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# The Cenozoic Diatom Zonation and Its Significance for Stratigraphic Correlations in the North Pacific

**A. Yu. Gladenkov**

*Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017 Russia*

*e-mail: agladenkov@ilran.ru*

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**Abstract**—The current state of the North Pacific Cenozoic diatom zonation is reviewed. The high resolution of diatom zonation is shown, which is comparable to that of groups of calcareous planktonic microfossils. The significance of diatom assemblages for the dating and correlation of various Tertiary marine sediments in the North Pacific is discussed. Recent examples of subdivision of the Oligocene–Neogene sequences of this region and dating of geological events on the zonal basis are given.

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*Key words*: Diatoms, Cenozoic, zonal stratigraphy, North Pacific.

## INTRODUCTION

The correctness of geological reconstructions depends largely on the state of the stratigraphic foundation. Its improvement and further refinement are, therefore, among the main objectives of stratigraphy. The results obtained in this field contribute to the detailed subdivision of deposits and substantiated regional and interregional correlations. Among various methods, paleontology remains the most effective and promising. The wide use of zones in stratigraphic research of the last decades should be especially emphasized. Without overstatement, the wide introduction of zones to geological practice is among the outstanding achievements of stratigraphy. Zones are smaller stratigraphic units than stages. On average, their duration is about 1 Ma. They are usually established on a biostratrigraphic foundation, taking into account the evolutionary phases of fossil organisms. A zone can be referred to as deposits that were accumulated during the existence of a particular paleontological assemblage that reflects an evolutionary phase of a floral or faunal group and differs from assemblages of adjacent beds. When dealing with the Phanerozoic marine deposits, the zones that are established based on planktonic organisms are of the greatest value because they provide the highest resolution. As planktonic assemblages evolve rapidly and have wide geographical distribution, their study provides detailed subdivision and wide correlations of sedimentary sequences. In this context, micropaleontological data are of particular importance, because microfossils occur in abundance throughout the Phanerozoic and serve as a primary biostratigraphic tool for borehole investigation. The study of fossil microorganisms with application of modern methods of their extraction from rocks as well as relevant equipment for their identification is very effective for subdivision of the enclosing deposits, including those that were earlier considered to be barren. As for the marine Cenozoic, most of the zones (especially when deep-sea drilling in the World Ocean started in the late 1960s) are established based on microplankton. It is precisely the data on zonal stratigraphy that served as a baseline for the reconstructions described in this paper. The author is striving to cover the main attainments of the detailed Cenozoic stratigraphy based on the study of diatom algae (microorganisms with siliceous frustules), using the example of the North Pacific.

## THE SIGNIFICANCE OF MICROPLANKTON FOR CENOZOIC ZONAL STRATIGRAPHY

During the past 35–40 years, the marine Cenozoic stratigraphy made great advances. This is to a great extent connected with the study of numerous sedimentary cores recovered in the World Ocean by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP). First, the study of deep-sea cores revealed numerous micropaleontological remains. Second, microfossils were shown to be valuable as a primary tool for detailed subdivision and wide correlations of host sediments. It was the tracing of assemblages of various groups of planktonic microorganisms in nearly complete marine sections that made it possible to construct oceanic scales with the continuous succession of zones. In biostratigraphic studies of microfossils, attention was paid not only to calcareous plankton (foraminifers and coccolithophorids), but also to siliceous microplankton (diatoms and radiolarians), as the latter is particularly important for the subdivision of extratropical sediments. Having appeared in the Early Cretaceous, marine diatoms occurred widely since the Middle Eocene and became dominant in the phytoplankton at high–middle latitudes of the World Ocean in the Oligocene–Neogene. Therefore, they are most significant for Cenozoic stratigraphy, and are currently actively used in geological practice. This is the case in the North Pacific, where calcareous microfossils are absent or extremely rare in post-Eocene deposits. Since the Neogene, the diatom flora has prevailed in the plankton of the North Pacific. In the Middle Miocene–Pliocene, diatoms reached their maximal development and biological productivity, being the main source of biogenic silica for bottom sediments. In particular, this fact determined the prevalence of biosiliceous sedimentation in this region.

### *Spatial Constrains of Diatom Zones*

To date, the study of deep-sea cores combined with data on onshore sequences has allowed efficient construction of zonations based on diatoms. It has been shown that, at least since the Oligocene, diatom assemblages have been characterized by a certain degree of provincialism. As a result, several diatom zonations are used for vast regions of different latitudes. They differ in the number of zones, with the boundaries outlined by different taxa. Therefore, in the strict sense of the word, there is no global Upper Cenozoic diatom zonation. Generally, different zonal units are used for the subdivision of sedimentary sequences depending on the region: the low latitudes, the Southern Ocean, the North Pacific, or the North Atlantic. Taking into account the large area of these regions, their zonal units, which form a continuous succession of biozones with constant boundaries, can be viewed as zones of wide regional scale. Unlike local zones, which are revealed in sections of limited areas and restricted to particular facies, the wide regional zones are traced within large segments of the ocean and surrounding areas of thousands of square kilometers.

## CONSTRUCTION OF THE NORTH PACIFIC DIATOM ZONATION

Problems of detailed subdivision and correlation of the Cenozoic sediments are crucial for the North Pacific. This vast region, which includes a large portion of the ocean and its framing, is characterized by the widespread development of multifacies Paleogene and Neogene deposits. Therefore, the reconstruction of Cenozoic history is a major task for geology of this region. In addition, the Tertiary sequences often contain mineral wealth accumulations, primarily oil and gas. Diatoms are one of the main paleontological groups that are used for the study of the post-Eocene sediments of this region at the zonal level.

In terms of zonal stratigraphy, the combination of data on the ocean bottom and land sequences is of particular significance. During the study of onshore sequences, remains of marine diatoms (often rock-forming) were revealed to be typical in many cases for the Miocene–Quaternary sediments. By the beginning of the 1970s, studies of a number of sections from the Kamchatka Peninsula, Sakhalin Island, Japan, and California as well as piston cores of marine bottom sediments had revealed assemblages of different ages (Kanaya, 1959, 1969; Jousé, 1962, 1968, 1969; Sheshukova-Poretskaya, 1967; Wornardt, 1967; Koizumi, 1968, 1973a; etc.). Comparative analysis of diatom assemblages (primarily, planktonic) showed their high potential for correlation of Neogene and Quaternary deposits of remote sections. The phases of the floral development in the region were tentatively reconstructed, and several biostratrigraphic units based on diatoms were proposed. These latter were mostly horizons and beds with flora.

However, the most important results, which allowed the construction of the Cenozoic zonation, were derived from deep-sea sequences. Material from the deep-sea drilling, started in the North Pacific in the early 1970s, was used for this study. In contrast to the shelf and slope sedimentary successions, pelagic sediments are usually represented by laterally sustained homogeneous facies, i.e., biogenic sediments and clays of relatively small thicknesses. Prior to the study of deep-sea cores, information on the pre-Late Pliocene oceanic sediments had been virtually lacking. These data shed light on the composition, distribution, and stratigraphic succession of the Tertiary sequences recovered, and simultaneously allowed their detailed subdivision. This became possible by tracing successive changes in assemblages of various microfossil groups in relatively continuous sections of pelagic facies: primarily nannoplankton and planktonic foraminifers in the Paleocene through Eocene and diatoms in the Neogene. One of the first versions of oceanic diatom zonation was proposed by Koizumi (1973b, 1975), a Japanese researcher who established a series of Middle Miocene–Quaternary successive zones for the northwest Pacific. Additional material collected by later biostratigraphic research from the late 1970s to the early 1990s, significantly improved and refined the zonation. The results obtained allowed researchers to determine zones, arrange them in a strict order, and trace them over a vast territory. General and consistent regularities in successive changes in stratigrapically significant taxa were revealed by determining their stratigraphic ranges in the North Pacific sections. Developing Koizumi's study, Barron and Akiba proposed more detailed and refined versions of the zonation and thoroughly analyzed its applicability in various parts of the region to explore ways to expand its applicable age range (Koizumi, 1977, 1980, 1985; Barron, 1980, 1981, 1985; Akiba, 1983, 1986; Koizumi and Tanimura, 1985; etc.). The modified zonation included 15 zones, with an average duration of 1.15 Ma (down to 0.2–0.3 Ma). Note that the zones are primarily established based on stratigraphic occurrences of species from rapidly evolved genera. Therefore, the differences in the composition of successive zonal assemblages are mostly expressed in a limited number of species. To determine zonal and subzonal boundaries, datum levels are used. These are primarily levels of the first and last occurrences of planktonic index species or, more rarely, the levels of abrupt change in their quantity. This practice provides a continuous succession of detailed and stable biostratigraphic units with relatively isochronous boundaries. Taxa that are easy to identify, constantly present, relatively abundant, and show a definite and stable stratigraphic range are chosen as zonal taxa. At the same time, supplementary datum levels within zones are established, which are usually traceable within a more limited area of the region. When filling the zones in a particular succession, these levels play an important role as biostratigraphic markers for the analysis of diatom assemblages and determination of their age on the infrazonal basis.

The North Pacific diatom zonation has provided a valuable tool for the dating, subdivision, and correlation of the Middle Miocene to Quaternary marine sediments. It has been widely applied in stratigraphic research within this region. The successful application of oceanic zonation to studies of Cenozoic sequences on land and in marginal seas should be especially emphasized. The studies of diatom assemblages from the sections of Japan, Sakhalin Island, the Kamchatka and Chukchi peninsulas, California, and other regions, and their correlation with the standard diatom zonation, allowed the refinement and even revision of the dating of a number of formations and regional stages. These data substantiated a detailed subdivision of numerous Neogene sequences, contributing significantly to the development of new regional Cenozoic stratigraphic schemes.

## FURTHER REFINEMENT OF THE ZONATION AND EXTENSION OF ITS RANGE

Despite the considerable success achieved by the mid-1990s, some important problems of the diatom zonation remained unsolved. For example, the datum levels marking the zonal and subzonal boundaries were directly correlated with the magnetostratigraphic scale in the North Pacific only starting with the uppermost Miocene. Older biohorizons (older than 6 Ma) were dated mostly based on analysis of the curves of sediment accumulation rates calculated for sequences of deep-sea cores. The lack of reliable dating for the majority of Miocene boundaries complicated the precise correlation of zones with the International Stratigraphic Chart. On the other hand, zonation of pre-Miocene sediments was absent. The Lower Miocene units were tentative because their succession was not traced in continuous sequences. Recent refinements of the zonation are an important contribution to this problem. These results have primarily been derived from the deep-sea drilling material obtained during the ODP Leg 145 in the subarctic Pacific. The Oligocene to Quaternary sequences were primarily stratified based on diatoms (Rea et al., 1993; Barron and Gladenkov, 1995; Gladenkov and Barron, 1995). The diatom zonation used for the Middle Miocene through to the Quaternary closely followed the slightly modified zonation of Akiba (1986). The entire succession of the Middle Miocene through Quaternary diatom zones was traced in the sedimentary sequences obtained by ODP sites. This proved once again the applicability of the zonation for the detailed stratigraphy beginning from the Lower Miocene–Middle Miocene boundary beds. Particular attention should be paid to two important achievements in the context of diatom stratigraphy. The ages of more than forty Miocene datum levels were first estimated in the high–middle latitudes of the North Pacific based on direct correlations with the magnetostratigraphic

**Table 1.** Ages of some important datum levels of the Neogene of the North Pacific on the basis of diatom data (after Barron and Gladenkov, 1995): (FO) first occurrence; (LO) last occurrence; (FCO) first common occurrence; and (LCO) last common occurrence. Absolute dates according to the geochronological scale of Berggren et al. (1995)

| Datum levels | Age, Ma |
|---|---|
| FO *Crucidenticula sawamurae* | 18.4 |
| FO *Crucidenticula kanayae* | 16.9 |
| FO *Denticulopsis praelauta* | 16.3 |
| FO *Denticulopsis lauta* | 15.9 |
| FO *Actinocyclus ingens* var. *nodus* | 15.8 |
| FO *Denticulopsis hyalina* | 14.9 |
| FCO *Denticulopsis hustedtii* | 13.1 |
| FO *Denticulopsis praedimorpha* | 12.9 |
| FO *Proboscia barboi* | 12.5 |
| LCO *Denticulopsis praedimorpha* | 11.5 |
| FO *Denticulopsis dimorpha* | 9.9 |
| FO *Thalassionema schraderi* | 9.5 |
| FO *Denticulopsis katayamae* | 9.3 |
| LO *Denticulopsis dimorpha* | 9.2 |
| LCO *Denticulopsis hustedtii* | 8.6 |
| FO *Thalassiosira gravida* | 8.2 |
| LCO *Thalassionema schraderi* | 7.6 |
| FO *Neodenticula kamtschatica* | 7.4 |
| LO *Cavitatus jouseanus* | 6.7 |
| FO *Thalassiosira praeoestrupii* | 6.1 |
| LO *Rouxia californica* | 5.9 |
| FO *Thalassiosira oestrupii* | 5.5 |
| FO *Thalassiosira jacksonii* (plicate) | 5.2 |
| FO *Thalassiosira latimarginata* | 5.1 |
| LO *Thalassiosira jacksonii* (plicate) | 4.8 |
| LO *Cosmiodiscus insignis* | 4.8 |
| FO *Neodenticula koizumii* | 4.0 |
| LO *Pyxidicula zabelinae* | 2.0 |
| LO *Neodenticula koizumii* | 2.0 |

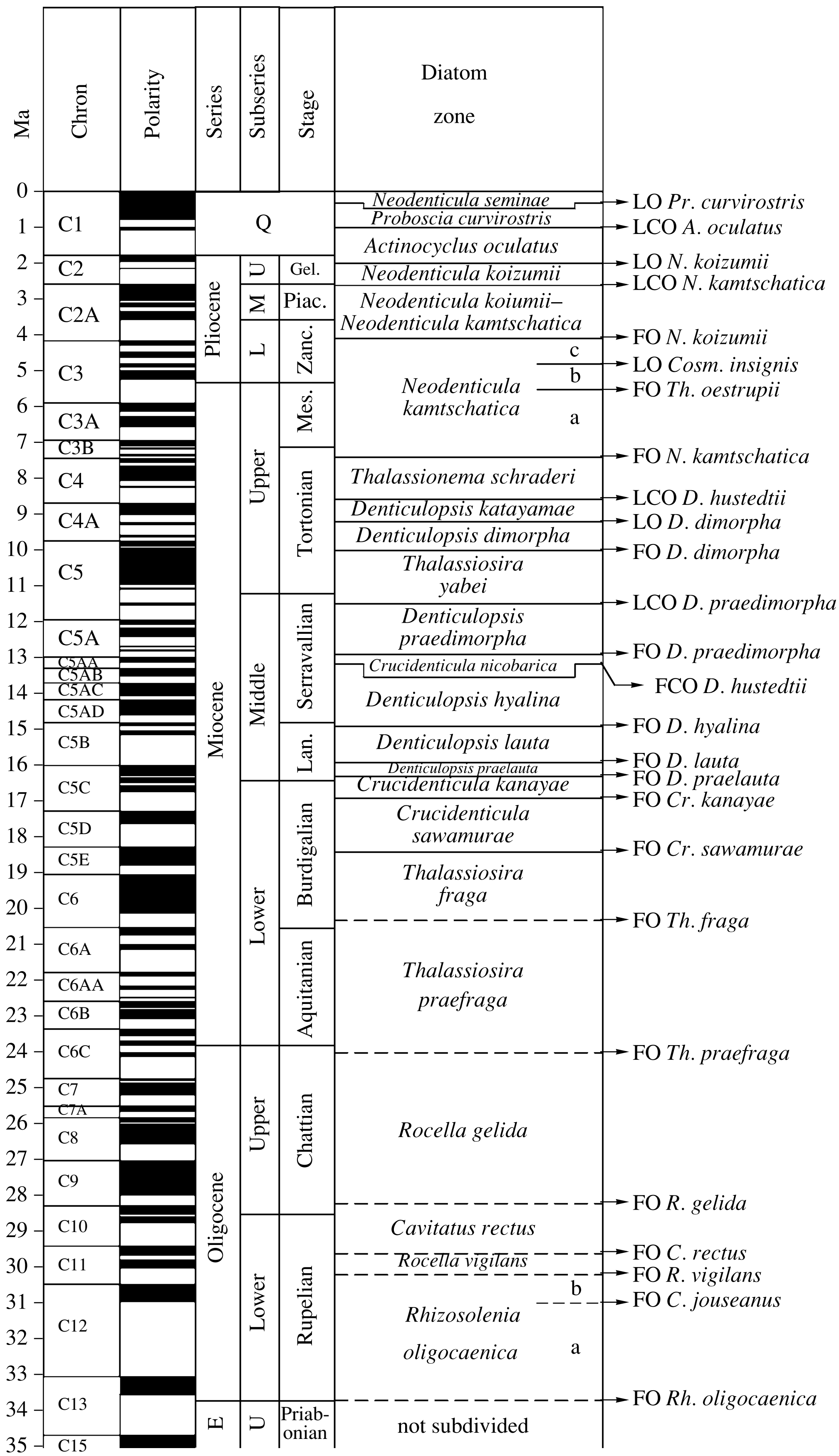
Ma
Chron
Polarity
Series
Subseries
Stage
Diatom zone
Q
Pliocene
Miocene
Oligocene
E
U
M
L
Upper
Middle
Lower
Gel.
Piac.
Zanc.
Mes.
Tortonian
Serravallian
Lan.
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Neodenticula seminae
Proboscia curvirostris
Actinocyclus oculatus
Neodenticula koizumii
Neodenticula koiumii–Neodenticula kamtschatica
Neodenticula kamtschatica
Thalassionema schraderi
Denticulopsis katayamae
Denticulopsis dimorpha
Thalassiosira yabei
Denticulopsis praedimorpha
Crucidenticula nicobarica
Denticulopsis hyalina
Denticulopsis lauta
Denticulopsis praelauta
Crucidenticula kanayae
Crucidenticula sawamurae
Thalassiosira fraga
Thalassiosira praefraga
Rocella gelida
Cavitatus rectus
Rocella vigilans
Rhizosolenia oligocaenica
not subdivided
LO Pr. curvirostris
LCO A. oculatus
LO N. koizumii
LCO N. kamtschatica
FO N. koizumii
LO Cosm. insignis
FO Th. oestrupii
FO N. kamtschatica
LCO D. hustedtii
LO D. dimorpha
FO D. dimorpha
LCO D. praedimorpha
FO D. praedimorpha
FCO D. hustedtii
FO D. hyalina
FO D. lauta
FO D. praelauta
FO Cr. kanayae
FO Cr. sawamurae
FO Th. fraga
FO Th. praefraga
FO R. gelida
FO C. rectus
FO R. vigilans
FO C. jouseanus
FO Rh. oligocaenica

**Fig. 1.** The North Pacific Oligocene through Quaternary diatom zonation correlated to the geochronologic and geomagnetic polarity time scales of Berggren et al. (1995) (after Barron and Gladenkov, 1995; Gladenkov and Barron, 1995; Gladenkov, 1998, 1999; modified). Designations: (FO) first occurrence, (LO) last occurrence, (FCO) first common occurrence, (LCO) last common occurrence, (E) Eocene, (U) Upper, (M) Middle, (L) Lower, (Q) Quaternary, (a–c) subzones, (Lan.) Langian, (Mes.) Messinian, (Zanc.) Zanclean, (Piac.) Piacenzian, and (Gel.) Gelasian.

record within the interval of 18.8–6.9 Ma to show their general isochronism. This enables the boundaries of the zonal Miocene units to be dated on a factual basis, and the duration of zones to be precisely determined and correlated with the International Stratigraphic Chart (Fig. 1; Table 1). In addition, the ages of about twenty Late Miocene–Pliocene datum levels were estimated for the first time. Based on the documented successive first occurrences of planktonic index species (Fig. 1), a continuous series of seven zones for the Oligocene and Early Miocene was first proposed (*Rocella vigilans* to *Crucidenticula kanayae* zones). Subsequently, a synthesis of these results and the data on diatom assemblages from the sections of the northwestern Pacific framing made it possible to establish the oldest Early Oligocene *Rhizosolenia oligocaenica* Zone (Gladenkov, 1998, 1999). The Oligocene and Lower Miocene zones proposed were an important contribution to the Cenozoic diatom zonation to extend its application up to the basal Oligocene.

Thus, the current knowledge of diatoms provides high-resolution Cenozoic stratigraphy in the North

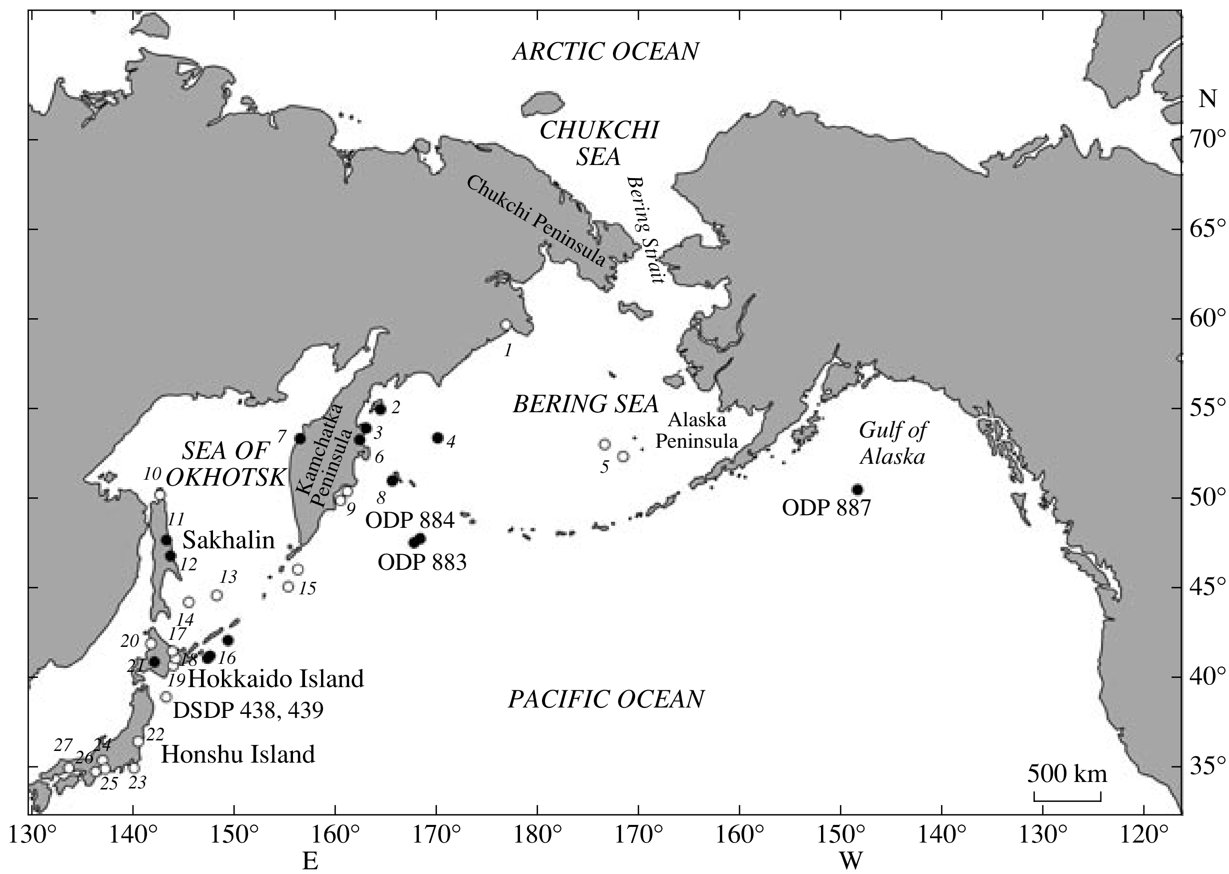


**Fig. 2.** Geographical position of the main stratigraphic sections of the North Pacific and its framing where Oligocene and Early Miocene diatom assemblages are recorded. Black circles indicate sections that were studied by the author, sections with data obtained by other authors are marked with white circles. Designations: (ODP 883, 884, 887) Ocean Drilling Program sites; (DSDP 438, 439) Deep Sea Drilling Project sites; (*1*) Nizhne-Khatyrka Depression (borehole 32); (*2*) Karaginskii Island; (*3*) Ozernoi Peninsula; (*4*) Shirshov underwater ridge; (*5*) Navarin Basin; (*6*) Ozernoi Bay (cape Tupoi); (*7*) Tochilinskii section, western Kamchatka Peninsula; (*8*) Bering Island; (*9*) Kronotskii Bay; (*10*) Schmidt Peninsula; (*11*) Lunskaya Depression; (*12*) Pogranichnyi Depression; (*13*) South-Okhotsk Basin; (*14*) Terpeniya submerged ridge; (*15*) Vityazya underwater ridge; (*16*) external zone of Lesser Kuril Island Ark; (*17–21*) sections of Hokkaido Island: (*17*) Kitami-Tsubetsu area (Tsubetsu and Tokomuro sections), (*18*) Tokachi Province (the Morawan River section), (*19*) Kushiro coal-field (Okubonasawa and Honbetsu sections), (*20*) Sankebetsu section, (*21*) Karamatsu locality (upper part of the Poronai Formation); (*22–27*) sections of Honshu Island: (*22*) Joban Coal Field and Matsushima area, (*23*) Boso Peninsula, and (*24–27*) series of sections in the southern part of Honshu Island.

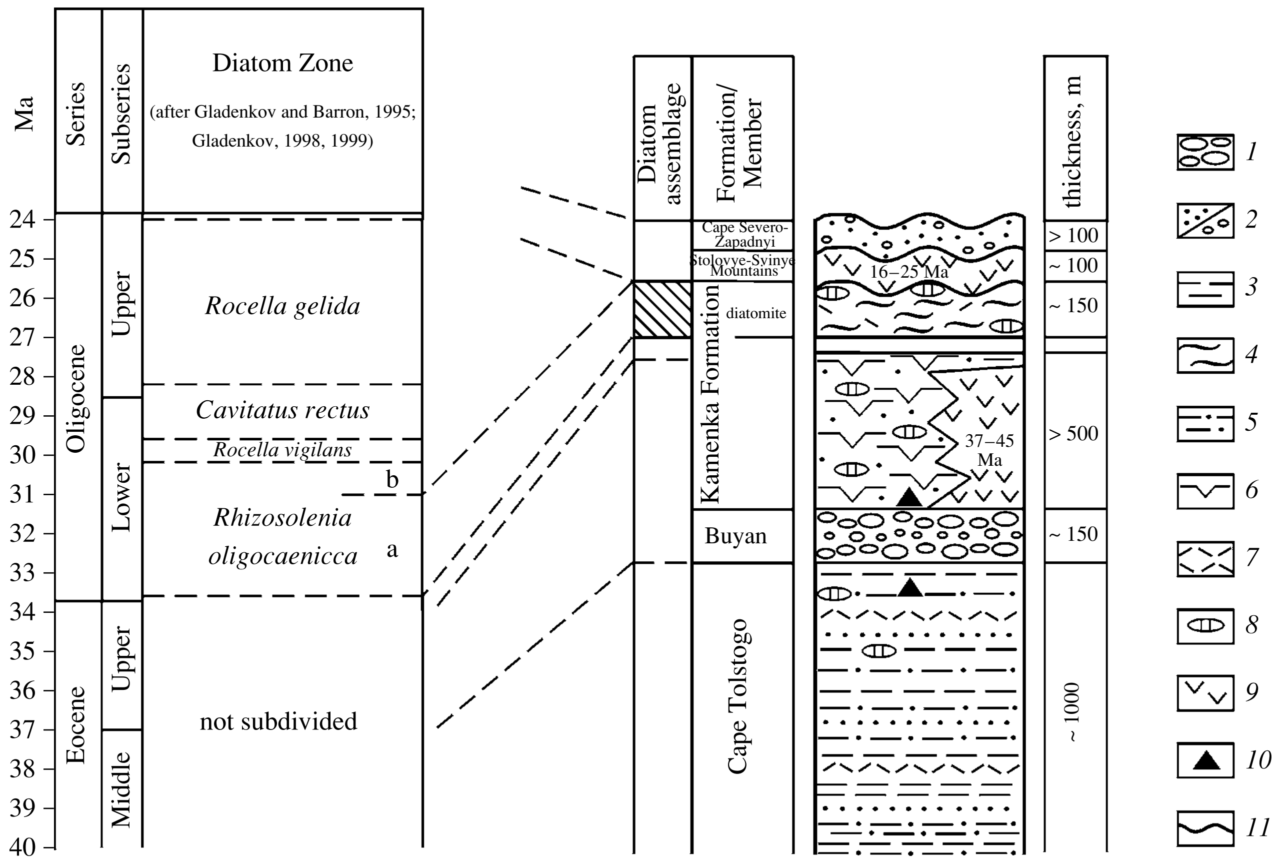


**Fig. 3.** Correlation of the Oligocene diatom assemblage from the Bering Island section (Commander Islands) with the North Pacific diatom zonation (after Gladenkov, 1998, 1999, with inclusion of data by Fedorchuk et al., 1987; Tsvetkov et al., 1990; Gladenkov and Shcherbinina, 1991). Designations: (*1–9*) lithology: (*1*) conglomerates, tuffconglomerates; (*2*) sandstones, tuffstones, gritstone; (*3*) siltstones, tuffaceous siltstones; (*4*) diatomites, tuffaceous diatomites; (*5*) claystones; (*6*) opokas; (*7*) tuffs; (*8*) carbonate concretions; (*9*) basalts, andesites; (*10*) finds of nannofossils; and (*11*) unconfirmity; (16–25 Ma, 37–45 Ma) radiometric datings.

Pacific, which is comparable to the zonations based on calcareous planktonic microfossils. Moreover, it is possible to further develop the current diatom zonation. Some principal refinements to the construction of infrazonal scales based on additional markers were recently analyzed by Gladenkov (2001). At the same time, certain characteristic features and restrictions on the use of datum levels and zonal units within the region depending on the latitudinal position of the sections and their locality in different parts of the basin were also analyzed (Gladenkov, 2001; and others).

## APPLICATION OF DIATOM DATA IN GEOLOGICAL PRACTICE

The zonation described above is shown to be efficient in studies of the Cenozoic sediments of various regions of the North Pacific. Several indicative examples are given below to emphasize the significance of diatoms in the solution of important geological problems and in accurate dating of geological events. These results were recently obtained in regions with different geological structures and Cenozoic deposits formed in different periods and settings.

### *Oligocene and Lower Miocene Stratigraphy*

As mentioned above, the remains of calcareous microplankton (planktonic foraminifers and coccolithophorids), successfully used for the subdivision of the Paleocene and Eocene sediments in the North Pacific, are almost absent from the higher stratigraphic levels. Therefore, until recently their reliable dating met difficulties. It was the study of siliceous microfossils that enabled the subdivision of the Oligocene and Lower Miocene. For example, the discovery of Oligocene diatoms in the Tertiary section of Bering Island (the Commander Islands) made it possible to date part of the Cenozoic section (Figs. 2, 3) with certainty. The analysis of the flora (which is typical of the Early Oligocene) and the data on deep-sea cores allowed the oldest Oligocene zone to be proposed for the North Pacific diatom zonation (Gladenkov, 1998; 1999).

Another example is Ozernoi Bay (eastern Kamchatka Peninsula), where monoclinal bedding was sup-

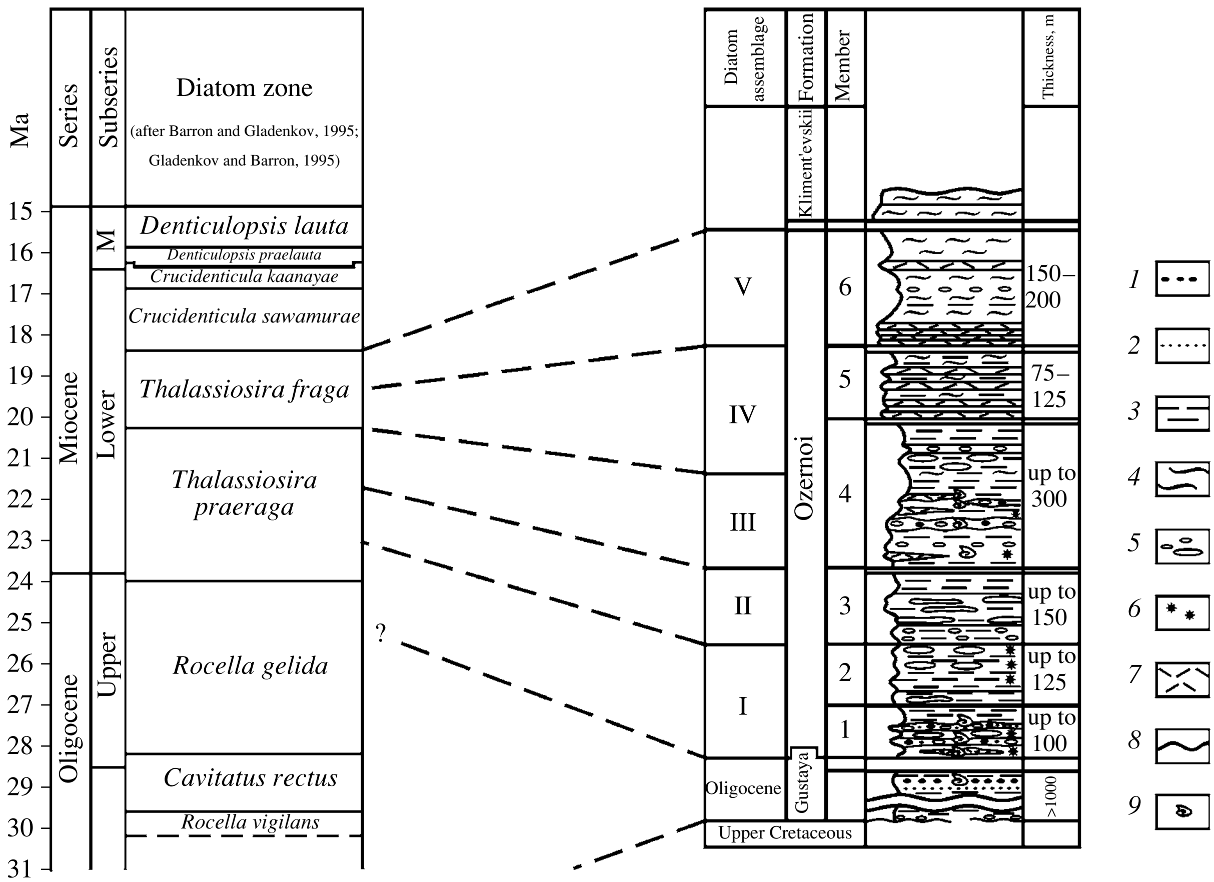


**Fig. 4.** Correlation of the diatom assemblage from the Ozernoi Formation of the eastern Kamchatka Peninsula (Ozernoi Bay) with the North Pacific zonation (after Gladenkov et al., 1998). Designations: (*1–8*) lithology: (*1*) conglomerates, gritstones; (*2*) sandstones; (*3*) siltstones, claystones; (*4*) diatomites; (*5*) carbonate concretions; (*6*) glendonites; (*7*) tuffs; (*8*) unconformity; and (*9*) finds of fossil mollusks.

posed for the Tertiary sequence. However, the finds of Oligocene–Lower Miocene diatom assemblages in the Ozernoi Formation and their correlation with the North Pacific diatom zonation (Figs. 2, 4) proved, the block structure of the section with some units being repeated. Thus, it became possible to reveal an imbricated structure of the sequence and establish true stratigraphic relationships.

The results from Sakhalin Island, where the dating of oil-bearing deposits is among the most topical issues, are also illustrative in this respect. For example, the precise age of siliceous and sandy sediments of eastern Sakhalin, in particular, the Pilenga and Bora formations in the Pogranichnyi Depression remained unknown until Oligocene and Miocene diatom assemblages were found (Figs. 2, 5).

These and other examples demonstrate a real efficiency of the zonation proposed for the Oligocene–Lower Miocene. Available data allow a new correlation scheme for the Oligocene–Lower Miocene (Fig. 6). This scheme is based on the comparison of diatom assemblages from more than thirty localities of the region, from the Bering Sea in the north to Japan in the south (Fig. 2).

*The Time of the First Opening of the Bering Strait*

I participated in a study of the formation of the Bering Strait for several years, in particular, in the dating of the first opening (appearance) of this strait. In the context of this problem, the results obtained are a prominent example of how paleontological data and detailed stratigraphy contribute to the reconstruction of geological events.

According to available geological data, Eurasia and North America were united by the Bering Land Bridge during the last approximately 100 Ma (since the Albian). This means that the northernmost Pacific represented a giant sea gulf. The first water exchange between the Arctic and Pacific basins through the Bering Strait appeared only in the Neogene, influencing the regime of oceanic circulation, climate, sedimentation, and development of various biotic assemblages in the Northern Hemisphere. The first opening of the strait

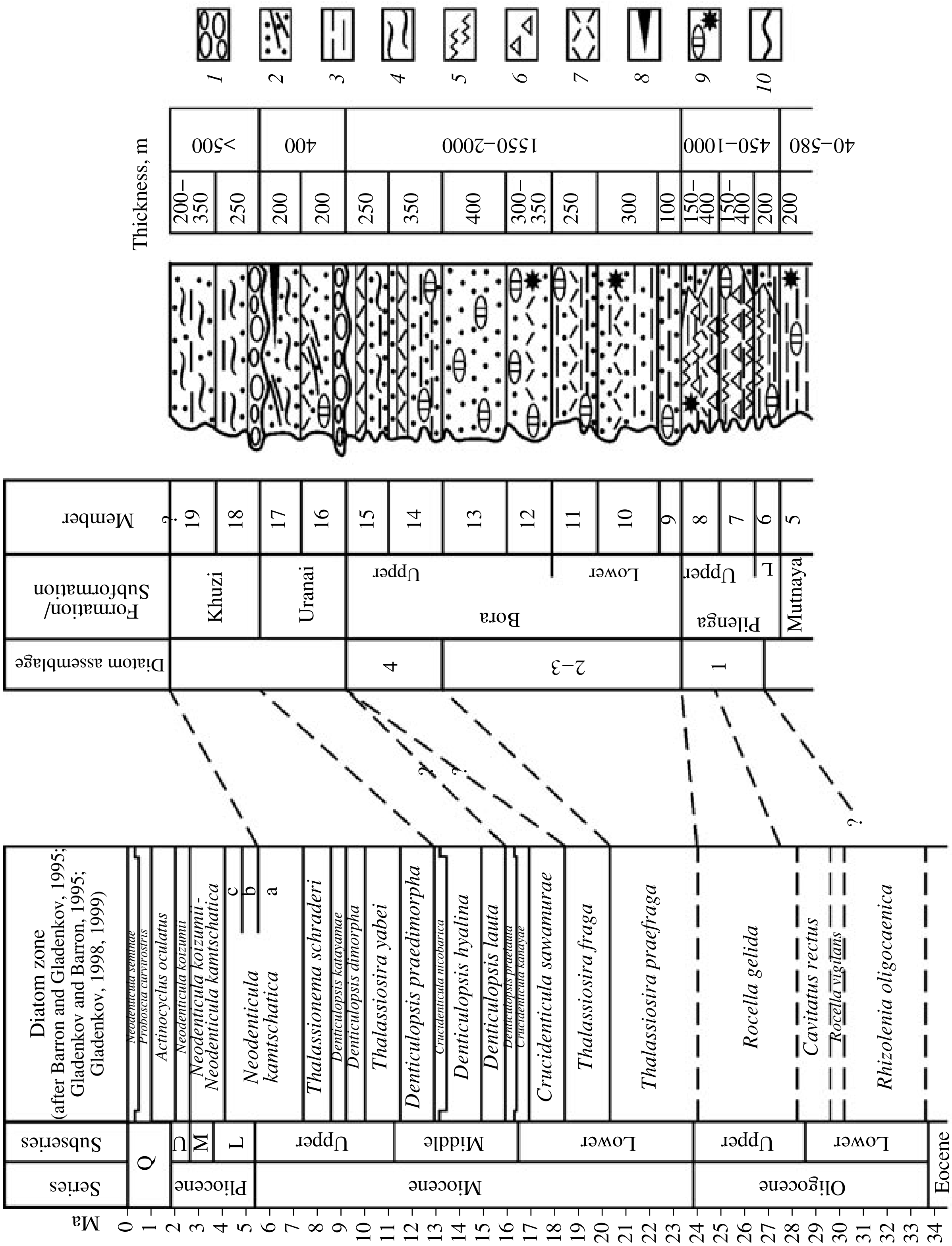


**Fig. 5.** Correlation of diatom assemblages from the section of the Pogranichnyi Depression (eastern Sakhalin) with the North Pacific diatom zonation (after Gladenkov and Gladenkov, 1999; Gladenkov et al., 2000). Designations: (*1–9*) lithology: (*1*) conglomerates, gritstones; (*2*) sandstones; (*3*) siltstones, claystones; (*4*) diatomites; (*5*) siliceous claystones; (*6*) siliceous mudstones, shales; (*7*) tuffs; (*8*) coal, lignite; (*9*) carbonate concretions and glendonites; (*10*) unconformity; (*U*) Upper; (*M*) Middle; and (*L*) Lower.

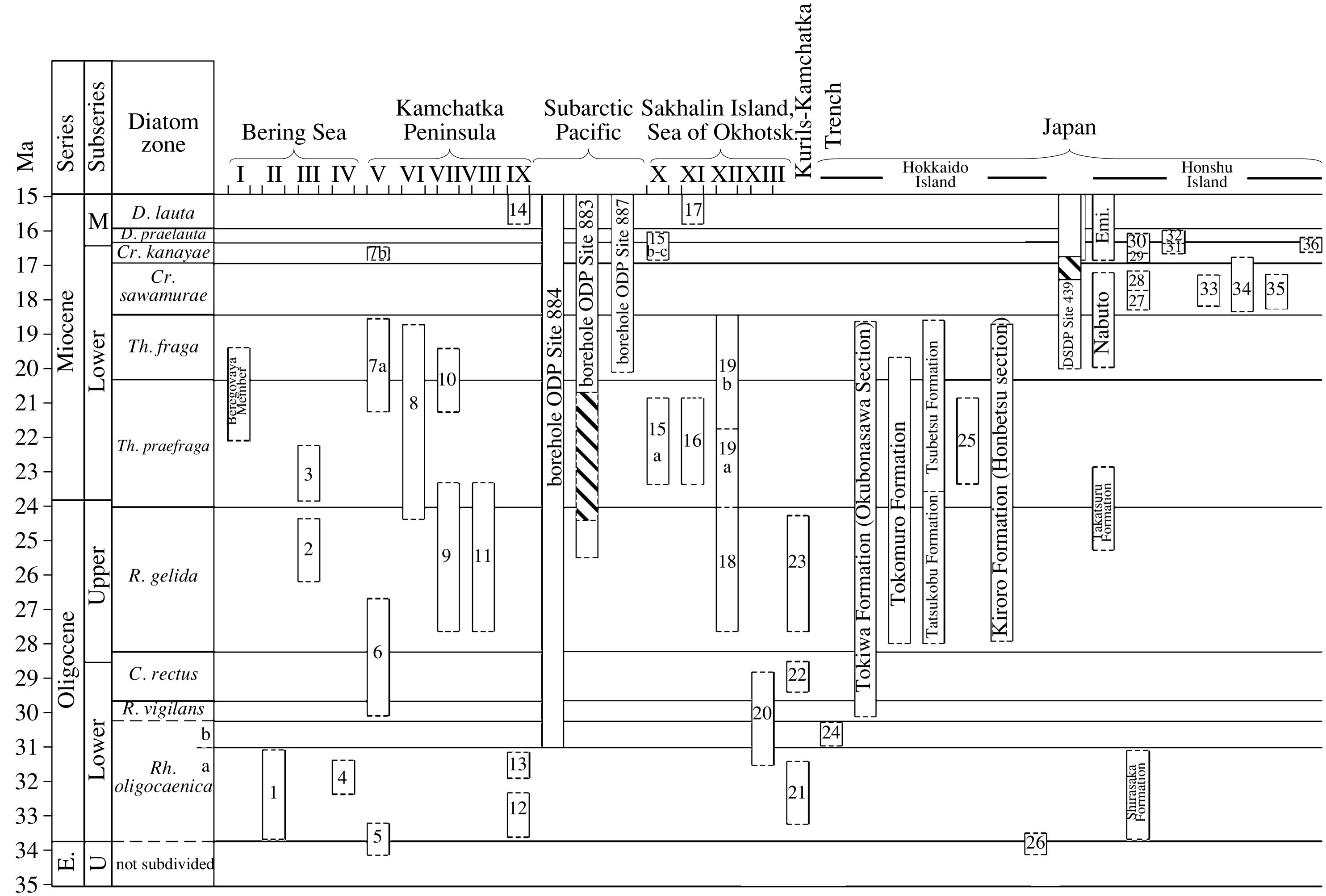


**Fig. 6.** Stratigraphic correlation of the sections from the North Pacific region with the North Pacific Oligocene through Lower Miocene diatom zonation (after Gladenkov, 1998, modified). Designations: (I) Nizhne-Khatyrka Depression (borehole 32); (II) Commander Islands; (III) continental slope of the Navarin Basin; (IV) Shirshov underwater ridge; (V) Karaginskii Island; (VI) Ozernoi Bay (Cape Tupoi); (VII) Ozernoi Peninsula; (VIII) Kronotskii Bay; (IX) Tochilinskii section, western Kamchatka Peninsula; (X) southern part of the Sea of Okhotsk (South-Okhotsk Basin, Terpeniya underwater ridge); (XI) Schmidt Peninsula; (XII) Pogranichnyi Depression; (XIII) Lunskaya Depression; (1–35) formations, groups, etc.: (1) upper part of the Kamenka Formation; (2, 3) dredged sediments from the Navarin Basin, Bering Sea; (4) dredge sediments from the Shirshov underwater ridge; (5) upper part of the Tons Cape Formation; (6) the Il'khatunvayam Formation and sandstone with *Laternula*-formation; (7) Pestrotsvetnaya Formation: (7a) lower and (7b) upper parts; (8) Ozernoi Formation; (9) Shagaevskii Klyuch Formation; (10) Makedonia Formation; (11) dredge sediments from the Kronotskii Bay; (12) upper part of the Gakkh Formation; (13) upper part of the Viventek Formation; (14) lower part of the Kakert Formation; (15) dredge sediments from the southern part of the Sea of Okhotsk: (15a) Terpeniya underwater ridge and (15b) slope of the South Okhotsk Basin; (16) upper part of the Machigar Formation; (17) lower part of the Pil'vo Formation; (18) upper part of the Pilenga Formation; (19) Bora Formation: (19a) Lower and (19b) Upper Bora subformations; (20) undifferentiated Mutnaya and Pilenga formations; (21) Vityazya underwater ridge; (22, 23) external zone of the Lesser Kuril Island Ark; (24) Morawan Formation; (25) upper part of the Sankebetsu Formation; (26) upper part of the Poronai Formation; (27) Kamenoo Formation; (28) Taira Formation; (29) Shirado Group; (30) Takaku Group; (31) Ajiri Formation; (32) Matsushima Formation; (33) Yamanouchi Formation; (34) Morozaki Group; (35) Ikuchise Group; (36) upper part of the Bihoku Group and middle part of the Takakura Formation; grey rectangle indicates sediments recovered by DSDP Site 438.

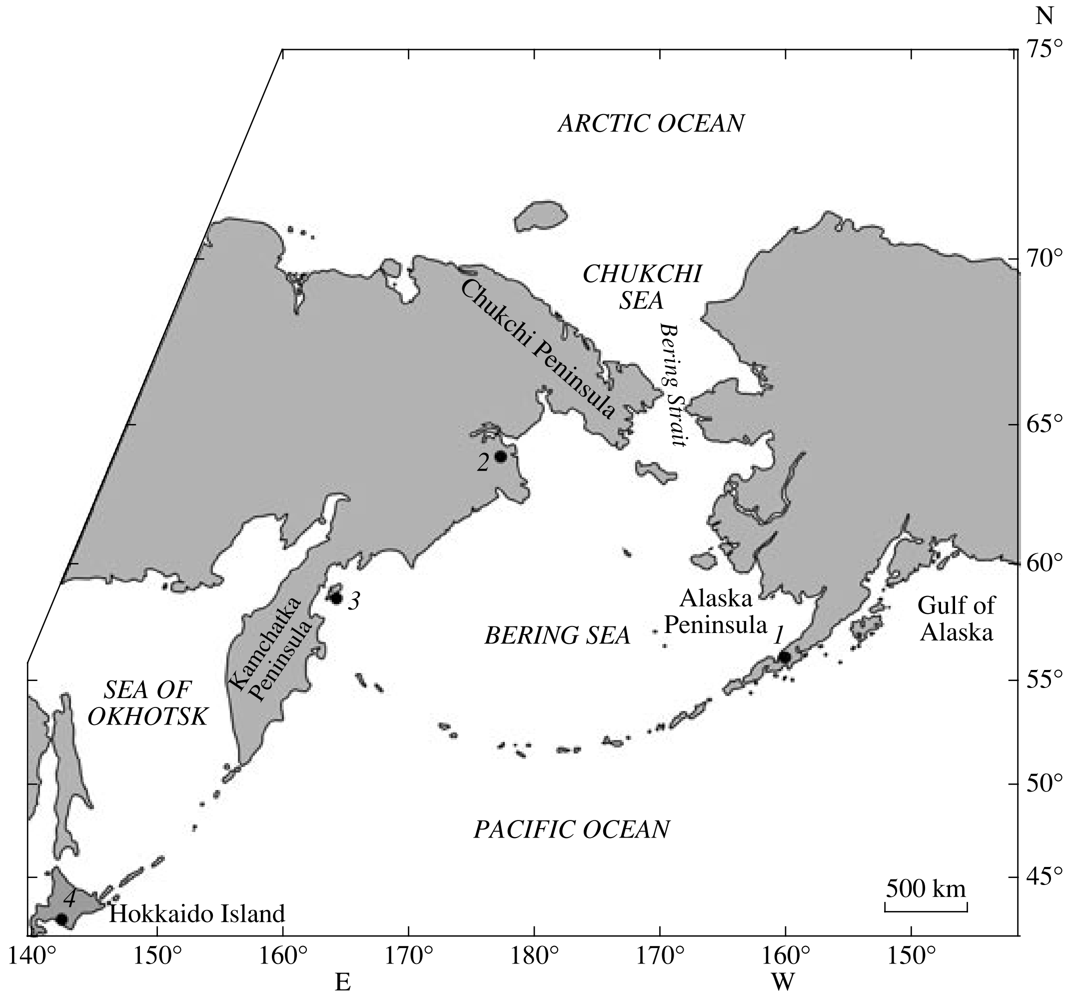


**Fig. 7.** Geographical position of Neogene sections (black circles) that contain the oldest *Astarte* in the North Pacific region (after Gladenkov and Gladenkov, 2004). Designations: (*1–4*) sections: (*1*) Sandy Ridge section, Alaska Peninsula; (*2*) Anadyr Depression (Chukchi Land); (*3*) Karaginskii Island (northeastern Kamchatka Peninsula); and (*4*) Hokkaido Island (northern Japan).

was estimated within the range of 3.5 to 4.4 Ma. These estimates were based primarily on the stratigraphic position of the fossil marine bivalve *Astarte*. It was revealed that Neogene *Astarte* has an Arctic–North Atlantic origin; therefore, its first appearance in the North Pacific stratigraphic sections indicates the earliest opening of the strait (Marincovich and Gladenkov, 1999, 2001). The oldest material of *Astarte* is known from several sections in the region (Fig. 7). However, until recently, it was impossible to determine their age with certainty because of the absence of data on age-diagnostic planktonic microfossils from these levels. The recent data on the Sandy Ridge stratigraphic section, Alaska, is of particular importance in this context (Figs. 7, 8). Reexamination of this section allowed the determination of the precise stratigraphic position of the earliest *Astarte*. The stratigraphically lowest specimens of *Astarte* occur in the basal part of the Milky River Formation (Fig. 8). I studied fossil diatoms from samples collected throughout the section. Marine diatoms were found in more than fifty samples, in particular, in samples from the stratigraphically lowest *Astarte*-bearing horizon. The presence of stratigraphically significant species throughout the section allowed correlation with the diatom zonal scale and precise dating of the enclosing deposits (Gladenkov et al., 2002; Gladenkov, 2003, 2006; Fig. 8). These are the first finds of marine diatom assemblages including age-diagnostic taxa from the Cenozoic of Alaska. In particular, the stratigraphic horizon with the oldest *Astarte* was dated as terminal Miocene, within a narrow interval of 5.5–5.4 Ma. This suggests that the Bering Strait first opened very near the end of the Miocene. In general, this conclusion is consistent with paleontological data from the Kamchatka and Chukchi peninsulas and Japan, where the oldest known *Astarte* are of similar age and can be attributed to the latest Miocene–earliest Pliocene (Gladenkov and Gladenkov, 2004; Fig. 9).

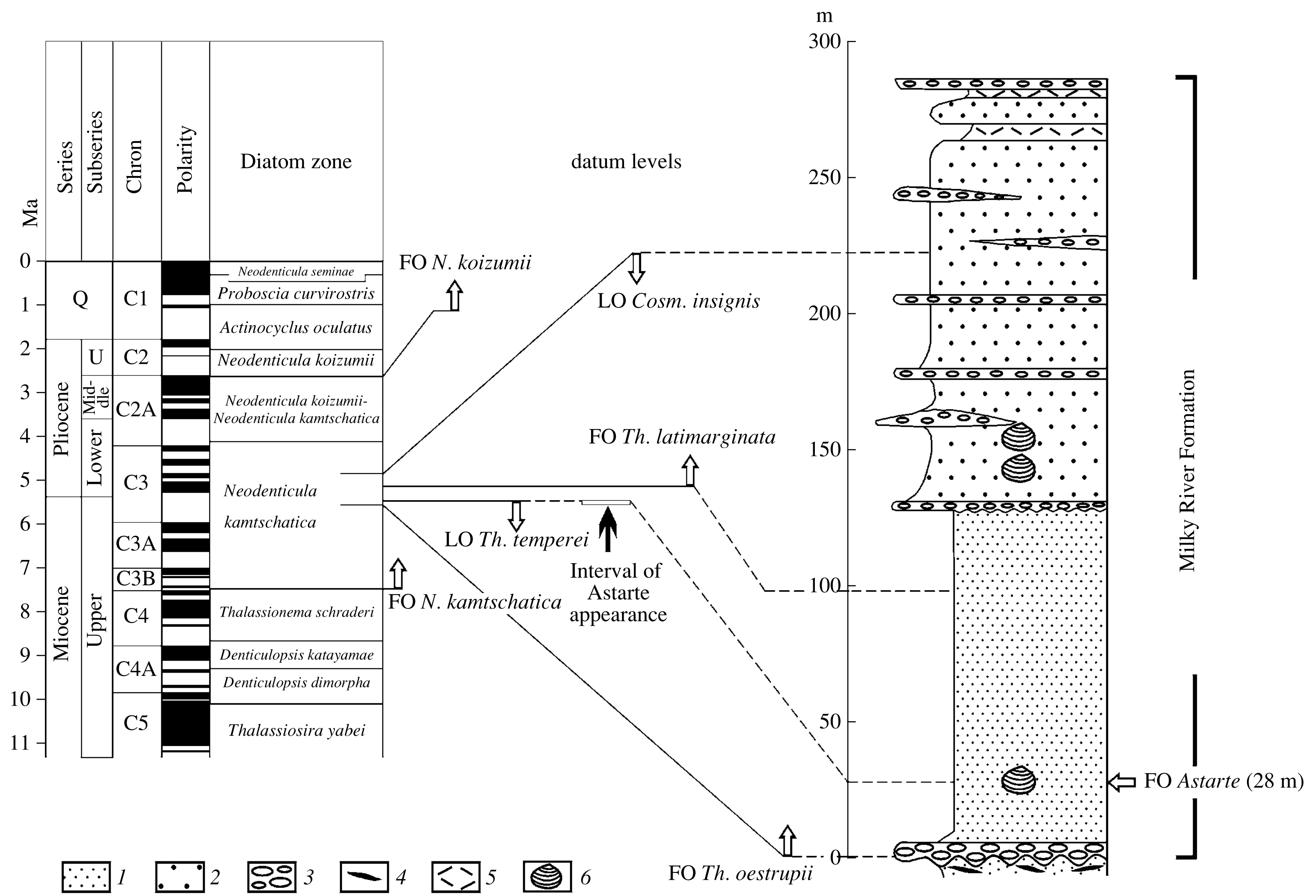


**Fig. 8.** Correlation of the diatom assemblages from the Sandy Ridge section of the Alaska Peninsula with the North Pacific diatom zonation, and the age range of the stratigraphically lowest *Astarte*-bearing horizon (after Gladenkov et al., 2002; Gladenkov, 2003, 2006). Designations: (FO) first occurrence; (LO) last occurrence; (*1–5*) lithology: (*1*) fine–middle-grained sandstones, (*2*) very coarse and coarse-grained sandstones, (*3*) conglomerates and gritstones, (*4*) coal, (*5*) tuffs, and (*6*) fossil mollusks *Astarte*.

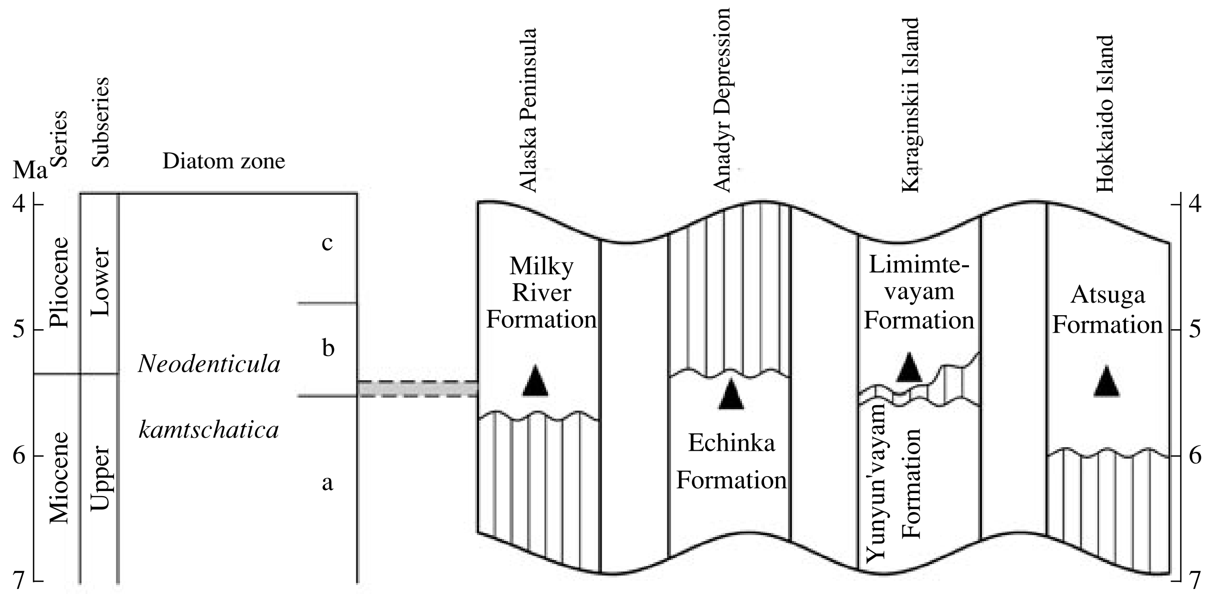


**Fig. 9.** Stratigraphic position of the oldest Neogene *Astarte* (triangles) in the North Pacific sections (after Gladenkov and Gladenkov, 2004). Designations: (a–c) subzones.

## CONCLUSIONS

Thus, to date, the North Pacific Oligocene through Quaternary diatom zonation including more than 20 zones has been constructed. The application of zones that are established on the basis of the successive diatom evolution, in combination with available physical methods (paleomagnetic, radiometric, isotopic, and others) has brought the Cenozoic stratigraphy of the region to a higher level. The high resolution of diatoms for stratigraphic reconstructions and common occurrence of their remains in sediments allow the use of this group for the detailed subdivision of the Upper Cenozoic and reliable correlation of the North Pacific sections, even as remote as hundreds or thousands of kilometers.

The application and interpretation of diatom data are also important in terms of historical geology. The development of diatom assemblages occurred against a background of various geological events; therefore, the results of detailed biostratigraphic and paleontological studies are valuable for the reconstruction of the geological history of the region. This idea is embodied in calendars of geological events and their analysis. They provide a basis for revealing changes in early ecosystems, as well as for estimating the degree of their synchronism and possible relationships to processes of different nature and scale. Some of these questions have recently been discussed by Gladenkov (2005).

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