of cores and collection of samples for OSL dating were carried out in a darkened laboratory in orange light. The boundary between the marine and glaciofluvial deposits was initially determined during sampling based on the presence of marine shells and sediment reaction with hydrochloric acid (HCl). Samples were taken from each layer, in accordance with macroscopically visible differences in grain size distribution.

OPTICALLY STIMULATED LUMINESCENCE (OSL) DATING

OSL ages were determined for a total of 43 samples: 22 samples (from four cores) of sand and gravelly sand of glaciofluvial and marine origin, 11 samples (from three cores) of ice-marginal lake silts and sandy silts, and for 10 samples (from five sites) of sand and gravelly sands of the costal ridges of ice-marginal lake (Table 1).

OSL measurements were performed using medium-sized grains quartz (90–125 μm) that were extracted from the sediment samples. The treatment consisted of submerging the sample in 20% hydrochloric acid (HCl) and 20% hydrogen peroxide (H_2O_2). Subsequently, the quartz grains were separated using density separation by means of sodium polytungstate solutions leaving grains of densities between 2.62 and 2.75 g/cm^3. Sieving of the grains was performed twice, before and after a 60 min etching with concentrated hydrofluoric acid (HF).

The quartz aliquots of diameter 6 mm were prepared by spraying silicone oil onto 10 mm-diameter stainless steel discs through a mask. This resulted in ~1 mg of grains being stuck to the disks.

The OSL measurements were carried out using an automated *Daybreak 2200 TL/OSL* reader (Bortolot, 2000). This reader uses blue diodes (470 ±4 nm) delivering about 60 mW/cm^2 at sample position. Laboratory irradiations were performed using a calibrated ^{90}Sr/^{90}Y beta source mounted onto the reader delivering a dose rate of 3.0 Gy/min. The OSL was recorded having been filtered through a 6 mm *Hoya U-340* filter.

The equivalent doses were determined using the single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000). Between 12 and 24 single aliquots were used per sample. Pre-heat temperatures used were 260 and 220°C for the regeneration and test doses, respectively. The equivalent doses were estimated on the basis of preliminary measurements and then three regeneration doses were used to construct the growth curves to which single saturating exponential functions were fitted. A zero-regeneration dose was included to check for recuperation and a repeat point for changes of sensitivity-corrected response. The ages were calculated using the Central Age Model (CAM) (Galbraith et al., 1999).

The annual dose rates comprising beta and gamma radiation were calculated based on results of gamma spectrometry performed in the laboratory with the application of a Canberra spectrometer equipped with the HPGe detector. The sample mass was about 200 g and each measurement lasted at least 24 hours. The annual doses were calculated using the conversion factors of Adamiec and Aitken (1998), while the cosmic ray dose rate to the samples was estimated as described by Prescott and Stephan (1982). We assumed that the water content was equal to (30 ±10)% or (50 ±10)% depending on the lithology. The high water content is justified by the sediments being completely submerged under water during the majority of deposition time. The HF etching and grain size were taken into account as recommended by Fleming (1979: 21, 42). Beta dose attenuation was calculated after Mejdahl (1979). Based on these data, dose-rates were calculated (see Table 1).

RADIOCEASIUM (^{137}Cs)

The caesium-137 content was measured in 38 samples of marine sands from five cores: S1-2, S2-1, S2-2*, ZA-2 and ZA-3* (Table 2). The activity was measured using a *Canberra* semiconductor high-resolution spectrometer equipped with a high-purity germanium detector at the laboratory of the Institute of Physics in Silesian University of Technology. The minimum time of measurement was 24 hours and the sample mass was about 200 g. The reference material Soil-375 was used as ^{137}Cs activity standard, and the reference material Soil-6 was used as quality control, both supplied by IAEA. The results of measurements were expressed in Bq/kg and corrected for radioactive decay since the time of sample collection.

Table 1

Results of OSL dating

Core/site and sample No.	Depth in the core [m bgs]	U-238 [Bq/kg]	u(U) [Bq/kg]	Th-232 [Bq/kg]	u(Th) [Bq/kg]	K-40 [Bq/kg]	u(K) [Bq/kg]	Mean water content [%]	Doese equivalent [Gy]	u(De) [Gy]	Dose rate [Gy/ka]	u(Dr) [Gy]	Age [ka]	u(Ag) [ka]	Lab. Code GdTL
S1-1*	Φ 54°59'1.093" λ 17°06'1.620" 23.3 m b.s.l.														
RM 7	**0.0–0.10**	7.22	0.38	9.35	0.50	458.97	24.75	30.0	9.52	0.64	1.566	0.081	6.57	0.65	**2029**
RM 6	**0.65–1.75**	13.00	0.43	13.61	0.58	457.38	22.58	30.0	16.45	0.69	1.687	0.077	10.58	0.80	**2028**
RM 5	**1.6–1.7**	21.86	0.45	22.13	0.67	506.77	16.47	30.0	18.72	1.21	2.080	0.078	9.77	0.83	**2027**
RM 4	**2.0–2.1**	16.32	0.36	17.43	0.49	524.55	21.73	30.0	16.43	0.66	1.966	0.084	9.07	0.66	**2026**
RM 3	**2.9–3.0**	8.55	0.42	10.28	0.51	422.98	21.89	30.0	16.41	0.61	1.466	0.072	12.16	0.94	**2025**
RM 2	**3.7–3.8**	12.38	0.46	14.17	0.58	472.50	22.51	30.0	15.40	0.85	1.711	0.079	9.77	0.83	**2024**
RM 1	**4.95–5.0**	19.10	0.51	17.87	0.62	406.77	11.46	30.0	17.29	0.94	1.701	0.061	11.05	0.84	**2023**
S1-2	Φ 54°59'21.845" λ 17°06'0.217" 23.9 m b.s.l.														
RM 11	**2.5–2.6**	10.11	0.30	12.33	0.41	475.63	24.83	30.0	13.48	0.73	1.520	0.078	9.62	0.85	**2033**
RM 10	**2.95–3.05**	5.13	0.37	8.30	0.46	521.79	26.77	30.0	16.28	0.44	1.758	0.089	10.06	0.76	**2032**
RM 9	**3.95–4.05**	7.60	0.42	11.30	0.59	536.06	26.03	30.0	16.71	0.77	1.634	0.088	11.11	0.97	**2031**
RM 8	**5.2–5.3**	6.47	0.39	10.96	0.57	452.66	24.22	30.0	17.39	0.51	1.651	0.081	11.45	0.84	**2030**
S2-1	Φ 54°54'59.265" λ 16°40'38.625" 15.8 m b.s.l.														
RM 45	**0.8–0.9**	15.92	0.48	30.54	0.86	551.45	23.07	30.0	8.54	0.47	2.236	0.090	4.11	0.33	**2067**
RM 44	**1.7–1.8**	11.40	0.45	11.27	0.61	387.47	19.32	30.0	9.22	0.29	1.452	0.066	6.86	0.48	**2066**
RM 43	**2.30–2.40**	10.10	0.43	10.08	0.56	361.92	18.45	30.0	12.05	0.55	1.345	0.062	9.71	0.76	**2065**
RM 42	**3.15–3.25**	13.22	0.35	14.53	0.48	578.54	29.29	30.0	16.51	0.59	2.018	0.098	8.88	0.68	**2064**
RM 41	**3.65–3.75**	8.33	0.35	9.99	0.51	401.39	16.41	30.0	15.74	0.39	1.412	0.064	12.10	0.83	**2063**
RM 40	**4.90–5.00**	4.17	0.41	7.51	0.60	347.12	18.55	30.0	12.15	0.47	1.163	0.060	11.33	0.91	**2062**
S2-2*	Φ 54°55'22.429" λ 16°38'44.278" 16.1 m b.s.l.														
RM 50	**0.9–1.0**	21.75	0.48	22.12	0.71	518.12	18.53	30.0	19.59	0.96	2.120	0.081	10.03	0.75	**2072**
RM 49	**1.55–1.6**	13.44	0.42	9.99	0.54	390.47	19.34	30.0	19.35	1.07	1.474	0.067	14.30	1.20	**2071**
RM 48	**2.57–2.67**	23.03	0.39	20.74	0.50	474.73	15.19	30.0	28.66	1.51	2.001	0.073	15.60	1.20	**2070**
RM 47	**3.64–3.74**	10.39	0.40	0.96	0.33	348.60	16.09	30.0	23.04	1.39	1.177	0.058	21.30	2.00	**2069**
RM 46	**5.05–5.15**	8.22	0.36	7.69	0.52	346.97	16.35	30.0	18.76	0.90	1.230	0.058	16.60	1.40	**2068**
ZA-1	Φ 54°52'34.122" λ 17°08'17.394" 33.3 m b.s.l.														
RM 16	**0.05–0.10**	29.07	0.65	33.00	0.91	724.91	35.69	50.0	169.58	7.94	2.819	0.123	70.50	5.00	**2038**
RM 15	**2.20–2.30**	38.08	0.84	45.16	1.21	906.20	49.72	50.0	113.51	4.19	3.589	0.160	37.10	2.40	**2037**
RM 14	**3.30–3.40**	29.89	0.54	33.36	0.75	662.73	28.18	50.0	174.41	8.81	2.680	0.108	76.30	5.40	**2036**
RM 13	**4.30–4.40**	28.44	0.62	32.00	0.91	649.89	29.19	50.0	104.69	3.74	2.602	0.108	47.20	2.90	**2035**
RM 12	**5.15–5.25**	21.77	0.55	24.74	0.78	621.12	28.19	50.0	81.12	3.98	2.309	0.101	41.10	3.00	**2034**
ZA-2	Φ 54° 51' 54.53" λ 16° 58' 54.014" 30.5 m b.s.l.														
RM 61	**1.20–1.30**	12.44	0.44	10.88	0.58	377.58	16.56	50.0	16.52	0.23	1.322	0.059	14.51	0.81	**2083**
RM 60	**2.15–2.25**	29.62	0.62	30.29	0.89	611.43	22.27	50.0	27.78	0.39	2.510	0.097	12.92	0.64	**2082**
RM 59	**3.20–3.30**	27.63	0.59	28.25	0.91	597.15	22.65	30.0	33.22	2.41	2.480	0.095	14.60	1.40	**2081**
RM 58	**4.20–4.30**	37.74	0.80	34.42	1.15	674.09	32.04	50.0	145.89	7.99	2.854	0.116	59.90	4.40	**2080**
RM 57	**5.60–5.70**	24.07	0.45	20.37	0.56	461.03	21.21	50.0	210.29	13.8	1.822	0.075	135.00	12.0	**2079**
ZA-3	Φ 54°51'24.268" λ 17°32'54.686" 24.3 m b.s.l.														
RM 26	**1.3–1.4**	3.10	0.25	4.77	0.29	169.24	8.68	30.0	6.61	0.23	0.642	0.030	11.09	0.79	**2048**
Żelazao 1	Φ 54°39'33.300" λ 17°16'29.639" 4.7 m a.s.l.														
LEB 1	1.10	4.22	0.19	6.41	0.26	236.42	7.23	30.0	13.84	0.45	0.896	0.050	15.38	1.00	**2164**
LEB 2	0.90	3.94	0.17	6.18	0.15	239.02	6.64	30.0	12.47	0.29	0.904	0.050	13.73	0.84	**2165**
Żelazao 2	Φ 54°39'37.260" λ 17°15'48.061" 4.3 m a.s.l.														
LEB 3	1.55	3.06	0.16	3.86	0.21	207.30	6.33	30.0	11.88	0.27	0.760	0.044	15.56	0.98	**2166**
LEB 4	1.35	3.67	0.14	5.41	0.24	214.40	6.58	30.0	13.62	0.43	0.813	0.046	16.7	1.10	**2167**
Łokciowe	Φ 54°41'16.503" λ 17°16'23.401" 2.1 m a.s.l.														
LEB 5	1.05	3.01	0.15	4.62	0.19	235.53	6.48	50.0	11.15	0.38	0.754	0.039	14.72	0.92	**2168**
LEB 6	0.85	2.81	0.19	4.36	0.25	238.70	7.09	50.0	10.79	0.20	0.764	0.040	14.05	0.79	**2169**
Nowęcin 1	Φ 54°45'17.520" λ 17°35'48.180" 3.1 m a.s.l.														
LEB 7	1.70	10.66	0.24	16.59	0.47	360.82	10.53	30.0	17.39	0.64	1.401	0.074	12.35	0.80	**2170**
LEB 8	1.40	5.29	0.12	7.89	0.17	224.65	5.95	30.0	13.82	0.33	0.893	0.047	15.42	0.90	**2171**
Nowęcin 2	Φ 54°45'17.700" λ 17°35'52.561" 2.9 m a.s.l.														
LEB 9	1.80	13.75	0.53	16.21	0.45	402.20	11.15	30.0	17.04	0.66	1.536	0.081	11.03	0.73	**2172**
LEB 10	1.33	6.54	0.28	11.05	0.38	243.27	7.54	30.0	16.19	0.42	1.000	0.052	16.13	0.94	**2173**

u – uncertainties

Table 2

Results of ^{137}Cs analyses

Core No.	Sample position in core (m)	^{137}Cs content (Bq/kg)	unc
S1-2	0.0–0.2	0.62	0.22
S1-2	0.2–0.4	0.51	0.26
S1-2	0.4–0.6	0.29	0.23
S1-2	0.6–0.8	0.14	0.22
S1-2	0.8–1.0	–0.03	0.35
S2-1	0.0–0.2	0.97	0.27
S2-1	0.2–0.4	0.25	0.22
S2-1	0.4–0.6	–0.11	0.59
S2-2*	0.0–0.2	0.76	0.2
S2-2*	0.2–0.4	0.83	0.21
S2-2*	0.4–0.6	0.44	0.24
S2-2*	0.6–0.8	0.68	0.22
S2-2*	0.8–1.0	0.28	0.21
S2-2*	1.0–1.2	0.47	0.23
S2-2*	1.2–1.4	0.17	0.56
S2-2*	1.4–1.6	0.11	0.59
S2-2*	1.6–1.8	–0.20	0.48
S2-2*	1.8–2.0	–0.05	0.48
S2-2*	2.0–2.2	–0.30	0.56
S2-2*	2.2–2.4	–0.12	0.52
S2-2*	2.4–2.6	0.15	0.21
ZA-2	0.0–0.2	0.04	0.4
ZA-2	0.2–0.4	–0.04	0.46
ZA-2	0.4–0.6	0.12	0.23
ZA-2	0.6–0.75	–0.27	0.61
ZA-3*	0.0–0.2	–0.02	0.2
ZA-3*	0.2–0.4	–0.23	0.4
ZA-3*	0.4–0.6	0.21	0.2
ZA-3*	0.6–0.8	0.29	0.21
ZA-3*	0.8–1.0	0.26	0.21
ZA-3*	1.0–1.2	0.21	0.23
ZA-3*	1.2–1.4	0.42	0.26
ZA-3*	1.4–1.6	0.32	0.23
ZA-3*	1.6–1.8	0.33	0.23
ZA-3*	1.8–2.0	0.69	0.23
ZA-3*	2.0–2.2	0.08	0.48
ZA-3*	2.2–2.4	–0.09	0.46
ZA-3*	2.4–2.6	–0.02	0.20

Co-ordinates of cores are given in Table 1

RADIOCARBON DATING

Seven accelerator mass spectrometry (AMS) radiocarbon dates of marine shells (six of *Cerastoderma* sp. and one of *Scrobicularia* sp.) from five cores were obtained (Table 3). In the AMS technique, the ^{14}C concentration is measured in graphite obtained from the carbon contained in the sample. The graphite targets for accelerator mass spectrometry were prepared in the Gliwice Radiocarbon Laboratory (Piotrowska, 2013). The radiocarbon dates were calibrated by *OxCal 4.2.2* calibration program (Bronk Ramsey, 2009) using *Marine13* curve (Reimer et al., 2013) and Local Marine Delta_R=55 ±56 years.

GRAIN SIZE DISTRIBUTION

Altogether, 72 grain size analyses of sandy and gravelly-sandy marine and glaciofluvial sediments were performed. Samples for grain size analysis were taken from each layer visible macroscopically in the cores. Sieving was used for grain size analysis. Grain size fraction content was defined in 1 Φ unit intervals using sieves: 32.0, 16.0, 8.0, 4.0, 2.0, 1.0, 0.5, 0.25, 0.125 and 0.063 mm. For sandy-silty and silty-clayey sediments of ice-dammed lake, 11 samples were analyzed according to grain size distribution. After removing organic matter with 30% hydrogen peroxide (H_2O_2), grain size analysis was carried out using an *Analysette 22* (Fritsch) laser particle sizer. Percentages of the following grain sizes were determined: 0.25, 0.125, 0.063, 0.032, 0.016, 0.008, 0.004, 0.002, 0.001 and <0.001 mm.

MINERALOGICAL-PETROGRAPHIC COMPOSITION

Sand samples for distinguishing marine and glaciofluvial sediments were taken. The mineral-petrographic composition was determined in 43 samples. Analyses were performed in the fraction of 1.0–0.5 mm. Quartz, feldspar, and crystalline, sandstone, and limestone rock fragments were identified.

POLLEN ANALYSIS

Palynological analyses were done for ice-marginal lake deposits. Samples were collected every 50 cm from 2 cores. In total, 22 samples were analysed. Samples for microscopic examination were prepared using the standard method (Fægri and Iversen, 1975; Berglund, 1979). Results were presented in the form of histograms obtained with the *POLPAL* software. The percentage of each taxon in the pollen spectra was calculated in relation to the sum of trees, bushes and herbaceous plants (AP+NAP). In deposit samples, in which the low frequency of pollen grains did not allow calculating the percentage, presence of single grains was marked with a "+" sign.

RESULTS AND INTERPRETATION

While analysing and dating glaciofluvial sandy and sandy-gravelly deposits occurring in the seabed below marine sediments, the basic problem is to identify the boundary between them. The first method is the seismoacoustic profiling. Glaciofluvial delta deposits are clearly distinguishable due to a

Table 3

Results of radiocarbon dating

Lab. No.	**Core name and sample position** (dated material)	Age ^{14}C (BP)	Range of calendar (calibrated) age 68% confidence level	Range of calendar (calibrated) age 95% confidence level
GdA-3638	**S1-1* 0.8 m** *Cerastoderma* sp. shell	1080 ±22	666BP (68.2%) 628BP	694BP (93.8%) 593BP 579BP (1.6%) 566BP
GdA-3639	**S1-2 1.43 m** *Cerastoderma* sp. shell	6198 ±31	6694BP (68.2%) 6597BP	6734BP (95.4%) 6541BP
GdA-3640	**S2-1 0.80 m** *Cerastoderma* sp. shell	468 ±22	105BP (44.4%) 41BP 30BP (23.8%)	185BP (1.6%) 165BP 146BP (93.8%)
GdA-3641	**S2-1 2.68 m** *Cerastoderma* sp. shell	6100 ±27	6577BP (68.2%) 6476BP	6620BP (95.4%) 6440BP
GdA-3642	**S2-2* 1.04 m** *Cerastoderma* sp. shell	104.56 ±0.27 pMC	1990.86AD (68.2%) 1991.74AD	1957.5AD (8.4%) 1958.52AD 1990.18AD (87.0%) 1992.18AD
GdA-3645	**ZA-3* 0.9 m** *Cerastoderma* sp. shell	6127 ±38	6615BP (68.2%) 6504BP	6657BP (95.4%) 6448BP
GdA-3646	**ZA-3* 1.75 m** *Scrobicularia* sp. shell	114.95 ±27 pMC	1956.68AD (12.2%) 1956.88AD 2009.04AD (56.0%) 2009.6AD	1956.52AD (26.7%) 1957.54AD 2007.92AD (68.7%) 2009.68AD

Co-ordinates of cores are given in Table 1

strong reflector of its erosional top surface and the large-scale oblique bedding. However, the boomer used for seismo-acoustic profiling allowed recognizing the boundary with an accuracy of ±0.5 m. The second criterion is the macroscopic description carried out during the core sampling for OSL dating. As it was mentioned earlier, the boundaries between marine and glaciofluvial sediments were preliminarily recognized by reaction with HCl. Nevertheless, at the stage of selecting samples for OSL dating, it was impossible to recognize clearly the boundary between marine and glaciofluvial sediments. For the above reasons, both glaciofluvial and marine sediments were among the dated samples, as reflected by the wide spectrum of the ages obtained. In a later stage, mineral-petrographic composition and content of cesium 137 were analysed, as well as marine shells were dated by the radiocarbon method. The occurrence of cesium 137 in the sediments indicates the thickness of a dynamic layer which has been redeposited after 1945. However, the thickness of marine sediments in some cases is greater, as it is shown by the occurrence of *Cerastoderma* sp. shells that could have been deposited or redeposited before 1945. Also, the mineral-petrographic composition of some samples showed intermediate features between glaciofluvial deposits containing significant amount of sedimentary rock fragments, and marine sediments that contain much lesser amount of them. Taking into account all available indicators for the origin of the sediments from the Słupsk Bank, 10 samples of marine origin and 12 samples of glaciofluvial origin have been finally distinguished.

MARINE SANDS AND SANDY-GRAVELLY SEDIMENTS

The OSL ages of samples that have been classified as marine sediments range from 4.11 ±0.33 ka to 10.58 ±0.16 ka (Fig. 3). The base of marine sediments in the S1-1* and S1-2 cores occurs at a depth of about 25.4–26.5 m b.s.l. (2.1–2.6 m below seabed surface) and their OSL ages were determined at 9.07 ±0.66 ka and 9.62 ±0.85 ka, respectively. The water level in the Baltic Sea at that time was ~25–20 m lower than currently (Uścinowicz, 2003, 2006). So, the sea was just entering the Słupsk Bank, and the glaciofluvial deposits were exposed to sunlight due to erosion. The sediment transported and deposited in the very shallow coastal zone could be completely zeroing, so the OSL age of the marine sands in the S1-1* and S1-2 cores correlates well with the time of transgression. The older ages of marine sediments (9.77 ±0.83 and 10.58 ±0.16 ka), obtained from the S1-1* core, can be explained by poor bleaching during the depositional episode.

A very similar situation is in the case of core S2-1 taken from a depth of 15.8 m. The base of marine sands (3.25 m below seabed surface) was OSL dated at 8.88 ±0.68 ka, which correlates well with the age of transgression; sea level was then ~15–20 m lower than currently (Uścinowicz, 2003, 2006). However, it should be stated that other OSL ages of marine sedi-

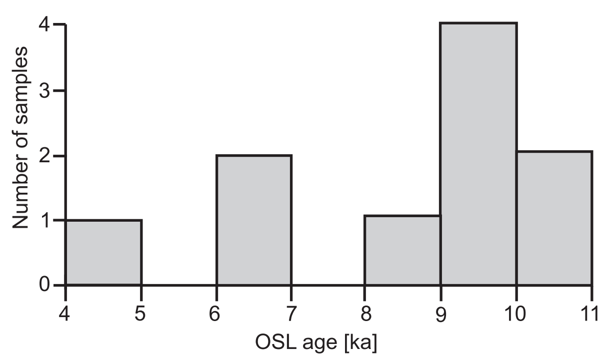

Fig. 3. Distribution of OSL ages of marine sand and sandy-gravelly sediments

ments are older than radiocarbon ages of shells from the corresponding layers. This means that except the time of transgression and opportunities for exposure of sediments to the sunlight in very shallow water, later when the sea level rose, opportunities for total bleaching were potentially poor.

A layer of marine sediments has been recently redeposited during storms to depths of 1.8 m (sand) and 1.2 m (sandy-gravelly deposits) with regard to ^{14}C dating of the marine shells and their position along the core profile, as well as distribution of ^{137}Cs content in the core (Tables 2 and 3).

GLACIOFLUVIAL DELTAS

The OSL ages of 12 samples that have been classified as glaciofluvial sediments range from 9.77 ±0.83 to 21.3 ±2.0 ka (Fig. 4). However, there are differences between four of the investigated cores. The OSL ages of glaciofluvial deposits from cores S1-1* and S1-2, taken from the delta situated at ~23–24 m b.s.l., and core S2-1, taken from the delta at a water depth of 15.8 m, are between 9.77 ±0.83 ka and 12.16 ±0.9 ka. The OSL ages of glaciofluvial deposits, obtained from these three cores, are younger than the expected age (i.e. 14–16 ka) of the tested deltas.

The S1-1* and S1-2 cores were taken on the sides, i.e. the "wings" of the delta (considering the perpendicular cross-section to the transport direction). In these parts of the delta, diffractions are visible on the seismoacoustic profile, indicating a disturbed layer system. In the second of the studied deltas, the core (S2-1) was taken at a distance of about 500 m from the delta front, where layering disturbances are also visible on the seismoacoustic profile.

The S2-2* core was collected in the distal part of the delta, at a water depth of 16.1 m. (Figs. 1 and 5). In this core, marine sands and gravelly sands are currently redeposited up to a depth of about 1.3 m below bottom surface, as indicated by the content of radiocesium (^{137}Cs) and the age of *Cerastoderma* sp. shell (Fig. 5 and Tables 2, 3). Below the marine sediments there are glaciofluvial delta deposits composed of sandy gravel at the top, grading downward into gravelly sand and fine- and medium-grained sands. OSL ages of glaciofluvial deposits from the S2-2* core range from 14.3 ±1.2 to 21.3 ±2.0 ka (Fig. 5).

The OSL ages of glaciofluvial deposits in four discussed cores range from 9.77 ±0.83 to 21.3 ±2.0 ka (Fig. 4 and Table 1). Taking into account available data about deglaciation timing in northern Poland (Wysota, 2002; Marks, 2010) and southern Sweden (e.g., Lundqvist and Wohlfarth, 2001; Houmark-Nielsen, 2008; Johnsen et al., 2009; Anjar et al., 2014), it was assumed that the OSL ages of the glaciofluvial delta sediments from the Słupsk Bank should be in the range of 16–14 ka. Therefore, only three dates obtained from core S2-2* (14.3 ±1.2, 15.6 ±1.2 and 16.60 ±1.40 ka) determine the most probable deposition time of the glaciofluvial delta at ~15.5 ka. One age older than the expected time of deltas deposition can be explained by lack of opportunities for total bleaching.

Surprisingly, many OSL ages of glaciofluvial deposits are younger than expected for the time-frame of ice sheet decay in the southernmost Baltic area. It can be explained as resulting from a contact with sunlight (partial or total bleaching) when dead-ice blocks buried in sediments were melted. It was possible in the period between deposition of the deltas and marine transgression.

ICE-MARGINAL LAKE DEPOSITS

Ice-marginal lake deposits, its spatial spreading, thickness and lithology, are well-documented in the Polish part of the southern Baltic Sea (Kramarska, 1991; Uścinowicz and Zachowicz, 1991; Pikies and Jurowska, 1994). They have been found in the area between the western edge of the Słupsk Bank and the Polish coast in the west and in the western part of the Gulf of Gdańsk (eastern part of the Polish coast). Grain size of the deposits varies significantly; in most cases they consist of laminated silty clay, clayey silt and sandy silt, sometimes with sandy interlayers. Silty sand and fine sand occur locally, and post-sedimentary deformation structures are frequently present. Generally, the organic matter content is about 1.5%. The thickness of ice-marginal lake deposits depends on the relief of the substratum, and varies from several tens of centimetres to 25 m (Uścinowicz, 1996, 1999). However, the age of the ice-marginal lake is poorly known. There are only a very few pollen spectra of those sediments (16 samples analysed in four cores) (Uścinowicz et al., 2014). Nevertheless, they indicate that the sedimentation took place during the Late-Glacial period. Those analyses also show that the topmost sections of the deposits filling the depressions contain a significant percentage of juniper (*Juniperus*) and hazel (*Corylus*) pollen, which suggests that, at least locally, water bodies (lakes) persisted during the transition period from the Late-Glacial to the Holocene and during the Early Holocene (Uścinowicz et al., 2014).

During research discussed in the present paper, three sediment cores of ice-marginal lake deposits were acquired and analysed (Fig. 1). The spectrum of OSL ages of 11 samples is extremely large ranging between 11.09 ±0.79 and 135.00 ±12.0 ka (Fig. 6).

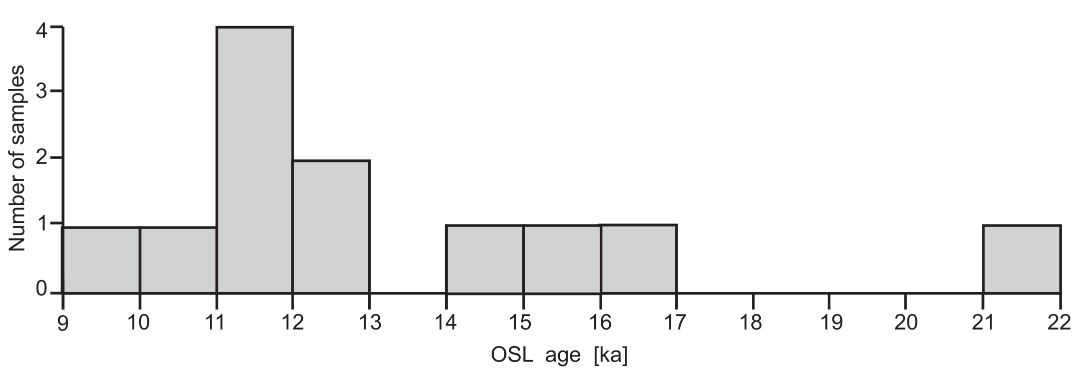

Fig. 4. Distribution of OSL ages of glaciofluvial sand and sandy-gravelly sediments

Assuming the existence of an ice-marginal lake during the last deglaciation, we can discuss only four ages of ice-marginal lake deposits. Two of them (14.51 ±0.81 ka and 14.6 ±1.4 ka) fit well into the expected time of ice-marginal lake existing in front of the Słupsk Bank moraines. Two others (11.09 ±0.79 ka and 12.92 ±0.64 ka) are younger, which can be explained as resulting from contact with sunlight, when dead-ice blocks buried in sediments were melted. It is also possible that these "too young ages" are related to the lakes that persisted in the area after drainage of the ice-marginal lake. In that case, the sample dated to 14.51 ±0.81 ka in core ZA-2 located above the sample dated to 12.92 ±0.64 ka (Fig. 7) could not be totally bleached.

The assumption that the OSL ages older than 30 ka (Fig. 6 and Table 1) respond to the older interstadials or interglacials (MIS 3, MIS 4, MIS 5d/MIS 6) can be ignored due to not only the lack of coarse-grained lag deposits on their top, but also in the light of previous studies (Kramarska, 1991; Uścinowicz and Zachowicz, 1991; Pikies and Jurowska, 1994; Uścinowicz et al.,

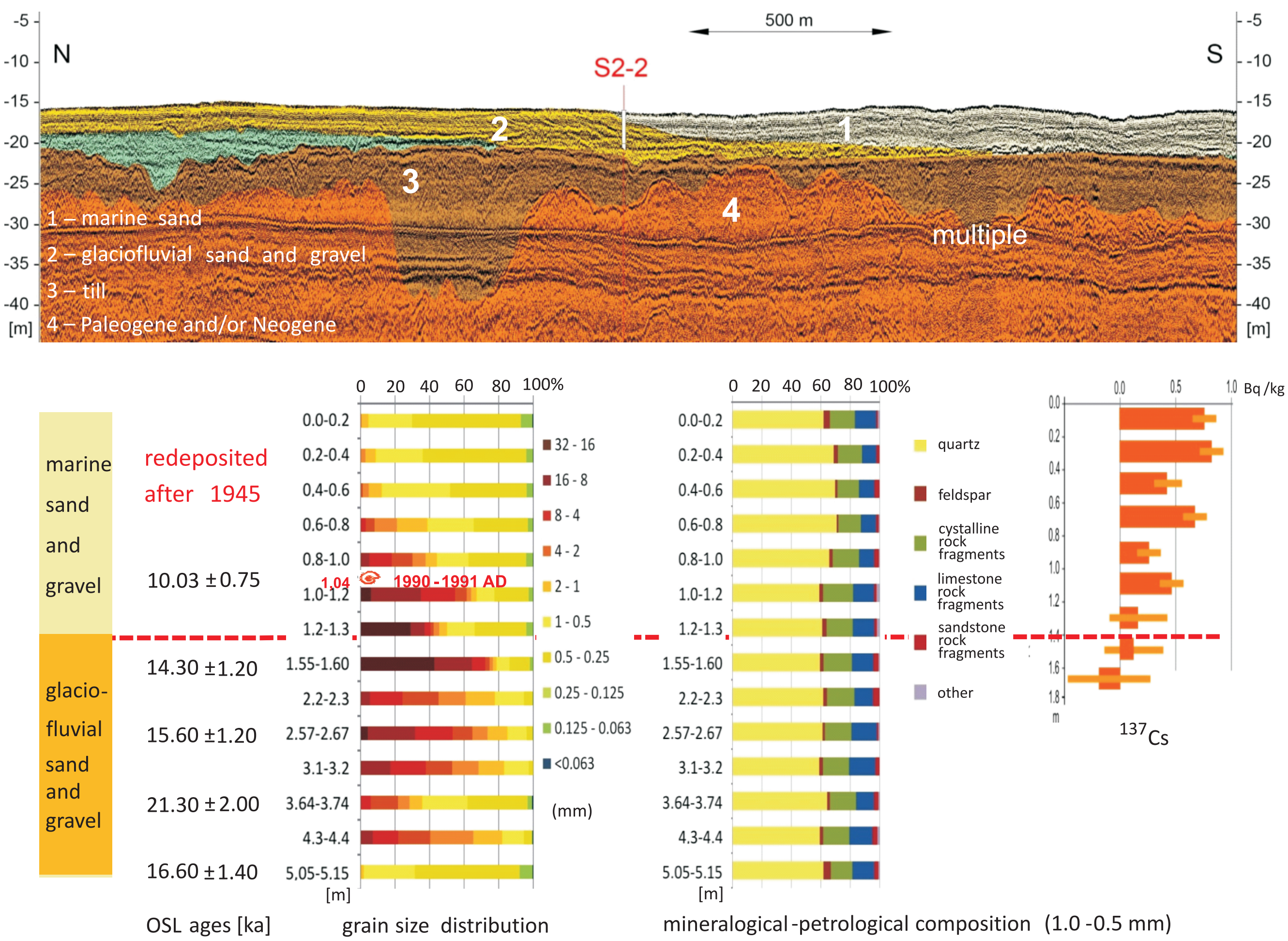

Fig. 5. Seismoacoustic profile of glaciofluvial delta and results of S2-2 core study

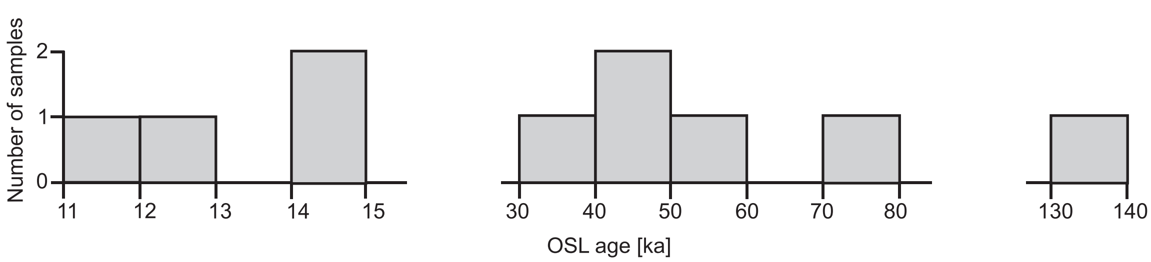

Fig. 6. Distribution of OSL ages of silty-sandy sediments of ice-marginal lake between the Słupsk Bank and the Polish coast

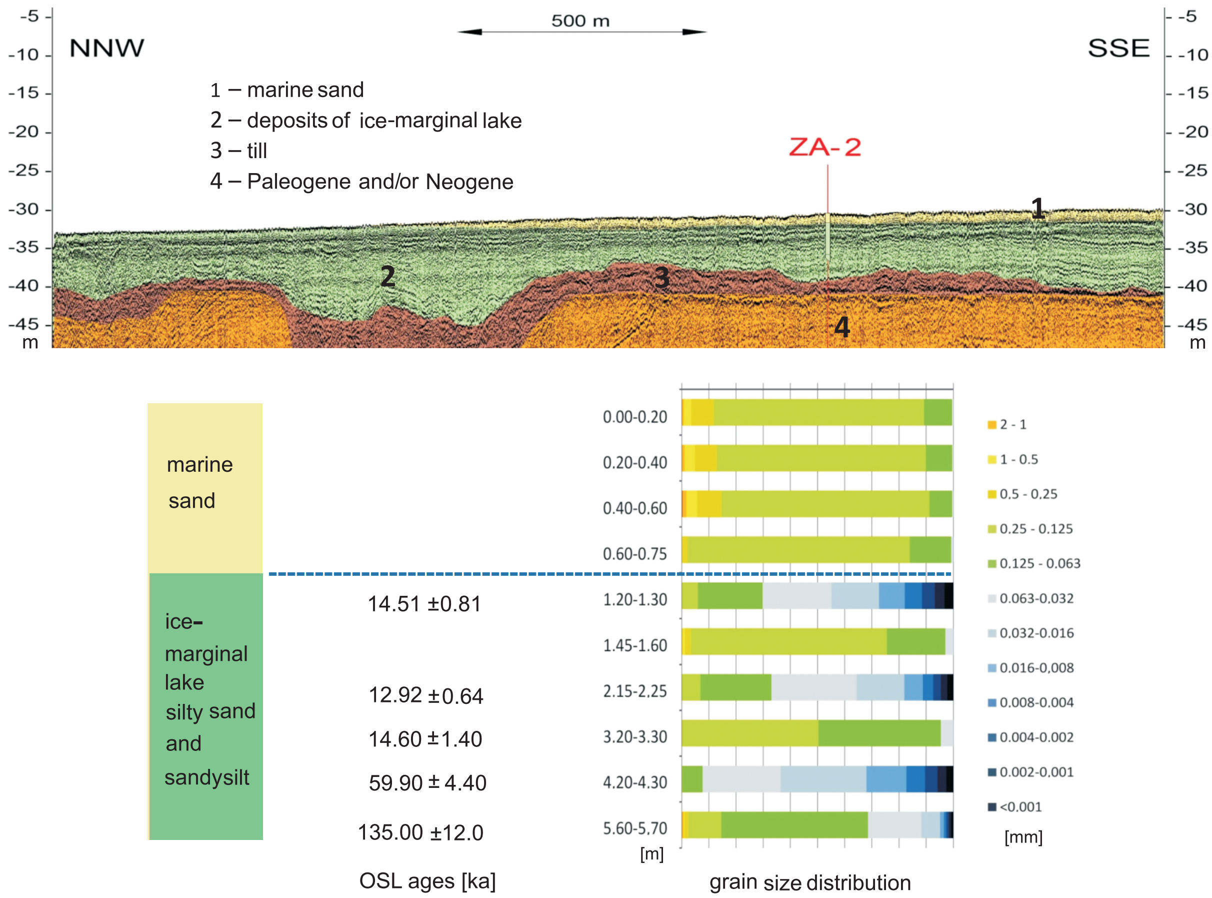

Fig. 7. Seismoacoustic profile of ice-marginal lake deposits and results of ZA-2 core study

2014). Evidences for the statement are also provided in the present paper (Fig. 8). The poor tree species composition, with predominance of pine (*Pinus*) and birch (*Betula*), and the presence of species characteristic for tundra, such as *Betula nana, Salix, Saxifraga, Ephedra,* and *Artemisia* (Fig. 8), indicate the sedimentation took place during cold, arctic climate. The presence of *Pediastrum kawraiskyi* green-alga indicates that the sediments were deposited in cold and oligotrophic waters.

The ice-marginal lake sediments from cores ZA-1 and ZA-2 contain also a significant amount of corroded pollen grains, especially in the lower part of the cores. In that, there is a significant number (up to 34%) of pollen grains of Paleogene/Neogene plants. On the diagram (Fig. 8), the Paleogene/Neogene species are illustrated by Rebedded and *Ilex* columns. The corroded grains of pollen species with significant climatic requirements: elm (*Ulmus*), hazel (*Corylus*) and alder (*Alnus*), are also present. These grains could be redeposited from older interglacial or interstadial deposits.

COASTAL RIDGES OF THE ICE-MARGINAL LAKE IN THE GARDNO-ŁEBA LOWLAND

During the fieldwork in the Gardno-Łeba Lowland we had only a hypothesis that the ridges could be older than Holocene. During the sampling we did not find any indicators for marine or aeolian origin of the ridges.

The ridge in Żelazo is composed of medium sand with a minor admixture of fine gravel with poorly visible lamination. Well-developed podzsolic soils with a clear Orstein level (level with a high content of ferric compounds) occur at the top of the ridge. The ridge in Łokciowe is composed of fine- and medium-grained massive sand (no visible lamination). The sand is covered by a fossil podzolic soil with an Orstein level. A thin layer of muddy peat and 20 cm of aeolian sand at the surface occur above the fossil podzolic soil (Fig. 9). The Nowęcin ridge is composed of sandy-gravelly deposits with horizontal bedding; however, it is disturbed by a frost wedge and tree roots in the upper part. Like in Żelazo and Łokciowe, podzolic soils with an Orstein level occur at the surface of the ridge.

The most coherent set of OSL ages comes from low ridges in the Gardno-Łeba Lowland (Fig. 1, Żelazo, Łokciowe and Nowęcin sites). The OSL ages of 10 samples of sandy and sandy-gravelly deposits range from 11.03 ±0.73 to 16.13 ±0.94 ka (Figs. 9, 10 and Table 1), so only two of them are definitely younger than expected time of their deposition. The youngest ages occur in the upper samples where disturbances of the bedding are visible, which can indicate possibility of short exposition to sunlight. The average age of eight samples from the range of 13.73 ±0.84 ka – 16.70 ±1.10 ka is 15.21 ka.

DISCUSSION

The research was carried out on landforms and sediments of different origin; however, according to previous studies (Uścinowicz 1995, 1996, 1999, 2010), they are related to each

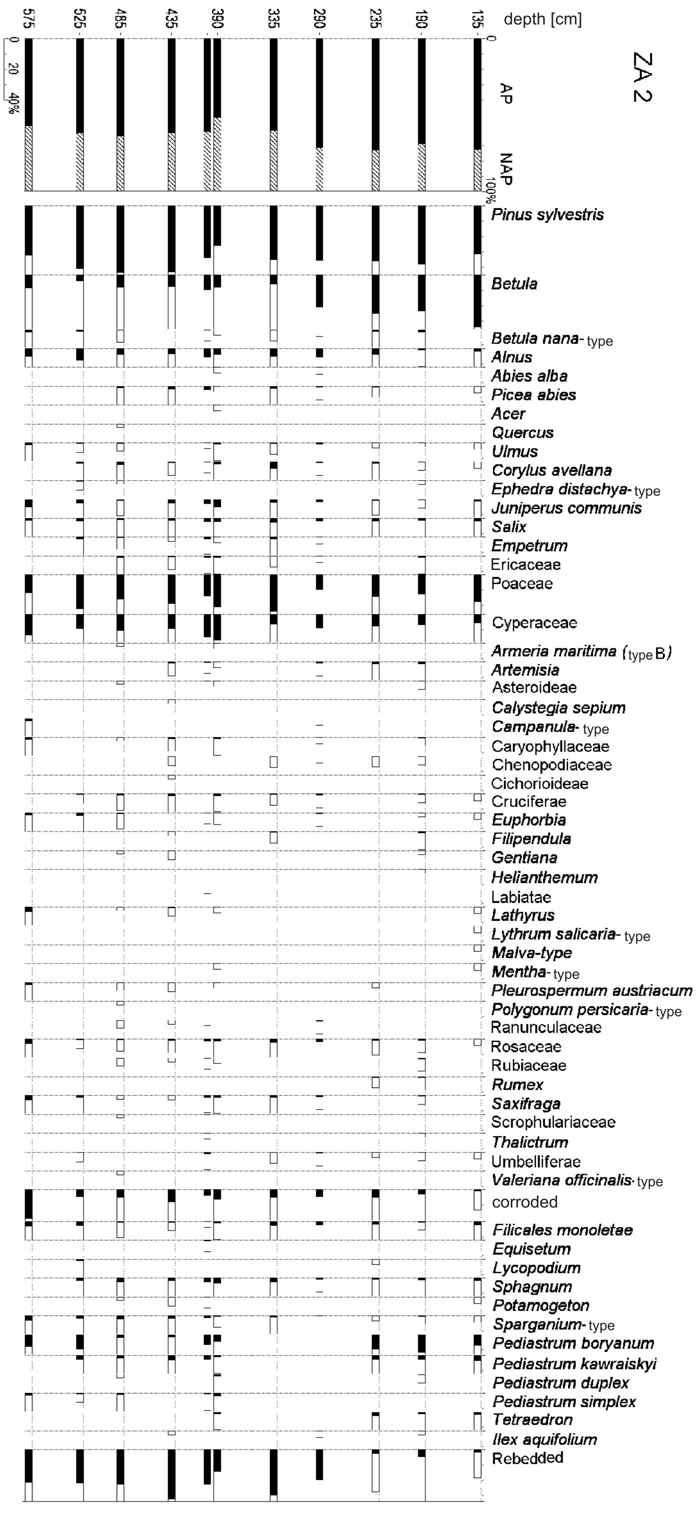

Fig. 8. Pollen diagram of ice-marginal lake sediments in ZA-2 core

other and were formed at the same time. Altogether, 43 samples were dated by the OSL method. The spectrum of obtained OSL ages was extremely large – from 4.11 ±0.33 to 135.0 ±12.0 ka. Nevertheless, when we exclude the seven ages of ice-marginal lake deposits, which are definitely too old (i.e. older than MIS 2), and neglect the ages of marine sediments, then 26 ages in a range of 9.77 ±0.83–21.3 ±2.0 ka remain, i.e. related to the Late Glacial and Early Holocene. Among the results that include three ages of glaciofluvial deposits, two ages of ice-marginal lake, and eight ages of coastal ridges of the lake, there are 13 ages (50%) that fit well into the expected (most probable) period of deglaciation of the southernmost Baltic area (Fig. 11). The average age is 15.18 ka and the standard deviation is 0.91 ka. On this basis we can state that the Słupsk Bank Phase, when glaciofluvial deltas were formed in front of an end moraine ridge, and the huge ice-marginal lake existed south of that reaching the present Polish coast, took place most likely ~15,200 years ago.

According to the average age of the Słupsk Bank Phase, the ages of silty-sandy sediments of ice-marginal lake are a little younger (14.51 ±0.81 and 14.6 ±1.4). The same applies to position and ages (14.05 ±0.79 and 14.72 ±0.92 ka) of a coastal ridge in the Łokciowe site. It can be explained that those sediments were deposited during recession of ice sheet front from the Słupsk Bank. The samples of ice-marginal lake sediment were taken from the uppermost and the youngest part of the sediments. The ridge in Łokciowe is younger than ridges in Żelazo and Nowęcin, and it is situated north of the ridge in Żelazo.

In that case, the ridges in Żelazo and Nowęcin mark a maximal range of the ice-marginal lake and the ridge in Łokciowe is a recessional one.

Below, there are two other, less important debatable issues. Firstly, the attempt to explain the problem of older or younger ages than the expected time of deglaciation of the southernmost Baltic area was presented earlier; however, some doubts still remain, especially for eight ages of glaciofluvial deltas younger than 14 ka. The mineral-petrographic composition of the samples is typical for glaciofluvial deposits and the sediments do not contain marine shells. Therefore, it is rather impossible that the sediments were redeposited during the Middle Holocene (Littorina Sea) transgression. In case of cores S1-1* and S1-2, it is possible that discussed sediments were shortly redeposited during the high stands of the Baltic Ice Lake and especially the Ancylus Lake. In case of core S2-1, it is less probable due to its bathymetric position. However, in seismoacoustic records in all three cases, the disturbances in sediment bedding are visible, so the processes related to melting of dead-ice blocks are the best explanation so far. Besides, we know only very little how it looked like and what the possibilities for sediment bleaching were. Secondly, a debatable issue could be also the origin and age of low, gentle ridges in the Gardno-Łeba Lowland. Nevertheless, due to obtained ages and lack of any other indicators for another origin, the discussed ridges have been classified as coastal forms (coastal ridges or relics of a spit) of ice-marginal lake that existed south of the Słupsk Bank at the same time when glaciofluvial deltas were being formed.

We have also tried to correlate the Słupsk Bank Phase with other recessional phases of the last SIS in Scandinavia and on the eastern coast of the Baltic Sea. A short stop of ice sheet front at the Słupsk Bank took place most probably ~15.2 ka ago (Fig. 12), during a short period of climate cooling 15.1–14.8 ka BP (Alley, 2004). The Słupsk Bank Phase can thus be correlated with the Göteborg Phase (~15.4–14.5 ka) (Lundqvist and Wohlfarth, 2001; Lundqvist, 2002; Stroeven et al., 2016) or the Phases of Central Skåne (16–15 ka) (Houmark-Nielsen, 2008) in southern Sweden.

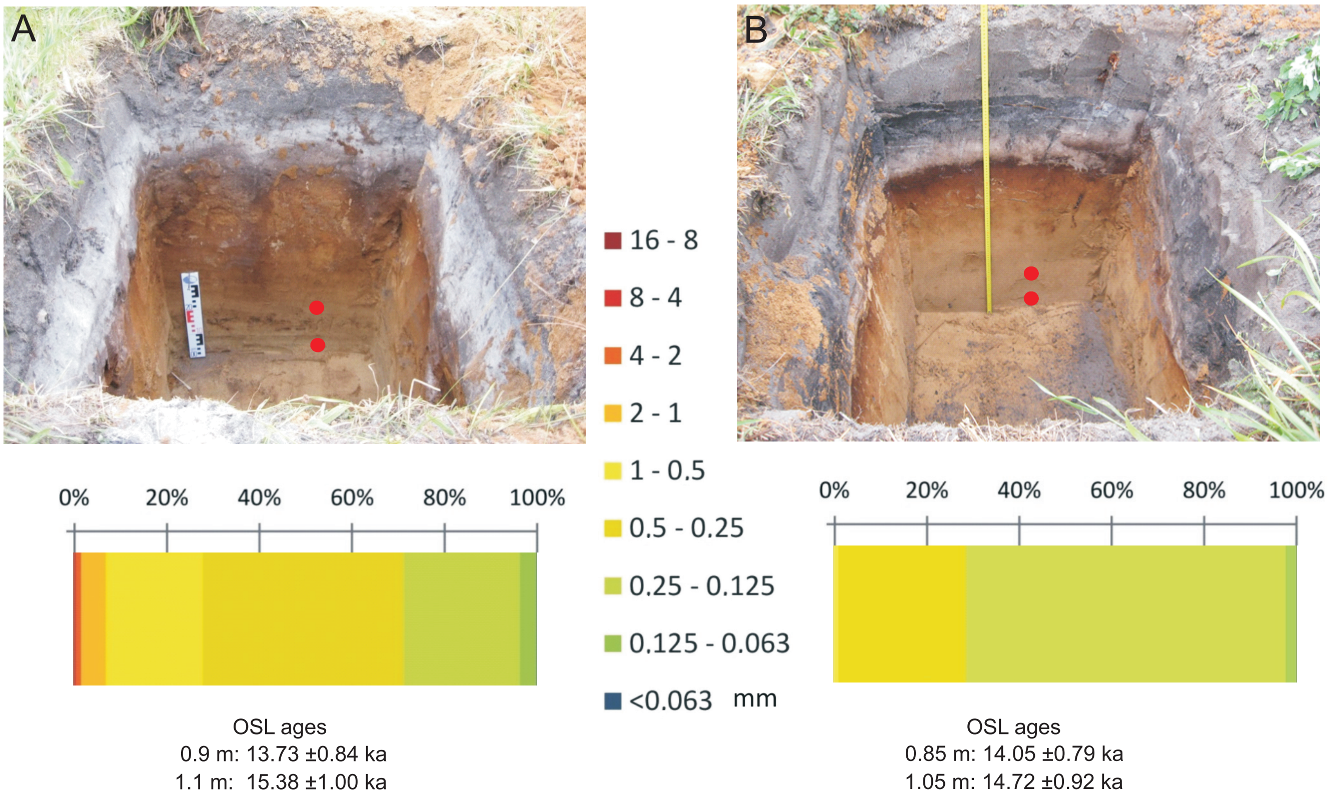

Fig. 9. Excavations in coastal ridges of ice-marginal lake, and results of investigations

Żelazo 1 (A) and Łokciowe (B) sites (red dots indicate points of samples collection)

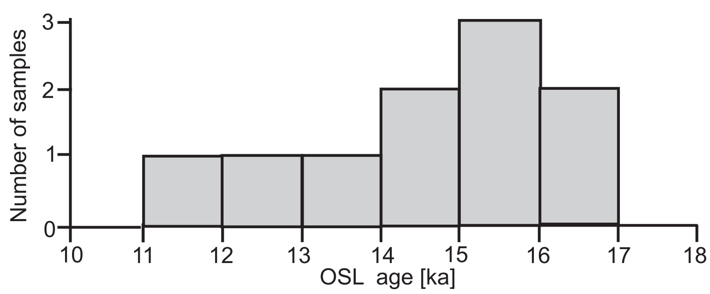

Fig. 10. Distribution of OSL ages for sands and gravelly sands of coastal ridges of ice-marginal lake in the Łeba-Gardno Lowland

However, in relation to other data (Anjar et al., 2014), the Słupsk Bank Phase may be correlated with the timing of deglaciation of eastern Skåne (15.0 ±1.0 ka) or southernmost Småland (15.8 ±0.9 ka). It does not have to be in conflict with ^{10}Be ages from Bornholm (16.6 ±0.9 ka) and southernmost Småland (16.1 ±0.9 ka). It is possible that ice lobes were located in Hanø Bay and the Bornholm Basin, whereas Bornholm island remained free of ice.

To the east, the Słupsk Bank Phase could be related to the North Lithuanian Phase (Haanja–Luga Phase) described by Veinbergs et al. (1995), Pirrus and Raukas (1996) and Kalm (2006). Recession of the ice sheet from the end moraines in the Słupsk Bank was rather fast due to a distinct climate warming at the onset of the Bøllinge-Allerød chronozone, and it is probable that the ice sheet front retreated to the Southern Middle Bank during the next 500–700 years. Thus, a short stop of ice-sheet front at the Southern Middle Bank could take place ~14.5 ka ago. This phase of southern Baltic area deglaciation may be correlated with the Berghem and/or Vimmerby moraines, the age of which was estimated at 14.2–14.6 ka by Lundqvist and Wohlfarth (2001), Anjar et al. (2014), Stroeven et al. (2016) in southern Sweden, and with the Otepää Phase (Pirrus and Raukas, 1996; Kalm 2006) on the Latvian coast.

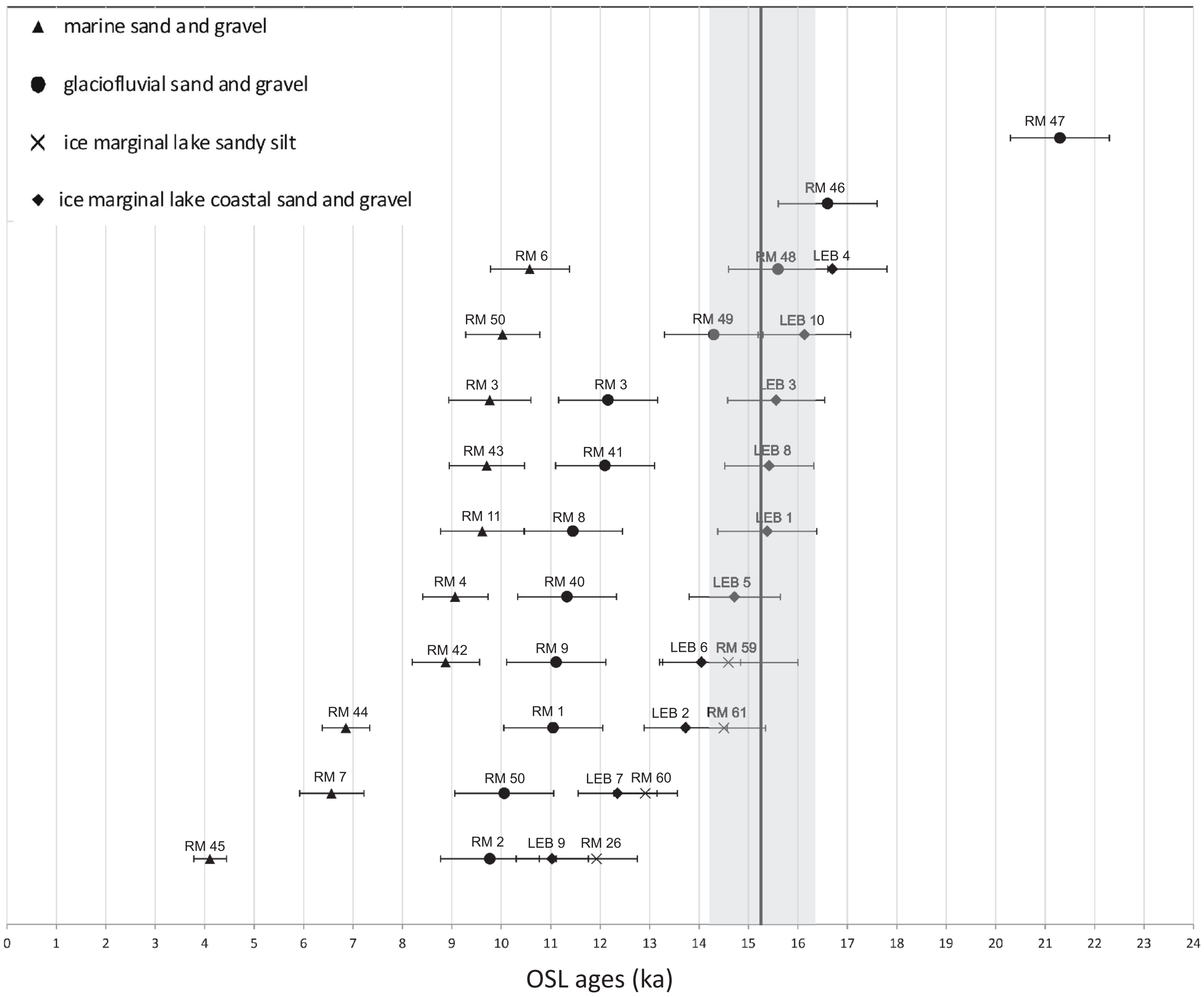

Fig. 11. OSL ages of investigated sediments

Grey line and light grey rectangle marks the average and standard deviation of sediment's age related to the Słupsk Bank Phase

According to the results of the present paper, indicating that the Słupsk Bank Phase took place ~15.2 ka ago, the moraines marking the last ice sheet advance in northern Poland (Gardno Phase) must be a little older and most probably were formed between 16,000–15,500 years ago.

Taking the above into account, the Gardno Moraines may be correlated to the Halland Coastal Moraines (Lundqvist and Wohlfarth, 2001) in Sweden. Although Anjar et al. (2014) presents slightly older ages for the Halland Coastal Moraines (16.8 ±1.0 ka) and Göteborg Moraines (16.1 ±1.0 k) their connections with the Gardno Moraines is still possible. However, the position of ice margin in the vicinity of Bornholm Island at that time remains debatable. To the east, the Gardno Phase most probably corresponds to the Middle Lithuanian Phase (Raukas et al., 1995).

The Słupsk Bank Phase is dated in the present paper and, at the moment, it is correlated with the southernmost Sweden and north Lithuanian moraines not only by spatial correlations of the ice-marginal forms and sediments remained on the southern Baltic seabed, but also according to its ages. Attributions of the Gardno and Southern Middle Bank Phases to the deglaciation phases in southern Sweden and the eastern Baltic coast still remain only as spatial correlations; however, cool periods visible on the plot of palaeotemperatures of Greenland (Fig. 12) slightly support these suppositions.

CONCLUSION

The sediments of four types of environment and different lithologies were dated by the OSL method.

The OSL ages of marine sands and sandy-gravelly deposits ranges from 4.11 ±0.33 to 10.58 ±0.16 ka BP and correspond mainly with the Middle Holocene marine transgression on the Słupsk Bank. The ages younger than 8 ka indicate later redeposition when contact with sunlight was possible. The dates older than the time of transgression are explained by lack of opportunities for total bleaching during deposition.

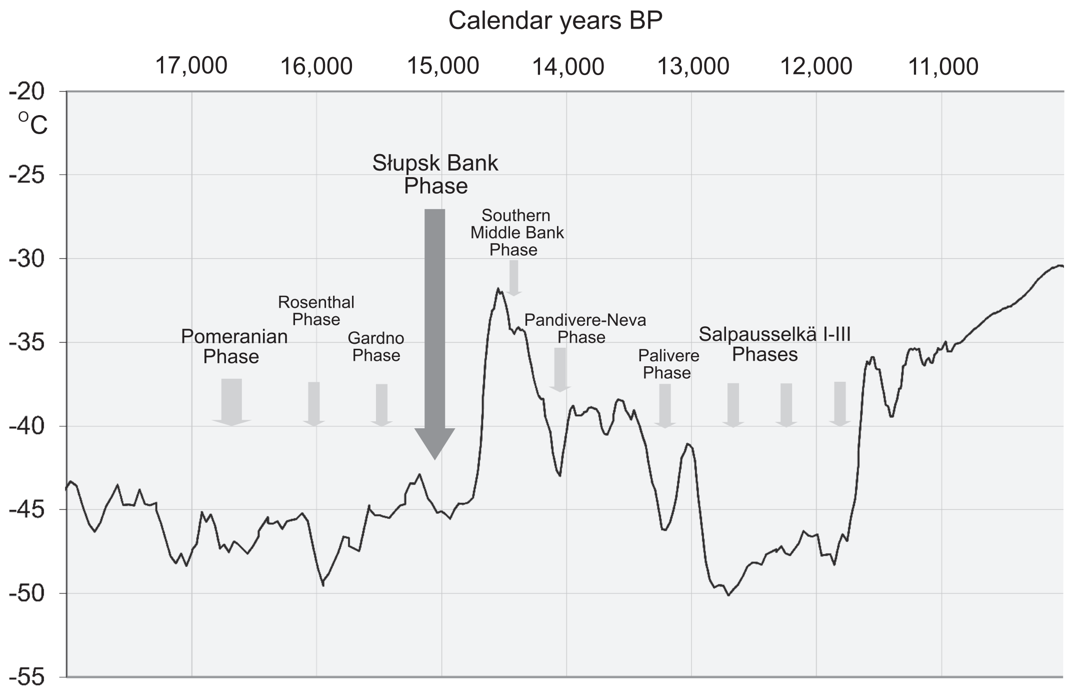

Fig. 12. Palaeotemperatures of Greenland (based on ice core GISP2; Alley, 2004) and the most likely age of the Słupsk Bank Phase, as well as possible ages of other phases of SIS decay in northern Poland and the Baltic Basin

Among 12 OSL ages of glaciofluvial deltas, three of them (14.3 ±1.2, 15.6 ±1.2 and 16.60 ±1.40 ka) fit into the most probable time of deposition. A similar case (2 out of 11 ages) refers to fine-grained ice-marginal lake deposits. The best results (8 out of 10 ages) are obtained from coastal sandy and sandy-gravelly deposits of ice-marginal lake. Nevertheless, when seven oldest ages (i.e. older than MIS 2) were excluded, 26 ages in a range of 9.77 ±0.83–21.3 ±2.0 ka have remained. Among those results, 50% of them (i.e. three ages of glaciofluvial deposits, two ages of ice-marginal lake, and eight ages of coastal ridges of the lake) fit well into the expected (most probable) period of deglaciation of the southernmost Baltic area. On this basis we can state that the Słupsk Bank Phase, when glaciofluvial deltas were formed in front of an end moraine ridge, and the huge ice-marginal lake existed south of that reaching the present Polish coast, took place most likely approximately 15,200 years ago. Older ages are explained by a well-known effect of inheritance of former OSL signals and poor opportunities for bleaching during the depositional episode. Another very important factor for fine-grained sediments of the ice-marginal lake is the probable admixture of older, redeposited deposits. A large number of OSL ages of glaciofluvial and ice-marginal lake deposits younger than expected or even possible for the time-frame of ice sheet decay in the southernmost Baltic can be explained by the possible contact with sunlight (partial or total bleaching), when dead-ice blocks were melted buried in sediments. Nevertheless, in all cases, OSL ages should be tested against available regional numerical event-stratigraphic glaciation chronologies to determine whether overestimation or underestimation is possible.

The final conclusion is that the mode of deglaciation was changed from frontal and aerial into subaqueous after ice sheet retreat from moraines of the Gardno Phase. A large ice-marginal lake existed in front of the ice sheet during the Słupsk Bank Phase. The average age of this episode during the last SIS decay is 15.2 ka with a standard deviation of 0.9 ka.

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