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Quantitative Parameters of Pleistocene Pelagic Sedimentation in the World Ocean: Global Trends and Regional Features

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Abstract—A comparative analysis of Pleistocene pelagic sedimentation in the Pacific, Indian, and Atlantic oceans revealed the predominance of terrigenous sediments, while carbonate and siliceous sediments are second and third in abundance. During Pleistocene, the mass of terrigenous and siliceous sediments increased, while that of carbonates slightly decreased. The latter is related to the fact that the bottom waters aggressive to carbonates became increasingly generated at high latitudes, thus exceeding an increase in the productivity of plankton carbonate organisms. The peculiarities of accumulation of the main types of bottom sediments in the Pleistocene are considered. It is concluded that the Pleistocene geological history of continents, especially neotectonic uplift and continental glaciations, played an important role in pelagic sedimentation.

Keywords: bottom sediments, pelagic zone, World Ocean, Neopleistocene, Eopleistocene, areas, dry sediment mass, volumes, masses of sediments per time unit, terrigenous sediments, carbonate ooze, siliceous ooze

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INTRODUCTION

As known, sedimentology and sedimentary geochemistry are focused not only on the qualitative characteristics of sedimentary processes, but also on the quantitative parameters of sedimentation. For instance, the rates of sedimentation and diagenetic/catagenetic consolidation are traditionally calculated in the basin analysis (Leonov and Volozh, 2004). The total fluxes of sedimentary matter, sediment-forming components, minerals, and chemical elements are calculated using the mass accumulation rate method (Arkhangel'skii, 1927). The volumetric method involves the computation of areas, volumes, and mass of dry sedimentary matter, and sediments per time unit (Ronov, 1949).

The World Ocean sediments are usually quantified using the absolute mass method, which was intensely developed in our country by N.M. Strakhov and A.P. Lisitzin. Already in 1970–1980s, this method was used to generalize the results of deep-water drilling (Van Andel et al., 1975; Levitan et al., 1980; Levitan and Bogdanov, 1980a, 1980b; Lisitzin et al., 1980; Thiede and Ehrmann, 1986; Emelyanov et al., 1989; Steinberg, 1989). Of great importance is the monograph by Lisitzin (1978), which demonstrated for the first time the calculations of absolute mass of terrigenous, carbonate, and siliceous sediments for the modern sedimentation stage in the pelagic areas of all main oceanic basins. Close results on the oceanic sedimentary formation were later derived using a volumetric method (Ronov et al., 1986). The results of application of this method to Mesozoic–Pliocene sediments of the World Ocean were summarized by Ronov in his last monograph (Ronov, 1993).

Most works on the evolution of Quaternary sedimentation in the World Ocean are dedicated to the glacial–interglacial cycles expressed in sediments assigned to different marine isotope stages (Fig. 1), rather than to the entire Pleistocene or its main constituents. It is seen in Fig. 1 that the Pleistocene may be subdivided into two large stages connected by the Middle Pleistocene transitional period. These stages are from 1.8 to 0.8 Ma (Eopleistocene—Q_1), with 41-ka periodicity of mainly low-amplitude climatic changes and from 0.8 to 0.01 Ma (Neopleistocene—Q_{2+3}) with 100 ka periodicity of large-amplitude climatic changes. The transitional period lasted approximately from 1.2 Ma to 0.7 Ma. In general, the average temperature of the near-bottom waters of the World Ocean in the Eopleistocene was much higher than in the Neopleistocene.

Unfortunately, the problems of quantitative evolution of pelagic sedimentary process in the World Ocean in the Pleistocene were not considered earlier, except for the author's team from Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences (GEOKHI RAS). This

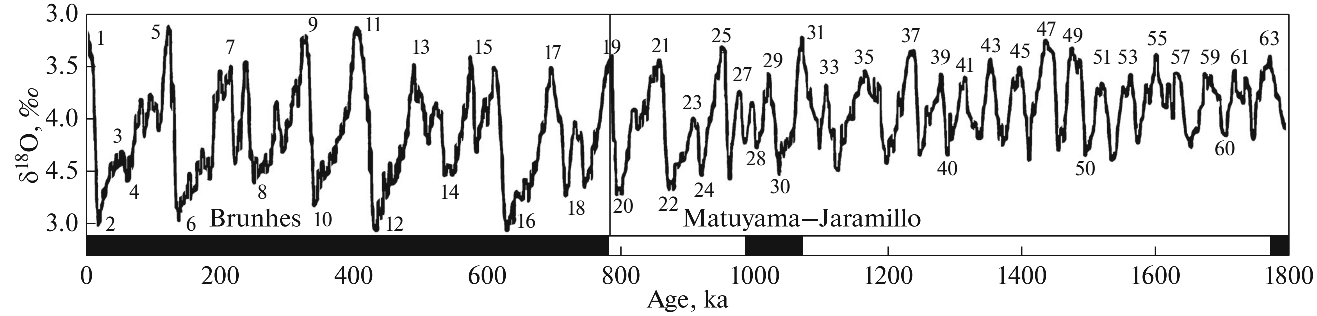

Fig. 1. Reference plot of $\delta^{18}O$ variations in the shells of secretion benthic foraminifers of the World Ocean (modified after Lisiecki and Raymo, 2005). The lower scale shows the age, in ka. Numerals in the plot are the numbers of isotope-oxygen stages.

paper completes the cycle of studies of quantitative parameters of the Pleistocene sedimentation in the pelagic zone of the World Ocean using the volumetric method by A.B. Ronov (Levitan et al., 2013, 2014; Levitan, 2016; Levitan and Gel'vi, 2016). Some repetitions are inevitable, but the main attention is now paid to the comparative analysis of previously obtained results for separate oceanic basins.

FACTUAL MATERIAL AND METHODS OF STUDY

Let us consider the spatial–temporal constraints on the studied object. The pelagic zones of the World Ocean are referred to as deep-water oceanic areas (usually deeper than 3000 m) beyond continental margins. In the Pacific Ocean, the boundary lies along the "andesite" line, however pelagic zones include the Philippine Sea. The pelagic sedimentation area in this zone does not include Scotia Sea and is located beyond the Antarctic continental rise. In the Indian Ocean, the boundary of the pelagic zone is drawn along the Sunda deep-water trench and also along continental foot margins. In the Atlantic Ocean, the regions of active continental margins (Caribbean and Scotia seas) as well as the Gulf of Mexico are not involved in the analyzed area. Shelves and continental slopes of passive margins were also omitted from consideration. The Atlantic pelagic zones are bounded by the Fram Strait in the north and the Weddell Sea continental margin in the south.

As known, a new interpretation of the Quaternary stratigraphy with its lower boundary at 2.6 Ma was accepted in 2008 (Gradstein et al., 2012). Before this, the level of around 1.8 Ma was taken as the lower boundary during all deep-water drilling cruises (and, in general, during the study of Quaternary deposits). Since our generalizations are based on the results of deep-water drilling data (www.iodp.org) on lithology, stratigraphy, thickness, and physical properties of Quaternary sediments, the old geological scale was applied (Gradstein et al., 2004).

This study was based on data obtained during deep-water drilling cruises nos. 5–9, 16–21, 28–35, 54–70, 84–92, 112, 124E, 126, 129–132, 134–135, 138, 145, 147, 181, and 191 for the Pacific Ocean and cruises nos. 22–28 and 115–121 for the Indian Ocean. The Atlantic Ocean was analyzed using data obtained from all holes that recovered pelagic Pleistocene from 1968 to 2014 (283 holes, in total).

According to (Ronov et al., 1986), the accuracy of geological mapping in oceans on the basis of deep-water drilling was taken to be 5%. Unfortunately, significant part of the southern Pacific Ocean, southwestern Indian Ocean, and almost entire Arctic Ocean are not spanned by drilling. Therefore, the mapping accuracy varies depending on the region.

On the basis of deep-water drilling data, two lithological-facies maps on a scale of 1 : 35000000 were compiled for the Eopleistocene and Neopleistocene in the transverse azimuthal equal-sized projection for each of the main oceanic basins. In general, the reliability of mapping presumably decreases from the Atlantic to the Indian and further to the Pacific oceans. It should be noted that only the widest spread sediments ascribed to groups of terrigenous, carbonate and siliceous sediments were mapped. Red clays in our calculations were included in terrigenous sediments, although they belong to polygenic sediments. Such oceanic deposits and rocks as, for instance, metalliferous and edaphogenic sediments, volcanic ashes and tuffites, reef limestones, ferromanganese nodules and crusts, phosphorites, and deep-water sulfides, are not shown in legend. For the Atlantic Ocean (unlike other oceans), the legend also includes contourites as well as carbonate turbidites and calcareous (30–70% $CaCO_3$) sediments.

Analysis of all maps by Ronov volumetric method provided data on areas (thou km^2) and volumes (thou km^3) of mapped lithogenetic types and lithological complexes, which then were recalculated to dry sediment (trillion tons) and sediment mass per time unit (trillion tons/Ma). The volume of natural sediments was recalculated into a dry sediment mass using formula from (Levitan et al., 2013).

Data were processed using a comparative-lithological method proposed by Strakhov (1945), facies anal-

Table 1. Areas of pelagic parts of oceans (thou km^2)

Age	Pacific	Indian	Atlantic	Arctic
Modern	144577	65279	61304	2873
Neopleistocene	140512	62488	70579	–

Dash denotes data are absent.

Table 2. Comparative analysis of the sediment masses per time unit (I, 10^{21} g/Ma) in the lithological-facies zones of oceanic pelagic zone

Lithological-facies zones	Oceans					
	Pacific		Indian		Atlantic	
	Neopleistocene	Eopleistocene	Neopleistocene	Eopleistocene	Neopleistocene	Eopleistocene
Hemipelagic	674	301	585	420	1515	1174
Miopelagic	358	207	231	263	236	383
Eupelagic	155	128	107	113	0	0

ysis of oceanic sediments (Murdmaa, 1987), and volumetric method (Ronov, 1949).

Since deep-water drilling in the pelagic zone of the Arctic Ocean was performed only in the near-polar segment of the Lomonosov Ridge (Backman et al., 2006), it is impossible yet to compile lithological-facies maps for this area. The mass of pelagic Pleistocene in this oceanic basin was estimated using lithological and stratigraphic data on the Quaternary deposits from the indicated ACEX drilling cruise (O'Regan et al., 2008), seismostratigraphic data (Poselov et al., 2012; Jokat et al., 2013; Daragan-Sushchova et al., 2015; Gaina et al., 2016, etc), lithological and physical properties of the Upper Quaternary deposits (Thiede and Hempel, 1991; Stein and Fahl, 1997; Stein et al., 2010), and the average sedimentation rates over the past five marine isotope stages (Levitan, 2015).

RESULTS

Areas of Pelagic Parts and their Facies Structure

In 1961, Stepanov (1961) published the results of calculation of oceanic pelagic zone areas, including deep-water ocean floor beyond continental margins (excluding seas) with depths more than 3000 m (Table 1). In Table 1, these values for the modern stage of the evolution of the Pacific, Indian, and Atlantic oceans are given according to Stepanov (1961), and for the Arctic Ocean, according to (Jakobsson et al., 2004). Neopleistocene data are given for the Pacific Ocean (Levitan et al., 2013), Indian Ocean (Levitan et al., 2014), and Atlantic Ocean (Levitan and Gel'vi, 2016).

Some excess of these values above Neopleistocene areas for the modern stage of the evolution of the Pacific and Indian oceans is caused by disagreement in the determination of pelagic areas by V. N. Stepanov, on the one hand, and authors of this paper, on the other. A clear disagreement for the Atlantic Ocean is because Stepanov did not include seas of the Norwegian—Greenland basin in calculations, unlike Levitan and Gel'vi (2016).

Table 2 shows variations in the mass of bottom sediments accumulated in the different lithological-facies zones during Pleistocene. It should be noted that, as compared to our first publications, we changed the name of these zones to make their classification more logical. For instance, the Pacific and Indian oceans were subdivided into hemipelagic, pelagic and abyssal zones. Classification proposed in Table 2 seems to be more justified.

A comparative analysis showed that sediment mass accumulated per time unit in the Neopleistocene hemipelagic zone strongly increased as compared to that of the Eopleistocene in all oceans. Different situations are observed in the miopelagic lithological-facies zone: continuing growth in the Neopleistocene as compared to the Eopleistocene in the Pacific Ocean, at a weak decrease of sedimentation in the Indian Ocean and a strong decrease in the Atlantic Ocean. The same tendency is observed in the eupelagic zone in the Pacific and Indian oceans, but is absent in the Atlantic ocean due to the relatively high total sedimentation rates. This demonstrates that the sedimentary differentiation in the Pleistocene obviously increased in the Atlantic Ocean, slightly increased in the Indian Ocean, and remained practically unchangeable in the Pacific Ocean. At the same time, a clear growth of sedimentation intensity from ocean center to margin is clearly observed at all age sections in all oceans, which is quite logical. The causes of described phenomena will be considered later. Now, we would like to note that the Arctic pelagic area in the Pleistocene involved only a hemi-

Table 3. Comparative analysis of the absolute masses of sedimentary matter in the oceanic pelagic zone (10^{21} g/Ma)

Components	Pacific Ocean			Indian Ocean			Atlantic Ocean			Arctic Ocean			World Ocean		
	age			age			age			age			age		
	Holocene	Neopleistocene	Eopleistocene	Holocene	Neopleistocene	Eopleistocene	Holocene	Neopleistocene	Eopleistocene	Holocene	Neopleistocene	Eopleistocene	Holocene	Neopleistocene	Eopleistocene
Terrigenous matter	0.78	0.91	0.58	0.30	0.71	0.61	0.64	0.94	0.30	0.02	0.043	0.031	1.74	2.60	1.52
$CaCO_3$	0.31	0.32	0.14	0.23	0.25	0.19	0.54	0.33	0.77	0	0	0	1.08	0.90	1.09
Biogenic opal	0.10	0.039	0.027	0.093	0.084	0.049	0.093	0.054	0.049	0	0	0	0.283	0.177	0.125

pelagic lithological-facies zone represented by terrigenous sediments of different genetic types.

Absolute Mass of Sedimentary Material in the Pelagic Zones of the World Ocean in the Pleistocene (10^{21} g/Ma)

Table 3 and Fig. 2 demonstrate the distribution of absolute masses of main components of bottom sediments (terrigenous matter, $CaCO_3$, and biogenic opal) in the pelagic zones of the World Ocean and constituent oceanic basins in the Pleistocene. While analyzing Table 3, it should be taken into account that Holocene data on the Pacific, Indian, and Atlantic oceans were taken from work (Lisitzin, 1978), which was based on materials (Stepanov, 1961) for the pelagic zones of the World Ocean. The values (in mass per time unit) indicated in this work for the modern period were recalculated by the author for Holocene by multiplying by 10000 and adjustment to 10^{21} g/Ma accepted in our papers. Data on the Holocene of the Arctic Ocean were taken from (Levitan et al., 2012). Values obtained for the Pleistocene of this ocean are presented in this paper for the first time and are only hypothetical, which imposes some imprint on the corresponding data for the World Ocean.

In addition, it should be taken into account that all above indicated values in (Lisitzin, 1978) were obtained by calculating the distribution maps of the absolute masses of terrigenous matter (including, however, up to 30% total $CaCO_3$ and SiO_2 am.[1]), calcium carbonate and SiO_2 am. determined by chemical methods. An experience of the comparison of application of old (up to 1990s) techniques of SiO_2 am chemical determination in our country with new international generally accepted methods (Levitan, 2016) indicates that the old results are 1.5 times underestimated. Data for the Neo- and Eopleistocene were obtained by volumetric method from lithological-facies maps, i.e., from types of sediments. The comparison with data (Lisitzin, 1978) is quite correct for terrigenous sediments, while the content of $CaCO_3$ and SiO_2 am in the carbonate and siliceous sediments, respectively, are lower than 100%. On the basis of preliminary data, the average $CaCO_3$ content in the carbonate sediments is 85%, while SiO_2 am. content in the siliceous sediments is 60%. This should be taken into account while studying Table 3.

A comparative analysis of data in Table 3 is of great interest. First, it is obviously that sedimentation structure determined for the modern stage has existed in the Pleistocene: all age stages were dominated by accumulation of terrigenous matter, while carbonates and biogenic opal were second and third in abundance, respectively. Second, the intensity of sedimentation of sediment-forming components in all oceanic basins, except for $CaCO_3$ in the Atlantic Ocean, was higher in the Neopleistocene as compared to the Holocene; and in the Neopleistocene as compared to the Eopleistocene. The last statement may be exemplified by ratios of sedimentation intensities in the Neopleistocene to that in the Eopleistocene in the following order: Pacific Ocean, Indian Ocean, Atlantic Ocean, Arctic Ocean, and World Ocean (data on the latter are given only for terrigenous sediments). Thus, the ratios are as follows: 1.6, 1.2, 3.1, 1.4 for terrigenous sediment; 2.4, 1.3, 0.4 for $CaCO_3$; and 1.4, 1.7, 1.1 for biogenic opal. Taking the value of this parameter between 1.0 and 2.0 as background values, three exceptions can be recognized: for terrigenous matter of the Atlantic Ocean (3.1), for $CaCO_3$ of the Pacific Ocean (2.4), and for $CaCO_3$ of the Atlantic Ocean (0.4). The above mentioned tendency to the growth during Pleistocene for terrigenous matter and biogenic opal is preserved for

[1] SiO_2 am—amorphous silica or biogenic opal.

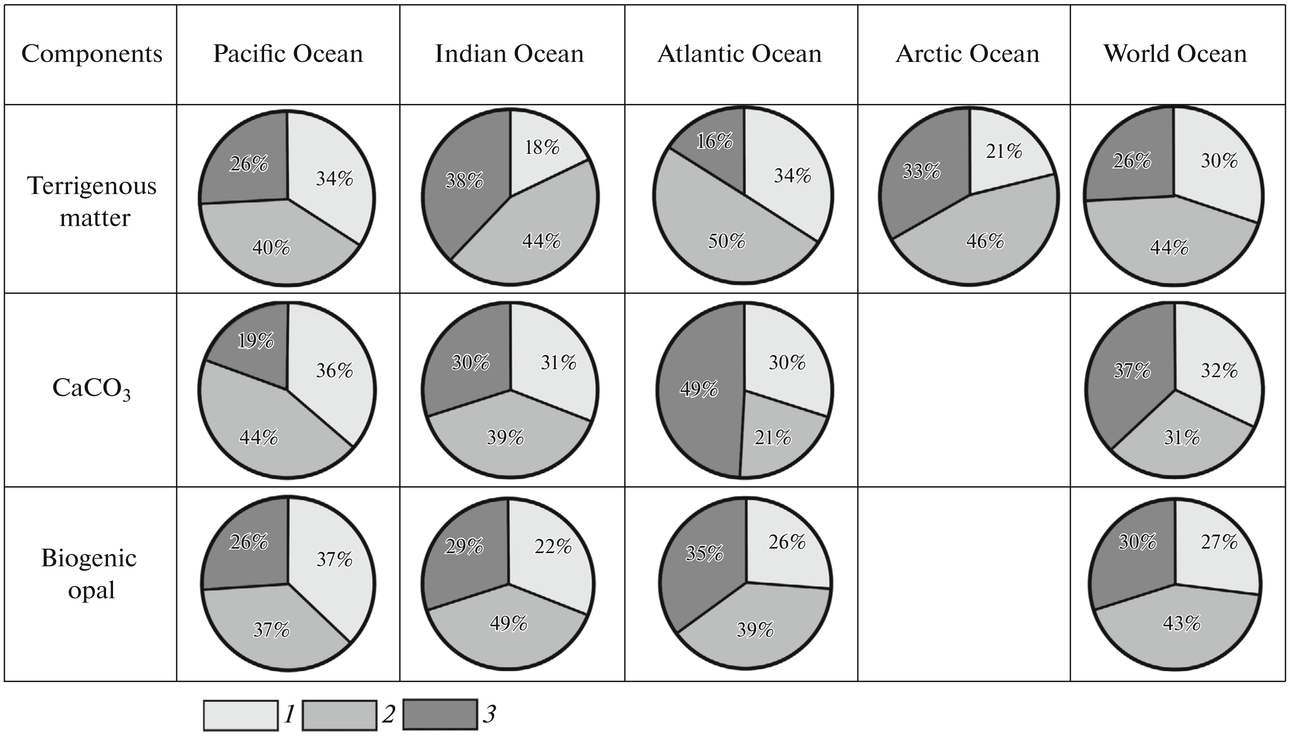

Fig. 2. Cyclogram of masses per time unit (10^{21} g/Ma) of terrigenous matter, carbonate and siliceous sediments from pelagic zones of the main oceanic basins in the Holocene, Neo- and Eopleistocene: *1*—Holocene; *2*—Neopleistocene; *3*—Eopleistocene.

the World Ocean. $CaCO_3$ shows tendencies noted for the Atlantic Ocean: the higher values of intensity in the Eopleistocene as compared to the Neopleistocene. The same but more clearly expressed tendencies are obtained by calculating using above indicated corrections for the Holocene SiO_2 am. contents, for $CaCO_3$ and SiO_2 am. in the Pleistocene carbonate and siliceous sediments, respectively. Note that the rate of carbonate accumulation in the Atlantic Ocean in the modern period was equal to its total rate in the Pacific and Indian oceans (Lisitzin, 1978). Therefore, it is not surprising that the history of carbonate accumulation in the Atlantic Ocean became determinative for the entire World Ocean.

Sediment Mass per Time Unit (I, 10^{21} g/Ma) for Different Types of Oceanic Deposits

In this section, the presented above peculiarities of accumulation of terrigenous, carbonate, and siliceous sediments in different oceanic basins during Pleistocene are shown in detail using information on the widest spread types of sediments (Table 4, Fig. 3). The possible reasons for the considered features will be discussed separately, in the next section of the paper.

Terrigenous sediments. We considered terrigenous turbidites, hemipelagic clays, and marine–glacial deposits. Abyssal red (pelagic) clays, which as mentioned above are polygenic sediments (Lisitzin, 1978), will be discussed separately.

Terrigenous turbidites. In the Pacific Ocean, terrigenous turbidites are developed in the northeastern part of the basin: on the continuation of the Gulf of Alaska (mainly) and in the Cascadia transect. In both the regions, the deep-water trenches on the underwater margin of North America are completely filled with sediments; as a result, turbidite flows in the Pleistocene are freely propagated over the abyssal plains, escaping natural sedimentation traps. In the Indian Ocean, the main field of terrigenous turbidites are related to the complexes of deep-water fans of the great Indian rivers: Indus in the Arabian Sea and Ganges and Brahmaputra in the Bengal Bay and southerly, in the Central deep-water basin. The main volumes of terrigenous turbidites in the Atlantic Ocean are related to the Amazon River runoff, which penetrates eastward up to the transform faults of the equatorial zone. The definite role is also played by turbidite complexes of the deep-water runoff of the Congo River, and some complexes in the North American deep-water basin.

In general, the terrigenous turbidites in the Neopleistocene were represented by the giant masses of sedimentary matter in the hemipelagic lithological–facies zones, and were much lower in all oceans in the Eopleistocene. The strongest increase of masses was noted in the Atlantic Ocean, while the Pacific and

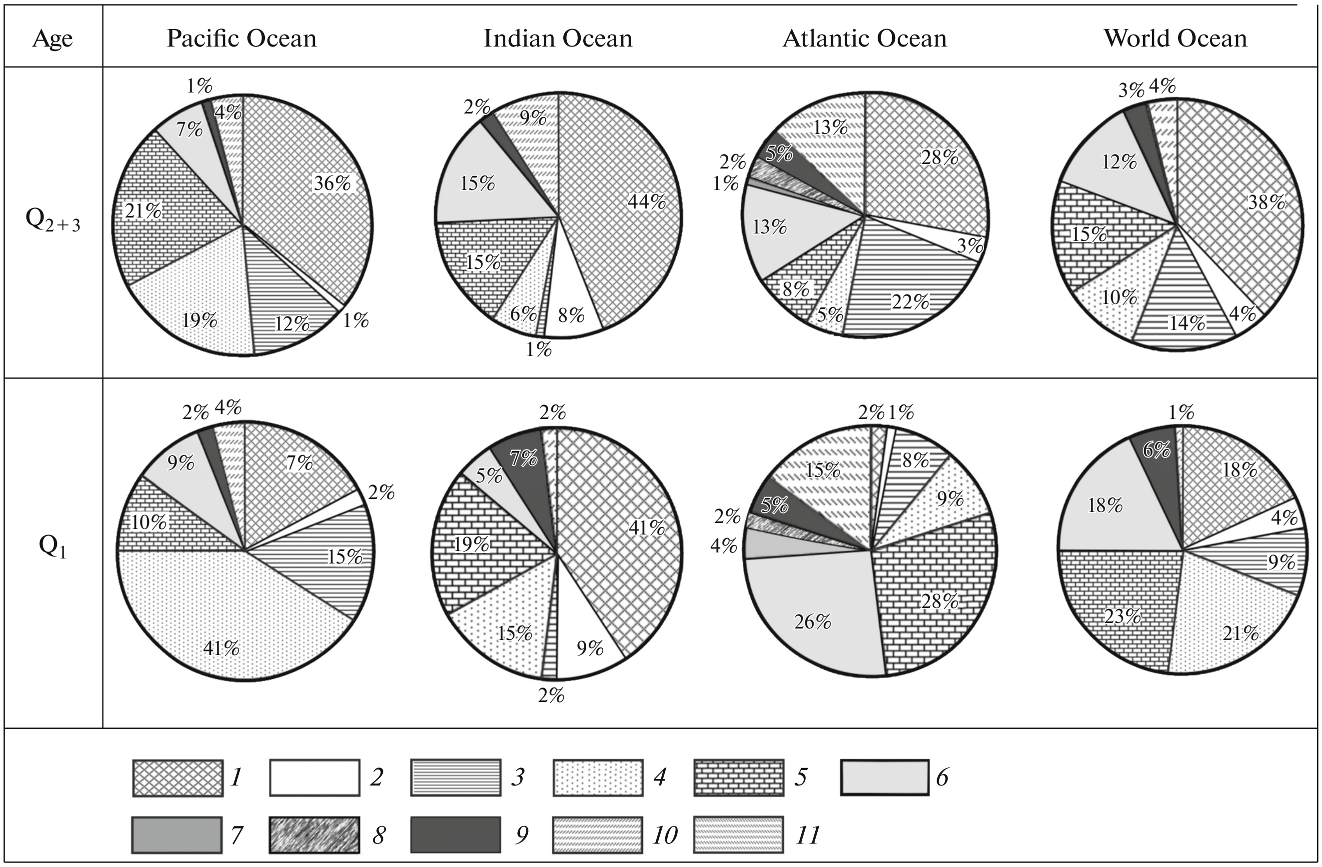

Fig. 3. Cyclograms of the masses of main types of pelagic sediments per time unit (10^{21} g/Ma) in the main oceanic basins in the Neopleistocene (Q_{2+3}) and Eopleistocene (Q_1). Symbols: *1*—terrigenous turbidites; *2*—hemipelagic clays; *3*—glacio-marine deposits; *4*—pelagic clays; *5*—nanoplankton ooze; *6*—foraminiferal–nanoplankton ooze; *7*—marly sediments; *8*—carbonate turbidites; *9*—diatom ooze and clay; *10*—radiolarian–diatom ooze; *11*—contourites.

Indian oceans are on the second and third places, respectively.

In the Arctic Ocean, the terrigenous turbidites in the pelagic area are mainly confined to the deep-water basins (Darby et al., 1989). According to data on the modern structure of the solid runoff and bathymetric position of the abyssal plain floor in the Nansen Basin as compared to that of the Amundsen Basin (Levitan, 2015), the most intense development of the terrigenous turbidites in the Pleistocene sedimentary cover should be expected in the Nansen Basin.

Hemipelagic clays. The values of matter mass per time unit (I) for hemipelagic and pelagic clays of the Pacific Ocean in Table 4 slightly changed as compared to data presented in (Levitan et al., 2013). On the basis of new data, the mass of hemipelagic clays slightly increased at the expense of pelagic clays in the northeastern part of the ocean. In general, the mass of hemipelagic clays in the pelagic zones of the World Ocean is very insignificant and may be comparable only with mass of diatom oozes (Table 4). They reached the lowest values in the Pacific Ocean, are slightly higher in the Atlantic Ocean, and maximal in the Indian Ocean. As compared to the Eopleistocene, the masses of hemipelagic clays in the Neopleistocene slightly increased in the Atlantic Ocean, to lesser extent, in the Indian Ocean, and decreased in the Pacific Ocean. In general, the World Ocean is characterized by the low IQ_{2+3}/IQ_1 for hemipelagic clays (1.3 as compared to 2.8 for turbidites).

Glacio-marine sediments. The masses of marine–glacial deposits are sufficiently high. They reach the highest values in the Atlantic Ocean (first and foremost, at the expense of the Norwegian–Greenland Basin). The Pacific Ocean is the second in this value, while the Indian Ocean is the third, with extremely low values. During Pleistocene, the masses of these sediments per time unit most strongly increased in the Atlantic Ocean, to lesser extent, in the Pacific Ocean, and decreased in the Indian Ocean. The IQ_{2+3}/IQ_1 ratio in the World Ocean is 2.0.

Pelagic clays. The masses of pelagic clays (total mio- and eupelagic clays) are huge in the Pacific Ocean, being 3–4 times lower in the Indian and Atlantic oceans. Thus, the general sedimentary structure of the pelagic zones of the World Ocean noted for

Table 4. Masses of sediments per time unit (I, 10^{21} g/Ma) for different types of oceanic deposits

Sediments	Stratigraphy	Pacific Ocean		Indian Ocean		Atlantic Ocean		World Ocean	
Terrigenous turbidites	Q_{2+3}	484.2		529.2		460.1		1473.5	
	Q_1	134.6	(3.6)	371.2	(1.4)	24.6	(18.7)	530.4	(2.8)
Hemipelagic clay	Q_{2+3}	1.9		97.7		46.5		146.1	
	Q_1	12.1	(0.2)	81.0	(1.2)	17.3	(2.7)	110.4	(1.3)
Glacio-marine deposits	Q_{2+3}	167.7		13.4		352.8		533.9	
	Q_1	113.8	(1.5)	22.8	(0.6)	125.0	(2.8)	261.6	(2.0)
Pelagic clay	Q_{2+3}	259.2		69.2		76.8		405.2	
	Q_1	324.5	(0.8)	137.9	(0.5)	135.3	(0.6)	597.7	(0.7)
Nannoplankton ooze	Q_{2+3}	280.8		178.1		132.5		591.4	
	Q_1	78.3	(3.6)	176.0	(1.0)	418.0	(0.3)	672.3	(0.9)
Foraminiferal-nannoplankton ooze	Q_{2+3}	87.5		184.1		216.1		487.7	
	Q_1	72.7	(1.2)	41.4	(4.4)	395.7	(0.5)	509.8	(0.96)
Marly sediments (30–70% $CaCO_3$)	Q_{2+3}	–		–		12.8		–	
	Q_1	–		–		63.4	(0.2)	–	–
Carbonate turbidites	Q_{2+3}	–		–		33.5		–	
	Q_1	–		–		23.5	(1.4)	–	–
Diatom ooze and clay	Q_{2+3}	14.6		27.8		90.0		132.4	
	Q_1	17.4	(0.8)	68.4	(0.4)	81.0	(1.1)	166.8	(0.8)
Radiolarian-diatom ooze	Q_{2+3}	50.9		107.9		–		158.8	
	Q_1	27.8	(1.8)	15.1	(7.1)	–	–	42.9	(3.7)
Contourite	Q_{2+3}	–		–		213.2			
	Q_1	–		–		221.0	(0.96)		

(1) dash denotes data are absent; (2) quotient of IQ_{2+3} division by IQ_1.

the recent stage by Lisitzin (1978) is preserved. Obtained result is quite expectable, because the relative role of abyssal basins accumulating pelagic clays in the pelagic zones of the Pacific Ocean is the highest (Harris et al., 2014). It is characteristic that the mass of pelagic clays per time unit in all studied oceanic basins was lower in the Neopleistocene than in the Eopleistocene (average IQ_{2+3}/IQ_1 for the World Ocean is 0.7). This parameter shows approximately equal decrease in all oceans. This fact once more confirms the assignment of terrigenous sediments and polygenic clays to different groups of oceanic deposits.

Carbonate sediments. In this section, we consider data on the nanoplankton and foraminiferal–nanoplakton sediments that compose the most part of pelagic carbonate deposits of the World Ocean. Data on these sediments are available for all main oceanic basins. Marly sediments and carbonate turbidites will be mentioned only in the context of carbonate accumulation in the Atlantic Ocean, because they were not distinguished specially and mapped in other oceans.

In general, the main varieties of pelagic carbonate deposits are accumulated at low and moderate latitudes, and their distribution is controlled by the interaction of three main factors: productivity of carbonate plankton organisms, dilution by material of different genesis (for instance, terrigenous or siliceous), dissolution in water sequence and on the floor surface. The foraminiferal–plankton sediments are usually accumulated at shallower depths than nanoplankton ooze.

Nanoplankton ooze. These sediments in the pelagic zones of the World Ocean are the second in mass after terrigenous turbidites. During Pleistocene, their mass sharply increased per time unit in the Pacific Ocean ($IQ_{2+3}/IQ_1 = 3.6$), remained practically unchanged in the Indian Ocean, and decreased two times in the Atlantic Ocean. This resulted in the $IQ_{2+3}/IQ_1 = 0.9$ for the World Ocean.

Foraminiferal–nanoplankton ooze. These sediments are presumably third in mass in the pelagic regions of the World Ocean. In the Pleistocene, their mass per time unit weakly increased in the Pacific Ocean, sharply increased ($IQ_{2+3}/IQ_1 = 4.4$) in the Indian Ocean, and significantly decreased ($IQ_{2+3}/IQ_1 = 0.3$) in the Atlantic Ocean. The average value of this parameter for the World Ocean is 0.96.

A strong decrease of the mass of marly sediments per time unit ($IQ_{2+3}/IQ_1 = 0.2$) and some increase of carbonate turbidites ($IQ_{2+3}/IQ_1 = 1.4$) during Pleistocene was noted in the Atlantic Ocean. It was previously mentioned (Levitan and Gel'vi, 2016) that carbonate turbidites in composition are ascribed to a group of carbonate deposits, but in terms of genesis they are closer to terrigenous sediments, which is supported by the above mentioned IQ_{2+3}/IQ_1 ratio.

Siliceous sediments. Siliceous sediments are represented by diatom ooze and clays, as well as by radiolarian–diatom ooze. They play insignificant role in the general structure of sediment mass in the pelagic zone of the World Ocean. In general, in the pelagic zones of the World Ocean, diatom sediments predominate in so-called northern (in the Pacific Ocean) and southern (in all oceans) opal belts of silica accumulation. The radiolarian–diatom sediments are wider distributed but are usually confined to the lower latitudes, including the equatorial opal belt in the Pacific and Indian oceans. These sediments usually contain more silica, but have the lower moisture and higher density than diatom sediments. Corrected data on the Pacific Ocean are shown in Table 4 (Levitan, 2016).

Diatom ooze and clays. The mass of diatom sediments per unit during Pleistocene decreased in the Pacific and Indian oceans, and preserved approximately at the same level (may be, slightly increased) in the Atlantic Ocean. In general, the IQ_{2+3}/IQ_1 ratio for diatom ooze in the World Ocean is 0.8, i.e., the global intensity of their accumulation in the Eopleistocene was slightly higher than in the Neopleistocene. It is highly possible that new data on the southern belt of silica accumulation in the Pacific sector will increase data on diatom oozes in the Neopleistocene as compared to the Eopleistocene (see Discussion).

Radiolarian–diatom ooze. The content of these sediments in the Atlantic Ocean is too low to show in our maps. The mass of radiolarian–diatom ooze per time unit in the Pacific and Indian oceans in the Neopleistocene was much higher as compared to the Eopleistocene, especially in the Indian Ocean ($IQ_{2+3}/IQ_1 = 7.1$). This value in the World Ocean on average is 3.7.

DISCUSSION

The total area of the oceanic pelagic zones discussed in the text (Table 1) is 274033 thou. km^2, which accounts for 53.7% of the Earth's surface. This justifies our attempt to interpret the obtained results on a global scale. In this case, the land area (continental blocks) should be considered as the water drainage area for the World Ocean as the sedimentation basin (even with allowance for 11% drainless areas of the total land area). Hence, understanding the terrestrial geological process is required to provide insight into pelagic sedimentation of the World Ocean.

Neotectonics of Continents

From our point of view, of great importance is the reliably proved existence of neotectonic epoch recorded since mid-Cenozoic, Oligocene, for continental blocks (Levitan, 1992; Trifonov and Sokolov, 2015). This epoch was accompanied by the increasing rate of tectonic uplifting, which was strongly intensified in the Pliocene–Quaternary, and locally, in the Quaternary. Recent generalizations (Trifonov, 1999, 2016; Trifonov et al., 2002; Ollier, 2006; Herman et al., 2013; Trifonov and Sokolov, 2015) indicate that typical uplifting rates are within 0.2–2.0 mm/yr; their highest rates are typical of the high mountain belts: Alpine–Himalayan, Altai–Stanovoy, northeast Asian, western North and South America ones. In addition to them, tectonic uplifts with amplitude above 1 km spanned in the Pliocene–Quaternary time the East African rift system, while vast platform areas were involved in less significant uplifting. Calculations indicate that up to 70–90% of continents were involved in tectonic movements during the last 5–3 Ma.

Neotectonic uplifting is accompanied by several important geological consequences: (1) increase of land area subjected to erosion, mechanical and chemical weathering; (2) development of continental glaciations. Below, we briefly consider them.

An increase of land area. Erosion and mechanical weathering with increasing land area subjected to these processes lead to the increase of solid sediment fluxes into accumulation basins. Available data (Table 5) indicate a positive correlation between solid and ionic runoff from continents. Correlation coefficient is calculated to be 0.76. Climatic features also should be taken into account. For instance, it was proved that the equatorial humid zone (amounting only 26% of continental surface) supplies 76% of suspended particulate matter (Lisitzin, 1991). Most part of dissolved matters, including those determining plankton feed in the photosynthesis zone (phosphates, nitrates, etc), are also supplied from this zone.

It is known that only about 7–8% of solid terrigenous material supplying from continent reaches oceanic pelagic zones (Lisitzin, 1991). Other sediments are precipitated on submarine continental margins, including three levels of avalanche sedimentation (Lisitzin, 1988). Therefore, a direct comparison of the masses of terrigenous material that supplied from continents, on the one hand, and material that precipitated in the pelagic oceanic zones, on the other hand,

Table 5. Recent annual continental runoff in ocean (Mt) (modified by Alekin, 1966; Lopatin, 1950)

Continents	Runoff of particulate matter	Ionic runoff
Asia	7445	583
Africa	1395	425
North America	1503	421
South Africa	1676	442
Europe	420	222
Australia	257	79

is not correct. At the same time, their qualitative comparison is quite possible.

Above described distribution of the Pleistocene terrigenous turbidites indicates a leading role of tectonics (relation of the Amazon River heads with Andes, the heads of the great Indian rivers with Himalayas, and turbidites of the northeastern Pacific Ocean with Cordilleras). Certain role is also played by climatic features. For instance, the water drainage areas of the Amazon and Congo rivers are located in the equatorial humid zone.

In the paper dedicated to the Atlantic Ocean, Levitan and Gel'vi (2016) have already stated that the formation of turbide currents flows on slopes is mainly determined by critical masses of terrigenous matter, i.e., the possibility of formation of mud flows which later are transformed into turbidites increases with a sharp increase of sediment influx to the shelf margin and the upper part of continental slope. This fact presumably determined the above mentioned sharp increase of mass of terrigenous turbidities per time unit for all oceans in the Neopleistocene as compared to the Eopleistocene. Additional role belongs to sea level fluctuations related to the formation of continental glacial sheets and their thawing, as well as earthquake serving as triggers. By the way, the role of earthquakes in the traditional concepts on turbidites is probably strongly overestimated. In any case, the observations on the East African continental slope showed that mud flows were formed not only above earthquake sources but also in aseismic zones (Liu et al., 2016).

In the Neopleistocene as compared to the Eopleistocene, the role of terrigenous turbidites increased relative to hemipelagic clays in the hemipelagic zones of all oceans, thus reflecting a radical change of separate agents of the transportation of terrigenous material due to the drastic increase of its supply from continents. It is pertinent to mention that obtained data indicate that the ratio of water drainage area to the ocean basin area (B/L, Lisitzin, 1974) played no significant role in terrigenous process. An important role belongs to the neotectonic and climatic features of continents.

Proved phenomenon of intense terrigenous influx during neotectonic epoch (including Pleistocene) is confirmed by Sr isotope study of carbonate shells of marine organisms (Veizer et al., 1999). It was previously shown that beginning from the mid-Cenozoic, the mass of terrigenous matter per time unit began increase simultaneously on continents and in oceans (Levitan, 1994).

In relation with the noted growth of not only mechanical but also chemical weathering with an increasing rate of neotectonic uplifting, atmospheric CO_2 contributed significantly in chemical weathering of silicate and aluminosilicate rocks, especially basalts. Special studies showed a directed increase of atmospheric carbon dioxide bound in the processes of the indicated chemical weathering during Cenozoic (Moore et al., 2015), i.e., weathering favored some decrease of partial CO_2 pressure in atmosphere.

The CO_2 content in the atmosphere also decreases due to the increase of photosynthesis intensity and, hence, the primary production on continents in the Cenozoic (Lapo, 1987; Ronov, 1993). At last, CO_2 emission decreases with formation of oceanic lithosphere owing to the decrease of lithosphere generation since the mid-Cenozoic (Conrad and Lithgow-Bertelloni, 2007). The presented examples of change in CO_2 content owing to different processes are not occasional: many researchers, including Markov (1960), Ronov (1993), and others, believe that this greenhouse gas plays an important role in climatic changes. Regardless of proportions between CO_2 content in atmosphere and its temperature, beginning from the mid-Cenozoic, the lowered CO_2 contents coincide with cooling stages, while its elevated contents, with warming. This observation is true for both atmosphere and waters of the World Ocean (Makkaveev and Bol'shakov, 2015). Insignificant cooling of the surface water leads to the increase of CO_2 solubility and thus, more intense sink of atmospheric carbon dioxide in the World Ocean. A decrease of its partial pressure in atmosphere in combination with a decrease of moisture leads to the decrease of the greenhouse effect and facilitates further decrease of air temperature (Markov, 1960). An increase of temperature of surface waters of the World Ocean leads to opposite effects. The noted processes are tightly related to the below discussed glaciation problems.

Cenozoic glaciation. Let us consider the second important consequence of neotectonic orogenesis:

relation with glaciation. The effect of orogenesis is long known. Let us remember, for instance, the relationship of the Tibet orogenesis with establishing monsoon conditions in Southeast Asia or relation of Himalayan orogenesis with the emergence of the South Asian monsoon. The emergence of mountain chains and lands changes the fields of pressure, temperature and moisture of atmosphere, as well as directly affects the atmospheric circulation. In the troposphere, the plot of cooling with height (0.3°C per each 100 m) fits ideally the plot of decreasing the water vapor concentration. It is clear therefore that few kilometers uplifting of the area provides the prevalence of dry cold climate favorable for the formation of glaciers, especially at the polar latitudes. Owing to the intense atmospheric circulation, such climate rapidly propagated over the area. This point of view exists for a long time and, in particular, was mentioned by Markov (1960).

The Cenozoic glacial era (Chumakov, 2015) began at the Eocene–Oligocene boundary by the continental glaciation of East Antarctica. The first signs of glaciation were noted in the Gamburtsev and Transantarctic mountains, while more than half of the Antarctic area by the end of Eocene was a mountain country with altitudes over 1000 m (Wilson et al., 2011). The next important frontier in the development of continental glaciation in the Southern Hemisphere was Middle Miocene (a frontier around 14 Ma), when glaciation was displaced to West Antarctica. Approximately at the same time (Darby, 2008), pack ice appeared in the Arctic Ocean. The last important frontier in the development of the Cenozoic glacial era is 3 Ma, when polythermal glaciers in East Antarctica gave way to the glaciers with solid contact between ice and underlying rocks (Ehrmann et al., 1990), and slightly later onset of continental glaciation in the Northern Hemisphere, which was locally directly related to neotectonic uplifting (Knies et al., 2014).

Hence, there are grounds to believe that the Cenozoic glaciation was primarily caused by neotectonic upifting, and the propagation of increasing cooling was accompanied by the aridization owing to the decrease of the content of major greenhouse gas—water vapor (Eronen et al., 2012). This conclusion is consistent with the known role of cosmic factors in the evolution of the Cenozoic glaciation, however indicates that launching and the main trends of this process are caused by terrestrial (geological) reasons, while cosmic factors (oscillations of insolation and orbital parameters) played an important role in modulating these trends.

The influence of climate on the accumulation of Pleistocene pelagic terrigenous sediments is well illustrated by the development of the marine–glacial sediments (Table 4). It is pertinent to mention that relatively small mass of these sediments in the Indian ocean as compared to other oceanic basins is presumably explained by sufficiently weak dynamics of the continental East Antarctic ice sheet (with solid contact with underlying bedrocks) as compared to the powerful dynamics of the continental West Antarctic glacial sheet of polythermal type (Ingolfsson, 2004). The same conclusion was made for the Northern Hemisphere concerning the greater stability of the Greenland glacial sheet affected by the cold East Greenland current as compared to the British, Scandinavian, and Barents–Kara ice sheets affected by warm Atlantic waters (Levitan and Lavrushin, 2009).

Thus, data on the pelagic regions of the World Ocean allowed us to confirm the previously established trends of increasing neotectonic activity and intensity of glaciation of continental blocks in the Pleistocene.

Pelagic Biogenic Sedimentation

This section is dedicated to the discussion of the general regularities of biogenic sedimentation, including data on organic matter, biogenic opal, and carbonate sediments.

Silica accumulation. *A*s shown in the previous section (Tables 3, 4), data on silica accumulation indicate a general increase of accumulation of biogenic opal in the Pleistocene. It was proved that the productivity of siliceous plankton organisms is tightly related to the primary oceanic production. Available data on C_{org} (in percents and absolute masses) in the Cenozoic sediments of the World Ocean (Trotsyuk, 1976; Levitan et al., 1980; Romankevich and Vetrov, 1997; Baturin, 2008), and on the reconstruction of paleoproductivity (Levitan, 1992) showed that the paleoproductivity of the World Ocean increased since mid-Cenozoic. This was accompanied by the increasing consumption of atmospheric CO_2 for photosynthesis.

The study of ocean chemistry revealed that influx of so-called biogenic (nutrients) matters, (for instance, phosphates, nitrates, dissolved silica) is compensated by their accumulation in the bottom sediments of the World Ocean (Ivanenkov, 1979). The excess influx of phosphates over precipitation in the modern epoch is related to their removal owing to anthropogenic activity (Savenko and Savenko, 2007). This balance was maintained in the Pleistocene. Thus, it is not surprising that a revealed increase of mass of biogenic opal per time unit in the Neopleistocene as compared to the Eopleistocene coincides with a trend of increasing neotectonic activity, which led to the increase of runoff of dissolved (including nutrient) matters from continents into ocean. This is the temporal aspect of the problem.

As to spatial aspect, it should be remind that nutrients were supplied from land into ocean mainly in zones of moderate humid and, especially equatorial humid climate (Lisitzin, 1988). As demonstrated in our publications, the latitudinal belts of silica accumulation similar to those of the present epoch existed in the oceanic pelagic zones in the Pleistocene. Geographically, they represent a peculiar continental continuation of the humid climatic areas regardless of the interpretation of this phenomenon: climatic (A.P. Lisitzin) or hydrodynamic (N.M. Strakhov).

Data on the Pleistocene of the Pacific and Indian oceans were used to put forward a concept of "two oceans"—"ice" and "non-ice" (Levitan, 2016), which suggests in particular that the accumulation of radiolarian–diatom oozes at the moderate and low latitudes in the Neopleistocene was higher than in the Eopleistocene. In contrast, the northern Pacific Ocean and southern Indian Ocean show a tendency of increasing mass of diatom ooze per time unit in the Eopleistocene as compared to the Neopleistocene. Data on the Atlantic Ocean (Levitan and Gel'vi, 2016) made it possible to specify this scheme. In the areas of the development of dynamic continental ice sheets with polythermal glaciers (West Antarctica), the supply of dissolved silica acid in ocean was presumably slightly higher in the epochs of deglaciations and terminations during general glaciation and, hence, in the Neopleistocene, as compared to the development areas of weakly mobile East Antarctica glacial sheets, where removal of dissolved silica acid predominated in the Eopleistocene.

Thus, in general, in spite of the existence of the known conveyor of thermohaline circulation in the World Ocean, which provided the water exchange between oceanic basins for approximately 1.5 ka, and concept of nutrient influx in the photosynthesis zone, the sources of these matters are related to the areas of their consumption. We believe that this phenomenon is related to the well known hydrogeochemical heterogeneity of oceanic basins (Ragueneau et al., 2000), which was caused by geological and geochemical features of their drainage basins and preserved for a long time (as minimum, in the Quaternary period).

Carbonate accumulation. If, as shown above, the paleoproductivity during Pleistocene in the pelagic zones of the World Ocean increased, this would affect also the accumulation of planktonogenic carbonate ooze. Indeed, data on the Pacific and Indian oceans (Table 4) in general confirm this assumption. More careful study of the problem revealed interesting regional features: the Pacific Ocean was characterized by the most intense growth of nanoplankton ooze mass per time unit owing to the large depth of basins, while foraminiferal–nanoplankton oozes were most developed in the Indian Ocean. The situation in the Pacific Ocean may be explained by not only redeposition of the fine nanoplankton material from rises (Levitan et al., 2013), but also by expansion of sedimentation area of these sediments at their sufficiently weak dissolution. It was already concluded for the Indian Ocean that the dissolution of nanoplankton oozes in the Neopleistocene increased as compared to the Eopleistocene (Levitan et al., 2014).

The Atlantic Ocean shows principally different pattern (Levitan and Gel'vi, 2016): in the Neopleistocene, all types of carbonate oozes were subjected to significant dissolution, with variations of IQ_{2+3}/IQ_1 ratios in compliance with bathymetric position of certain sediments. On the basis of analysis of carbonate content in the Quaternary sediments obtained from several deep-water boreholes in the equatorial zones of the Pacific and Atlantic oceans (Sexton and Barker, 2012), the sharp increase of this dissolution began in the Atlantic Ocean at 1.1 Ma, i.e. during the Middle Pleistocene transition. Correspondingly, we believe that data on residual masses of carbonate sediments per time unit in the Atlantic Ocean (Table 4) recorded the interaction of carbonate fluxes from surface water, which increased in the Neopleistocene, and much stronger dissolution of carbonates by reaction cold waters from the near-bottom and deep-water Atlantic masses. The opinion concerning increasing productivity of carbonate organisms in the Atlantic Ocean during Pleistocene is indirectly confirmed by data on not only Pacific and Indian oceans, but also on the carbonate turbidites of the Atlantic Ocean (Table 4). The assumption that the generation of aggressive near-bottom and deep waters was intensified at the high latitudes in the Neopleistocene is confirmed by data on the simultaneous sharp increase of the mass of marine–glacial sediments per time unit. An increase of the rate of contour currents in the Atlantic Ocean during Eopleistocene indicates a link of this parameter with intensity of circulation in the high-latitude sources of deep waters generation, rather than with their volume.

Thus, oceans are arranged in the following order on the basis of increasing influence of near-bottom waters on the carbonate sediments during Pleistocene: Pacific Ocean–Indian Ocean–Atlantic Ocean. This series is quite systematic: the largest Pacific Ocean contained only one source of these waters, in its southern part, in the Ross Sea; one source also existed in the smallest Indian Ocean, Prydz Bay; in contrast, three huge sources existed in the Atlantic Ocean: in the Weddell Sea in the south, and in the Labrador Sea and the Norwegian Greenland basin in the north. In the Atlantic Ocean, all sources were confined to the development zones of most dynamic continental ice sheets.

One more important point, which should be taken into account in analyzing the Pleistocene history of the pelagic carbonate accumulation, is the bottom topography, more exactly, the ratio of areas of different rises to those of deep-water basins. With decrease of this parameter, as for the modern period (Harris et al., 2014), the ocean can be arranged as follows: Atlantic Ocean–Indian Ocean–Pacific Ocean. As seen from Table 4, the same order is typical of the decreasing the total mass of carbonate ooze per time unit both for the Neo- and Eopleistocene.

Pelagic Clays

Data obtained on pelagic clays (Table 4) clearly demonstrate two features: (1) sediment mass per time unit in the Pacific Ocean in the Pleistocene was few times higher as compared to that of the Indian and Atlantic oceans; (2) this parameter decreases from the Eopleistocene to Neopleistocene in all oceans. The first feature is determined by the size and bottom topography of ocean (see above). The second feature is presumably caused by the decrease of accumulation area of pelagic clays during Pleistocene owing to the expansion of accumulation areas of terrigenous and biogenic sediments.

CONCLUSIONS

The analysis of lithofacies maps of the pelagic zones of the Pacific (Levitan et al., 2013), Indian (Levitan et al., 2014), and Atlantic oceans (Levitan and Gel'vi, 2016) for the Neo- and Eopleistocene using the volumetric method of Ronov allowed us to draw some global trends and regional features of pelagic sedimentation in the World Ocean.

Among global trends is the presence of the present-day main structure of pelagic sedimentation in the Pleistocene. It was previously shown that such structure existed in the World Ocean at least since Cretaceous (Levitan, 1998). In addition, the masses of terrigenous and siliceous sediments per time unit clearly increased in the Neopleistocene as compared to the Eopleistocene. This phenomenon is best expressed for the terrigenous turbidites, marine–glacial sediments, and radiolarian–diatom ooze. This is caused by neotectonic uplifting of a land and related bipolar glaciation of continents and oceans. One more global trend is a decrease of mass of pelagic clays per time unit during Pleistocene in response to the dilution by sedimentary material of different genesis.

The carbonate accumulation in the Pacific and Indian oceans also corresponds to the indicated regularity, while the Atlantic Ocean shows some peculiarities caused by a sharp growth of carbonate dissolution by aggressive near-bottom and deep waters in the Neopleistocene. Regional features include differences in the hydrochemical structure, which are caused by specifics of the geological and geochemical structure of the water drainage areas of different oceans. In addition, oceans also differ in the bottom topography, which in particular is expressed in the accumulation of carbonate ooze and pelagic clay. It was revealed that dynamics of continental glacial sheets in the Pleistocene played an important role, affecting, for instance, the accumulation history of marine-glacial sediments and diatom oozes.

Pelagic sedimentation also differs during different glacial–interglacial cycles and marine isotope stages. This problem is beyond scope of this paper, but is very brightly expressed in all oceans.

The geological history of continents played significant role in the Pleistocene evolution of pelagic sedimentation in the World Ocean. The main conclusion of the study is the fact that the described variations of quantitative parameters of pelagic sedimentation in the Pleistocene completely correspond to the evolution trends existing since mid-Cenozoic.

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