NUKLEONIKA 2008;53(Supplement 2):S105–S111

ORIGINAL PAPER

Sedimentation rates and dating of bottom sediments in the Southern Baltic Sea region

Maria M. Suplińska,
Zofia Pietrzak-Flis

Abstract. Sedimentation rates and dating of bottom sediments were estimated in two sampling stations of the Gulf of Gdańsk and in four stations in the open sea area. Estimations were based on vertical distributions of ^{210}Pb, ^{137}Cs and ^{239,240}Pu activity concentrations in sediment core samples taken in 1998–2007. Two dating models based on changes of activity concentrations of $^{210}\text{Pb}_{\text{unsup}}$ were used: 1) CF:CS (Constant Flux Constant Sedimentation rate-model) and 2) CRS (Constant Rate of Supply-model). ^{137}Cs and ^{239,240}Pu were applied as time markers. ^{137}Cs originates mostly from the Chernobyl accident in 1986, whereas ^{239,240}Pu comes from the global fallout in 1963. The validation of the ^{210}Pb methods was performed by activity peak of ^{137}Cs and ^{239,240}Pu. Sediment accumulation rate ($\text{g·cm}^{-2}\text{·y}^{-1}$) was constant along sediment core. Annually accumulated layer, (mm·y^{-1}) decreased with sediment depth in all the locations. In the Gulf of Gdańsk sedimentation rate in the upper layer was about 3.6 mm·y^{-1}, and it decreased in the deeper layers to about 1.1 mm·y^{-1}. Sedimentation rates in the open sea area were lower than in the gulf region and the lowest was observed in the Bornholm Deep, being about 0.95 mm·y^{-1} in the upper layer and 0.35 mm·y^{-1} in the deeper layer. The growth of a 5 cm thick layer took 27–37 years in the Gulf of Gdańsk, and 61–105 years in the open sea area. It is suggested that the mean values obtained from the models would give a most reliable estimation of the sedimentation rates.

Key words: sedimentation rate • ^{210}Pb • ^{137}Cs • ^{239,240}Pu • Southern Baltic • bottom sediment

M. M. Suplińska✉, Z. Pietrzak-Flis
Department of Radiation Hygiene,
Central Laboratory for Radiological Protection,
7 Konwaliowa Str., 03-195 Warsaw, Poland,
Tel.: +48 22 8110011 ext. 227, Fax: +48 22 8111616,
E-mail: suplinska@clor.waw.pl

Received: 29 October 2008
Accepted: 20 January 2009

Introduction

Bottom sediments are formed from organic and inorganic particles which settle from water body of aquatic reservoirs. Sedimentation process causes a continuous increase of the sediment, with a sedimentation rate characteristic of a given location. However, in the long period of time sedimentation rate may vary considerably. The uneven distribution of various sediments reveals the dynamic nature of the sedimentation processes in the Baltic Sea. The central region of the Southern Baltic is characterised by accumulation of fine-grained, soft silty and muddy sediments [5]. Contaminants from water are adsorbed on the settled particles and bottom sediments. Particles reach the seafloor by vertical transport and by near-bottom lateral transport [3]. Accumulated radionuclides are more or less permanently fixed to the bottom sediments depending on their properties and sediment qualities. Horizontal and vertical distributions of artificial radionuclides in the bottom sediments show contamination sources and their variability in time [5].

The sediment accumulation rate is the main parameter in contamination studies in the aquatic environment, and ^{210}Pb is widely applied as a tracer in the deposition history of bottom sediments, their dating and estimation of sedimentation rates. The main source of ^{210}Pb ($T_{1/2}$ = 22.3 years) in the environment is the direct dry and wet deposition from atmosphere. Most of ^{210}Pb derives from the decay of gaseous ^{222}Rn introduced into the atmosphere from the earth's crust. In addition, ^{210}Pb was introduced to atmosphere during nuclear explosions in the reaction ^{208}Pb $(2n,\gamma)^{210}$Pb [8].

Small content of ^{210}Pb is also introduced from phosphoric fertilizers reach in ^{226}Ra [6] and, as a result, of conventional coal power plants and petrol combustion [7]. Part of ^{210}Pb in bottom sediments also results from the decay of ^{226}Ra present in the sediment.

Dating methods, which are based on activity concentrations of ^{210}Pb, can be applied for the last 100–150 years [1, 2, 10]. The ^{210}Pb methods need an independent validation. The chronology of changes in the environment is validated by the distribution of other isotopes along the bottom sediment profiles. Validation for the last 30–40 years is made via fallout records of artificial radionuclides, like ^{137}Cs, ^{239,240}Pu or ^{241}Am which exist in the environment since the first weapon tests.

The purpose of this study was to determine sedimentation rate in the Basin of Gdańsk (two locations in the Gulf of Gdańsk and two in the open sea area) and in the Bornholm Basin (two locations). For determination of sedimentation rates the ^{210}Pb method was used. The results obtained were validated by applying activity peaks of ^{137}Cs and ^{239,240}Pu.

Materials and methods

Sampling

Bottom sediment core samples were collected in 1998–2007 from various regions of southern part of the Baltic Sea. Sampling cruises into the Baltic Sea with research vessel "Baltica" were organised by the Institute of Meteorology and Water Management once a year from June to August. At each sampling station, five or six core samples were taken with the gravity corer of the Niemisto type of inner diameter 55 mm. Core samples were sectioned into sub-samples: 1 cm slices from 0 to 5 cm and 2 cm slices from 5 to 19 cm depth. Sub-samples from each sampling station were combined and frozen immediately after sampling. In the Laboratory unfrozen samples were weighed before and after drying. The location (latitude and longitude), depth of sampling stations and coring date are presented in Table 1.

Analytical methods

The ^{210}Pb and ^{137}Cs activity concentrations were determined by gamma spectrometry from the gamma emission at 46.52 and 661.66 keV, respectively [1]. The gamma spectrometer consisted of a high purity germanium detector with an energy resolution of 1.8 keV for ^{60}Co (1332 keV) and with a relative efficiency of 33%. The detector was placed inside a lead shield with walls 10 cm thick which were lined with a 2 mm layer of copper. Till year 2001, the detector was connected to a multichannel analyser Canberra, Series 90. Since the year 2002 it was connected to Canberra MULTIPORT II MCA with GENIE-2000. Lower limit of detection (LLD) of ^{210}Pb and ^{137}Cs for counting time 170,000 s was 0.13 Bq/sample and 0.025 Bq/sample, respectively.

Plutonium was separated by ion exchange, followed by the electrodeposition onto stainless steel disks. ^{242}Pu was used as an internal tracer for counting alpha activity and chemical recovery [14]. Activity of plutonium was measured by alpha spectrometry using a PIPS detector with an efficiency of 32% placed in a vacuum chamber. LLD for counting time of 164,000 s was 0.2 mBq/sample.

Concentration of ^{226}Ra was determined radiochemically using the emanation method (measurement of ^{222}Rn and its daughters in the Lucas-type scintillation chambers) preceded by separation of radium [13]. LLD with the counting time 21,600 s was equal to 0.73 mBq/sample.

The reliablity of the applied methods was checked in the determinations of radionuclides in reference materials (IAEA-300, IAEA-326, IAEA-327, IAEA-375) and in the Proficiency Test organized by the IAEA in 2002. Analytical results for ^{137}Cs, ^{210}Pb, ^{239,240}Pu and ^{226}Ra are presented in Table 2. Calculated u-test values indicate that our results do not differ significantly from the IAEA values at the probability greater than 0.1. Calculated precision was on average 7.1% for ^{137}Cs, 18.9% for ^{210}Pb, 9.30% for ^{239,240}Pu and 19.2% for one sample of ^{226}Ra. The above data show that the applied methods fulfil the IAEA criteria of accuracy and precision.

Models

The vertical distribution of naturally occurring ^{210}Pb has been used for the sediment dating and estimation of sediment accumulation rate. The total activity concentrations of ^{210}Pb (^{210}Pb$_{tot}$) in the bottom sediments consist of ^{210}Pb unsupported (^{210}Pb$_{unsup}$), originated from atmosphere, and ^{210}Pb supported (^{210}Pb$_{sup}$) formed as a result of radioactive decay of ^{226}Ra in the sediment. In

Table 1. Sampling stations, location and year of sampling

Sampling station/depth (m)	Location: latitude and longitude		Sampling years
P110/71	54°30,0'N	19°06,8'E	1998, 2002, 2003, 2005, 2006, 2007
P116/90	54°39,1'N	19°17,6'E	1999, 2003, 2004, 2005, 2006
P1/108	54°50,0'N	19°19,0'E	1999, 2002, 2003, 2005, 2007
P140/89	55°33,3'N	18°23,0'E	2002, 2004, 2005, 2007
P5/90	55°14,0'N	15°59,0'E	2002, 2005, 2006
P39/63	54°44,0'N	15°08,0'E	2002, 2003, 2004, 2006

Table 2. Radionuclide concentrations in reference materials and spiked matrix

	Radionuclide	Unit	Recommended value	Activities measured in this work
	^{137}Cs	Bq·kg^{-1}	1066.6	1055 ± 37.8
IAEA-300 – Sediment	^{210}Pb	Bq·kg^{-1}	364 ± 57	370 ± 7.44
	^{239,240}Pu	Bq·kg^{-1}	3.55	3.20 ± 0.40
	^{137}Cs	Bq·kg^{-1}	137.5 ± 19.0	129 ± 3.1
IAEA-326 – Soil	^{210}Pb	Bq·kg^{-1}	53.3 ± 10.6	51.0 ± 1.52
	^{226}Ra	Bq·kg^{-1}	32.6 ± 6.2	33.8 ± 0.81
	^{137}Cs	Bq·kg^{-1}	24.9 ± 1.8	26.2 ± 0.66
IAEA-327 – Soil	^{210}Pb	Bq·kg^{-1}	58.8 ± 12.1	58.0 ± 1.61
	^{239,240}Pu	Bq·kg^{-1}	0.58 ± 0.06	0.46 ± 0.05
	^{137}Cs	Bq·kg^{-1}	5280	5281 ± 57
IAEA-375 – Soil	^{226}Ra	Bq·kg^{-1}	20.0	20.5 ± 1.42
	^{239,240}Pu	Bq·kg^{-1}	0.30	0.297 ± 0.032
	^{239,240}Pu	Bq	0.077 ± 0.0016	0.080 ± 0.0057
	^{239,240}Pu	Bq	0.077 ± 0.0016	0.081 ± 0.0069
Proficiency Test, spiked matrix	^{239,240}Pu	Bq	0.077 ± 0.0016	0.077 ± 0.0058
	^{239,240}Pu	Bq·g^{-1}	0.244 ± 0.0049	0.241 ± 0.0175
	^{137}Cs	Bq·kg^{-1}	34.9 ± 1.0	32.57 ± 0.74
	^{137}Cs	Bq·kg^{-1}	21,200 ± 320	22,279 ± 563

the dating models, activity concentrations of ^{210}Pb$_{unsup}$ in particular layers of the bottom sediments was used. Two dating models based on changes of activity concentrations of ^{210}Pb were used: 1) CF:CS (Constant Flux Constant Sedimentation rate-model) and 2) CRS (Constant Rate of Supply-model) [2, 12].

The validation of the above methods was performed by the activity peak of ^{137}Cs or ^{239,240}Pu. Caesium-137 in the Baltic Sea originates mostly from the fallout of the Chernobyl accident in 1986, whereas plutonium originates from the weapon tests, giving the maximum global fallout in 1963 [4, 9]. In calculations it was accepted that the sedimentation rate has been constant between the year 1986 or 1963 and the sampling year.

Results and discussion

Activity concentrations of ^{210}Pb strongly differed in the subregions. In the upper layer 0–1 cm of the sediments, activity concentrations of total ^{210}Pb decreased from about 430 Bq·kg^{-1} in the Gulf of Gdańsk to about 60 Bq·kg^{-1} in the Bornholm Basin. Unsupported ^{210}Pb decreased from 400 to 20 Bq·kg^{-1}, respectively. Also differed the smallest depths in the bottom sediment where the activity concentrations of total ^{210}Pb were the same as the concentration of ^{226}Ra. The smallest depth was 12–16 cm in the Gulf of Gdańsk, 5–8 cm in the Gdańsk Deep, and 3–5 cm in the Bornholm Basin. Figure 1 shows the vertical distribution of activity concentrations of the total ^{210}Pb and unsupported ^{210}Pb at chosen stations and years in the Gulf of Gdańsk, the Gdańsk Deep and the Bornholm Basin.

Table 3 presents the sediment accumulation rates (SAR), annual accumulation layer (AAL), and total ^{137}Cs activity estimated at six stations from 27 sediment cores. SAR and AAL were estimated with the CF:CS model. The highest SAR values were observed at the P110 sampling station (Gulf of Gdańsk), whereas the lowest were in P5 (Bornholm Deep). SAR and ^{137}Cs$_{tot}$ varied in the sampling years. The smallest differences between SAR values (456–613 g·m^{-2}·y^{-1}) were found at P110. The largest differences occurred at station P1, where SAR ranged from 151 to 685 g·m^{-2}·y^{-1}. Similar observations were reported by Mattila *et al.* [9] in the Gulf of Finland and the Baltic Proper. According to their explanation, these variations result from the heterogeneity of soft sediment deposits. At Eastern Gotland spatial variability of SAR were 10.5–527 g·m^{-2}·y^{-1} with an average value of 129 ± 112 [3].

The highest total ^{137}Cs activities occurred at station P110 in the Gulf of Gdańsk (average 4722 Bq·m^{-2}). At other stations in the region of the Gdańsk Basin these activities were lower (average from 2034 Bq·m^{-2} at P116

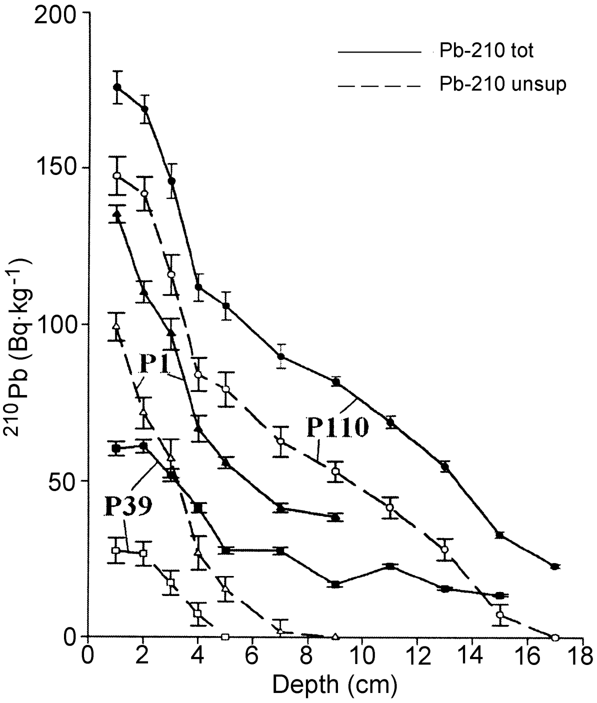

Fig. 1. Vertical distribution of ^{210}Pb$_{unsup}$ and ^{210}Pb$_{tot}$ in bottom sediments in the Gulf of Gdańsk (P110/2002), in the Gdańsk Deep (P1/2003) and in the Bornholm Basin (P39/2003).

Table 3. Sediment accumulation rate (SAR) and annual accumulation layer (AAL) estimated with CF:CS model, and total ^{137}Cs activity ($^{137}Cs_{tot}$)

Sampling year	SAR ($g \cdot m^{-2} \cdot y^{-1}$)	AAL ($mm \cdot y^{-1}$)	$^{137}Cs_{tot}$ ($Bq \cdot m^{-2}$)
		Gulf of Gdańsk (P110)	
1998	609 ± 53[a]	2.92 ± 0.17[b]	4775 ± 197[a]
2002	613 ± 73	2.48 ± 0.36	5050 ± 152
2003	512 ± 49	2.11 ± 0.24	4745 ± 152
2005	456 ± 39	1.80 ± 0.15	4204 ± 128
2006	480 ± 63	1.47 ± 0.11	4829 ± 150
2007	588 ± 48	2.50 ± 0.22	4731 ± 137
		Gulf of Gdańsk (P116)	
1999	497 ± 45	2.78 ± 0.17	2462 ± 105
2003	176 ± 13	0.98 ± 0.16	1826 ± 64
2004	402 ± 36	2.35 ± 0.44	2189 ± 76
2005	274 ± 29	1.78 ± 0.26	1878 ± 60
2006	238 ± 22	1.50 ± 0.47	1814 ± 74
		Gdańsk Deep (P1)	
1999	685 ± 66	3.90 ± 0.31	4144 ± 148
2002	223 ± 50	1.49 ± 0.38	2012 ± 47
2003	109 ± 11	0.70 ± 0.13	1404 ± 52
2005	195 ± 28	1.01 ± 0.15	1938 ± 66
2007	151 ± 42	0.93 ± 0.18	1629 ± 55
		Gdańsk Basin (P140)	
2002	250 ± 92	0.89 ± 0.04	2904 ± 90
2004	579 ± 116	2.13 ± 0.09	4404 ± 132
2005	368 ± 101	1.46 ± 0.06	3584 ± 103
2007	293 ± 76	1.19 ± 0.06	2872 ± 88
		Bornholm Deep (P5)	
2002	142 ± 72	0.74 ± 0.11	1527 ± 50
2005	68 ± 14	0.82 ± 0.10	1274 ± 36
2006	114 ± 29	0.52 ± 0.02	1428 ± 39
		Bornholm Basin (P39)	
2002	340 ± 68	1.56 ± 0.16	1772 ± 52
2003	137 ± 33	0.66 ± 0.08	1093 ± 36
2004	295 ± 111	1.37 ± 0.22	2047 ± 64
2006	221 ± 83	0.70 ± 0.10	1297 ± 56

[a] Value ± standard uncertainty.
[b] Mean ± standard error of the mean.

to 3441 $Bq \cdot m^{-2}$ at P140). Significantly lower were the ^{137}Cs activities in the Bornholm Basin: 1400 $Bq \cdot m^{-2}$ at P5 and 1552 $Bq \cdot m^{-2}$ at P39.

Correlation coefficients (r) between the SAR and total ^{137}Cs activity were high, particulary for the stations P116, P1, P140, and P5, being 0.97, 1.00, 0.98 and 1.00, respectively. For the calculation of r numbers of samples in particular locations were: 5 in P116, 5 in P1, 4 in P140, and 3 in P5. High correlations indicate that the estimation of SAR is correct. The same was earlier concluded by Mattila *et al.* [9].

The AAL values for the layer 0–10 cm ranged from 0.52 $mm \cdot y^{-1}$ in core taken in 2006 from the Bornholm Deep to 3.90 $mm \cdot y^{-1}$ in core taken in 1999 from the Gdańsk Deep (Table 3). The above values are in good agreement with the values reported earlier by Niemisto [10] for the Baltic Proper (0.5–2.0 $mm \cdot y^{-1}$) and Pempkowiak [11] for the Southern Baltic (0.15–2.26 $mm \cdot y^{-1}$).

Average values of annually accumulated layers ($mm \cdot y^{-1}$) in consecutive layers at each station are presented in Fig. 2 to Fig. 6. In all locations the AAL decrease with depth of the sediment. The highest values were found in the Gulf of Gdańsk (Fig. 2); they decreased from about 3.6 $mm \cdot y^{-1}$ in the upper layer to about 1.1 $mm \cdot y^{-1}$ in the deepest layer. The lowest AAL values were found in the Bornholm Deep (Fig. 6) – from 0.95 $mm \cdot y^{-1}$ in the upper layer to 0.35 $mm \cdot y^{-1}$ at the depth of 12 cm. In the Bornholm Basin (Fig. 5) the AAL values were about two times higher than those at P5 – 1.98 $mm \cdot y^{-1}$ and they decreased to 0.89 $mm \cdot y^{-1}$ in the depth of 12 cm. Decrease of AAL values in deep layers is associated with increasing sediment density. In the Gulf of Gdańsk at P110 and P116 the density of sediments varied between the upper and deepest layer by a factor of about 3 and 4, respectively. Similar factor was found for the Gdańsk Deep (P1), whereas in the

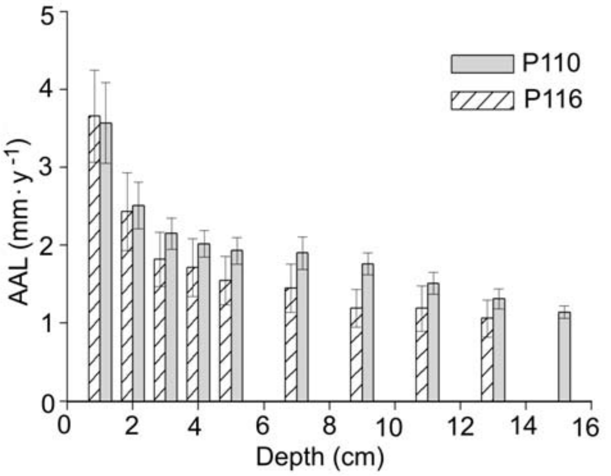

Fig. 2. Average annual accumulation layers at P110 and at P116 stations in the Gulf of Gdańsk.

open see the differences were smaller, being about 2. AAL values changed inversely with density. This means that the deeper layer of the sediments were more compressed than the upper ones.

In the Gulf of Gdańsk SAR and AAL are higher than those in the open sea. This can be explained by the close distance (about 15 km of the P110 station and about 30 km of the P116 station) from the mouth of the Vistula river which transports large amounts of organic and inorganic particles causing an increase of the sedimentation.

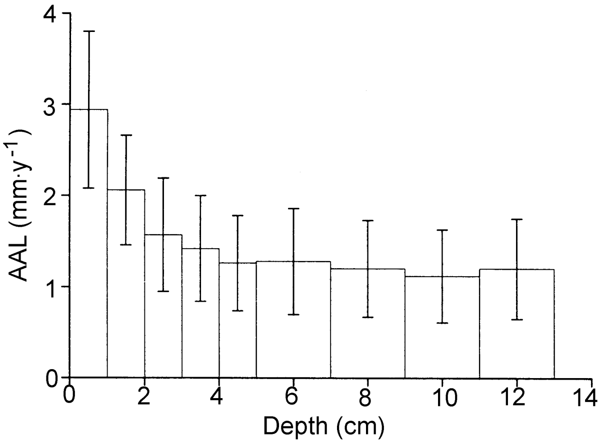

Fig. 3. Average annual accumulation layers at P1 station in the Gdańsk Deep.

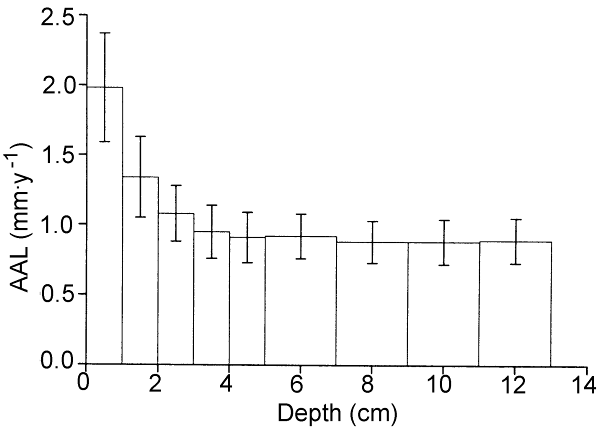

Fig. 5. Average annual accumulation layers at P39 station in the Bornholm Basin.

In Table 4 there are presented the average AAL and SAR estimated by means of two ^{210}Pb models and by the ^{239,240}Pu and ^{137}Cs models. The latter artificial isotopes are used as time markers for validation of the ^{210}Pb models. However, the validation was possible only for four locations, situated in the Basin of Gdańsk. In the Bornholm Basin the patterns of the ^{239,240}Pu and ^{137}Cs distribution profiles were broad and their peaks were not clear enough to be used as reliable time markers. In Table 4 there is also given the age of the 5 cm layers of sediments.

AAL estimation by means of the CF:CS model was performed for the 5 cm and 10 cm layers in all locations, while estimation by the CRS model for the 5 cm and 10 cm layers was made only for P110 and P116. At the other locations, such calculation was limited to 5 cm layer. The peak of ^{137}Cs was always observed in the 5 cm layer, whereas the peak of ^{239,240}Pu was usually observed at the depth of 7–9 cm.

Table 4 shows that the results obtained with the models used can differ by up to 60 percent. Typically, values of AAL obtained with the CRS, ^{239,240}Pu and ^{137}Cs models are by 20% to 30% lower than those obtained with the CF:CS model. SAR estimated by ^{239,240}Pu were about 40% lower or about 50% higher than those esti-

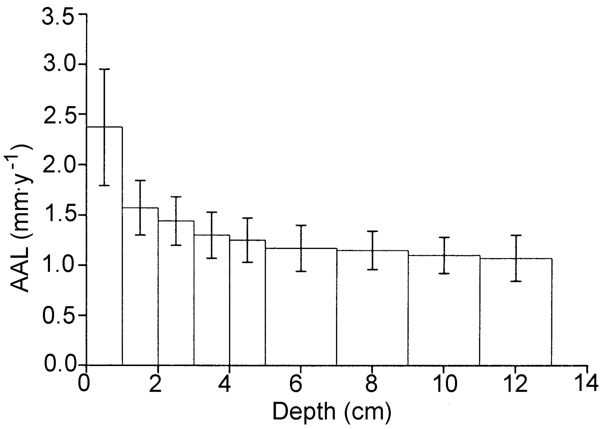

Fig. 4. Average annual accumulation layers at P140 station in the Gdańsk Basin.

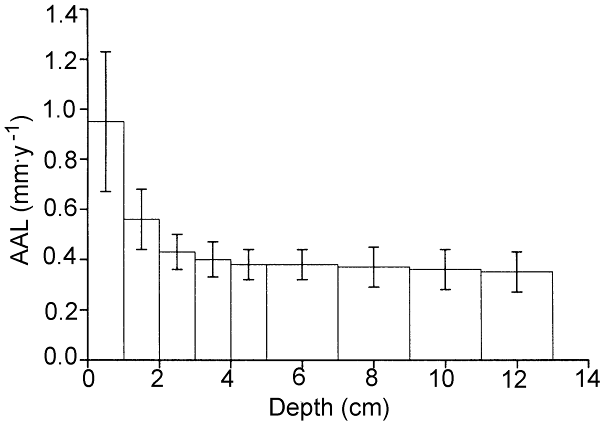

Fig. 6. Average annual accumulation layers at P5 station in the Bornholm Deep.

Table 4. Average AAL and SAR estimated by means of ^{210}Pb, ^{239,240}Pu and ^{137}Cs models, and age of 5 cm layers

Sampling station	Layer (cm)	Model								Age of 5 cm layer (years)
		CF:CS		CRS		^{239,240}Pu		^{137}Cs		
		AAL (mm·y^{-1})	SAR (g·m^{-2}·y^{-1})	AAL (mm·y^{-1})	SAR (g·m^{-2}·y^{-1})	AAL (mm·y^{-1})	SAR (g·m^{-2}·y^{-1})	AAL (mm·y^{-1})	SAR (g·m^{-2}·y^{-1})	
P110	0–5	2.43 ± 0.26[a)]		1.90 ± 0.28						
	0–10	2.21 ± 0.22	543 ± 28	1.33 ± 0.19	456 ± 48	1.70 ± 0.41	567 ± 46	1.70 ± 0.07	368 ± 31	27 ± 3
P116	0–5	2.24 ± 0.35		1.50 ± 0.28						
	0–10	1.88 ± 0.32	317 ± 58	1.10 ± 0.27	250 ± 52	1.23 ± 0.15	192 ± 37	1.68 ± 0.16	217 ± 39	37 ± 5
P1	0–5	1.82 ± 0.62		1.17 ± 0.61						
	0–10	1.75 ± 0.59	273 ± 105		203 ± 91	1.97 ± 0.28	405 ± 57	1.48 ± 0.33	189 ± 61	69 ± 19
P140	0–5	1.59 ± 0.31		1.12 ± 0.19						
	0–10	1.42 ± 0.26	378 ± 73		302 ± 53	1.77 ± 0.26	491 ± 15	2.28 ± 0.32	538 ± 78	71 ± 11
P5	0–5	0.57 ± 0.15		0.53 ± 0.10						
	0–10	0.52 ± 0.13	108 ± 21		103 ± 19	–	–	–	–	105 ± 37
P39	0–5	1.25 ± 0.24		0.72 ± 0.16						
	0–10	1.12 ± 0.21	248 ± 44		196 ± 68	–	–	–	–	61 ± 10

[a)] Mean ± standard error of the mean.

mated by the CF:CS model. Usually, the ^{137}Cs models gave lower values of SAR in comparison to the CF:CS model. This indicates that most reliable would be the values of the mean from different models.

Dating of the bottom sediments were estimated applying the CRS model. The rate of growth of the sediments strongly differs in the locations studied (Table 4). The fasters growth occurred in the Gulf of Gdańsk, where the growth of 5 cm layer takes 27–37 years. Evidently, it is associated with the close distance to the mouth of the Vistula river, which transports organic and inorganic material. The 5 cm depth layers in P1 and P140 grow for 69 and 71 years. In the Bornholm Basin, the process of growing takes 61 years in the sampling station P39, and about 105 years in P5.

Conclusions

Activity concentrations of ^{210}Pb differed in the studied locations of sampling stations, being the highest in the Gulf of Gdańsk and the lowest in the Bornholm Basin. Sedimentation rates (SAR and AAL) calculated from the vertical distribution of unsupported ^{210}Pb differ in subregions. In the Gulf of Gdańsk they are higher than those in the open sea what can result from the transport of organic and inorganic particles with the Vistula river water.

AAL and SAR estimated by the means of the CF:CS model were on average about 20% higher than those from the CRS model. This small difference indicates that both the models are comparable. Validation of the models based on unsupported ^{210}Pb using of ^{239,240}Pu and ^{137}Cs time markers confirm reliability of the estimated SAR and AAL values. It is suggested that the mean value from all the applied models should be taken for the estimation of dating and of sedimentation rate.

The results of this study indicate that the process of the formation of bottom sediments in the open sea is much slower than that in the gulf areas. In the Gulf of Gdańsk the 5 cm layers of the sediments were formed during 27 to 37 years, while in the open sea it took from 61 to 105 years.

References

1. Alvarez-Iglesias P, Quintana B, Rubio B, Perez-Arlucea M (2007) Sedimentation rates and trace metal input history in intertidal sediments from San Simon Bay (Ria de Vigo, NW Spain) derived from ^{210}Pb and ^{137}Cs chronology. J Environ Radioact 98:229–250
2. Appleby PG (1997) Dating of sediments by ^{210}Pb: problems and solutions. In: Proc of a Seminar Dating of Sediments and Determination of Sedimentation Rate, Helsinki, Finland. STUK A145:7–24
3. Hille S, Leipe T, Seifert T (2006) Spatial variability of recent sedimentation rates in the Eastern Gotland Basin (Baltic Sea). Oceanologia 48:297–317
4. Ilus E, Mattila J, Klemola S, Ikaheimonen K (1997) Evaluation of sedimentation rate at two sampling stations in the Gulf of Finland based on Pb-210, Cs-137 and Pu-239,240 profiles in sediment. In: Proc of a Seminar Dating of Sediments and Determination of Sedimentation Rate, Helsinki, Finland. STUK A145:136–147

5. Ilus E, Niemisto L, Bojanowski R (1995) Radionuclides in sediment and suspended particulate matter. In: HELCOM 1995. Radioactivity in the Baltic Sea 1992–1998. Balt Sea Environ Proc 61:69–87
6. Jaworowski Z (1969) Radioactive lead in the environment and in the human body. At Energ Rev 7:3–45
7. Jaworowski Z, Bilkiewicz J, Kownacka W, Włodek S (1972) Artificial sources of natural radionuclides in environment. In: Natural radiation environment II 2:809–818
8. Krishnaswami S, Lal D (1978) Radionuclide limnochronology. In: Lerman A (ed) Lakes: chemistry, geology, physics. Springer, New Jork, pp 157–177
9. Mattila J, Kankaanpaa H, Ilus E (2006) Estimation of recent sediment accumulation rates in the Baltic Sea using artificial radionuclides ^{137}Cs and ^{239,240}Pu as time markers. Boreal Env Res 11:95–107
10. Niemisto L, Voipio A (1981) Notes on the sediment studies in the Finnish pollution research in the Baltic Sea. Rapp P-v Reun Cons Inst Explor Mer 181:87–92
11. Pempkowiak J, Widrowski H (1988) Pollution of upper layer of bottom sediments of Southern Baltic Sea with heavy metals. Arch of Environ Protect 1/2:55–66
12. Robbins JA (1978) Geochemical and geophysical applications of radioactive lead. In: Nriagu JO (ed) Biogeochemistry of lead in the environment. Elsevier, Amsterdam, pp 285–393
13. Rushing D, Garcia WJ, Clark DA (1964) The analysis of effluents and environmental samples from uranium mills and to biological samples for radium, polonium and uranium. In: Radiological health and safety in mining and milling of nuclear materials. Vol. II. IAEA, Vienna, pp 187–230
14. Taipale TK, Tuomainen K (1985) Radiochemical determination of plutonium and americium from sea-water, sediment and biota samples., Helsinki, Finland. STUK-B-Valo 26, pp 1–29