Experience of Deep-Sea Drilling in the World Ocean: Methodical and Practical Significance for Stratigraphic Studies

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Abstract—The results of stratigraphic studies carried out in the process of international deep-sea drilling in the last fifty years are presented. They make a great contribution to development and improvement of the methods for detailed stratigraphic studies and dating of marine sedimentary sequences as well as reconstructions of past oceanological and climatic events. The results obtained are of great methodological importance for stratigraphic investigations of the whole Phanerozoic. The distinguished Cenozoic biostratigraphic zones can really be traced across the whole tropical and subtropical area. The study data on planktonic microorganism (calcareous and siliceous) assemblages which were an integral part of Mesozoic and Cenozoic marine ecosystems made a considerable contribution to these works. These assemblages developed over time against the background of variable oceanic circulation and sedimentation conditions, changes in deep and surface water productivity, water temperature, etc. In general, the evolution trend of biotic communities reflects the development and reorganization stages of the past ecosystems. All these data make it possible to reveal the real sequence of not only biotic but also abiotic events (climatic, oceanographic, and eustatic) in the World Ocean for the last 70–75 million years.

Keywords: deep-sea drilling, marine Cenozoic, detailed stratigraphy, microfossils, methodological and practical approaches, correlation, and paleoclimates

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INTRODUCTION

The history of stratigraphic research is marked, perhaps, by two international projects which have played a particularly important role in the development of stratigraphy as one of major branches of geology. The *first* project was implemented at the end of the nineteenth century. At that time, the task was set to create a geological map of Europe. To begin the practical solution thereof, geologists from different countries gathered together in 1878 at the First International Geological Congress (IGC) and organized a special commission to develop the International Stratigraphic Scale (ISS). The commission focused its attention on the creation of a universal stratigraphic classification and nomenclature, relying on the experience accumulated by that time in the stratigraphic work of European countries (Leonov, 1973; Menner, 1991). This work took more than 20 years, and the ISS was approved at the eighth session of the IGC in 1900; hence, the ISS celebrated its 120th anniversary in 2020. This very scale served as a basis for development of the geological map of Europe and, later, maps of individual regions of other continents and the world. This scale proposed a certain hierarchy of the main stratigraphic units (erathems, systems, and series)

which were used until the mid-1970s. And only in the 1970s were the stages added to it (previously they belonged to regional categories), which made the scale much more detailed. It is hard to overestimate the importance of the ISS as a global geological document. First of all, it is a remarkable geological generalization reflecting certain development stages of the Earth and its biosphere for over 4 billion years. On the other hand, it defined the methodological basis for the subdivision and correlation of ancient sequences in different regions. This scale was based on a historical–geological approach to the identification of stratigraphic units with an important role of the paleontological method in their substantiation. Finally, the ISS proved to be an indispensable tool for professional communication between geologists from around the world. About 120 years after creation, the ISS improved under the auspices of the International Commission on Stratigraphy still plays the most important role in all geological disciplines which are related to interpretation of the history of our planet.

The *second* important international geological project of the last century, which also had a great influence on the stratigraphic studies, was the Deep-Sea Drilling Project in the World Ocean, which is

known to occupy more than 70% of the planet's surface, but which remained extremely poorly studied in terms of geology by the middle of the twentieth century. The project was started in 1968, and its 50th anniversary was celebrated by the international scientific community in 2018. This gigantic geological experiment focused on the study of the seabed structure made it possible to obtain voluminous data on material composition and age of sedimentary cover deposits, as well as on the geological history of the oceans in general. To date, more than 3000 deep-sea cores were drilled in the seabed under the Deep-Sea Drilling Project (1968−1983), as well as under international programs such as the Ocean Drilling Program (1985−2003), Integrated Ocean Drilling Program (2004−2012), and International Ocean Discovery Program (2013 to date) (Fig. 1). Recent years were marked by major improvements in drilling and coring technologies, as well as by modernization and increase in the number of onboard drilling platforms. Today, these achievements enable the drilling with a high core recovery percentage in almost all regions of the World Ocean and in the variable-density rocks. The advanced technologies made it possible to reach a drilling depth of up to 1500 m and to carry out drilling at a sea depth of up to 4000 m. Moreover, the latest-generation Chikyu vessel built in Japan is generally capable of drilling holes down to 10000 m below sea level and over 2000 m below the seafloor. In 2012, it already drilled holes at a water depth of more than 6960 m as well as to a depth of 2111 m below the seafloor. Brief reviews containing useful information on the history, main results, and prospects of drilling in the oceans were given in the papers by I.A. Basov (2001), N.K. Rubanik (2008), and A.G. Matul (2010). A wide range of modern scientific and technical advances in deep-sea drilling is regularly covered in the *Scientific Drilling* specialized journal, which has been published since 2005.

It should be emphasized that these works were international: scientists from many countries of the world participated in the above-mentioned studies, and the obtained data are available to all interested specialists. These studies should be regarded as a tremendous scientific achievement not only in relation to the study of the seabed structure and geological history of the oceans but also for development and improvement of the methods of stratigraphic research. In addition, they provided the rich material to reconstruct geological events and changes in the natural settings of past eras. The choice and implementation of topical research lines finally yielded both the comprehensive scientific materials obtained by different expeditions and numerous regional summary reports (for example, *Geological...*, 1990; Kennett, 1982; Litvin, 1987; *Okeanologiya...*, 1980; *Plankton...*, 1985; *Productivity...*, 1989; Seibold and Berger, 1982; *The Miocene...*, 1985; Udintsev, 1987; etc.).

It should be noted that, until 1993, the Soviet and Russian specialists (including those involved in the stratigraphy field) were actively involved in both the scientific cruises of drilling vessels and the data processing. The stratigraphers included V.A. Krasheninnikov, I.A. Basov, A.P. Jousé, N.I. Strelnikova, M.G. Petrushevskaya, E.D. Zaklinskaya, N.G. Muzylev, V.V. Shilov, A.Yu. Gladenkov, and others. Unfortunately, then, owing to various reasons, such participation ceased, and Russia, unlike the Soviet Union, is not among the countries (currently 26) involved in the international deep-sea drilling program.

It should be specially noted that the core materials of all drilled boreholes are stored in several special depositories located in the United States, Germany, and Japan. They are available for study by scientists from different countries.

In this paper, we would like, taking into account the stratigraphic data obtained during the deep-sea drilling, to focus on the main methodological and practical approaches used in stratigraphic studies of the Paleogene and Neogene, which can be useful for solving the stratigraphic issues not only in the Cenozoic but also in other parts of the Phanerozoic scale such as the Mesozoic and Paleozoic.

METHODOLOGY OF BIOSTRATIGRAPHIC SUBDIVISION AND AGE DETERMINATION, AND CORRELATION OF MARINE SEDIMENTARY SEQUENCES IN THE OCEAN BOTTOM SECTIONS

Before the start of deep-sea drilling, the scientists' knowledge of material composition and structure of the ocean floor was relatively limited to the study of samples taken from the upper young sediment layer (up to a few meters thick) using bottom piston corers or by dredging of separate bottom sections.

The regular deep-sea drilling begun in the late 1960s made it possible to obtain the voluminous data on sections of ocean bottom sequences with a thickness of hundreds of meters, penetrated in various climatic zones and regions of the World Ocean. According to these data, sedimentary deposits of the ocean floor are mainly of Cenozoic age. Cretaceous and, occasionally, Jurassic sediments are noted less frequently; the most ancient Middle Jurassic sequences (more than 150 Ma) were uncovered in the marginal regions of the Pacific and Atlantic oceans. Sedimentary deposits overlie the oceanic basement usually composed of the Mesozoic volcanic rocks (basalts). The age of the most ancient (Bathonian−Callovian) sedimentary deposits was was determined using radiolarians radiolarians in the section exposed in the Pigafetta Basin, Western Pacific region (Matsuoka, 1992). Our analysis objective was the Cenozoic sequences.

Importance of Micropaleontological Data

The drilling carried out made it possible to obtain the data on undisturbed columns of samples in the
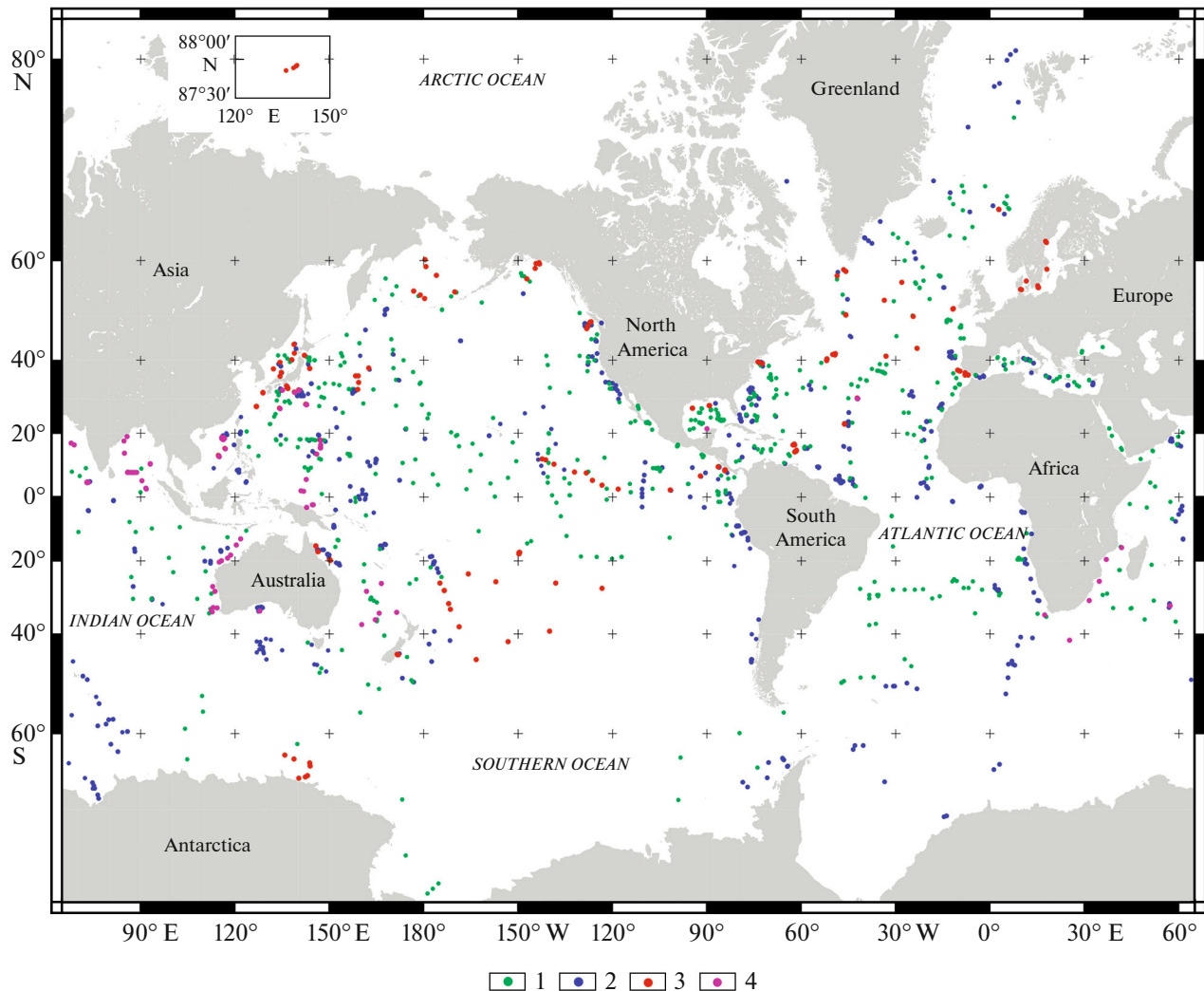
Fig. 1. Map of deep sites in the World Ocean (https://iodp.tamu.edu/scienceops/maps.html). (1−4) Deep-sea cores: (1) DSDP Legs 1-96; (2) ODP Legs 100-210; (*3*) Integrated Ocean Drilling Program (expeditions 301−348), (4) International Ocean Discovery Program (expeditions 349−371).

marine sedimentary successions (primarily, Cenozoic) composed of various-facies deposits with different thicknesses. The attempts to correlate these sequences at the ocean scale on the lithostratigraphic basis turned out to be untenable. The biostratigraphic method based on the study of the fossil microorganism sequence in the sections turned out to be the most effective. When studying the deep-sea core sections, it was revealed that the marine microorganism remains were almost everywhere in bottom sediments. They represented a whole ancient biota "world" earlier insufficiently studied. Microfossils began to be used for stratigraphic purposes as early as the first half of the twentieth century. However, the onshore sections sections of marine sediments studied at that time were not always complete and continuous and also contained predominantly shallow benthic organisms. Therefore, tracing of typical marine microbiota assemblages in them (with identification of marker-forms and their

stratigraphic ranges) and the corresponding correlations encountered great difficulties. In contrast to the sequences formed in the marginal oceanic and near-continental regions, the open ocean sediments are generally represented by rather laterally sustained facies composed mainly of biogenic sediments and deep-sea clays with a relatively small thickness. It was established during the paleontological data processing that the use of microfossils first of all gave the most effective results in the subdivision of the Cenozoic and Mesozoic sedimentary sequences.

The study of drilled sedimentary sequences, on one hand, made it possible to trace the successive stratigraphic change of microorganism assemblages in the relatively complete pelagic facies sections in different regions. On the other hand, the intervals of stratigraphic ranges and spatial distribution of many fossil forms (including those previously unknown in the

onshore sections) were estimated to determine their importance for biostratigraphic subdivision and correlation. The data on *microplanktonic* organisms are of the greatest interest, because they rapidly evolve and are widespread in geographic terms. It is important that the frequent occurrence of microfossils in the rocks and their distribution in sections without large hiatuses provide a layer-by-layer characterization of the studied deposits. For this reason, the study of microfossils ultimately enables the detailed subdivision and broad correlation of sedimentary sequences. The results were obtained from the studies of both carbonate microplankton (primarily planktonic foraminifera and calcareous nannofossils), especially characteristic of tropical and subtropical latitudes, and siliceous microplankton (diatoms and radiolarians), typical of the boreal and natal belts (although siliceous microorganisms also developed in the equatorial belt, where they occasionally could be even predominant in plankton). It should be specially noted that a great contribution to these studies was made by the improvement of microfossil identification equipment, in particular, the widespread practical use of electron microscopy since the 1970s. The advanced equipment made it possible to make significant progress in the study of ultrastructure and morphological features of skeletons, shells, and frustules, to identify new genera and species, and to revise the classification and taxonomy of different paleontological groups.

Zonal Units and Methodology of Their Establishing

It should be emphasized that, in many respects, it was the deep-sea drilling information which was used to develop the metodology to establish the stratigraphic units such as *biostratigraphic zones* with subsequent widespread introduction thereof into geological practice. Although, as is known, the first zonal Jurassic schemes based on ammonites were created in the middle of the nineteenth century by A. Oppel, many methodological mapping issues remained the matter of debate for many years (Stepanov and Mesezhnikov, 1979; Gladenkov, 2004, 2010). The study of Cenozoic fossil assemblages of various microorganisms in the deep-sea core sections in different oceans provided a real basis for the development of detailed oceanic schemes and scales as the *continuous successions* of zonal units. The developed scales consist of zones with an average duration of 1−2 to 0.1−0.2 m.y., which are distinguished taking into account the evolution stages of fossil microorganisms. It should be noted that, during the subdivision of oceanic sections, the method was developed to identify zones of various types. These types are described in detail in the International Stratigraphic Guide (International..., 1999) and the Stratigraphic Code of Russia (2019). As shown in practice, two or three types of biostratigraphic zones are of paramount importance for the division of sections. First of all, the assemblage zone and the interval zone should be noted (Fig. 2). *Assemblage zone* is the body of strata characterized by an assemblage of three or more fossil taxa, which is different from assemblages of the underlying and overlying strata. *Interval zone* is the body of strata which are enclosed between two identified biohorizons (first or last occurrence levels of any characteristic taxa). They are most often used in broad correlations. However, in practice, other types of zones are also used (concurrent-range zones, taxon-range zones, etc.), depending on the geological situation and paleontological material.

It should be specially noted that the boundaries of zones are drawn according to *datum levels* such as *datum planes*, first of all, according to the first and last occurrence levels of marking planktonic forms or taking them into account. On the basis of the accumulated experience, the most effective results in zone identification are achieved precisely through the analysis of stratigraphic distribution of individual species, less often, genera. Such a boundary determination method suggests that the zones often do not reflect major development stages of a particular group of organisms, while the zonal assemblages are not always consistance in the section. However, the use of such an approach when "combining" different types of zones makes it possible to establish detailed and continuous biostratigraphic subdivisions with relatively isochronous boundaries. The use of datum levels is a convenient practical tool, which, in fact, is primarily aimed precisely at identification of detailed biostratigraphic subdivisions and marking horizons. For example, this method was used to develop, with one of the authors of this paper involved, the North Pacific Oligocene to Quaternary diatom zonation which is correlated with the ISS and includes more than twenty zones (Fig. 3).

The taxa which meet certain requirements began to be selected as *index forms* to characterize zonal boundaries on the ocean scales. First of all, they include constant occurrence and wide area distribution of fossils and their definite and stable stratigraphic range. In the absence of any main criteria, the datum levels can occasionally be used as characteristic boundaries of subzones or local markers, which are not as stable as compared to the zonal ones.

This section is concluded with two comments. Firstly, it should be remembered that, when subdividing a section (core), we can distinguish a lot of biostratigraphic zones ("parallel" zones created according to different paleontological groups) often with mismatched boundaries (Fig. 4). Therefore, to use them in practice, we have to select one (two) of the zonal scales as a reference or "standard." Secondly, it should be borne in mind that the listed zones belong to the category of "*special*" (biostratigraphic) subdivisions in the Stratigraphic Code of Russia (2019). "Chronozones" are assigned in the code (some researchers call them "oppelzones") to the *major* units of the General Stratigraphic Scale, being complex substantiation sub-
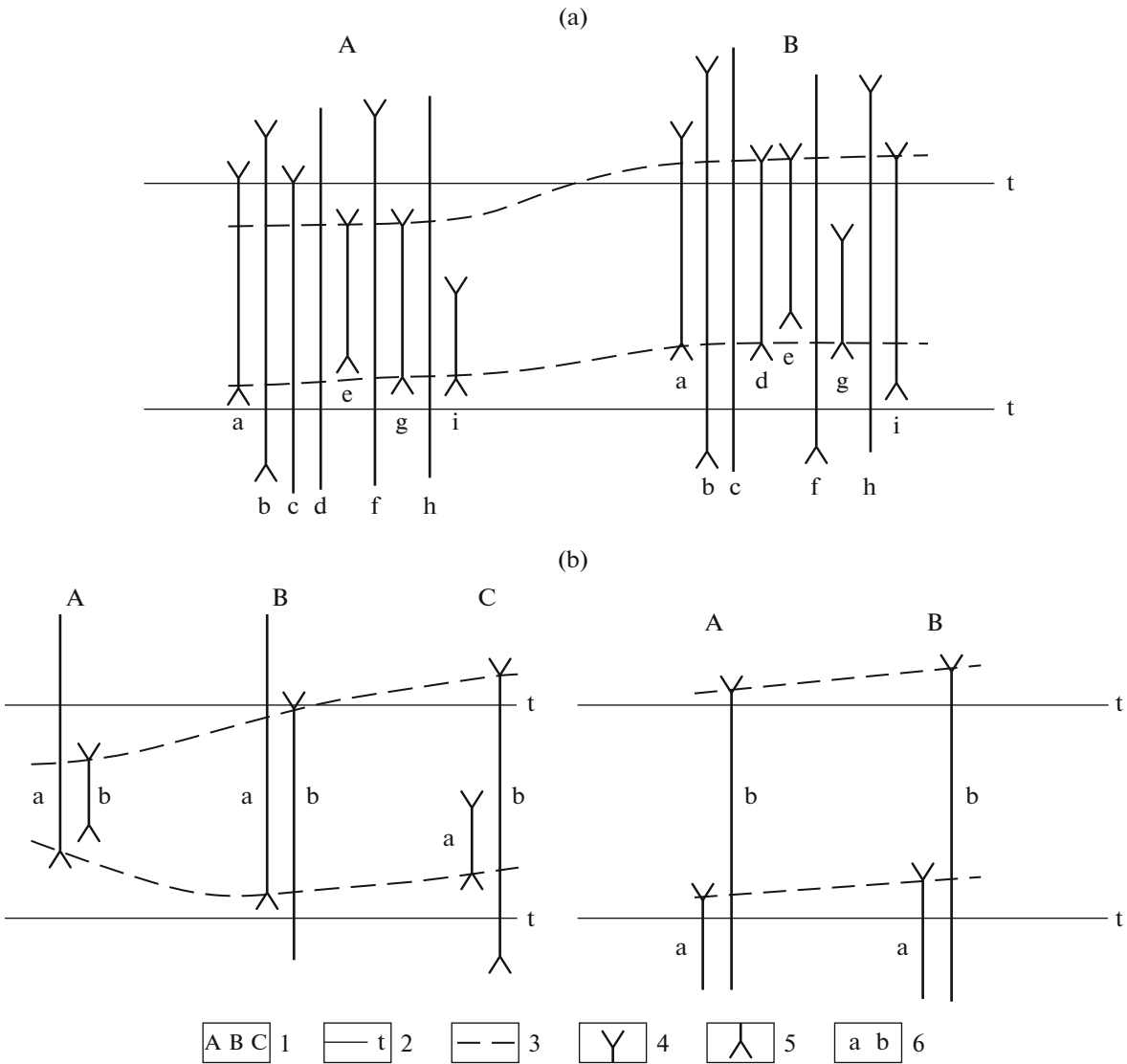
Fig. 2. (a) Assemblage zone and (b) interval zones (according to International..., 1999). (1) Stratigraphic sections, (2) time surface, (3) boundaries of interval zones, (4) highest occurrence of taxon in the specific section, (5) lowest occurrence of taxon in the specific section, (6) taxa.

divisions and more detailed than the stage. Although the chronozones are established from the biostratigraphic data, they can include sediments with a fossil assemblage which differs from the zonal one, or without it if the same age of the compared sediments is proven. However, it should be noted that, in the latest International Stratigraphic Guide (Reference) (International..., 1999), the chronozone is considered as a subdivision of indefinite rank not included in the hierarchy of generally accepted chronostratigraphic units. In some cases, incomplete sections complicate the identification of a full biostratigraphic zone, and the researchers have to turn to "*teilzones*," i.e., the layers corresponding to the real distribution of any taxon (or their group) in the specific section of a particular area.

Age of Zones and Integration of Data Obtained by Different Methods

When establishing the zones of oceanic scales, a number of practical questions arise: how to determine their age and how to set age position of datum levels. In this respect, the method which can help is the correlation of the zones identified in ocean sediments with the zones detected in stratotypes of onshore sections, especially if these stratotypes were dated on the basis of their age characteristics as different geochronological levels (for example, according to magnetostratigraphic or radiological determinations). In this case, the problem is to make the correct correlations.

As for the age of datum levels, it is determined in the oceanic sections, first of all, by paleomagnetism data and radiological dating. In many cases, in the
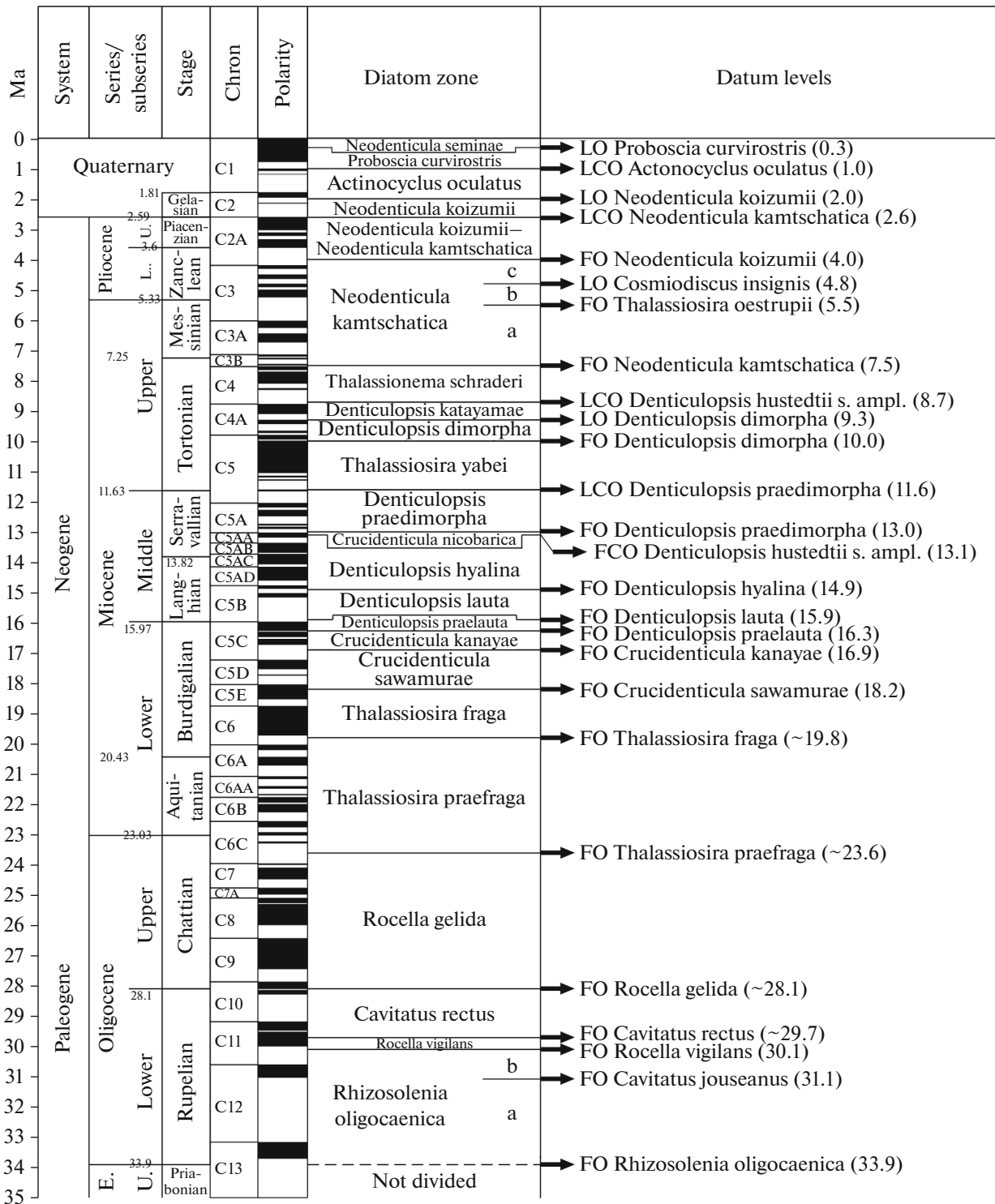
Fig. 3. The North Pacific Oligocene to Quaternary diatom zonation (after Barron and Gladenkov, 1995; Gladenkov, 2007), correlated to the geochronological and geomagnetic polarity time scales according to (Ogg et al., 2016). (FO) First occurrence level, (LO) last occurrence level, (FCO) first common occurrence level, (LCO) last common occurrence level, (a–c) subzones, (E.) Eocene, (U.) Upper.

deep-sea core sections, the zone boundaries were correlated directly with the Geomagnetic Polarity Time Scale. This method made it possible not only to date boudaries of zones and to determine the "duration" of zones but also to directly compare them with the ISS (*A Geologic*..., 2004; Berggren et al., 1995; *Geologic*..., 2020; Ogg et al., 2016; *The Geologic*..., 2012). The identification of subdivisions in the modern Cenozoic
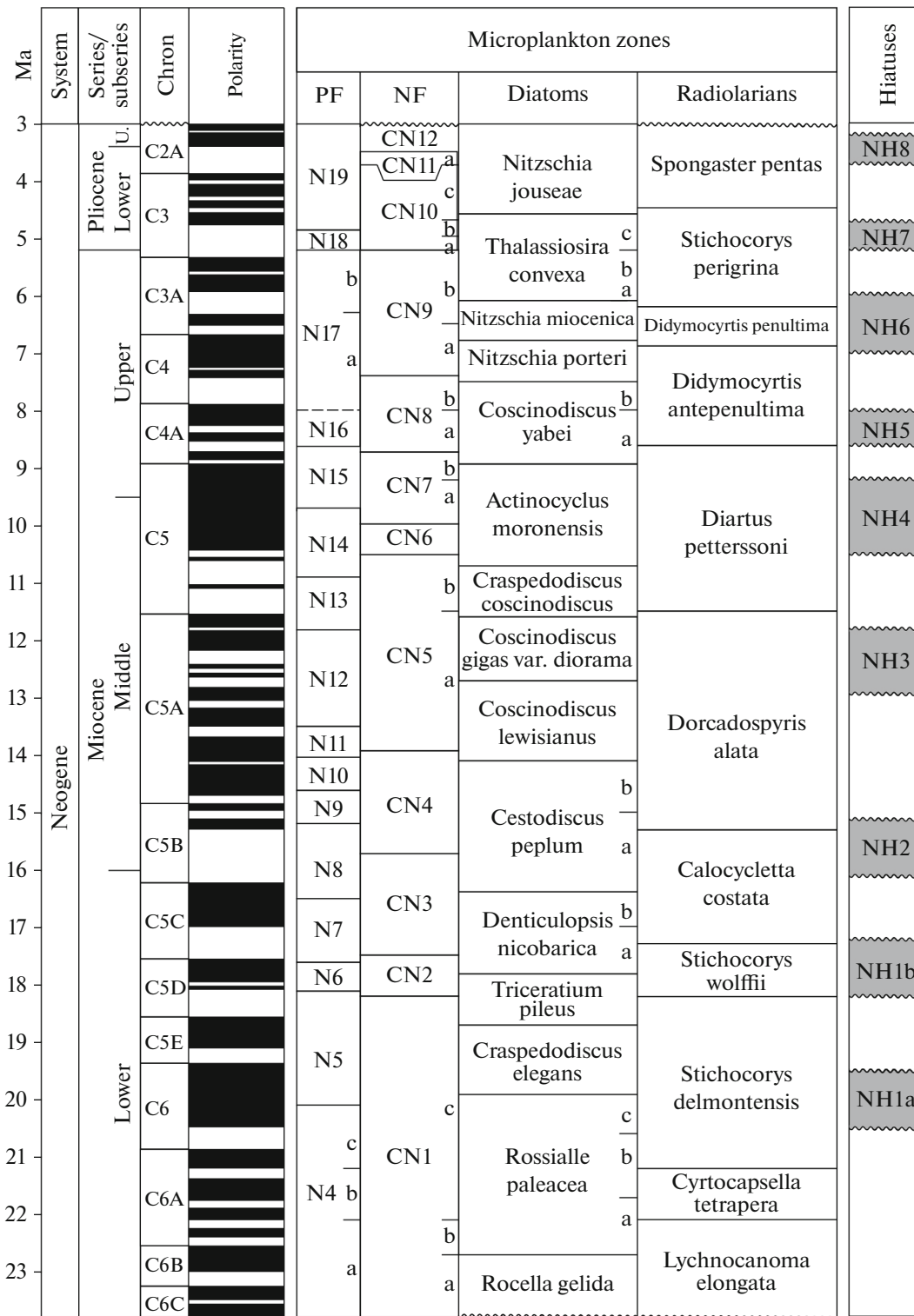
Fig. 4. Correlation of the Lower Miocene to Pliocene zones based on different microplankton groups of low latitudes with the paleomagnetic time scale (correlated with the magnetic polarity scale) and hiatuses identified in the Neogene ocean sediments (after Keller and Barron, 1983, 1987, simplified). (PF) Planktonic foraminifera, (NF) calcareous nannofossils, (a−c) subzones.

geomagnetic polarity time scales (paleomagnetic chrones, subchrones, forward and reverse polarity episodes) and dating thereof are based primarily on the analysis of magnetic profiles in the study of magnetic anomalies in the ocean spreading zones, first of all, in the South Atlantic region (*Geologic...*, 2020; Cande and Kent, 1992, 1995; *The Geologic...*, 2012). Figures 5 and 6 show illustrative examples of the biostratigraphic

zones (based on diatoms) correlated to the magneto-stratigraphic scale in the Oligocene−Quaternary interval, on one hand, in the tropical−subtropical region and, on the other hand, in the southern high latitudes (these data were obtained by drilling in these regions).

Along with that, it is worth paying attention to the obtained estimated duration of intervals between the datum planes. They often reach a degree of detail which is impressive for the Phanerozoic (as small as hundreds of thousands of years or even less). As an example, Table 1 shows the dating of biostratigraphic levels (biohorizons) based on diatoms taking into account the drilling data on the North Pacific region. The geological practice likely did not achieve such detailed division of the Phanerozoic sections earlier (probably only small Jurassic biostratigraphic units identified in certain regions of Europe based on ammonites (Page, 2003) are close to such accuracy; meanwhile, these subdivisions are hardly provided with paleomagnetic and radiological characteristics to the same extent as the Cenozoic zones of oceanic scales).

It should also be noted that the absence of a complete "set" of established zones in a number of bottom sediment sections makes it possible to identify either erosion of individual layers or sedimentation hiatuses with the determination of their duration. One of the impressive examples of the studies related to dating and spatial distribution of the identified hiatus in the Neogene oceanic sediments is the work carried out on the basis of the planktonic microorganism data (Keller and Barron, 1983, 1987). Along with that, the analysis of the distribution of eight identified hiatuses (Fig. 4) allowed the authors to approach the identification of major paleooceanographic and paleoclimatic rearrangements in the Neogene with the stages of changes in sedimentation, biogeographic distribution, and productivity of planktonic assemblages.

Features and Possibilities of Using the Biostratigraphic Zones on a Global and Regional Scale

The results obtained in the study of deep-sea drilling data made it possible for the first time to show the zone tracing potential using various microplankton groups within the vast regions of the World Ocean. First of all, a striking example is the Cenozoic zones based on planktonic foraminifera (Berggren et al., 1995; Berggren and Pearson, 2005; Wade et al., 2011) and calcareous nannofossils (Agnini et al., 2014; Bukry, 1973, 1975; Okada and Bukry, 1980; Raffi et al., 2016) identified in the holes drilled in low latitudes. It should be noted that the zonal scales were developed taking into account the biostratigraphic data obtained earlier for various microfossil groups, primarily, planktonic foraminifers and nannofossils, from the most representative and paleontologically well-characterized sections on land (Bandy, 1964; Berggren, 1969; Blow, 1969; Bolli, 1966; Bramlette

and Riedel, 1954; Hay et al., 1967; Krasheninnikov, 1969; Martini, 1971; Morozova, 1959; Shutskaya, 1970; Subbotina, 1960; etc.).

Meanwhile, the data obtained are indicative of the fact that there are no *global* microplankton zones for the entire Cenozoic in the strict sense. In general, subglobal biostratigraphic units can include, for example, the zones based on the Paleocene−Eocene planktonic foraminifers (Fig. 7) (the warming period marked by expansion of warm-water carbonate plankton areas from tropical to arctic−boreal and natal latitudes). Cosmopolitan forms are typical of the zoo- and phytoplankton assemblages which characterize the zones of this age. However, starting from the Oligocene, characterized by global cooling and latitudinal climatic zoning close to the recent conditions, the micropaleontological assemblages of low, middle, and high latitudes began to differ markedly. Therefore, different zonal scales are used within them with a variable number of zones whose boundaries are often set according to various species (Fig. 8). Zonal assemblages of different latitudes can be drastically different in taxa, and different forms are often chosen as datum levels. Owing to the fact that carbonate plankton fossils are rare or absent in the high-latitude sedimentary sequences with an age younger than the Eocene, the siliceous microorganisms are used as main tools for biostratigraphic division and age determination purposes.

It should be emphasized that the datum planes of the same stratigraphically important species during the transition from one latitudinal region to another can turn out to be diachronic, thus preventing the correct correlation of sections of different climatic zones. There should be focus on this problem, because in a number of cases, under the "hypnosis" of studying the zones in one section, the researchers "straighten" the zonal boundaries in other sections, neglecting the "straightening" tolerance. Owing to the fact that the *full* stratigraphic interval of markers should be taken into account when drawing the zone boundaries (in particular, based on plankton), it is necessary to use the oldest available dating level when assessing the age of first occurrence of taxa (and vice versa, the level with the youngest date should be used when determining the age of last occurrence of taxa). In this case, the "spread" of age dates at any level selected as a zonal boundary characteristic should not exceed the required accuracy limits. Therefore, in specific situations, it is necessary to focus on the fact that the available tolerance or "gap" is an exactly minimum part of the zonal interval. This is a reason why it is of great importance both to study fossil assemblages in a wide range of sections and to use other control paleontological groups, as well as to analyze various markers (paleomagnetic, isotopic, lithological, etc.), when drawing the boundaries.

However, despite certain complications, the creation of subglobal ocean zonal scales of the Cenozoic,
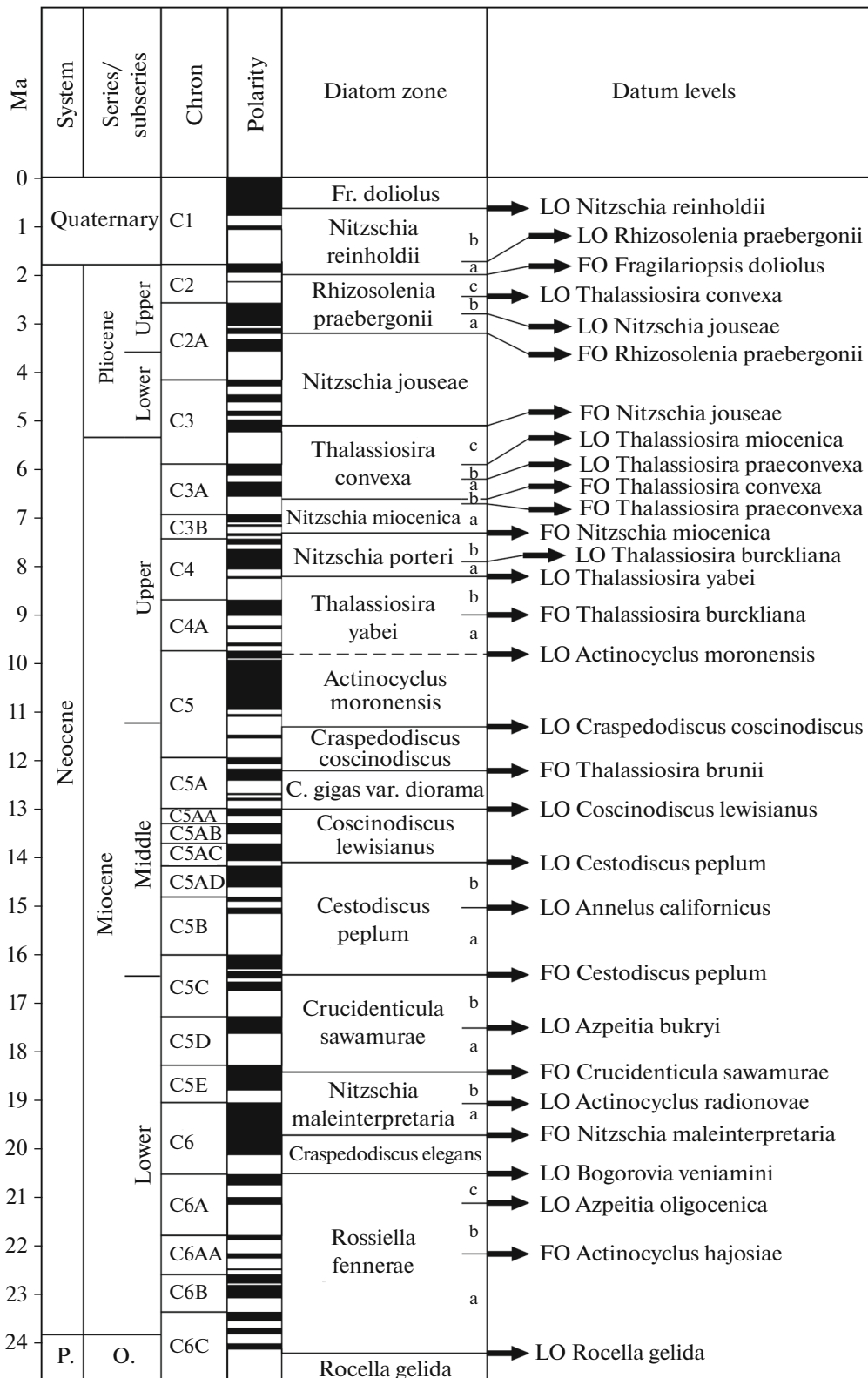
Fig. 5. The low latitudes Neogene to Quaternary oceanic diatom zonation correlated with paleomagnetic time scale by Cande and Kent (1992, 1995) (after Barron, 2003, 2005, simplified). (FO) First occurrence level, (LO) last occurrence level, (a–c) subzones, (P.) Paleogene, (O.) Oligocene, (C.) *Coscinodiscus*, (Fr.) *Fragilariopsis*.
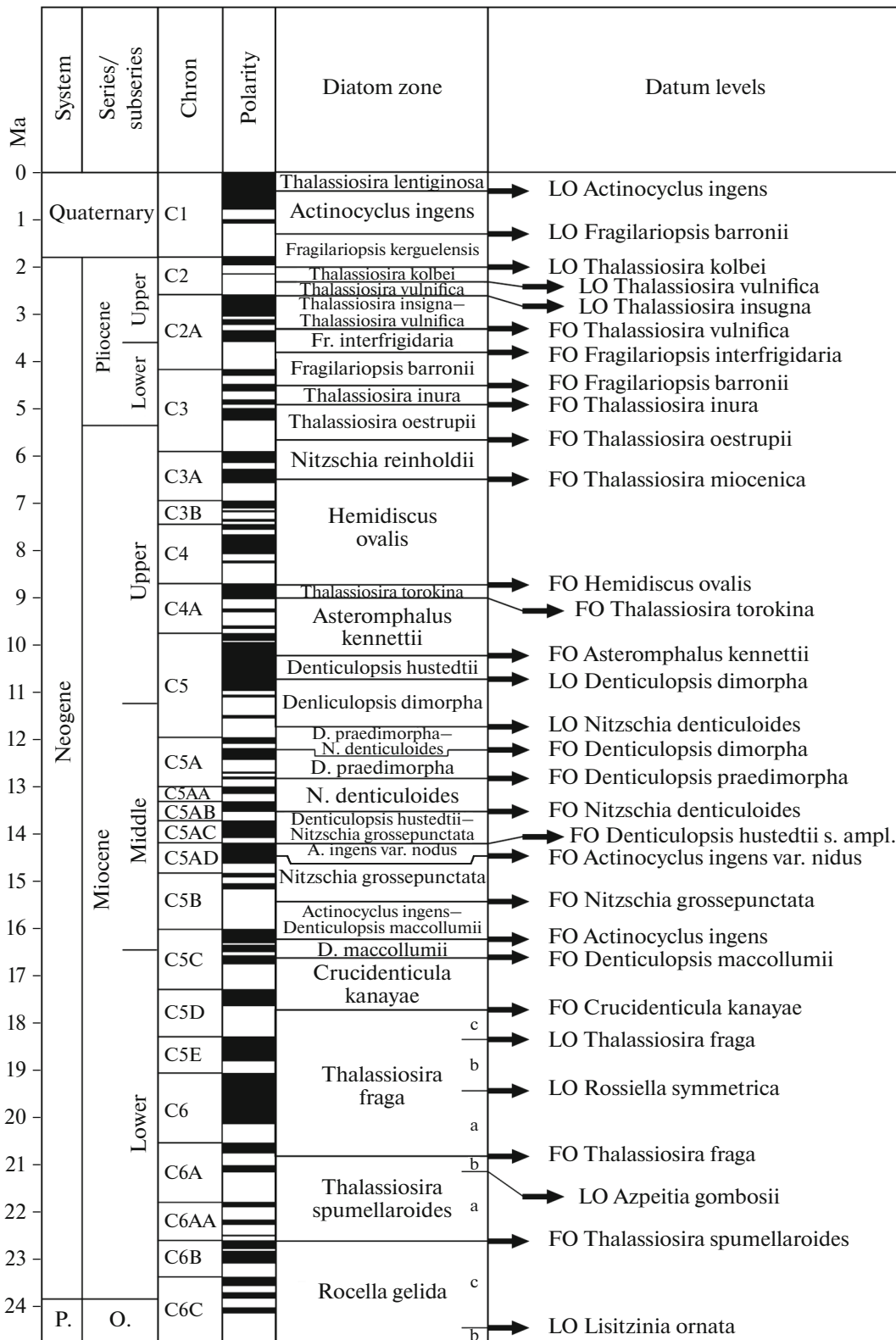
Fig. 6. The southern high latitudes Neogene to Quaternary oceanic diatom zonation correlated with paleomagnetic time scale by Cande and Kent (1992, 1995) (after Barron, 2003; Harwood and Maruyama, 1992, simplified). (Fr.) *Fragilariopsis*, (N.) *Nitzschia*, (D.) *Denticulopsis*, (A.) *Actinocyclus*; see other abbreviations in Fig. 5.

Table 1. The age of the stratigraphically important Neogene−Quaternary datum levels based on diatoms determined by direct correlation with the magnetostratigraphic record in the deep-sea core sections in the Subarctic Pacific region (after Barron and Gladenkov, 1995, with additions)

Datum levels	Age, Ma
FO Crucidenticula sawamurae	18.2
FO Crucidenticula kanayae	16.9
FO Denticulopsis praelauta	16.3
FO Denticulopsis lauta	15.9
FO Actinocycluus ingens var. nodus	15.8
FO Denticulopsis hyalina	14.9
FO Denticulopsis hustedtii s. ampl.	14.6
FCO Denticulopsis hustedtii s. ampl.	13.1
FO Denticulopsis praedimorpha	13.0
FO Proboscia barboi	12.6
LCO Denticulopsis praedimorpha	11.6
LO Mediaria splendida	11.0
FO Denticulopsis dimorpha	10.0
FO Thalassionema schraderi	9.6
LCO Denticulopsis katayamae	9.4
LO Denticulopsis dimorpha	9.3
LCO Denticulopsis hustedtii s. ampl.	8.7
FO Thalassiosira gravida	8.2
FO Pyxidicula zabelinae	8.0
LCO Thalassionema schraderi	7.7
FO Neodenticula kamtschatica	7.5
LO Cavitatus jouseanus	6.7
FO Thalassiosira praeoestrupii	6.2
LO Rouxia californica	6.0
LO Ikebea tenuis	5.5
FO Thalassiosira oestrupii	5.5
FO Thalassiosira jacksonii (plicate)	5.2
FO Thalassiosira latimarginata	5.1
LO Cosmiodiscus insignis	4.8
LO Thalassiosira jacksonii (plicate)	4.8
FO Neodenticula koizumii	4.0
LCO Neodenticula kamtschatica	2.6
LO Pyxidicula zabelinae	2.0
LO Neodenticula koizumii	2.0
LCO Actinocyclus oculatus	1.0
LO Proboscia curviristris	0.3

(FO) first occurrence level, (LO) last occurrence level, (FCO) first common occurrence level, and (LCO) last common occurrence level.

as well as scales for large ocean segments (for example, for northern part of the Pacific Ocean or high southern latitudes) based on the data obtained under the International Deep Sea Drilling, seems to be one of the most important achievements of geology in recent decades. It is now generally accepted that the biostra-

tigraphic zones of the tropical belt can be traced in all three oceans, the Pacific, Atlantic, and Indian, indeed, on a subglobal scale. They serve as the basis for corrections to estimated stages in the ISS Cenozoic stratotypes identified in the onshore sections. Today, almost all boundaries of the Paleogene and Neogene
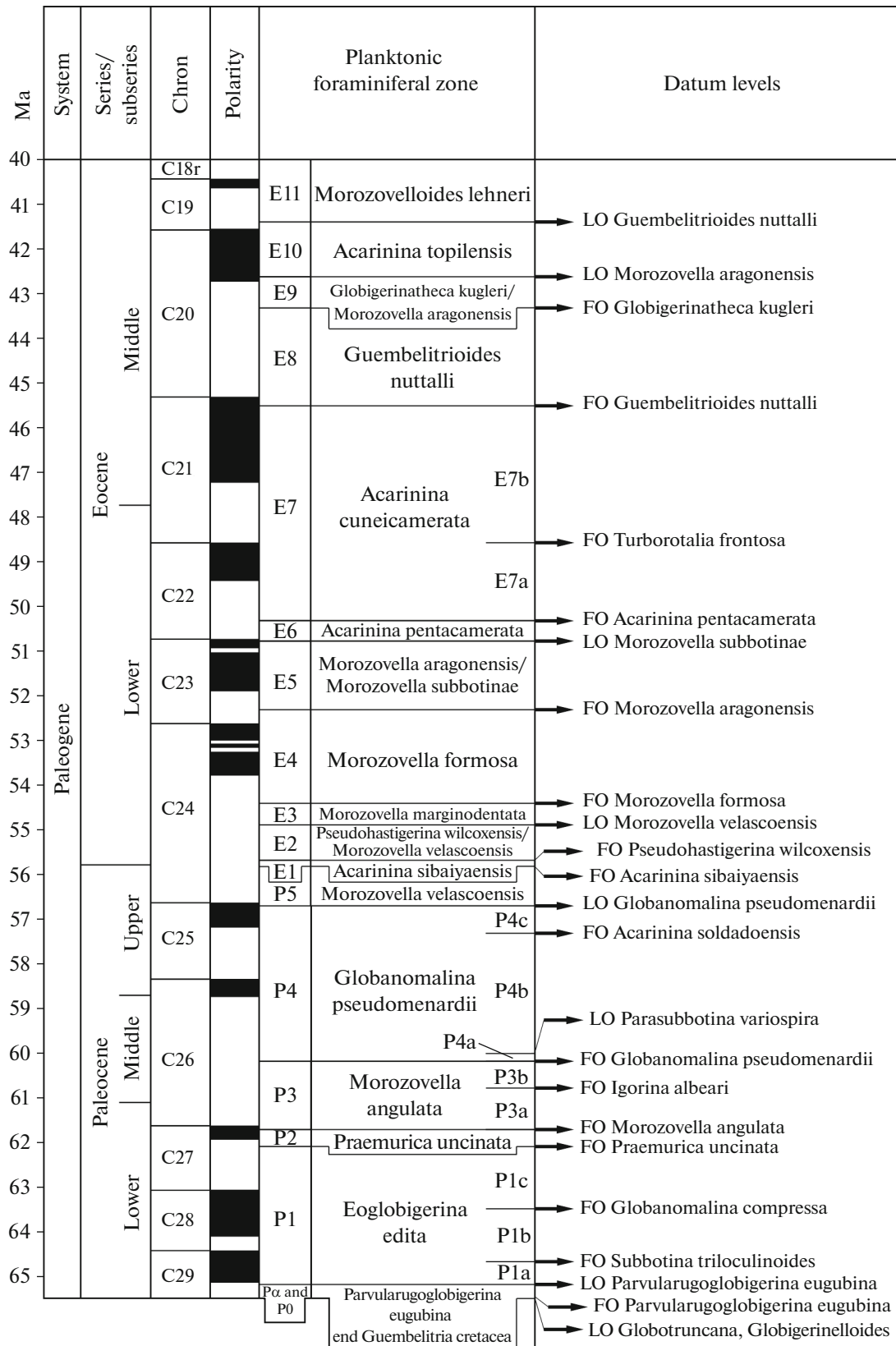
Fig. 7. Paleocene to Eocene planktonic foraminiferal zonation correlated with paleomagnetic time scale *A Geologic Time Scale 2004* (after Wade et al., 2011, simplified). (a–c) Subzones. See abbreviations in Fig. 5.

Ma	Chron	Polarity	Series/subseries	Stage	(Sub)tropical Berggren et al. (1995)		Blow (1969)	Transitional Berggren et al. (1983, 1995)		(Sub)antarctic Berggren (1992)	
	C5AD		Middle / Ser.		M7	Globorotalia peripheroacuta	N10	Mt6	Orbulina suturalis/ Globorotalia peripheroronda		
15	C5B			Langhian	M6	Gl. peripheroronda	N9				
16					M5 b	Praeorbulina sicana– Orbulina suturalis	N8	Mt5 b	Praeorbulina sicana– Orbulina suturalis	AN4	Globorotalia miozea
					a			a			
17	C5C		Lower	Burdigalian	M4 b	Catapsydrax dissimilis– Praeorbulina sicana	N7	Mt4	Gl. miozea		
					a			Mt3	Globorotalia praescitula– Globorotalia miozea	AN3	Globorotalia praescitula
18	C5D				M3	Globigerinatella insueta– Catapsydrax dissimilis	N6				
19	C5E										
20	C6				M2	Catapsydrax dissimilis	N5	Mt2	Globorotalia incognita– Globorotalia semivera	AN2	Globorotalia incognita
21	C6A										
22	C6AA			Aquitanian	M1 b	Globorotalia kugleri	N4	Mt1 b	Globorotalia kugleri	AN1	Globorotalia brazieri
23	C6B				a			a			
24	C6C		Ol. U.	Chattian	P22	Globigerina ciperoensis	P22	P22	Globigerina ciperoensis	AP16	Globigerina euapertura

Fig. 8. Lower to Middle Miocene planktonic foraminiferal zonations in different climatic latitudinal zones (after Berggren et al., 1995, simplified). (Ol.) Oligocene, (U.) Upper, (Ser.) Serravallian, (a–b) subzones.

stages in the stratotype sections of Western Europe are dated largely with the help of the carbonate plankton assemblages compared with the assemblages of ocean zonal scales.

Along with that, one more circumstance follows from the deep-sea drilling data. The Cenozoic zones marked in one ocean (for example, Pacific) do not *always exactly* coincide with the zones of another ocean (Atlantic or Indian). In other words, the paleontological characteristics and stratigraphic distribution of a number of individual Cenozoic zones used within one ocean (for example, low latitudes of the Pacific Ocean) do not always exactly coincide with those of the same latitudes in another ocean (low latitudes of the Atlantic Ocean) (for example, Agnini et al., 2014, Berggren et al., 1995; Wade et al., 2011). This is likely due to certain differences in water masses of large ecosystems such as the oceans. This fact is clearly established in the course of the detailed analysis of fossil bioassemblages and means that the ocean

waters were not uniform in all aspects in different regions and parts of the oceans. In addition, it is necessary to take into account different roles of many biotic and abiotic factors affecting the formation of paleocomplexes (evolutionary transformations, competitive relationships of taxa in biotic communities, activity of currents, water chemical composition, processes affecting the preservation of microorganism remains upon descending to the seabed, their burial in sediments, and fossilization in sedimentary rocks, etc.). It is also appropriate to take notice of cases of a specific peculiarity of biotic assemblages observed in various regions of the oceans (in particular, in their margins and in epicontinental basins characterized, in addition to latitudinal zoning, by circumcontinental zoning) and consisting in the first occurrence of individual *endemics*, *subspecies*, and *morphotypes* and the disappearance of some forms typical of other water areas. In practice, this fact suggests the appearance of *provincialism*, which was likely also characteristic of the Paleozoic and Mesozoic sea basins.

According to the practical experience, the developed zonal scales based on various plankton groups can also be used successfully for dating, subdivision, and correlation of sequences and onland sections. The study of micropaleontological assemblages and correlation thereof with assemblages of zonal scales in such sections in many cases made it possible to carry out a detailed division of the Cenozoic sequences and to revise or clarify the age of various suites , formations, and regional stages. In the shelf sections, it is often fairly difficult to trace the zones identified in the ocean sequences in their entirety and to recognize their boundaries. In such sections, ocean facies containing "reference" zonal paleontological assemblages are observed only in ideal cases. As a result, this leads to discontinuity of zones in relatively shallow marine facies. In addition here, the first and last occurrence levels of stratigraphically important taxa can be inconsistent with their actual occurrence and extinction levels. Moreover, during the transition from oceanic to shallower sediments, the number of typical ocean species decreases (until their absence) in the assemblages, and the forms characteristic of coastal waters begin to dominate. Therefore, regional or local biostratigraphic units (characterized mainly by relatively shallow-water assemblages) are often distinguished and then correlated with oceanic zones.

USE OF DEEP-SEA DRILLING DATA IN RECONSTRUCTION OF PAST CONDITIONS AND PARAMETERS OF THE ENVIRONMENT

The processing of deep-sea drilling data not only made an important contribution to the development of methods and techniques of zonal biostratigraphic division and reasonable dating of the Cenozoic sea sequences but also made it possible to obtain a huge array of new data which were very important for reconstructing the past parameters of the environment and tracing the changes in ocean circulation, climate, and sedimentation, as well as identifying the features of development of ancient marine biota.

Cenozoic Paleooceanology and Paleoclimate Based on the Isotopic Composition Analysis Data on Fossil Foraminifera Shells

The study of quantitative changes in oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopic composition in the shells of deep-sea benthic foraminifera from the Cenozoic sections of deep-sea holes drilled in the World Ocean is highly valuable for paleoclimatic and paleooceanological reconstructions. The $\delta^{18}O$ data are used to assess the rate and scale of changes in temperature of deep ocean waters over time, as well as the continental ice volume. The formation of deep-sea waters is mainly related to the cooling and declining in sea waters temperatures in the polar regions; their temperatures

simultaneously reflect those of surface waters in high latitudes (Kennett, 1982; Zachos et al., 2001; etc.). The method used to determine the ratio of heavy and light oxygen isotopes in the benthic foraminifera shells consisting of calcium carbonate is the main tool for reconstructing the absolute paleotemperatures in deep waters (the higher the $\delta^{18}O$ value, the lower the temperatures, because foraminiferal shells are enriched in the light oxygen isotope under warming and in the heavy isotope under cooling). In addition, this method makes it possible to obtain information on temperature gradients of the paleoenvironment and variations in the composition of sea waters. On the other hand, the analysis of the carbon isotopic composition ($\delta^{13}C$) of benthic foraminifer shells provides valuable information on nutrient flow and major changes in the cycle of these substances and carbon dioxide in the ocean depths. This method is based on the estimation of rare stable/common carbon isotopes in shells and is generally carried out in parallel with the oxygen isotope analysis.

As already mentioned, the ranges of sections were uncovered in deep-sea holes drilled in different climatic zones. These sections were composed of almost continuous sedimentary sequences accumulated in various Cenozoic intervals. The use of modern techniques made it possible to carry out a detailed analysis of records of high-resolution $\delta^{18}O$ and $\delta^{13}C$ variation. For the first time, the researchers managed to accumulate a large array of isotopic data hardly imaginable earlier. It became possible to identify the climate change intervals, to determine the climatic rearrangement rate and scale, and also to draw conclusions about their impact on the ocean circulation regime and past environmental conditions (Cramer et al., 2009; Miller et al., 1987, 1991; Zachos et al., 2001, 2008; etc.). A more detailed description of the results obtained is given below. The data based on the studies of thousands of samples from ocean sequences were not available before the start of deep-sea drilling. They made it possible to interpret in a new way many features of paleoclimatic and paleooceanological environments.

According to the reconstructions based on the isotope method, at the beginning of the Cenozoic, in the first half of the Paleocene, the Earth as a whole was dominated by the equally warm and even climate with small temperature gradients between the equator and the poles. The ocean thermal structure was relatively homogeneous with a bottom water temperature of about +8°C. There were no steep meridional thermal gradients, and the tropical zones were wider than the recent ones. Therefore, the ocean was characterized by the latitudinal warm-water circulation. The bottom water circulation and temperature were generally dependent on salinity rather than thermal stratification. The mid-Paleocene (about 59 Ma) was marked by a distinct global warming trend with a duration of

~10 m.y. At the end of the Paleocene (about 56 Ma), the bottom water temperature increased by more than 5°C. This short-term interval (~170 k.y. in duration) is called the Paleocene–Eocene Thermal Maximum (PETM). The warming continued in the Early Eocene, reaching the maximum about 50 Ma (Early Eocene Climatic Optimum = EECO). According to the data obtained, the Early Eocene climate (53–50 Ma) was the *warmest throughout the Cenozoic*, with a bottom water temperature of +10°C and more; about 50 Ma, the temperature of deep waters reached +14°C. This warming led to a further decrease in temperature gradients between the circumpolar and subequatorial regions.

After the temperature peak, at the very end of the Early Eocene (about 49 Ma), according to the oxygen isotope ratio, the beginning of the global Cenozoic cooling trend was recorded in the oceans; it characterized the Earth's history over the past 50 m.y. This climatic trend, however, was complex and heterogeneous in nature: falling temperatures of water bodies alternated with stable conditions and relative warming intervals. For example, the most distinct warming against the background of the global cooling trend in the Middle Eocene was recorded in the range of ~40.6–40.0 Ma (Middle Eocene Climatic Optimum = MECO) with a peak about 40 Ma, when the bottom water temperatures reached +8°C. Meanwhile, the Middle and Late Eocene was characterized by a greater contrast between water temperatures of low and high latitudes because of the drop in temperatures of the latter as a result of the cooling. A decrease in temperature in the near-polar regions led to the formation of colder bottom waters. Bottom waters differed from surface waters in the fact that, after formation and spreading in the horizontal direction, they changed just slightly over vast oceanic spaces. For this reason, their penetration toward the equator could have deepened the temperature contrast between surface and bottom waters at low and middle latitudes and also increased the latitudinal thermal gradient. An increase in the vertical temperature gradient resulted in a thermocline which caused the "separation" of surface and deep waters, thus preventing the latter from rising to the surface. It is interesting to note that, according to the deep-sea drilling data obtained in the Antarctic eastern coast (Barron et al., 1991), glaciation on the East Antarctica coast and sea ice accumulation on its shelf could probably have taken place already at the end of the Middle Eocene (about 39 Ma).

However, as evidenced by the oxygen isotope ratio, the most outstanding event occurred near the Eocene and Oligocene boundary (~34 Ma). At that time, the temperature of bottom waters in the World Ocean and surface waters in the southern circumpolar region dropped (Oligocene oxygen isotope event *Oi-1*). Abundant evidence suggests that the beginning of the extensive glaciation of Antarctic region and sea ice accumulation on its shelf margin dates back to this time. In the shallow areas adjacent to the Antarctic region,

low-temperature dense Antarctic bottom waters spread to the north owing to the normal-salinity surface water cooling and lowering. This outflow was compensated by the rise of less dense circumpolar deep waters which formed the Antarctic divergence zone with a higher biological productivity. Therefore, the analysis of isotopic composition of benthic foraminifer shells in these regions provides information not only on glacier volume and bottom water composition and temperature but also on near-polar surface water temperature. Thus, the formation of cold bottom waters during the cooling peak at the very beginning of the Early Oligocene led to the cryosphere formation in the high latitudes of the Southern Hemisphere and to the *psychrosphere* formation in the ocean depths, i.e., to changes in the entire temperature regime of the planet (so-called "greenhouse" regime was replaced by "ice house"). The advanced influence of the polar regions on the global ocean circulation and the climate regime in general by the beginning of the Oligocene led to changes in the general ocean circulation and climate. Enhanced thermal gradients between high and low latitudes due to high-latitude cooling enhanced the vertical and surface ocean circulation. Well-defined thermal gradients in the water column caused changes in surface water characteristics and circulation and also surface current intensification. The predominantly latitudinal warm-water circulation at all depths, generally characteristic of the World Ocean in the Early Paleogene, was replaced mainly by the meridional thermohaline cold-water circulation. Enhanced thermal gradients between high and low latitudes due to high-latitude cooling intensified the vertical and surface ocean circulation. This process, in turn, led to a greater activity of coastal and trade winds followed by coastal and equatorial *upwellings*. The ocean circulation variations were especially pronounced in high southern latitudes, where a circumpolar silica accumulation belt appeared at the beginning of the Oligocene; this belt demonstrated a vast uplifting zone of deep nutrient-rich waters. The thermal barriers in high southern latitudes as Antarctic and subtropical convergence zones became the main biogeographic barriers affecting the distribution of planktonic organisms.

The general trend of the global Cenozoic cooling was complex and heterogeneous over the past 50 m.y. Although the climatic and oceanographic changes at the end of the Middle Eocene led to some increase in the latitudinal temperature gradient and contrast between deep and surface waters, the major restructuring of ocean circulation and climate took place near the Eocene and Oligocene boundary. It was at this time when the hiatus of the Early Paleogene general circulation and temperature balance caused the psychrosphere and cryosphere formation and the beginning of the planet's transition from the general "greenhouse" temperature regime to the "glacial" conditions. However, these changes did not immediately lead to the recent latitudinal zoning with the lowest

temperatures at high latitudes in comparison with the previous epochs. Starting from the Oligocene, sudden drops in temperature alternated with stable conditions and relative warming periods. The largest scale warming with a higher temperature of deep waters was noted at the end of the Oligocene and Middle Miocene (the Miocene Climatic Optimum between the Early and Middle Miocene). In general, the oxygen isotope analysis results are indicative of the fact that water temperatures in the circumpolar regions until the end of the Middle Miocene (beginning of the gradual cooling) remained several degrees higher compared with the recent ones, while permanent continental ice did not exist. The East Antarctic region was covered by permanent ice only since the end of the Middle Miocene, whereas the West Antarctic glaciation was formed since the beginning of the Pliocene. The continental glaciation of the Northern Hemisphere began in the Middle Pliocene. Hence, at the beginning of the Early Oligocene, the tropical and subtropical zones were wider than the recent ones. The Earth's climate was milder than the recent conditions, glaciation of the high southern latitudes was not permanent, and water temperatures in these regions were not as low as they are now. However, despite this fact, the psychrosphere formation and thermal water stratification were *irreversible*. These conditions, along with the global ocean circulation changes, were of decisive importance for changes in development and distribution of both planktonic organisms and oceanic biota as a whole. In general, the Cenozoic paleoclimatic evolution had three main features: (1) a general decrease in temperature since the end of the Early Eocene; (2) dramatic cooling in high latitudes and slight cooling in tropical latitudes; (3) not gradual, but jumplike cooling (Zachos et al., 2001) (Fig. 9). And to date, the generalizations based on an even more extensive array of isotopic data substantially supplemented and improved the $\delta^{18}O$ and $\delta^{13}C$ variation curves and also clarified the age of the reconstructions that occurred (Cramer et al., 2009).

It should be specially noted that the study of quantitative changes in oxygen isotope composition in the ocean sediment sections made a huge contribution to the identification of Neogene–Quaternary "marine isotope stages" (MIS). The detailed scale of these stages reflecting the sequence of relatively short warming and cooling periods provides the basis for detailed climatic–stratigraphic subdivision and dating of Quaternary marine sediments and their correlation with continental sequences.

When studying the deep-sea cores, in addition to biostratigraphic and magnetostratigraphic methods, as well as studying the changes in oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopic composition for the purpose of geological and paleoclimatic reconstructions and also rock age determination, today, other methods and approaches are also used to one degree or another (Sr,

Os, and S isotope stratigraphy, radioisotope geochronology, astrochronology, TECH$_{86}$, etc.). Perhaps some of them are not of decisive and large-scale importance yet, but their role is constantly growing. In particular, the *strontium isotope chemostratigraphy* (based on the study of $^{87}Sr/^{86}Sr$ variations), which is gaining momentum, helps in a number of cases to improve stratigraphic maps, their correlations, and paleogeographic models. The study of Cenozoic carbonate sediment samples, primarily Neogene, from different parts of the World Ocean revealed the same $^{87}Sr/^{86}Sr$ ratio in even-aged sediments; hence, the Sr isotope characteristic can be used as a means of correlation (DePaolo and Ingram, 1985; Farrell et al., 1995; Hodell et al., 1989; Koepnick et al., 1985; etc.). Owing to the fact that $^{87}Sr/^{86}Sr$ steadily increased in the Cenozoic, the high gradient of this ratio makes it possible to distinguish the age of marine sediments up to the stage and even more precisely (Kuznetsov et al., 2018). But the detailed description of different methods is not our objective, and we refer the reader to the corresponding summaries of recent years (for example, McArthur et al., 2001, 2020).

Some Features of Development and Distribution of Micropaleontological Assemblages in the Cenozoic

A great contribution to the reconstruction of changes in marine environment, ocean circulation, and climate of the past was made by the detailed analysis of data on taxonomic composition and spatial distribution of different age microplankton assemblages obtained during the study of deep-sea cores. This is explained by the fact that, firstly, microorganisms are relatively sensitive indicators of seawater temperature variations, and, secondly, the nature of spatial distribution and biogenic sedimentation rate reflect the ocean circulation and sedimentation features.

In the present-day World Ocean, the taxonomic composition of planktonic assemblages is largely dependent on the latitudinal climatic zoning: different geographic zones are dominated by carbonate or siliceous organisms of certain species. The temperature conditions of surface water masses depend on the position of climatic zones and the activity of currents in these belts. They are separated by transitional "frontal" zones (fronts) which extend sublatitudinally in accordance with the climatic zone boundaries. The mixed communities being transitional between complexes of neighboring water bodies developed in the frontal zones. The fronts serve as thermal barriers to the migration of many plankton representatives; therefore, the distribution of these species is limited to a specific surface water body and is most indicative for it. In other words, various planktonic assemblages are confined to the belts which generally extend parallel to the equator. Such belts can be traced in the ocean sediments where the microorganism fossils occur in the
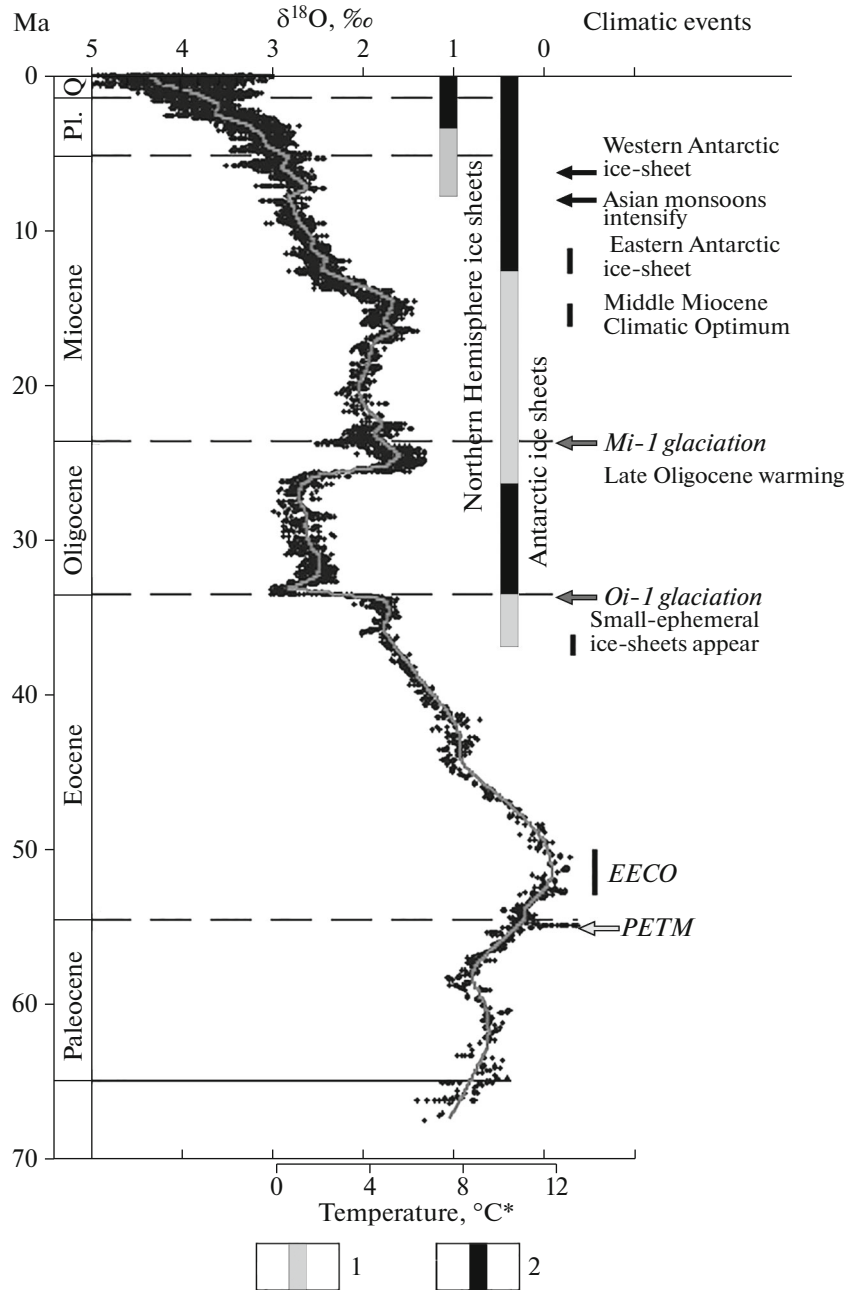
Fig. 9. $\delta^{18}O$ deep-sea oxygen isotope curve for Cenozoic deep-sea sediments and the "calendar" of important Paleocene−Quaternary climatic events (after Zachos et al., 2001). (1, 2) Ice-sheets: (1) partial or ephemeral, (2) full-scale or permanent; (PETM) Paleocene−Eocene Thermal Maximum, (EECO) Early Eocene Climatic Optimum. (Pl.) Pliocene, (Q.) Quaternary.

sedimentation process (Lisitzin, 1978). On the other hand, the warm-water bodies of low−middle latitudes are generally dominated by carbonate plankton, which is the main biogenic carbonate source in bottom sediments. Carbonate plankton is much less frequent in occurrence or is almost absent in the high-latitude cold waters. These waters are dominated by siliceous microplankton, primarily diatoms, which causes the predominantly biogenic silica accumulation. The exception, perhaps, is the North Atlantic region and

the adjacent seas where deep waters are partially formed owing to the northern "young" water inflows which are formed on the border with the Arctic basin and are insufficiently enriched in dissolved silica. Therefore, shells and skeletons of siliceous microorganisms undergo dissolution at the bottom owing to interaction with deep waters. For this reason, the biogenic siliceous sedimentation is negligible. It should also be noted that, because of the undersaturation of sea waters with silicic acid, the active development of

siliceous phytoplankton (the main biogenic silica producer and supplier to sediments) is possible only in the vertical water mixing areas; as a result of mixing, deep waters enriched in minerals, including silica, rise to the surface (for example, in divergence and upwelling zones). Hence, the diatom development in plankton (and productivity) and participation in biogenic sedimentation in different parts of the World Ocean are heterogeneous and, ultimately, depend on the global ocean circulation conditions. Accordingly, three main belts of recent siliceous sedimentation are distinguished in the World Ocean (Lisitzin, 1978). In general, the position of these belts coincides with that of the regions whose surface waters are characterized by the most abundant diatom flora. Consequently, changes in the diatom flora productivity in the surface waters of a particular region in the corresponding geological time can be judged from changes in distribution and sedimentation velocity of siliceous sequences.

According to the deep-sea drilling data, the latitudinal zoning was also characteristic of the ancient microplankton distribution. The study of taxonomic composition of uneven-aged fossil assemblages in the core sections in different ocean regions made it possible to trace the time shift of surface water bodies relative to the equator as a result of climatic fluctuations reflecting the warming and cooling periods. On the other hand, the analysis of spatial distribution of carbonate and siliceous fossils in the sections made it possible to draw conclusions about temporal displacement of "warm" and "cold" water bodies, contrast of latitudinal temperature gradients in the oceans, and changes in the ocean circulation. In particular, the analysis of features of distribution of Cenozoic marine biogenic siliceous strata (Baldauf and Barron, 1990; Barron et al., 2015) provided the possibility of revealing the differences in the development of siliceous phytoplankton in the oceans in different Paleogene and Neogene intervals, as well as relating them to changes in the climate and ocean circulation.

In addition, the data obtained in the course of processing the deep-sea drilling materials were used to identify specific features of the Cenozoic paleobiotic communities in open basins and shelf zones, to detail the development of open-ocean, semi-isolated, and marginal ocean ecosystems, and to analyze the evolution of microorganism assemblages in different provinces.

General Features of Evolution of Ocean Ecosystems

The summarization of the data given above serves as the basis for interpreting a number of general features of development of marine paleoecosystems and trends of paleogeographic settings. Many works devoted to this topic (Kennett, 1982; etc.) are presented below in a brief form.

(1) The data on *development stages* of various marine fauna and flora groups (with recording of the periods of outbreaks of morphogenesis and taxonomic diversity) were obtained taking into consideration the development of both individual species and communities. This very information was used in the analysis of geological development of large marine ecosystems (Atlantic, Pacific, Antarctic, and Arctic basins) and their parts.

(2) Differences between bioassemblages were established in relation to their *latitudinal confinement*, i.e., their belonging to different climatic zones (tropical, boreal, natal, and arctic).

(3) The study of micropaleontological complexes in the sections of oceanic *ecotone zones* made it possible to determine features of the biological communities in these transition zones and their temporal displacement depending on climatic fluctuations.

(4) The influence of *sea currents* and *upwellings* on the biota distribution was assessed when studying and reconstructing the conditions of development and formation of ancient microorganism assemblages. In the same respect, many sea *straits* turned out to be important (the Drake Passage in the Southern Hemisphere, the Strait of Gibraltar in the Northern Hemisphere, etc.).

(5) Diachronic appearance and disappearance of certain microplankton taxa in the sections of various sea basins are noteworthy. In some cases, they are apparently related to the biota migration caused by the climatic factor (under warming, for example, tropical species migrate to the north, often lagging behind in time of the first occurrence in high latitudes by tens of thousands and even, possibly, by a few million years). In other cases, they are related to the opening of sea straits and paleocommunity migration from one basin to another; as a result, the same taxa occur in different basins not simultaneously. However, it is often hard to scale the extent of such discrepancies. Meanwhile, differences were established between paleobiotic communities of open basins and *shelf* zones where the aforementioned "first and last occurrence levels" of individual taxa were also diachronous. Finally, we have to take into account specific features of biota development in epicontinental, semi-isolated, and marginal ocean ecosystems with their *provinces*, which can also be marked by cases of diachronous levels.

(6) *Bipolarity* was revealed in the distribution of some fossil biotic plankton assemblages. For example, bipolar ranges were recently determined for a number of planktonic diatom species at the beginning of Early Oligocene, and the possible mechanisms of their formation were proposed (Gladenkov, 2014).

(7) *Paleoclimatic fluctuations* were plotted and paleogeographic settings were reconstructed for different time slices on a stratigraphic basis. The data on microorganisms were used to detail changes in the past *climate settings*, in particular, the replacement of "greenhouse" climate by "glacial" type near the

Eocene and Oligocene boundary (Cramer et al., 2009; Zachos et al., 2001; this work) (Fig. 9).

(8) The experience gained in the study of paleontological complexes in the deep-sea core sections made a great contribution to assessment of the diversity of marine microorganisms in the past eras. In particular, it was revealed that the generic and species *biodiversity* of carbonate microphytoplankton (coccolithophorids) and dinoflagellates reached the maximum in the Late Cretaceous and then decreased from the Eocene to the present time. On the contrary, the siliceous microphytoplankton (diatoms) biodiversity increased throughout the Cenozoic with a distinct activation near the Eocene and Oligocene boundary and then in the Middle–Late Miocene. Thus, siliceous and carbonate phytoplankton is characterized by different diversity trends which do not coincide in time. Such contrast likely reflects the specific phytoplankton development in different ecological conditions as adaptation to changes in environmental conditions (Falkowski et al., 2004). In particular, diatoms can live in the conditions when the vital material supply to the photosynthesis zone is pulsating rather than constant. Under favorable conditions, the algae actively use this "resupply," and the diatom flora actively grows. Thus, the conditions are favorable for diatoms when the high hydrodynamic activity periods alternate with the relatively stable water column. On the contrary, calcareous nannofossils and dinoflagellates tend to dominate and develop productively in relatively calm and stable conditions. Similar optimum conditions for carbonate plankton were characteristic of the Mesozoic and Early Paleogene, when the "greenhouse" climate prevailed on the Earth with low latitudinal temperature gradients between the equatorial and polar regions and with gentle winds. Such conditions predetermined a slow stable water circulation in relatively warm oceans in the absence of psychrosphere and steep thermoclinic barriers in the water column. This period was characterized by carbonate phytoplankton prosperity. The transition to the "glacial" climate and the global thermohaline circulation at the beginning of the Early Oligocene caused a pronounced thermocline and more active surface water circulation. Environmental changes preconditioned the greater diatom diversity and, on the contrary, the carbonate phytoplankton regression.

(9) It should be specially noted that the deep-sea drilling data made it possible to solve in a new way the complex problem of *eustatics* and relative fluctuations in the World Ocean level (for example, Haq et al., 1987; Hardenbol et al., 1998; Miller et al., 2020; Vail and Hardenbol, 1979). In this regard, it is necessary to recall the widespread use of the *seismostratigraphic method*, which is now applied in almost all oceanological studies to identify the bottom structure of the oceans and their margins.

(10) Corrections were made to *stage boundaries* in the Upper Cretaceous, Paleogene, and Neogene stra-totypes identified in the sections of the continental blocks; the boundaries of stratigraphic units with different rank and marker age were clarified.

(11) The sequence and relationship of a number of biotic and abiotic *events* in the World Ocean for the last 70−75 m.y. were revealed. This achievement makes it possible to compile the *calendars* of various geological events which clearly record certain stages of past natural processes and their scale. Such calendars can be both subglobal and regional. The well-known calendar of Cenozoic events compiled by (Zachos et al., 2001) can be given as an illustration of the global calendar. The regional-scale calendars include the reconstructions made by one of the authors of this paper for the Late Cenozoic in the North Pacific region (Gladenkov, 2007) (Fig. 10).

Apparently, this list of general and particular features of development of the marine ecosystems can be continued. Meanwhile, it should be remembered that all these factual and methodological data obtained during the processing of deep-sea drilling materials can be used even today in the construction of regional and interregional stratigraphic maps not only for the Cretaceous and Cenozoic but also for the entire Phanerozoic.

The findings given above represent the current assessment of stratigraphic results of deep-sea drilling. Along with that, we should also remember the opinion of those specialists who were involved in these works in the past years and who even earlier evaluated many of their results from the standpoint of not only regional constructions but also general stratigraphic problems. In this regard, it is appropriate to recall, for example, some conclusions of V.A. Krasheninnikov, one of the most famous stratigraphers and specialists in the study of fossil foraminifera, who is the author of several large monographs on the deep-sea drilling results, which are distinguished by the enormous amount of material involved and by broad analysis thereof. We will recall only some of these conclusions, without fear of certain repetitions and taking into account that they were made many years ago (Krasheninnikov, 1969, 1973; Krasheninnikov and Basov, 2007). V.A. Krasheninnikov was one of the first to note that drilling in ocean basins brought vast, previously *unknown information* about their geological structure and development history during the Mesozoic and Cenozoic. In his opinion, it followed from the drilling experience that the *biostratigraphic method* was major in the study of the planet's sedimentary cover, despite the intensive development of various physical and chemical methods to study sedimentary sequences in recent decades. He also noticed that the *paleontological base* of the Mesozoic stratigraphy and, above all, the Cenozoic *changed* over time. Planktonic microorganisms (foraminifera, calcareous nannofossils, diatoms, and radiolarians) became the basis of the subglobal stratigraphic scales. Benthic organisms (nummulitids,
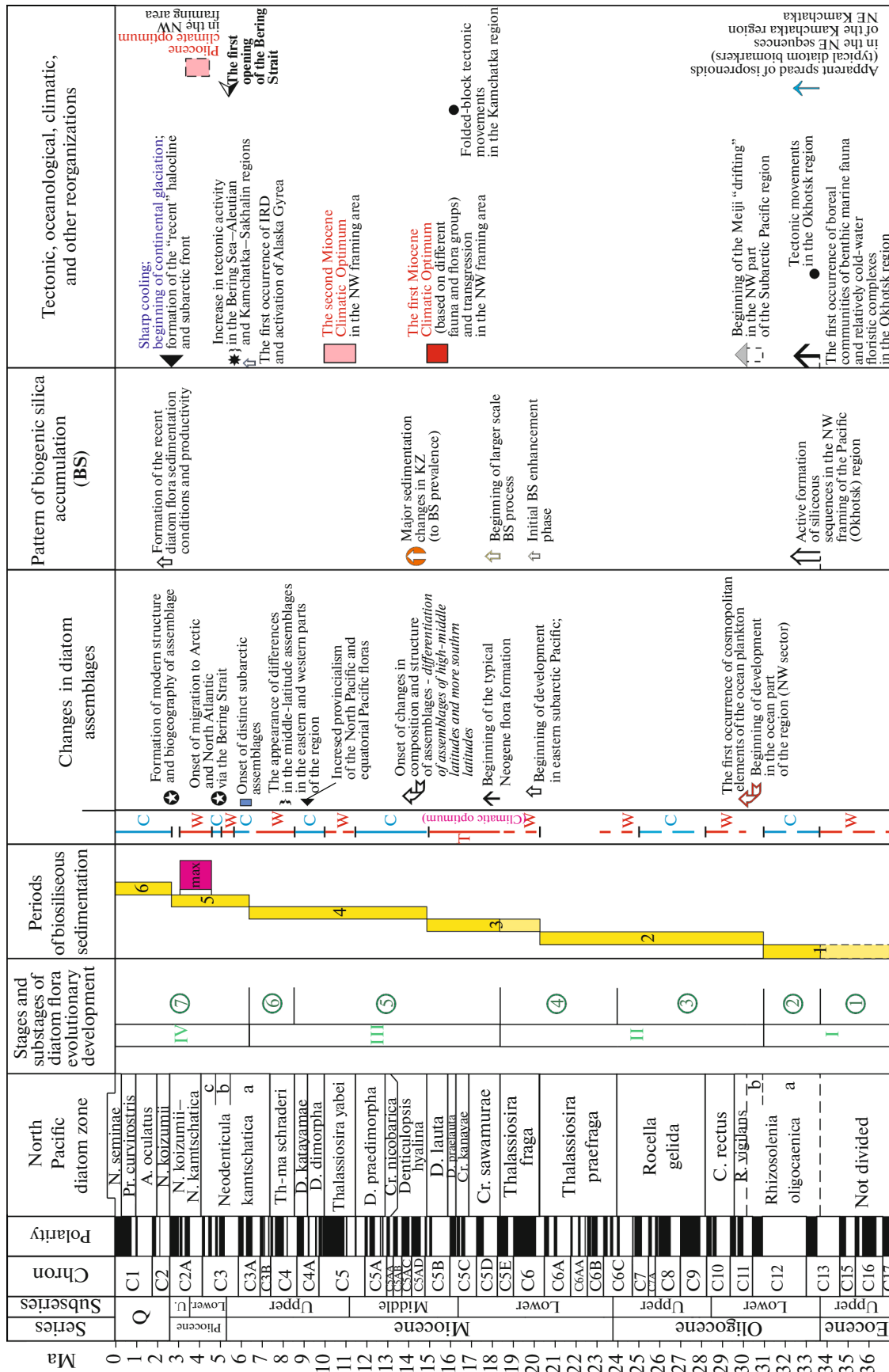
Fig. 10. Changes in diatom assemblages and Oligocene–Neogene geological events in the North Pacific region (after Gladenkov, 2007). (W) Warm-water diatom assemblages, (C) cold-water diatom assemblages.

small benthic foraminifera, mollusks, and sea urchins) retained their importance for the development of regional stratigraphic scales, but, in general, were not the subglobal stratigraphic information carriers. Among planktonic microorganisms, foraminifera occupy the leading position in the Cenozoic. On one hand, they are the best-studied traditional microfauna group based on history, and on the other hand, they are distinguished by worldwide distribution and rapid rate of evolution. Planktonic foraminifera were the most developed in the tropical region. They served as the basis for the zonal (Caribbean) scale proposed in 1957 by Bolli (1957a, 1957b, 1957c) and modified in 1969 by Blow (1969), while the deep-sea drilling made it possible to confirm its high stratigraphic and correlation potential. It was clear to V.A. Krasheninnikov for a long time that, upon the transition to the Paleogene and Neogene subtropical deposits, the fractional stratigraphic division into planktonic foraminifers became somewhat lower, and the zonal boundaries could be located at other levels. However, when moving to higher latitude areas, the sediment division detail based on planktonic foraminifers decreases, but the stratigraphic scale fundamentals remain unchanged. According to V.A. Krasheninnikov, from the methodological point of view, it should be recommended to subdivide the sections using *species complexes*, rather than individual taxa (someone may disagree with this). The latter should be considered as an additional argument when justifying the subdivision boundaries. The parallel use of different groups of planktonic organisms (for example, planktonic foraminifera and calcareous nannofossils) improves the reliability of stratigraphic constructions. Definitely, these and many other considerations of V.A. Krasheninnikov testify to his broad understanding of the deep-sea drilling results and their role in development of the stratigraphy of sedimentary deposits of the globe. His ideas remain very useful to date.

CONCLUSIONS

Hence, the results of stratigraphic studies carried out during deep-sea drilling for over 50 years have largely a "breakthrough character." They make a great contribution to development and improvement of the methods for detailed stratigraphic study and dating of marine sedimentary complexes, as well as reconstruction of the past oceanological and climatic events. The results obtained are of great methodological importance for conducting stratigraphic studies throughout the Phanerozoic. It is no coincidence that the data obtained in the deep-sea drilling processes are constantly discussed at international congresses on stratigraphy and in other scientific forums. A lot of such data were used, in particular, in the recently published extensive summary on various stratigraphic problems (*Geologic...*, 2020).

It is proved for the first time that the identified zonal Cenozoic subdivisions can actually be traced over a vast area, throughout the tropical belt of three oceans (Pacific, Indian, and Atlantic). Today, such fractional biostratigraphic units have already become an indispensable element of stratigraphic maps which are being developed for ancient sea sequences exposed on land.

Along with that, the study of microorganism assemblages which were an integral part of the Mesozoic and Cenozoic marine ecosystems played an important role. These assemblages developed in time against the background of changes in the ocean circulation and sedimentation conditions and variations in the productivity of deep and surface waters, their temperatures, and other characteristics. In general, the evolution trend of biotic communities reflects the stages of development of the past ocean ecosystems and the corresponding rearrangements. Therefore, the study of the stages of microorganism development made it possible to establish the sequence and synchronicity of different-scale natural processes and understand their relationship and influence on the biota formation. All these facts made it possible to reveal the general sequence of not only biotic but also abiotic (climatic, oceanographic, paleogeographic, and eustatic) events in the World Ocean for the last 70−75 m.y. The comprehensive study of Cenozoic zonal stratigraphy peculiarities carried out during the deep-sea drilling for over past 50 years and more deserves the highest rating. The stratigraphic research experience gained during the implementation of the International Deep-Sea Drilling is worthy of further study and interpretation.

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