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Late Cenozoic Evolution of Northern Eurasian Marginal Seas Based on the Diatom Record

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THEME 11: Cenozoic Sedimentary Archives of the Eurasian Marginal Seas: Sampling, Coring and Drilling Programmes

Summary: Based on an analysis of fossil diatom assemblages in the upper Cenozoic beds of the northernmost Eurasian coast and adjacent shelf areas and their correlation with zonal stratigraphical subdivisions of the sub-Arctic regions of North Atlantic and North Pacific the spatial-temporal evaluation of the main paleoceanological events in the Arctic have been established. The similarity of the Late Cenozoic diatom floras of the eastern Arctic and the North Pacific existed since the Middle Miocene. The end of the Middle Miocene as well as the Late Miocene were the epochs of transgressions on the eastern Eurasian Arctic shelf. Sea basins occupied coastal lowlands of northern Chukotka, the shelves of the East Siberian and Laptev Seas, and the region around the New Siberian Islands. A deep ingressive bay occupied the North Siberian lowland and reached the Ust'-Yenisei region. The Middle Miocene diatom assemblages of the eastern Arctic seas are characterized by a high taxonomic diversity of the warm water species, the Late Miocene ones by the abundance of cold water species and the appearance of Arctic-boreal species including sea-ice species. The end of the Late Pliocene and early to middle Pleistocene epochs in the Eurasian Arctic shelf regions were marked by marine transgressions. Paleoceanological and ice conditions in the Arctic seas during this time were close to the modern ones, being affected by continuous intensive advection of North Atlantic and Pacific waters.

INTRODUCTION

Upper Cenozoic marine and continental deposits are widespread over the Arctic shelf of Eurasia and adjacent coastal lowlands. However, the stratigraphical subdivision of the upper Cenozoic sequence and, sometimes, the reconstruction of its origin are still under debate. The establishment of reliable stratigraphical datum-levels based on marine organisms is therefore of great importance for the Arctic paleogeography. This is especially true for diatoms since a detailed diatom zonation has already been worked out for the North Pacific (KOIZUMI 1992, KOIZUMI & TANIMURA 1985, BARRON 1992, BARRON & GLADENKOV 1995, YANAGISAWA & AKIBA 1998), North Atlantic (BALDAUF 1984, 1987) and Nordic Seas (SCHRADER & FENNER 1976, KOC & SCHERER 1996, DZHINORIDZE et al. 1978).

The advantages of diatom stratigraphy, among other things, lie in the fact that it is based on planktonic organisms. In the northern hemisphere, diatoms belong to the single Arctic-boreal phytogeographic zone including the North Pacific and North Atlantic (BEKLEMISHEV & SEMINA 1986, SEMINA 1997). This allowed us to use diatom schemes of the North Pacific and North Atlantic regions for stratigraphic investigations of the Arctic areas.

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Though representative assemblages of fossil diatoms are rare in marine deposits of the Eurasian Arctic lowlands and adjacent shelf areas, a considerable amount of information on the different stages of evolution of marine late Cenozoic diatom flora has accumulated by now (Fig.1, Tab.1, POLYAKOVA 1997).

Since the stratigraphical subdivision and correlation of upper Cenozoic deposits of northern Eurasia is still provisional, the author's investigation is aimed at:

(1) the analysis of species composition of marine diatom floras of the Late Cenozoic age;
(2) the determination of their stratigraphic range taking into account the most recent achievements of the zonal diatom stratigraphy;
(3) the correlation of marine sequences and the main transgressive cycles of the continental margin of northern Eurasia and adjacent shelf areas.

The correlation of the Arctic marine upper Cenozoic assemblages with the diatom zonation of the North Pacific and North Atlantic is based on diatom index-species and the total taxonomic composition of diatom assemblages (Fig.2). For correlations with the North Pacific we used the diatom zonation of YANAGISAWA & AIBA (1998) calibrated against the paleomagnetic scale (CANDE & KENT 1995, BERGGREN et al. 1995). In addition, we used datum-levels of the first and last appearance of diatom species in the North Pacific sequences established through correlation with the paleomagnetic scale (BARRON 1992, BARRON & GLADENKOV 1995).

In order to correlate the Late Cenozoic diatom assemblages from the Arctic regions with the North Atlantic we used the scheme of SCHRADER & FENNER (1976) for the Norwegian-Greenland Basin and the scheme of KOC & SCHERER (1996) for the Iceland Sea.

RESULTS AND DISCUSSION

Diatom Stratigraphy

Miocene assemblages of marine diatoms are mainly restricted to the sediments of northernmost North-East Asia. These include coastal lowlands of northern Chukotka (Val'karaiskaya, Vankaremskaya, and Chaunskaya depressions), the Svyatoi Nos Peninsula, and the New Siberian Islands (Figs. 1, 2). In northern Siberia, redeposited Miocene species were also found in the Quaternary deposits of the Ust'-Yenisei region. No reliable marine Miocene diatoms have been reported from northern Europe and the Barents Sea shelf whereas from Siberia good records are available.

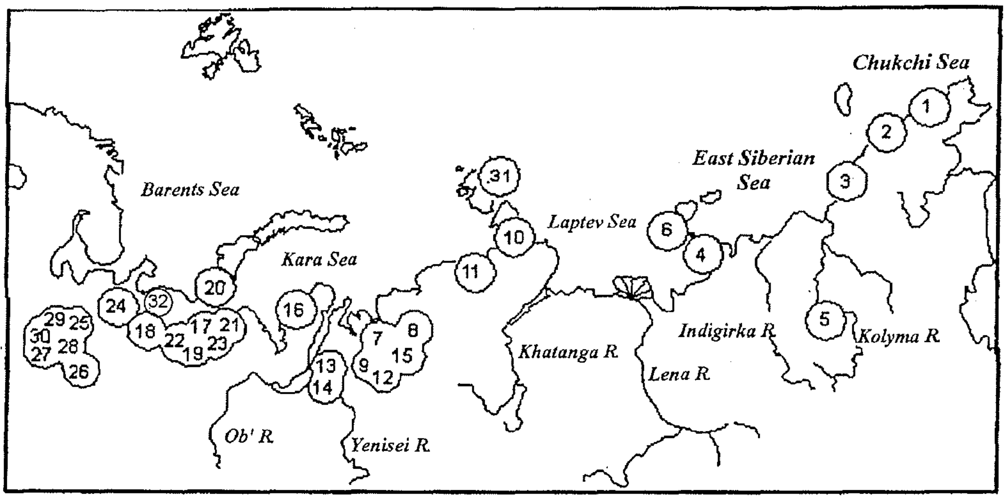


Fig. 1: Main locations of marine diatom assemblages in upper Cenozoic deposits of Northern Eurasia (POLYAKOVA 1997). (1) Vankaremskaya Lowland, (2) Val'karaiskaya Lowland, (3) Aion Island, (4) Svyatoi Nos Peninsula, (5) Kolyma river, (6) New Siberian Islands, (7) Yenisei river (section near Pustoe Winter Hut), (8) Agapa river, (9) Solenaya river, (10) Serebryanka river, (11) Schrenk river, (12) Kheta river, (13) northeastern coast of Tazovskii Peninsula, (14) southeastern coast of Tazovskii Peninsula, (15) „Ice Hill" section, (16) coast of Ob' Bay (Yamal Peninsula), (17) Kolva river (borehole SDK-80, Khorey-Ver settlement), (18) Pechora river (borehole 53, Khabarikha village), (19) Shapkina river (borehole 74), (20) Pechora Sea (boreholes 139, 124, 123), (21) Khaipudyrskaya Bay (boreholes 703, 704, 706), (22) country between Laya and Yuryakha rivers, (23) Kosma river (eastern slope of Timan Mountains), (24) Peza river, (25) sections near Lipovik village (Severnaya Dvina), (26) sections along Viled' river, (27) section near Koleshki stream (Vaga river basin), (28) section near Smotrakovo village (Vaga river basin), (29) section near Konovalovskaya village (Severnaya Dvina basin), (30) section at Led' river (Vaga river basin, (31) Severnaya Zemlya, (32) Safonovo village.

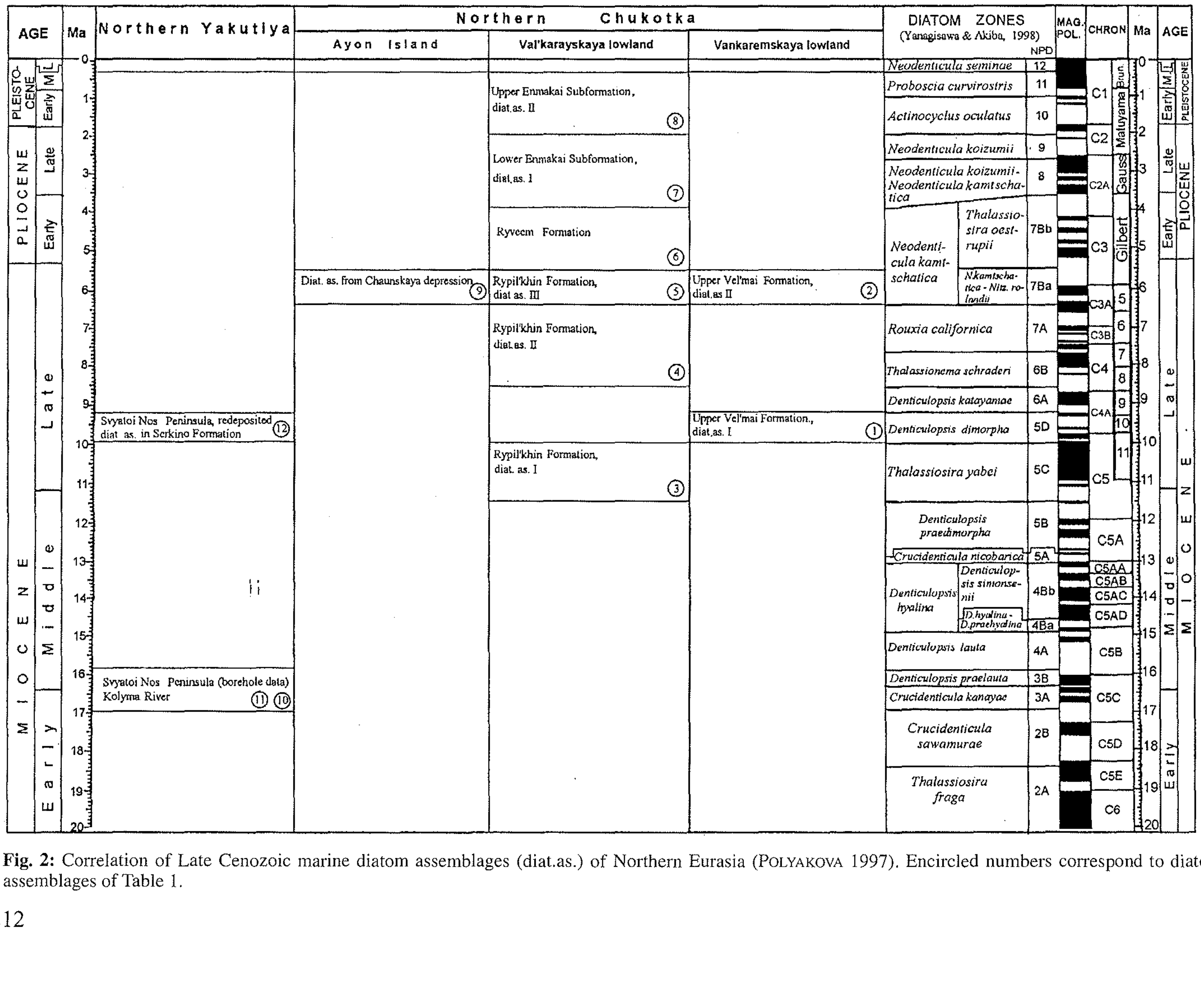
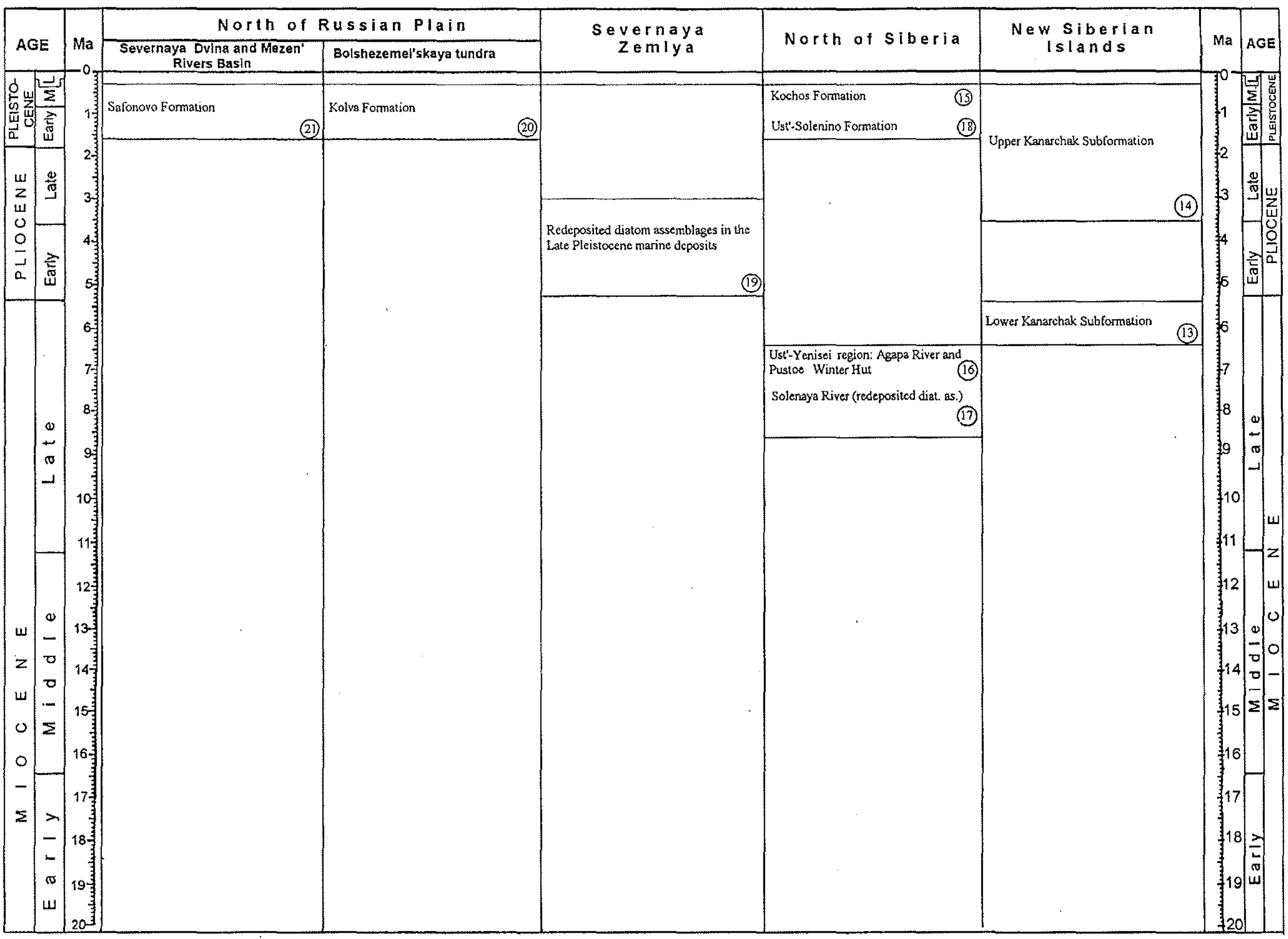


Fig. 2: Correlation of Late Cenozoic marine diatom assemblages (diat.as.) of Northern Eurasia (POLYAKOVA 1997). Encircled numbers correspond to diatom assemblages of Table 1.

The most abundant assemblages of marine diatoms were found in northern Chukotka (POLYAKOVA 1997), where the lowlands are composed of Cenozoic continental and marine beds. So far, their stratigraphical subdivision was based on palynological data with rather controversial age interpretations. The establishment of reliable stratigraphical datum-levels for marine organisms (primarily diatoms) is therefore of fundamental importance not only for the stratigraphical subdivision of northern Chukotka, but also for the solution of cardinal problems of the late Cenozoic paleogeography of the Arctic.

In the Vankaremskaya lowland (Figs. 1, 2) marine diatoms are restricted to the Cenozoic deposits of the upper Vel'mai Formation (POLYAKOVA 1997). They are represented by two groups of assemblages of different age (Tab. 1). The first one corresponds to the *Denticulopsis dimorpha* zone of the North Pacific diatom zonation (beginning of the Late Miocene) based on the presence of the index-species *Denticulopsis dimorpha* (YANAGISAWA & AKIBA 1998, KOIZUMI 1992). This group of assemblages is dominated by the diatom species *Thalassionema hirosakiensis, Denticulopsis cf. hustedtii, Thalassiosira manifesta, T. grunowii, T. yabei, Ikebea tenuis, Pyxidicula inermis.* The second group of assemblages corresponds to the *Neodenticula kamtschatica - Nitzschia rolandii* subzone (end of the Late Miocene) of the North Pacific diatom zonation (YANAGISAWA & AKIBA 1998). It is characterized by the occurrence of *Thalassiosira convexa v.aspinosa, T. miocenica, Cosmiodiscus insignis, Actinocyclus ingens, Ikebea tenuis*.

Further west, marine diatom assemblages were found in the upper Cenozoic deposits of the Val'karaiskaya lowland (Fig. 1, POLYAKOVA 1997, DANILOV & POLYAKOVA 1989). Miocene assemblages of different age were distinguished in the Rypil'khin Formation (Fig. 2, Tab. 1). Based on the known stratigraphical occurrence of the diatom species *Actinocyclus ingens, Ikebea tenuis, Pyxidicula schenckii, Thalassiosira grunowii, T. manifesta, T. yabei* in the North Pacific the oldest assemblage (Fig. 2, Tab. 1) was correlated with the *Thalassiosira yabei* zone to the beginning of the Late Miocene of the North Pacific zonation (YANAGISAWY & AKIBA 1998, KOIZUMI 1992). The second assemblage (Tab. 1) corresponds to the *Thalassionema schraderii* and *Rouxia californica* zones (mid-Late Miocene). It is dominated by the species of *Thalassiosira* genus: *Thalassiosira manifesta, T. punctata, T. undulosa, T. nativa, T. nidulus, T. haynaldiella, T. marujamica, T. orientalis, T. singularis,* as well as by *Pyxidicula zabelinae* and *Cosmiodiscus insignis*. The third assemblage (Fig. 2, Tab. 1) reflects sedimentation within lagoons due to the co-occurrence of freshwater and marine species *Aulacoseira praegranulata, Paralia jouseana, P.sulcata, Pyxidicula zabelinae.* No stratigraphically significant marine diatom species have been recorded in it. Palynological evidence suggests its age to be probably no younger than the end of the Late Miocene (DANILOV & POLYAKOVA 1989).



π	Location	Name of formation	Age assignment acc. to NPDZ	Ref.	Names of stratigraphic marker species and paleoecological significant species
1	Vanka-remskaya Lowland	Upper Vel'mai Fm, diat. ass. I	Denticulopsis dimorpha	(1)	*Thalassionema hirosakiensis, Denticulopsis cf.hustedtii, Thalassiosira manifesta, T.grunowii, T.yabei, Ikebea tenuis, Pyxidicula inermis, Detonula confervaceae,Fragilariopsis oceanica,Chaetoceros septentriopnalis*
2	Vanka-remskaya Lowland	Upper Vel'mai Fm, diat. ass. II	Neodenticula kamtschatica, Nitzschia rolandii	(1)	*Thalassiosira miocenica, T.convexa v.aspinisa, T.miocenica, T.gravida f.fossilis, Actinocyclus ingens, Cosmiodiscus insignis, Ikebea tenuis, Fragilariopsis oceanica*
3	Val'ka-rayskaya Lowland	Rypil'khin Fm, diat.ass. I	Thalassiosira yabei	(1)	*Actinocyclus ingens, Ikebea tenuis,Pyxidicula schenckii, Thalassiosira grunowii, T.manifesta, T.yabei*
4	Val'ka-rayskaya Lowland	Rypil'khin Fm, diat.ass. II	Thalassionema schraderii and Rouxia californica	(1)	*Thalassiosira manifesta, T.punctata, T.undulosa, T.nativa, T.nidulus, T.jacksonii, T.haynaldiella, T.singularis, T.marujamica, Pyxidicula zabelinae, Cosmiodiscus insignis, Fragilariopsis oceanica, Detonula confervaceae, Chaetoceros septentrionalis*
5	Val'ka-rayskaya Lowland	Rypil'khin Fm, diat.ass. III	late Late Miocene	(2), (1)	*Pyxidicula zabelinae, Paralia sulcata, P.joiseana, Aulacoseira praegranulata,*
6	Val'ka-rayskaya Lowland	Ryveem Fm	Thalassiosira oestrupii	(1)	*Thalassiosira nidulus, T.punctata, T.oestrupii, T.jacksonii, T.convexa, T.antiqua, Pyxidicula zabelinae, Cosmiodiscus intersectus, Bacterosira fragilis, Thalassiosira nordenskioeldii, Porosira glacialis, Detonula confervaceae, Fragilariopsis oceanica*
7	Val'ka-rayskaya Lowland	Lower Enmakai Sub-Fm, diat.ass. I	Neodenticula koizumii, N. kamtschatica, N.koizumi	(1)	*Thalassiosira jouseae, T.punctata, Cosmiodiscus insignis+C.intersectus, Pyxidicula zabelinae, T. nordenskioeldii, Bacterosira fragilis, Fragilariopsis oceanica, F.cylindrus*
8	Val'ka-rayskaya Lowland	Upper Enmakai Sub-Fm, diat.ass. II	Actinocyclus oculatus and Proboscia curvirostris	(1)	*Proboscia barboi, P.curvirostris, P.matuyamae. Thalassiosira nidulus+T.jouseae,Actinocyclus divisus+A.ochotensis, T. nordenskioeldii, T.oestrupii, Coscinodiscus asteromphalus, C.perforatus, Bacterosira fragilis, Fragilariopsis oceanica, F.cylindrus*
9	Ayon Island	Diat.as. from Chaunskaya depression	Neodenticula kamtschatica-Nitzschia rolandii	(3)	*Thalassiosira manifesta,T.nidulus, Cosmiodiscus insignis, Bacterosira fragilis, Detonula confervaceae, Thalassiosira kryophila Rhizosolenia hebetata f.hebetata, R.hebetata f.semispina, Porosira glacialis, Fragilariopsis oceanica*
10	Northern Yakutiya, Kolyma River		late Early Miocene-early MidMiocene	(4) (1)	*Actinocyclus ingens, Paralia sulcata, P.polaris, Cymatopleura elliptica*
11	Northern Yakutiya, Svyatoi Nos Peninsula (borehole data)		late Early Miocene-early MidMiocene	(5) (1)	*Actinocyclus ehrenbergii, A.ingens, Actinoptychus thumii, A.splendens, Pyxidicula schenkii*
12	Northern Yakutiya, Svyatoi Nos	Redeposited diat.as. in Serkino Fm	Late Miocene	(6)	*Azpetia endoi, Actinoptychus splendens,A.vulgaris*

π	Location	Name of formation	Age assignment acc. to NPDZ	Ref.	Names of stratigraphic marker species and paleoecological significant species
	Peninsula				
13	New Siberian Islands	Lower Kanarchak Fm	late Late Miocene	(7) (8)	*Pyxidicula zabelinae, Thalassiosira miocenica, Cosmiodiscus insignis*
14	New Siberian Islands	Upper Kanarchak Fm	Late Pliocene-Middle Pleistocene	(1)	*Coscinodiscus curvatulus, Thalassiosira hyperborea, Paralia sulcata*
15	N of Siberia, Taimyr Peninsula, Serebryanka River	Kochos Fm, diat.ass. I	Late Pliocene - Early Pleistocene	(9)	*Proboscia barboi, Hyalodiscus obsoletus, H.af.dentatus, Actinocyclus divisus+A.ochotensis, Coscinodiscus asteromphalus*
16	N of Siberia, Taimyr Peninsula, Schrenk River	Kochos Fm, diat.ass. II	Early - Middle Pleistocene	(9)	*Proboscia curvirostris, Thalassiosira jouseae,Hyalodiscus obsoletus, Actinocyclus divisus+A.chotensis, Coscinodiscus asteromphalus, Detonula confervaceae, Fragilariopsis oceanica, Porosira glacialis, Bacterosira fragilis*
17	N of Siberia, Ust' Yenisei Agapa River, Pustoe Winter Hut	Redeposited diat. ass. in Late Pleistocene sediments	Late Miocene	(10)	*Thalassiosira punctata, T.undulosa, T.haynaldiella, T.orientalis, T.grunowii, T.singularis*
18	N of Siberia: Solenaya River	Redeposited Diat.as. in Pleistocene Sediments	Late Miocene	(11) (9)	*Thalassiosira punctata, T.undulossa, T.haynaldiella, T.orientalis, T.grunowii, T.singularis*
19	N of Siberia: Solenaya River	Ust'-Solenino Fm	Early-Middle Pleistocene	(11) (9)	*Proboscia barboi, P.curvirostris, Thalassiosira jjouseae, Actinocyclus divisus+A.ochotensis*
20	Severnaya Zemlya	Redeposited Diat.as.in Late Pleistocene Sediments	late Late Miocene-Early Pliocene	(12)	*Hialodiscus dentatus, Thalassiosira nidulus, T.punctata, Cosmiodiscus intersectus*
21	Bolshezemel'skaya tundra, adjacent Barents Sea shelf	Kolva Formation	Late Pliocene – Early-Middle(?) Pleistocene	(13) (14) (15)	*Probosscia barboi, P.curvirostris, Thalassiosira jouseae, Actinocyclus divisus+A.ochotensis, Hyalodiscus obsoletus, Thalsassiosira antarctica, T.oestrupii, Bacteriosa fragilis, Fragilariopsis oceania*
22	Bolshezemel'skaya tundra	Padimei Fm	Early-Middle Pleistocene	(13) (14)	*Proboscia barboi, P.curvirostris, Thalassiossira jouseae, Actinocyclus divisus+A.ochotensis, Thalssiosira antarctica, T.hyalina, Bacteriosa fragilis, Fragilariopsis oceania*
23	Severnaya Dvina and Mezen' Rivers Basin	Safonovo Fm	Late Pliocene – Early Pleistocene	(16)	*Proboscia barboi, Thalassiosira jouseae*

Tab. 1: Location and occurrence of stratigraphic marker species. References: (1) POLYAKOVA 1997, (2) DANILOV & POLYAKOVA 1989, (3) STEPANOVA 1989, (4) CHANYSHEVA & KOSTYAEV 1991, (5) EVTEEVA et al. 1989, (6) IVANOV 1970, (7) TRUFANOV 1982, (8) ALEKSEEV 1989, (9) STEPANOVA 1990, (10) SKABICHEVSKAYA 1984, (11) BELEVICH 1965, (12) BOL'SHIYANOV & MEKEEV 1995, (13) LOSEVA 1992, (14) YAKHIMOVICH & ZARKHIDZE 1990, (15) SAMOILOVICH et al. 1993, (16) FILIPPOV & CHOCHIA 1991.

Pliocene diatom assemblages (*Thalassiosira oestrupii* subzone of the North Pacific diatom zonation) were found in the Ryveem Formation of the Val'karaiskaya lowland (POLYAKOVA 1997, Figs. 1, 2, Tab. 1). These associations consist not only of extinct Neogene species (*Thalassiosira nidulus, T. punctata, T. jacksonii, T .convexa, T. antiqua, Pyxidiculà zabelinae, Cosmiodiscus intersectus)*, but also of recent Arctic-boreal forms *(Bacterosira fragilis, Chaetoceros diadema, Thalassiosira nordenskioeldii, T. oestrupii, Porosira glacialis, Detonula confervaceae, Fragilariopsis cylindrus).*

The most abundant and taxonomically diverse diatom associations were reported from the marine deposits of the Enmakai Formation (POLYAKOVA 1997). They are dominated by neritic species: *Thalassiosira nordenskioeldii, T. gravida + T. antarctica, Bacterosira fragilis, Porosira glacialis* and other species typical of the modern Arctic phytoplankton. *Chaetoceros* spores and sea-ice diatoms *(Fragilariopsis oceanica, F.cylindrus)* are numerous (Fig. 2, Tab. 1).

Two diatom assemblages of different age were established in the Enmakai Formation corresponding to the lower and upper Enmakai Subformations (Fig. 2, Tab. 1). The percentage of the extinct Neogene forms *(Thalassiosira joiseae, T. punctata, Cosmiodiscus insignis + C. intersectus, Pyxidicula zabelinae)* in diatom assemblage of the Lower Enmakai Subformation nearly equals that of the recent species. It has much in common with the fossil Upper Pliocene floras of the eastern Kamchatka and Karaginskii Island, i.e. the Limimtevayam Formation and Tusatuvayam beds (ORESHKINA 1980). The latter are correlated with the two Upper Pliocene units of the North Pacific diatom zonation, namely the *Neodenticula koizumii - N .kamtschatica* and *N. koizumii* zones. Diatom assemblages of the Upper Enmakai Subformation are dominated by the modern species and correspond to the *Actinocyclus oculatus* zone and *Proboscia curvirostris* zone (early and middle Pleistocene) of the North Pacific zonation (YANAGISAWY & AKIBA 1998, KOIZUMI 1992). The correlation of diatom assemblages corresponding to these zones is based on the presence of the extinct species of *Proboscia* genus: *P. barboi* (the upper stratigraphic limit is 0.3 Ma), *P. curvirostris* (stratigraphic range 1.58-0.3 Ma), and *P. matuyamae* (0.91(1.05) - 0.85 (0.95) Ma), along with the extinct *Thalassiosira nidulus + T. jouseae* (up to 0.28 Ma). The assemblages also contain abundant and morphologically diverse species of the *Actinocyclus* genus (*A. divisus + A. ochotensis*) that is not typical of the modern diatom flora of the Arctic seas but characteristic for the end Pliocene - Early Pleistocene of the North Pacific, JOUSE 1962, 1969).

A thick sequence of marine and continental deposits was found further west in the Chaunskaya depression (Ayon Island in the Chaun Bay, Fig. 2, Tab. 1). STEPANOVA (1989) described a marine diatom assemblage corresponding in age (end of the Late Miocene) to the *Neodenticula kamtschatica - Nitzschi rolandii* subzone (YANAGISAWY & AKIBA 1998). Besides various extinct Neogene cold-water species *(Thalassiosira gravida f. fossilis, T. manifesta, T. nidulus, T. tertiaria, T. orientalis, Cosmiodiscus insignis)* it includes several representatives of the modern Arctic-boreal diatom flora *(Bacterosira fragilis, Detonula confervaceae, Thalassiosira kryophila, Rhizosolenia hebetata f. hebetata, R. hebetata f. semispina)*. In the North Pacific, these species are known only since the second half of the Pliocene (ORESHKIŅA 1980), and in the Nordic Seas some of them are known since the Middle Miocene (KOC & SCHRADER 1996).

Neogene marine microfossils (including diatoms) were found in the middle Kolyma River region (Figs.1, 2, Tab. 1) at elevations of 280-450 m. The high content of thermophilic arboreal species in the pollen spectra (up to 15-25 %) proves that the sediments started to accumulate during the Neogene thermal optimum (end of Early/beginning of Middle Miocene). This is in good accordance with the stratigraphical range of the described marine diatom species represented by *Actinocyclus ingens, Paralia sulcata, P.polaris, Cymatopleura elliptica, Cosmiodiscus sp.* (CHANYSHEVA & KOSTYAEV 1991, POLYAKOVA 1997).

EVTEEVA et al. (1989) and the author (POLYAKOVA 1997) described a marine Miocene diatom assemblage *(Actinocyclus ehrenbergii, A. ingens, Actinoptychus thumii, A. splendens, A. vulgaris, Paralia sulcata, Pyxidicula schenckii)* in the sediment samples of the deep borehole (110 m) drilled on the Svyatoi Nos Peninsula (Figs. 1, 2, Tab. 1). The sediments are dated as late Early to early Middle Miocene according to palynological data. In the same region Belevich (IVANOV 1970) determined reworked marine Late Miocene diatoms *(Azpeitia endoi, Actinoptychus splendens, A. vulgaris)* in the sediments of the Serkino Formation (Figs. 1, 2, Tab. 1). According to the palynological evidence the formation has a Late Pliocene - Early Pleistocene age.

Single marine Late Miocene diatoms *(Pyxidicula zabelinae, Thalassiosira miocenica, Cosmiodiscus insignis)* were found by Belevich (ALEKSEEV 1989) in the Lower Kanarchak Subformation of the New Siberian Islands (Figs. 1, 2, Tab. 1). Their Late Miocene age is supported by foraminiferal and palynological data. In the upper Kanarchak Subformation diatoms are rare and represented by the marine species: *Coscinodiscus curvatulus, Thalassiosira hyperborea, Paralia sulcata* (POLYAKOVA 1997). Paleomagnetic and palynological data give evidence for a Late Pliocene to middle Pleistocene age of these sediments (ALEKSEEV 1989).

In the Taimyr Peninsula, marine diatom assemblages of different age were reported from the sediments of the Kochos Formation (STEPANOVA 1990). These sediments probably have an early-mid-Pleistocene age (POLYAKOVA 1997, Figs. 1, 2, Tab. 1) as indicated by the presence of stratigraphically important diatom species like *Proboscia barboi, P. curvirostris, Thalassiosira jouseae* together with abundant and morphologically diverse species of the *Actinocyclus* genus (*A. divisus, A. ochotensis*).

In northern West Siberia, abundant and taxonomically diverse assemblages of Late Miocene marine diatoms were reported from the Ust'-Yenisei region. Their composition resembles the Late Miocene assemblages of the eastern Arctic seas. SKABICHEVSKAYA (1984) described *Thalassiosira punctata, T. undulosa, T. haynaldiella, T. orientalis, T. grunowii, T. singularis* and other species in the Pleistocene marine deposits of the well known sections near Pustoe winter hut and along the Agapa River (Figs. 1, 2, Tab. 1). BELEVICH (1965) and STEPANOVA (1990) found the same species in the Ust'-Solenino beds (lower Yenisei River, Figs. 1, 2, Tab. 1). The presence of *Proboscia curvirostris* gives evidence for a Pleistocene age.

BELEVICH (1965) and STEPANOVA (1990) found the same redeposited Miocene species (*Thalassiosira punctata, T. undulosa, T haynaldiella, T. orientalis, T. grunowii, T. singularis* and others) in the Ust' Solenino beds (lower Yenisei River (Figs. 1, 2, Tab. 1). At the same time, the following species typical of the modern and Pleistocene Arctic diatom plankton (*Coscinodiscus oculus-iridis, C. marginatus, C. perforatus, C. asteromphalus, Rhizosolenia hebetata, Thalassiosira hyperborea, T. gravida, T. antarctica* and others) are present, along with stratigraphically significant species, i.e. *Proboscia barboi, P. curvirostris, Thalassiosira jouseae, Actinocyclus divisus, A. ochotensis.* This suggests a possible age for the Ust' Solenino beds (Fig. 2, Tab. 1) as early to middle Pleistocene based on the stratigraphical range of *Proboscia curvirostris* and *Thalassisira jouseae* (POLYAKOVA 1997).

Redeposited valves of marine Miocene diatoms are frequently found in the Pleistocene and Holocene sediments of the East Siberian and Laptev Seas (POLYAKOVA 1997). Thus, marine deposits of Miocene age should be widespread on the eastern Arctic shelf of Eurasia and subject to erosion and redeposition.

Extinct Neogene, probably redeposited, species (*Hialodiscus dentatus, Thalassiosira nidulus, T. punctata, Cosmiodiscus intersectus* and others) have a 20 % share in marine assemblages from the Middle-Upper Pleistocene deposits of the Severnaya Zemlya Islands (BOL'SHIYANOV & MAKEEV 1995).

In the North Russian Plain (Figs. 1, 2, Tab. 1), the oldest Upper Cenozoic assemblages of marine diatoms were reported from the Kolva Formation deposited in the overdeepened valleys and depressions of the Bol'shezemel'skaya Tundra (LOSEVA 1992, YAKHIMOVICH & ZARKHIDZE 1990), the adjacent Barents Sea shelf (SAMOILOVICH et al. 1993) and in the Severnaya Dvina and Mezen' Rivers Basin (FILIPPOV & CHOCHIA 1991). Besides diverse modern species they include stratigraphically important diatom species (Tab. 1) as *Proboscia barboi, P. curvirostris, Thalassiosira jouseae* and abundant and morphologically diverse species of the *Actinocyclus* genus (*A. divisus, A. ochotensis, A. oculatus*). *P. curvirostris* is not always present in diatom assemblages from the Kolva deposits. This allows to assume that the deposits assigned to the Kolva Formation occupy different stratigraphical ranges from the Late Pliocene to the Early Pleistocene. This is supported by findings of stratigraphically significant foraminifera, i.e. *Cibicides grossus, Protelphidium pustulatum* (YAKHIMOVICH & ZARKHIDZE 1990).

Diatom assemblages with *Proboscia barbaroi, P. curvirostris, Thalassiosira jouseae, Actinocyclus divisus* and *Actinocyclus ochotensis* (Fig. 2) were also found in the Padimei Formation overlying the Kolva beds (LOSEVA 1992, YAKHIMOVICH & ZARKHIDZE 1990). The presence of *P. curvirostris* gives evidence for the accumulation of the beds during the early to Middle Pleistocene. Diatom assemblages with *Proboscia barboi, Thalassiosira jouseae* were found in the overdeepened valleys of the Severnaya Dvina and Mezen' River Basin (Fig. 1, 2, Tab. 1). Their probable Late Pliocene age is supported by palynological evidence (FILIPOV & CHOCHIA 1991).

Diatom assemblages containing only modern species correspond to the final stage in evolution of the Arctic marine diatom flora. They might be correlated with the *Neodenticula seminae* zone of the North Pacific zonation and *Thalassiosira oestrupii* zone of the Nordic Seas (Figs. 1, 2). These assemblages are typical of the sediments of the „Boreal" (Eemian) transgression (LOSEVA 1992, SMIRNOVA 1979, 1983) and the so called „Late Moscow Sea" (SMIRNOVA 1981, 1986) that existed during the late Rissian. Sediments of these Pleistocene transgressions are present in the Severnaya Dvina and Mezen' River basins as well as in the Karga transgressive sediments and the upper Pleistocene-Holocene sediments of the Arctic seas (POLYAKOVA 1997).

Paleoceanography

Until recently, the Miocene epoch was considered as a continental stage in the evolution of the northern Eurasian margin during which the Arctic Ocean was isolated from the Pacific. The data obtained (POLYAKOVA 1997, Fig. 2) show, however, that during the late Early to early Middle Miocene marine basins occupied shelf regions of the East Siberian and Laptev Seas. Ingressive bays penetrated inland into the Chaunskaya Lowland and along the Kolyma River valley as indicated by findings of foraminifers and marine diatoms (partly redeposited). The shallow marine deposits with a sublittoral diatom associations found in the Svyatoi Nos Peninsula (see above, Fig. 2) indicate that the coastline was probably located close to its present position. Correlative marine deposits with fossil diatom assemblages of the Middle Kolyma River were uplifted up to 450 m elevation due to positive neotectonic movements (CHANYSHEVA & KOSTYAEV 1991, POLYAKOVA 1997).

The end of the Middle Miocene and Late Miocene were epochs of transgressions, during which the sea invaded the shelves and coastal lowlands of eastern Arctic Eurasia and Siberia (Figs. 2, 3). Sea basins occupied coastal lowlands of northern Chukotka, shelves of the East Siberian and Laptev Seas, the region around the New Siberian Islands and Severnaya Zemlya. Ingressive bays covered the North Siberian Lowlands and reached the Ust'-Yenisei region.

The assemblage composition of the marine Miocene diatom flora of the Upper Cenozoic deposits of northern and northeastern Eurasia gives evidence for a gradual decrease of the surface temperature in the Arctic Ocean. The assemblages of the *Thalassiosira yabei* zone from Vankaremskaya Lowland (Figs. 2, 3) with *Thalassiosira yabei, T. grunowii, Ikebea tenuis* are the most thermophilic. In the northwestern Pacific this period corresponds to the second Miocene optimum. Arctic-boreal and boreal Neogene diatoms (*Coscinodiscus marginatus f. fossilis, Thalassiosira manifesta, Denticulopsis hustedtii, Pyxidicula inermis, Thalassionema hirosakiensis* and others) predominate (from 60 to 80 % and more) in diatom assemblages from the Late Cenozoic deposits of the Vankaremskaya Lowland (Figs. 2, 3) correlative to the Late Miocene *Denticulopsis dimorpha* zone (10.0-9.2 Ma). Single representatives of the modern ice-neritic (*Thalassiosira gravida*) and sea-ice (*Detonula confervaceae, Chaetoceros septentrionalis, Fragilariopsis oceanica*) diatom flora occur since this epoch. They indicate low water temperatures and

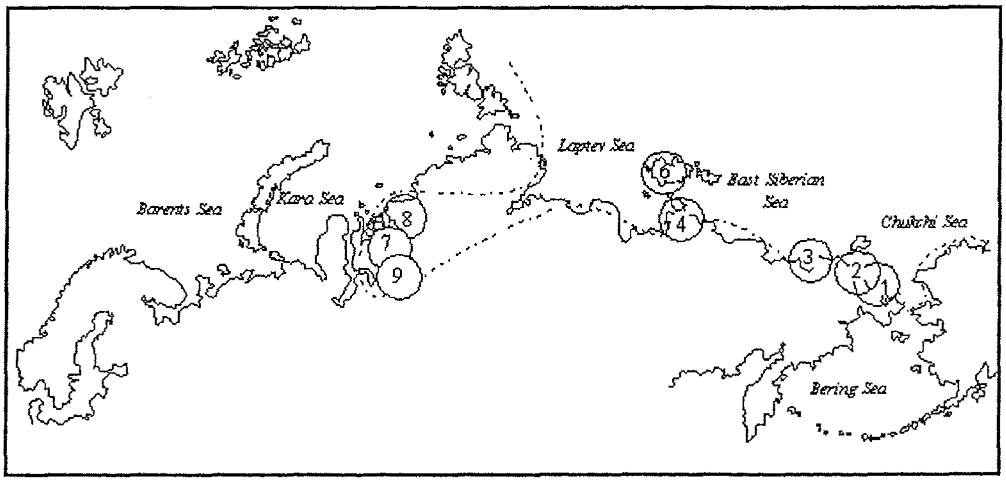


Fig. 3: Eurasian Arctic seas during Late Miocene. Dotted lines show location of coastline at that time. Encircled numbers show locations of sections, see Fig. 1.

probable seasonal ice cover. This is in good accordance with the data on the North Atlantic and Nordic Seas (WOLF & THIEDE 1991) giving evidence for the onset of glaciation in the high latitudinal regions of the northern hemisphere about 10 Ma ago.

The subsequent Late Miocene transgression recorded in the sediments of the Val'karaiskaya Lowland, corresponds to the *Thalassionema schraderii* and *Rauxia californica* zones of the North Pacific diatom zonation (mid-Late Miocene, Figs. 2, 3). Most species of the diatom assemblages related to this zone belong to the Neogene cold-water group *(Thalassiosira gravida, T. nidulus, T. punctata, Pyxidicula zabelinae, Cosmiodiscus insignis* and others*)*. During the Neogene they were distributed in the boreal regions of the North Pacific. The occurrence of sea-ice species *(Fragilariopsis oceanica, Detonula confervaceae)* probably indicates the appearance of the seasonal sea-ice cover. These species became more abundant in diatom assemblages of the Vankaremskaya Lowland and Chaunskaya depression (Figs. 2, 3) during the end of the Late Miocene (*Neodenticula kamtschatica - Nitzschia rolandii* subzone). Along with various extinct Neogene cold-water species diatom assemblages of this subzone include several representatives of the modern Arctic-boreal diatom flora *(Bacterosira fragilis, Detonula confervaceae, Thalassiosira kryophila, Rhizosolenia hebetata f. hebetata, Rhizosolenia hebetata f. semispina, Porosira glacialis).* It should be noted that in the North Pacific some of these species evolved only since the second part of the Pliocene (ORESHKINA 1993). The occurrence of sea-ice species (*Fragilariopsis oceanica, Detonula confervaceae, Chaetoceras septentrionalis*) indicates a sea-ice cover.

Thus, marine diatom assemblages of different age from deposits of the eastern Arctic and Siberian shelves and the adjacent lowlands give evidence for Middle-Late Miocene transgressions caused by tectonic movements (AFANAS'EV et al. 1988, PALEOGENE 1989). At the same time, the absence of any marine microfossils of Miocene age in the Western Arctic sector of Eurasia proves the predominance of neotectonic uplift movements and a regime of continental sedimentation in this region (AFANAS'EV et al. 1988).

One of the most debated problems of Arctic paleoceanography is the age of renewed interactions between the Arctic and Pacific oceans during the Late Cenozoic after their interruption in the Late Cretaceous due to tectonic re-arrangements in the eastern Arctic (ZONENSHAIN & NATAPOV 1989). Based on the immigration of Pacific molluscs to the North Atlantic, it has long been thought that the connection through the Bering Strait was re-established in the mid Pliocene not earlier than 3.4 Ma ago (GLADENKOV 1978). Recent investigations in the sub-Arctic Pacific (Karaginskii Island, eastern Kamchatka, Southern Alaska) suggest earlier dates for this event, i.e. Early Pliocene 4.5 Ma (BASILYAN et al. 1991) or even Late Miocene (7.3-7.4 Ma) (MARINKOVICH & GLADENKOV 1999). These age estimations are based on the findings of bivalve species of the *Astarte* genus in the upper Cenozoic beds of the North Pacific. These species are typical representatives of the Arctic and north Atlantic molluscan faunas.

The author has studied assemblages of marine diatoms from the Upper Cenozoic deposits of the Arctic coastal lowlands of North-East Asia that are systematically similar to the diatom flora of the high latitudinal and temperate Pacific. They show that the connection between the Arctic and Pacific oceans was re-established even earlier (POLYAKOVA 1997). Correlation of the Arctic diatom assemblages with the diatom zonation of the North Pacific has revealed that the first new connection between the Arctic and Pacific oceans occurred at the end of the Early Miocene (about 17 Ma ago). Later the connection was open at the end of the Middle Miocene (about 13-12 Ma) and during the whole Late Miocene (11.2-5.3 Ma).

Marine diatom assemblages that are taxonomically similar to the Miocene assemblages of the Arctic were described from the Miocene deposits of the Norwegian Basin (DZINORIDZE et al. 1978) the Iceland (KOC & SCHERER 1996) and Labrador Seas (MONJANEL & BALDAUF 1989). All of them include *Thalassiosira yabei, T. grunowii, Ikebea tenuis, Cosmiodiscus insignis* and other species, thus giving evidence for the existence of a large biogeographical area in the Miocene occupying the shelves of the Arctic Ocean, the North Pacific, the Nordic Seas and the Labrador Sea.

During the Late Pliocene and Early Pleistocene vast coastal regions of Arctic Eurasia were flooded by transgressive seas (Figs. 2, 4) due to tectonic subsidence of northern Eurasia that had started in the Late Pliocene. The predominance of modern Arctic boreal and bipolar species (*Thalassiosira nordenskio-*

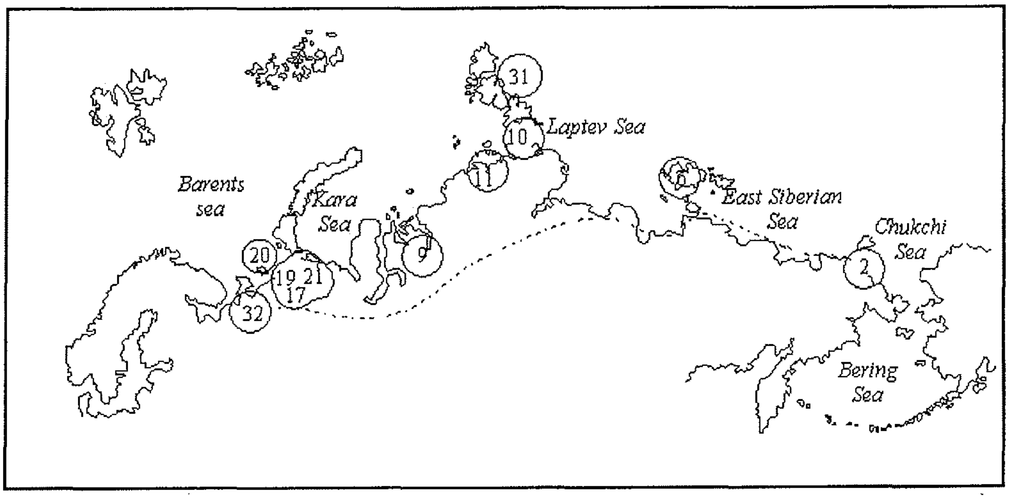


Fig. 4: Eurasian Arctic seas during Late Pliocene to Early Pleistocene. Dotted lines show location of coastline at that time. Encircled numbers show locations of sections, see Fig. 1.

eldii, T. gravida + T. antarctica, T. hyalina, Bacterosira fragilis, Porosira glacialis and others) in all local assemblages gives evidence for a low temperature regime of the eastern Arctic seas. The abundance of sea-ice diatoms *(Fragilariopsis oceanica, F.cylindrus, Fossula arctica, Detonula confervaceae, Chaetoceros septentrionalis)* indicates a considerable extent of the sea ice cover. At the same time, the presence of thermophilic species *(Proboscia alata, Rhizosolenia calcar-avis, Coscinodiscus asteromphalus, C. radiatus, Actinocyclus divisus, Chaetoceros didymus* and others*)* that are now brought into the eastern Arctic seas with the Bering Sea current and to the western Arctic seas with the North Atlantic current (POLYAKOVA 1989, 1997) points to intensive advection of North Pacific and Atlantic waters into the Eurasian Arctic seas. North Atlantic waters entered the north-eastern Barents Sea, flowed around Novaya Zemlya and reached the Taimyr Peninsula. To the south (Ust'-Yenisei region), their influence decreased. The afflux of the North Atlantic waters to the coastal areas of the European North (Pechorskaya Lowland) was insignificant (LOSEVA 1992, POLYAKOVA 1997).

CONCLUSIONS

1) A close systematic composition of the Late Cenozoic diatom floras of the eastern Arctic and North Pacific suggests that a connection between the Arctic Ocean and North Pacific existed since the Middle Miocene.

2) The end of the Middle Miocene as well as the Late Miocene were the epochs of transgressions on the eastern Eurasian Arctic shelf. Sea basins occupied the coastal lowlands of northern Chukotka, the shelves of the East Siberian and Laptev Seas, and the region around the New Siberian Islands.

3) The Middle Miocene diatom assemblages of the eastern Arctic seas are distinguished by a high taxonomic diversity of the warm water species, the Late Miocene ones by the abundance of cold water species and the appearance of several Arctic-boreal and sea-ice species.

4) The end of the Late Pliocene and early - middle Pleistocene epochs in the Eurasian Arctic shelf regions were characterized by marine transgressions. Paleoceanographic and ice conditions in the Arctic seas during this time were close to the modern ones being affected by a continuous intensive advection of the North Atlantic and Pacific waters.

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