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The North Pacific advanced Oligocene to lower Miocene diatom stratigraphy

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Abstract: The current state of the North Pacific Oligocene and lower Miocene diatom stratigraphy is reviewed and its significant progress of the past 10-15 years is detailed. Biostratigraphic research in the region of the last decade demonstrates a real efficiency of the Oligocene to early Miocene diatom zonation based mainly on the materials from deep-sea cores. Significance of diatom zonation and its application for dating and subdivision of the Oligocene and lower Miocene sequences which previously proved difficult are discussed. The possibility of application of the oceanic zonation in studies of onshore stratigraphic sequences is emphasized. It is shown that in the North Pacific diatoms representing siliceous microplankton are the best biostratigraphic tool for age determination and correlation of the Oligocene and lower Miocene marine sediments lacking calcareous planktonic microfossils. Compilation of available diatom data from different localities allows a new correlation scheme to be proposed for the North Pacific Oligocene and lower Miocene.

Keywords: North Pacific, Oligocene, lower Miocene, diatoms, biostratigraphy, microplankton, correlation, zonation

1. Introduction

Since there is a wide development of multifacies Cenozoic deposits in the North Pacific, detailed subdivision and correlation of the Neogene and Paleogene sediments are crucial for this vast region, which embraces a large segment of the ocean and its margins. In this regard, fossil one of the main paleontological groups that are used for studies of the post-Eocene sediments. Diatoms occur widely in Cenozoic open ocean and onshore stratigraphic sequences in the middle to high latitudes of the North Pacific and are the primary biostratigraphic tool for age determination and correlation of the Neogene marine sediments in this region. During the past 35 years, the Cenozoic diatom stratigraphy has made significant progress and diatom zonation has developed rapidly. In many respects, this progress is connected with the study of sedimentary cores recovered by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP).

The first North Pacific Cenozoic diatom zonations were proposed in the pioneer works by Koizumi (1973) and Schrader (1973) and based mainly on the materials from the deep-sea drilling started in the North Pacific in the early 1970s. Drilling of ocean bottom sediments has revealed an overwhelming prevalence of diatoms among other micropaleontological remains in the North Pacific since the middle Miocene due to the development and high biological productivity of diatoms which prevailed in the plankton. It was the tracing of planktonic diatom assemblages in nearly complete marine deep-sea sequences that made it possible to construct oceanic scales with the continuous succession of zones. The version of Koizumi (1973) included a series of middle Miocene to Quaternary zones for the Northwestern Pacific. Their boundaries were determined by datum levels based mainly on appearance or extinction of planktonic marker-species. In general, this scheme of Koizumi served as an initial framework for the North Pacific oceanic diatom zonation. Data obtained in the course of later biostratigraphic research in the middle 1970s - early 1990s, contributed significantly to improvement and refinement of the zonation. These results allowed the refinement of biostratigraphic zones, their arrangment in a strict order, and traced them over a wide region of the North Pacific and its margins. Consistent and general regularities in the successive changes of stratigrapically significant taxa were revealed by determining their age ranges in the North Pacific sections, first of all from DSDP and ODP sites. I. Koizumi, J. Barron, T. Maruyama and F. Akiba proposed more detailed and refined versions of the zonation by thoroughly analyzing its applicability in various parts of the region and expanding its applicable age ranges (Koizumi, 1975, 1977, 1985, 1992; Barron, 1980, 1981, 1985, 1992; Akiba *et al.*, 1982; Maruyama, 1984; Koizumi and Tanimura, 1985; Akiba, 1986; and others). The middle Miocene to Pleistocene diatom zonation proposed by Akiba (1986) was most widely accepted and with some modifications continues to be used. The

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North Pacific diatom zonation has provided a real tool for the dating, subdivision, and correlation of the Neogene marine sediments. It became widely applied in stratigraphic research within this region. The successful application of the oceanic zonation in studies of Neogene sequences on land and in marginal seas should be specially emphasized. The studies of diatom assemblages from the sections of Japan, Sakhalin, Kamchatka, Chukotka, Alaska and California allowed refinement or, in some cases, even revision of the age of a number of formations and regional stages.

Currently, the high-resolution North Pacific middle Miocene through Quaternary diatom zonation includes numerous biohorizons based on datum levels of planktic species correlated with the magnetostratigraphic record (Barron and Gladenkov, 1995; Yanagisawa and Akiba, 1998). The age resolution of this zonation is comparable to that of groups of calcareous planktonic microfossils. However, despite the considerable success achieved by the mid-1990s, some important problems of the diatom zonation were left in abeyance.

2. Results and discussion

2.1 The North Pacific Oligocene through early Miocene diatom zonation

One of the main problems has concerned the pre-middle Miocene zonation: 1) the lower Miocene diatom biostratigraphy was in largely preliminary because the succession of diatom assemblages had not been traced in continuous sequences; 2) the Oligocene zonation was essentially missing. Biostratigraphic data obtained in the mid-1990s on materials from ODP Leg 145 in the subarctic Pacific contributed significantly to the solution of this problem. Besides the middle Miocene to Quaternary diatom-bearing sediments, ODP sites recovered Oligocene to lower Miocene sequences that contained fossil diatoms (Barron and Gladenkov, 1995; Gladenkov and Barron, 1995). Based on the documented successive first occurrences of planktonic marker-species in a nearly complete section, a continuous series of seven diatom zones for the Oligocene and early Miocene (the *Rocella vigilans*, *Cavitatus rectus*, *Rocella gelida*, *Thalassiosira praefraga*, *Thalassiosira fraga*, *Crucidenticula sawamurae*, and *Crucidenticula kanayae* zones) was first proposed (Fig. 1). Simultaneously, within the zones, the stratigraphic ranges of other stratigraphically-important taxa were also outlined or refined. Later, a synthesis of these data and materials on diatom assemblages from onshore sequences of the Northwestern Pacific margins made it possible to establish the oldest early Oligocene *Rhizosolenia oligocaenica* Zone (Gladenkov, 1998, 1999) (Fig. 1). The proposed Oligocene and early Miocene zones were an important contribution to the Cenozoic diatom zonation, extending its application up to the basal Oligocene.

2.2 Application of Oligocene to early Miocene diatom zonation for stratigraphic correlation within the North Pacific region

Precise age determination and reliable correlation of Oligocene and lower Miocene sedimentary successions are among the most difficult problems of the North Pacific stratigraphy. On the one hand, remains of planktonic foraminifera and coccolithophorids, which are successfully used for the subdivision of the Paleocene and Eocene in the North Pacific, are practically lacking in younger stratigraphic levels. On the other hand, in many cases the Cenozoic regional stratigraphy of the North Pacific framing (including Japan, Sakhalin, Kamchatka, and Chukotka) is based on data on mollusks and benthic foraminifera. But for the Oligocene and lower Miocene, these data did not allow to soundly identify and trace a succession of stratigraphic units having an accurate biochronology. That is why, until recently, the reliable dating and subdivision of the Oligocene to lower Miocene sequences has proven difficult. Meanwhile, stratigraphic subdivision and correlation are among the most important tasks of geological investigations. First, the sequences of this age are often rich in minerals, in particular, oil and gas. Second, data on Oligocene and early Miocene are valuable for deciphering the Cenozoic history of the region in general, because the geological events taking place during that time caused both the subglobal and regional changes. In particular, numerous obtained data around the world reveal the onset of radical changes of global oceanic circulation and climatic regime in the Cenozoic. In this regard, further application of the proposed North Pacific diatom zones and an analysis of the previously published data on diatoms could represent a promising data set for more reliable and precise age determination of host sediments.

The recent results of biostratigraphic research in the North Pacific region demonstrate a real efficiency of the proposed Oligocene through early Miocene diatom zonation. Diatom assemblages correlative to zonal assemblages have been found and documented from various parts including sequences from Japan, Sakhalin, Kamchaka and adjoining marine zones (Morita *et al.*, 1996; Yu. Gladenkov *et al.*, 1998, 1999; Yanagisawa and Akiba, 1998, 1999; Watanabe *et al.*, 1999; A. Gladenkov *et al.*, 2000; Tsoy, 2000, 2002 a, b; Tsoy and Shastina, 2000, 2005; Urabe *et al.*, 2003; Suto *et al.*, 2005; and others) (Fig. 2). On the other hand, a critical analysis of the published data also allowed the diatom assemblages documented previously from a number of localities (Fig. 2) to be interpreted as Oligocene or early Miocene (Gladenkov, 2006, 2007). It should be noted however, that in some cases the application of the Oligocene to lower Miocene diatom zonation faces difficulties owing to the following limitations:

1) The incompleteness of sequences or fragmentary

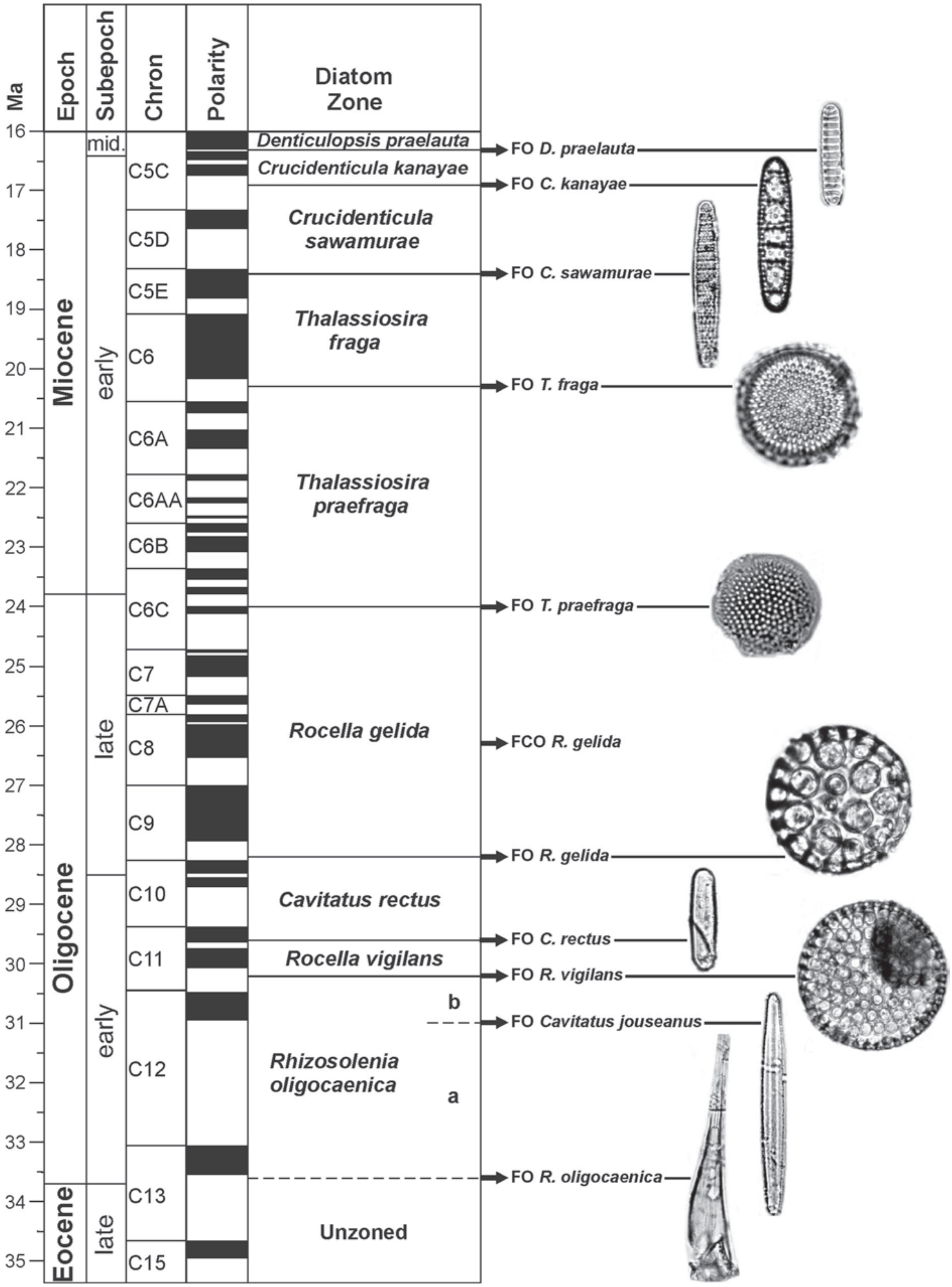

Fig. 1 The North Pacific Oligocene through early Miocene diatom zones (after Barron and Gladenkov, 1995; Gladenkov and Barron, 1995; Gladenkov, 1998, 1999) with the boundaries illustrated by key marker species and correlated to the geochronologic and geomagnetic polarity time scales of Berggren *et al.* (1995)

Key: FO - the first occurrence. FCO - the first common occurrence. a-c - subzones. mid. - middle. Magnifications for illustrated species are different.

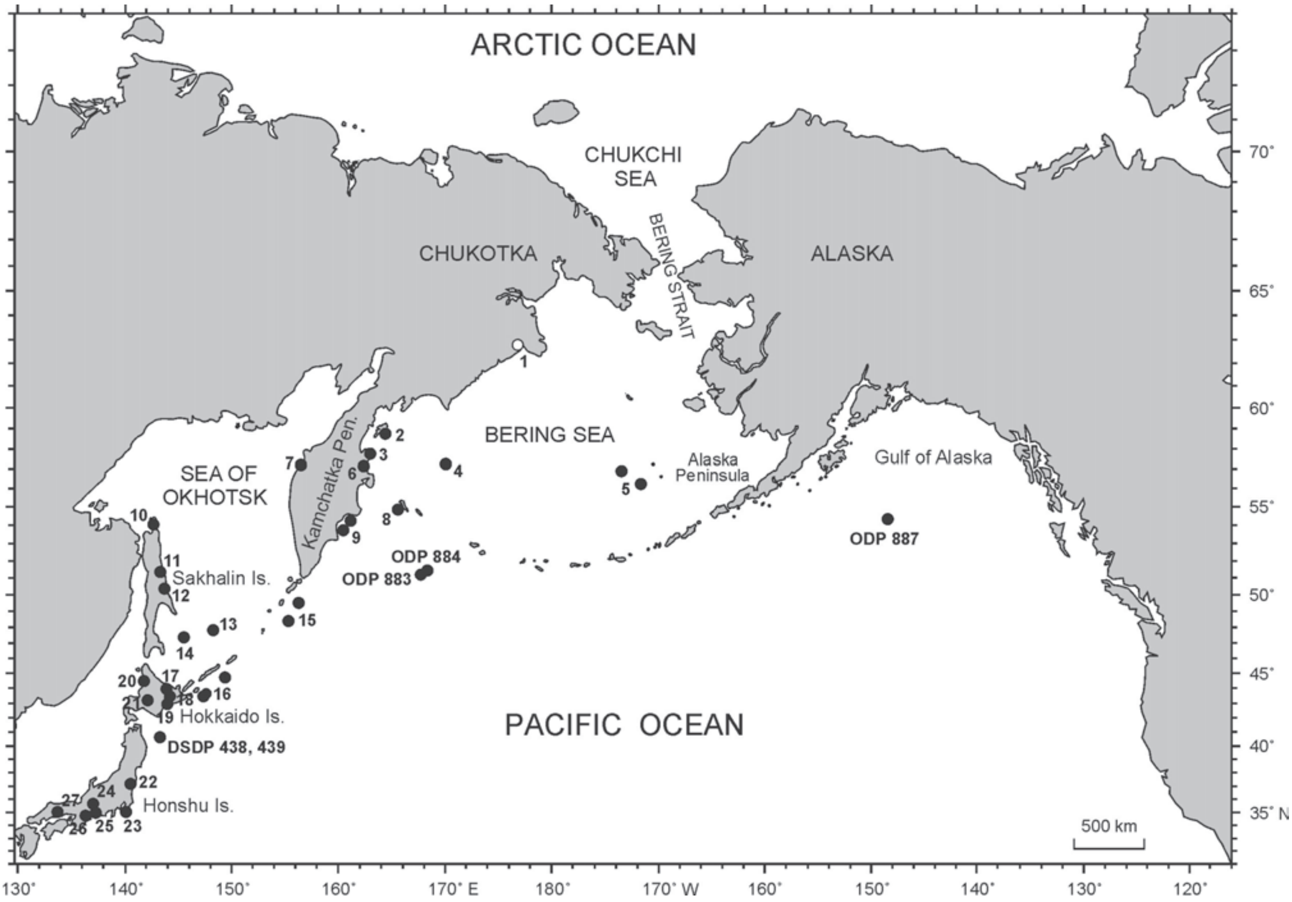

Fig. 2 Map of the North Pacific region showing locations of stratigraphic sections (black circles) where Oligocene and early Miocene diatom assemblages are documented or interpreted from literary data (after Gladenkov, 2006, 2007)
Key: ODP 883, 884, 887 - Ocean Drilling Program sites. DSDP 438, 439 - Deep Sea Drilling Project sites. 1 - Nizhne-Khatyrka Depression (borehole 32). 2 - Karaginskii Island, Northeast Kamchatka. 3 - Ozernoi Peninsula, East Kamchatka. 4 - Shirshov underwater ridge, the Bering Sea. 5 - Navarin Basin of the Bering Sea. 6 - Ozernoi Bay (cape Tupoi), East Kamchaka. 7 - the Tochilinskii section, West Kamchatka. 8 - Bering Island, westernmost end of Aleutions. 9 - Kronotskii Bay, Southeast Kamchatka. 10 - Schmidt Peninsula, North Sakhalin. 11 - Lunskaya Depression, East Sakhalin. 12 - Pogranichnyi Depression, East Sakhalin. 13 - South-Okhotsk Basin, the Okhotsk Sea. 14 - Terpeniya underwater ridge, the Okhotsk Sea. 15 - Vityazya underwater ridge. 16 - external zone of Lesser Kuril Island Ark. 17-21 - sections of Hokkaido Island. 17 - Kitami-Tsubetsu area (the Tsubetsu and Tokomuro sections). 18 - Tokachi Province (the Morawan River section). 19 - Kushiro coal-field (the Okubonasawa and Honbetsu sections). 20 - the 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. 24-27 - series of sections in the southern part of Honshu Island.

nature of their paleontological characteristics (in some cases remains of diatoms are confined to separate rare samples) often doesn't allow tracing a succession of changing of stratigraphically-important species;

2) The absence of age-diagnostic taxa in diatom assemblages due to a selective dissolution of diatom valves in sediments;

3) The absence of zonal species and other marker-species in diatom assemblages of the same age due to paleoecological exclusion because of different paleoenvironments in which flora was formed (for example, nearshore marine diatom assemblages are commonly different from those in the deep pelagic realm);

4) There are sometimes difficulties while analyzing some previously published data because full check-lists of studied assemblages and/or illustrations of taxa known now as age-diagnostic are absent in some publications. Furthermore, some stratigraphically-important taxa (*Rhizosolenia oligocaenica*, *Kisseleviella ezoensis*, *Crucidenticula sawamurae*, and others) including species described recently (*Cavitatus rectus*, *Thalassiosira praefraga*, *Odontella sawamurae*, and others) were not an object of special attention and often were not taken into consideration in previous studies of diatom assemblages.

However, despite the notes above, the available data allow a new preliminary correlation scheme to be proposed for the Oligocene and lower Miocene (Fig. 3). This zonal scheme is based on the comparative characteristics

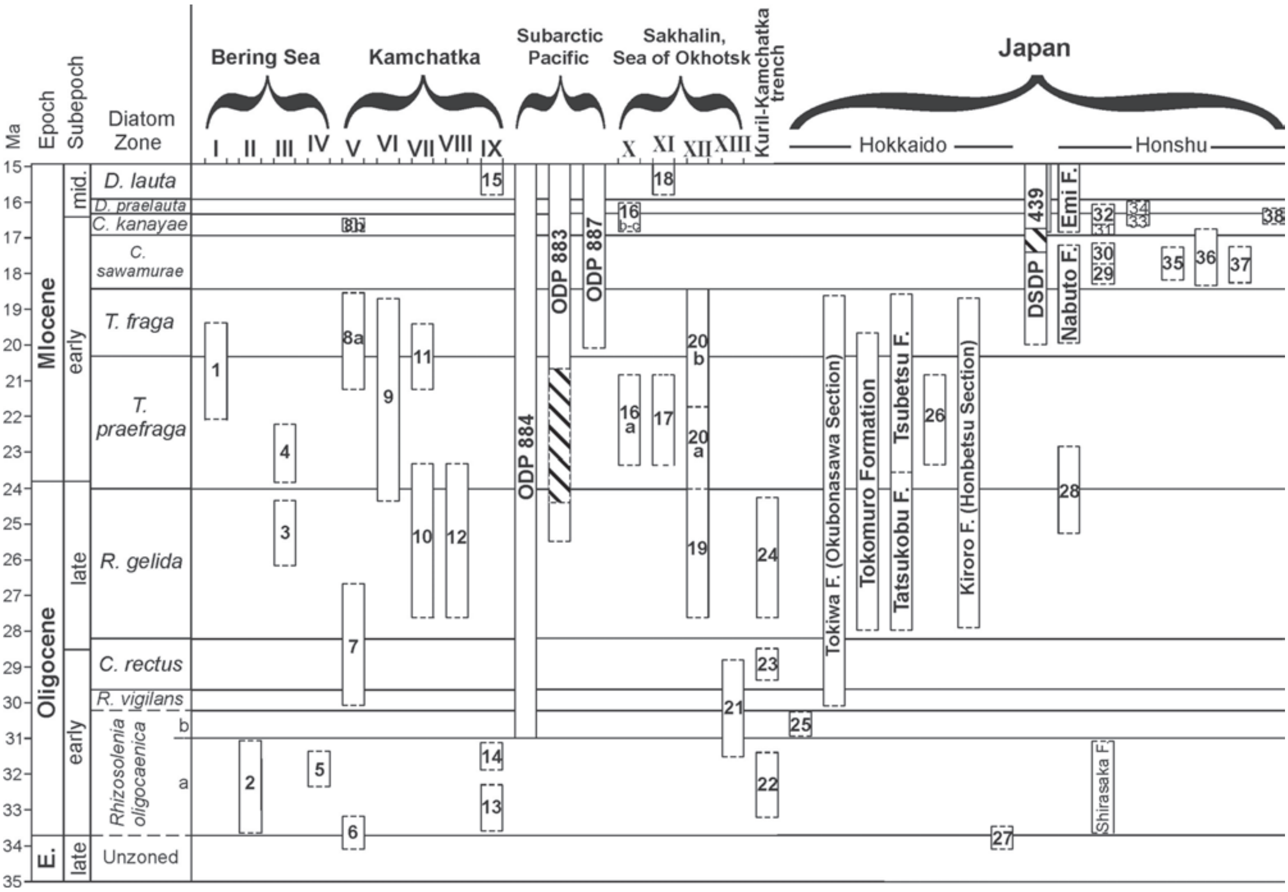

Fig. 3 Stratigraphic correlation of the Oligocene and lower Miocene diatom-bearing sections from the North Pacific region with the North Pacific diatom zones (after Gladenkov, 2006, 2007)

Key: I - Nizhne-Khatyrka Depression (borehole 32). II - Bering Island. 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 - the Tochilinskii section, West Kamchatka. X - southern part of the Okhotsk Sea (South-Okhotsk Basin, Terpeniya underwater ridge). XI - Schmidt Peninsula. XII - Pogranichnyi Depression. XIII - Lunskaya Depression. 1-35 - formations, subformations, groups, etc. 1 - the Beregovaya Member. 2 - upper part of the Kamenskaya Formation. 3-4 - dredge sediments from the Navarin Basin, Bering Sea. 5 - dredge sediments from the Shirshov underwater ridge. 6 - upper part of the Tons Cape Formation. 7 - the Il'khatunvayamskaya Formation and the *Laternula*-bearing Sandstones Formation. 8 - the Pestrotsvetnaya Formation (8a - lower part, 8b - upper part). 9 - the Ozernovskaya Formation. 10 - the Shagaevskaya Formation. 11 - the Makedonskaya Formation. 12 - dredge sediments from the Kronotskii Bay. 13 - upper part of the Gakhinskaya Formation. 14 - upper part of the Viventekskaya Formation. 15 - lower part of the Kakertskaya Formation. 16 - dredge sediments from the southern part of the Okhotsk Sea (16a - Terpeniya underwater ridge, 16b - slope of the South Okhotsk Basin. 17 - upper part of the Machigarskaya Formation. 18 - lower part of the Pil'skaya Formation. 19 - upper part of the Pilengskaya Formation. 20 - the Borskaya Formation (20a - the Lower Borskaya subformation, 20b - the Upper Borskaya subformation). 21 - undifferentiated the Mutnovskaya and Pilengskaya formations. 22 - dredge sediments from the Vityazya underwater ridge. 23-24 - dredge sediments from the external zone of Lesser Kuril Island Ark. 25 - the Morawan Formation. 26 - upper part of the Sankebetsu Formation. 27 - upper part of the Poronai Formation. 28 - the Takatsuru Formation. 29 - the Kamenoo Formation. 30 - the Taira Formation. 31 - the Shirado Group. 32 - the Takaku Group. 33 - the Ajiri Formation. 34 - the Matsushima Formation. 35 - the Yamanouchi Formation. 36 - the Morozaki Group. 37 - the Ikuchise Group. 38 - upper part of the Bihoku Group and middle part of the Takakura Formation.

Grey rectangle indicates sediments recovered by DSDP Site 438. Rectangles marked by diagonal lines indicate intervals of possible unconformities. See Figure 2 for locations of sections.

of the diatom assemblages from more than thirty localities in the region: from the Bering Sea in the north to Japan in the south. It is important to note also, that the data obtained on some Oligocene and lower Miocene onshore marine sequences facilitate direct correlations between assemblages of siliceous microplankton (diatoms) and benthic fossils (mollusks and benthic foraminifera), thus imparting certain indicative properties to benthic fauna. One of the latest examples is new data on paleontological characteristic of the Oligocene in the

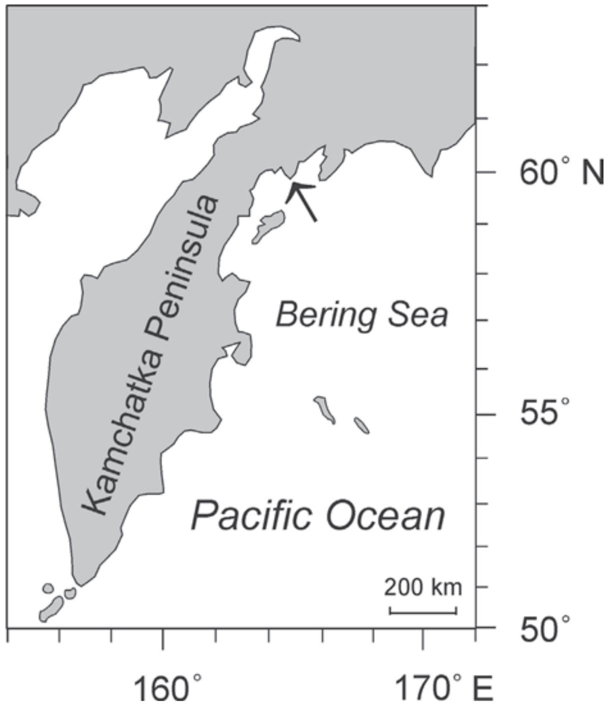

Fig. 4 Location of the Il'pinskii Peninsula (shown by black arrow) in Kamchatka

Il'piskii Peninsula stratigraphic section, Northeast Kamchatka, which is a reference section for the marine Paleogene (over 2500 m thick) of Northeast Asia (Fig. 4).

Paleocene and Eocene calcareous planktonic microfossils (foraminifera and nannofossils) have been previously discovered and studied from a lower part of the Il'piskii Peninsula section (Volobueva *et al.*, 1994). Assemblages of these microfossils correlative with their analogues from standard Paleogene zones were used to subdivide in detail the host sedimentary succession and to determine age of relevant stratigraphic units. Meanwhile, two upper formations (the Gailkhavilanskaya and Aluginskaya) of the Paleogene section have been considered until recently as barren of planktonic microorganisms. These formations (in total, over 1200 m thick) are mainly composed of tuffaceous siltstones, tuffaceous argillites, and tuffstones, and shales with interbeds and lenses of tuffstones (Fig. 5). The rocks contain shape- and size-variable carbonate concretions. The Oligocene Stage and position of its lower boundary were determined in this section based on fossil benthic assemblages of mollusks and foraminifera (Volobueva *et al.*, 1994). According to these data, the Aluginskaya Formation, which is approximately 900 m thick, was attributed to the Oligocene, and the underlying Gailkhavilanskaya Formation (about 250 m thick) – to the upper Eocene.

Additional material was collected from these formations during field work at the Il'pinskii Peninsula stratigraphic section during recent field work conducted together with Japanese colleagues (A. Gladenkov and Yu. Gladenkov, 2007). The work was aimed, in particular, at collecting samples for diatom analysis, first of all from the Aluginskaya Formation. In addition, fossil mollusks from this formation and underlying strata were studied more thoroughly than before. As a result, for the first time, fossil diatoms have been found in the samples collected from the Aluginskaya Formation comprising the uppermost part of the section (A. Gladenkov and Yu. Gladenkov, 2007). Analysis of diatom assemblages from different stratigraphic levels makes it possible to distinguish the "beds with diatoms" and infer their ages. The beds with *Stephanopyxis* spp. are determined in the lower part of the Formation, and the beds with *Cavitatus* cf. *jouseanus* – *Odontella sawamurae* – in the higher stratigraphic interval (Fig. 5). *Cavitatus* cf. *jouseanus* Williams and *Odontella sawamurae* Akiba are of some significance for estimating the lower age limit of their beds. The presence of genus *Cavitatus* in the latter beds indicates the age of enclosing sediments not older than ~31 Ma (the early Oligocene). Based on data of F. Akiba who has described *Odontella sawamurae* in Morita *et al.* (1996), this marine species is characteristic of the Oligocene to early Miocene in the Northwest Pacific, and its oldest finds in Hokkaido, Japan, are confined to the *Rocella vigilans* diatom Zone of the early Oligocene (30.2 to 29.6 Ma). On the one hand, the mentioned above species may indicate that this part of the Aluginskaya Formation is not older than 30.2 Ma, while on the other hand, the first occurrence of *Odontella sawamurae* has not been determined precisely as yet in areas northward of Hokkaido. For example, in sequences from the island slope of the Kuril-Kamchatka Trench *Odontella sawamurae* ranges from an interval of the early Oligocene corresponding to the *Rhizosolenia oligocaenica* diatom Zone (Tsoy, 2002 a). Therefore, it possible to state now only that the presence of this taxon in the Aluginskaya Formation indicates only the early Oligocene and not older age of enclosing sediments. The first data on diatoms from stratigraphically well-controlled samples reliably supports the Oligocene age of the Aluginskaya Formation in the Il'pinskii Peninsula section. Thus, diatom data confirm the age inferred previously based on fossil benthic fauna. The obtained data also made possible direct correlations between assemblages of diatoms and mollusks, imparting certain indicative properties to benthic fauna. These data give a basis for further tracing of distinguished beds with benthic assemblages even in sequences lacking diatoms.

3. Conclusions

The North Pacific Oligocene to lower Miocene diatom stratigraphy has made a significant progress during the past 10-15 years. The elaborated early Oligocene through early Miocene diatom zonation is based mainly on the materials from deep-sea cores. This zonation

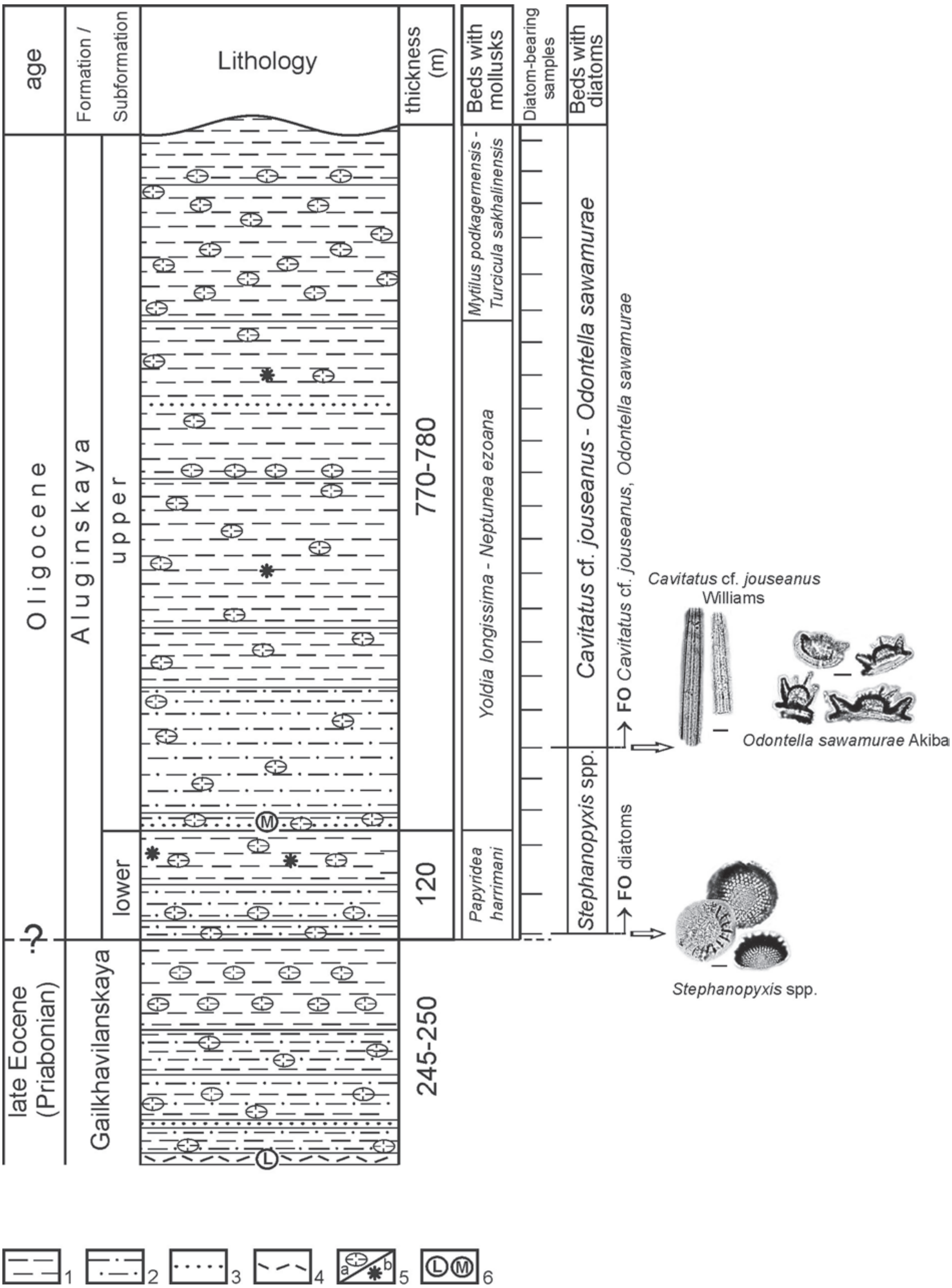

Fig. 5 Generalized stratigraphic column of the Aluginskaya Formation and underlying strata of the Il'pinskii Peninsula stratigraphic section, northeastern Kamchatka, with indicated position of diatom-bearing samples, and defined beds with diatoms and mollusks (modified from A. Gladenkov and Yu. Gladenkov, 2007)

Key: 1 - shale, tuffaceous shale. 2 - siltstone, tuffaceous siltstone. 3 - sandstone, tuffstone. 4 - silicic tuffs. 5 - carbonate concretions (a) and glendonites (b). 6 - Laparelamskii (L) and Mulatkhanskii (M) lithologic marker "horizons". FO - the first occurrence levels.

Scale bars for illustrated diatom specimens are 10 micrometers.

consists of series of diatom zones based on the successive first occurrences of planktonic marker-species. Biostratigraphic research in the region of the last decade demonstrates a real efficiency of the proposed zonation for dating and subdivision of the Oligocene and lower Miocene marine and onshore stratigraphic sequences in the middle to high latitudes of the North Pacific. Since sediments of this age essentially lack calcareous planktonic microfossils, diatoms represent the primary biostratigraphic tool for age determination and refined correlation of the Oligocene and lower Miocene marine sediments in this region. It has brought the Cenozoic stratigraphy of the region to a higher level. A new preliminary correlation scheme based on recent diatom data can be proposed for the North Pacific Oligocene and lower Miocene. The application and interpretation of diatom data are important in terms of direct correlations of fossils benthic assemblages and siliceous microplankton from onshore sequences, thus imparting certain indicative properties to benthic fauna.

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北太平洋地域における漸新統から下部中新統の最新珪藻化石層序

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要　旨

本論では現在の北太平洋地域における漸新統から下部中新統の珪藻化石層序と、加えて過去 10 ～ 15 年間に急速に進歩した内容を述べる。この北太平洋地域での過去 25 年間、特に深海掘削のコア分析に基づいて、漸新統から下部中新統の珪藻化石帯の確立とそれを用いた化石帯の認定が劇的に進歩した。これら珪藻化石帯を基本として、これを陸上域における堆積シークエンスへ適応していった過程があるので、それらの研究意義についても触れる。

北太平洋地域の漸新統から下部中新統は石灰質微化石の産出がまれで、珪藻に代表される珪質のプランクトン生物による生層序区分と年代・対比が最適の手段である。北太平洋地域の様々な堆積盆からの珪藻化石の層序的データを用いた統合的珪藻の生層序によって、漸新統から下部中新統の年代と対比にあらたな展開を見せている現状を紹介する。