# DIVERSE ACOUSTIC MANIFESTATIONS OF SHALLOW GAS IN THE GDAŃSK BAY (SOUTHERN BALTIC SEA)

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**Abstract:** *Continental shelves and sub-bottom layers of shallow seas are considered as the areas of main importance when it comes to global emission of methane from the marine environment. Due to relatively low solubility in water, methane can be often accumulated in shallow sediments as a gas. Presence of methane in shallow sediments is dependent on factors such as oxic/anoxic conditions, organic matter inflow and decomposition processes, which all are affected by recent intensification of climate changes. Non-invasive acoustic methods enable us to reveal various features of gas presence and distribution through distinct acoustic gas manifestations. This study is focused on assessing the extent of sediments saturated by gas (methane) in the Gdańsk Bay as well as identifying and analyzing the spatial variability of acoustic manifestations. Our approach was based on the combination of synthesis and digitization of various historical data obtained from literature, and analysis of new data from multi-device acoustic measurements (single and split-beam echosounders, multi-beam echosounder and side-scan sonar). Acoustic backscattering data from sub-bottom layers, sediment surface and water column were analyzed. In addition, verification of methane presence based on geochemical analyses of upper layers of sediments taken by core samplers were performed. The obtained results revealed that the total area of the Gdańsk Bay sea bottom sediments saturated by gaseous methane constitutes of about 380 km$^2$. Within the area of interest, at least three subareas of distinct gas presence features can be specified based only on acoustic data. Moreover, the results indicate strong spatial variation of gassy sediments as well as gas emission from seafloor characterized by distinct acoustic recordings.*

***Keywords:*** *Shallow gas in sediments; acoustic imaging; single- and multi-beam echosounders; marine GIS*

## 1. INTRODUCTION

Sediments of shallow seas and continental shelves are the source of considerable amount of microbial methane (80% of the global oceanic production), mostly from the decomposition of organic matter [1]. Acoustic imagery evidence for methane presence in gaseous form in sediments of shallow seas is widely described in the literature [1]. Significant concentrations of methane in the organic-rich sediments of the Gdańsk Bay have been reported [2,3] since 1990s, and later verified by numerous acoustic and geochemical studies [3,4,5,6,7,8]. The main aim of this study is examination of the variability of acoustic manifestations of shallow gas (up to 10 m below sediment surface) in sediments of the area. For that reason, re-analysis of archival data together with recently collected acoustic data has been performed.

## 2. STUDY AREA

The investigations were carried out in the Gdańsk Bay (Fig.1) (Southern Baltic Sea), where the estuary of one of the biggest rivers in the region – the Vistula – is situated . High nutrient and organic matter loads from the river lead to the high primary production (225g $C \cdot m^{-2}y^{-1}$) [9]. Strong seasonal water stratification causes oxic depletion near the bottom, creating favorable conditions for methanogenesis through organic matter decomposition [9,10]. The bottom in the area of shallower waters of the Gdańsk Bay is covered by fine and medium-grain sands. Sediments graining gradually changes with the bottom depth, turning into better sorted and lower mean grain sizes clays and silts (Fig.1) [11,12]. The sedimentation rate varies from 1.0 to 3.9 $mm \cdot y^{-1}$, with higher values near the coast [13]. Significant concentrations of methane (6-8 $mmol \cdot dm^{-3}$) are widely present in sediments of the Gdansk Bay, at depths of 25-100 cm below sea floor (bsf) (Fig.1) [2,3].

## 3. MATERIAL AND METHODS

The historical data were collected based on various literature sources, such as local periodicals and reports with limited access, and unpublished archival data covering about 1000 $km^2$ of the area, which were subjected to digital processing, analyzed and mapped in the GIS environment (Fig.1). New data (2018-2019) have been collected using multifrequency hydroacoustic equipments in three subareas M1, M2, M3 of the Gdańsk Bay (Fig.1). The equipment consisted of: single-beam echosounder (12kHz) ODOM Echotrack MKIII, split-beam echosounders (38, 120, 333 kHz) Simrad EK80, multibeam echosounder (400 kHz) Reson SeaBat 7125 SV2 and side-scan sonar (300 & 900 kHz) Edge Tech Multi-Purpose Survey System 4200 with Ultra-Short Baseline (USBL) Easytrak Nexus 2690 Applied Acoustics. Calibration process of the echosounders and the measurements scheme were done accordingly to the general recommendations based on the hydrographic standards [14]. The analyzed informations included sub-bottom, sediment surface and water column backscattering data processed in: SonarWizz (side-scan sonar), Qinsy and Qimera software (multibeam) and furthermore in the MATLAB environment (single and split-beam). The analyses were conducted taking into account recognition of backscattering anomalies, in data from various acoustic devices, which pointed to gas presence in the study area.

## 4. RESULTS AND DISCUSSION

**Gassy sediments in the Gdańsk Bay – summary of archival data**

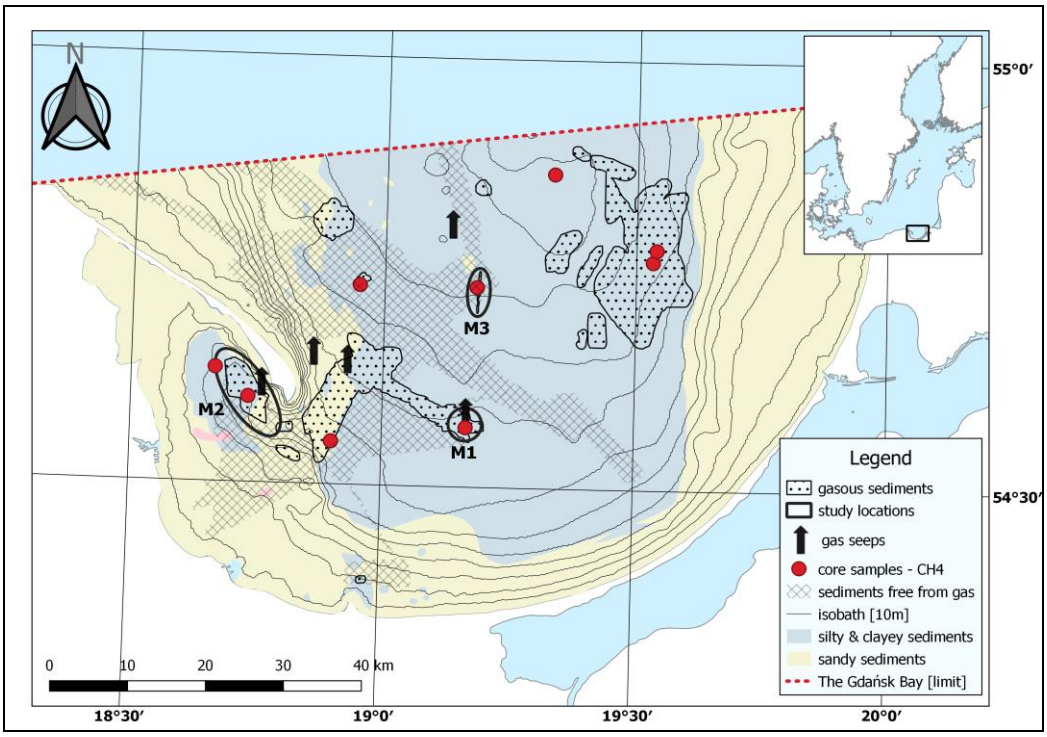


**Fig. 1** Map of spatial distribution of gas saturated sediments and gas seeps in the Gdańsk Bay. Selected geochemical core sampling points are presented with red points. M1, M2 and M3 indicate study areas of our acoustic and geochemical measurements.

The summary of the key acoustic results concerning shallow gas distribution in the Gdańsk Bay is presented in Fig.1. The coverage by methane-saturated sediments in the Gdańsk Bay has been estimated acoustically and amounts to about 440 km$^2$. These sediments are marked on the map (Fig.1) as "gaseous sediments" [2,7,12,15,17]. The presence of acoustic anomalies in this area, associated with shallow gas presence, was confirmed by the geochemical studies [2,3,12].The dominant amount of results indicating gaseous methane presence in sediments, is associated with acoustic backscattering anomalies from sub-bottom layers of sediments. Most commonly recognized anomalies are: blanking in acoustic images echoes from sediments located beneath the upper boundary of gassy sediments (acoustic blanking), grainy blurry images due to many small reflections on gas intrusions (acoustic turbidity) and the enhancement of the sound reflection from the gas intrusions (layer enhancement) [2,3,7,12,15,16].

Within the Gdańsk Bay, numerous small surface pockmark structures connected with gas occurrence in sediments have been recognized [2,3,7,8,12]. Such structures create strong acoustic backscattering anomalies coupled with up to few meters of depression of sediment surface (Fig.2), which results from pockmark formation processes [3,7,8,17]. Such structures are most likely connected with gas migration from deeper layers of sediments, probably through formed gas chimneys [17,18]. Pockmarks in the area of the Gdańsk Bay vary in size and are up to 1 km$^2$. Their total estimated area is about 8.1 km$^2$. Pockmarks are usually found in clusters, typically get deeper in the bottom, up to 1-3 m, and have horizontal extension of

around 200 m [2,3,7,12,16]. Within the Gdańsk Bay, there are also structures classified as buried by semi-liquid sediments old pockmarks [3,7,16]. Few gas seeps from sediments were acousticaly observed in various regions of the Gdańsk Bay (Fig.1) [3,7,19].

## Spatial variation of shallow gas manifestations in the Gdańsk Bay

The subarea M1 (Fig. 1) is part of a large gas-saturated sediment structure located in the western Gdańsk Bay [16]. It is characterized by medium-to-intense acoustic anomalies associated with the gas presence. The most profound sub-surface anomalies are: acoustic turbidity, layer enhancement and acoustic blanking (Fig.2a). Sub-bottom anomalies are highly irregular with the strongest expression in the central part (the pockmark with gas seeps). After surveying the M1 zone (2.4 x 2.3 km), the area with significant sub-bottom acoustic anomalies (Fig.1) was estimated to be 0.93 km$^2$. Bathymetric data combined with sub-bottom and side-scan sonar data indicated presence of the pockmark with a relatively significant extent 0.18 km$^2$. This pockmark is characterized by irregular shape, deviated from typical for pockmarks round geometry and surrounded by numerous smaller pockmarks [17,18]. The migration of small gas bubbles (gas seeps) from the pockmark was observed by single-beam echosounder. Such events have been previously reported in literature, which means continuous pockmark activity in this area [3,7,8,16].

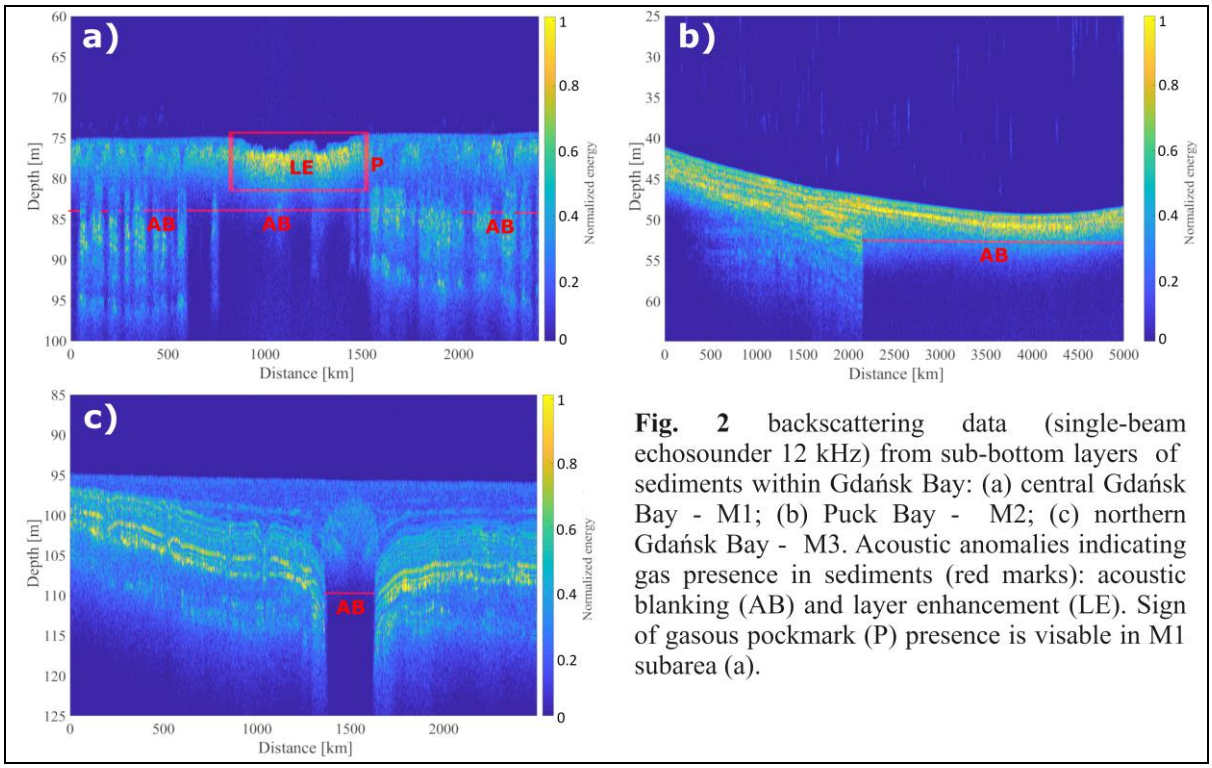


**Fig. 2** backscattering data (single-beam echosounder 12 kHz) from sub-bottom layers of sediments within Gdańsk Bay: (a) central Gdańsk Bay - M1; (b) Puck Bay - M2; (c) northern Gdańsk Bay - M3. Acoustic anomalies indicating gas presence in sediments (red marks): acoustic blanking (AB) and layer enhancement (LE). Sign of gasous pockmark (P) presence is visable in M1 subarea (a).

The subarea M2 is located in the inner, shallower part of the Gdańsk Bay named as the Puck Bay, sheltered from the open sea by the Hel Peninsula (Fig.1). Gas-saturated sediments have been estimated to cover 20.44 km$^2$ of the surface, which is considerably more than the previously reported area [3]. It suggests increasing range of methanogenesis in sediments, Gassy sediments are characterized by extensive and homogenous area (2-4 km wide; and 9.75 km in length) of acoustic blanking and layer enhancement (Fig.2b). The transition zone from gas saturated sediments to sediments without gas is very rapid in this area and visible as sudden change of the depths of acoustic penetration (Fig.2b). It is difficult to recognize any surface geomorphological structures connected to gas presence in sediments of this subarea [15]. We observed unevenly distributed, appearing periodically gas seeps in this region. In echograms, the gas seeps were presented as strings of few vertically migrating (ascending)

bubbles in the water column and disappearing along the path of 20 m (about half of the water depth) [15]. It is interesting that during summer and autumn seasons when the bottom water temperature is rising, single streams of seeping gas with fine diameter are observed by echosounders over extended shallower areas.

The subarea M3 have the average depth of 95 m and relatively flat bottom covered by clay sediments. Within this area, unusual forms of acoustic backscattering anomalies are observed. The acoustic anomaly reported for M3 subarea is 5.7 km long and of 150-300 m wide with the total estimated area of 1.19 $km^2$. The echogram (Fig. 2c) shows narrow strong acoustic blanking, typical for this area, due to sound attenuation by gas. There are no enhancing reflections of acoustic energy from gas intrusions. Bending down the acoustic images of the most intense sub-bottom backscattering data are most likely caused by sound speed lessening in mixed environment gas [20]. Unusual shape of the structure may indicate the "deeper" origin of methane, which migrates from deeper gas reservoir through geological faults [17,18]. Using the available set of equipment, it was difficult to recognize any geomorphological structures connected to gas presence on the surface of sediments in M3 subarea. During measurement campaigns in this area, no gas seeps were observed.

## 5. SUMMARY

The objective of this study was to show the synthesis of various acoustic studies carried out in the Gdańsk Bay, based on historical and newly collected data with reference to acoustic manifestation of shallow gas in sediments, and examine their diversity. The estimation of spatial distribution indicates about 440 $km^2$ of gas-saturated sediments. Most common acoustic manifestations of gas presence are sub-bottom backscattering anomalies such as acoustic blanking, acoustic turbidity, layer enhancement and distortion of sediment layering. Various types of sub-bottom acoustic anomalies usually co-exist with each other and their intensity vary gradually within saturated sediments (Fig.2b). Some compliance of this rule is observed in the subarea M1, where strong spatial variations of gas manifestation within sediments with significant amount of methane are observed (the central Gdańsk Bay – Fig. 2a). Based on the acoustic data, the transition zone between the area with gas-saturated sediments and gas-free sediments is usually very narrow. Markedly different features of acoustic anomalies were observed between three surveyed areas: M1, M2, M3 (Fig. 2). Within the Gdańsk Bay, there are numerous pockmarks (however, constituting minority of gas manifestation) of various size, up to 1 $km^2$, with average 1-3 m depth and around 200 m size. The total area of pockmarks in the Gdańsk Bay is estimetad to be 8.1 $km^2$. There are reported and observed (M1, M2 locations) few gas seeps from sediments (Fig.1). The observed diversity of gas manifestations in sediments requires application of various acoustic methods and devices working in broad frequency range, in order to comprehensively describe physical and geomorphological characteristics of gaseous methane in shallow sediments of the Gdańsk Bay.

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