The Conditions of Sedimentation of Gdańsk Bay Sediments (Baltic Sea, Poland) in the Light of Lithological Features and Carbon Content

Dorota Burska1, Ewa Szymczak2

1 University of Gdańsk, Institute of Oceanography, Division of Marine Chemistry and Environmental Protection, av. Marszałka Piłsudskiego 46, 81-378 Gdynia, Poland
2 University of Gdańsk, Institute of Oceanography, Division of Marine Geology, av. Marszałka Piłsudskiego 46, 81-378 Gdynia, Poland

dorota.burska@ug.edu.pl

Abstract. The research has been carried out for many years, the aim of which is to thoroughly identify sedimentation conditions in the area of the Gulf of Gdańsk. This process is conditioned by many factors, among which the quantity, type and quality of sedimentary material subject to sedimentation, the dynamics of the reservoir, its depth as well as the morphology of the bottom should be mentioned. Research sediments were collected in April 2014, during a research cruise on ORP Heweliusz. Sediment cores with a length of approx. 25 cm were taken in parts of the basin characterized by a different bathymetry, dynamics and a different distance from the main sources of supply of the terrigenous material. The GD core was taken from the Gdańsk Deep, the PB from the Puck Bay and the other two cores within the Gdańsk Deep slope: UP near Hel and VR at the level of the Vistula estuary. The sediments from collected cores were subjected to wet sieve analysis and pipette analysis. The obtained results allowed to determine the type of lithological sediment and the calculation of graining indices, on the basis of which the interpretation of the sedimentation conditions was carried out. In the sediments, the carbon content was determined using the Perkin Elmer 2400 CHNS / O elemental analyzer. It was found that clayey silts and silty clays dominated in the PB, UP, GD core throughout the profile. Only in the VR core, there was a clayey sand, which proved that the sedimentation environment is more dynamic, conditioning the deposition and the periodic redeposition of sediments. It is the shallowest located station near the source of supply with terrigenous sediments (estuary of the Vistula). In the surface layer of the cores, the total organic carbon (TOC) content exceeds 4.7% and reaches up to 8.3%. The lowest TOC content, ranging from 0.8 to 2%, was found in the VR core. The total inorganic carbon (TIC) ranged from 0.18% (VR) to 1.77% (UP). In all profiles, both carbon forms decreased with depth. The greatest dynamics of changes in the surface layer of sediments (10 cm) characterized the UP core (4.1–6.6%), while the smallest changes characterized the PB station (4.7–4.9%). The parameter relations indicate a close relationship between the carbon content and the dynamics of the sedimentation environment and the proximity of the power sources.

1. Introduction
The Gulf of Gdańsk is an interesting basin in terms of sedimentation processes and thus the conditions for sediment formation. The formation of sediments is influenced not only by wind-driven waves,
currents and lack of tides, but also by the inflow of water from the Vistula, upwellings along the Hel Peninsula, as well as shoreline configuration, sea bottom morphology and changing water depth in the Gdańsk Basin. Sediments, deposited on the bottom, have been supplied from various sources, including river inflow, shore abrasion and bottom erosion, as well as from the port deepening/dredging activities (anthropogenic sources).

The aim of the present study was to characterize sedimentation conditions in selected locations of the Gulf of Gdańsk, based on lithological and geochemical features of the collected sediment cores.

2. Study area
The Gulf of Gdańsk is located in the southern part of the Baltic Sea (figure 1). Its area covers nearly 5852 km². This water reservoir is relatively shallow; the average depth is only 50 meters, in the deepest place (Gdańsk Deep) it reaches 118 m.

![Figure 1. Gulf of Gdańsk and the location of study sites.](image)

The bottom morphology of the Gulf of Gdańsk is very diversified. It was shaped by the activity of the last glacier and its meltwaters [1]. Nowadays, the water dynamics plays the most important role in the process of bottom formation.

There are two morphometrically different areas within the Gulf of Gdańsk, i.e. shallow water and deep water. The first one is bounded by the coastline and extends to the 55 m isobath, while the second covers a larger area – it stretches from a depth of 55 meters to the deepest part of the Gdańsk Deep.

The bottom relief of the Gulf of Gdańsk is diversified, it includes both relic forms of land origin and the forms of marine, polygenetic or anthropogenic origin. The most extensive areas of the bottom, up to a depth of about 70 m, are covered by erosion-aggradation plains and, in the deepest parts of the basin, also by aggradation plains [2]. The coastal slope extends up to a depth of about 15 m from the coastline.

An important source of sedimentary material to the Gulf of Gdańsk is the river inflow. The largest contribution in the supply of terrigenous material to the Gulf of Gdańsk is provided by the Vistula, which introduces 1027 m³ s⁻¹ of water, and from 0.4 to 1.4 tonnes·y⁻¹ of bedload and about 1.2 million tonnes of suspended load [3]. A significant part of the terrigenous material, mainly sands, is deposited within
the Vistula river cone. Sediments transported in suspension settle down to the bottom in the zone of a hydrological front. They are distributed with waters of the Vistula further into the Gulf of Gdańsk [3, 4]. Both shore abrasion and bottom erosion play an important role in the balance of sedimentary material in the Gulf of Gdańsk. Also, the contribution of sedimentary material of anthropogenic origin, from the activities related to deepening of ports and approach fairways, is evident.

In the distribution of sediments in the Gulf of Gdańsk, the zonation associated with increasing water depth and decreasing energy of the environment is clearly visible. Consequently, the average diameter of sediment particles decreases with water depth. The coastal zone is dominated by coarse and fine-grained sands, which are often re-deposited. Along with the increase in water depth, the sands are replaced by clayey silts and silty clays. The rate of sedimentation varies depending on the distance from the shore and from the sources of sediment material supply. In the study area, this parameter ranges from 0.13 mm y$^{-1}$ to 2.92 mm y$^{-1}$ [5, 6, 7].

The main factor that is responsible for enriching marine sediments with organic carbon is the production of organic matter in surface waters [8]. In addition to autochthonous carbon, an important source of organic carbon is terrigenous inflow, with the riverine transport dominating in the case of the Gulf of Gdańsk. In sediments of the Baltic Sea, the share of terrigenous organic carbon is 10-30% of the total organic carbon (TOC) contained in sediments [9], and is significantly higher compared to the sediments of open seas and oceans. In the case of inorganic carbon, the mineral debris of calcite and dolomite, as well as skeletal parts and shells of benthic organisms are considered as the main source. Due to easier dissolution of inorganic carbon of biological origin than that of terrigenous origin, the share of biological part in the total pool of inorganic carbon is smaller. It has been estimated that organic carbon in the surface sediments (up to 2 cm) of the Gulf of Gdańsk reaches up to 8.8% [10, 11]. There is a correlation between the distribution of individual components in bottom sediments and their grain size [12]. The lowest values of TOC content in sediments of the Gulf of Gdańsk, similarly to the entire Baltic Sea area, are observed in sands, while the highest – in silts (figure 2). Generally, the increase in TOC content of sediments, resulting from the increase in the contribution of fine fractions (particles smaller than 0.063 mm), is related to increasing water depth of the basin. However, there are many regional and local exceptions resulting both from the distribution of natural and artificial sources of particular components as well as from the diversity of environmental conditions (circulation systems of sea currents, bottom topography or different values of dissolved oxygen in benthic waters) [11].

![Figure 2. Variability in the TOC content as a function of the sediment type [11].](image)
3. Materials and methods
The study was carried out in the period from 10 to 17 April 2014, during the research cruise onboard ORP Heweliusz. In selected parts of the Gulf of Gdańsk (figure 1), characterized by different bathymetry, dynamics and distance from the main sources of terrigenous material, four cores were collected (table 1) using a Niemistö-type corer. The obtained sediment cores were from 10 cm (VR) to 25 cm long (GD, PB, UP).

Table 1. Description of the sampling sites.

| Station                     | Depth [m] | Bottom forms of marine origin | Sedimentation conditions                            |
|-----------------------------|-----------|-------------------------------|-----------------------------------------------------|
| Gdańsk Depth – GD           | 102       | aggradation plain             | deposition area of muds                              |
| Hel Peninsula Spit – UP      | 78        | spit slope                    | area of deposition, periodic redeposition of sandy-muddy sediments |
| Puck Bay – PB               | 49,5      | erosion-aggradation plain     | deposition area of muds                              |
| Vistula River Estuary VR    | 59,5      | erosion-aggradation plain/slope| deposition area of fine grained sands                |

The collected cores were cut into 1-cm layers up to a depth of 5 cm; then into 2-cm and 3-cm layers (up to a depth of 10 cm); deeper parts were cut into 5-cm layers. Sediment samples were subjected to the granulometric analysis based on pipette method [13]. The obtained results were used for determination of the percentage share of individual fractions in sediment samples and for calculation of grain size indices based on logarithmic Folk and Ward method [14].

The content of TOC, TIC and TON in sediments was determined using a CHNS/O elemental analyzer, Perkin Elemer model 2400 [15].

4. Results
The first variable that differentiated sediment samples in the study area, both spatially and vertically, was the lithology. The most homogeneous sediments, in terms of lithology [16], were found in the GD core collected from the central part of the Gdańsk Deep. They belong to the group of clayey silts (figure 3). The average diameter of sediment particles varied in a small range from 5.7 to 6.4 phi. The highest variation of this parameter was observed in the surface layer (5 cm). Similarly small variation of sediments was found in the core originating from the sedimentation basin of the Puck Bay (PB). The sediments were classified as clayey silts; at a depth of 7-15 cm there was a layer of silty clay and sand-silt-clay types of sediments (figure 3), for which the average diameter values were 5.8 and 7.1 phi, respectively. In other parts of the core, the parameter changed from 5.9 to 6.1 phi.

Sediments from the UP core, collected on the slope of the Hel Peninsula, were much more diversified. Clayey silts predominated, and they were interlayered by silty clay and sand-silt-clay types (figure 3). As a consequence, the average diameter of particles varied as follows: 6.0-6.5 phi, 6.3-6.7 phi and 5.5-6.0 phi for respective types of sediments. For the UP site, there was observed the greatest variation of this parameter as compared to the other cores.

The core taken from the Vistula river estuary (VR) contained clayey sands, which average diameter was 4.7-5.1 phi. Sediments in the surface layer of the core (0-1 cm) were found to be silty sands (figure 3).
When analysing the other grain size related parameters, we observed that the sediments of collected cores are poorly sorted (GD, UP, PB) and very poorly sorted (VE), which in each case was caused by different factors. Poor sorting of sediments in the VE core results from the vicinity of the Vistula – a source of sedimentary material. The grain size parameters of UP and BP cores indicate variable conditions favouring deposition or re-deposition of sediments. The process of sedimentation in the GD area is less influenced by hydrodynamic factors and related to settling out of non-homogeneous suspension. Moreover, at all stations, periodically, the formation of sediments settling down from the suspension was accompanied by differentiation of the material under conditions of high saturation of the environment with sedimentary material. This was particularly clear for VE and PB stations.

An important part of marine sediments is organic matter. Its quantity and quality determines the processes of early diagenesis. In this context, determination of TOC in sediments of the study area allowed to characterize two sedimentary basins (sedimentary basin of the Puck Bay and the Gulf of Gdańsk) and the areas with increased dynamics related to strong upwellings and downwellings – Hel Peninsula spit and the estuary of the Vistula river.

In the GD core, the average content of organic carbon was 5.82% (3.69–8.27%). There was a clear decrease of TOC with sediment depth. In the 0-7 cm layer we observed significant variations, while in deeper layers (below 10 cm) the profile of TOC content was smoother (figure 4). The C/N ratio ranged from 8.6 to 9.9 and was characterized by a slight, irregular increase down the core.

In sediments of the PB core, the average TOC content was 4.26% (2.72–5.12%). We observed a decrease in the TOC with sediment depth. The layer of high TOC values, i.e. values >4.5%, was up to 7 cm thick (figure 4). The organic matter deposited in sediments was characterized by a molar C/N ratio in the range of 8.2–10.6, which increased gradually down the core. This may indicate a high rate of aerobic mineralization in relatively shallow Puck Bay, in sediments deposited at the beginning of the 20th century, in the period preceding strong anthropogenic pressure in this area. The sedimentation rate of sediments in the location of the collected core was 1.6 mm y⁻¹ [6].

![Figure 3. Mean diameter [phi] and sediment types.](image-url)
In the UP core, the average TOC content was 5.01% (3.5-6.62%) and the observed differences between successive layers were the highest (figure 4). The minimum TOC value was recorded at 15 cm bsf and the downward decrease in TOC content did not exceed 2%. The C/N ratio ranged from 7.1 to 8.2 and did not show any trends. Extreme values occurred alternately, and lowest values were found in the 3-10 cm layer. The lowest TOC content was reported for the VE station, with the average value of 0.9% (0.53-1.16%). This parameter was characterized by irregular variability in the profile (figure 4). The C/N ratio varied between 6.7 and 9.1, showing an irregular increase with depth. Data analysis allowed to conclude that the highest coefficients of TOC variation were found for GD (27%) and VE (23%) cores. Slightly lower values were calculated for PB and UP cores (18.8%).

![Figure 4. Total organic carbon (TOC) in sediment.](image)

Although the share of inorganic carbon in sediments of the Gulf of Gdansk is not high, it is still possible to describe the study area based on this parameter, taking into account different sources of sedimentary material. The content of inorganic carbon (TIC) was lowest at GG and VE stations (figure 5). The average TIC value was 0.54% (0.31-0.69%) and 0.45% (0.18-0.65%), respectively. However, the coefficient of variation was much higher in the vicinity of the Vistula estuary (37%). The highest average TIC content of 1.25% (0.86-1.77%) was found for the UP core. In sediments of this site, the surface layer was characterized by lower share of TIC, while the maximum values were found at a depth of 4-5 cm bsf. In turn, the PB core was characterized by high variation (25%) of TIC content, with an average share of 0.93% (0.52-1.26%). Two maxima were found for layers of 2-3 cm bsf and 7-10 cm bsf (figure 5). In all cores, the TIC content decreased with depth.
In terms of spatial distribution, organic matter in the study area was characterized by an increasing C/N ratio, from 4.80 in the estuary to a maximum value of 8.56 at the deepest GD station, indicating a typical increase in the degree of degradation of sedimentary material (figure 6). In the case of two stations, the presence of terrigenous refractive organic matter was also observed. The highest value was found for the PB station (0.6%), about two times lower for the VE station, clearly lower (0.14%) in the case of UP and below 0.05% for GD. The latter locations are outside the direct impact of the terrigenous material inflow. Similar relationships, i.e. the increased share of refractive material in the organic matter content was observed by Graca and Burska [17].

![Figure 5. Total inorganic carbon (TIC) in sediment.](image)
5. Conclusions
The content of organic carbon forms (TOC) in sediments was dependent on the type of sediment. The lowest content of TOC (average 5-cm layer = 0.99%) was found in clayey sands (4.7-5.1 phi) from the southern slope of the Gdańsk Basin, and the highest – in clayey silts (5.7-6.4 phi) from the Gdańsk Deep (average 5-cm layer = 7.06%).

Based on the obtained results, we distinguished two areas, VE and PB, where constant undisturbed inflow of sedimentary material was found in the surface 5-6 cm layer, which was indicated by aligned TOC values and grain size indices.

Irregular supply of organic matter at UP and GG stations determines the processes initiated in the coastal zone, which are reflected in the deeper zone. The UP station is located in the area of intensive upwelling [18, 19, 20, 21] where the presence of elevated concentrations of nutrients leads to intensive primary production, being the source of organic matter supplied to the sediments. The similarity of changes in the organic carbon content in UP and GD sediments suggests that the area of Hel upwelling is also an important source of organic matter to sediments of the western part of the Gdańsk Basin.

In the case of PB and UP, the sources of inorganic carbon may indicate the alongshore transport of bedload, both from the sea and from the gulf, and the possibility of transport from areas with increased presence of benthic organisms.

References
[1] E. Mojski, Structural conditions of Pleistocene ice-sheet development, [in:] Geological atlas of the Southern Baltic, 1995.
[2] J. Mojski (ed.), Geological atlas of the Southern Baltic, Polish Geological Institute, 1995.
[3] E. Szymczak and D. Galińska, “Sedimentation of suspensions in the Vistula River mouth”, *Oceanological and Hydobiological Studies*, 42 (2), pp. 195–201, 2013. DOI: 10.2478/s13545-013-0075-x.

![Figure 6. Relationship between organic carbon and organic nitrogen (C/N mol) in sediment.](image-url)
[4] E. Szymczak and D. Burska, Distribution of Suspended Sediment in the Gulf of Gdansk off the Vistula River mouth (Baltic Sea, Poland), IOP Conf. Ser.: Earth Environ. Sci. 221, 2019, doi:10.1088/1755-1315/221/1/012053.

[5] J. Walkusz, S. Roman, and J. Pempkowiak, Contamination of the southern Baltic Surface sediments with heavy metals, Biul. MIR 1 (125), pp. 33–37, 1992.

[6] A. Szymkiewicz, and T. Zalewska, Sediment deposition and accumulation rates determined by sediment trap and 210Pb isotope methods in the Outer Puck Bay (Baltic Sea), Oceanologia, 56 (1), pp. 85–106, 2013, doi:10.5697/oc.56-1.085.

[7] M. Szymczak-Żyła, M. Krajewska, A. Winogradow, A. Zaborska, G. D. Breedveld and G. Kowalewska, Tracking trends in eutrophication based on pigments in recent coastal sediments, Oceanologia, 59(1), pp. 1–17, 2017, DOI 10.1016/j.oceano.2016.08.003.

[8] T. Pedersen and S. Calvert, Anoxia vs. productivity: What controls the formation of organic carbon-rich sediments? Am. Assoc. Petrol. Geol. Bull., 74; pp. 454–466, 1990.

[9] A. Miltnner, K-C. Emeis, Terrestrial organic matter in surface sediments of the Baltic Sea, Northwest Europe, as determined by CuO oxidation, Geochim. Cosmochim. Acta, 65 (8), pp.1285–1299, 2001.

[10] D. Burska and B. Graca, Factors affecting organic carbon and nutrient contents in sediments, [in:] Sz. Uścinowicz (ed). Geochemistry of Baltic Sea Surface Sediments, PGI-IRI, pp. 172-174, 2011.

[11] D. Burska, Organic carbon, [in:] Sz. Uścinowicz (ed). Geochemistry of Baltic Sea Surface Sediments, PGI-IRI, pp. 175-186, 2011.

[12] T. Szczepańska, Sz. Uścinowicz, geochemical atlas of Southern Baltic Sea, 1:500000, PGI, 1994. (in Polish).

[13] L. Łeczyński and E. Szymczak, Physical properties of sediments, [in:] J. Bolałek (ed.), Physical, biological and chemical studies of marine bottom sediments, Wyd. UG, pp. 69-118, 2010.

[14] S.J Blott and K. Pye, Particle size scales and classification of sediment types based on particle size distributions: Review and recommended procedures, Sedimentology 59, pp.2071–2096, 2012. (in Polish).

[15] D. Burska, Elemental analysis (CHNS), J. Bolałek (ed.), Physical, biological and chemical studies of marine bottom sediments, Wyd. UG, pp. 291-298, 2010. (in Polish).

[16] F.P. Shepard, Nomenclature based on sand-silt-clay ratios, J. Sediment Petrol., v.24:151, 1954.

[17] B. Graca and D. Burska, Assessment of the impact of dredging pits on sediment and surface water chemistry, [in:] L., Kruk-Dowgiallo, R., Opiola (eds.), Development of a program of restoration of the post-dredgings pits area in the Puck Bay, Instytut Morski Gdańsk, pp. 131–144, 2009. (in Polish).

[18] K. Bradtke, D. Burska, M. Matciak and M. Szymelfenig, Suspended particulate matter in the Hel upwelling region (the Baltic SEA). Oceanological and Hydrobiol. Stud., Vol. XXXIV, Suppl. 2, pp. 53–73, 2005.

[19] D. Burska and M. Szymelfenig, The upwelling of nutrients in the coastal area of the Hel Peninsula (the Baltic Sea). Oceanological and Hydrobiol. Stud., Vol. XXXIV, Suppl. 2, pp. 75–96,2005.

[20] M. Matciak, D. Burska, K. Bradtke, M. Kaluzny, L. Szymanek and M. Szymelfenig, Description of hydrological conditions in the Hel upwelling region (the Baltic Sea). Oceanological and Hydrobiol. Stud., Vol. XXXIV, Suppl. 2, pp. 11–33, 2005.

[21] M., Kowalewski The influence of Hel upwelling (Baltic Sea) on nutrient concentrations and primary production – the results of ecohydrodynamic model, Oceanologia, 47(4), pp. 567-590. 2005.