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**EXPERIMENTAL ARTICLES**

# The Process of Microbial Sulfate Reduction in Sediments of the Coastal Zone and Littoral of the Kandalaksha Bay of the White Sea

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**Abstract**—Microbiological and biogeochemical investigations of the coastal zone and the littoral of the Kandalaksha Bay of the White Sea were carried out. The material for investigations was obtained in the series of expeditions of the Institute of Microbiology, Russian Academy of Sciences, in August 1999, 2000, 2001, and in March 2003. The studies were conducted on the littoral and in the water area of the Kandalaksha Preserve, the Moscow University Belomorsk Biological Station, and the Zoological Institute Biological Station, Russian Academy of Sciences. Sediment sampling on the littoral was carried out in the typical microlandscapes differing in the sediment properties and macrobenthos distribution. The maximal sulfate reduction rate (SRR) was shown for the shallow part of the Chernorechenskaya Bay (up to 2550 μg S/(dm$^3$ day)) and in the Bab'ye More Bay (up to 3191 μg S/(dm$^3$ day)). During the winter season, at a temperature of $-0.5 \times 0.5$°C, the SRR in the sediments of the Kartesh Bay was $7.9 \times 13$ μg S/(dm$^3$ day). In the widest limits, the SRR values varied in the sediment cores sampled on the littoral. The minimal values (11 μg S/(dm$^3$ day)) were obtained in the core samples on the silt–sandy littoral. The littoral finely dispersed sediments rich in organic matter were characterized by high SRR values (524–1413 μg S/(dm$^3$ day)). The maximal SRR values were shown for the sediments present within the stretch of decomposing macrophytes, in local pits at the lower littoral waterline, and in the mouth of a freshwater stream (51–159 mg S/(dm$^3$ day)). A sharp difference in the level of $H_2S$ production in the type microlandscapes was shown. The average hydrogen sulfide production in finely dispersed sediments constituted 125 mg S/(m$^2$ day); in stormy discharge deposits, 1950 mg S/(m$^2$ day); in depressions under stones and in silted pits, 4300 mg S/(m$^2$ day). A calculation made with regard to the area of microlandscapes with increased productivity shows that the daily $H_2S$ production per 1 km$^2$ of the littoral (August) is 60.8 to 202 kg S/(km$^2$ day), while the organic carbon consumption for sulfate reduction per 1 km$^2$ of the littoral is 46 to 152 kg $C_{org}$/(km$^2$ day).

*Key words*: microbial processes, microbial number, microbial sulfide reduction, hydrogen sulfide production, littoral, the White Sea.

Microbiological studies of the seas of the arctic basin are connected, in large measure, with the name of the outstanding microbiologist Academician B.L. Issatchenko, who gave in his works a detailed characteristic of the processes of nitrogen fixation, denitrification, and sulfate reduction in the seas of the Arctic Ocean. It is he who considered that the continuation of studying the polar seas is one of the crucial tasks of marine microbiologists [1]. At present, because of an ever increasing anthropogenic load on the coastal ecosystems and the threat of global climatic changes, Russian and foreign investigators display a keen interest in the biogeochemical processes occurring in the ecosystems of the polar seas [2, 3].

A distinctive feature of the White Sea from the other polar seas is the vastness of the coastal zone. With a surface area of 90 thousand km$^2$, the length of only the mainland coast (excluding the islands) exceeds 2.5 thousand km [4]. The shallow waters of the White Sea have a special hydrological regime. The intense continual mixing of the water column caused by tides occurring twice a day is observed to a depth of 30 m. A considerable part of the White Sea coastline is bordered by macrophytes, the covering area constituting 1000 km$^2$ and the total biomass being 1.5 million tons [5]. In the opinion of some investigators, the White Sea productivity is determined, in large measure, by its coastal part including the shallow waters and littoral [6], where the organic matter (OM) of both autochthonous and allochthonous genesis is concentrated.

The White Sea and the Kandalaksha Bay in particular belong to the best-studied regions of the polar basin. Regular observations are carried out in the Kandalaksha Preserve, as well as at two biological stations—the

Moscow University Pertsov Belomorskaya Biological Station (BBS) and the Kartesh Biological Station, Zoological Institute, Russian Academy of Sciences. Considerable material was collected during many years research by marine biologists and oceanologists. The main subjects of research were phyto- and zooplankton, macrophytes, benthos, ichthyofauna, marine mammals, and birds. However, the evidence concerning microorganisms and their activity on the White Sea littoral is scarce [7, 8] and devoted to the study of phototrophic and colorless sulfur bacteria.

The process of bacterial sulfate reduction in marine sediments is known to play a leading role in the terminal pathways of anaerobic OM destruction [2, 9, 10]. Therefore, the estimation of the scale of bacterial sulfate reduction in the sediments of the coastal part of the White Sea is required for developing quantitative models of OM turnover in the ecosystems of shallow waters.

The main objectives of our work that included three summer and one winter expeditions to the Kandalaksha Bay of the White Sea were to obtain quantitative estimates of the rate of microbial sulfate reduction in the sediments of the shallow coastal zone and characteristic microlandscapes of the littoral.

## MATERIALS AND METHODS

The materials for this study were obtained in a series of expeditions of the Institute of Microbiology, Russian Academy of Sciences, in August 1999, 2000, 2001, and in March 2001. The studies were conducted on the littoral and in the water area of the Kandalaksha Preserve, the Moscow University BBS, and the Kartesh Biological Station. The scheme of location of the sampling stations is given in the figure. To make data analysis more convenient, the numerical index of each station includes the year when the study was conducted and the station number, e.g., 99-20 (Table 1). The selection of specific sampling sites in the water area of the Kandalaksha Bay was made in compliance with the recommendations of the Preserve services. Sediment sampling on the littoral was carried out in typical microlandscapes differing in both the sediment structure and properties and the macrobenthos distribution [11].

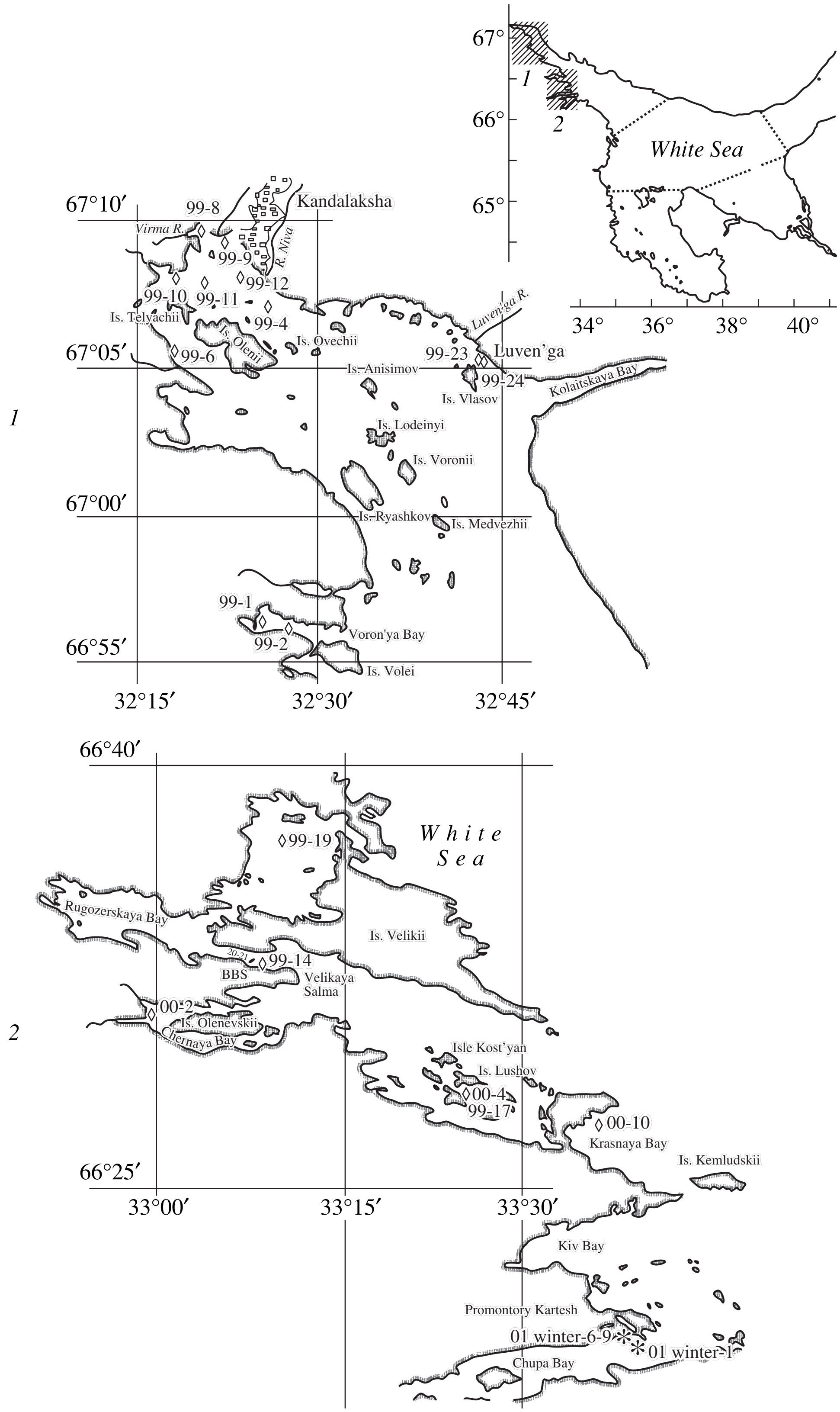
The sulfate reduction rate (SRR) was determined with the radioactive label method using $Na_2{}^{35}SO_4^{2-}$ according to the technique described in detail in [12, 13]. The sediment sampling was carried out using a limnological stratimeter with changeable (disposable) 6-cm tubes. The sediment or bacterial mat samples were placed into 5-cm$^3$ plastic syringes with a rubber piston and a cut off edge and closed with a gas-proof rubber cap with no air access. Using a microsyringe, 0.2 ml of $^{35}$S-sulfate solution was injected into the sample. The samples were incubated for 4 to 6 h in the summer season and for 24 h in the winter season. The samples from the littoral were incubated directly at the sampling site. The samples were fixed with 2 M KOH solution. Under laboratory conditions, quantitative separation of hydrogen sulfide $H_2{}^{35}S$ and $H_2{}^{35}S$ in the composition of pyrite, organic, and elemental sulfur was performed according to the method described in detail in [13].

Quantitative enumeration of sulfate-reducing bacteria was performed by the 10-fold dilution method using the marine liquid mineral base of Widdel's medium with the addition of sodium lactate (3 g/l). The cultivation was carried out in Hungate's test tubes at room temperature.

The isotopic composition of the sulfate and hydrogen sulfide sulfur ($\delta^{34}S$) was determined using an MI-1201V mass spectrometer (Ukraine) furnished with an SNG-3 three-channel system of gas admission according to the technique described in detail in [14]. The accuracy of determinations was ±0.2‰.

**Brief characterization of the region of work.** The coastal stations of the Kandalaksha Bay can arbitrarily be divided into a number of groups (figure, Table 1). The first group includes typical stations of the open part of the bay with a depth of 13 to 25 m (stations 99-4, 99-6, 99-11, and 99-12). The second group includes the stations situated in remote parts of little bays, as well as separated from the open part of the bay by chains of islands (stations 99-2, 99-3, 99-5, 99-8, 99-10, 99-16, and 99-17), with a depth of 6 to 20 m. Some of the stations included in this group are situated in the zone subject to the direct influence of anthropogenic contamination (stations 99-9, 99-12, and 99-6). Among the stations of this group, there are two situated in the former areas for artificial mussel breeding (stations 99-17 and 00-4). The rows of pontoons and vertical ropes retained until now keep in check the mixing of the water column and prevent the upper horizon of the bottom sediments from eroding. The Bab'ye More Bay is a special-type reservoir. The connection with the sea is effected by the bodies of water circulating through two shallow whitewater zones. The depth of the Bab'ye More station (station 99-19) is 25 m (the maximal depth for this bay).

Lake Polusolenoe (station 14) is located on the littoral 2 km eastward from the Moscow University BBS. The lake is shallow (no more than 2 m), warms up well, and has a periodic connection with the sea during seasonal storms. The lake is demineralized by means of a forest stream flowing into it on the side of the mainland shore. At the time when the studies were conducted, the chloride ion content in the lake surface water varied between 770 and 6500 mg/l. In Lake Polusolenoe, the sediments are buried under a layer of cyanobacterial mats. The mat surface is of purple, green, or brown-olive color. Different colored and whitish slimy clots occur in the mat thickness. The layer of a reduced black sediment is 5 to 20 mm thick, and it is underlain by a dense sandy–gravel layer inaccessible to tube sampling.




The scheme of the region where the studies were conducted in the Kandalaksha Bay of the White Sea. (*1*) The water area of the town of Kandalaksha and the Kandalaksha Preserve. (*2*) The water area of the Moscow University BBS and the Kartesh Biological Station. ◇, the water area and littoral stations studied. ◇ 99-19, Bab'ye More Bay. ✻, stations at which investigations were performed in winter.

**Table 1.** Sulfate reduction rate in the sediments of the Kandalaksha Bay of the White Sea

| Station no., coordinates | Station location, sea depth, m | Sediment horizon, cm | Eh, mV | Sediment description | $SO_4^{2-}$ (mg/l) | Sulfate reduction rate, µg S/(dm$^3$ day): ΣS compounds | Sulfate reduction rate, µg S/(dm$^3$ day): $H_2S$ (%) | $H_2S$ production (mg S/(m$^2$ day)) | Consumption of $C_{org}$ (mg C/(m$^2$ day)) |
|---|---|---|---|---|---|---|---|---|---|
| **Stations of the open part of the bay** | | | | | | | | | |
| **00-10** 66°25′334 N 033°38′20 E | Krasnaya Bay, open part, 18 | 0–10 | 190 | Gray sandy–aleurite sediment | 1850 | 18 | 67 | 2.7 | 2.03 |
| **99-11** | Sea channel in line of Isle Telyachii, 18 | 0–5 | +65 | Silt consisting of friable lumpy aggregates of pelite particles with ligneous detritus. 17 to 25 cm. Friable sediment without ligneous detritus | 890 | 7.5 | 60 | 4.7 | 3.53 |
| 67°07′807 N | | 5–17 | +75 | | 800 | 43.1 | 95 | | |
| 032°19′952 E | | 17–25 | +73 | | 820 | 35 | 81 | | |
| **99-6** | Bulk plant, opposite the moorage, 13 | 0–6 | –50 | Aleurite--pelite silt with muscovite and hydroxide mineral plates. Coarse sand and small gravel occur as admixtures | 650 | 66 | 68 | 8.0 | 6.0 |
| 67°04′965 N 032°19′460 E | | 6–15 | +140 | | 700 | 44 | 73 | | |
| **99-4** | The buoy opposite Ovechii Isle, 23 | 0–5 | +150 | Silt consisting of small clump-like pelite aggregates with biotite and muscovite plates of aleurite dimension | 720 | 14 | 54 | 40.4 | 30.3 |
| 67°06′806 N 032°26′740 E | | 10–15 | –100 | | 700 | 397 | 95 | | |
| **Stations in little bays and shallow waters at the estuary** | | | | | | | | | |
| **01-winter-1** | Little bay of the Kartesh station, 38 | 0–5 | 90 | Homogeneous gray sediment with particles of sand and gravel dimension | 1650 | 7.9 | 67 | 1.7 | 1.28 |
| 66°20′01 N 033°41′10 E | | 5–10 | 40 | | 1650 | 13.0 | 65 | | |
| **99-10** | Remote part of the little bay of the Kan Bay, 13 | 0–2 | 220 | Silt consisting of friable lumpy aggregates of pelite particles with an admixture of vegetable detritus | 630 | 0 | | 3.5 | 2.63 |
| 67°08′145 N | | 2–10 | 55 | | 500 | 20.4 | 98 | | |
| 032°17′808 E | | 10–17 | 20 | | 450 | 37.8 | 95 | | |
| **99-9** | Port of Kandalaksha, 19.5 | 0–3 | 100 | Silt consisting of friable lumpy aggregates of pelite particles with an admixture of vegetable and zoogenous detritus | 1300 | 23 | 48 | 10.4 | 7.8 |
| 67°09′091 N 032°22′658 E | | 3–13 | 60 | | 969 | 96.6 | 95 | | |
| **99-2** | Voronya Bay, the central part, 6 | 0–7 | –79 | Aleurite--pelite silt with a high content of mineral mica plates. Scraps of black and golden-black tubes of polychaetes | 660 | 62.5 | 94 | 39.5 | 29.6 |
| 66°56′654 N 032°25′677 E | | 7–15 | –50 | | 520 | 454 | 95 | | |
| **99-12** | Sea channel at the port of Kandalaksha, 25 | 0–2 | +180 | Silt consisting of lumpy aggregates of pelite particles. Abundant ligneous detritus. The 10- to 20-cm layer. Pelite silt. Abundant vegetable and zoogenous detritus | 800 | 0 | | 42.9 | 32.2 |
| 67°08′214 N | | 2–10 | 0 | | 700 | 375 | 95 | | |
| 032°23′944 E | | 10–17 | –60 | | 670 | 258 | 93 | | |

**Table 1.** (Contd.)

| Station no., coordinates | Station location, sea depth, m | Sediment horizon, cm | Eh, mV | Sediment description | $SO_4^{2-}$ (mg/l) | Sulfate reduction rate, µg S/(dm$^3$ day) | | $H_2S$ production (mg S/(m$^2$ day)) | Consumption of $C_{org}$ (mg C/(m$^2$ day)) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ΣS compounds | $H_2S$ (%) | | |
| **99-8** 67°09′446 N 032°20′482 E | Remote part near the Virna River, 7 | 0–10 | –130 | Silt consisting of friable aggregates of pelite particles. Ligneous residues and mica plates occur. Hydrogen sulfide odor is produced by the layer from 10 to 20cm | 840 | 861 | 97 | 70.6 | 52.9 |
| | | 10–20 | –190 | | 600 | 34 | 79 | | |
| **00-2** 66°31′20 N 033°01′07 E | Chernorechenskaya Bay, remote part, 4.5 | 0–2 | 140 | Silt consisting of friable aggregates of pelite particles. Grains of sand and gravel dimensions occur in abundance. Small black clumps of pelite particles occur in the 10- to 15-cm layer | 685 | 1710 | 76 | 242 | 182 |
| | | 2–5 | 120 | | 520 | 1080 | 73 | | |
| | | 5–10 | 60 | | 510 | 2550 | 57 | | |
| | | 10–15 | –105 | | 470 | 960 | 85 | | |
| **Shallow Bay of Bab'ye More and abandoned mussel plantations** | | | | | | | | | |
| **99-19** 66°37′100 N 033°10′100 E | Bab'ye More (central part), 25 | 0–5 | +80 | Silt consisting of friable aggregates of pelite particles disintegrating into tiny flakes and transparent scales of hydroxide micas upon dilution | 1050 | 11 | 100 | 131 | 98.3 |
| | | 5–15 | –10 | | 780 | 836 | 95 | | |
| | | 15–23 | –160 | | 760 | 680 | 91 | | |
| | | 23–30 | –180 | | 700 | 3191 | 95 | | |
| **99-17** 66°28′554 N 033°25′585E | Mussel plantations, (Isle Lushov), 14 | 0–5 | 60 | Silt consisting of lumpy aggregates of pelite particles with quartz grains and biotite plates of aleurite dimension. Partially decomposed fragments of algae are present | 880 | 0 | | 96.4 | 72.3 |
| | | 5–12 | –180 | | 580 | 1703 | 95 | | |
| | | | –120 | | 520 | 160 | 95 | | |
| **00-4** 66°28′55 N 033°25′58 E | Mussel plantations, (Isle Lushov), 15 | 0–2 | 120 | Silt consisting of friable aggregates of pelite particles. Particles of aleurite dimension and fragments of shell material occur | 1110 | 8 | 100 | 204 | 153 |
| | | 2–5 | 70 | | 910 | 1860 | 63 | | |
| | | 5–10 | 40 | | 830 | 2960 | 94 | | |
| **Bacterial mats and sediments in the shallow reservoirs on the littoral** | | | | | | | | | |
| **99-14-1** 66°32′90 N 033°08′05 E | Lake Polusolenoe. The mouth of a freshwater stream | Pink mat 0–1 | –70 | Black silt consisting of friable aggregates of pelite particles. Dense sandy–gravel layer below 7 cm | 50 | 1063 | 88 | 177.5 | 133 |
| | | Sediment, 1–7 | –125 | | 60 | 1490 | 57 | | |
| | | 5–7 | –80 | | 50 | 1847 | 85 | | |
| **00-14-1** 66°32′90 N 033°08′05 E | Lake Polusolenoe. The mouth of a freshwater stream | Pink mat, 0–2 | –50 | Semiliquid silt consisting of friable aggregates of pelite particles and black lumps. Sandy sediment with pelite silt inclusions below 5cm | 260 | 28800 | 69 | 1639 | 1229 |
| | | Sediment, 2–5 | –90 | | 250 | 14960 | 78 | | |
| | | 5–10 | 30 | | 215 | 22200 | 53 | | |
| | | 10–15 | 50 | | 220 | 2130 | 75 | | |
| **01-14-1** 66°32′90 N 033°08′05 E | Lake Polusolenoe. The mouth of a freshwater stream | Pink mat, 0–5 | –230 | Friable mat consisting of pink and brown clumps. Semiliquid pelite silt reaching sandy bed at a depth of 15 cm | 300 | 54300 | 65 | 3755 | 2816 |
| | | Sediment under the mat, 5–15 | –160 | | 250 | 10400 | 76 | | |
| **99-14-2** 66°32′90 N 033°08′05 E | Mats near the mainland shore | White mat, 0–1 | –30 | A dense sandy–gravel layer under the mat layer | 175 | 237 | 22 | 29.8 | 22.3 |
| | | Pink mat, 0–1 | –90 | | 180 | 231 | 51 | | |
| | | Green mat, 0–1 | –110 | | 160 | 127 | 29 | | |

**Table 1.** (Contd.)

| Station no., coordinates | Station location, sea depth, m | Sediment horizon, cm | Eh, mV | Sediment description | $SO_4^{2-}$ (mg/l) | Sulfate reduction rate, µg S/($dm^3$ day): ΣS compounds | Sulfate reduction rate, µg S/($dm^3$ day): $H_2S$ (%) | $H_2S$ production (mg S/($m^2$ day)) | Consumption of $C_{org}$ (mg C/($m^2$ day)) |
|---|---|---|---|---|---|---|---|---|---|
| **00-14-2** 66°32′90 N 033°08′05 E | Mats near the mainland shore | Olive mat, 0–1 | –70 | A dense sandy–gravel layer under the mat layer | 370 | 8460 | 89 | 898 | 673 |
| | | Pink mat, 0–1 | –90 | | 310 | 3490 | 82 | | |
| **99-14-3** 66°32′90 N 033°08′05 E | Mats near the island shore | Pink mat, 0–1 | –60 | Black silt consisting of friable aggregates of pelite particles and flakes of different color. A dense sandy–gravel layer below 20 cm | 200 | 1590 | 90 | 151.2 | 113 |
| | | Sediment, 1–2 | –150 | | 180 | 2720 | 97 | | |
| | | 2–20 | –290 | | 160 | 1080 | 94 | | |
| **00-14-3** 66°32′90 N 033°08′05 E | Mats near the island shore | Purple mat, 0–1 | 40 | Black silt consisting of friable aggregates of pelite particles. A dense sandy–gravel layer below 7 cm | 690 | 14150 | 88 | 368.3 | 276 |
| | | Sediment, 1–3 | –150 | | 490 | 5560 | 82 | | |
| | | 3–7 | –160 | | 420 | 2890 | 81 | | |
| **Sediments of the open areas of the littoral** | | | | | | | | | |
| **99-21** 66°32′80 N 033°04′5 E | BBS. Sediment along the upper waterline of the sandy littoral | 0–10 | +80 | Sandy-aleurite sediment, with an admixture of shell detritus with lumpy aggregates | 200 | 11 | 91 | 1.65 | 1.27 |
| | | 10–15 | +60 | | 200 | 13 | 46 | | |
| **Finely dispersed sediments containing organic matter (soil humus) at different littoral levels** | | | | | | | | | |
| **99-1** 66°56′70 N 032°23′5 E | Voronya Bay, the remote part | 0–0.2 | 100 | Pelite silt containing black humus particles. Remnants of the chitin sheaths of larvae and filamentous algae | 680 | 1005 | 99 | 75.6 | 56.7 |
| | | 0.2–1 | –80 | | 560 | 3206 | 98 | | |
| | | 1–5 | –10 | | 560 | 1199 | 60 | | |
| **00-8** 66°32′80 N 033°04′5 E | BBS. The soil humus sites on the littoral | 0–3 | –20 | Aleurite–pelite silt with traces of bioturbation and black inclusions. Admixtures of particles of sand dimension in the lower layer | 760 | 982 | 87 | 100.1 | 75.1 |
| | | 3–10 | –115 | | 570 | 634 | 76 | | |
| | | 10–20 | –30 | | 740 | 524 | 59 | | |
| **99-22** 67°05′6 N 032°43′2 E | Luven'ga. Ilistaya Bay, soil humus sites | 0–3 | –60 | Sandy silt consisting of different-dimension grains predominantly of the quartz composition. Remnants of algae and shell fragments of shrimps | 440 | 1093 | 82 | 110 | 82.5 |
| | | 3–10 | –150 | | 510 | 1104 | 95 | | |
| **01-06** 66°32′95 N 033°04′01 E | BBS. The soil humus sites on the littoral | 0–15 | –220 | Grayish aleurite–pelite silt with traces of bioturbation and fragmentary black inclusions | 750 | 1413 | 77 | 212 | 159 |
| **Deposits of the stormy discharge stretch** | | | | | | | | | |
| **99-20** 66°32′80 N 033°04′5 E | BBS. Stormy discharge stretch | 0–5 | –150 | Finely dispersed sandy silt. Abundant organic detritus consisting of mollusk shell fragments | 500 | 1909 | 82 | 173.8 | 130 |
| | | 5–10 | –160 | | 500 | 1566 | 86 | | |
| **01-03** 66°32′78 N 033°10′05 E | A stretch of stormy discharge in the mouth of the stream | 0–5 | –330 | Friable sandy–aleurite silt with pelite inclusions containing vegetable material | 400 | 18940 | 62 | 1293 | 970 |
| | | 5–20 | –280 | | 300 | 3460 | 76 | | |

**Table 1.** (Contd.)

| Station no., coordinates | Station location, sea depth, m | Sediment horizon, cm | Eh, mV | Sediment description | $SO_4^{2-}$ (mg/l) | Sulfate reduction rate, μg S/(dm$^3$ day) | | $H_2S$ production (mg S/(m$^2$ day)) | Consumption of $C_{org}$ (mg C/(m$^2$ day)) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ΣS compounds | $H_2S$ (%) | | |
| **00-5/1**<br>66°32′80 N<br>033°04′5 E | BBS. A deposit in the zone of the stormy discharge stretch | 0–1<br>1–8<br>8–11 | –40<br>–100<br>–75 | Stratified sandy–aleurite silt abounding in particles of vegetable material | 1180<br>850<br>850 | 51034<br>51020<br>9758 | 93<br>89<br>90 | 4374 | 3281 |
| **Depressions under stones, silted pits preserving aqueous layer during low tides, the mouth of a freshwater stream** | | | | | | | | | |
| **00-9**<br>66°32′80 N<br>033°04′5 E | Silted "bath" on the littoral | 0–1<br>1–5<br>5–10 | 120<br>–15<br>10 | An olive organic deposit above, a sandy–aleurite sediment with brown and black flakes underneath | 410<br>340<br>570 | 6067<br>5093<br>3631 | 40<br>67<br>73 | 495 | 371 |
| **99-23**<br>67°05′4 N<br>032°43′1 E | Luven'ga. A silt pit near Gorelyi Isle | 0–4<br>4–10 | 20<br>–220 | 0–4 cm. Aleurite--pelite silt consisting of a mixture of lumpy aggregates and quarts grains. 4–10 cm. Silt consisting of friable aggregates of pelite particles | 600<br>400 | 0<br>10310 | <br>91 | 618 | 464 |
| **00-5/2**<br>66°32′80 N<br>033°04′50 E | BBS. A pit near the stone along the lower waterline of the littoral during low tides | Mat, 0–1<br>Sediment, 1–8<br>8–11 | –65<br>–95<br>–75 | Black liquid silt with numerous pink flakes. Black silt consisting of the friable aggregates of pelite particles. Black silt with sandy particles | 1100<br>630<br>620 | 74130<br>51308<br>42962 | 68<br>88<br>85 | 5621 | 4216 |
| **01-05**<br>66°32′95 N<br>033°04′01 E | A pit under a stone at the lower waterline of the littoral | 0–10 | –350 | Black liquid silt with numerous pink flakes, with underlying silt consisting of friable aggregates of pelite particles | 1050 | 75500 light<br>137300 dark | 62<br>45 | 10640* | 7980 |
| **01-04**<br>66°32′78 N<br>033°10′05 E | BBS. A pink mat in the mouth of the freshwater stream on the littoral | 0–7 | –340 | The water layer abounding in pink and brown flakes, detritus particles, and residues of vegetable material | 820 | 40300 ight<br>159000 dark | 57<br>51 | 6976** | 5232 |
| **Littoral sediments studied in the winter period** | | | | | | | | | |
| **01 winter-6**<br>66°20′01 N<br>033°41′1 E | Kartesh. The upper waterline of the littoral | 0–10 | –50 | Gray sandy–aleurite sediment with dark-gray inclusions | 1580 | 20.8 | 68 | 3.12 | 2.34 |
| **01 winter-7**<br>66°20′01 N<br>033°41′1 E | Kartesh. The central part of the littoral | 0–5<br>5–10 | –20<br>–60 | Gray sandy–aleurite sediment with dark-gray inclusions and traces of bioturbation | 1520<br>1520 | 41.7<br>423.7 | 72<br>93 | 44.5 | 33.4 |
| **01 winter-8**<br>66°20′01 N<br>033°41′1 E | Kartesh. The central part of the littoral | 0–15 | 10 | Homogeneous dark-gray sandy–aleurite sediment | 1440 | 30.3 | 82 | 5.55 | 4.16 |
| **01 winter-9**<br>66°20′01 N<br>033°41′1 E | Kartesh. The lower waterline with a *Fucus* community | 0–15 | –50 | Friable dark-gray pelite sediment | 1240 | 361.3 | 68 | 54.2 | 40.7 |

* The calculation was made for 10 to 15 cm of the surface sediment.
** The calculated production is the mean value of the dark and light flasks.

**Table 2.** Number of sulfate-reducing bacteria in the sediments studie

| Station no. | Station location | Horizon, cm | Number of SRB, cells/ml silt |
|---|---|---|---|
| 00-4 | Mussel plantations (Lake Lushov) | 0–2 | $10^2$ |
| | | 2–5 | $10^4$ |
| | | 5–10 | $10^4$ |
| 00-14-1 (B-6) | Lake Polusolenoe. The mouth of the fresh water stream | Pink mat, 0–2 | $10^3$ |
| | | Sediment under the mat, 2–5 | $10^5$ |
| | | 5–10 | $10^5$ |
| | | 10–15 | $10^4$ |
| 00-8 | BBS. Soil humus sites on the littoral | 0–3 | $10^4$ |
| | | 3–10 | $10^4$ |
| | | 10–20 | $10^3$ |
| 00-5/1 | BBS. Deposits in the zone of the stormy discharge stretch | 0–1 | $10^4$ |
| | | 1–8 | $10^5$ |
| | | 8–11 | $10^5$ |

**Table 3.** Sulfate reduction rate and the isotopic composition ($\delta^{34}S$) of sulfur compounds in the sediment and cyanobacterial mat samples

| Station no. and location | Horizon, cm | SR rate, mg S/(dm$^3$ day) | $\delta^{34}\Sigma S_{S^{-}}$, ‰ | $\delta^{34}\Sigma S_{SO_4^{2-}}$, ‰ |
|---|---|---|---|---|
| 00-14-1 (B-6). Lake Polusolenoe, the mouth of freshwater stream | Pink mat, 0–2 | 28.8 | | 5.2 |
| | Sediment under the mat, 2–5 | 14.9 | | 7.8 |
| 00-14-3 (B-7). Lake Polusolenoe, mats near the island shore | Purple mat, 0–1 | 14.2 | | 15.0 |
| | Sediment under the mat, 1–3 | 5.6 | | 22.6 |
| 00-5/1(B-5). BBS. Deposits in the zone of the stormy discharge stretch | 0–1 | 51.0 | –14.5 | 24.7 |
| | 1–8 | 51.0 | –15.2 | 19.5 |
| 00-5/2 (B-5). BBS. A pit near the stone at the lower littoral waterline | Pink mat, 0–1 | 74.1 | –14.1 | 22.6 |
| | Sediment under the mat, 1–8 | 51.3 | –22.5 | 19.4 |
| 00-8. Soil humus sites on the littoral | 0–3 | 0.98 | –36.7 | 13.6 |
| 00-9. BBS. Silted “bath” on the littoral | 0–5 | 5.5 | –5.8 | 22.1 |

The third group included the stations situated on the littoral (stations 1 and 20–23). The littoral is defined as a zone situated in the zone exposed to flood tides, where zero depths should be considered as the lower borderline and the greatest possible increase in the flood tide level should be considered as the upper borderline [15]. The littoral is characterized by sharp daily fluctuations in temperature, salinity, moisture content, aeration degree, etc.

## RESULTS

**Physicochemical characteristic of the sediments studied.** The sediment core samples studied in the water area of the Kandalaksha Bay (Table 1) were represented by sandy–aleurite–pelite silts. In a number of core samples, detritus of vegetable and, rarer, zoogenic origin occurred in abundance. Swollen ligneous particles occurred in the sediments of the stations near the port of Kandalaksha. As a rule, the surface sediment layer was brown, and below it was black. At most stations, the upper sediment layer (0–5, 0–10 cm) was oxidized, assuming reduced properties below 5 cm. At some of the stations, all the sediment layers tested were slightly oxidized (stations 99-11, 99-9, 99-10, 00-4). At two stations (99-2 and 99-8), reduced sediments were found. The sediment temperature ranged between 11 and 13°C during the summer season and between –0.5 and 0.5°C during the winter season.

Sediment sampling on the littoral was carried out in zones typical of microlandscapes. The sediment of the sandy–silt littoral (stations 99-21 and 01winter-8) was gray and had a positive redox potential. The thin silt areas accumulating in places with impaired hydrodynamics, the so-called soil humus areas, differ from the sandy and sandy–silt littoral zones. As a rule, these are local depressions, where OM is conserved [5]. In the sediment cores sampled from the soil humus sites, the redox potential value attained –220 mV (station 01-06). The sediment found within the stretch of the stormy discharge of marine macrophytes into the mouth of the freshwater stream (station 01-03) had a special structure: it represented a mixture of vegetable detritus and mineral particles.

**The rate of sulfate reduction processes.** The SRR values in the core samples of bottom sediments of the coastal stations in the summer period varied between 7.5 and 3190 μg S/($dm^3$ wet silt day) (Table 1). The maximal SRR was recorded in the central shallow part of the Chernorechenskaya Bay (up to 2550 μg S/($dm^3$ day)), in the bay at the site where the Virna River flows into it (up to 861 μg S/($dm^3$ day)), in the former mussel plantations near Isle Lushov (up to 2960 μg S/($dm^3$ day)), and in the Bab'ye More (up to 3191 μg S/($dm^3$ day)).

The sediments of most of the bay stations were characterized by rather low SRR values (7.5 to 66 μg S/($dm^3$ day)) in the surface layer and by higher SRR values (35 to 450 μg S/($dm^3$ day)) in the 5- to 15-cm layer. During the winter season, at a temperature of –0.5 to 0.5°C, the SRR values were lower. In the sediments of the Kartesh Bay, they constituted 7.9 to 13 μg S/($dm^3$ day).

The studies of the cyanobacterial mats and sediments in Lake Polusolenoe were conducted at three permanent stations for three summer seasons. Between-the-year weather and stormy differences determined the difference in the level of water in the lake, as well as in the degree of its mineralization. At station 99-14-1 situated in the mouth of the freshwater stream, the minimal SRR value was recorded in 1999 (1.06 mg S/($m^3$ day) in the mat layer and up to 1.85 mg S/($m^3$ day) in the sediment under the mat, Table 1). The studies conducted at the same station in 2000 and 2001 showed that the SRR values in the mat layer (28.8 and 54.3 mg S/($m^3$ day), respectively) were higher than the 1999 estimates by a factor of 30 to 50. In the sediment under the mat, the SRR value in 2000 and 2001 exceeded the 1999 values 15- and 7-fold, respectively.

In the widest ranges, the SRR values varied in the core samples of sediments obtained from the littoral. The minimal values (11 μg S/($dm^3$ day)) were recorded for the homogeneous sediment core on the silt–sandy littoral (station 99-21). The soil humus sediments were characterized by similar profile values of the sulfate reduction process (524 to 1413 μg S/($dm^3$ day), stations 99-22, 01-06, and 00-8). The maximal values of the process rate were recorded for the sediments present within the stretch of decomposing macrophytes, in local pits, along the lower littoral waterline, and in the mouth of the freshwater stream (51000 to 159000 μg S/($dm^3$ day)).

The studies conducted on the littoral in winter showed that the sulfate reduction process in the sediments did not stop. The SRR value in the sediments covered with snow and ice (station 01winter-6-9) constituted 21 to 424 μg S/($dm^3$ day).

The sediments studied exhibited apparent differences in the ratio of hydrogen sulfide to other reduced sulfur compounds formed in the process of bacterial sulfate reduction. The newly formed hydrogen sulfide in the surface horizons of sediments with a high sulfate reduction rate was found to constitute from 90 to 100% of the sum of all reduced sulfur compounds (Table 1). The insignificant amount of iron compounds determining the discharge of hydrogen sulfide in the form of pyrite in the process of sedimentogenesis results in an increased concentration of free $H_2S$. A relatively high proportion of reduced sulfur compounds, the highest among the series explored, was found in the mats of Lake Polusolenoe and in the mats on the littoral in the mouth of the freshwater stream (station 01-04). $H_2S$ binding in the mats and sediments is likely to occur due to the iron entering with fresh swamp waters.

The high sulfate reduction rates observed in the littoral sediments agree with the data of quantitative enumeration of sulfate-reducing bacteria (SRB) in mineral medium with lactate (Table 2). The number of sulfate-reducing bacteria attained dozens and hundreds of thousands in the sediments of station 00-14-1 situated in the mouth of the freshwater stream in the littoral. In the sediments of coastal stations, the SRB number did not exceed one thousand cells per 1 $cm^3$ of wet silt.

**Isotopic composition of sulfur compounds.** The analysis of the isotopic composition of the sulfur of sulfate and reduced sulfur compounds (Table 3) confirmed the differences in the rates of transformation of sulfur compounds in the sediments of different zones of the Kandalaksha Bay. A typically marine sulfate ($\delta^{34}S_{SO_4^{2-}}$ = 19.4‰) was revealed in the surface sediment along the lower littoral waterline. Here, complete washing out with the sea water is observed twice a day, with the ingress of the sulfates to be consumed in the sulfate reduction process. The increased sulfate sulfur heavy isotope content recorded for a number of the sediments studied ($\delta^{34}S_{SO_4^{2-}}$ from 22.1 to 22.6‰, stations 00-5/2, 00-9, and 00-14-3) was indicative of the process of consumption of the light isotope in the process of bacterial sulfate reduction.

In the water contained in the pink mat and in the silt water of the sediment (station 00-14-1), an isotopically light sulfate ($\delta^{34}S_{SO_4^{2-}}$ = 5.2–7.8‰) was found, which is unusual for typical marine sediments. Its presence is impossible to explain by the ingress of the isotopically light sulfate of terrigenous discharge, since the mineralization of the water of the freshwater stream flowing into Lake Polusolenoe was less than 10 mg/l. In our opinion, the presence of the isotopically light sulfate in the mat and sediment samples at station 14-1 can be explained by the sulfur cycling at the water–sediment interface. The first stage of this cycle is sulfate reduction by sulfate-reducing bacteria, resulting in the for-

**Table 4.** Hydrogen sulfide production in the main ecotopes of the sand–silt littoral of the Kandalaksha Bay of the White Sea

| Main littoral ecotopes | Occupied area, % | $H_2S$ production (mg S/($m^2$ day)) | $H_2S$ production (kg S/($km^2$ day)) | Ecotope contribution to $H_2S$ production, % |
|---|---|---|---|---|
| Sandy and sandy–silt sediments | 84–94 | 2–4 | 1.7–3.7 | 1.8–2.8 |
| Thin silts (soil humus) | 5–10 | 125 | 6.3–12.5 | 6.1–10.4 |
| Stormy discharge stretches | 0.5–3 | 1950 | 9.8–59 | 16.1–28.9 |
| Silted pits and depressions | 1–3 | 4300 | 43–129 | 63.2–70.7 |
| Total on the littoral | 100 | | 60.8–204 | 100 |

mation of isotopically light hydrogen sulfide. The hydrogen sulfide formed is consumed by phototrophic bacteria dominating the mat community, and this leads to the formation of sulfate significantly enriched with the light sulfur isotope. Upon dilution with the seawater, the isotopic sulfate composition is characterized by $\delta^{34}S_{SO_4^{2-}}$ = 5.2–7.8‰.

## DISCUSSION

**Sediments of the coastal zone stations.** The rate of the process of sulfate reduction in the sediments of marine reservoirs is primarily determined by the content of available organic matter. Hydrogen sulfide production increases when reservoirs are contaminated by household and industrial wastes containing organic matter [16].

The data obtained allow us to give an average SRR estimate for most of the stations explored. The average SRR value for 20 horizons at nine stations was 130 μg S/($dm^3$ wet sediment day). An increased rate of sulfate reduction was recorded in the sediments of abandoned mussel plantations rich in organic matter: in the Bab'ye More Bay, a reservoir with a high level of allochthonous $C_{org}$ ingress and with bottom sediments protected from the erosion by tidal currents by a shallow whitewater zone, as well as in the shallow Chernaya Rechka Bay, in the zone of mixture of fresh and sea waters. The daily hydrogen sulfide production value in the sediments of these stations exceeded the average production in the total data file three- to fivefold.

One of the objectives of our investigation was to compare SRR in the bottom sediments of the stations situated in the contamination zone and of the stations remote from the sources of contamination. The studies showed that at the stations situated in close proximity to industrial works (the bay channel near the bulk plant, the port of Kandalaksha, and the sea channel in the port area), no increased level of the process of sulfate reduction was revealed. All the stations mentioned above are situated in the zone of intense tides. As a result, a considerable amount of allochthonous organic matter is carried to the deeper part of the bay and to the littoral.

Our studies showed a high level of hydrogen sulfide production in the mats and sediments of Lake Polusolenoe (150 to 3755 mg S/($m^2$ day), Table 1). The high $H_2S$ production determines abundant development of phototrophic and colorless sulfur bacteria oxidizing hydrogen sulfide to sulfur and sulfate.

The influence of light on $H_2S$ production in illuminated surface horizons of marine sediments was shown in a number of works. The SRR in dark flasks significantly exceeded the rate of the process occurring on the exposure to light [9, 17]. At a number of the stations, we conducted studies to determine SRR in parallel in the dark and on the exposure to light. The SRR was shown to be higher in the dark flasks (Table 1, stations 01-04, 01-05). These results can be explained by the high activity of phototrophic bacteria oxidizing, in the light, part of the hydrogen sulfide formed in the process of sulfate reduction. Considering that at the end of the summer season the dark and light periods of the day are approximately equal, we used an average value between the dark- and light-incubated flasks to calculate the daily $H_2S$ production at these stations.

**Intensities of sulfate reduction in the sediments of the coastal shallow waters and different littoral ecotopes.** To study the scale of the processes occurring on the littoral, it is necessary to identify typical zones having characteristic features in common. The most conventional stratification scheme regards a littoral from the point of view of vertical zonation. Indeed, the composition and structure of littoral ecotopes is to a large extent determined by the vertical zonation schemes and, accordingly, by the sediment flooding and denudation times. The type of littoral community depends on the character of the ground and the hydrological characteristics of the coastal water areas. The local state of a community depends on the degree of sediment enrichment with organic matter. In their works, hydrobiologists distinguish certain microlandscapes differing in the composition of the plant and animal community. The basis for this distinguishment is, as a rule, a local topical trait. Among the littoral biotopes, the phytal, occupying the lower littoral border, soil humus sites, stretches of stormy deposits of dead algae, and local silted depressions conserving moisture during low tides are distinguished.

In our investigations, we showed a striking difference in the level of hydrogen sulfide production in the microlandscapes identified. The average hydrogen sulfide production in the soil humus constituted 125 mg S/($m^2$ day); in the deposits of stormy discharge stretches, 1950 mg S/($m^2$ day); in depressions under stones and slabs in silted pits serving as traps for suspended OM, 4300 mg S/($m^2$ day). The assessment of the share of microlandscapes with increased productivity made within the stretch of the sandy–silt and sandy–boulder littoral 1 km long and 30 to 80 m wide (the total area 0.065 $km^2$) showed that the soil humus sites accounted for 5 to 10% of the littoral area; the stretches of stormy deposits, for 0.5 to 3.0%; and the silted pits preserving aqueous layer during low tides, for 1.0 to 3.0% (Table 4). The pools in depressions on the surface of stones were not taken into account. With such an assessment, the share of the rest of the littoral area is 84 to 94%, no less than 20% accounting for the areas occupied by rocks, individual stone slabs, and boulders. The calculation shows that the daily hydrogen sulfide production from a 1-km littoral stretch (August) was 60.8 to 202 kg S/($km^2$ day). Using the coefficient derived in accordance with the equation $2[CH_2O] + SO_4^{2-} = H_2S + 2HCO_3^-$, it is possible to calculate that the consumption of organic carbon for sulfate reduction per 1 $km^2$ of the littoral stretch is 46 to 152 kg $C_{org}$/($km^2$ day). A similar calculation was carried out for the coastal shallow waters of the Kandalaksha Bay that we explored. The hydrogen sulfide production in the open part of the Kandalaksha Bay for the coastal shallow waters of the Kandalaksha Bay averaged 14.0 kg S/($km^2$ day); in little bays (inlets), 68.2 kg S/($km^2$ day).

In conclusion, it is expedient to compare the values of hydrogen sulfide production that we recorded in the coastal zone sediments to the published data available.

| Sampling site | Productivity, g S/($m^2$ day) | Author |
|---|---|---|
| Barents Sea littoral | 1.18–3.15 | Ivanov [18] |
| North Sea littoral (Denmark) | 0.64–1.60 | Jorgensen [17] |
| Silt sediments, Limfjorden, Denmark | 0.07–0.64 | Jorgensen [17] |
| Coastal sediments, Troitsa Bay | 0.08–40.48 | Karnachuk [9] |
| Coastal sediment, Vostok Bay | 0.77–20.8 | Karnachuk [9] |
| Black Sea, the Danube delta sediments | 0.017–2.13 | Lein [19] |
| Caribbean Sea, the Gulf of Batabano sediments | 0.36–13.9 | Namsaraev [20] |
| White Sea, marine coastal sediments | 0.003–0.24 | Our data |
| White Sea, littoral sediments and mats | 0.002–10.6 | Our data |

The SRR estimates that we obtained for the coastal shallow-water sediments are somewhat inferior to the values known for Limfjorden. However, the maximal values of SRR that we recorded are higher than the values determined for North Sea coastal sediments and are comparable to the $H_2S$ production values in the shallow-water sediments of the coastal waters of the Danube estuary [19]. The sulfate reduction rate values are inferior to the values known for the coastal sediments of the Vostok and Troitsa Bays, subject to significant anthropogenic contamination [9], as well as for the shallow-water silt sediments of the Gulf of Batanabo (Caribbean Sea) characterized by extremely high values of primary production and organic matter content [20].

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