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Diatom Assemblages from the Daginsky Mud Volcano Sediments (Eastern Sakhalin) and Their Implication

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Abstract: Diatom assemblages in mud volcanoes are quite rare and are poorly studied. The finding of a rich diatom flora in the sediments of the Daginsky Mud Volcano (DMV), located in the tidal zone of the Nyisky Bay of the Sea of Okhotsk, is of interest to study the conditions for the formation of host sediments in the zone of influence of various extreme factors, such as outflows of gases and water–mud mass, thermal springs, and tides. For this purpose, the taxonomical composition of diatom assemblages and concentration of diatoms in DMV sediments were studied. A comparison was made with the diatoms of geothermal springs of the Russian Far East associated with volcanic activity, and the stratigraphic occurrence of the found extinct diatoms was analyzed, which is important for determining their source and the age of the mud volcano roots. Diatom assemblages from DMV sediments are mainly characterized by the predominance of *Metascolioneis tumida*, *Paralia sulcata*, *Odontella aurita*, *Pinnunavis yarrensis*, *Petroneis marina*, *Cocconeis scutellum*, and *Navicula digitoradiata*. They consist of diatoms of different biotopes and extinct species. The diversity and abundance of brackish water and marine species indicates the predominant influence of sea waters on the formation of DMV sediments. The diverse freshwater species were mainly introduced into sediments with river runoff, but it is likely that some of these, such as the cosmopolitan alkaliphilic species, are inhabitants of geothermal springs. The presence of extinct species from the underlying Neogene sediments from where they were carried with gas–water–mud masses is the most typical for diatom assemblages of the DMV.

Keywords: diatom assemblages; sediments; Daginsky Mud Volcano; thermal springs; Nyisky Bay; Eastern Sakhalin

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1. Introduction

Mud volcanoes are geological structures formed as a result of the release of clay material mixed with water and gas through eruptive channels, forming a mud breccia on the surface [1–5]. Mud volcanism is confined to development zones of alpine folding, confined mainly to Cenozoic Molasses deflections [5]. Mud volcanoes often form in oil and gas regions and are important indicators in the search for oil and gas and other minerals, as well as an indicator of the geodynamic state of the earth's crust [2–7]. Mud volcanoes are characteristic of basins with a thick sedimentary cover and abnormally high reservoir fluid pressures [2]. In addition, mud volcanism is a potentially dangerous geological phenomenon [8,9] and a significant source of greenhouse gases [1,10,11]. In the Russian Far East, mud volcanoes are known in Kamchatka, the Kuril Islands and Sakhalin Island (Figure 1). In Kamchatka and the Kuril Islands, mud volcanoes and mud pots are associated with post-volcanic phenomena, the solfataric stage of the activity of ordinary lava volcanoes [12]. The long-lived center of gas–fluid emanations associated with mud volcanism was recently discovered on the western slope of the Kuril Basin of the Sea of Okhotsk [13].

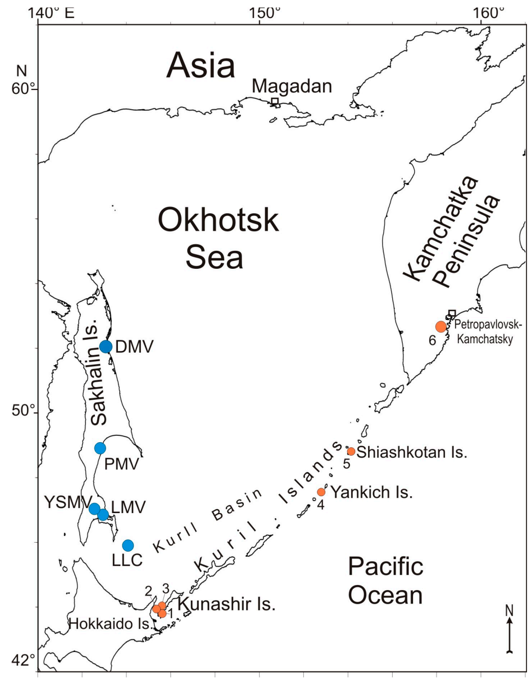

Figure 1. Location of mud volcanoes on Sakhalin Island (blue circles) and thermal springs associated with volcanoes mentioned in the text (orange circles). DMV—Daginsky Mud Volcano [4,10,11,14,15], PMV—Pugachevsky Mud Volcano [1,10,11], YSMV—Yuzhno-Sakhalinsky Mud Volcano, LMV—Lesnovsky Mud Volcano [4], LLC—Long-Live Center of Gas–Fluid Emanations [13]. Thermal springs: 1—Golovnin Volcano, 2—Alekhin Bay, 3—Stolbchaty Cape [16,17], 4—Craternaya Bay [18], 5—Shiashkotan Is. [16,17], 6—Dachnyye, Malkinskiye, Nachkinskiye, and Verkhne-Paratunskiye thermal springs near Petropavlovsk-Kamchatsky [19–21].

Sakhalin Island is one of the few regions of Russia where classical mud volcanoes are common, through the outlets of which a multi-clastic mud mass saturated with water and gas is ejected—forming hill breccia [3,4]. The Yuzhno-Sakhalinsky, Pugachevsky, and Lesnovsky mud volcanoes located in the south of Sakhalin Island are associated with Upper Cretaceous rocks [3,5], while the Daginsky Mud Volcano (DMV) located in the northeast of Sakhalin is confined to the Oligocene—Neogene deposits [7]. When studying the sediments of the DMV, numerous diatoms were discovered for the first time [11]. The diatom flora of the DMV sediments is characterized by high species richness (278 species and intraspecific taxa) [22]. A diverse diatom flora (131 species and varieties) was found in the phytoplankton and periphyton of the Daginsky hydrothermal springs [17], which are closely related to the DMV.

Information on diatoms of mud volcanoes is extremely scarce, although they were noted in the first microscopic studies of mud volcanic breccias in Italy in the 19th century [6]. The mass number of diatoms, represented mainly by Rhizosolenids (members of the family *Rhizosoleniaceae*), *Thalassionema* spp., *Chaetoceros* spp., found in the late Quaternary sapropels of the Napoli Mud Volcano in the Mediterranean Sea [23]. The age (5.6–4.6 Ma) of the mud volcano roots was determined from diatoms found in the breccia of the mud volcanoes of Baikal Lake [24]. Six diatom species were described in a silty water suspension from the Bulganak mud volcanoes of the Kerch Peninsula of Crimea [25]. More data on the algal flora of geothermal springs in Kamchatka Peninsula and the Kuril Islands are associated with active magmatic volcanism. Review and analysis of research on these sources has shown that up to 95% of the microalgae flora are diatoms [16,17,19–21,26–28]. The algal flora of geothermal springs consists mainly of freshwater, cold-water species that have adapted to high temperatures, but at a water temperature of more than 60 °C, the species composition of the algal community is significantly depleted. Diatom assemblages found in soils around the thermal springs of the Kamchatka Peninsula include 49 aquatic and terrestrial species [26]. A total of 48 taxa of diatoms, among which benthic forms predominated, were found in the sediments of Craternaya Bay (Yankich Island, Central Kuril Islands), which is a crater of the active Ushishir Volcano [18]. Geothermal springs and mud volcanoes around the world are characterized by a diversity and a fairly high abundance of diatoms (e.g., [12,29–40]). Information on the diatom composition of sediments formed under extreme conditions is important for environmental knowledge and the reconstruction of paleoenvironments in the geological past. The purpose of our paper is to determine the features of the diatom assemblages from the DMV and conditions for the formation of host sediments.

2. Materials and Methods

2.1. Study Area

DMV was discovered and described by N.D. Tsitenko [14] in 1954 on the coast of the Nyisky (Daginsky) Bay. It differs from other mud volcanoes of Sakhalin in the absence of a central eruptive channel and explosive eruptions [7,14], and is called the Dagi mud volcanic manifestation [3,4] or the Dagi Geothermal System [11,41]. It consists of a group of small mud volcanoes which are flooded and destroyed during high tides and re-formed during low tides, so the location and number of volcanoes often changes. Mud volcanoes and thermal springs have a single cause of formation and activity, which is associated with the flow of hydrocarbon gas and water from the subsurface through tectonic fissures [14,15]. DMV is located in the tidal zone of the Nyisky Bay, separated from the Okhotsk Sea by a long sandy spit and several islands (Figure 2).

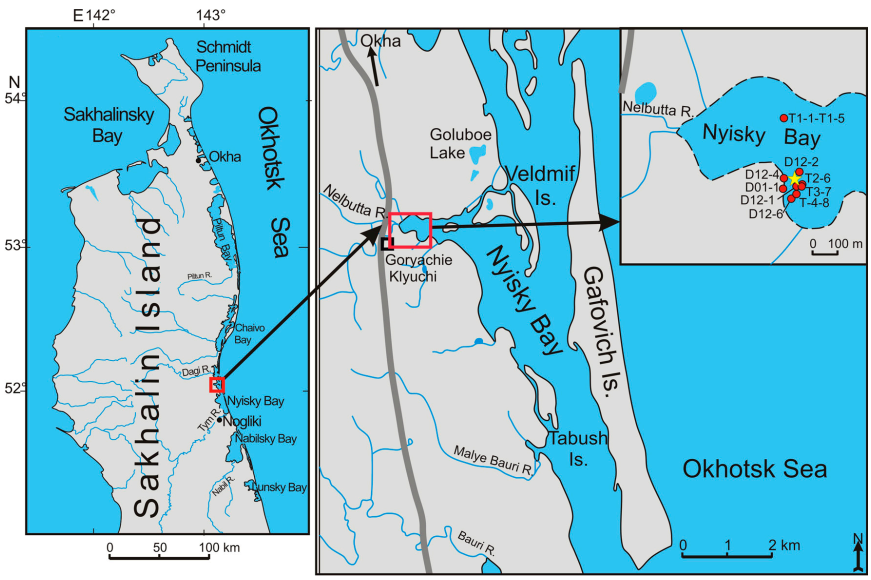

Figure 2. Daginsky Mud Volcano location and sediment sampling map (sampling sites—red circles). A yellow asterisk marks the Kalmar gas–hydrothermal spring.

In the south, one of the largest rivers of Sakhalin, the Tym River flows into it, while in the north there is the Dagi River. The hydrological regime of the bay is determined by the influence of river runoff and the action of the tides. During the day, sharp changes in temperature, salinity and water level occur. The salinity in the strait areas of the Nyisky Bay reaches 30.7 psu. In the estuarine areas of the rivers, the salinity is minimal and does not exceed 1.0 psu [42]. The DMV waters and thermal springs are significantly affected by the surface waters of the Nyisky Bay, and this obscures the true picture of the composition of waters coming from deep horizons [7]. The Dagi thermal springs belong to neutral or slightly alkaline terms (pH = 7–8), with a temperature of 25–55 °C and a sodium chloride composition with a mineralization of 1.2–9 g/L [43]. The temperature of the water and mud breccia of the small volcanos reaches 21.5 °C, and the temperature of mineral waters at their outlet reaches 36.5 °C and 39.7 °C [44,45]. In the craters of the thermal springs the water temperature was noted to be 55 °C [14]. Within the geothermal field of DMV (Figure 3) there are about 15 water and gas sources (Figure 4).

Figure 3. DMV geothermal field at low tide, Nyisky Bay, Eastern Sakhalin. Photo by A. Venikova.

Figure 4. Gas outflow in the DMV area. Photo by N. Sokolova.

The main component of gases is methane, formed presumably as a result of anaerobic decomposition of organic matter at depths of at least 2 km [11]. The geochemical features of the DMV silt are typical for near-continental terrigenous formations, the formation of which are influenced by the active Garomai Fault and the associated natural outputs of thermogenic methane with a small proportion of microbial gases [41]. The DMV thermal mineral springs and muds are characterized by their high therapeutic quality [46].

The DMV is located in the area that is part of the North Sakhalin sedimentary basin, composed of the thick Cenozoic sedimentary sequences (Figure 5a,b). It is the largest industrial oil and gas basin in the Okhotsk region [47,48].

Diatoms were found in the Nutovskaya Formation (upper Miocene—Pliocene) of the Dagi area; in the underlying Okobykayskaya, Daginskaya, Ujninskaya, Daekhurinskaya, and Machigarskaya formations, diatoms are absent [47,49]. On the adjacent shelf, diatoms occur in the deposits of the Nutovskaya and Okobykayskaya formations [50]. The Neogene deposits are overlain everywhere by Quaternary sediments represented by modern floodplain, biogenic, lagoon, and eluvial–deluvial formations [51]. The geochemical features of the DMV sediments have characteristics typical of most of the continental terrigenous formations [41]. The concentration of arsenic (As) and silver (Ag) in the sediments is obviously influenced by the nearby active Garomai Fault.

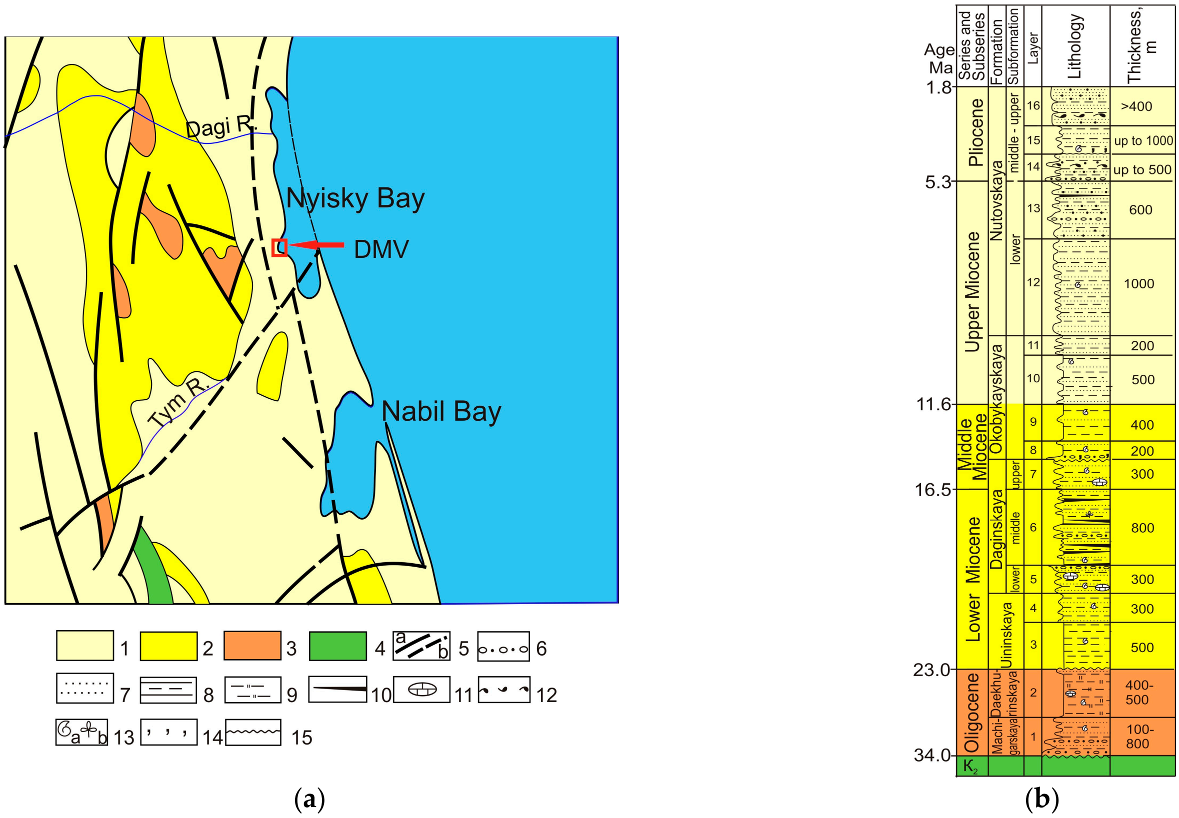

Figure 5. Scheme of geology (**a**) and stratigraphy (**b**) of the Dagi area of Eastern Sakhalin [47]. 1—Upper Miocene–Pliocene; 2—Lower to Middle Miocene; 3—Paleogene; 4—Mesozoic; 5—faults (a—established, b—assumed); 6—conglomerates, gravelites; 7—sandstones; 8—siltstones, mudstones; 9—diatomites, including sandy–siltstone–clayey diatomites; 10—coal beds; 11—calcareous concretions; 12—shell lenses; 13—remains of fauna (a) and flora (b); 14—glaconite; 15—erosion. K2—Upper Cretaceous, DMV—Daginsky Mud Volcano.

2.2. Sampling and Treatment

Samples were collected by collaborators of the Laboratory of Gas Geochemistry at the Il'ichev Pacific Oceanological Institute, at the Far East Branch of the Russian Academy of Sciences (POI FEB RAS) in the DMV area during field expeditions in 2001, 2012 and 2014. Eight sediment samples were collected around the Kalmar gas–hydrothermal spring, the water temperature of which reaches 41 °C [52], with 5 samples in a gassing "bath" located about 150 m northwest of the site (Figure 2; Table 1).

All samples were taken from the upper layer of sediments (0–1 cm) except for samples T1-3, T1-4 and T1-5, which were taken below the surface in the intervals of 10–11 cm, 30–31 cm and 40–41 cm, respectively. The selected sediments are represented by liquefied clayey silts of a dark gray color with up to 70% organic remains (mainly diatom algae).

The sediment treatment and preparation of slides for microscopy, as well as estimation of the diatom concentration (valves per gram of the air–dry sediment) were conducted based on the standard procedure [53,54]. The samples were enriched with a heavy potassium–cadmium liquid ($H_2O:CdI_2:KI$ = 1:2.5:2.25) with a density of 2.6 [53]. For the preparation of slides, a highly refractive MOUNTEX mounting resin (refractive index 1.67) (Darmstadt Germany) was used.

Table 1. Samples from the Daginsky Mud Volcano, Nyisky Bay, Eastern Sakhalin.

Sample Number	Latitude, N	Longitude, E	Sediment Type
D01-1	52°02′50″	143°05′38″	clayey silt
D12-1	52°02′50″	143°05′41″	clayey silt
D12-2	52°02′52″	143°05′42″	clayey silt
D12-4	52°02′51″	143°05′39″	clayey silt
D12-6	52°02′48″	143°05′40″	clayey silt
T2-6	52°02′50.1″	143°05′42.7″	compacted silt
T3-7	5 m south-west of T2-6		clayey silt
T4-8	52°02′48.8″	143°05′41.5″	clayey silt
T1-1	52°02′58.8″	143°05′38.8″	clayey silt
T1-2	"–"	"–"	clayey silt
T1-3 (10–11 cm)	"–"	"–"	compacted silt
T1-4 (30–31 cm)	"–"	"–"	compacted silt
T1-5 (40–41 cm)	"–"	"–"	compacted silt

The diatoms were identified and enumerated with an IMAGER.A1 light microscope (magnification = ×1000; Carl Zeiss AG, Oberkochen Germany) and imaged with an AxioCamMrC digital video camera (Carl Zeiss AG). The species were identified from the following main sources: [55–73] and specific taxonomic publications. The analysis of the ecological structure of diatom flora and assemblages was mainly carried out in relation to salinity: marine, brackish water, freshwater, and euryhaline; by habitat: benthic, planktonic, and benthic–planktonic. Ecological and biogeographic characteristics of diatoms are given mainly according to [74–77] and the above-mentioned sources. A taxonomic reference of diatoms and silicoflagellates of the DMV sediments are given in [22].

3. Results

3.1. Concentration Diatoms in Sediments

The concentration of diatoms (valves per gram of air-dry sediment) in the DMV sediments varied considerably from 0.7 to 9.1 mln valves/g with an average of 4.8 mln valves/g (Figure 6; Table S1).

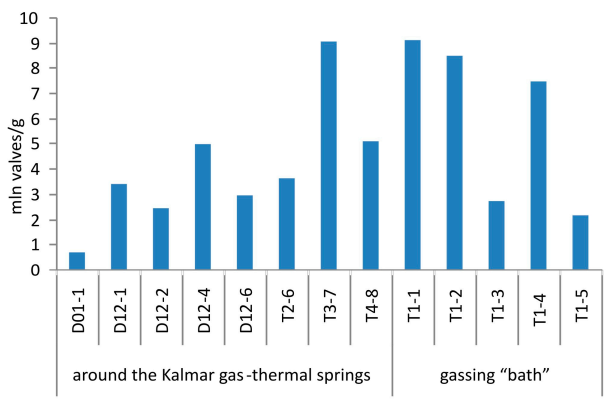

Figure 6. Content of diatoms (mln valves/g air-dry sediment) in samples from the DMV sediments.

The minimum abundance was observed in sample D01-1, taken near the boundary of the tidal zone of the Nyisky Bay. The maximum concentration was found in clay silts near the Kalmar gas–hydrothermal spring (sample T3-7) and a gassing "bath" located northwest of the Kalmar spring (samples T1-1, T1-2).

3.2. Diatom Assemblages

The studied sediments contain 278 species and intraspecific taxa belonging to 100 genera (Table S2). The most species-rich genera were *Navicula* (18 taxa), *Tryblionella* (15), *Pinnularia* (14), *Nitzschia* (12), *Thalassiosira* (11), *Diploneis* (8), *Aulacoseira* (7), and *Chaetoceros* (7).

Diatom assemblages from the studied sediments are similar in dominant and subdominant species, and in species composition in general. The assemblages contain from 63 to 141 species and intraspecific taxa of different biotopes (Table S2). Brackish water diatoms are diverse (18–36 taxa in the samples) and abundant, and dominate in almost all samples (33–56.3%) (Figure 7).

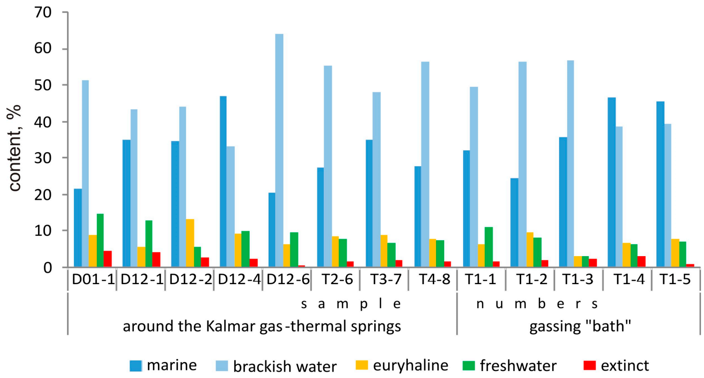

Figure 7. Content (%) of ecological groups (marine, brackish water, euryhaline, and freshwater) and extinct species in diatom assemblages from the DMV sediments.

Benthic species *Pinnunavis yarrensis* (1.0–12.3%), *Petroneis marina* (2.8–11.3%), *Cocconeis scutellum* (3.5–10.7%), as well as *Coronia echeneis*, *Nitzschia linearis*, *Fallacia pygmaea*, *Delphineis kippae*, *Navicula maculata*, *Diploneis mereschkowskyi*, *D. interrupta*, *Scoliotropis latestriata*, *Rhabdonema arcuatum*, *Amphora proteus*, *A. libyca*, *Halamphora coffeiformis*, *Surirella brebissonii*, *Tryblionella compressa*, *T. granulata*, *T. punctata*, *T. hungarica*, *T. circumsuta* (Figures 8 and 9), which were found mainly as single specimens, more than half of which are alkaliphilic species.

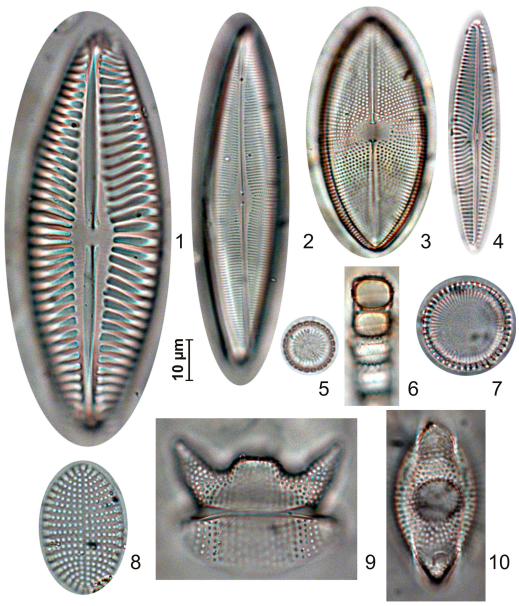

Figure 8. Dominant and frequently occurring diatoms in the DMV sediments. 1—*Pinnunavis yarrensis*; 2—*Metascolioneis tumida*; 3—*Petroneis marina*; 4—*Navicula digitoradiata*; 5–7—*Paralia sulcata*; 8—*Cocconeis scutellum*; 9, 10—*Odontella aurita*. 1–4, 8—brackish water and euryhaline benthic species; 5, 6, 9, 10—marine benthic–planktonic species. Scale bar: 10 µm.

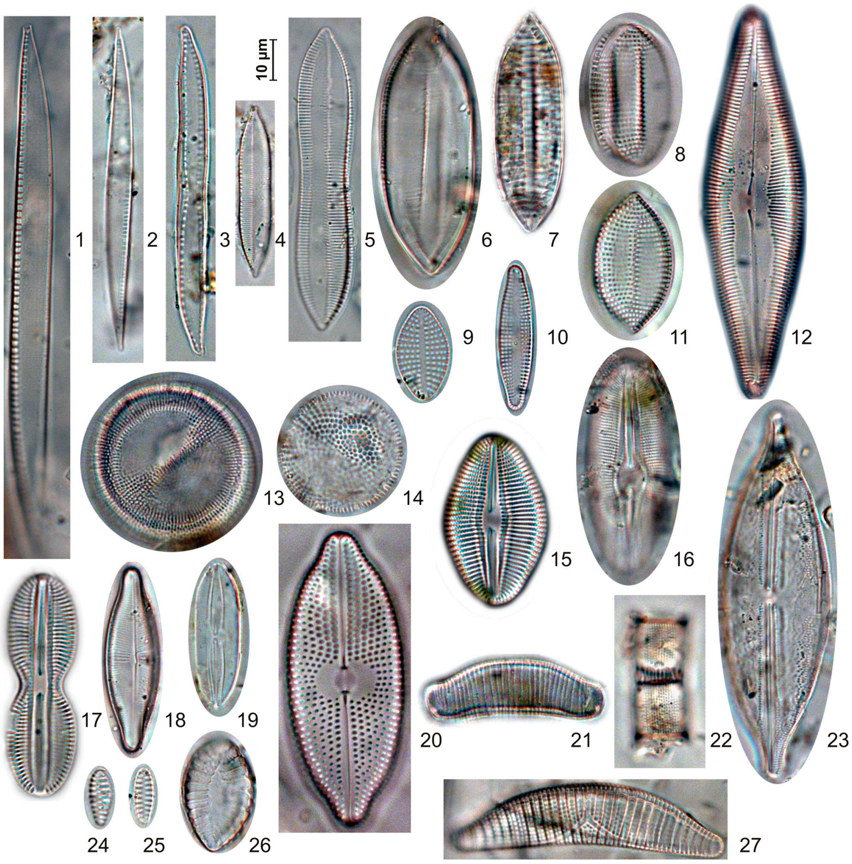

Figure 9. Diatoms of different ecological groups from the DMV sediments. 1, 2—*Nitzschia sigma*; 3—*N. clausii*; 4—*Tryblionella hungarica*; 5—*T. acuminata*; 6—*T. circumsuta*; 7—*T. levidensis*; 8—*T. granulata*; 9—*Delphineis surirella*; 10—*D. kippae*; 11—*Tryblionella compressa*; 12—*Caloneis bivittata* var. *lata*; 13—*Thalassiosira lacustris*; 14—*T. hyperborea*; 15—*Diploneis mereschkowskyi*; 16—*D. ovalis*; 17—*D. interrupta*; 18—*Prestauroneis crucicula*; 19—*Fallacia pygmaea*; 20—*Navicula maculata*; 21—*Eunotia praerupta*; 22—*Aulacoseira italica*; 23—*Anomoeoneis sphaerophora*; 24, 25—*Staurosirella martyi*; 26—*Surirella brebissonii*; 27—*Epithemia turgida*. Brackish water (1–12,14,15,17,19,20,26), euryhaline (13,18,23). and freshwater (16,21–22,24,25,27) diatoms. Scale bar: 10 µm.

Marine species (16−40 taxa) are also abundant and stably subdominant (20.3–46.7%). They are characterized by a large number (18.8–25%) of benthic–planktonic species *Paralia sulcata*, *Odontella aurita*, *Actinoptychus senarius*, *Rhabdonema arcuatum* et al. A noticeable number of planktonic species (12–17.1%) was observed only in samples T2-6, T3-7 and D12-6. Almost all assemblages also contain planktonic species inhabiting both the neritic and oceanic zones: *Actinocyclus curvatulus*, *Coscinodiscus marginatus*, *Bacterosira bathyomphala*, *Thalassionema nitzschioides* (Figure 10). Oceanic species *Neodenticula seminae*, *Rhizosolenia hebetata*, *Coscinodiscus obscurus*, *C. asteromphalus*, *Shionodiscus biporus* occurred rarely. Benthic species are diverse (*Cosmioneis grossepunctata*, *Navicula pennata*, *Petroneis glacialis*, *Tabularia fasciculata*, *Tryblionella granulata*, *T. compressa*, et al.), but they are rare, and their total amount in samples does not usually exceed 1.5% on average.

Euryhaline species (4–15 taxa) are characterized by the dominance of the benthic species *Metascolioneis tumida* (8–22.5%), as well as benthic *Navicula digitoradiata*, *Anomoeoneis sphaerophora*, *Auliscus sculptus*, *Prestauroneis crucicula*, benthic–planktonic alkaliphilic *Caloneis bacillum*, *Achnanthes brevipes*, and planktonic *Thalassiosira lacustris*, *T. hyperborea*, *Ditylum brightwellii*, and *Cyclotella meneghianiana*.

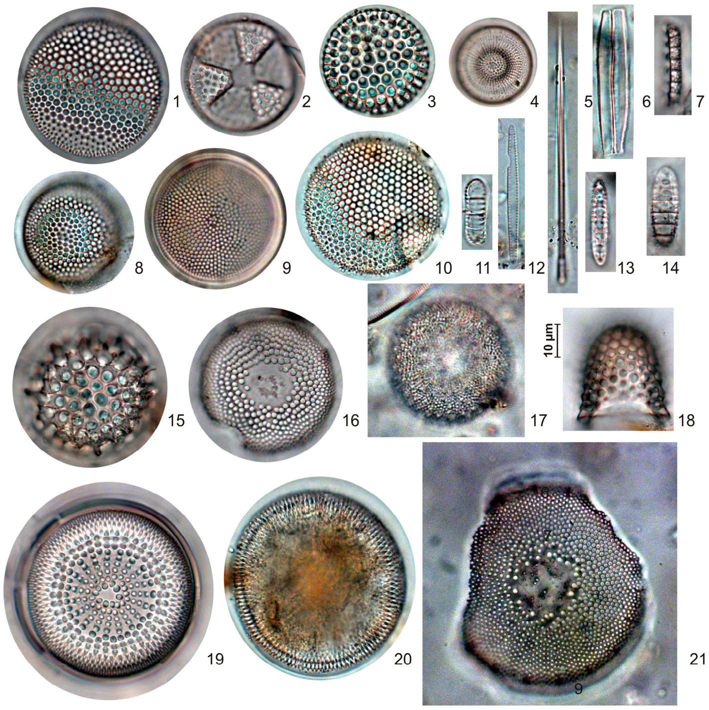

Figure 10. Marine planktonic (1–5, 8–12) and extinct (6, 7, 13–21) species of diatoms from the DMV sediments. 1—*Coscinodiscus radiatus*; 2—*Actinoptychus senarius*; 3—*Coscinodiscus marginatus*; 4—*Bacterosira bathyomphala*; 5—*Sundstroemia setigera*; 6—*Ikebea tenuis*; 7—*Denticulopsis hyalina*; 8—*Thalassiosira antarctica*; 9—*Actinocyclus curvatulus*; 10—*Thalassiosira eccentrica*; 11—*Neodenticula seminae*; 12—*Thalassionema nitzschioides*; 13—*Denticulopsis katayamae*; 14—*D. praedimorpha*; 15—*Eupyxidicula schenckii*; 16—*Thalassiosira insigna*; 17—*Porosira punctata*; 18—*Eustephanias inermis*; 19—*Actinocyclus ingens*; 20—*Eupyxidicula zabelinae*; 21—*Cosmiodiscus intersectus*. Scale bar: 10 µm.

Freshwater species (12–40 taxa) were found in all samples, but mostly in single specimens. They are predominantly represented by cosmopolitan alkaliphilic planktonic (*Aulacoseira italica*, *A. islandica*), and benthic (*Gyrosigma acuminatum*, *Diploneis ovalis*, *Eunotia praerupta*, *Pinnularia viridis*, *Amphora copulata* et al.) species. In addition, freshwater–brackish water, alkaliphilic species of *Nitzschia clausii*, *N. thermalis*, and *Cyclotella atomus* were found. A high diversity (30–40 taxa) and a significant abundance (12.7–14.3%) of freshwater diatoms were observed in sediments near the edge of the intertidal zone (sample D01-1) and near the Kalmar gas–hydrothermal spring (D12-1). Some freshwater diatoms are alkaliphilic (*Amphora lybica*, *Eunotia bilunaris*, et al.) or indifferent to pH (*Fragilaria capucina*, *Pinnularia borealis*, *Stauroneis phoenicenteron*, *Ulnaria ulna* et al.) and salinity (*Caloneis silicula*, *Nitzschia amphibia*, *Diploneis ovalis*, *Gyrosigma acuminatum* et al.) (Table S2). The species diversity of freshwater diatoms is probably associated with the influence of the Nelbutta River runoff, which flows into the Nyisky Bay in this area. It cannot be ruled out that these species can inhabit the DMV waters, which are characterized by low salinity and weak alkalinity.

Extinct species are characteristic of all assemblages. They are represented by 25 species, among which are mainly marine species of *Eupyxidicula schenckii*, *Stephanogonia hanzawae*, *Ikebea tenuis*, *Denticulopsis lauta*, *D. hyalina*, *D. katayamae*, *Thalassiosira marujamica*, extinct in the Miocene, and species of *Eupyxidicula zabelinae*, *Eustephanias inermis*, *Porosira punctata*, *Cosmiodiscus intersectus*, *Coscinodiscus pustulatus*, *Thalassiosira insigna*, *T. nidulus*, extinct mainly at the end of the Pliocene to early Pleistocene [78–82] (Figure 10), and 2 freshwater species *Aulacoseira canadensis* and *A. praegranulata* var. *praeislandica* f. *praeislandica* extinct in the Miocene and Pliocene, respectively [59,83]. Their content in the assemblages is insignificant (0.3–4.3%).

Thus, diatom assemblages from the studied DMV sediments are similar and are characterized mainly by the species *Metascolioneis tumida*, *Paralia sulcata*, *Odontella aurita*, *Pinnunavis yarrensis*, *Petroneis marina*, *Cocconeis scutellum*, and *Navicula digitoradiata*, which prevail there. They contain diatoms of various ecological groups (marine, brackish water, euryhaline, and freshwater) and extinct species. These groups differ in the number of species and abundance in the studied samples. Brackish water and marine species are numerous in the diatom assemblages, accounting for 33–64% and 20.3–46.7%, respectively. Freshwater and euryhaline species are usually found in single specimens, but their total number in assemblages is quite significant: 3.0–14.3% and 3.0–13.1%, respectively. Extinct species are diverse and are encountered constantly, but in single specimens.

3.3. Silicoflagellates

In addition to diatoms, silicoflagellates (Dictyochophyceae) *Distephanus octangulatus*, *Stephanocha speculum* var. *minuta*, and *Octactis speculum* were found (Table S2). The findings of silicoflagellates—typical inhabitants of marine plankton—in the sediments of the DMV, the salinity of the surrounding waters of which often does not exceed 1 psu [42], can be explained by transportation with seawater during tides. The species *Octactis speculum* can inhabit desalinated marine waters [84] which is proved by recent finds of this species in the apex of the Ulban Bay (Sea of Okhotsk), where the salinity of the waters does not exceed 8 psu [85]. This species is characteristic of the Neogene deposits of Sakhalin Island [81,86] and could get into sediments with water–mud masses when passing through the sedimentary sequences.

4. Discussion

The concentration of diatoms in sediments mainly indicate the productivity of surface waters [75,87,88]. The diatom content in the DMV sediments (0.7–9.1 mln valves/g) is higher than in the sediments of the Sakhalin Bay of Northern Sakhalin (0.03–3.5 mln valves/g) [89], Academy Bay (0.7–5.8 mln valves/g) [85], Aniva Bay of South Sakhalin, and Lunsky and Nabilsky bays of Eastern Sakhalin (about 2.0 mln valves/g) [87], comparable to that in Terpeniya Bay of South Sakhalin (2–10 mln valves/g) [87], but lower than in the sediments of the productive northern shelf—5–15.3 mln valves/g and the central part of the Sea of Okhotsk, where the concentration of diatoms reaches from 60 mln valves/g [88] to 152 mln valves/g [87]. Therefore, despite the extreme conditions, it should be noted that the concentration of diatoms in the DMV sediments is quite high. This indicates the high productivity of the waters of the Nyisky Bay and the main role of these waters play in the formation of DMV sediments.

A significant abundance and diversity of brackish water and marine species in all of the studied samples indicates a main influence of marine waters on the formation of the diatom assemblages of DMV sediments. The dominant and constantly occurring species of the different ecological groups are mainly characteristic of coastal marine, lagoon, and estuarine waters, and tidal shoals (e.g., [71,90–92]).

To find out which diatom flora develops in similar conditions, we compared the diatoms of DMV sediments and thermal springs of the Kamchatka Peninsula, Sakhalin Island, and the Kuril Islands (Kunashir, Shiashkotan, Yankich), studied by T. Nikulina with co-authors [16,17,19–21] and L. Ryabushko & V. Tarasov [18]. The comparison showed that a noticeable number of identical species with DMV diatoms are found only in diatom assemblages of thermal springs located on the sea coast. The maximum number of the same species is found in the Dagi thermal springs associated with DMV (Figure 11).

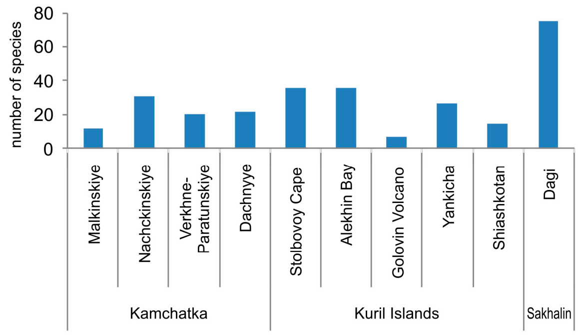

Figure 11. The number of identical species of diatoms from thermal springs of the Russian Far East and the DMV sediments.

They contain 75 identical species, including diatoms of different ecological groups—freshwater, brackish water and marine. A significant number of identical species are found in the diatom flora of the thermal springs of Stolbchaty Cape (36 species) and Alekhin Bay (36 species) of Kunashir Island, located on the coast of the Sea of Okhotsk [16,17], and Craternaya Bay (27 species) of Yankich Island [18], connected to the Rikord Strait by a narrow shallow channel. These are mainly freshwater (*Eunotia bilunaris*, *Gomphonema parvulum*, *Hantzschia amphioxys*, *Fragilaria vaucheriae*, *Rhoicosphenia abbreviata*, *Tabellaria flocculosa*, *Ulnaria ulna*, *Pinnularia borealis*, *Ctenophora pulchella*, *Aulacoseira granulata*) and brackish water (*Cocconeis scutellum*, *Surirella brebissonii*) species. The minimum number of identical species (7) is noted in the thermal spring from the caldera of the Golovnin Volcano (the southern part of the Kunashir Island), the temperature of which varies from 60° to 103 °C [16,17].

Almost all of the above-mentioned thermal springs as well as DMV sediments contain freshwater *Rhoicosphenia abbreviata*, *Nitzschia amphibia*, *Gomphonema parvulum*, *Diploneis ovalis*, *Eunotia bilunaris*, *Epithemia adnata*, *Frustulia vulgaris*, *Ulnaria ulna*, euryhaline *Caloneis bacillum*, *Anomoeoneis sphaerophora*, and brackish water *Tryblionella apiculata*, *Amphora libyca* species. All of these species are alkaliphilic cosmopolitans, and most dominate the diatom assemblages of the thermal springs of Sakhalin (Dagi), the Kuril Islands, and Kamchatka [16,17,19–21]. The algal flora of geothermal springs consists mainly of cold-water species that have adapted to high temperatures [16,17,19]. The true thermophiles *Pinnularia acidojaponica*, *P. acidophila*, and *Nitzschia thermaloides*, typical of thermal springs [16,17,19], are not found in DMV sediments. Part of the freshwater species (27 taxa) of the DMV sediments are common for the diatom flora of the Dagi River, which includes 86 species and intraspecific taxa [76].

A feature of DMV diatom assemblages is the diversity of extinct species (total 25 taxa). Among them are species with a limited age range: *Eupyxidicula zabelinae* (8.0–2.3 Ma), *Porosira punctata* (8.4–1.5 Ma), *Thalassiosira insigna* (7.9–5.0 Ma), *Actinocyclus ingens* (18.4–7.7 Ma), *Denticulopsis lauta* (15.9–13.1 Ma), *D. hyalina* (14.9–13.1 Ma), *D. praedimorpha* (12.4–11.5 Ma), and *D. katayamae* (9.3–8.5 Ma), [78,82]. The percentage of extinct diatoms in the sediments is insignificant (0.8–4.3%). Most of the found extinct species (e.g., *Porosira punctata*, *Eupyxidicula zabelinae*, *Thalassiosira insigna*, *T. nidulus*, *T. marujamica*, *Eustephanias inermis* et al.), are typical for the Nutovskaya Formation of the Late Miocene—Pliocene of the Eastern Sakhalin shelf [50,79]. The outcrops of this formation are common in the Dagi region, but diatoms in these rocks have not been observed [47]. The extinct diatoms are also characteristic of the Mayamrafskaya and Matitukskaya formations of the Late Miocene to Pliocene in the Schmidt Peninsula [80,86], located in the very north of Sakhalin. Therefore, it is assumed that the fossil diatoms could get into DMV sediments as a result of drainage of the Nutovskaya Formation, extended in the Dagi area and adjacent shelf. *Denticulopsis lauta*, *D. hyalina*, and *D. praedimorpha*, which are zonal species of the Middle Miocene zones [82], as well as *Actinocyclus ingens*, *Ikebea tenuis*, and *Stephanogonia hanzawae*, characterize the Middle Miocene deposits of the Sakhalin Island (e.g., [81,93]). Diatom assemblages of the Middle Miocene were identified in the drilled well on the Veninskaya area of the adjacent shelf. The assemblage of the *Denticulopsis hyalina* Zone (14.9–13.1 Ma) characterizes the lower part of the Okobykayskaya Formation (1080–1280 m interval), and the assemblage of the *Denticulopsis praedimorpha* Zone (12.9–11.5 Ma)—the upper part of the formation (720–1000 m interval) [50]. However, diatoms of these diatom zones are not found in the same formation in the Dagi area of Sakhalin [49,94]. The data obtained suggest that the source of the fossil Miocene diatoms is the Okobykayskaya Formation, which is located below the sea floor at depths of 1280–720 m of the adjacent shelf. It is assumed that the roots of the volcano are located approximately at these depths or deeper, and are located under the shelf. The source of gases and water and mud masses is probably the Veninskoye gas condensate field located on the adjacent shelf. Thus, in DMV sediments, extinct species could presumably have come from the underlying Neogene sediments of the Okobykaiskaya and Nutovskaya formations with gas, mud, and water flows. It cannot be excluded that the fossil diatoms may have been introduced into the sediments of the DMV sediments by rivers and streams as a result of the erosion of the sediments of these formations. However, no extinct species were found among the diatoms of the Dagi River and other Sakhalin rivers flowing in the areas of the Neogene sedimentary rocks [28,76]. The findings of extinct diatoms in DMV sediments confirm the existence of an active fluid dynamic system that drains oil and gas complexes of the Dagi area [11] and the adjacent shelf.

5. Conclusions

The diatom assemblages from DMV sediments are distinguished by species diversity, a mixed ecological composition, and extinct species. They are mainly characterized by the predominance of *Metascolioneis tumida*, *Paralia sulcata*, *Odontella aurita*, *Pinnunavis yarrensis*, *Petroneis marina*, *Cocconeis scutellum*, and *Navicula digitoradiata*. The diversity and abundance of brackish water and marine species indicates the predominant influence of sea waters of the Nyisky Bay on the formation of DMV sediments. The diverse freshwater species were mainly introduced into sediments with river runoff, but it is likely that some of them, such as the cosmopolitan alkaliphilic species, are likely inhabitants of geothermal springs. Species characteristic of thermal springs are poorly represented and insignificant. No true thermophilic species were found. The extinct marine species redeposited from the Okobykaiskaya (Middle Miocene) and Nutovskaya (Upper Miocene–Pliocene) formations of the adjacent shelf, from where they were carried with gas–water–mud masses due to an active fluid–dynamic system. The presence of extinct species from the underlying Neogene sediments is the most typical for diatom assemblages of the DMV.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/quat6030049/s1, Table S1: List of studied samples from the Daginsky Mud Volcano, Eastern Sakhalin. Sample number, coordinates, sediment type, and total diatom content. Table S2: List of diatom and silicoflagellate taxa from sediments of the Daginsky Mud Volcano, their ecological and biogeographic characteristics, and abundance (%).

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