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Quantitative Parameters of Pleistocene Pelagic Sedimentation in the Atlantic Ocean

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Abstract—Lithological–facies maps of Eopleistocene and Neopleistocene sediments (with 10 and 20 m isopachs) are compiled for the pelagic part of the Atlantic Ocean based on materials recovered by 283 ocean drilling sites. Data for both maps were calculated using A.B. Ronov's volumetric method. The calculated results include such quantitative sedimentation parameters of major sediment types as the areas covered by these sediments, their volumes, masses of the dry sedimentary material, and masses of sedimentary material deposited per specified time unit. These parameters are compared for both Eopleistocene and Neopleistocene time, and the data are utilized to separately interpret the results for terrigenous, carbonate, and siliceous sediments. The supply of terrigenous material is proved to have been enhanced in the Pleistocene as a result of both tectonic uplift of continents and climatic changes, including intensification of continental glaciation at high latitudes in both hemispheres. The growth in the productivity of carbonate plankton was overridden by growing generation of bottom and deep water masses and ensuing intensification of the dissolution of pelagic carbonates. The productivity of siliceous plankton practically did not change, perhaps, because of a favorable combination of the supply of dissolved silica and other nutrients from both West and East Antarctica.

Keywords: bottom sediments, pelagic zone, Atlantic Ocean, Eopleistocene, Neopleistocene, surface areas, volumes, masses, sedimentation intensity, contourites, turbidites, carbonate oozes, siliceous oozes, glacial-marine sediments

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INTRODUCTION

Several Soviet and Russian prominent lithologists and geochemists (A.D. Arkhangel'skii, N.M. Strakhov, A.B. Ronov, P.L. Bezrukov, and A.P. Lisitsyn) are known to have paid much attention to quantifying parameters of sedimentation. The processes of Mesozoic–Cenozoic sedimentation in the Atlantic Ocean were also described in several publications with the application of the mass accumulation rate method (Emel'yanov et al., 1989; Trimonis, 1995; Steinberg, 1989; Thiede and Ehrmann, 1989). Regretfully, no attempts have ever been made to quantify the evolution of pelagic sedimentation in the Atlantic Ocean in the Pleistocene. This paper presents the results of our continuing research aimed at quantitative evaluation of sedimentation parameters in the oceanic pelagic zone based on A.B. Ronov's volumetric method (Levitan et al., 2013, 2014; Levitan, 2016).

MATERIALS AND METHODS

The spatiotemporal limits of the subject of this publication is outlined as follows: herein we discuss the pelagic zone of the Atlantic Ocean, including the abyssal plains and (in this only instance) continental rise. The regions of active continental margins (Caribbean and Scotia seas) and the Gulf of Mexico are not included in the study area. Furthermore, we also exclude from our analysis the shelves and continental slopes of passive margins. The Atlantic Ocean is bordered by the Fram Strait in the north and the continental margin of the Weddell Sea in the south.

We do not discuss all sediments of the modern Quaternary system (Gradstein et al., 2012) at these areas but only those of the late and mid-Pleistocene, i.e., Neopleistocene Q_{2+3} (the "boundary line" is drawn at 0.0117–0.130 Ma for Upper Pleistocene sediments and at 0.130–0.773 for the Middle Pleistocene ones) and also sediments of the Calabrian Stage of the Lower Pleistocene (0.773–1.80 Ma), i.e., Eopleistocene Q_1 (Head and Gibbard, 2015). We do not consider herein sediments of the Gelasian Stage (1.80–2.58 Ma), i.e., Paleopleistocene (?) because this stage was invented as a part of the Quaternary only in the early 21st century, and all earlier DSDP and ODP reports made use of a geological chart with the lower Pleistocene boundary set at 1.80 Ma. The age for the boundaries is assumed at roughly 0.01–0.8 Ma for the

Neopleistocene and 0.8–1.8 Ma for the Eopleistocene. This means that the boundary line between the Neo- and Eopleistocene corresponds to the boundary between the Brunhes and Matuyama chrons in the magnetostratigraphic scale, and the lower Eopleistocene boundary corresponds to the end of the Olduvay subchron (Gradstein et al., 2012).

Methodologically, we applied N.M. Strakhov's (1945) comparative lithological, I.O. Murdmaa's (1987) facies analysis of oceanic sediments, and A.B. Ronov's (1949) volumetric method. For comparison, we considered a map of the lithological composition of modern surface-layer sediments (Emel'yanov et al., 1989–1990).

Our estimates were made based on materials recovered by 283 deep-sea drilling sites, which were drilled in 1968–2014 inclusive and penetrated Eo- and Neopleistocene sediments (Fig. 1) and provided information on the lithology and stratigraphy of the sediments and on their thicknesses and physical characteristics (www.iodp.org). We used these materials to compile 1 : 35000000 lithological-facies maps for the Eopleistocene (Fig. 2) and Neopleistocene (Fig. 3) in azimuthal equal-area equatorial projection. These are our first maps whose legends include turbidites of two types: terrigenous and carbonate. The maps reflect modern data on the distribution of contourites in Atlantic drifts (Rebesco et al., 2014) and bottom topography data presented on the latest maps for the North and South Atlantic (Harris et al., 2014). Both maps show 10 and 20 m isopachs and the hemipelagic and miopelagic zones, whereas the eupeliagic regions are negligibly small in area and are thus not shown.

Both maps were analyzed using the volumetric method suggested by A.B. Ronov to derive data on the surface areas (in thous. km^2) and volumes (in thous. km^3) of the mapped genetic types of the sediments and the lithological complexes, with these data then recalculated into the masses of dry sedimentary material (in trillion tons) and the masses of sediments deposited per time unit (trillion tons per Ma).

RESULTS

The map area for Eopleistocene sediments (Fig. 2) is 71417 thous. km^2, including 31093.0 thous. km^2 of the miopelagic facies zone and 36747.4 thous. km^2 of the hemipelagic zone. The rest of the area corresponds to the regions of the Neopleistocene–Holocene crust in the Mid-Atlantic Ridge.

According to their surface areas in the miopelagic zone, the most abundant sediments are nanoplankton–foraminiferal oozes (14142.4 thous. km^2), and the second and third most widely spread sediments are red (miopelagic) clays (6993.7 thous. km^2) and calcareous nanoplankton oozes (1974.4 thous. km^2). The regions composed of intercalating sediments of various type make up 5.47% of the total area of this facies zone. The total volume of Eopleistocene sediments in the miopelagic zone amounts to 780.4 thous. km^3. The volumetric proportions of the sediments are as follows: nanoplankton–foraminiferal ooze 54.1%, red clays 26.7%, nanoplankton oozes 12.1%, diatom oozes 2.5%, calcareous turbidites 2.4%, and terrigenous turbidites 0.9%.

In the hemipelagic zone, the most widely spread sediments are glacial–marine ones (13876.3 thous. km^2), which are followed by nanoplankton–foraminiferal oozes (8757.6 thous. km^2), diatom oozes and clays (4062.8 thous. km^2), nanoplankton oozes in zones of glacial–marine sedimentation (5580.9 thous. km^2), and areas made up of intercalating sediments of different type, which account for 15.07%. The total volume of the sediments is 1490.7 thous. km^3. The volumetric proportions of the sediments are as follows: diatom oozes and clays 16.2%, nanoplankton–foraminiferal oozes 14.6%, contourites 13.3%, terrigenous turbidites 13.0%, nanoplankton oozes 12.9%, glacial–marine silty clays 7.7%, calcareous oozes 7.6%, carbonate turbidites 8.1%, hemipelagic clays outside the glacial–marine sedimentation zone 6.0%.

Data on the areas for Neopleistocene are as follows: the total map area (Fig. 3) is 70579 thous. km^2, the area of the miopelagic facies zone is 31880.9 thous. km^2, and that of the hemipelagic zone is 37 269 thous. km^2. The area of erosion regions increased, compared to that in the Eopleistocene, to 316.9 thous. km^2.

The most widely spread sediments of the miopelagic zone are nanoplankton–foraminiferal oozes (17175.7 thous. km^2), which are followed by red clays (7631.2 thous. km^2) and finally nanoplankton oozes (3960.9 thous. km^2); the areas of interbedding sediments of various type make up 6.20% of the total area of this facies zone. The total volume of Neopleistocene sediments in the miopelagic zone is 400.1 thous. km^3. The volumetric proportions of the sediments are as follows: nanoplankton–foraminiferal oozes 50.2%, red clays 30.2%, nanoplankton oozes 13.3%, carbonate turbidites 2.5%, terrigenous turbidites 1.4%, diatom oozes and clays 1.4%, glacial–marine sediments 0.8%. Compared to the Eopleistocene, the structure of the composition of sediments in the miopelagic facies zone had changed very insignificantly, whereas the total volume of the sediments had notably decreased.

In the hemipelagic facies zone, the most widely spread sediments are nanoplankton–foraminiferal oozes (8799.1 thous. km^2), and the second and third ones are diatom clays (6982.9 thous. km^2) and contourites (4392.3 thous. km^2). Areas where sediments of various type intercalate amount to 9.89%. The total volume of the sediments is 1316.2 thous. km^3. The volumetric proportions of the sediments are as follows: glacial–marine silty–pelitic oozes 24.7%, terrigenous turbidites 22.8%, diatom oozes and clays 16.9%, con-

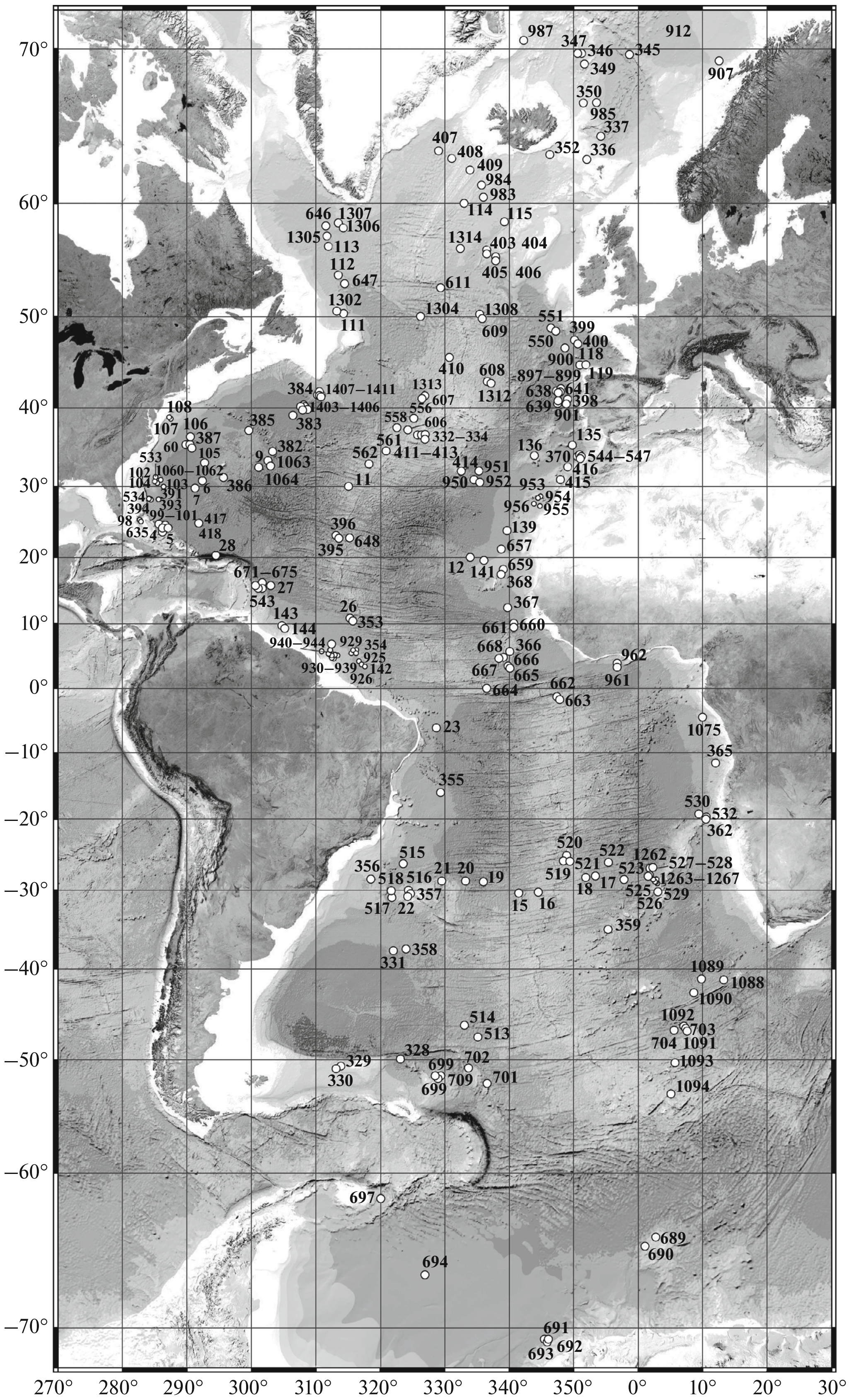

Fig. 1. Location map of deep-sea drilling sites in the Atlantic Ocean whose materials were utilized in this study.

Table 1. Volume (V, thous. km^3), masses of dry sedimentary material (M, tril. tons), and masses of sediments deposited per specified time unit (I, tril. tons/Ma) of Pleistocene pelagic sediments in the Atlantic Ocean

Sediment	Stratigraphy	V	M	I	I_{Q2+3}/I_{Q1}
Terrigenous turbidites	Q_{2+3}	305.5	363.5	460.1	18.7
	Q_1	20.1	24.6	24.6	
Hemipelagic clays	Q_{2+3}	101.3	36.8	46.5	2.7
	Q_1	47.6	17.3	17.3	
Glacial-marine sediments	Q_{2+3}	327.9	278.7	352.8	2.8
	Q_1	115.8	125.0	125.0	
Miopelagic clays	Q_{2+3}	121.3	60.7	76.8	0.6
	Q_1	208.1	135.3	135.3	
Nanoplankton oozes	Q_{2+3}	116.8	104.6	132.5	0.3
	Q_1	402.15	418.0	418.0	
Foraminiferal–nanoplankton oozes	Q_{2+3}	297.8	170.7	216.1	0.5
	Q_1	640.95	395.7	395.7	
Marly sediments (30–70% $CaCO_3$)	Q_{2+3}	22.1	10.1	12.8	0.2
	Q_1	114.3	63.4	63.4	
Carbonate turbidites	Q_{2+3}	27.4	26.5	33.5	1.4
	Q_1	27.1	23.5	23.5	
Diatom oozes and clays	Q_{2+3}	195.8	71.0	90.0	1.1
	Q_1	224.2	81.0	81.0	
Contourites	Q_{2+3}	187.2	168.4	213.2	0.96
	Q_1	199.1	221.0	221.0	

tourites 14.2%, hemipelagic clays outside the glacial–marine sedimentation zone 7.7%, nanoplankton–foraminiferal oozes 7.4%, nanoplankton oozes 4.4%, and carbonate turbidites 1.3%. Compared to the Eopleistocene, the structure of the composition of sediments of this facies had significantly changed, and their total volume had insignificantly decreased.

We utilized data on the relative water content and bulk density of natural sediments to recalculate these volumes into masses of dry sedimentary material (Levitan et al., 2013), which were then recast into masses of sediments deposited per specified time unit (Table 1) using the aforementioned data on the duration of the Eo- and Neopleistocene.

DISCUSSION

Terrigenous Sediments

In Table 1, this group comprises turbidites, hemipelagic clays, and glacial-marine sediments. Note that the I_{Q2+3}/I_{Q1} ratio of all of the sediments (Table 1) is typically greater than 1.0. This means that the influx of terrigenous material was higher in the Neopleistocene than in the Eopleistocene, with the accumulation of terrigenous turbidites increasing most significantly.

Turbidity currents that deposit turbidites are formed on the continental slope and, more rarely, on the slopes of oceanic rises and ridges of various nature. These currents start to flow when a certain “critical mass” of water-rich sedimentary material is accumulated, with the amount of the material depending on the angle of the slope, and with the currents sometimes triggered by earthquake shocks. The main reasons for the enhancement of the accumulation of terrigenous turbidites in the Pleistocene seem to have been the neotectonic uplift of the water catchment areas, first of all, in high-mountain regions (Herman et al., 2013). This follows, for example, from the significant enhancement in the accumulation turbidite material supplied by the Amazon River due to the tectonic uplift of the Andes. The neotectonic uplift then

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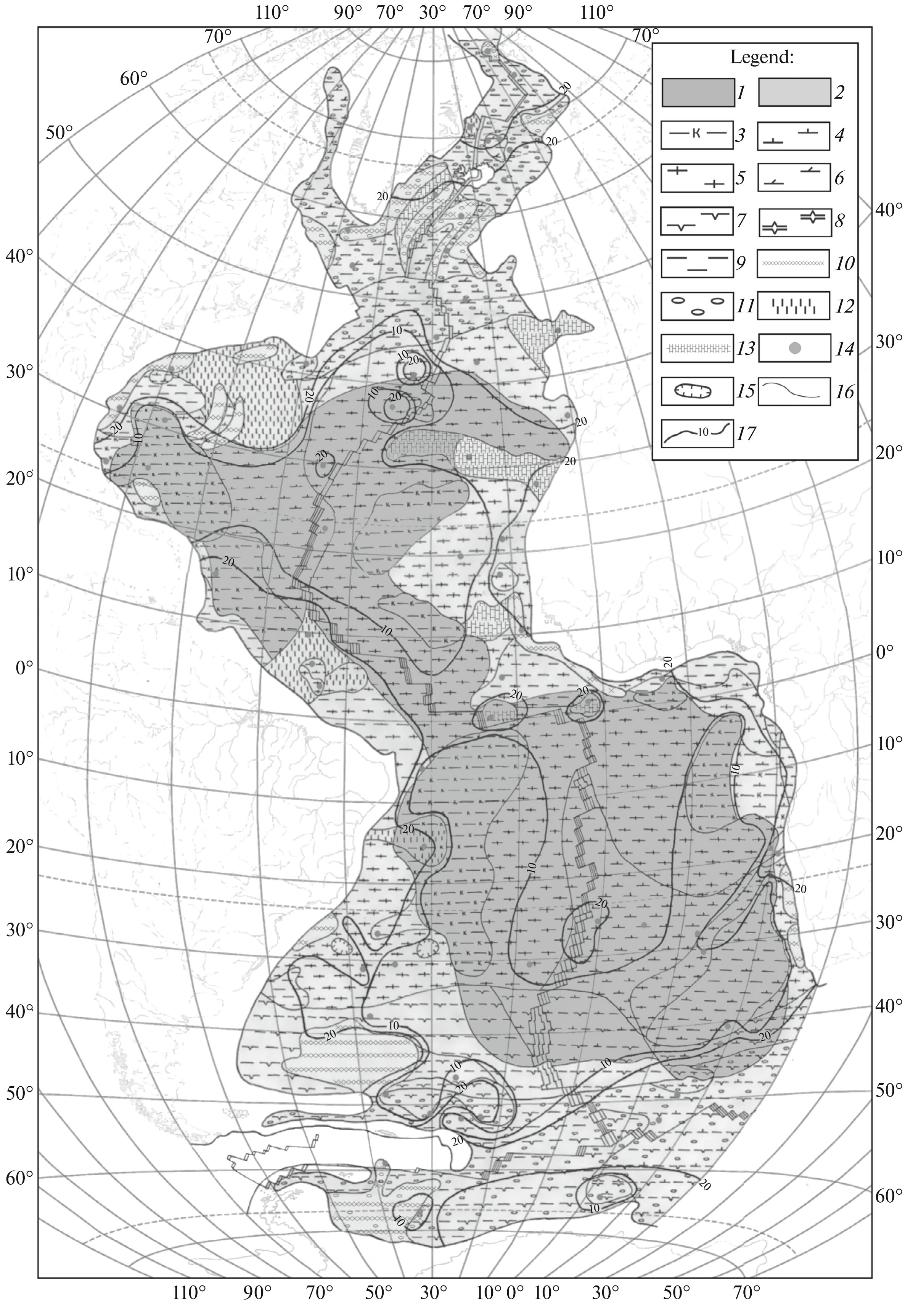
Fig. 2. Lithological–facies map of pelagic Eopleistocene sediments in the Atlantic Ocean. (*1*) Miopelagic facies zone; (*2*) hemipelagic facies zone; (*3*) red (miopelagic) clays; (*4*) nanoplankton oozes; (*5*) foraminiferal–nanoplankton oozes; (*6*) calcareous oozes; (*7*) diatom oozes; (*8*) radiolarian–diatom oozes; (*9*) hemipelagic clays; (*10*) contourites; (*11*) ice-rafted debris (IRD); (*12*) terrigenous turbidites; (*13*) carbonate turbidites; (*14*) some ODP holes; (*15*) sediment-free areas; (*16*) lithological boundaries; (*17*) isopachs.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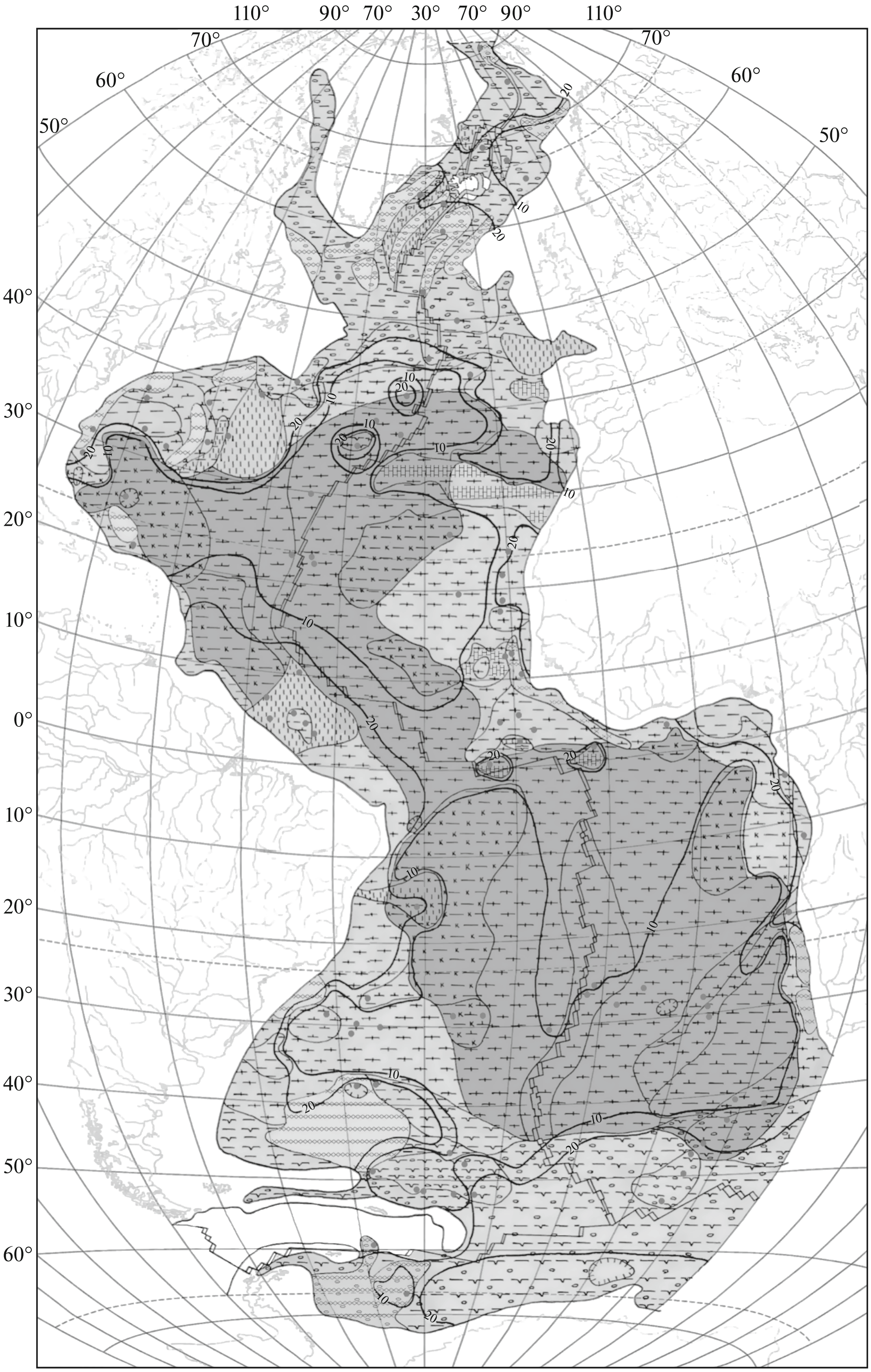

Fig. 3. Lithological–facies map of pelagic Neopleistocene sediments in the Atlantic Ocean. See Fig. 2 for symbol explanations.

also involved several low mountain ranges, such as the Appalachians (Miller et al., 2013), and plains. Obviously, neotectonic uplift enhanced erosion, first of all, physical weathering. Another important reason for the amassing of terrigenous turbidites in the Pleistocene was significant changes in the sealevel due to glaciation (glacial–interglacial) cycles, with these changes being much more significant in the Neopleistocene than in the Eopleistocene, at the simultaneous overall lowering of the sealevel (Lisiecki and Raymo, 2005). Any lowering in the sealevel is known to lead, first, to fall in the base level and, second, to exposure of vast areas made up of loose sediments on the former shelves. These processes are favorable for an increase in the influx of terrigenous material into the sedimentation basins. Finally, the third of the most important reasons for the intensification of turbidite accumulation in the Neopleistocene may have been certain climatic changes in continental glaciation regions and ensuing deposition of glacial turbidites (Matishov, 1984). Circumstantial evidence of this process is provided by the intensification of the deposition of glacial-marine sediments. All three of the aforementioned reasons may have intensified the accumulation of hemipelagic clays, although the more probable reason of this phenomenon with reference to the glacial-marine sediments was likely climatic changes, which should have “pushed” continental ice sheets toward the ocean during glaciations (Levitan et al., 2007). Thereby vast masses of terrigenous material were transferred into the ocean. Recall that glacial climate at high latitudes was generally more harsh in the Neopleistocene than Eopleistocene (Lisiecki and Raymo, 2005). It is known that neotectonic uplift may be correlate with the onset of continental glaciation, as was the case, for example, with the Atlantic shore of Norway in the Pliocene (Knies et al., 2014).

Latest paleoceanological studies, conducted with the application of foraminifera analysis, in the North Atlantic (Bashirova, 2014) and its southern part (Rudolph, 2006) have confirmed the earlier hypothesis (Barash, 1988) that major hydrological fronts shifted toward the equator during the glaciation phases of glacial–interglacial cycles and toward the poles during their interglacial phases. The boundaries of the sea ice and glacial-marine sediments thereby changed correspondingly. This demonstrates that the processes are correlated on seasonal basis, as well as on the scale of glacial–interglacial cycles (dozens to hundreds of years) and, as was demonstrated above in this publication, during the Eo- and Neopleistocene (a few million years). This implies that climate plays an important role in the evolutionary history of sedimentation in the Atlantic pelagic zone in the Pleistocene.

Finally, it should be mentioned that turbidity currents started to play a more important role among the agents transporting terrigenous material in the Neopleistocene compared to Eopleistocene not only in the Atlantic but also in the Pacific (Levitan et al., 2013) and even in the Indian Ocean (Levitan et al., 2014). We believe that this provides more probable evidence for the domination of neotectonic uplift as the main reason for the increase in the supply of terrigenous material in the Pleistocene.

No doubt that the significant activation of atmospheric circulation that was undeniably proved for the Late Pleistocene as compared to the Holocene (Brook et al., 2006) should have increased the relative role of wind transportation in the accumulation of thin terrigenous material in the oceanic pelagic zone in the Neopleistocene compared to Eopleistocene. Unfortunately, the techniques we utilized to conduct this study did not allow us to verify this hypothesis.

Carbonatite Sediments

This group of sediments in Table 1 comprises nanoplankton and nanoplankton–foraminiferal oozes and marly sediments. It is pertinent to stress that the I_{Q2+3}/I_{Q1} ratio of these sediments (Table 1) is typically lower than 1.0. This means that the integral accumulation of carbonate material was lower in the Neopleistocene than Eopleistocene. This can be interpreted as resulting from the decrease in the productivity of carbonate plankton in the Pleistocene or as a consequence of some other processes.

Below we consider some distinguishing features of modern sedimentation in the Atlantic (Emel’yanov et al., 1975; Lisitsyn, 1974, 1978). First, all of the compositional–genetic types of carbonate sediments were accumulated at middle and low latitudes, and second, their accumulation is correlated with the vertical zoning of the ocean, i.e., with the bathymetric levels. For example, foraminiferal–nanoplankton oozes are accumulated in the oceanic pelagic zone at the shallowest levels (and in regions of elevated production), nanoplankton oozes are deposited at greater depths (and in regions of relatively low primary production), and finally, marly (calcareous) sediments containing 30–70% $CaCO_3$ are deposits at the greatest depths. The modern distribution of calcareous pelagic oozes is generally controlled by relations between the following three major factors: the productivity of carbonate-concentrating organisms, the degree of dilution of this material with sediments of other composition (for example, terrigenous or siliceous), and the extent of dissolution in aggressive seawater.

Returning to the table, note that the I_{Q2+3}/I_{Q1} ratio systematically decreases according to the aforementioned sequence: it is 0.5 for foraminiferal–nanoplankton oozes, 0.3 for nanoplankton oozes, and 0.2 for marly sediments.

Consider now the probable effects of each of the aforementioned factors of pelagic sedimentation. As was demonstrated above, indeed, the role of diluting with terrigenous material in the Neopleistocene significantly increased compared to the Eopleistocene.

This does not, however, anyhow explain the I_{Q2+3}/I_{Q1} ratios of various types of the carbonate sediments.

A relative decrease in the paleoproductivity of carbonate plankton also provokes certain doubt in the absence of obvious reasons for this. First, more active erosion of continents resulted in the enhancement not only of physical but also of chemical weathering and, hence, also in the supply of nutrients required for primary production. It is thus reasonable to expect that the carbonate production should have also been increased but not decreased. Second, at low and middle latitudes in both the Pacific and Indian oceans, this production did increase, but not decrease, in the Pleistocene (Levitan et al., 2013, 2014), and it is not clear why this trend should have been opposite for the Atlantic.

We are thus left with the only possibility that the leading role was played by the third factor: an increase in the aggressiveness of seawater in the Pleistocene (including that compared to the Pacific and Indian oceans). Recall that significant sources of bottom and deep waters operate in a single ocean, in the Atlantic, and these waters are characterized by active dissolution of carbonates and occur at high latitudes in both the Northern and the Southern hemispheres: in the Labrador Sea, Norwegian–Greenland Basin, and Weddell Sea. These waters flow southward in the Northern Hemisphere and northward in the Southern Hemisphere. Such water masses are known to occur together over much of the pelagic zone of the Atlantic, with the bottom waters being Antarctic bottom water mass and the deep water being water from the North Atlantic. It follows that even the modern Atlantic possesses a powerful potential of carbonate dissolution, which is much more significant than those of the Pacific and Indian oceans. As was already mentioned, glaciation at high latitudes was more significant in the Neopleistocene due to progressive cooling. Of course, this increased then generation of waters able to actively dissolve carbonates due to ice formation in the autumn (Rodrigez-Sanz et al., 2012). Additional evidence of these climatic changes is provided by the aforementioned significant intensification of the accumulation of glacial-marine sediments in the Neopleistocene compared to Eopleistocene. Moreover, it is this exactly factor that is able to ideally account for the aforementioned systematic variations in the I_{Q2+3}/I_{Q1} ratio in various types of carbonate sediments.

This led us to suggest that the enhanced influx of carbonate pelagic material in the Pleistocene was associated with its dilution with terrigenous material and with even more significant dissolution of carbonates in the lower water layers. Conceivably, the aforementioned expansion of sediment-free areas in the Neopleistocene as compared to the Eopleistocene is also explained, first of all, by the dissolution of carbonates.

Carbonate Turbidites

According to their nature, carbonate turbidites are dualistic: their composition is closely similar to that of carbonate sediments, whereas the mechanisms of their transport and accumulation are similar to those of terrigenous turbidites. As was already mentioned above, carbonate turbidites in the Atlantic are spread so much more widely than in other oceans that these sediments were even introduced into the legends of lithological facies maps and were mapped (Figs. 2, 3). Carbonate turbidites are particularly widely spread in the North American and Canary deep-sea basins, although they were found in other basins and also locally on the slopes of the Mid-Atlantic Ridge and some other ridges and rises.

Their average I_{Q2+3}/I_{Q1} ratio is 1.4 (Table 1). Since the sedimentary material for these deposits is accumulated on carbonate shelves, crests of ridges and rises, on the upper parts of continental (and other) slopes, the value of 1.4 is not anyhow related to the neotectonic uplift of continental blocks but can rather be explained by the growing productivity of carbonate-concentrating organisms in the surface water masses in the Neopleistocene as compared to Eopleistocene, as was suggested above. Of course, the aforementioned changes in the sealevel also might play a certain role, first and foremost, in discharging materials from carbonate shelves. The elevated sedimentation rates typical of all turbidites are favorable for their fast burial and, hence, for precluding the dissolution of much of their carbonates in the bottom waters.

Contourites

Similar to turbidites, contourites are a genetic type of oceanic and marine sediments (Frolov, 1984) but not their composition–genetic type. These sediments are accumulated at unusual sedimentary ridges (drifts) that mark the flow pathways of bottom currents and are localized mostly on continental rises. Contourites posses a variegated composition but are dominated by terrigenous and carbonate varieties. As was mentioned above, contourites are much more widely spread in the Atlantic Ocean than in other ones (Rebesco et al., 2014), first of all, south of Iceland and in the western part of the ocean, because of which we pay much attention to these sediments in this publication.

To character the environments and conditions of the origin of contourites, we consider a simplified schematic diagram showing neighboring occurrence of various litho-dynamic regimes in a bottom water layer in the oceanic pelagic zone (Fig. 4). The diagram is based on comparison of the mass accumulation rates of accumulated sediments and the velocities of bottom currents. Neither the abscissa nor the ordinate are numerically graduated because the values should be different for sediments of various composition. It can be generally seen that at low current velocities, the dominant regime is the accumulation of sediments (regime I). As the flow velocities increase, the currents start to deposit sedimentary material, with the sedimentation rate first increasing until a certain maximum (regime IIa, i.e., transitional accumulation), after which the role of erosion increases (regime IIb, i.e., transit erosion). Considered together, these regimes describe how contourites are formed. Finally, when the velocities of the currents become high enough, no sediments are accumulated at all, and they are only eroded (regime III).

It was already mentioned above that contour currents in the Atlantic Ocean are related to the following three major sources: Weddell Sea in the Southern Ocean, Labrador Sea and Norwegian–Greenland Basin in the North Atlantic. The main problem that we faced and that is actively discussed in the literature is how and how much contourites are related to the generation of cold bottom waters in these areas and, particularly, to climatic changes there. For example, some researchers are prone to believe that this generation was enhanced during glaciations (Rodrigez-Sanz et al., 2012). Conversely, other scientists suggest that interglacial periods are more favorable for this (Bell et al., 2015).

According to our data, the average I_{Q2+3}/I_{Q1} ratio of contourites is roughly equal to 1, or more specifically, is 0.96 (Table 1). This means that somewhat more contourites were then deposits in the Atlantic in warmer climate than it was in the Neopleistocene. It is worth discussing a few illustrative examples presented below. In the Hatton and Snorry Drifts south of Iceland, the velocity of the contour currents (which were calculated from the grain size of the sorted silt of 0.01–0.63 mm) were higher during interglacial periods in the Late Pleistocene than during the glacial periods (Sivkov et al., 2015). Deep sea drilling materials show that the accumulation rates of sediments in the Eirik Drift south of Iceland in the Eopleistocene were higher than in the Neopleistocene, whereas those in the Gardar Drift were lower (www.iodp.org). Finally, it was determined that the velocities of contour currents in the Ioffe Drift, SW Atlantic, locally resulted in seafloor erosion and, hence, were much higher in the Eopleistocene than Neopleistocene (Ivanova et al., 2016). With regard for Fig. 4, this led us to conclude that the velocity of contour currents in the Atlantic were somewhat higher at warmer times that when the climate was colder.

Paleoceanological data (Sarnthein et al., 2001; Bell et al., 2015; and others) indicate that the horizontal and vertical circulation in the aforementioned areas where cold bottom waters is generated was very sluggish during Pleistocene glaciations, and this resulted in merely weak ventilation of the bottom and deep water masses. Conversely, convection was much more active during interglacial periods and caused significant ventilation of the lower water layer.

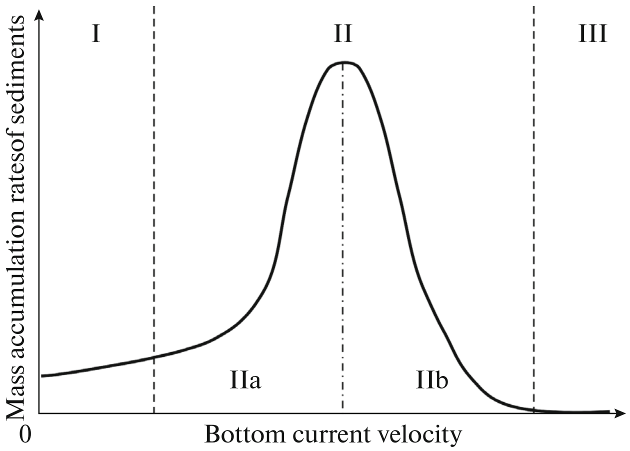

Fig. 4. Model relations between mass accumulation rates of sediments and velocities of bottom currents in the ocean pelagic zone. See text for explanations.

The active circulation in the areas where bottom waters are generated during warm climate periods increased the velocities of contour currents outside these areas. During cold periods of time, for example, during glaciation, these processes were slow. However, as we tried to demonstrate above, the overall generation of bottom waters in these areas was still greater when the climate was cold. Hence, the velocities of the contour currents reflect the circulation velocities at the areas where bottom waters are generated but not the volumes of the generated water masses.

Diatom Oozes and Clays

Similar to what occurs in the modern Atlantic Ocean, biogenic siliceous oozes were accumulated in the Eo- and Neopleistocene mostly within the so-called southern belt of silica accumulation (Figs. 2, 3). Radiolarian–diatom oozes or diatom ethmodiscus oozes are also locally found at middle and low latitudes, for example, in the equatorial zone or on the slopes of the Walvis Ridge, but they always occupy there such small areas that cannot be mapped at conventionally used scale of the maps.

As follows from the lithological descriptions, diatom clays thereby obviously dominate over “pure” diatom oozes. The average I_{Q2+3}/I_{Q1} ratio is 1.1 (Table 1), i.e., the intensity of their accumulation was roughly equal in the Eo- and Neopleistocene. An analogous conclusion that the paleoproduction of opal in the Atlantic sector of the Southern Ocean during Pleistocene was similar during glacial and interglacial periods was earlier derived by German researchers (Frank et al., 2000). Our estimates of the residual concentrations of biogenic opal in sediments in the South Atlantic calculated from ocean drilling materials are presented in Table 2. These data indicate that the concentrations of biogenic opal practically did not vary throughout the whole Pleistocene (the only exception is the material recovered by Hole 701). The calculated mass accumulation rates of biogenic opal in the South Atlantic show

Table 2. Arithmetic mean concentrations (wt %) of biogenic opal in Eo- and Neopleistocene sediments from ODP Holes 701–704, 513, 514, and 697 drilled in the South Atlantic

Age of sediments	Hole 701	Hole 702	Hole 703	Hole 704	Hole 513	Hole 514	Hole 697
Neopleistocene	89.0	37.0	10.0	57.3	77.0	50.5	6.8
Eopleistocene	64.5	37.0	10.0	60.4	72.6	54.7	5.4

See Fig. 1 for location of the holes.

that diatoms were accumulated somewhat more intensely in the areas of northern boreholes in the Eopleistocene and more intensely in more southern areas (where Hole 701 was also drilled) in the Neopleistocene (Cortese et al., 2004). Thereby the boundary between the northern and southern holes coincides with the Polar hydrologic front, at which silica accumulation reached a maximum at 2 Ma.

The facts and considerations presented above seem to suggest that our concept of "two oceans" (Levitan, 2016) does not to pertain to this part of the Atlantic. Consider this problem in more closely. It has been demonstrated that the highest paleoproductivity of biogenic opal in the ocean was reached during interglacial periods at high latitudes and during glacial periods at middle and low latitudes (i.e., in the ice-free ocean) (Levitan, 2016). The southern continental boundary of the Weddell Sea marks the boundary between the East and West Antarctic ice sheets. The former is made up of vast ice volumes of about 26 million km^3 (Ingólfson, 2004) and is characterized by a solid contact between the ice and underlying bedrocks and a low dynamics with time. The parameters of the West Antarctic ice cap are opposite: the ice volume is much smaller (3.3 million km^3), the contact is polythermal, and the dynamics is very high (Levitan and Leichenkov, 2014). It is, for example, though that this ice sheet could have completely disappeared at the time of the so-called warm Pliocene, and hence, the sealevel may have become 5 m higher by the Middle Pliocene, whereas the melting of the East Antarctic cap could have heightened this levels by as little as 2 m (Naish, 2010). Because of this, the supply of dissolved silica from Antarctica to the Weddell Sea varied differently with time for its eastern and western sectors. This may have been the main reason for the approximate equality in the accumulation of siliceous sediments in the South Atlantic in the Eo- and Neopleistocene. Given the aforementioned increase in the content of biogenic opal in Neopleistocene sediments south of the Polar front, it is realistic to suggest that the main volume of dissolved silica and other nutrients was supplied during deglaciation periods of the West Antarctic ice cap. This does not however rule out that other factors may have played certain roles, as is mentioned in (Cortese et al., 2004), but their roles should have been subordinate.

Miopelagic Clays

The only type of red clays that is relatively widely spread in the pelagic Pleistocene sediments in the Atlantic is miopelagic clays. The amounts of the eupelagic and zeolite abyssal clays are so insignificant that they cannot be shown on the scale of the maps. Of course, miopelagic clays are found only in certain basins (Figs. 2, 3) because their accumulation rates are too slow for them to "compete" with other types of pelagic sediments.

The I_{Q2+3}/I_{Q1} ratio of the clays is 0.6 (Table 1), i.e., the intensity of their accumulation in the Neopleistocene was remarkably lower than in Eopleistocene. We believe that the simplest explanation of this is that the period of time was characterized by significant intensification of the supply of terrigenous material and, to a lesser extent, also carbonate turbidites (see above), which "forced" miopelagic clays further away from continental margins and "suppressed" their accumulation areas.

CONCLUSIONS

We utilized data on 283 deep oceanic drilling holes to construct two lithologic–facies isopahs maps of pelagic sediments in the Atlantic Ocean for the Eo- and Neopleistocene. The application of A.B. Ronov's (1949) technique allowed us to use the maps to derive such quantitative parameters of the evolutionary history of sedimentation as the surface areas, volumes, and masses of the sedimentary materials and the masses of sediments deposited per specified time unit for all of the mapped sediment types.

Our evaluations show that the supply of terrigenous material, and not so much carbonate turbidites, increased in the Pleistocene. At the same time, the intensity of accumulation of carbonate sediments and miopelagic clays obviously decreased, whereas the accumulation of contourites and siliceous sediments (diatom oozes and clays) practically did not change.

We believe that the main reasons for these variations in the quantitative parameters of pelagic sedimentation were neotectonic uplift of continental areas and associated significant climatic changes owing to progressive climatic cooling and related glaciation at high latitudes in both hemispheres. The consequences of these natural processes involved the enhancement of the fluxes of physical and chemical weathering products from continents, drastic changes in the sea-level at its general fall, an increase in the paleoproductivity at low and middle latitudes, and more intense generation of cold bottom (and deep) waters in some areas in the North and South Atlantic. This was associated with intensification of water circulation in these areas during interglacial periods, and generally in periods with warmer climate, which led to an increase in the velocities of the contour currents and, hence, changes in the sedimentation rate of the contourites.

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