ISSN 1995-4255, Contemporary Problems of Ecology, 2017, Vol. 10, No. 4, pp. 380–394. © Pleiades Publishing, Ltd., 2017.
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Modern and Fossil Diatom Assemblages from Bol'shoy Lyakhovsky Island (New Siberian Archipelago, Arctic Siberia)

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Received @@@ @@, @@@; in final form, @@@ @@, @@@@

Abstract—This article discusses the results of a taxonomic and ecological investigation into diatoms from polygonal ponds and quaternary permafrost deposits of Bol'shoy Lyakhovsky Island (New Siberian Archipelago) and the reconstruction of climatic changes on the island during Late Pleistocene/Holocene transition using fossil diatom assemblages from the permafrost deposits. The taxonomic list of diatoms includes 159 diatom species. The main ecological factors that determine the distribution of diatoms in the investigated data set are mean air temperature in July, pH, conductivity, water depth, and the concentration of Si^{4+} and Al^{3+}. An increase in water depth and stable lacustrine conditions in the Lateglacial–Holocene in the ancient thermokarst lake relate to Lateglacial warming before 11860 ± 160 years BP and during the early Holocene between 11210 ± 160 and 7095 ± 60 years BP.

Keywords: high Arctic, Bol'shoy Lyakhovsky Island, diatoms, ecological factors, Pleistocene, Holocene

DOI: 10.1134/S1995425517040060

INTRODUCTION

The territory of the high Arctic zone (71°N and higher), which includes the New Siberian Islands, has extreme climatic conditions (long winters, constant low temperatures, and short growing seasons). Therefore, this zone remains almost unaffected by anthropogenic impact and consequently has an exceptional potential to be used for the reconstruction of historical environment (Cremer, Wagner, 2003; Palagushkina et al., 2014, Frolova, 2016). Palaeoarchives of such arctic conditions are benthic sediments in both modern aquatic ecosystems and permafrost sequences formed on the place of existing lakes (Wetterich et al., 2009 a). Diatoms are widely used as palaeoindicators but remain relatively poorly studied in the palaeoarchives of the high Arctic zone of Siberia. Some literature data on the quaternary deposits of diatoms was collected on both islands of the New Siberian Archipelago, namely, Bol'shoy Lyakhovsky Island (Romanovsky, 1958; Rapoport, Romanovsky, 1959; Pirumova, 1968; Archangelov et al., 1996; Kunitsky, 1998; Grigor'ev, Kunitsky 2000; Andreev et al., 2004; Andreev et al., 2009, Andreev et al., 2011) and Zhokhov Island (Anisimov et al., 2009a; Anisimov et al., 2009b). The investigation into species composition and ecological parameters of diatoms in the high Arctic will provide additional data for regional databases and will help increase the accuracy of paleoecological reconstructions.

The purpose of this work is to study the taxonomic composition and ecological features of diatoms in the palaeoarchives of Bol'shoy Lyakhovsky Island and identify the main ecological factors that determine the diatom communities nowadays and during the last transition between glacial and interglacial conditions.

MATERIALS AND METHODS

The complex research of the Russian and German expedition team was performed on the Bol'shoy Lyakhovsky Island in July 2007 (Fig. 1). According to climatic zoning, the territory of studies belongs to the arctic zone and is characterized by great difference in the amount of sunlight in winter and summer, 9-month-long cold period, and a frostless period of 30–45 days. The mean temperature in January varies from –32 to –35°C; the mean temperature in July varies from +6 to +8°C. The mean annual precipitation rate is less than 150 mm; the summer season accounts for more than 60% of them (Gavrilova, 1973). Thermokarst lakes are rather rare in the modern relief

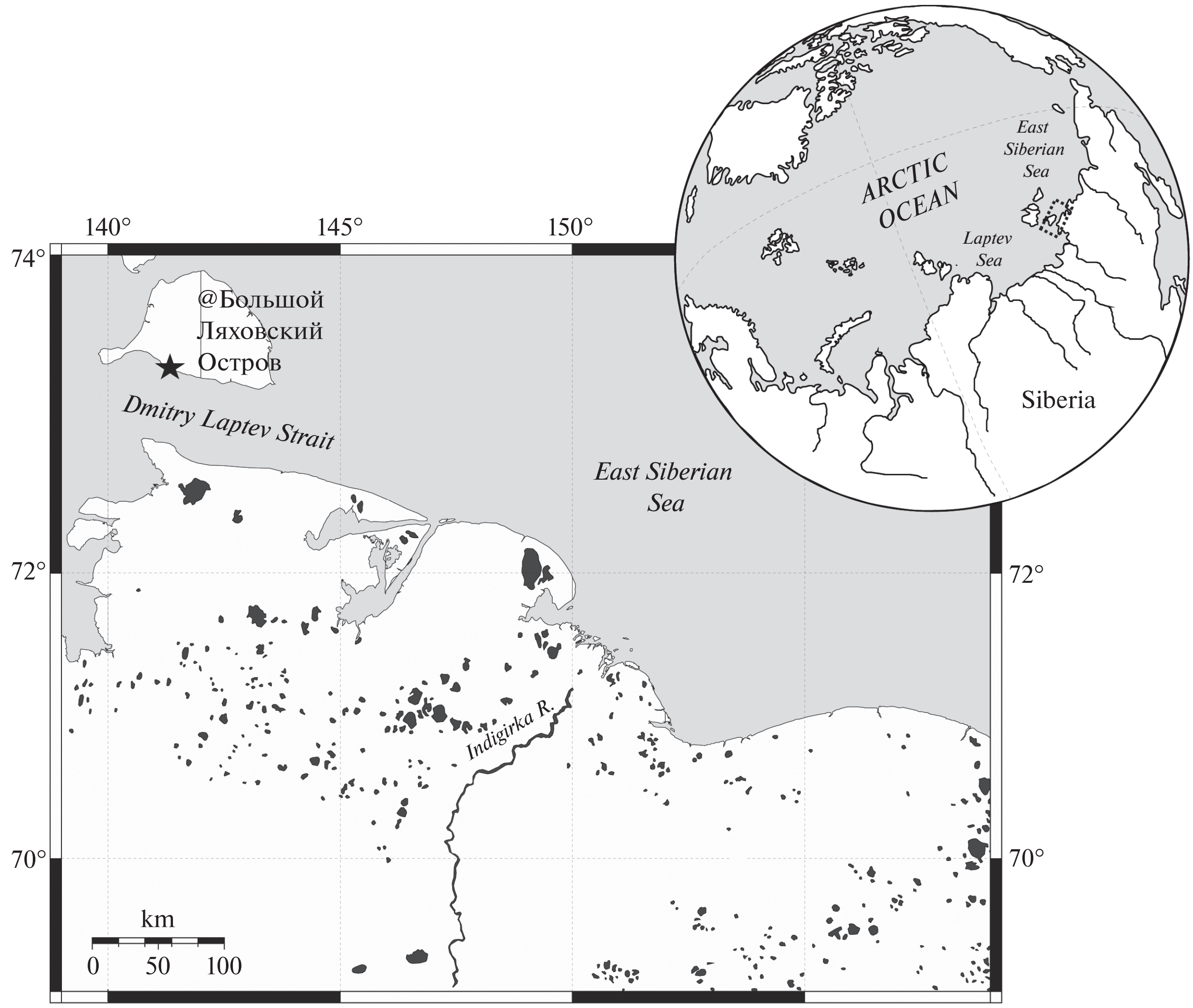

Fig. 1. Study site on Bol'shoy Lyakhovsky Island.

of the island, but thermoerosional valleys and polygonal ponds are common parts of its periglacial landscape (Wetterich et al., 2009b).

We studied 15 polygonal ponds (LAP 1d-15) in different landscape elements of the southern coastal zone of Bol'shoy Lyakhovsky Island (73°N, 141°E). The study material included water samples and the samples of superficial benthic sediments consisting of silty or sandy matter with some detritus. We measured water temperature, pH, and conductivity (Wetterich et al., 2009 a; Nazarova et al., 2011). The chemical composition of water was hydrocarbonate–chloride (Wetterich et al., 2008) with a low mineralization rate (Alekin, 1970) and low hardness. The water pH was neutral or slightly alkaline (Palagushkina et al., 2012a; Palagushkina et al., 2013). Daily monitoring of water temperature in LAP-01d water body showed that it mainly depends on air temperature (Fig. 2), which varied from –1 to +25°C, while water temperature varied from +3 to +17°C. More detailed data on studied polygonal ponds of the island is presented in (Palagushkina et al., 2012a).

The samples of frozen deposits for micropaleontological analysis were collected in a composite profile L7-08 on a cliff situated near the Laptev Strait. The profile consisted of subprofiles AB and CD (Fig. 3), separate samples of which were analyzed by radiocarbon dating using accelerator mass spectrometry (AMS). The geochronological, lithological, and first paleontological data of the L7-08 profile based on the analysis of pollen and ostracods have already been published (Wetterich et al., 2009a). Based on geochronological, sedimentological, biochemical, and cryolithological measurements, we divided the horizons into three groups: taberal (A), which consists of late Pleistocene complex; lacustrine (B and C), which consists of lateglacial and early Holocene sediments of thermokarst lake and contains mollusc shells, ostracods, and wood

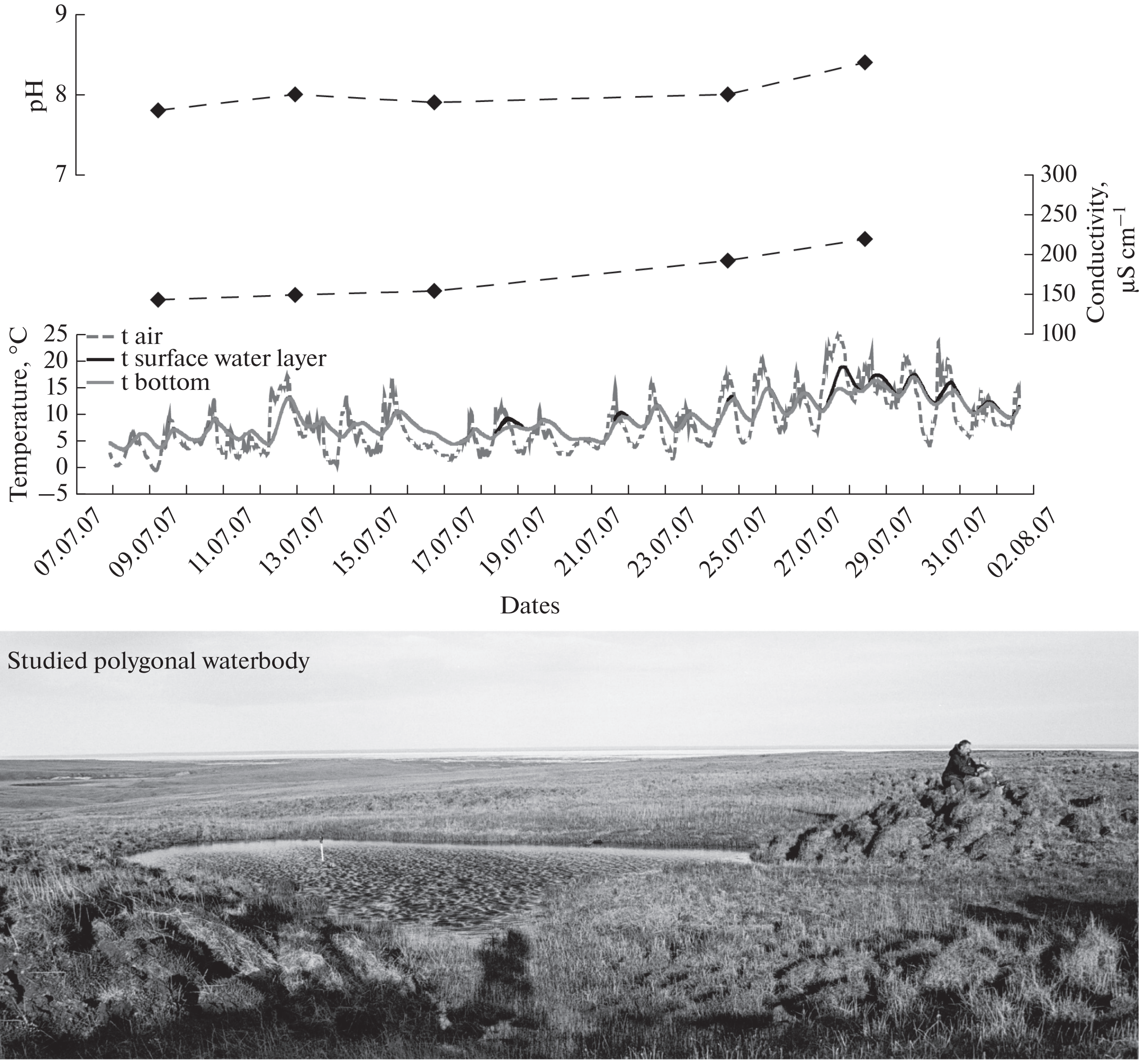

Fig. 2. Monitoring of air temperature, water temperature, pH, and conductivity in a polygonal pond LAP-01d on Bol'shoy Lyakhovsky Island.

fragments; and waterlogged (D), which was accumulated in tundra during Holocene (Wetterich et al., 2009 a) (Fig. 3).

The samples of benthic sediments of polygonal ponds and frozen deposits were treated using the water bath method (Battarbee, 1986) in the laboratory of Alfred Wegener Institute (Potsdam, Germany). For the preparation of slides, we used high refracting Naphrax resin. The species were identified using Russian and other key books (Zabelina et al., 1951; Krammer, Lange-Bertalot, 1986, 1988, 1991a, 1991b). When creating the list of species, we took the latest revisions in systematics into account (Genkal et al., 2013; http://www.algaebase.org/browse/taxonomy/?id=77640). The valves were counted by parallel transects up to 500 pieces in a sample of modern sediments and up to 200 pieces in a sample of frozen deposits using Axioplan Zeiss light microscope and immersion oil. The total number of valves was considered to be 100%. Dominant species were those which accounted for 10% of the total amount or more; subdominants were species which accounted for 5–10%.

The ecological and geographical parameters of diatoms included their habitat, water pH and salinity, geographical distribution, temperature diapason, and water velocity (Davydova, 1985; Barinova et al., 2006). The similarity of diatom taxonomic composition was estimated using the Sorensen coefficient (Sorensen, 1948).

Statistical analysis was performed using the Canoco 4.5 program and mainly according to the procedures described by Nazarova et al. (Nazarova et al., 2013; Nazarova et al., 2015). The analysis included diatom taxa found in at least one lake with a relative

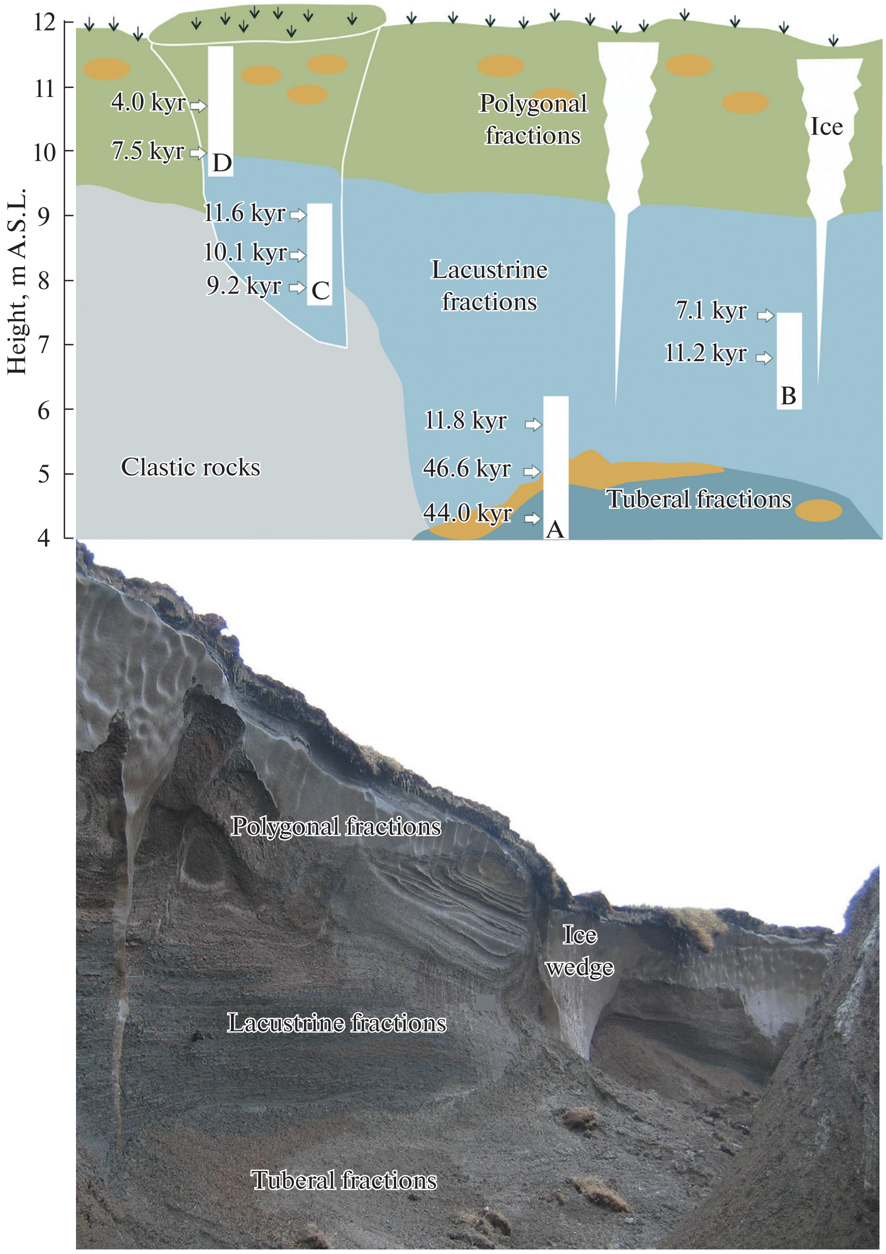

Fig. 3. Composite profile of quaternary permafrost deposits of L7-08 profile on the cliff of Bol'shoy Lyakhovsky Island. Profile horizons: (A) taberal, (B, C) lacustrine, and (D) waterlogged.

abundance of at least 5%. According to the results of DCA, the gradient length of axis was 1.68 units of standard deviation, which means that the linear method of ordination (redundancy analysis, RDA) needs to be used (Birks, 1995; ter Braak, Šmilauer, 2002). Statistical analysis included ecological factors such as mean air temperature in July (New et al., 2002), water temperature, water depth, water transparency, conductivity, pH, and the concentration of Cl^-, SO_4^{2-}, HCO_3^-, O_2, Si^{4+}, Ca^{2+}, Mg^{2+}, Na^+, Al^{3+} Fe_{total}. The ecological parameters with a variance inflation factor (VIF) of more than 20 (ter Braak, Šmilauer, 2002) was removed one by one until all the remaining VIF values were lower than 20. The significance of ecological factors that determine the variation of diatom distribution was estimated by the forward selection method. The proportion of modern diatom communities and the samples of frozen deposits of Bol'shoy Lyakhovsky Island was analyzed using an RDA "time-track"; the fossil data was projected in a passive way. The diagram of distribution of diatom taxa in the profile of frozen deposits was built in C2 program (Juggins, 2007) and zoned by cluster analysis in the PAST program (Hammer et al., 2001).

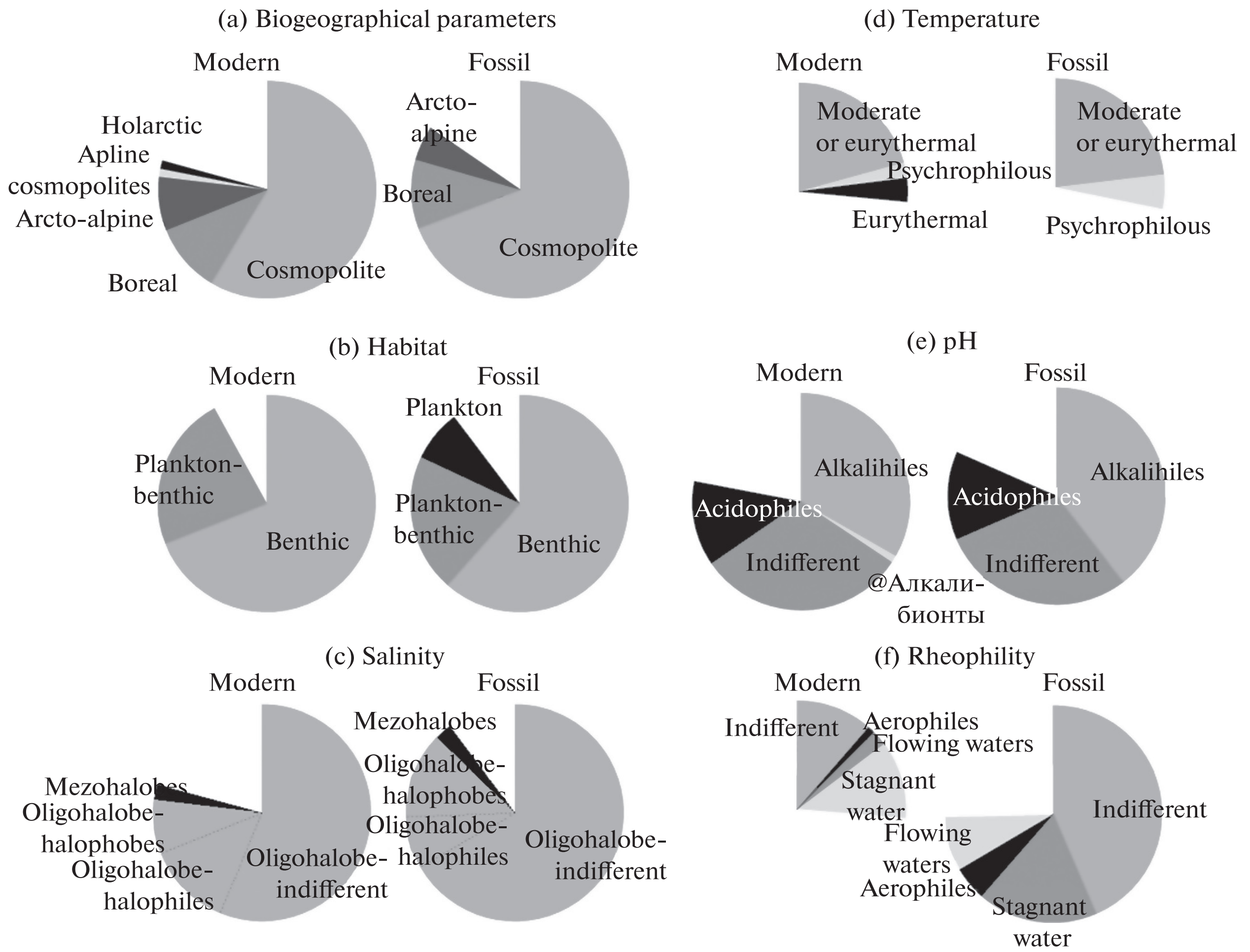

Fig. 4. Ecological and geographical parameters of modern and fossil diatoms of the Bol'shoy Lyakhovsky Island.

RESULTS

Species Composition of Diatoms and the Factors of Their Distribution

The diatomic flora of modern sediments of 15 polygonal ponds of the Bol'shoy Lyakhovsky Island included 84 species (see table); the number of species per water body varied from 18 to 34. The dominant species were *Achnanthidium minutissimum* (Kütz.) Czarnecki, *Caloneis amphisbaena* (Bory) Cl., *Cymbopleura angustata* (W.Sm.) Kram., *Eunotia praerupta* Ehr., *E.tenella* (Grun.) Hust., *Fragilaria brevistriata* Grun., *Gomphonema angustatum* var. *angustissima* H.F.Van Heurck, *Nitzschia frustulum* (Kütz.) Grun., *N. paleacea* (Grun.) Grun., *Tabellaria fenestrata* (Lyngb.) Kütz., and *T. flocculosa* (Roth) Kütz.

The ecological and geographical analysis of species composition showed that these are cosmopolitan benthic species either inhabiting stagnant waters or indifferent to water temperature and flow (Fig. 4). Only two psychrophilous species were found: *E. praerupta* Ehr. and *Pinnularia brevicostata* Cl. The low mineralization rate in most water bodies contributes to the dominance of freshwater oligohalobs; the composition of mezohalobs include *Eucocconeis flexella* (Kütz.) Meist. and *Tryblionella levidensis* W.Smith. Most of the species preferred neutral or slightly alkaline pH.

The diatoms of late Pleistocene/Holocene frozen deposits from 17 samples collected in L7-08 thermokarst profile included 40 taxa; the number of taxa varied from 2 to 21 between layers (Fig. 5). These diatoms were mostly cosmopolitan benthic and plankton–benthic species. Only 5% of species were arcto-alpine, and only 8% were planktonic. The temperature preferences of most taxa were unknown, or they were indifferent; two of the species were psychrophilous: *E. praerupta* Ehr. and *Gyrosigma acuminatum* (Kütz.) Rabenh. The samples found in frozen deposits also induced oligohaline and alkaliphilic conditions (Fig. 4, 5).

The redundancy analysis based on all ecological parameters and the composition of diatoms in modern water bodies and frozen deposits of the Bol'shoy Lyakhovsky Island showed that the level of Ca^{2+}, Mg^{2+}, Na^{+} and Cl^{-} ions and conductivity correlate with each

Table 1. Species composition and abundance of diatoms on the Bol'shoy Lyakhovsky Island

Authors		a	b	c	d	d
Species		f	f	f	m	f
1	*Achnanthes oblongella* Østrup				+	
2	*Achnanthes trinodis* (Ralfs) Grunow				+	
3	*Achnanthidium bioretii* (H.Germain) Monnier, Lange-Bertalot & Ector				+	
4	*Achnanthidium minutissimum* (Kützing) Czarnecki				+	
5	*Achnantheiopsis delicatula* (Kützing) Lange-Bertalot			+		
6	*Actinocyclus normanii* (W.Gregory ex Greville) Hustedt					+
7	*Amphora ovalis* (Kützing) Kützing			+		
8	*Amphora libyca* Ehrenberg				+	
9	*Aneumastus tuscula* (Ehrenberg) D.G.Mann & A.J.Stickle					+
10	*Asterionella formosa* Hassall	+	+			
11	*Aulacoseira granulata* (Ehrenberg) Simonsen	+	+			+
12	*Aulacoseira granulata* var. *angustissima* (Otto Müller) Simonsen	+	+			
13	*Aulacoseira italica* (Ehrenberg) Simonsen	+	+			
14	*Aulacoseira lacustris* (Grunow) Krammer					+
15	*Aulacoseira valida* (Grunow) Krammer		+			+
16	*Aulacoseira distans* (Ehrenberg) Simonsen	+	+			
17	*Brebissonia lanceolata* (C.Agardh) Mahoney & Reimer	+				
18	*Caloneis amphisbaena* (Bory) Cleve	+	+	+	+	
19	*Caloneis leptosoma* (Grunow) Krammer		+	+		
20	*Caloneis silicula* (Ehrenberg) Cleve				+	
21	*Cocconeis pediculus* Ehrenberg			+		
22	*Cyclostephanos dubius* (Hustedt) Round			+		
23	*Cymbella affinis* Kützing			+		
24	*Cymbella aspera* (Ehrenberg) Cleve			+		
25	*Cymbella cymbiformis* C.Agardh			+	+	
26	*Cymbella cistula* (Ehrenberg) O.Kirchner				+	
27	*Cymbella heteropleura* (Ehrenberg) Kützing		+			
28	*Cymbella gracilis* (Ehrenberg) Kützing		+			
29	*Cymbopleura angustata* (W.Smith) Krammer				+	
30	*Cymbopleura austriaca* (Grunow) Krammer			+		
31	*Cymbopleura incerta* (Grunow) Krammer					+
32	*Cymbopleura lata* (Grunow ex Cleve) Krammer			+		
33	*Cymbopleura naviculiformis* (Auerswald ex Heiberg) Krammer				+	
34	*Cymbopleura subcuspidata* (Krammer) Krammer				+	
35	*Cymbopleura tynnii* (Krammer) Krammer					+
36	*Denticula tenuis* Kützing				+	
37	*Diatoma tenuis* C.Agardh				+	
38	*Diatoma vulgaris* Bory		+	+		
39	*Didymosphenia geminata* (Lyngbye) Mart.Schmidt			+		
40	*Diploneis elliptica* (Kützing) Cleve					+
41	*Diploneis oblongella* (Nägeli ex Kützing) Cleve-Euler				+	
42	*Diploneis puella* (Schumann) Cleve				+	
43	*Encyonema alpinum* (Grunow) D.G.Mann				+	

Table 1 (Contd.)

Authors		a	b	c	d	d
Species		f	f	f	m	f
44	*Encyonema hebridicum* Grunow ex Cleve	+	+	+		
45	*Eucocconeis flexella* (Kützing) Meister				+	
46	*Eucocconeis laevis* (Østrup) Lange-Bertalot				+	
47	*Encyonema latens* (Krasske) D.G.Mann				+	
48	*Encyonema mesianum* (Cholnoky) D.G.Mann				+	+
49	*Encyonema minutum* (Hilse) D.G.Mann				+	
50	*Encyonema paucistriatum* (Cleve-Euler) D.G.Mann				+	
51	*Encyonema perpusillum* (Cleve-Euler) D.G.Mann		+			
52	*Encyonema silesiacum* (Bleisch) D.G.Mann	+	+	+	+	+
53	*Eunotia arcus* Ehrenberg		+			
54	*Eunotia bidens* Ehrenberg			+		
55	*Eunotia bigibba* Kützing		+	+		
56	*Eunotia bilunaris* (Ehrenberg) Schaarschmidt	+	+	+	+	+
57	*Eunotia denticulata* var. *denticulata* (Brébisson ex Kützing) Rabenhorst			+		
58	*Eunotia dio*don Ehrenberg		+	+		
59	*Eunotia exigua* (Brébisson ex Kützing) Rabenhorst	+	+	+	+	
60	*Eunotia faba* Ehrenberg			+	+	
61	*Eunotia fallax* A.Cleve	+	+			
62	*Eunotia inflata* (Grunow) Norpel-Schempp & Lange-Bertalot	+	+			
63	*Eunotia monodon* Ehrenberg			+		
64	*Eunotia parallela* Ehrenberg				+	
65	*Eunotia papilio* (Ehrenberg) Grunow	+	+			
66	*Eunotia pectinalis* (Kützing) Rabenhorst		+	+		
67	*Eunotia praerupta* Ehrenberg	+	+	+	+	+
68	*Eunotia satelles* (Nörpel-Schempp & Lange-Bertalot) Nörpel-Schempp & Lange-Bertalot			+		
69	*Eunotia septentrionalis* Østrup			+		
70	*Eunotia sudetica* Otto Müller			+		
71	*Eunotia tenella* (Grunow) Hustedt	+	+	+	+	
72	*Eunotia triodon* Ehrenberg		+			
73	*Fragilaria bidens* Heiberg				+	
74	*Fragilaria brevistriata* Grunow				+	
75	*Fragilaria capucina* Desmazières				+	
76	*Fragilariforma constricta* (Ehrenberg) D.M.Williams & Round				+	
77	*Fragilaria tenera* var. *nanana* (Lange-Bertalot) Lange-Bertalot & S.Ulrich				+	
78	*Fragilaria tenera* (W.Smith) Lange-Bertalot				+	
79	*Fragilariforma virescens* (Ralfs) D.M.Williams & Round				+	
80	*Fragilaria virescens* var. *exigua* Grunow					+
81	*Fragilaria* sp.					+
82	*Frustulia rhomboides* (Ehrenberg) De Toni					+
83	*Frustulia spicula* Amossé				+	
84	*Frustulia vulgaris* (Thwaites) De Toni				+	
85	*Gomphonema acuminatum* Ehrenberg			+	+	
86	*Gomphonema angustum* C.Agardh			+		

Table 1 (Contd.)

Authors		a	b	c	d	d
Species		f	f	f	m	f
87	*Gomphonema angustatum* var. *angustissima* H.F.Van Heurck				+	+
88	*Gomphonema turris* Ehrenberg			+		
89	*Gomphonema gracile* Ehrenberg				+	
90	*Gomphonema minutum* (C.Agardh) C.Agardh				+	
91	*Gomphonema olivaceum* (Hornemann) Brébisson		+	+	+	+
92	*Gomphonema olivaceum* var. *minutissimum* Hustedt				+	
93	*Gomphonema parvulum* (Kützing) Kützing			+	+	+
94	*Gomphonema truncatum* Ehrenberg		+		+	+
95	*Gyrosigma acuminatum* (Kützing) Rabenhorst					+
96	*Gyrosigma attenuatum* (Kützing) Rabenhorst			+		
97	*Hantzschia amphioxys* (Ehrenberg) Grunow	+	+	+	+	+
98	*Hantzschia virgata* (Roper) Grunow		+			
99	*Humidophila contenta* (Grunow) Lowe, Kociolek, J.R.Johansen, Van de Vijver, Lange-Bertalot & Kopalová				+	
100	*Navicula amphibola* Cleve	+	+	+		
101	*Navicula bryophila* Østrup			+		
102	*Navicula cryptocephala* Kützing	+	+	+	+	
103	*Navicula lanceolata* Ehrenberg			+		
104	*Luticola mutica* (Kützing) D.G.Mann	+	+	+		
105	*Luticola nivalis* (Ehrenberg) D.G.Mann					+
106	*Luticola pseudokotschyi* (Lange-Bertalot) Metzeltin & Lange-Bertalot	+	+			
107	*Luticola ventricosa* (Kützing) D.G.Mann			+		
108	*Navicula semen* Ehrenberg	+				
109	*Navicula rhynchocephala* Kützing				+	+
110	*Navicula vulpina* Kützing				+	
111	*Neidium affine* (Ehrenberg) Pfitzer					+
112	*Neidium bisulcatum* (Lagerstedt) Cleve				+	
113	*Neidium iridis* (Ehrenberg) Cleve		+		+	+
114	*Nitzschia bulnheimiana* (Rabenhorst) H.L.Smith				+	
115	*Nitzschia commutatoides* Lange-Bertalot				+	
116	*Nitzschia frustulum (Kützing) Grunow*				+	
117	*Nitzschia frustulum* var. *tenella* Grunow				+	
118	*Nitzschia linearis* W.Smith				+	
119	*Nitzschia gracilis* Hantzsch				+	
120	*Nitzschia palea* (Kützing) W.Smith				+	
121	*Nitzschia paleacea* (Grunow) Grunow				+	
122	*Nitzschia subtilis* (Kützing) Grunow				+	
123	*Nitzschia vermicularis* (Kützing) Hantzsch					+
124	*Nitzschia* sp.					+
125	*Orthoseira roeseana* (Rabenhorst) O'Meara				+	+
126	*Pinnularia alpina* W.Smith				+	
127	*Pinnularia borealis* Ehrenberg	+	+	+	+	+
128	*Pinnularia brevicostata* Cleve			+	+	

Table 1 (Contd.)

Authors		a	b	c	d	d
Species		f	f	f	m	f
129	*Pinnularia divergens* W.Smith			+		
130	*Pinnularia intermedia* (Lagerstedt) Cleve	+	+		+	
131	*Pinnularia interrupta* W.Smith			+	+	
132	*Pinnularia gentilis* (Donkin) Cleve		+			
133	*Pinnularia gibba* Ehrenberg			+		
134	*Pinnularia lata* (Brébisson) W.Smith	+	+	+		+
135	*Pinnularia microstauron* (Ehrenberg) Cleve		+		+	+
136	*Pinnularia subcapitata* W.Gregory		+			
137	*Pinnularia viridis* (Nitzsch) Ehrenberg	+	+	+	+	+
138	*Platessa conspicua* (Ant.Mayer) Lange-Bertalot					+
139	*Placoneis elginensis* (W.Gregory) E.J.Cox					+
140	*Placoneis placentula* (Ehrenberg) Mereschkowsky			+		
141	*Psammothidium levanderi* (Hustedt) Bukhtiyarova & Round				+	
142	*Rhoicosphenia abbreviata* (C.Agardh) Lange-Bertalot				+	
143	*Sellaphora pupula* (Kützing) Mereschkovsky		+	+	+	
144	*Stauroneis anceps* Ehrenberg	+	+		+	+
145	*Stauroneis phoenicenteron* (Nitzsch) Ehrenberg	+	+	+	+	+
146	*Staurosirella pinnata* (Ehrenberg) D.M.Williams & Round				+	+
147	*Stephanodiscus alpinus* Hustedt				+	+
148	*Stephanodiscus minutulus* (Kützing) Cleve & Möller			+		
149	*Stephanodiscus niagarae* Ehrenberg					+
150	*Stephanodiscus rotula* (Kützing) Hendey	+	+			
151	*Surirella angusta* Kützing					+
152	*Surirella minuta* Brébisson ex Kützing, nom. illeg.				+	
153	*Tabellaria fenestrata* (Lyngbye) Kützing			+	+	
154	*Tabellaria flocculosa* (Roth) Kützing	+	+		+	
155	*Tabularia fasciculata* (C.Agardh) D.M.Williams & Round				+	
156	*Tryblionella debilis* Arnott ex O'Meara				+	
157	*Tryblionella levidensis* W.Smith				+	
158	*Tetracyclus emarginatus* (Ehrenberg) W.Smith					
159	*Ulnaria ulna* (Nitzsch) Compère	+	+	+		
	Total:	31	48	55	84	40

(a) Rapoport and Romanovsky, 1959 (middle Pleistocene/Holocene);
(b) Pirumova et al., 1968 (middle Pleistocene/Holocene);
(c) Andreev et al., 2009 (late Pleistocene/Holocene);
(d) Palagushkina et al. (late Pleistocene/Holocene);
m indicates modern sediments and f indicates fossil deposits.

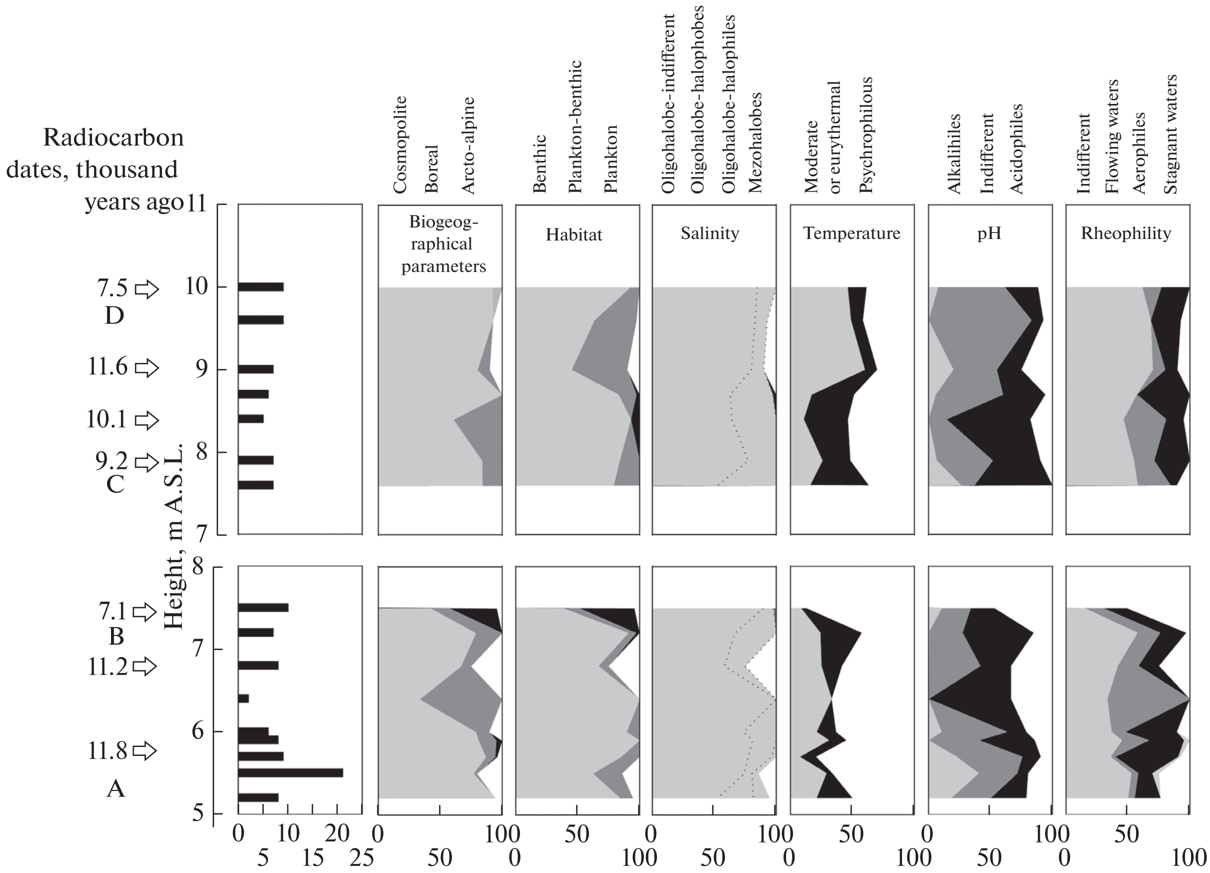

Fig. 5. Number of species and ecological and geographical parameters of diatoms in the horizons of L7-08 profile on Bol'shoy Lyakhovsky Island.

other to a great extent. Monte Carlo test with 499 permutations showed that significant factors that determined the distribution of diatoms ($P \leq 0.05$) are mean air temperature in July, pH, conductivity, water depth, and the concentration of Si^{4+} and Al^{3+}.

Reconstruction of Ecological Conditions of Lateglacial Period of Pleistocene/Holocene

Both subprofiles of L7-08 thermokarst had the same geological age. However, the horizons of upper CD profile were rearranged in the inverse order (Fig. 3, 5); therefore, this profile was excluded from further paleoecological interpretations. Basing on the age of deposits and the distribution of 14 dominant species, subprofile AB was divided into two zones: A and B (Fig. 6).

The samples of zone A (11860 ± 160 years BP, 5.7 m A.S.L.) belong to late Pleistocene. This zone contained 26 diatom species; the number varied from 6 to 21. The share of acidophilic and aerophilic species and species indifferent to water flow and salinity increased; the dominant species were *Pinnularia borealis* Ehr., *Hantzschia amphioxys* (Ehr.) Grun., *E. praerupta* Ehr., *Stauroneis phoenicenteron* (Nitzsch.) Ehr. The thermokarst water body is supposed to grow shallow and waterlogged as a result of the decreasing temperature of environment.

The samples of zone B (11210 ± 160 – 7095 + 60 years BP, 6.8–7.5 m A.S.L.) belong to early Holocene. This zone contained 13 diatom species; the number varied from 7 to 10. The number of diatom valves in the lower part of this zone was very small, which may indicate that the lake disappeared in early Holocene. The share of valves of planktonic, as well as acidophilic and arcto-alpine species in the middle and upper parts of this zone, increased significantly. In addition to the dominant species of zone A, larger benthic species of the genus *Pinnularia* (*P. lata* (Bréb.) W. Smith and *P. viridis* (Nitzsch) Ehrb.) and some planktonic species (*Aulacoseira valida* (Grun.) Kramm. and *A. lacustris* (Grun.) Kramm) were found. This could result from the increasing depth and the formation of stable lacustrine conditions in a thermokarst water body due to an increase in air temperature during the period of the Holocene temperature optimum. This period was determined by palynological analysis performed with the samples aged 9000–10000 years with mean July temperature of 5–

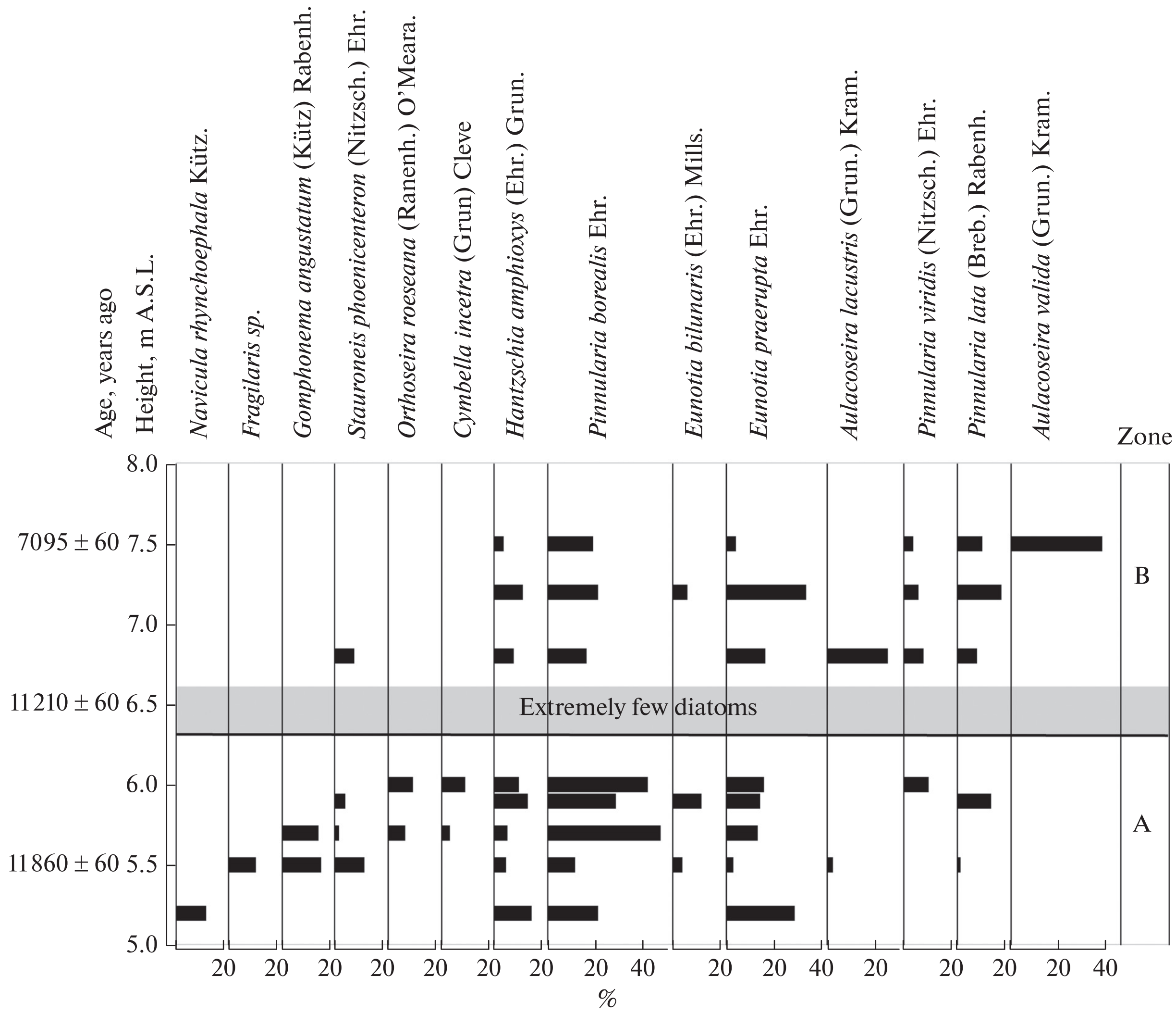

Fig. 6. Distribution of dominant diatom species in the zones of AB subprofile of quaternary permafrost deposits of the L7-08 profile of Bol'shoy Lyakhovsky Island.

7°C in the New Siberian Archipelago (Makeev Pitul'ko, 1991).

DISCUSSION

First data on the diatoms of late quaternary permafrost deposits of Bol'shoy Lyakhovsky Island were presented by Romanovsky and Rapoport (1959) and Pirumova (1968). These authors identified 31 and 48 diatom species, respectively (see table). Andreev et al. (2009) identified 55 diatom species in the permafrost deposits of late Pleistocene and Holocene. Our study showed that the diatoms of modern sediments of polygonal ponds and quaternary permafrost deposits of the Bol'shoy Lyakhovsky Island are numerous and various. The total taxonomic composition included 159 diatom species: 104 species from frozen deposits and 84 species from modern sediments of polygonal ponds; 19 of them were found more than once, which indicates the high adaptive potential of these species in changing environmental conditions in the quaternary period (see table).

The modern Holocene benthic sediments of diatoms are characterized by high species diversity of the genera *Achnanthes* (including those renamed *Achnanthidium* and *Psammothidium*), *Cymbella* (including *Cymbopleura* and *Encyonema*), *Fragilaria* (including *Fragilariforma* and *Staurosirella*), *Gomphonema*, and *Nitzschia*; the predominance of small species with high growth rate; high preferred mineralization rate; and high concentration of Si and P. The complete absence of planktonic forms is caused by the shallowness of modern polygonal ponds.

A previous investigation into benthic deposits of polygonal tundra water bodies in three subregions of northern Yakutia (Bol'shoy Lyakhovsky Island, the coast of Oygossky Yar, and an area near the settlement of Tiksi) showed that pH, conductivity, and water

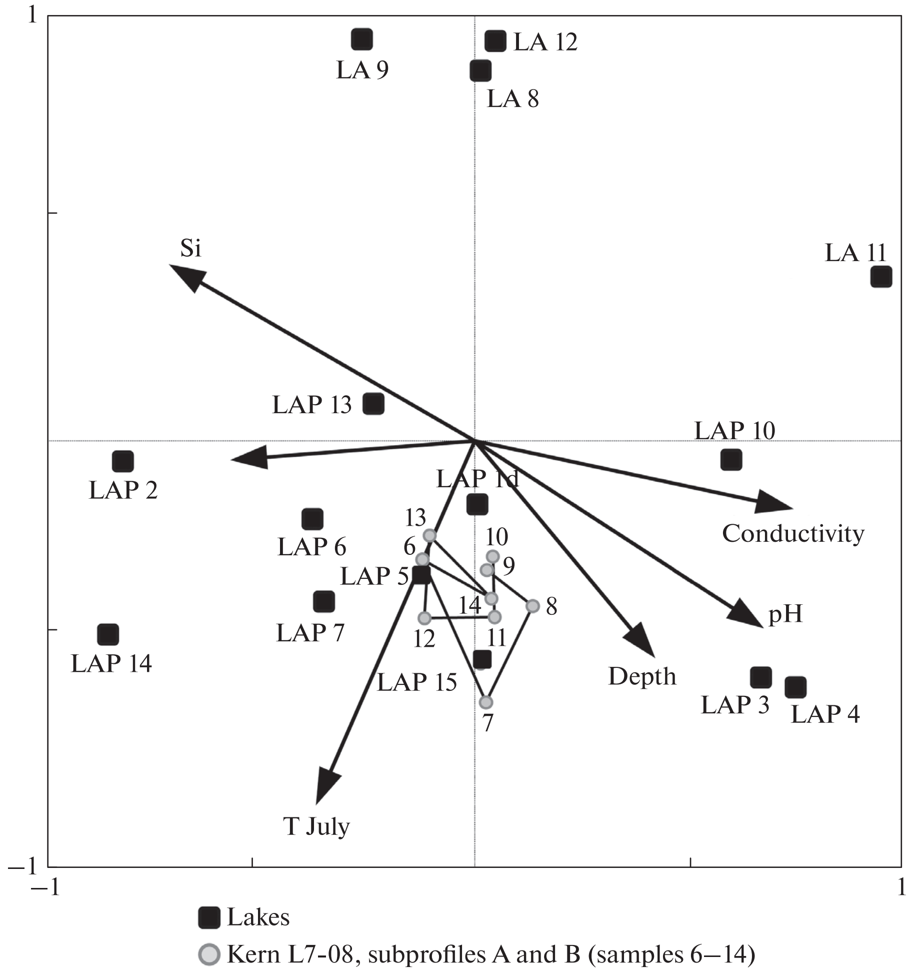

Fig. 7. Distribution of diatom samples in modern polygonal ponds and quaternary frozen deposits of L7-08 profile of Bol'shoy Lyakhovsky Island in relation to the main ecological factors. Note: (*6*, *7*, *8*, *9*, and *10*) samples collected in zone A; (*11*, *12*, *13*, and *14*) samples collected in zone B; LAP 1d to LAP 15: samples of modern sediments of polygonal ponds.

depth are the main ecological factors that determine the species composition of diatoms (Palagushkina et al., 2012 a). In the water bodies of Bol'shoy Lyakhovsky Island, significant factors other than pH, conductivity, and water depth are air temperature in July and the level of Si and Al ions. Since the climate of this region is very dry (Gavrilova, 1973) and the studied water bodies are shallow, air temperatures during summer period not only affect water temperature in water bodies (Wetterich et al., 2009a; Palagushkina et al., 2012b) but also determine the depth of thawing process in the active ice layer and evaporation rate and, consequently, the whole acid–base and salt balance of polygonal ponds of the island.

As for the diatom species composition of frozen deposits, most of the species belong to the genera *Eunotia*, *Pinnularia*, *Aulacoseira*, and *Navicula* (including renamed genera *Luticola*, *Placoneis*, and *Sellaphora*). The species of *Eunotia* and *Pinnularia* form freshwater psychrophilous complex of benthic and acidophilic mainly halophobic arcto–alpine and boreal species typical of alas deposits (Belevich et al., 1970; Kagan, 2012). According to literature data, the abundance of these two genera is determined by low concentrations of dissolved calcium, magnesium, carbonate, and hydrocarbonate ions and low pH values (Van Dam et al., 1994; Potapova et al., 2003; Stenina, 2008). In arctic water bodies with low mineralization rate, pH becomes the most important factor that affects the development of diatom communities (Rouillard et al., 2012).

Another complex, which mainly consists of alkaliphilic species of the genera *Aulacoseira* and *Navicula,* inhabits the alluvium of floodplain facies; this complex differs from the previous one by the presence of planktonic forms (Belevich et al., 1970). The development of *Aulacoseira ssp.* is usually associated with a decrease in the duration of ice cover caused by warming conditions, increasing duration and level of open water, and higher concentrations of Si compounds, the availability of which depends on water turbulence (Rühland et al.,2005; Paul et al., 2010). Both complexes of diatoms in frozen deposits indicate the presence of water ecosystems in late Pleistocene and the dynamics of environmental conditions of the past.

The comparison of species composition of diatom deposits in polygonal ponds and quaternary permafrost sequences showed that modern and fossil floras of the island are highly similar (by 40.3%).

A high importance of air temperature for the formation of conditions of algal development is observed in a modern shallow LAP 5 water body with low mineralization rate and L7-08 thermokarst associated with the late Pleistocene (sample 6, 5.2 m A.S.L.) and Holocene (samples 13–14, 7.2–7.5 m A.S.L.) (Fig. 7). These findings suggest that conditions formed in a thermokarst water body were similar to modern conditions.

Lacustrine conditions resulting from dramatic climate warming in the late Pleistocene in 12000 years BP and reconstructed by us provided the active development of a thermokarst on the Bol'shoy Lyakhovsky Island (Anisimov et al., 2009a; Anisimov et al, 2009b). These conditions are also evidenced by a palynological analysis of samples of the same age collected in the L7-08 profile, including such palynomorphes as the spores of *Pediastrum* and *Botryococcus* (Wetterich et al., 2009a). The presence of a well-formed thermokarst water body and stable lacustrine conditions before the start of the Holocene is also proved by a high number of ostracod valves in the horizons aged about 12500 years BP and 11600–10100 years BP (Wetterich et al., 2009a).

CONCLUSIONS

Our study provided new data on the taxonomic and ecological parameters of diatoms in the palaeoarchives of Bol'shoy Lyakhovsky Island and showed that modern and fossil diatomic flora is characterized by the dominance of cosmopolitan benthic alkaliphilic oligohalobs indifferent to water temperature and flow. The presence of some species in both fossil and modern sediments suggests that the diatoms of this region have a high adaptive potential in changing environmental conditions in the quaternary period. The main ecological factors that affect the distribution of modern and fossil diatoms are air temperature, pH, conductivity, water depth, and the level of Si and Al ions. An increase in water depth and stable lacustrine conditions in the Lateglacial–Holocene in an ancient thermokarst lake relate to Lateglacial warming before 11860 ± 160 years BP and during the early Holocene between 11210 ± 160 to 7095 ± 60 years BP.

ACKNOWLEDGMENTS

This study was supported by the Russian Scientific Foundation, project no. 16-17-10118; by the Arctic Ecological Network international project (Arc-EcoNet, BMBF 01DJ14003); and by the government (a subsidy for Kazan Federal University aimed at its higher competitiveness in the sphere of world education and science). The creation of databases was supported by DAAD (Mikhail Lomonosov program, A0972849), Germany. We thank Russian and German colleagues for their help in field studies and laboratory tests.

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Translated by Ya. Lavrenchuk

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