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BENTHIC DIATOMS (BACILLARIOPHYTA): DIVERSITY AND HIERARCHICAL STRUCTURE OF TAXOCENES ON SOFT BOTTOM OFF THE KRUGLAYA BAY (THE BLACK SEA, CRIMEA)

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The Kruglaya Bay (or the Omega Bay) holds high recreational value due to its sheltered location within the Sevastopol region, extensive beach area, and shallow waters with the soft bottom. These features necessitate monitoring of marine biota state. This work was aimed at determining the species richness and hierarchical structure of benthic diatoms (Bacillariophyta) in the Kruglaya Bay insufficiently studied before and at comparing them with coastal biotopes off the Crimea being under various anthropogenic load. Based on results of a benthic survey in 2004, we studied the species richness of Bacillariophyta off the Omega Bay and analyzed the taxonomic diversity applying floristic and formalized methods and using taxonomic distinctness indices: TaxDI (AvTD and VarTD). In total, 264 species and intraspecific taxa of benthic diatoms were identified: 256 species, 73 genera, 35 families, 21 orders, and 3 classes. We found 70 species and 5 genera previously recorded by us as new to the Bacillariophyta flora of the northern Black Sea shelf, along with 5 species of diatoms previously described by us as new to science. The greatest species similarity was revealed both between habitats with the lowest anthropogenic load (the Omega Bay – the Dvuyakornaya Bay and the Omega Bay – the Laspi Bay) and between heavily polluted water areas (the Sevastopol Bay – the Karantinnaya Bay and the Sevastopol Bay – the Balaklava Bay) regardless of their geographical proximity and differences in hydrological and hydrophysical conditions. Bacillariophyta taxocenes from heavily polluted sites feature low species richness and high proportion of mono- and oligospecies branches due to reduction of low pollution–sensitive taxa. AvTD values exceeded the average expected level for the Black Sea Bacillariophyta flora. In conditionally clean waters, diatom taxocenes exhibited high species richness, numerous polyspecies branches, and a low proportion of mono- and oligospecies branches aggregating at different levels of a hierarchical tree. AvTD values are below the average expected level for the Black Sea diatom flora. Features of diatom taxocene structure from the compared sites are mediated by a taxa-specific response to combined environmental stressors. Using TaxDI when analyzing Bacillariophyta taxonomic diversity allows for statistically reliable assessment of marine coastal waters under different pollution regimes.

Keywords: Omega Bay, TaxDI, species richness, anthropogenic load

Within the Sevastopol Bay system, the Kruglaya Bay (or the Omega Bay) holds high recreational value due to its location within the city, shallow soft bottom, and the lack of industrial facilities in the surrounding area. Its shores host extensive beaches and numerous cafes, resorts, and recreational areas. Such a heavy use of the coastline exerts substantial anthropogenic load on its waters necessitating evaluation of the state of its marine biota. The main tasks of the coastal ecosystem monitoring are the inventory and comprehensive assessment of biota. The resulting data makes it possible to track changes in the marine environment. Benthic diatoms (Bacillariophyta) are the key link in the functioning of coastal ecosystems. The assessment of their species richness is required for bioindication and analysis of the aquatic environment [Barinova et al., 2006; Blanco et al., 2012; Borja et al., 2013; Keck et al., 2016; Stenger-Kovács et al., 2016; Tokatli et al., 2020]. The study of benthic diatom diversity is of fundamental importance for the Black Sea shelf: there, increasing technogenic pollution and anthropogenic load affect the structure of taxocenes, and consequently reduce Bacillariophyta species richness [Guidelines, 2015; Nevrova, 2022; Petrov, Nevrova, 2004, 2007; Petrov et al., 2005, 2010]. To reveal aspects of Bacillariophyta taxonomic diversity, generalization of results and a comprehensive analysis based on both floristic and formalized methods are needed. In this regard, the aim of our work was to carry out a comparative assessment of current diversity and hierarchical structure of benthic diatom taxocenes in the previously insufficiently surveyed Kruglaya Bay and in Crimean coastal habitats subject to varying technogenic pollution involving taxonomic distinctness indices: TaxDI [Nevrova, 2022; Warwick, Clarke, 1998, 2001].

MATERIAL AND METHODS

Benthic diatoms were studied in the Omega Bay located in the northwestern Sevastopol within the Sevastopol Bay system (Fig. 1). Its low-gradient and abrasion-accumulative coasts composed of Sarmatian limestones and layers of marl form a leveled shoreline with alternating abrasion-erosion and accumulative sections [Agarkova-Lyakh, Lyakh, 2019; Ignatov et al., 2014]. Mean depths are approximately 0.5–1 m in the bay innermost part, about 5 m in the central area, and 16 m at the mouth. Bottom sediments are predominantly silt, fine-grained sand, and shells, both broken and unbroken [Zenkovich, 1960]. Compared to the open coast, the bay area is characterized by a calm wave regime, due to its enclosed type and mouth narrowing. The Kruglaya Bay is about 1 km long. It is characterized by a relatively weak water exchange and shallowness, thus promoting rapid summer heating of water. Since the bay's shores are among the most popular beaches in Sevastopol, and its coastline hosts dozens of tourist infrastructure facilities, the water area is subject to intensive recreational pressure during summer. This necessitates monitoring of the state of the biota.

Biological material was sampled on 28.07.2004 within a comprehensive survey conducted by IBSS Department of Benthos Ecology. Sampling covered sandy-silty sediments of the Omega Bay (44°35′N, 33°26′E) at depths ranging 1.5–16 m. Ten samples from five stations were processed. During a previous prognostic estimation of the diatom species richness, depending on the number of samples processed within a study area with similar biotopic conditions, it was revealed as follows: an analysis of only one station allows for accounting for approximately 35% of the total species richness, while an analysis of five stations, for 80% [Petrov, Nevrova, 2013, 2014]. Preliminary results of the study of diatom species richness in the Omega Bay are presented in the monograph [Nevrova, 2022]. In this paper, with the use of additional illustrative material, new data is discussed, and a further comparative analysis of Bacillariophyta hierarchical diversity in other biotopes of the Crimean coast is carried out.

The map of the study area was built using the digital sources https://d-maps.com/ [2024] and https://www.sasgis.org/ [2023], and then edited involving SAS.Planet and Adobe Photoshop software (Fig. 1).

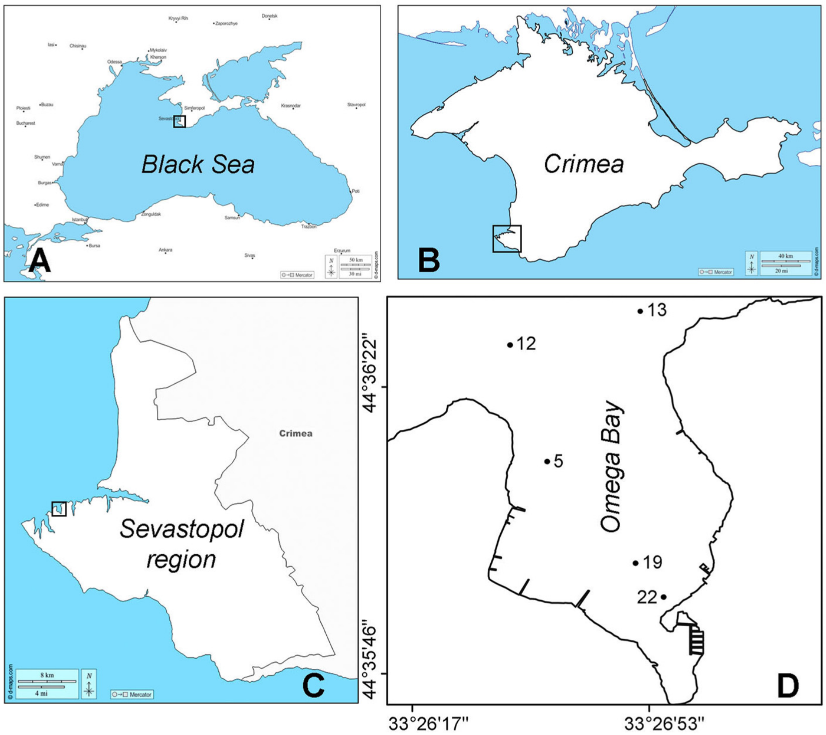

Fig. 1. Map of the study area: A, the Black Sea; B, the Crimean Peninsula; C, the Sevastopol region; D, sampling sites off the Omega Bay

Biological material was sampled by a diver with a meiobenthos core tube (S = 15.9 cm^2): the upper layer of soft bottom substrate was collected. To separate epipelon and epipsammon, the sediment was treated with ultrasound for 20 min. Permanent slides for a light and scanning electron microscopes (hereinafter LM and SEM, respectively) were prepared according to a standard method described in [Nevrova, 2022].

Microphotographs of valves were taken, and species in each sample were identified from permanent slides under a LM Nikon Eclipse E600 equipped with a PlanAPO ×100 objective and a digital camera Nikon DS-Fi1 at the Institute of Marine and Coastal Sciences (University of Szczecin, Poland) by the author. Ultrastructural microphotography was performed under a SEM Hitachi S-4500 (Japan) at the Goethe University (Frankfurt, Germany) by Professor H. Lange-Bertalot and master engineer M. Ruppel, and also under a SEM Hitachi SU3500 (Japan) (IBSS, Sevastopol, Russia) by the author and V. Lishaev, head of the Microscopy Laboratory.

Permanent slides for a LM are deposited in the collection of E. Nevrova in IBSS Department of Benthos Ecology, and partially in the collection of Professor A. Witkowski in the Department of Paleoceanology of the Institute of Marine and Coastal Sciences. Permanent stubs for a SEM are stored in the collection of Professor H. Lange-Bertalot at the Goethe University, and partially in the collection of E. Nevrova at IBSS.

We used the guides [Guslyakov et al., 1992; Levkov, 2009; Proshkina-Lavrenko, 1963; Witkowski et al., 2000] and other publications. The systematic position of benthic diatoms is based on [Round et al., 1990], with resent additions [AlgaeBase, 2024; Catalogue of Diatom Names, 2011; Guslyakov et al., 1992; Nevrova, 2013b; Witkowski et al., 2000*; etc.*]. Nomenclatural data is given in accordance with the International Plant Names Index [2024].

Morphometrics measurements of Bacillariophyta cells were performed using ImageJ software (v1.4.3.67) [2025].

During summer, near-bottom water of the Kruglaya Bay exhibits elevated concentrations of ammonium nitrogen, phosphorus, nitrates, and BOD_5 (biochemical oxygen demand) [Pavlova et al., 2001]. Bottom sediments are characterized by low-level technogenic pollution from urban runoff, high content of ammonium nitrates and phosphorus, and elevated values of BOD_5: the latter ones were approximately ten times higher in open waters at some stations [Mironov et al., 2003]. During hot season, intensive recreational load mediates oxygen depletion in near-bottom water and upper layer of bottom sediments. Nevertheless, in terms of technogenic pollution, the Omega Bay can be classified as a relatively unpolluted area, similar to the Dvuyakornaya and Laspi bays. These bays contrast sharply with heavily polluted ones: the Karantinnaya, Sevastopol, and Balaklava bays, where mean concentrations of heavy metals and organic pollutants in soft bottom sediments exceed background levels by 2–10 times [Nevrova, 2022]. The above-mentioned water areas were selected for comparative analysis precisely based on their pollution levels.

The hierarchical structure of diatom taxocenes in the Kruglaya Bay and in other areas along the Crimean coast of the Black Sea was analyzed in PRIMER v6 [Clarke, Gorley, 2006] using TaxDI. We applied the average taxonomic distinctness index (AvTD, Δ^+) and variation in taxonomic distinctness index (VarTD, Λ^+). Those were calculated according to a methodology described in [Nevrova, 2022; Warwick, Clarke, 1998, 2001].

RESULTS AND DISCUSSION

Species richness of benthic diatoms in the Omega Bay. The taxocene of benthic Bacillariophyta included 264 species and intraspecific taxa (hereinafter IST). Those were represented by 256 species, 73 genera, 35 families, 21 orders, and 3 classes (Table 1).

Table 1. Benthic diatoms on soft bottom off the Omega Bay

Taxon	Species
Class Coscinodiscophyceae Orders, 6 Families, 8 Genera, 14 Species, 20 Species and IST — 20	*Actinocyclus subtilis* (W. Greg.) Ralfs; *Amphitetras antediluvianum* Ehrenb.; *Auliscus sculptus* (W. Sm.) Ralfs; *Biddulphia rostrata* var. *alata* Proschk.-Lavr.; *Coscinodiscus radiatus* Ehrenb.; *Cyclotella choctawhatcheeana* Prasad*; *C. comensis* Grunow; *C. meneghiniana* Kütz.; *C. operculata* (C. Agardh) Kütz.; *Dimeregramma fulvum* (W. Greg.) Ralfs; *D. minor* (W. Greg.) Ralfs; *Glyphodesmis distans* (W. Greg.) Grunow; *Hyalodiscus scoticus* (Kütz.) Grunow; *Paralia sulcata* (Ehrenb.) Cleve; *Plagiogramma* sp.; *Puncticulata radiosa* (Lemmerm.) Håk.; *Stephanodiscus hantzschii* Grunow; *Thalassiosira eccentrica* (Ehrenb.) Cleve; *T. parva* Proschk.-Lavr.; *T. parvula* I. V. Makarova
Class Fragilariophyceae Orders, 7 Families, 7 Genera, 11 Species, 18 Species and IST, 18	*Ardissonea baculus* (W. Greg.) Grunow; *A. crystallina* (C. Agardh) Grunow; *Fragilaria* sp. 1; *Grammatophora marina* (Lyngbye) Kütz.; *G. oceanica* Ehrenb.; *Hyalosira aberrans* (Giffen) Navarro*; *Licmophora abbreviata* C. Agardh; *L. gracilis* (Ehrenb.) Grunow; *Microtabella delicatula* (Kütz.) Round; *Opephora krumbeinii* Witkowski, Witak et Stachura*; *O. marina* (W. Greg.) Petit; *O. mutabilis* (Grunow) Sabbe et Vyverman*; *O. pacifica* (Grunow) Petit*; *Psammodiscus nitidus* (W. Greg.) Round et D. G. Mann; *Rhabdonema minutum* Kütz.; *Tabularia gaillonii* (Bory) Bukht.; *T. tabulata* (C. Agardh) P. J. M. Snoeijs; *Thalassionema nitzschioides* (Grunow) Mereschk.

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Taxon	Species
Class Bacillariophyceae Orders, 8 Families, 20 Genera, 48 Species, 217 Species and IST, 226	*Achnanthes brockmannii* Hust.; *A. longipes* C. Agardh; *A. fimbriata* (Grunow) R. Ross; *Achnanthes* sp. O1; *Achnanthidium glyphos* Riaux-Gob., Compère et Witkowski*; *Amphora acuta* W. Greg.; *A. arcus* W. Greg.; *A. bigibba* Grunow ex A. Schmidt; *A. caroliniana* Giffen; *A.* cf. *abludens* Simonsen*; *A. crassa* W. Greg.; *A. cuneata* Cleve; *A. exigua* W. Greg.; *A. exilitata* Giffen*; *A. graeffeana* Hendey; *A. helenensis* Giffen*; *A. laevis* W. Greg.; *A. lineolata* Ehrenb.; *A. marina* W. Sm.; *A. obtusa* W. Greg.; *A. ocellata* Donkin; *A. ostrearia* Bréb.; *A. proteus* W. Greg.; *A. staurophora* Jahlin-Dannfelt; *A. subacutiuscula* Schoemann; *A. wisei* (Salah) Simonsen; *Amphora* sp. O1; *Amphora* sp. O2; *Aneumastus* sp. 1; *Anorthoneis excentrica* (Donkin) Grunow; *Astartiella bahusiensis* (Grunow) Witkowski, Lange-Bert. et Metzeltin*; *Astartiella* sp. O1; *Bacillaria paxillifera* (O. F. Müll.) Hendey; *Berkeleya scopulorum* (Bréb. et Kütz.) E. J. Cox; *Biremis ambigua* (Cleve) D. G. Mann; *B. lucens* (Hust.) Sabbe, Witkowski et Vyverman*; *B. ridicula* (Giffen) D. G. Mann*; *Caloneis densestriata* (Proschk.-Lavr.) Gusl.; *C. liber* (W. Sm.) Cleve; *Campylodiscus parvulus* W. Sm.; *C. thuretii* Bréb.; *Campylodiscus* sp. 1; *Catenula adhaerens* Mereschk.; *Chamaepinnularia alexandrowiczii* Witkowski, Lange-Bert. et Metzeltin*; *Chamaepinnularia* cf. *alexandrowiczii* Witkowski, Lange-Bert. et Metzeltin; *Ch. clamans* (Hust.) Witkowski, Lange-Bert. et Metzeltin*; *Ch. margaritiana* (Witkowski) Witkowski*; *Ch. truncata* (König) Witkowski, Lange-Bert. et Metzeltin*; *Climaconeis inflexa* (Bréb. ex Kütz.) E. J. Cox; *Cocconeiopsis breviata* (Hust.) Witkowski, Lange-Bert. et Metzeltin*; *C. fraudulenta* (A. W. F. Schmidt) Witkowski, Lange-Bert. et Metzeltin*; *C. patrickae* (Hust.) Witkowski, Lange-Bert. et Metzeltin*; *Cocconeis crispa* Edsbagge*; *C. clandestina* A. W. F. Schmidt*; *C. diminuta* Pant.*; *C. dirupta* var. *flexella* (Janisch et Rabenh.) Grunow; *C. discrepans* A. W. F. Schmidt*; *C. distans* W. Greg.; *C. engelbrechtii* Cholnoky; *C. euglypta* Ehrenb.; *C. guttata* Hust. et Aleem*; *C. molesta* var. *crucifera* Grunow; *C. pediculus* Ehrenb.; *C. pelta* A. W. F. Schmidt*; *C. peltoides* Hust.*; *C. placentula* Ehrenb.; *C. pseudocostata* Romero*; *C. scutellum* Ehrenb.; *C. scutellum* var. *parva* (Grunow) Cleve; *C. speciosa* W. Greg.; *C. stauroneiformis* (Rabenh.) Okuno; *Cocconeis* sp. O1; *Cocconeis* sp. O2; *Cocconeis* sp. 5W; *Cylindrotheca closterium* (Ehrenb.) Reimann et Lewin; *Dickieia resistans* Witkowski, Lange-Bert. et Metzeltin; *D. subinflata* (Grunow ex Cleve et J. D. Möller) D. G. Mann; *Diploneis bombus* (Ehrenb.) Cleve-Euler ex Backman et Cleve-Euler; *D. chersonensis* (Grunow) Cleve; *D. coffaeiformis* (A. W. F. Schmidt) Cleve*; *D. crabro* Ehrenb.; *D. didyma* Ehrenb.; *D. fusca* (W. Greg.) Cleve; *D. notabilis* (Grev.) Cleve; *D. notabilis* var. *tenera* Proschk.-Lavr.; *D. rex* Droop; *D. smithii* (Bréb.) Cleve; *D. smithii* var. *pumila* (Grunow) Hust.; *D. stroemii* Hust.*; *D. suborbicularis* (W. Greg.) Cleve; *D. vacillans* (A. W. F. Schmidt) Cleve; *D. vetula* (A. W. F. Schmidt) Cleve*; *Diploneis* sp. 1F; *Diploneis* sp. 1VS; *Entomoneis gigantea* var. *sulcata* (O'Meara) Gusl.; *Eolimna* sp. 2O*; *Fallacia cassubiae* Witkowski; *F. escorialis* (Simonsen) Sabbe et Vyverman*; *F. florinae* (Moeller) Witkowski*; *F. forcipata* (Grev.) A. Stickle et D. G. Mann; *F. margino-punctata* Sabbe et Vyverman*; *F. ny* (Cleve) D. G. Mann*; *F. oculiformis* (Hust.) D. G. Mann*; *F. schaeferae* (Hust.) D. G. Mann*; *F. subforcipata* (Hust.) D. G. Mann; *Fallacia* sp. 1F; *Fallacia* sp. 9O; *Gyrosigma attenuatum* (Kütz.) Cleve; *Halamphora acutiuscula* (Kütz.) Levkov; *H. angularis* (W. Greg.) Levkov; *H. coffeaeformis* (C. Agardh) Levkov; *H. eunotia* (Cleve) Levkov; *H. tenerrima* (Aleem et Hust.) Levkov*; *H. turgida* (W. Greg.) Levkov; *Hantzschia amphioxys* f. *capitata* O. Müll.; *H. marina* Donkin*; *H. virgata* (Roper) Grunow*; *Hantzschia* cf. 177-1; *Hantzschia* sp. O1; *Hippodonta* sp. 2; *Hippodonta* sp. 3; *Hippodonta* sp. 6; *Hippodonta* sp. 9; *Hippodonta* sp. O1; *Karayevia amoena* (Hust.) Bukht.; *Lunella ghalebii* Witkowski, Lange-Bert. et Metzeltin*; *Lyrella abruptapontica* Nevrova, Witkowski, Kulikovskiy & Lange-Bert.; *L. atlantica* (A. W. F. Schmidt) D. G. Mann; *L. barbara* (Heiden) D. G. Mann*; *L. clavata* (W. Greg.) D. G. Mann; *L. dilatata* (A. W. F. Schmidt) Nevrova, Witkowski, Kulikovskiy et Lange-Bert.**; *L. fogedii* Witkowski, Lange-Bert. et Metzeltin*;

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Taxon	Species
	L. hennedyi (W. Sm.) A. Stickle et D. G. Mann; *L. karayevae* Nevrova, Witkowski, Kulikovskiy et Lange-Bert.**; *L. lyroides* (Hendey) D. G. Mann; *L. majuscula* (Hust.) Witkowski*; *L. pontieuxini* Nevrova, Witkowski, Kulikovskiy et Lange-Bert.**; *L. pseudolyra* Nevrova, Witkowski, Kulikovskiy et Lange-Bert.**; *Mastogloia cuneata* (Meister) Simonsen*; *M. lanceolata* Cleve; *M. pumila* (Cleve et Möller) Cleve; *Navicula aleksandrae* Lange-Bert., Witkowski, Bogaczewicz-Adamczak et Zgrundo*; *N. arenaria* Donkin*; *N. bozenae* Lange-Bert., Witkowski, Bogaczewicz-Adamczak et Zgrundo*; *N. cancellata* Donkin; *Navicula* cf. *cancellata*; *N. capillata* Giffen*; *Navicula* cf. *opima* (Grunow) Grunow*; *N. cincta* (Ehrenb.) Ralfs; *N. digitoradiata* (W. Greg.) Ralfs; *N. flagellifera* Hust.*; *Navicula* cf. *flagellifera* Hust.; *N. germanopolonica* Lange-Bert., Witkowski, Bogaczewicz-Adamchak et Zgrundo*; *N. glabriuscula* var. *elipsoidales* Proschk.-Lavr.***; *N. gregaria* Donkin; *N. northumbrica* Donkin*; *N. palpebralis* Bréb.; *N. palpebralis* var. *angulosa* (W. Greg.) Van Heurck; *N. palpebralis* var. *minor* Grunow; *N. palpebralis* var. *semiplena* (W. Greg.) Cleve; *N. palpebrulum* Cholnoky*; *N. parapontica* Witkowski, Kulikovskiy, Nevrova et Lange-Bert.**; *N. perminuta* Grunow; *N. petrovii* Nevrova, Witkowski, Kociolek et Lange-Bert.** (syn. *N. scabriuscula* (Cleve et Grove) Mereschk.***); *N. phyllepta* Kütz.*; *N. phylleptosoma* Lange-Bert.*; *N. ramosissima* (C. Agardh) Cleve; *N. salinarum* Grunow; *N. salinicola* Hust.; *N. veneta* Kütz.; *N. viminoides* var. *cosmomarina* Lange-Bert., Witkowski, Bogaczewicz-Adamchak et Zgrundo*; *Navicula* sp. O1; *Navicula* sp. O2; *Nitzschia acuminata* (W. Sm.) Grunow; *N. aequorea* Hust.*; *N. agnita* Hust.*; *N. angularis* var. *affinis* (Grunow) Grunow; *Nitzschia* cf. *coarctata* Grunow; *N. compressa* (J. W. Bailey) Boyer; *N. constricta* (Kütz.) Ralfs; *N. dissipata* (Kütz.) Grunow; *N. frequens* Hust.*; *N. frustulum* (Kütz.) Grunow; *N. hybrida* Grunow; *N. inconspicua* Grunow; *N. insignis* W. Greg.; *N. liebetruthii* Rabenh.; *N. lorenziana* Grunow; *N. miserabilis* Cholnoky*; *N. pellucida* Grunow; *N. perindistincta* Cholnoky*; *N. persuadens* Cholnoky*; *N. rorida* Giffen*; *N. sigma* (Kütz.) W. Sm.; *N. spathulata* Bréb.; *N. spathulata* var. *hyalina* W. Greg.; *N. vidovichii* (Grunow) Grunow; *Oestrupia powellii* (Lewis) Heiden*; *Parlibellus delognei* (Van Heurck) E. J. Cox; *P. hamulifer* (Grunow) E. J. Cox; *P. plicatus* (Donkin) E. J. Cox; *Parlibellus* sp. O2; *Petroneis humerosa* (Bréb.) A. Stickle et D. G. Mann; *Pinnularia claviculus* (W. Greg.) Rabenh.*; *P. cruciformis* (Donkin) Cleve; *P. trevelyana* (Donkin) Rabenh.***; *Placoneis* sp. 1; *Plagiotropis elegans* (W. Sm.) Grunow; *P. lepidoptera* (W. Greg.) Kuntze; *P. pusilla* (W. Greg.) Kuntze*; *Planothidium delicatulum* (Kütz.) Round et Bukht.; *P. deperditum* (Giffen) Witkowski, Lange-Bert. et Metzeltin*; *P. quarnerensis* (Grunow) Witkowski, Lange-Bert. et Metzeltin; *Planothidium* sp. 2F; *Pleurosigma aestuarii* (Bréb.) W. Sm.; *P. angulatum* (Queckett) W. Sm.; *Psammodictyon panduriforme* (W. Greg.) D. G. Mann; *P. panduriforme* var. *continua* (Grunow) P. J. M. Snoeijs*; *Rhoicosphenia abbreviata* (C. Agardh) Lange-Bert.; *Seminavis* sp. 1; *Stauronella indubitabilis* Lange-Bert. et Genkal; *Staurophora salina* (W. Sm.) Mereschk.; *Surirella fastuosa* (Ehrenb.) Kütz.; *S. pandura* H. Perag. et Perag.; *Toxonidea insignis* Donkin***; *Trachyneis aspera* (Ehrenb.) Cleve

Note: *, species previously recorded by us as a new to the Black Sea flora; **, species previously described by us as a new to science; ***, species not registered within the last 50 or 100 years in the Black Sea.

Investigations in the Kruglaya Bay allowed revealing 70 species newly found for the Bacillariophyta flora of the northern Black Sea shelf, and 5 species described as new to science. Also, we noted 4 species not registered in the Black Sea within approximately 50 years of surveys [*Navicula glabriuscula* var. *elipsoidales*] or even 100 years [*Navicula petrovii* (syn. *N. scabriuscula*), *Toxonidea insignis*, and *Pinnularia trevelyana*]. Five genera are new for the Bacillariophyta flora of the Black Sea: *Astartiella* Witkowski, Lange-Bert. et Metzeltin, *Chamaepinnularia* Lange-Bert. et Krammer, *Cocconeiopsis* Witkowski, Lange-Bert. et Metzeltin, *Eolimna* Lange-Bert. et Schiller, and *Lunella* P. J. M. Snoeijs. Those are represented by the species *Astartiella bahusiensis*, *Astartiella* sp. O1, *Chamaepinnularia alexandrowiczii*, *Ch. clamans*, *Ch. margaritiana*, *Ch. truncata*, *Cocconeiopsis breviata*, *C. fraudulenta*, *C. patrickae*, *Eolimna* sp. 2O, and *Lunella ghalebii* [Nevrova, 2022].

Representatives of the classes Coscinodiscophyceae and Fragilariophyceae are few in number, and their shares are 7.5 and 6.8%, respectively. The contribution of taxa of the class Bacillariophyceae is 85.6%. The order Naviculales is the most diverse in terms of taxonomy: 9 families, 22 genera, and 101 species and ITS. Within the order Achnanthales, we report 3 families, 7 genera, and 35 species and IST. The order Thalassiophysales comprises 1 family, 4 genera, and 32 species and IST, while the order Bacillariales, 1 family, 5 genera, and 33 species and IST. In the Omega Bay water area, the most species-rich genera are *Navicula* (32 species and IST), *Nitzschia* (23), *Cocconeis* (22), *Amphora* (21), *Diploneis* (17), *Lyrella* (11), and *Fallacia* (11).

Several species could not be identified using the literature available. However, we included them in the general list for analysis based on their morphological differences from known diatoms. Micrographs of non-identified species and new and rare taxa are provided in Figs 2–6.

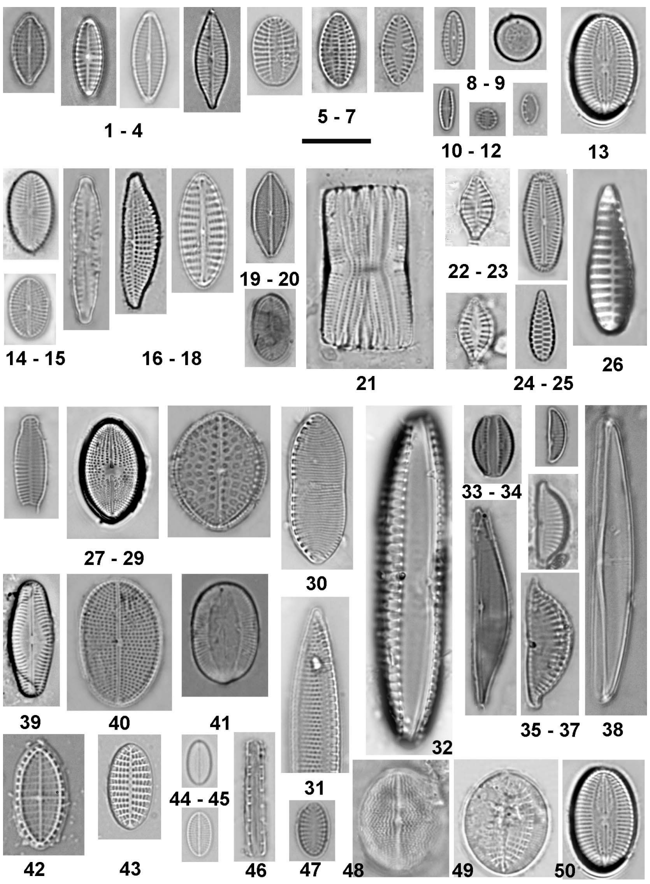

Fig. 2. Newly found for the Black Sea, rare, and non-identified species of benthic diatoms registered off the Omega Bay (a light microscope): 1, *Navicula viminoides* var. *cosmomarina*; 2, *N. bozenae*; 3, *N. aleksandrae*; 4, *N. phylleptosoma*; 5, *Cocconeis peltoides*; 6, *C. discrepans*; 7, *Planothidium deperditum*; 8, *Biremis lucens*; 9, *Cyclotella choctawhatcheeana*; 10, *Chamaepinnularia margaritiana*; 11, *Opephora krumbeinii*; 12, *Nitzschia inconspicua*; 13, *Fallacia oculiformis*; 14, *Diploneis* sp. 1; 15, *Cocconeiopsis breviata*; 16, *Hippodonta* sp. 6; 17, *Lunella ghalebii*; 18, *Hippodonta* sp. O1; 19, *Astartiella bahusiensis*; 20, *Astartiella* sp. O1; 21, *Hyalosira aberrans*; 22, 23, *Achnanthidium glyphos* [raphe valve (RV) and rapheless valve (RLV)]; 24, *Chamaepinnularia clamans*; 25, *Opephora mutabilis*; 26, *O. pacifica*; 27, *Karayevia amoena*; 28, *Cocconeiopsis fraudulenta*; 29, *Cocconeis guttata*; 30, *Nitzschia persuadens*; 31, *Hantzschia* cf. 177-1; 32, *Biremis ridicula*; 33, *Amphora helenensis*; 34, *Amphora* sp. O1; 35, *A. exilitata*; 36, *A. wisei*; 37, *Halamphora turgida*; 38, *Amphora* cf. *abludens*; 39, *Chamaepinnularia truncata*; 40, *Cocconeiopsis patrickae*; 41, *Cocconeis pelta*; 42, 43, *C. pseudocostata* (RV and RLV); 44, 45, *Cocconeis* sp. 5W (RV and RLV); 46, *Cocconeis* sp. O1; 47, *Nitzschia miserabilis*; 48, 49, *Cocconeis* sp. O2 (RV and RLV); 50, *Fallacia ny*. Scale bar is 10 μm

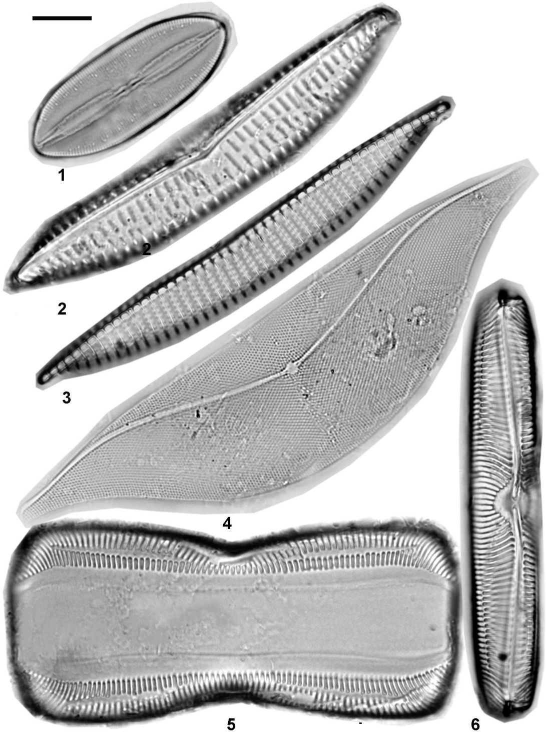

Fig. 3. Diatom species not recorded in the Black Sea within the last 100 years (a light microscope): 1, *Navicula glabriuscula* var. *elipsoidales*; 2, *N. petrovii* (syn. *N. scabriuscula*); 4, *Toxonidea insignis*; 5, 6, *Pinnularia trevelyana* (girdle and valve). Newly found species for the Black Sea: 3, *Hantzschia marina*. Scale bar is 10 μm

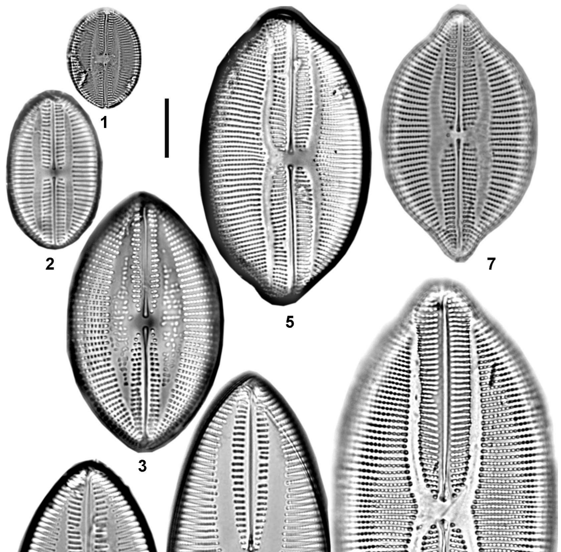

Fig. 4. Diatom species new for science (previously described by us) found off the Omega Bay (a light microscope): 1, *Lyrella fogedii*; 2, *L. majuscula*; 3, *L. abruptapontica*; 4, *L. karayevae*; 5, *L. dilatata*; 6, *L. pontieuxini*; 7, *L. barbara*; 8, *L. pseudolyra*. Scale bar is 10 μm

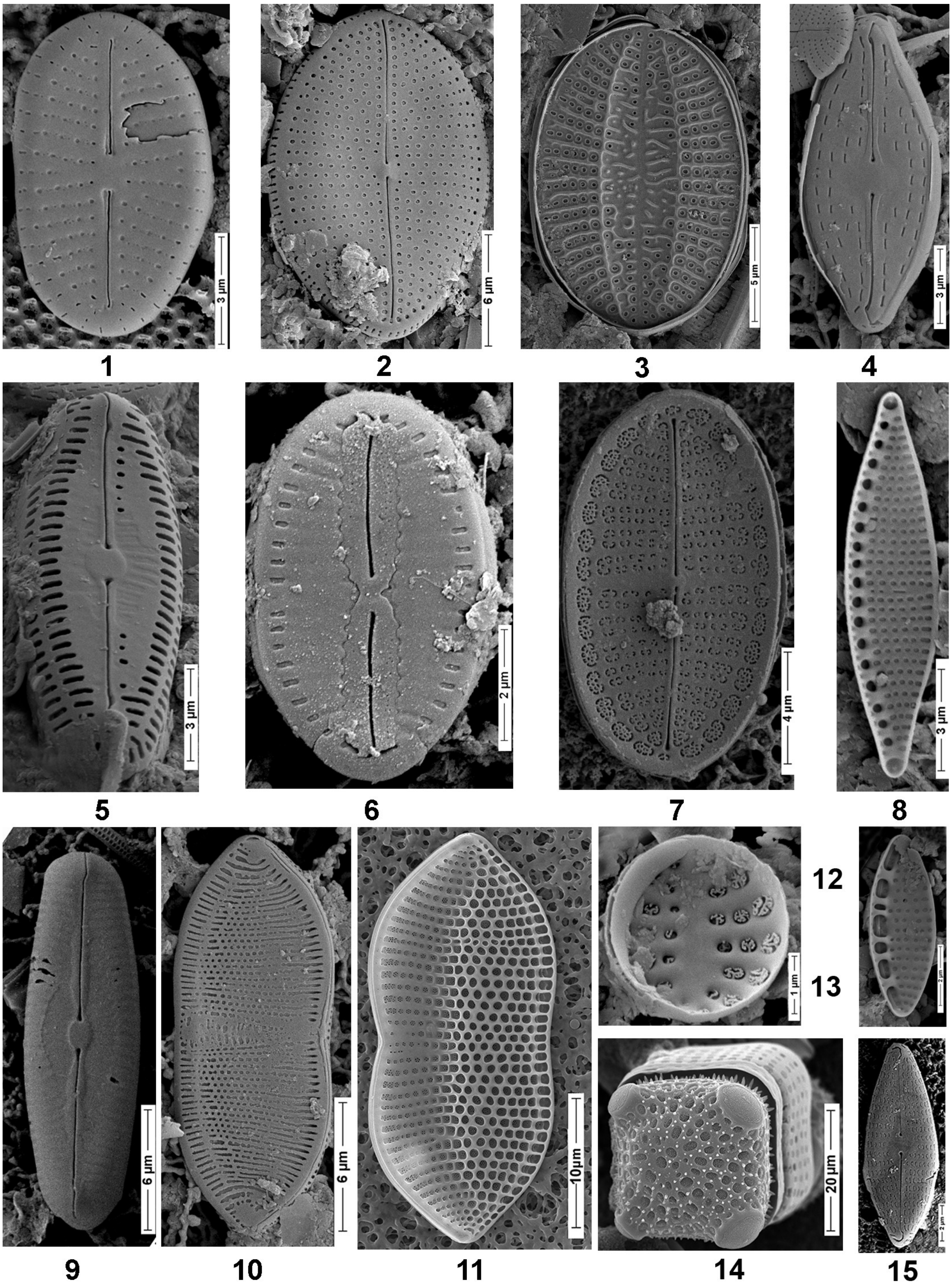

Fig. 5. Newly found to the Black Sea and rare species of benthic diatoms registered off the Omega Bay (a scanning electron microscope): 1, *Cocconeiopsis breviata*; 2, *Cocconeis clandestina*; 3, *C. pelta*; 4, *Navicula viminoides* var. *cosmomarina*; 5, *Chamaepinnularia alexandrowiczii*; 6, *Fallacia margino-punctata*; 7, *Cocconeis pseudocostata*; 8, *Nitzschia aequorea*; 9, *Chamaepinnularia truncata*; 10, *Nitzschia persuadens*; 11, *Psammodictyon panduriforme* var. *continua*; 12, *Opephora krumbeinii*; 13, *Nitzschia inconspicua*; 14, *Amphitetras antediluvianum*; 15, *Navicula aleksandrae*. Scale bars are 3 µm (1, 4, 5, 8); 6 µm (2, 9, 10); 5 µm (3); 10 µm (6, 11); 4 µm (7); 1 µm (12); 2 µm (13); 20 µm (14); 2 µm (15)

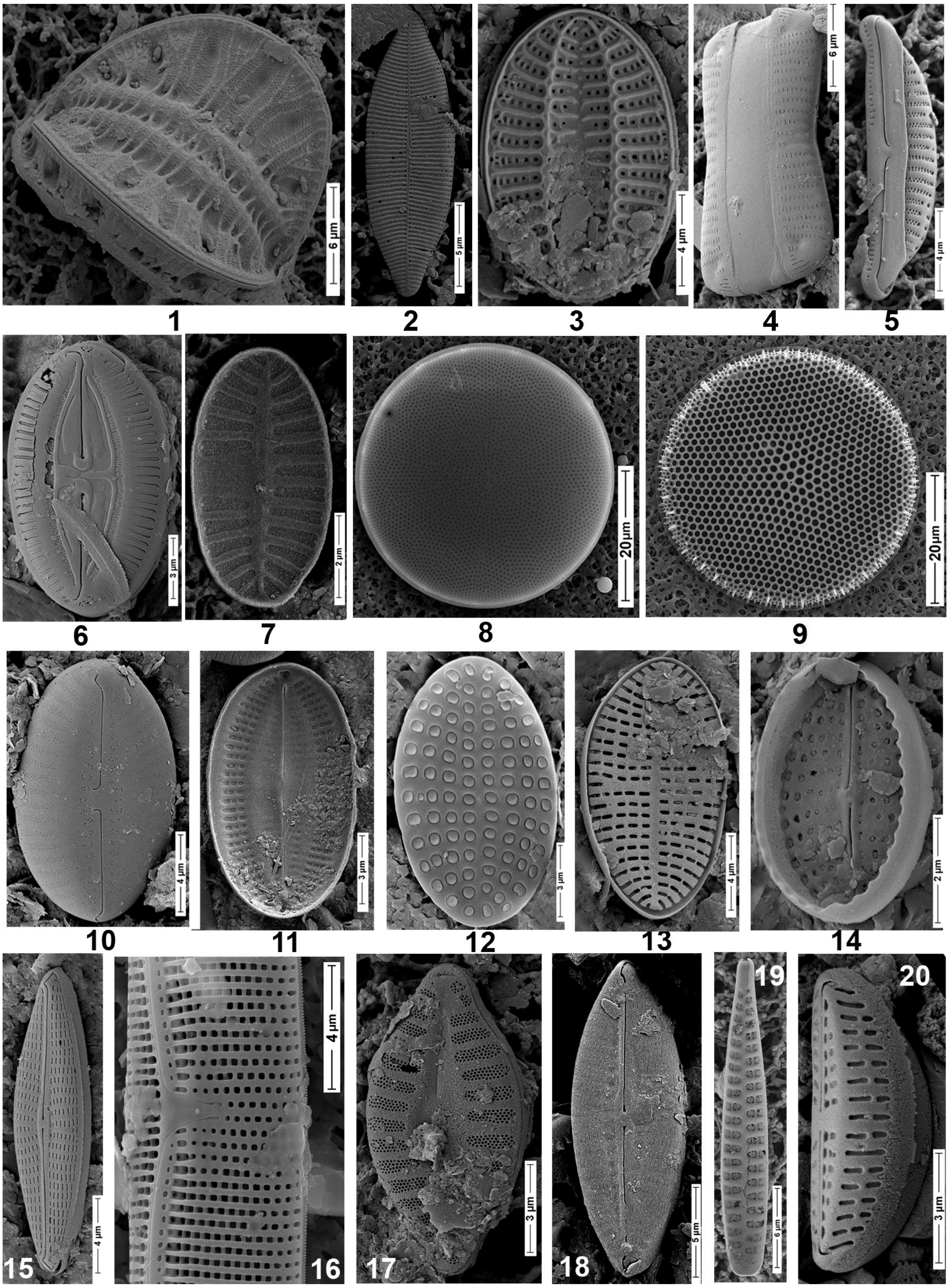

Fig. 6. Newly found for the Black Sea and rare species of benthic diatoms recorded off the Omega Bay (a scanning electron microscope): 1, *Campylodiscus* sp. 1; 2, *Astartiella bahusiensis*; 3, *Cocconeis peltoides*; 4, *Hippodonta* sp. 6; 5, *Halamphora tenerrima*; 6, *Fallacia florinae*; 7, *Planothidium deperditum*; 8, *Actinocyclus subtilis*; 9, *Thalassiosira eccentrica*; 10, *Diploneis coffaeiformis*; 11, *Fallacia oculiformis* (internal); 12, *Cocconeis guttata*; 13, *Cocconeis crispa*; 14, *C. diminuta*; 15, *Navicula phylleptosoma*; 16, *Nitzschia vidovichii* (central nodule); 17, *Planothidium delicatulum*; 18, *Navicula palpebrulum*; 19, *Opephora mutabilis*; 20, *Amphora helenensis*. Scale bars are 6 μm (1, 4, 19); 5 μm (2, 18); 4 μm (3, 5, 10, 13, 15, 16); 3 μm (6, 11, 12, 17, 20); 2 μm (7, 14); 20 μm (8, 9)

The biota of the Omega Bay has been studied in considerable detail regarding macrozoobenthic taxonomic richness, structure, and spatial distribution [Boltachova et al., 2022; Mironov et al., 2003], whilst microphytobenthos has been investigated only partially. Benthic diatom richness in the bay was surveyed by A. Proshkina-Lavrenko in October 1950 [1963], L. Ryabushko in the summer of 1990 [1994], and by a team of researchers in October 2016 [Ryabushko et al., 2022]. In the monograph authored by A. Proshkina-Lavrenko [1963], the registered diatom taxa are included in a general list, and this does not allow for determining which species were found in this biotope. L. Ryabushko reported 42 species and IST of benthic diatoms in the epiphyton [Ryabushko, 1994] and 14 species in the epipsammon [Ryabushko et al., 2022].

Importantly, among the 14 species listed in [Ryabushko et al., 2022], several are misidentified at the genus level. Thus, the one reported by the authors as *Pseudostaurosira medliniae* D. M. Williams et E. A Morales, 2010 [Ryabushko et al., 2022, Fig. 3D, E] and named the first record for the Kruglaya Bay and for the whole Black Sea, is misidentified, according to [Williams, Morales, 2010]. As the authors initially presumed, the species belongs to the *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova, 1996 complex based on the following traits: valve shape with slightly rostrate ends, absence of spines on valve margins, striae density (18 in 10 μm), and multiseriate areolae within striae [Van de Vijver et al., 2018]. Species from this complex are common and abundant in the Black Sea [Guslyakov et al., 1992; Nevrova, Revkov, 2003].

The species the authors identified as *Cocconeis pinnata* Gregory ex Greville, 1859 [Ryabushko et al., 2022, Fig. 5A, B] is *Planothidium deperditum* (Giffen) A. Witkowski, H. Lange-Bertalot & D. Metzeltin, 2000 in accordance with valve shape, striae density (30 in 10 μm), and multiseriate areolae within striae. This diatom was previously reported as new to the Black Sea [Nevrova, 2022].

The species identified as *Diplomenora cocconeiformis* (Schmidt) Blazé, 1984 [Ryabushko et al., 2022, Fig. 3A–C] does not belong to the indicated genus due to the absence of a raphe on both valves. The micrograph of a raphe valve provided by the authors illustrates the genus *Cocconeis* Ehrenberg.

The species identified as *Coscinodiscus concinnus* W. Smith, 1856 [Ryabushko et al., 2022, Fig. 1A] is *Actinocyclus subtilis* (W. Greg.) Ralfs, 1861 based on the presence of a pseudonodulus, numerous labiate processes, and striae density (17–18 in 10 μm) [Andersen et al., 1986]. Additionally, *C. concinnus*, indicated by the authors as new to the Black Sea flora, has already been repeatedly reported as a rare species in various areas of the Black Sea [Bodeanu, 1987; Guidelines, 2015; Guslyakov, Nevrova, 1987; Nevrova, 2013b; Proshkina-Lavrenko, 1963].

The species assigned to *Anorthoneis dulcis* M. K. Hein, 1991 [Ryabushko et al., 2022, Fig. 3F–H] and reported as a new find for the Black Sea is *Cocconeiopsis pullus* (Hustedt) Witkowski, Lange-Bertalot et Metzeltin, 2000 based on the shape of valve and a hyaline area on its inner part, arrangement of striae and their density, and the shape of terminal and central raphe fissures. These are a new genus and a new species for the Black Sea already discovered by us for the first time for this basin at two sites (Cape Fiolent and Dvuyakornaya Bay) [Nevrova, 2016; Nevrova, Petrov, 2019a].

Also, there was an error concerning the priority of the record for the Black Sea: *Cocconeis guttata* Hustedt et Aleem, 1951 [Ryabushko et al., 2022, Fig. 4H–K] indicated as a new species to the flora has already been found in at least seven areas of the Black Sea (the estuary of the Belbek River, the Zernov's *Phyllophora* Field, Balaklava Bay, Karadag coast, Cape Fiolent, Dvuyakornaya Bay, and Omega Bay), as reported in [Nevrova, 2013a, 2014a, b, 2015, 2016; Nevrova, Petrov, 2019a].

A comparative assessment of total richness of flora of benthic Bacillariophyta in the Omega Bay and previously surveyed areas off the Crimean coast (based on the Bray–Curtis dissimilarity) revealed the greatest similarity in species composition between biotopes of the Omega Bay and the Dvuyakornaya Bay (53.3) and the Omega Bay and the Laspi Bay (45.3) characterized by the lowest technogenic pollution (Table 2). The maximum values were registered for the bays strongly polluted with salts of heavy metals and petroleum hydrocarbons: the Sevastopol Bay and the Karantinnaya Bay (64.6) and the Sevastopol Bay and the Balaklava Bay (57.8).

Table 2. Similarity in species composition of benthic diatoms in the study areas (based on Bray–Curtis dissimilarity)

Areas off the Crimean coast and species richness (IST)	Omega Bay	Laspi Bay	Dvuyakornaya Bay	Karantinnaya Bay	Sevastopol Bay
Omega Bay (264)	*	*	*	*	*
Laspi Bay (217)	45.3	*	*	*	*
Dvuyakornaya Bay (304)	53.2	44.9	*	*	*
Karantinnaya Bay (136)	38.9	64.6	36.8	*	*
Sevastopol Bay (186)	39.9	64.1	36.3	64.6	*
Balaklava Bay (191)	43.0	56.4	42.4	53.8	57.8

Subsequently, we analyzed the taxonomic diversity and structure of Bacillariophyta taxocenes in the Kruglaya Bay in comparison with those of previously studied biotopes along the Crimean coast. We calculated mean values of TaxDI (Δ^+) and its variability (Λ^+), as well as its deviation from the expected level for the whole Black Sea (Fig. 7). The method was properly described before [Nevrova, 2022].

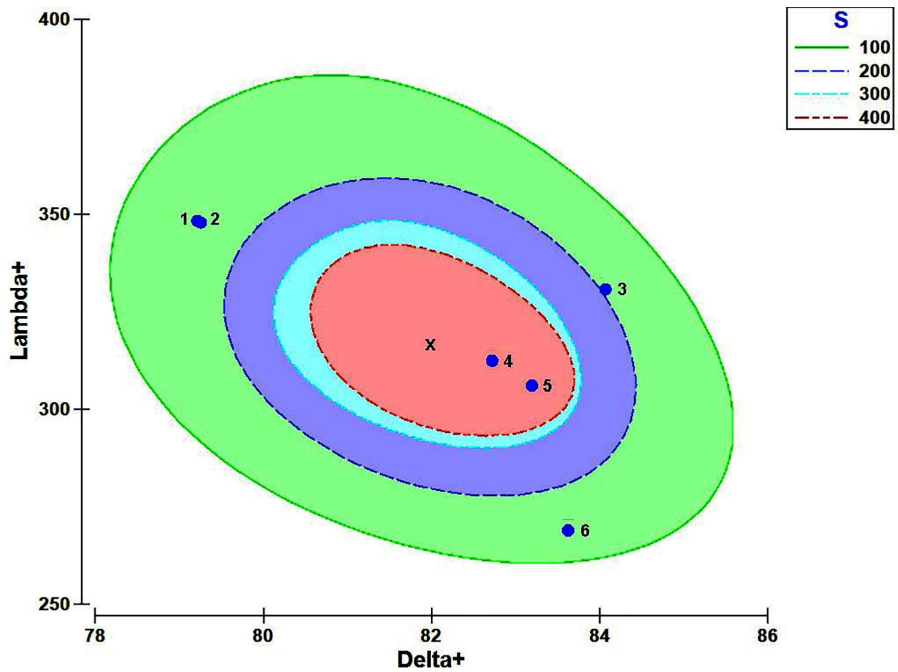

Fig. 7. Comparative assessment using TaxDI – AvTD (Δ^+) and VarTD (Λ^+) – of taxonomical diversity of benthic diatoms in various biotopes with different anthropogenic load off the Crimean coast: 1, the Omega Bay; 2, the Dvuyakornaya Bay; 3, the Balaklava Bay; 4, the Laspi Bay; 5, the Karantinnaya Bay; 6, the Sevastopol Bay; ×, average expected level for the Black Sea diatom flora. A 95% confidence ellipse

As already mentioned, the diversity of diatom taxocenes in the study areas was assessed by taxonomic distinctness indices: AvTD (Δ^+) and VarTD (Λ^+) [Clarke, Gorley, 2006; Clarke, Warwick, 2001; Warwick, Clarke, 1998, 2001]. Δ^+ represents the mean path length between every pair of species, randomly chosen from the list of a site, to a phylogenetically common node on a hierarchical tree of the taxocene. The index characterizes the vertical taxonomic evenness of the taxocene in the study area. Λ^+ describes the variability of pairwise distances (ω_{ij}) between pairs of species *i* and *j* relative to their mean value Δ^+. The value of Λ^+ shows the representation of taxa at increasing hierarchical levels and characterizes the horizontal asymmetry of the taxonomic tree [Warwick, Clarke, 1998, 2001]. The calculation algorithm allows for a reliable assessment of differences in taxonomic diversity and for recording deviations in the structure of diatoms in compared areas from the expected value for the Bacillariophyta flora of the whole Black Sea [Nevrova, 2022]. Despite the convenience of applying this method, the taxonomic diversity in marine microphytobenthos still has not been assessed (there are just a few works on freshwater microflora [Izsak et al., 2002; Leira et al., 2009]). For marine benthic Bacillariophyta, TaxDI is used for the first time [Nevrova, 2022].

TaxDI points corresponding to the biotopes with the highest technogenic pollution in the Karantinnaya, Balaklava, and Sevastopol bays are located in the lower right quadrant of the confidence ellipse. This is caused by high AvTD values and low VarTD variability, which reflect reduced taxonomic structure and decreased diversity within diatom taxocenes [Warwick et al., 2002]. The index values for these taxocenes are significantly above the expected value for the whole Black Sea flora ($\Delta^+ = 82.09$; $\Lambda^+ = 316.83$).

The structure of diatom taxocenes in heavily polluted bays shows low species richness and the disappearance of taxa with low resistance to technogenic contaminants; this reduces the species saturation of clades on the hierarchical tree and mediates an increase in taxonomic distances when calculating the index. Compared to the average expected level of TaxDI, a lower degree of vertical hierarchical evenness in the taxocene structure is characteristic of communities exposed to severe anthropogenic pollution. Such changes in the structure have been reported repeatedly [Ellingsen et al., 2005; Gottschalk, Kahlert, 2012; Heino et al., 2007; Masouras et al., 2021; Petrov et al., 2010; Stenger-Kovács et al., 2016].

TaxDI points corresponding to relatively unpolluted areas of the Omega and Dvuyakornaya bays are located in the upper left quadrant of the confidence ellipse. This is determined by the lowest AvTD values and the highest VarTD variability. The values of the indices fall below the expected ones for the Black Sea diatom flora. Such a taxocene structure is a reflection of high species richness and a large number of taxonomic clades of varying species saturation, which 'converge into nodes' at different hierarchical levels. The tree architecture is dominated by polyspecific clades closing at the genus level. Also, there are mono- and oligospecific clades: those aggregating at higher taxonomic levels (family and even order ones). Low Δ^+ and high Λ^+ values indicate vertical evenness and high variability in taxonomic distances between clades. A similar pattern has previously been described for pristine or minimally disturbed biotopes [Keck et al., 2016; Nevrova, Petrov, 2019b; Rimet, Bouchez, 2012].

For the diatom taxocene of the Laspi Bay (a relatively unpolluted site), AvTD and VarTD values are near the average expected level for the whole Black Sea. For the taxocene of the Balaklava Bay (a heavily polluted site), AvTD value is close to that of the Sevastopol Bay, but the variability is noticeably higher. Importantly, the values of all calculated indices lie within the 95% confidence ellipse.

TaxDI application for assessing taxonomic diversity allows for a deeper understanding of its aspects. The differences in the structure of the hierarchical tree of Bacillariophyta for the compared sites are largely driven by a response of benthic diatom taxocenes to combined factors and varying degrees of anthropogenic load. The greatest similarity in species richness and structure of Bacillariophyta taxocenes was revealed both between relatively unpolluted biotopes and between the most heavily polluted ones, indicating, regardless of the geographical distance between these sites, the heterogeneity of bottom substrates, and differences under hydrological conditions.

Conclusions:

1. The benthic diatom taxocene of the Kruglaya Bay (the Omega Bay) comprises 264 species and infraspecific taxa: 256 species, 73 genera, 35 families, 21 orders, and 3 classes. Representatives of the class Bacillariophyceae dominate. These include 70 species and 5 genera previously noted by us as new to the Bacillariophyta flora for the Black Sea northern shelf, as well as 5 diatom species we described as new to science before.
2. The similarity in species composition was registered both between biotopes with the lowest level of technogenic pollution (the Omega Bay – the Dvuyakornaya Bay and the Omega Bay – the Laspi Bay) and between areas strongly polluted with salts of heavy metals and petroleum hydrocarbons (the Sevastopol Bay – the Karantinnaya Bay and the Sevastopol Bay – the Balaklava Bay), regardless of their distance from each other and differences in hydrological and hydrophysical conditions.
3. Benthic diatom taxocenes in heavily polluted areas are characterized by low species richness and a predominance of mono- and oligospecific clades due to the elimination of taxa with low resistance to pollutants. AvTD values exceed the average expected level for the Bacillariophyta flora of the Black Sea.
4. In relatively unpolluted water areas, Bacillariophyta taxocenes are characterized by high species richness, a large number of polyspecific clades, and the presence of mono- and oligospecific clades aggregating at high levels of the hierarchical tree. AvTD values are lower as compared to the average expected level for the Black Sea benthic diatom flora.

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БЕНТОСНЫЕ ДИАТОМОВЫЕ ВОДОРОСЛИ (BACILLARIOPHYTA): РАЗНООБРАЗИЕ И ИЕРАРХИЧЕСКАЯ СТРУКТУРА ТАКСОЦЕНОВ НА РЫХЛЫХ ГРУНТАХ БУХТЫ КРУГЛАЯ (ЧЁРНОЕ МОРЕ, КРЫМ)

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Бухта Круглая, или бухта Омега, имеет большое рекреационное значение в связи со своим внутренним расположением в регионе Севастополя, протяжённой пляжной зоной и мелководной акваторией с песчаным дном. Эти особенности определяют необходимость контроля состояния морской биоты. Целью работы стало выявление видового богатства и иерархической структуры таксоценов бентосных диатомовых водорослей (Bacillariophyta) в недостаточно изученной ранее бухте Круглая и сравнительный анализ с прибрежными биотопами Крыма, находящимися под антропогенным влиянием различного уровня. По результатам пробоотбора 2004 г. исследовано видовое богатство бентосных диатомовых водорослей бухты Круглая и проанализировано таксономическое разнообразие на основе флористических и формализованных методов с использованием индексов таксономической отличительности TaxDI (AvTD и VarTD). Выявлено 264 вида и внутривидовых таксона донных диатомовых водорослей, представленных 256 видами, 73 родами, 35 семействами, 21 порядком и 3 классами. Обнаружено 70 видов и 5 родов, ранее отмеченных нами как новые для флоры Bacillariophyta северного шельфа Чёрного моря, а также 5 видов, описанных нами ранее как новые для науки. Наибольшее сходство видового состава зарегистрировано как между биотопами с наименьшим уровнем техногенного воздействия (бухта Омега — бухта Двуякорная и бухта Омега — бухта Ласпи), так и между акваториями, сильно загрязнёнными техногенными поллютантами (Севастопольская бухта — бухта Карантинная и Севастопольская бухта — Балаклавская бухта), независимо от их удалённости и различий в гидрологических и гидрофизических условиях. Таксоцены Bacillariophyta сильно загрязнённых полигонов характеризуются невысоким богатством видов и большой долей моно- и олиговидовых ветвей вследствие редуцирования низкорезистентных к поллютантам таксонов. Показатели AvTD превышают среднеожидаемый уровень для черноморской флоры Bacillariophyta. В условно чистых акваториях таксоцены диатомовых водорослей характеризуются высоким видовым богатством, большим количеством поливидовых ветвей и малой долей моно- и олиговидовых ветвей, агрегирующихся на разных уровнях иерархического древа. Значения AvTD находятся ниже среднеожидаемого уровня для флоры диатомовых водорослей Чёрного моря. Особенности структуры таксоценов Bacillariophyta сравниваемых полигонов обусловлены видоспецифической реакцией различных таксонов на сочетанные факторы влияния среды. Использование TaxDI при анализе таксономического разнообразия Bacillariophyta позволяет статистически достоверно оценивать состояние морских прибрежных акваторий с различным статусом загрязнения.

Ключевые слова: бухта Омега, TaxDI, видовое богатство, антропогенное воздействие