

Original article

Methodological Approaches to Comparative Assessing the Activity and Intensity of Stream Bubble Gas Emissions on the Shelf off the Crimea Coast (Black Sea)

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Abstract

Purpose. The purpose of the study is to detect bubble gas emissions and to quantitatively assess bubble gas fluxes on the Black Sea shelf off the southeastern coast of Crimea, as well as to focus specifically on methodological approaches to investigating the spatial localization and comparative evaluation of the activity and intensity of seafloor bubble gas emissions.

Methods and Results. The hydroacoustic records, seafloor video records, and hydrological measurement data collected during the scientific expeditions of R/V *Professor Vodyanitsky* (125th cruise, November 2022, 132nd cruise, July–August 2024, and 135th cruise, June 2025) were used in the study. The research consisted of three stages: 1) broad-scale shelf surveying at depths of 10–80 m, 2) boundary detailing of the sites with the identified seep clusters, and 3) monitoring of the activity of gas emissions at the selected sites. In total, more than 600 seeps were revealed over all the survey periods. Analysis of their distribution over depth showed that approximately 90% of all the recorded gas flares were located at depths of 35–45 m. To compare the temporal and spatial variability of gas emission activity, a specific indicator – the seep density (ratio of the seep number to the scanned bottom area) – was introduced. The maximum seep density reaching 6.3 seeps per hectare at the site near Cape Martyan was recorded in summer 2024. The hydroacoustic data made it possible to calculate the average values of gas emissions from individual seeps: 38 L/day (0.07 t/year) in 2022 and 10.7 L/day (0.011 t/year) in 2024.

Conclusions. The study results, including the data on spatial distribution, density dynamics, and flux magnitude, constitute the basis for monitoring gas emissions on the Crimean shelf. The pronounced interseasonal and interannual variability of seep density indicates the significant role of external factors in regulating gas emissions. The obtained data form a basis permitting assessment of the contribution of methane seeps to the regional carbon cycle.

Keywords: Black Sea, shelf, acoustic surveys, gas flares, seep, methane seep, bubble gas emission, hydroacoustic monitoring, South Coast of Crimea

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Introduction

Methane is a potent greenhouse gas that plays a significant role in Earth's global climate processes. One of its natural sources is cold methane seeps – localized bubble gas emissions from the bottom of water bodies [1–3]. They are widely distributed on the shelf and continental slope throughout the World Ocean [2], including the Black Sea [4]. Methane seeps in the Black Sea have been recorded across a wide depth range – from the lower boundary of the gas hydrate stability zone (725 m) and deeper [4, 5] to the shoreline [6, 7]. The emitted gas in different areas has varying origins (biogenic and/or thermogenic) [7], which, in turn, may determine different intensities and periodicities of gas emissions depending on the season or external conditions [8].

Gas fluxes from individual seeps have been studied in various regions of the World Ocean: in the Gulf of Mexico [9], on the Norwegian shelf [10, 11], in the North Sea [12], near Svalbard [13], in the Laptev Sea [14], on the California shelf [15], as well as in some areas of the Black Sea [16, 17]. The total methane flux from marine seeps into the atmosphere is estimated to be approximately 20–30 Tg·yr⁻¹ [1], while estimates from individual sources in different regions can vary by several orders of magnitude. During the 125th cruise of R/V *Professor Vodyanitsky*, methane seeps were first recorded off the southern and eastern coasts of Crimea [18]. Over the past decade, individual shallow-water gas emission sites have also been described [6, 7, 19, 20].

This paper presents the results of hydroacoustic studies on the Black Sea shelf off the southern coast of Crimea, obtained during scientific expeditions in November 2022, August 2024, and June 2025. Our research is aimed at detecting bubble gas discharge and providing a quantitative assessment of bubble gas fluxes in the specified area. Special attention is paid to methodological approaches to investigating the spatial localization and comparative evaluation of the activity and intensity of seafloor bubble gas emissions.

Study area: geomorphology and geology

The study area encompasses the Black Sea shelf along the southeastern coast of the Crimean Peninsula, including the section from Laspi Bay in the west (the Southern Coast of Crimea, SCC) to Feodosia Bay in the east (Fig. 1). In geomorphological terms, the shelf and continental slope off the Crimean coast are subdivided into three morphostructural districts: the Western – from Cape Tarkhankut to Cape Sarych and Laspi Bay; the Southern Coast (SCC) – from Cape Sarych to Cape Meganom; and the Eastern, from Cape Meganom to the Kerch Strait, including Feodosia Bay and the Kerch-Taman shelf. Within the studied section (along the SCC and the adjacent part of the Eastern district), the shelf is narrow; it widens east of Cape Meganom. The depth of its outer edge varies from 100 to 130 m. Along its entire length, an inner (abrasional) and an outer (accumulative) part are distinguished. The boundary between them runs along the 80–95 m isobath. The abrasional plain of the inner shelf is overlain by a sedimentary cover of limited thickness (10–20 m), primarily of Late Euxinian and Holocene age [21].

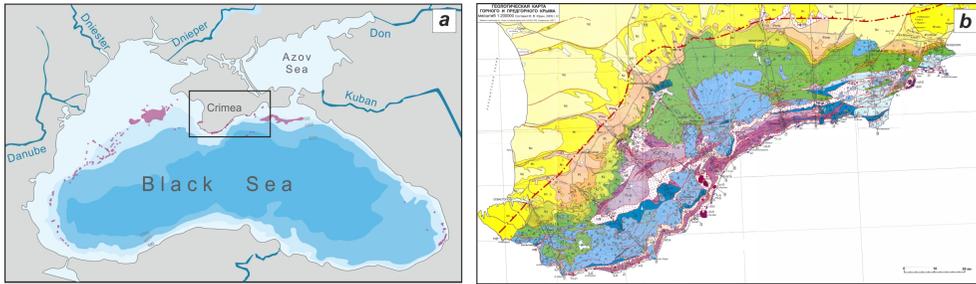


Fig. 1. Schematic map of the distribution of methane seeps in the Black Sea [4, 18] (the rectangle indicates the study area) (a), and a geological map of the study area ¹ (b)

Materials and methods

The data used in this study, including hydroacoustic records, seafloor video, and hydrological information, were collected during research expeditions aboard R/V *Professor Vodyanitsky*: the 125th (November 2022), the 132nd cruise (July – August 2024), and the 135th cruise (June 2025).

Hydroacoustic detection of bubble emission: data collection and processing.

The main dataset was obtained using the Simrad EK 500 scientific echosounder (operating frequencies of 38 and 120 kHz) installed aboard R/V *Professor Vodyanitsky*. Part of the data from the 125th cruise was acquired using a hardware-software complex developed at the Laboratory of Hydrology and Hydrophysics of LIN SB RAS, based on a Furuno FCV-1100 echosounder connected to the vessel's hydroacoustic transducers (88 and 50 kHz). The beam width of the Simrad EK 500 and Furuno FCV-1100 hydroacoustic transducers was 7° and 8°, respectively, with a pulse duration of 0.3 ms. Hydroacoustic recordings were conducted while the vessel was underway at a speed not exceeding 4 knots, as well as while adrift to record individual rising gas bubbles.

Data from the Simrad shipboard echosounder were recorded using proprietary software created at the Laboratory of Hydrology and Hydrophysics of LIN SB RAS. Data visualization was performed in the EchoView (SonarData, Myriax, Australia) program. Data from the Furuno echosounder were visualized using the proprietary software Echo-Baikal [22]. Processing and analysis of the volume backscattering data and calculation of gas fluxes were performed using Python code. Seeps were manually delineated in the EchoView program based on the criteria outlined below.

Criteria for seep identification. Recognition of bubble emission is based on the analysis of the nature of acoustic backscattering on echograms [13, 23]. The hydroacoustic image of intense bubble emission at great depths has a specific plume shape and depends on the current profile, vessel course, and the beam pattern of the hydroacoustic transducer [24]. For shallower depths and weak emission, there are a number of features that distinguish the hydroacoustic images of seeps on echograms from the typical plume shape characteristic of deep-water gas emissions. Therefore, for correct detection of individual bubbles and their clusters, proper

¹ Yudin, V.V., 2009. [Geological Map and Cross-Sections of the Mountain and Foothill Crimea: Designed for Specialists, Students, Tourists, and Nature Lovers]. Scale 1:200 000. Simferopol: Soyuzkarta (in Russian).

classification of acoustic backscattering targets in the water column is necessary. As shown in [25, 26], a single bubble or a cloud of bubbles on an echogram forms an almost straight line with a positive slope (Fig. 2, *a*). Since echograms display echo signal intensity (color) versus depth (y-axis) over time (x-axis), different vertical exaggeration can stretch the image of fish schools along the y-axis, leading to false detection of seeps (Fig. 2, *b, c*).

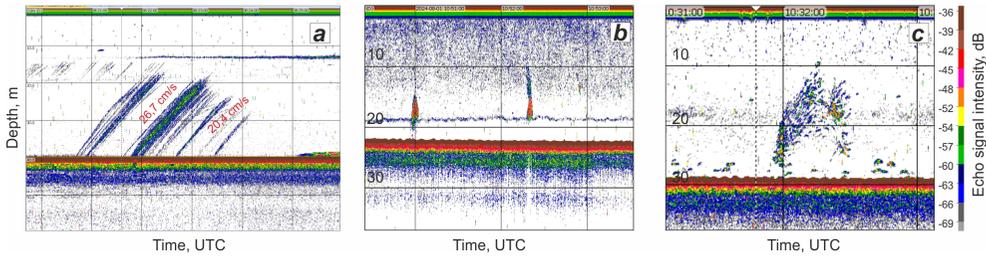


Fig. 2. Echograms of bubble gas emissions recorded at the seep site near Cape Martyan while at anchor on 7 August 2024 (Simrad EK 500, 120 kHz) (tracks of individual rising bubbles are visible) (*a*); examples of hydroacoustic anomalies of an ambiguous nature, the image of which does not allow them to be unambiguously interpreted as gas flares (*b, c*)

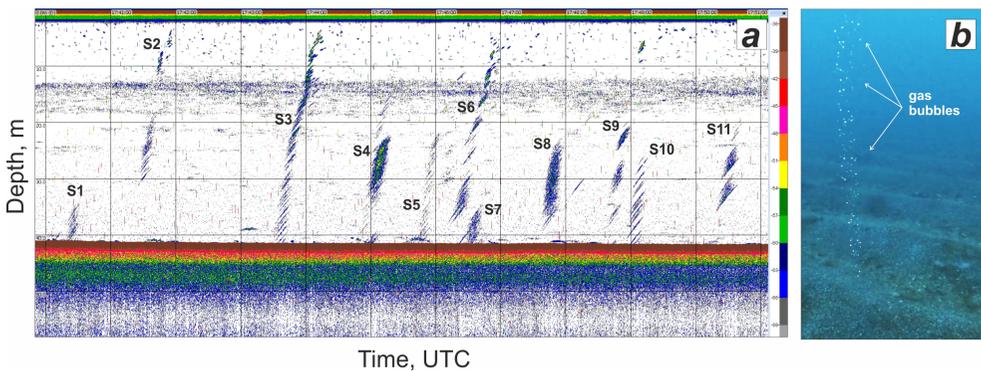


Fig. 3. An example of hydroacoustic anomalies identified as gas flares recorded during the 132nd cruise of R/V *Professor Vodyanitsky* (*a*); an underwater photograph of a continuous stream of gas bubbles at 15 m depth at the site near Cape Martyan (*b*)

Sufficient evidence for the gaseous nature of a detected anomaly is provided by hydroacoustic images with an inclined slope, as well as by recording the tracks of individual rising bubbles whose ascent velocities correspond to their size distribution [13]. Fig. 3, *a* shows an echogram with 11 identified seeps. For each emission site, an assessment of acoustic backscattering at the seabed–water interface was performed in the EchoView software, which was subsequently used to calculate the gas flux.

Hydrological measurements. An IDRONAUT Ocean Seven 320plus CTD oceanographic probe (Italy) was used for vertical profiling of hydrological parameters.

Calculation of gas emission volumes. An inverse method for calculating gas flux from a point source, described in detail in [13], was applied. The hydroacoustic

systems used in our work (Simrad, Echo-Baikal) are equipped with hydroacoustic transducers with beam widths of 7° and 8°. At depths of 30–50 m, they cover a seabed area of 10–38 m²; therefore, one or several gas plumes may be within the beam. Each plume consists of individual bubbles, the sizes and number of which follow a bubble size distribution law. The ascent velocity of a bubble was calculated according to the law given in [27], and the density of methane corresponds to its density at the gas emission depth.

Results

Hydrological conditions (comparison among seasons)

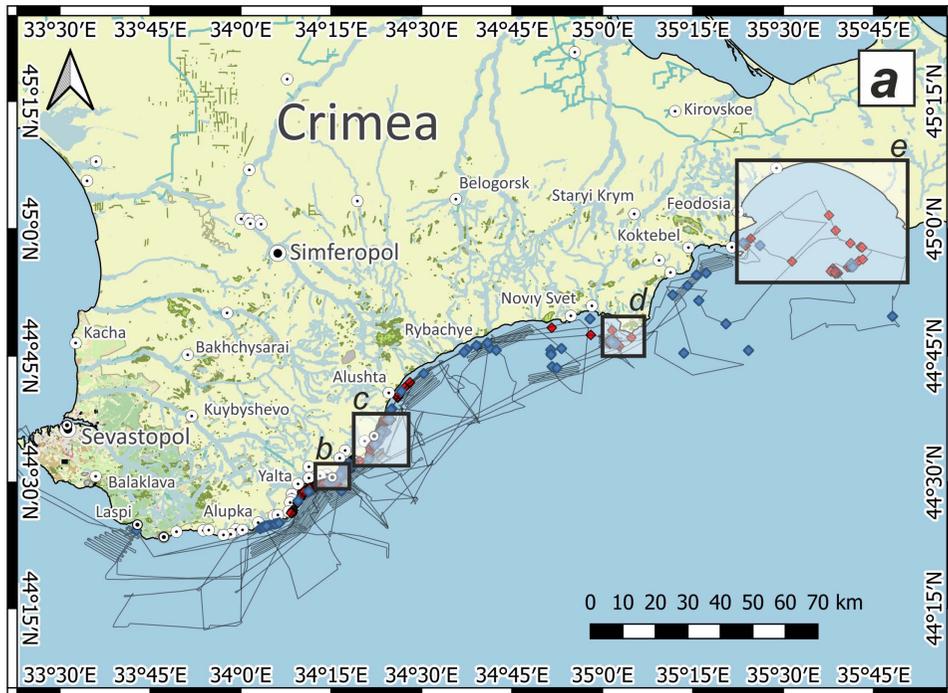
In August 2024, hydrological parameters were measured at five stations at depths ranging from 35 to 42 m. The near-bottom water temperature varied from 10 to 14 °C, corresponding to the range observed in November 2022 (12.5–15 °C). Dissolved oxygen concentration was 7.93–8.86 mg/L in August 2024 and 7.99–8.17 mg/L in November 2022. The near-bottom water temperature at depths greater than 35 m during the spring hydrological season of 2025 was somewhat lower compared to previous periods (8.7–10.1 °C).

Localization of seeps

On echograms, bubble gas emissions appeared as vertically elongated anomalies corresponding to individual rising bubbles or their clusters (Fig. 3, *a*). Due to the narrow beam width of both echosounders used, determining the actual plume height for each detected seep was not feasible, as the upper part of the plume was often lost from the beam when the vessel shifted relative to its center. However, some plumes reached the water surface (e.g., S2, S3 in Fig. 3, *a*). Furthermore, gas emission for most recorded seeps had a pulsating nature.

During the 125th cruise (November 2022), 14 sites from Laspi Bay to Feodosia Bay were selected for detailed acoustic survey. Hydroacoustic probing at the sites was conducted along shore-parallel transects with a spacing of no more than 0.2 nautical miles. At that time, 211 individual seeps were discovered over an area of 7.1 km² [18] (Fig. 4).

Depth distribution of seeps obtained at the first stage of the study showed that they were recorded within a depth range of 19.7–78.5 m (Fig. 5) and were predominantly located on the transect closest to the shore. Based on spatial grouping, four seep clusters were identified (near Alupka, Cape Martyan, Cape Plaka, and the village of Rybachye), located in the western part of the study area and comprising the majority of detected hydroacoustic anomalies. Nearly 90% of all gas plumes were recorded in the Cape Martyan area, mainly along the 35–45 m isobaths (Fig. 5, *a*). In the eastern part of the study area, single plumes predominated (see Fig. 4). It should be noted that the contribution of shallow-water seeps (at depths less than 35 m) is likely underestimated, as the survey of shallow waters was limited by the research vessel's draft. For example, shallow-water seeps located no more than 100 m from the shoreline, inaccessible to R/V *Professor Vodyanitsky*, have been described in Laspi Bay and near Cape Martyan and Ayu-Dag [20, 28].



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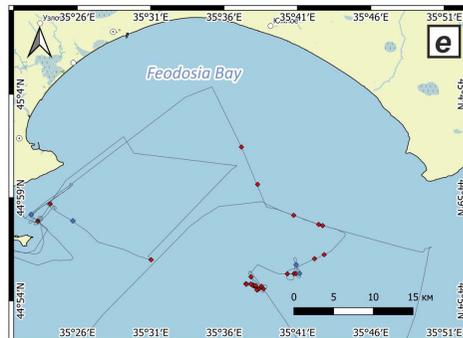
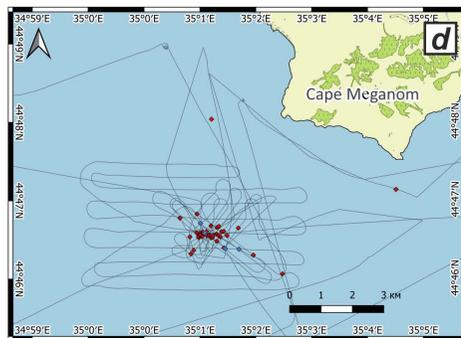
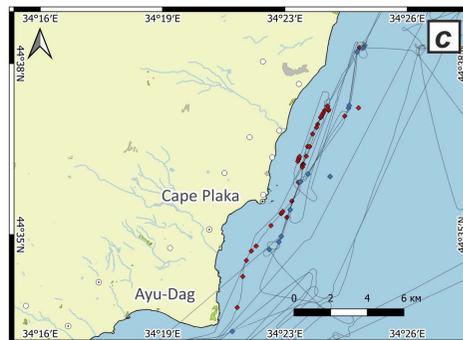
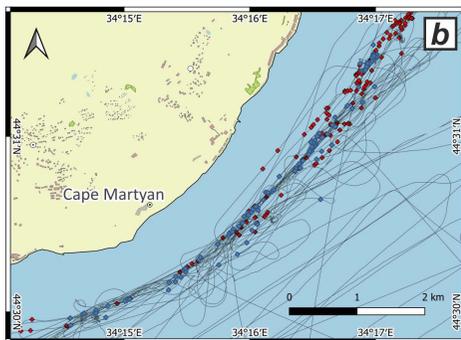


Fig. 4. Distribution of the seeps recorded in the study area during the 125th (blue diamonds) and 132nd (red diamonds) cruises of R/V *Professor Vodyanitsky* (a), as well as at the individual sites near Cape Martyan (b), Cape Plaka (c), Cape Meganom (d), and in Feodosia Bay (e). The grey line indicates the expedition route and hydroacoustic tracks

At the next stage, during the 132nd cruise (July–August 2024), a detailed survey of depths with the maximum seep density was carried out. Shore-parallel acoustic surveys at depths of 35–45 m significantly expanded the boundaries of the previously identified seep clusters. The proportion of the track covered at these depths amounted to about 90% of the total cruise track (Fig. 5, *b*). Detailed investigations in the area from Cape Ai-Todor to Cape Plaka showed an almost continuous distribution of seeps. A total of 402 seeps were recorded during the 132nd cruise. New gas emission sites were also identified near Cape Meganom and in Feodosia Bay, where previously only single plumes had been recorded.

During the 135th cruise (May – June 2025), four sites were selected for monitoring studies: Cape Martyan, Cape Plaka, Cape Meganom, and the city of Feodosia. Data on the number of recorded seeps and the area of seabed scanned for these sites during different cruises are given in the table.

Survey parameters and the number of seeps recorded at four selected gas emission sites during hydroacoustic sounding in three cruises of R/V *Professor Vodyanitsky*

Record date	Distance travelled, km	Area of the surveyed bottom, km ²	Number of recorded flares, pcs.	Number of flares for flux calculations, pcs.
<i>C. Martyan</i>				
15.11.2022	27.0	0.12	11	–
23.11.2022	62.0	0.27	59	26
25.07.2024	37.1	0.35	173	35
06.08.2024	28.6	0.19	121	23
07.08.2024	23.5	0.16	45	8
12.06.2025	15.2	0.09	0	–
<i>C. Plaka</i>				
23.11.2022– 24.11.2022	37.0	0.19	13	–
09.08.2024	20.1	0.12	37	12
10.06.2025	23.3	0.14	0	–
<i>C. Meganom</i>				
20.11.2022– 20.11.2022	34.5	0.19	4	–
04.08.2024	40.9	0.31	32	3
07.06.2025	19.4	0.12	12	–
<i>Feodosia Bay</i>				
02.08.2024	24.7	0.14	18	5
04.06.2025	20.0	0.12	6	–

Comparison of seasonal activity and intensity of seeps using the Cape Martyan gas emission site as an example

In this work, the activity of gas emissions is understood as a set of characteristics pertaining to both an individual plume (pulsation duration, the timing of active phases, and pauses between them) and the site as a whole (seep density).

The intensity of seeps is assessed based on the gas flux from individual plumes calculated using hydroacoustic data.

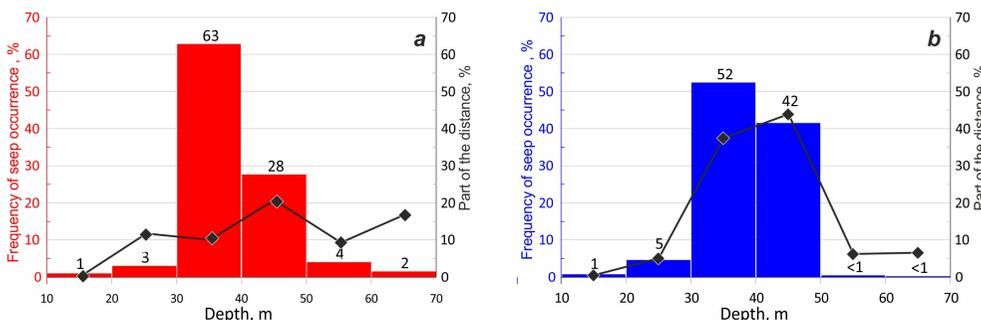


Fig. 5. Distribution of seeps by depth, and the proportion of the distance (black line) travelled at the selected depths (10 m intervals) relative to the total route length for each cruise, based on the data from the 125th (a) and 132nd (b) cruises of R/V *Professor Vodyanitsky*

Activity of gas seeps was studied in detail using the gas emission site near Cape Martyan as an example (Fig. 6). For this purpose, we compared hydroacoustic survey data collected in 2022, 2024, and 2025, both overall to identify interannual differences and to estimate variability within individual days during each cruise. Data from the 135th cruise are not presented, as not a single plume was recorded at the site. Fig. 6, a shows all recorded gas emission points (diamonds), i.e., locations where hydroacoustic anomalies in the water column were detected at least once. The spatial and temporal dynamics of gas emission activity during individual surveys are shown in Fig. 6 (b–f). Based on five surveys carried out at the Cape Martyan site (table, Fig. 6), it was established that gas bubble emission did not occur constantly but was intermittent, up to the complete absence of seeps, as observed in June 2025 (table).

Bubble gas fluxes

During the 125th cruise, data for 26 out of 202 recorded gas emissions at depths of 30–52 m were processed. Calculated gas discharge rates varied in the range of 4.07–88.6 L/day (0.04–0.101 t/year) with an average value of 38 L/day (0.07 t/year). During the 132nd cruise, over 412 gas emissions were recorded at depths of 16–64 m, with 67 processed for gas flux calculation. Calculated gas emission rates ranged from 5.01–136 L/day (0.006–0.163 t/year) with an average value of 10.7 L/day (0.011 t/year).

Activity of gas emissions

Periodicity of gas emissions can change over time scales ranging from several seconds [29] to hours [30] and days [31] under the influence of waves, tides, storms, and hydrological factors. Our previous data showed that the number of active seeps at the Cape Martyan site changed on a synoptic scale [18]. However, differences in initial data between cruises, such as track length and area of seabed scanned, often preclude direct comparison of gas emission activity based on the number of recorded plumes. Therefore, to compare the temporal and spatial variability of gas emission activity, a specific indicator – seep density (number of seeps per area of scanned

seabed) was used. Fig. 7 shows the seep density for the four sites studied in 2022–2025. At all sites, the maximum seep density was observed in 2024, reaching 6.3 seeps per hectare at the Cape Martyan site.

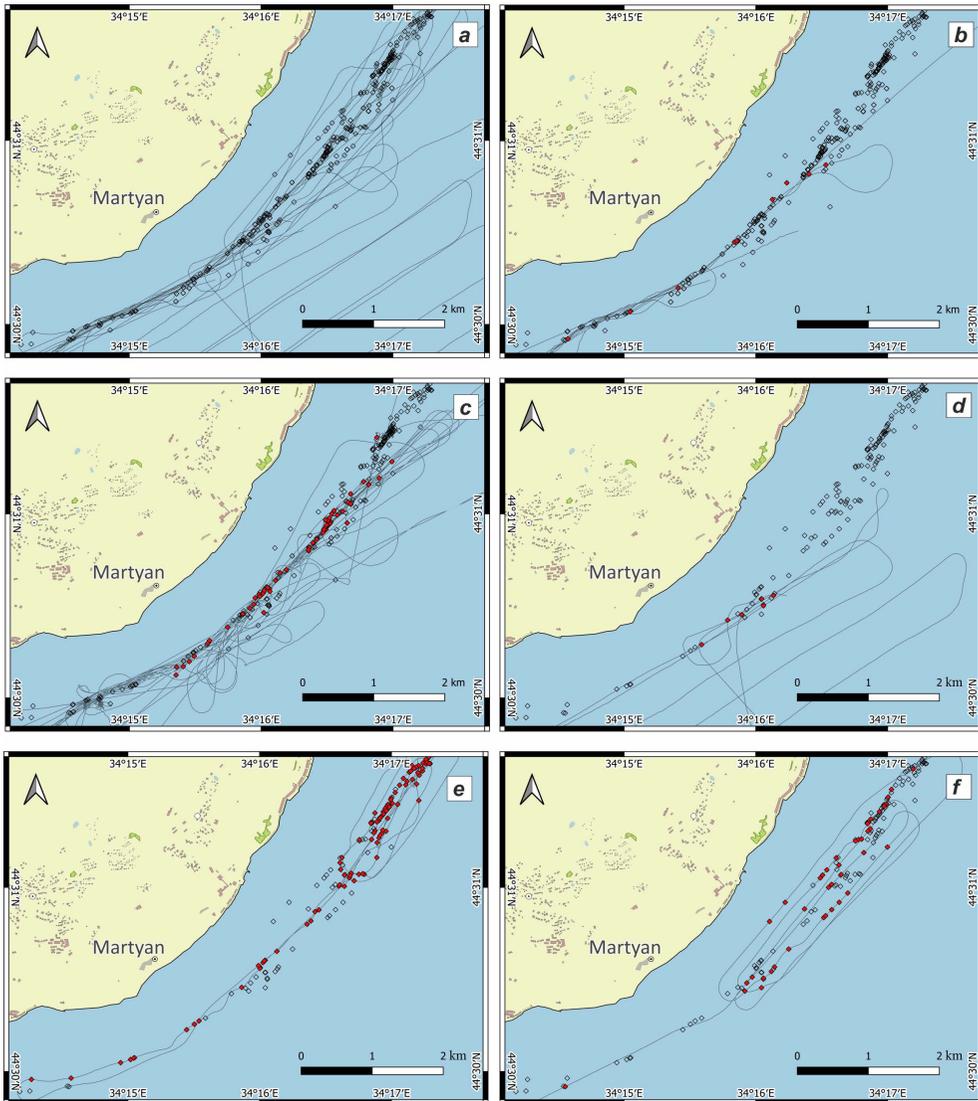


Fig. 6. Seep activity near Cape Martyan for the entire 2022–2025 study period (diamonds indicate all recorded gas emission points) (a) and on individual days of the 125th cruise: 12 November 2022 (b); 23 November 2022 (c) and the 132nd cruise: 25 July 2024 (d); 6 August 2024 (e); 7 August 2024 (f). Red diamonds indicate the points where active bubble emission was observed during the vessel passage; uncolored diamonds indicate points where, during the specified period, either no surveys were conducted or no gas emissions were observed

The decrease in seep activity during the 135th cruise, up to the complete absence of recorded plumes at the Cape Martyan and Plaka sites, may be explained by a change in the periodicity of gas emission: active phases became shorter, and pauses

significantly longer. For instance, study [32] demonstrated high sporadicity and irregularity of seeps in the Black Sea west of Crimea at a depth of 92 m. Most seeps were active for less than 20% of the observation time. The high variability in gas emission activity complicates the detection and recording of shallow-water seeps by standard acoustic methods, as the transit time of bubbles through the water column at depths less than 100 m does not exceed 7.5 min. On the other hand, short-term recording may lead to an overestimation of fluxes if information on the variability of individual seep activity is not considered.

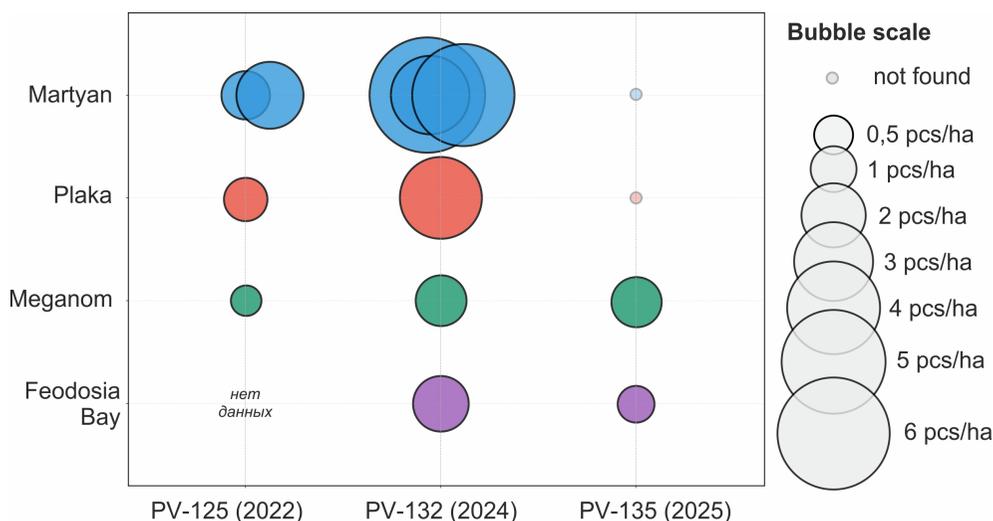


Fig. 7. Seep density (ratio of the seep number to the scanned seabed area, pcs/ha) for four sites surveyed in 2022–2025 (PV-125 denotes the 125th cruise of R/V *Professor Vodyanitsky*, PV-132 denotes the 132nd cruise, and PV-135 denotes the 135th cruise). At the site near Cape Martyan, several measurements were conducted in 2022 and 2024 (see table)

Using shallow-water seeps of thermogenic origin in Laspi Bay as an example, we showed that their periodicity depends on sea wave action: starting from a certain threshold wave amplitude, the period of small-scale seep pulsation correlated with the wave period [17]. At the same time, the seasonal and interannual activity of these emissions varies within a relatively narrow range. It is likely that processes in the upper layers of bottom sediments and the hydrosphere have a weak influence on gas release from a deep source, whereas biogenic gas from the sedimentary cover is more susceptible to factors affecting the hydrosphere.

Sources and origin of hydrocarbon fluids

One of the main unresolved questions in the study of shallow-water seeps is related to the nature of their occurrence in coastal areas at shallow depths. The sedimentary layer in shallow-water areas is thin (no more than 10–20 m [21]) and often composed of sandy deposits. In many cases, it remains an open question whether shallow-water bubble gas emissions result from gas seepage from deeper layers, or whether the emitted gas is generated in the upper sedimentary layer. Gas-geochemical studies demonstrate that shallow-water seeps in the SCC area have varying isotopic compositions of methane carbon, indicating different gas genesis

[7, 28]. The different nature of gas anomalies is also confirmed by geoacoustic studies conducted off the SCC [33].

Factors influencing distribution and activity of seeps

A critical factor for the manifestation of stable stream-like gas emissions from the seabed is the presence of an overlying seal layer that facilitates hydrocarbon accumulation, as well as fractures and/or faults forming migration pathways within the reservoir and through the seal to the seabed or atmosphere [34]. Hydrocarbon accumulation often occurs in anticlines and other traps [35], reflecting upward migration through the reservoir rock. Our monitoring studies confirmed the existence of specific points where gas emissions were active during different periods, indicating the presence of stable migration pathways. Most recorded seeps are located no deeper than 35–40 m. It is assumed that one of the potential gas migration pathways could be along weakened zones. In the coastal part, sandy-pebble deposits give way to clayey-silty rocks at greater depths, which can act as a fluid seal. Gas migration from deeper horizons is possible along the boundary between these deposits.

Intensity and periodicity of gas emissions are controlled by the pressure difference within the reservoir rock and the hydrostatic pressure, as well as the presence and thickness of the microbial filter. In [30] a model that accounts for the aforementioned fluid-dynamic processes is described. According to one conclusion from that work, a seep system is characterized by a response time to changes in a forcing factor, such as tidal hydrostatic pressure. This results in a highly nonlinear response of gas emissions to changes in hydrostatic pressure, with sensitivity being inversely proportional to the flux [30]. Furthermore, the mechanism of bubble and fluid gas release may be associated with the process of submarine discharge of fresh groundwater [36–38].

For gas of biogenic origin, the temperature of the near-bottom water layer can be a significant factor. Its increase may influence microbial activity in surface sediments, stimulating methane formation through the decomposition of organic matter [39].

Conclusion

During cruises of R/V *Professor Vodyanitsky* in 2022–2025, hydroacoustic studies were carried out on the Black Sea shelf off the southeastern coast of Crimea to identify and subsequently monitor zones of bubble gas emissions (seeps). The work included three stages: 1) broad exploratory work on the shelf off the southeastern coast of Crimea at depths of 10–80 m; 2) refinement of the boundaries of the discovered seep sites; 3) monitoring of gas emission activity at selected sites. In total, over 600 seeps were discovered during all research periods.

The depth distribution of seeps obtained at the first stage showed that about 90% of all recorded plumes are located at depths of 35–45 m. To analyze the temporal and spatial variability of gas emission activity, we used a specific indicator – seep density (ratio of the number of seeps to the area of scanned seabed). At all sites, the maximum seep density was observed in the summer of 2024, reaching 6.3 seeps per hectare at the Cape Martyan site.

Based on hydroacoustic data, average gas discharge rates from individual seeps were calculated, amounting to 38 L/day (0.07 t/year) in 2022 and 10.7 L/day (0.011 t/year) in 2024.

The work considers the genesis of seeps and natural factors that may influence their distribution and activity. Geochemical data indicate different methane genesis – from biogenic methane in surface sediments to thermogenic methane from deeper horizons. The distribution of seeps is concentrated mainly within the 35–45 m depth interval, which is likely associated with the contact zone between sandy-pebble and clayey-silty deposits, serving as a migration zone and/or fluid seal. The activity (periodicity and intensity of emissions) demonstrates a nonlinear dependence on external forcing factors, such as changes in hydrostatic pressure (tides, wave pressure), which exert a more significant influence on gas of biogenic origin.

The stream-like gas emissions recorded in the southern coastal sector of the Crimean Black Sea shelf require further research to estimate their role in shaping the ecological state of the ecosystem, including within the waters of the Cape Martyan Nature Reserve.

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