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Correlation of the Pliocene–Quaternary Foraminiferal and Nannofossil Zonations in the North Atlantic

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Abstract—A thorough investigation of calcareous plankton from the Pliocene–Quaternary sediments of DSDP Sites 397, 608, 609, and 611 enabled correlation between the foraminiferal and nannofossil zonations. The first and last occurrence levels of nannoplankton and foraminifer index species are defined and calibrated against the chronological scale by Berggren *et al.* (1995). First occurrence of *Globorotalia margaritae* is recorded in studied sections at 6.1–6.3 Ma and last occurrence of *Discoaster quinqueramus* corresponds to the level of 5.94 Ma. The first appearance of *Gephyrocapsa oceanica* is established at 1.87 Ma. The distinct correlation between the planktonic foraminiferal and nannofossil zonations is revealed in the North Atlantic region between 26° and 52°N.

Key words: Pliocene, Quaternary, foraminifers, nannofossils, correlation, zonations, datums, Atlantic.

INTRODUCTION

A central problem of stratigraphy, i.e., the detailed subdivision of sedimentary succession and the precise dating of stratigraphic units, can be solved by means of correlation of different biostratigraphic zonations, for instance, of zonations established for well-studied planktonic foraminifers and nannoplankton. The Pliocene–Quaternary zonations of these two groups of planktonic calcareous fossils are of a high resolution, tested in different regions of the World Ocean. As the boundaries between discriminated biostratigraphic units mostly do not coincide, the parallel analysis of two or more fossil groups leads to an enhanced stratigraphic resolution and to the more exact dating of strata.

The nannofossil and planktonic foraminiferal zonations have been correlated in some previous works (Krasheninnikov, 1978, 1980; Berggren *et al.*, 1985, 1995; Krasheninnikov *et al.*, 1999) though without proper attention to critical datum levels of microfauna and flora established in the same borehole sections and samples. In the above-mentioned works, the top of the nannoplankton *Discoaster quinqueramus* Zone NN11 (CN9) is placed below the first occurrence of *Globorotalia margaritae* or at the same level. The base of the *Discoaster brouweri* Zone CN12 (NN16–18) is established either within the *Globorotalia margaritae* Zone or at the top of this zone. Moreover, the detailed correlation with due regard for subzones discriminated by Okada and Bukry (1980) and for the high-resolution Quaternary nannofossil zonation (Gartner, 1977) has not been considered.

In this paper we discuss the correlation of the Pliocene–Quaternary sediments penetrated at DSDP Sites 397, 608, 609, and 611. All these sections have been studied by paleomagnetic methods. In her study of nannofossils, Golovina coordinated the results with the standard scale by Martini (1971), with the low-latitude zonation suggested by Okada and Bukry (1980), and with the Quaternary standard developed by Gartner (1977). Bylinskaya who studied planktonic foraminifers used for correlation the stratigraphic scale by Bolli and Saunders (1985) that was slightly modified not long ago (Bylinskaya *et al.*, 2002). The first and last occurrence levels (FO and LO, respectively) of most index species established in the studied sections are dated based on the chronological scale published by Berggren *et al.* (1995). The reported ages characterize events distinctly traceable in the sections and the levels of certain paleomagnetic reversals near the particular events.

STUDIED SITES AND STRATIGRAPHY

Southernmost DSDP Site 397 (26°50.7′ N, 15°10.8′ W, 2900 m) is located in the subtropical zone, on the continental slope of the northwestern African coast (Fig. 1). The Pliocene and Quaternary sediments accumulated here under combined hydrodynamic influence of the cold Canary Current and upwelling. The Pliocene sediments are 280 m thick and the Quaternary strata are about 140 m thick. Site 608 (42°50′ N, 23°05′ W, 3526 m) was drilled on the southern flank of the King's Trough complex, east of the Mid-Atlantic Ridge. The total thickness of the Pliocene and Quaternary deposits penetrated at the site is about 160 m. Site 609 (49°53′ N, 24°14′ W, 3883 m) is located in the eastern flank of the Mid-Atlantic Ridge, where a 350-m-thick sequence of

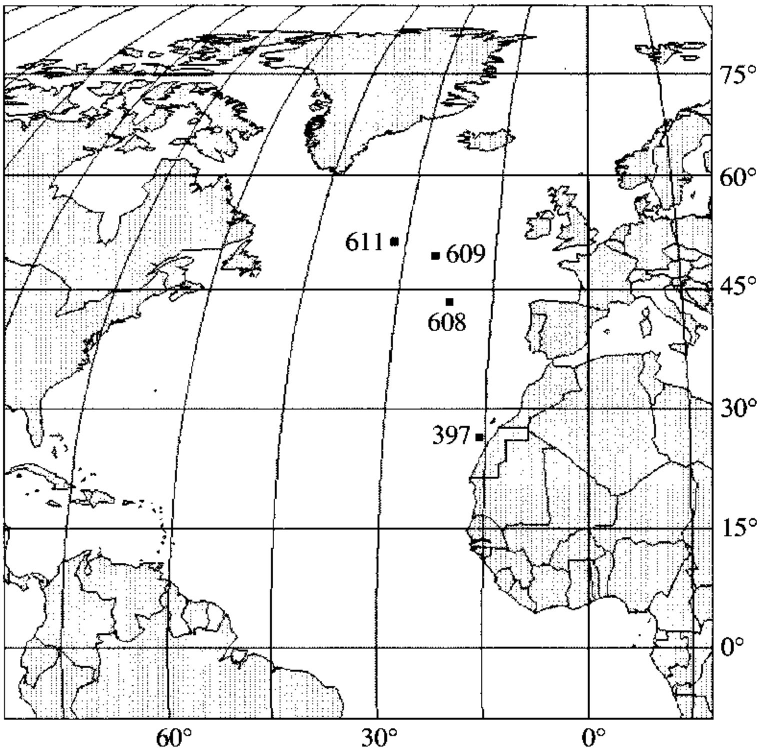

Fig. 1. Localities of the studied DSDP sites.

the Pliocene–Quaternary sediments was recovered. Site 611 (52°50′ N, 30°18′ W, 3230 m) is in a lower part of the Gardar Ridge southeastern flank, where sediments accumulated under influence of the deep-water overflow from the Norwegian Sea. The Pliocene and Quaternary deposits recovered here are about 330 m thick.

The Pliocene–Quaternary intervals of all the holes yield the diverse assemblages of planktonic foraminifers and nannofossils, which are suitable for a high-resolution biostratigraphic subdivision. The initial study of sediments during DSDP Legs 47 and 94 (von Rad *et al.*, 1979; Ruddiman *et al.*, 1987) was subsequently followed by the more thorough investigation (Krasheninnikov and Bylinskaya, 1999; Bylinskaya *et al.*, 2002). As the planktonic foraminiferal and nannofossil assemblages and zonal units recognized at the sites are described in detail in the last work, both issues are considered here in brief. It should be noted that zonal units are distinguished in this study based on their characteristic assemblage but not on individual key species. At the same time, the events of appearance and extinction of some forms in different climatic zones can serve as additional markers enabling a higher resolution of stratigraphic subdivision. The first and last occurrence datums defined for foraminiferal and nannofossil species most important in terms of stratigraphy are presented in the tables.

In our previous work (Bylinskaya *et al.*, 2002), we analyzed the calcareous plankton zonations in the Atlantic Ocean and proved the possibility to use the low-latitude zonations in higher latitudes, up to the boreal realm, although their resolution is different in various latitudinal belts. Analyzing zonation of planktonic foraminifers, we used the scheme by Bolli and Saunders (1985) that was detailed in the middle Pliocene interval.

The *Globorotalia margaritae, Globorotalia miocenica, Globorotalia tosaensis*, and *Globorotalia truncatulinoides* zones with subzones are distinguished in the Pliocene–Quaternary foraminiferal zonation at DSDP Sites 397, 608, 609, and 611. The nannofossil Zones CN10–CN12 with the corresponding subzones and five Quaternary biostratigraphic units by Gartner (1977) were recognized in addition.

RESULTS AND DISCUSSION

Site 397

Since the site is located in a warm-water region of the Atlantic, the nannofossil zonation was correlated herewith that of Okada and Bukry, although we failed to distinguish certain subzones, the index species of which are either lacking or show their earlier (later) occurrence in the section.

The Pliocene sediments are recovered by Cores 45 to 15 (Fig. 2). The base of the early Pliocene foraminiferal *Globorotalia margaritae* Zone is placed in the lowermost Core 45 (Bylinskaya *et al.*, 2002). The index species LO defines the zone upper boundary, being

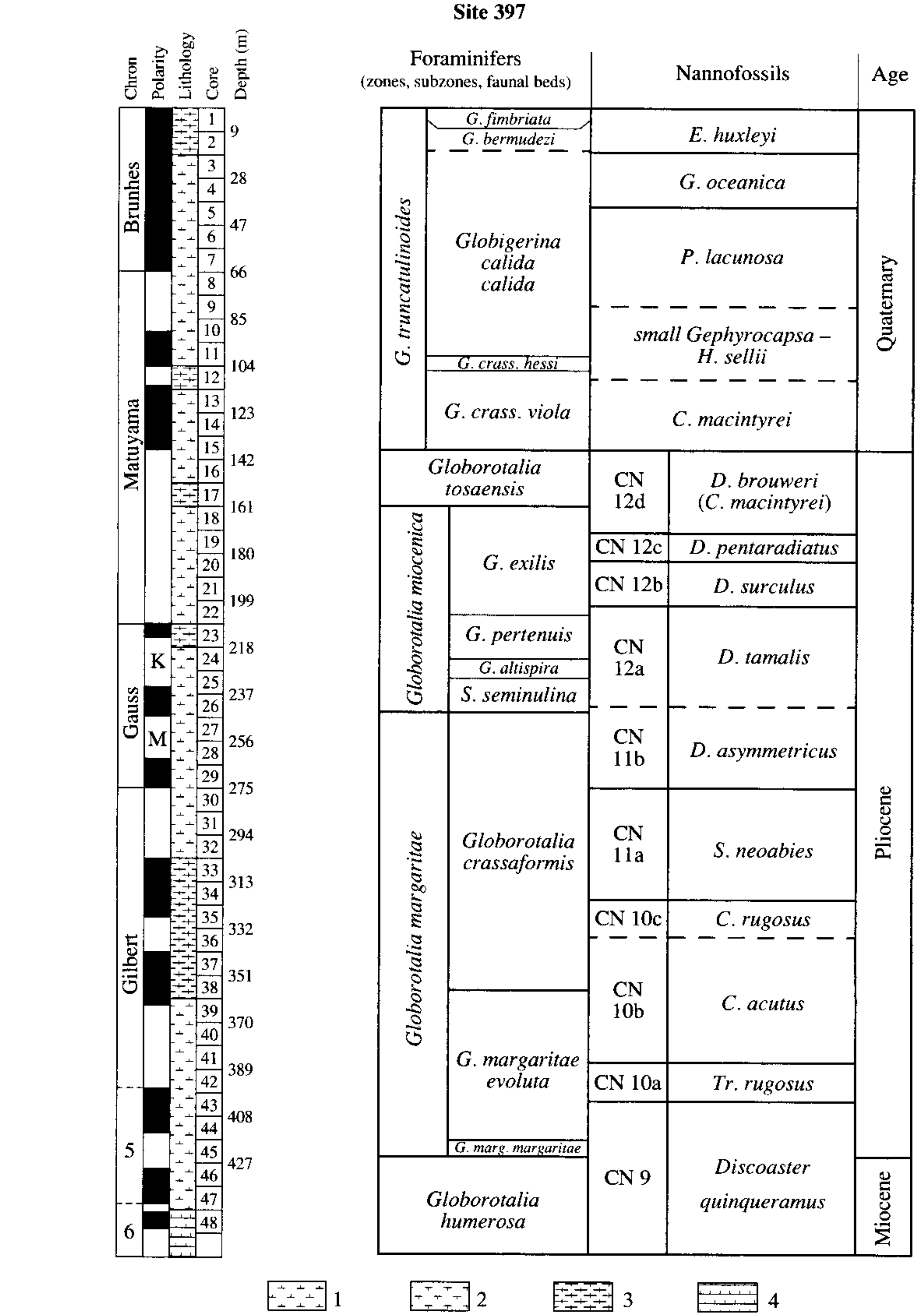

Fig. 2. Correlation between of the Pliocene–Quaternary zonal units of calcareous plankton from DSDP Site 397: (1) nannofossil, (2) foraminiferal, and (3) nanno-foraminiferal oozes; (4) nannofossil chalk; (K) Kaena Subchron; (M) Mammoth Subchron.

Table 1. First (FO) and last occurrence (LO) datums of planktonic foraminiferal species

Datum events	Age (Ma)			
	Site 397	Site 608	Site 609	Site 611
FO *G. calida calida*	1.05	1.07	0.99	
LO *G. crassaformis viola*		1.45	1.48	
FO *G. truncatulinoides*	1.95		1.95	
LO *G. extremus*	2.08		2.05	
LO *G. exilis*	2.30			
LO *G. miocenica*	2.40			
LO *Gq. altispira*	3.03	3.03		
FO *Sph. dehiscens*	3.13			
LO *Sph. seminulina*	3.14	3.10		
LO *G. margaritae*	3.23	3.47	3.92	
LO *Gq. dehiscens*	3.4			
FO *G. miocenica*	3.81			
FO *G. crassaformis viola*	4.0		4.18	
FO *G. exilis*	4.5			
FO *G. crassaformis hessi*	4.5		4.51	
FO *G. crassaformis ronda*	4.5		4.51	
LO *G. nepenthes*	4.88		4.51	
FO *G. puncticulata*	4.88		4.54	
FO *G. crassaformis*	5.06		4.62	
FO *G. margaritae*	6.21		6.13	6.31

Table 2. First (FO) and last occurrence (LO) datums of nannofossils

Datum events	Age (Ma)			
	Site 397	Site 608	Site 609	Site 611
LO *Pseudoemiliania lacunosa*	0.44	0.45	0.45	0.47
LO small *Gephyrocapsa*	0.95			
LO *Helicosphaera sellii*			1.38	1.25
LO *Calcidiscus macintyrei*	1.56		1.55	
FO *Gephyrocapsa oceanica* s.l.	1.87			
LO *Discoaster brouweri*	1.95			
LO *Discoaster pentaradiatus*	2.43		2.43	
LO *Discoaster surculus*	2.57		2.56	
LO *Discoaster tamalis*	2.84	2.76	2.85	
FO *Pseudoemiliania lacunosa*	3.78			
LO *Amaurolithus tricorniculatus*	4.47			
LO *Ceratolithus acutus*	4.70			
LO *Triquetrorhabdulus rugosus*	5.56			
LO *Discoaster quinqueramus*	5.94		5.93	

approximately located at the top of the Mammoth Subchron of the Gauss Chron. The zone is subdivided into the *Globorotalia margaritae margaritae* and *Globorotalia margaritae evoluta* subzones. The base of the *Globorotalia crassaformis* Beds distinguished in the upper part of the latter is defined within the Thvera Subchron of the Gilbert Chron (Table 1).

Within the foraminiferal *Globorotalia margaritae* Zone, the following nannofossil zonation is recognized (Fig. 2).

The uppermost part of the *Discoaster quinqueramus* Zone (CN9) is traceable up to Sample 397-43-2, 51–55 cm, where the index species LO is recorded. This level is 5.94 Ma old (Table 2). The *Triquetrorhabdulus rugosus* Zone (CN10a) corresponding to the lower part of the *Amaurolithus tricorniculatus* Zone NN12 in the standard zonation by Martini spans the interval from the *Discoaster quinqueramus* LO to the index species *Tr. rugosus* LO at 5.56 Ma. The *Ceratolithus acutus* Subzone (CN10b) corresponding to the upper part of the *Amaurolithus tricorniculatus* Zone NN12 is defined as the interval from the *Tr. rugosus* LO to the *C. rugosus* FO. In the hole under discussion, the top of the subzone is placed at the *C. acutus* LO. According to our conclusion, this event took place 4.70 Ma ago. The *Globorotalia crassaformis* FO is recorded within the last subzone at 5.06 Ma. The *Ceratolithus rugosus* Subzone (CN10c), spanning the joint interval of *Ceratolithus rugosus* (NN13) and *Discoaster asymmetricus* (NN14) zones in zonation by Martini, is defined in the section between the *C. acutus* LO and the *Amaurolithus tricorniculatus* LO at 4.47 Ma. The *Reticulofenestra pseudoumbilica* Zone (CN11a, b) corresponds to the Zone NN15 of the Martini's zonation and corresponds to the interval between the *A. tricorniculatus* LO in Sample 397-34-5, 46–50 cm, and the disappearance level of *R. pseudoumbilica* and/or of the genus *Sphenolithus*. Following Bukry, we recognized in Hole 397 the *Sphenolithus neoabies* (CN11a) and *Discoaster asymmetricus* (CN11b) subzones. The boundary between them is marked by the flourishing level of *D. asymmetricus* at the top of Core 30. The *Pseudoemiliania lacunosa* FO in association with small *Gephyrocapsa* forms at 3.78 Ma is the main event within the *R. pseudoumbilica* Zone. The top of the *Discoaster asymmetricus* Subzone at Site 397 is recorded in the middle of the Gauss Chron at 3.20 Ma. Like at Sites 608 and 609, the top of the *Reticulofenestra pseudoumbilica* Zone (CN11) is slightly above the top of the foraminiferal *Globorotalia margaritae* Zone. At Site 397, the latter is 3.23 Ma old and coincides with the top of the Mammoth Subchron of the Gauss Chron.

As noted previously (Bylinskaya *et al.*, 2002), the overlying foraminiferal *Globorotalia miocenica* Zone of subtropical sections can be subdivided into four intervals (faunal beds). In the sediments of Site 397, three lower units among them mainly correspond to the greater part of the *Discoaster tamalis* Subzone (CN12a), which is defined as the interval from the *R.*

pseudoumbilica LO to the *D. tamalis* LO at 2.84 Ma. The upper *Globorotalia exilis* Beds correspond to three nannofossil subzones distinguishable in the lower part of the *Discoaster surculus* Zone NN16 of the Martini scale. The lower *Discoaster surculus* Subzone (CN12b) is established between the *D. tamalis* and *D. surculus* extinction events, the latter recorded in the lowermost Matuyama Chron at 2.57 Ma. The next *Discoaster pentaradiatus* Subzone (CN12c) with the top at 2.43 Ma corresponds to the Zone NN17 by Martini, and the third unit spans (in this hole) the lower part of the *Discoaster brouweri* Subzone (Fig. 2). As is evident, the established datums are very close to that cited in the publications (Kučera, 1998; Kameo and Takayama, 1999, Spencer-Cervato, 1999). Thus, different groups of calcareous plankton from Site 397 enable recognition of 5 to 6 biostratigraphic units in the time span from 3.3 to 2.2 Ma.

It should be noted that certain biostratigraphic boundaries recognized at Site 397 differ in age from their analogues established in other holes (see below) and known from the literature. As reported previously (Bylinskaya, 1999), the southern part of the subtropical belt is characterized by the earlier appearance and later extinction of some calcareous plankton species. For instance, the published (Berggren *et al.*, 1995) and our own data on other holes (see below), the first occurrence levels of *Globorotalia crassaformis, G. puncticulata, G. miocenica*, and *Gephyrocapsa oceanica* s.l. are lower at Site 397, whereas the last occurrences of *Globorotalia margaritae* and, likely, of *Sphenolithus* forms are recorded here considerably higher (Tables 1 and 2).

The foraminiferal *Globorotalia tosaensis* Zone of the late Pliocene is defined within the interval from the *G. exilis* LO (*G. miocenica* disappeared slightly earlier at the site) to the *G. truncatulinoides* FO at 1.95 Ma. The zone corresponds to the last *Discoaster brouweri* (=*Calcidiscus macintyrei*) Zone CN12d of Pliocene nannofossils, the analogue of the Zone NN18 by Martini, and its top corresponds to the last occurrence level of index species at the base of the Olduvai Subchron. At Site 397, this event coincides with the appearance of *Globorotalia truncatulinoides*. Therefore the Pliocene–Quaternary boundary in this hole is identical in zonations of both the planktonic foraminifers and nannofossils.

In the Quaternary interval, the foraminiferal *Globorotalia truncatulinoides* Zone and five subzones after Bolli and Saunders (1985) are distinguished. Subdividing sediments based on nannoplankton, we used the Gartner's zonation and recognized in addition the zones after Okada and Bukry. Impediments for a detailed subdivision were therewith a turbidite layer present in Core 12 and an evident hiatus in the *Helicosphaera sellii*–small *Gephyrocapsa* interval. The foraminiferal *Globorotalia crassaformis hessi* Subzone shown in Fig. 2 is strongly reduced because of the hiatus.

In the lower Quaternary, two nannofossil zones and two subzones of planktonic foraminifers are distinguished at the site. The latter ones are the *Globorotalia crassaformis viola* and *G. crassaformis hessi* subzones, the last one strongly reduced in this hole. The *Calcidiscus macintyrei* Zone by Gartner is defined between the *D. brouweri* and *C. macintyrei* LO levels, and its top 1.56 Ma old is recorded in Sample 397-12-2, 62–66 cm. The *G. crassaformis viola* LO cannot be determined exactly because of the hiatus in the section. When correlating previously the calcareous planktonic zonations in the tropical Atlantic (Bylinskaya and Golovina, 1990), we also placed the top of the *C. macintyrei* Zone within the *G. crassaformis viola* Subzone.

The most important event in the interval under consideration is the first occurrence of typical large *Gephyrocapsa oceanica* s.l. in Sample 397-14-4, 60-64. Their first occurrence is dated back to 1.87 Ma, and this level is the oldest one among dates reported previously. The interval between the *D. brouweri* LO and *G. oceanica* s.l. FO corresponds to the Zone CN13 in the low-latitude zonation elaborated by Okada and Bukry.

Upward the section, the undivided *Helicosphaera sellii*–small *Gephyrocapsa* interval corresponds to the foraminiferal *Globorotalia crassaformis hessi* Subzone coupled with conjoined parts of the over- and underlying subzones. In studied section, the top of the *Gephyrocapsa* Zone is placed by convention above the upper boundary of the *Globorotalia crassaformis hessi* Subzone.

In the upper Quaternary interval of the section, we distinguished three foraminiferal and three nannofossil units. The *Pseudoemiliania lacunosa* Zone is correlated with a largest part of the foraminiferal *Globigerina calida calida* Subzone; its top at the level of 0.44 Ma is recorded within the *Globigerina calida calida* Subzone like in the tropical Atlantic. The upper boundary of the *Gephyrocapsa oceanica* Zone is defined by the first appearance of *Emiliania huxleyi* in Sample 397-2-5, 40–41 cm. As in the tropical Atlantic, the zone is within the *Globigerina calida calida* Subzone. At Site 397, the base of the overlying *Emiliania huxleyi* Zone is placed slightly below the base of the foraminiferal *Globigerina bermudezi* Subzone. The *Emiliania huxleyi* Acme zone was not distinguished in the studied cores.

Site 608

This DSDP site is located considerably northward of Site 397. However, zonations of planktonic foraminifers and nannofossils at both sites are well correlative, as we shall see below (Fig. 3).

We studied the calcareous plankton from the Pliocene–Quaternary interval starting with the middle part of Core 17. The Lower Pliocene *Globorotalia mar-*

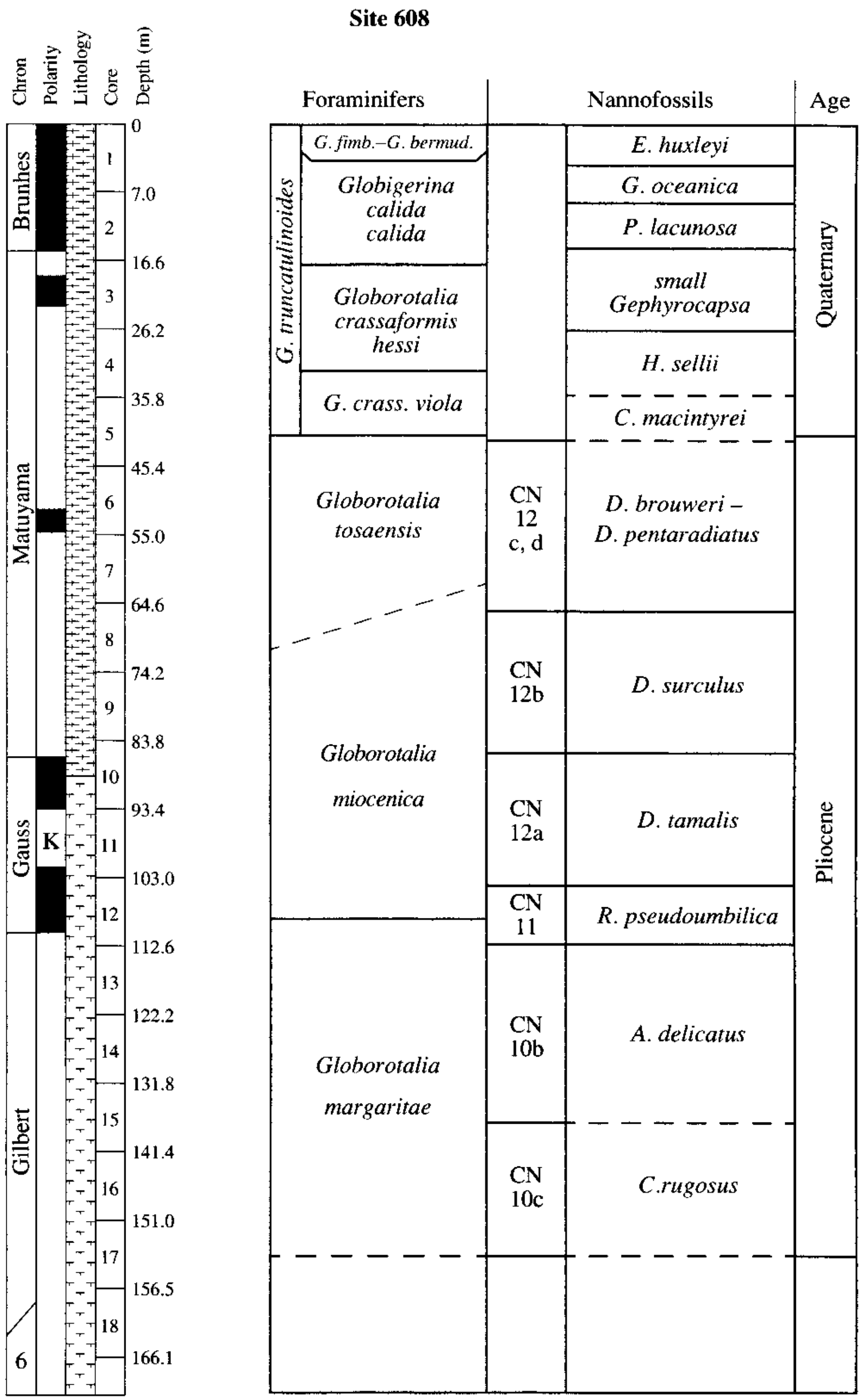

Fig. 3. Pliocene–Quaternary zonal units of calcareous plankton from DSDP Site 608 (symbols as in Fig. 2).

garitae Zone corresponds at the site to successive nannofossil zonal units. The lower *Ceratolithus rugosus* Subzone CN10c extends upward to the basal interval of Core 15, Sample 608-15-5, 95–97 cm, inclusive. The first occurrence of planktonic foraminifer *Globorotalia crassaformis* is recorded within the subzone, and its top coincides with the LO levels of *Globorotalia conomiozea* and *G. conoidea.* Higher in the section up to Sample 608-13-1, 99–101 cm, we recognized the *Amaurolithus delicatus* Subzone. Within this subzone, there is recorded the first occurrence of planktonic foraminifers *Globorotalia crassaformis viola*, and characteristic of its upper part are the last occurrence of *Globigerina nepenthes* and the appearance of *Globorotalia crassaformis hessi*. However, we failed to determine age of these events, because the magnetochronological records in this interval are unreliable (Weaver and Clement, 1986).

Higher in the section up to Sample 608-12-2, 100–102 cm, the undivided *Reticulofenestra pseudoumbilica* Zone (CN11) is recognized. Its range is evidently reduced. The top of the zone is placed, as at Site 397, in the lowermost foraminiferal *Globorotalia miocenica* Zone.

The undivided interval of *Globorotalia miocenica* and *Globorotalia tosaensis* zones includes here, like at Site 397, the succession of *Discoaster* subzones, of which the lowermost *Discoaster tamalis* Subzone (CN12a) with top dated at 2.76 Ma ranges upward to Sample 608-10-1, 96–98 cm. Planktonic foraminifers *Sphaeroidinellopsis seminulina, Globoquadrina altispira*, and *Globorotalia pertenuis* successively disappear within this subzone as at Site 397 (Table 1). The subzone lower boundary is placed, with certain reservations, at the last occurrence level of *Reticulofenestra pseudoumbilica.*

The overlying interval up to Sample 608-8-2, 95–97 cm, is assigned to the *Discoaster surculus* Subzone (CN12b). The subzone yields comparatively abundant and diverse nannofossils whose assemblage is of a relatively cold-water type, as indicated by abundance of *Coccolithus pelagicus* and by rarity of *Discoaster* forms. The base of the subzone is defined by the last occurrence of index species of the underlying unit. The foraminifer assemblage that includes the first appeared *Globorotalia tosaensis, G. inflata*, and *G. triangula* is also of a rather cryophilic character.

Upward the section the interval of the *Discoaster pentaradiatus* (CN12c) and *Discoaster brouweri* (=*Calcidiscus macintyrei* CN12d) subzones is recognized. It is difficult to separate undoubtedly these two units at Site 608. The top of the latter corresponds to the last occurrence of the index species in Sample 608-5-5, 68–70 cm.

It should be particularly emphasized that Sites 608 and 609 are located in the narrow geographic belt between 42° and 49° N, where the Pliocene–Quaternary boundary can be concurrently defined based on three events: on simultaneous extinction of *Discoaster brouweri* and *Neogloboquadrina atlantica* sin. and on the first appearance of *Globorotalia truncatulinoides.* Northward of the belt, the latter species appears for the first time later, whereas to the south species *Neogloboquadrina atlantica* are missing.

The Quaternary lower boundary that coincides with the base of the foraminiferal *Globorotalia truncatulinoides* Zone, is placed at Site 608 slightly above the *Discoaster brouweri* Subzone, the top of which is defined in Sample 608-5-2, 96–98 cm. The top of the *Calcidiscus macintyrei* Zone is within the foraminiferal *Globorotalia crassaformis viola* Subzone, as in the other studied sections, though at the site in question this level is established conventionally. Upward the section the *Helicosphaera sellii* Zone is distinguished up to the extinction of its index species, and the zone top is placed in Sample 608-4-1, 97–99 cm, within the foraminiferal *Globorotalia crassaformis hessi* Subzone. In the upper part of the zone (Sample 608-4-2, 94–96 cm), the first occurrence of large *Gephyrocapsa oceanica* is recorded.

Zone of small *Gephyrocapsa* forms occupies the uppermost part of the *Globorotalia crassaformis hessi* Subzone and partly overlaps the lowermost foraminiferal *Globigerina calida calida* Subzone. Sample 608-2-6, 95–97 cm, is typical of the zone and bears the nannofossil assemblage completely consisting of the index species. The Jaramillo Subchron is recorded in the middle part of the zone, as at Sites 397 and 609, whereas in the piston cores from tropical Atlantic the zone top corresponds to the subchron lower boundary (Bylinskaya and Golovina, 1990).

The *Globigerina calida calida* Subzone also includes ranges of the *Pseudoemiliania lacunosa* Zone (up to Sample 608-2-2, 98–100 cm) whose upper boundary is at 0.45 Ma and of the *Gephyrocapsa oceanica* Zone (up to Sample 608-1-5, 68–70 cm). The foraminiferal *Globigerina bermudezi* Subzone corresponds to the *Emiliania huxleyi* and *Emiliania huxleyi* acme zones.

Site 609

This site is located in the temperate belt, where the assemblages of foraminifers and nannofossils are substantially impoverished (Bylinskaya *et al.*, 2002). However, almost complete succession of zonal units of both groups of calcareous plankton can be recognized here (Fig. 4), and the units are close to those established at Site 608 (Fig. 3).

The *Globorotalia margaritae* Zone is distinguishable in the section beginning from the uppermost part of Core 37. Its base almost coincides in age with the same datum at Site 397 (Table 1). The range of the zone includes the following nannofossil units.

The upper part of the *Discoaster quinqueramus* Zone (CN9) is recovered in the lowermost Pliocene interval up to Sample 609-36-2, 98–100 cm. The last occurrence level of index species at 5.93 Ma is close to the same level at Site 397. A series of thermophilic species present in the assemblage permits the recognition of the interval as the *Amaurolithus primus* Subzone CN9b. The *Amaurolithus tricorniculatus* Zone CN10 undivided into subzones is distinguishable up to Sample 609-28-2, 99–101 cm. The first occurrence of

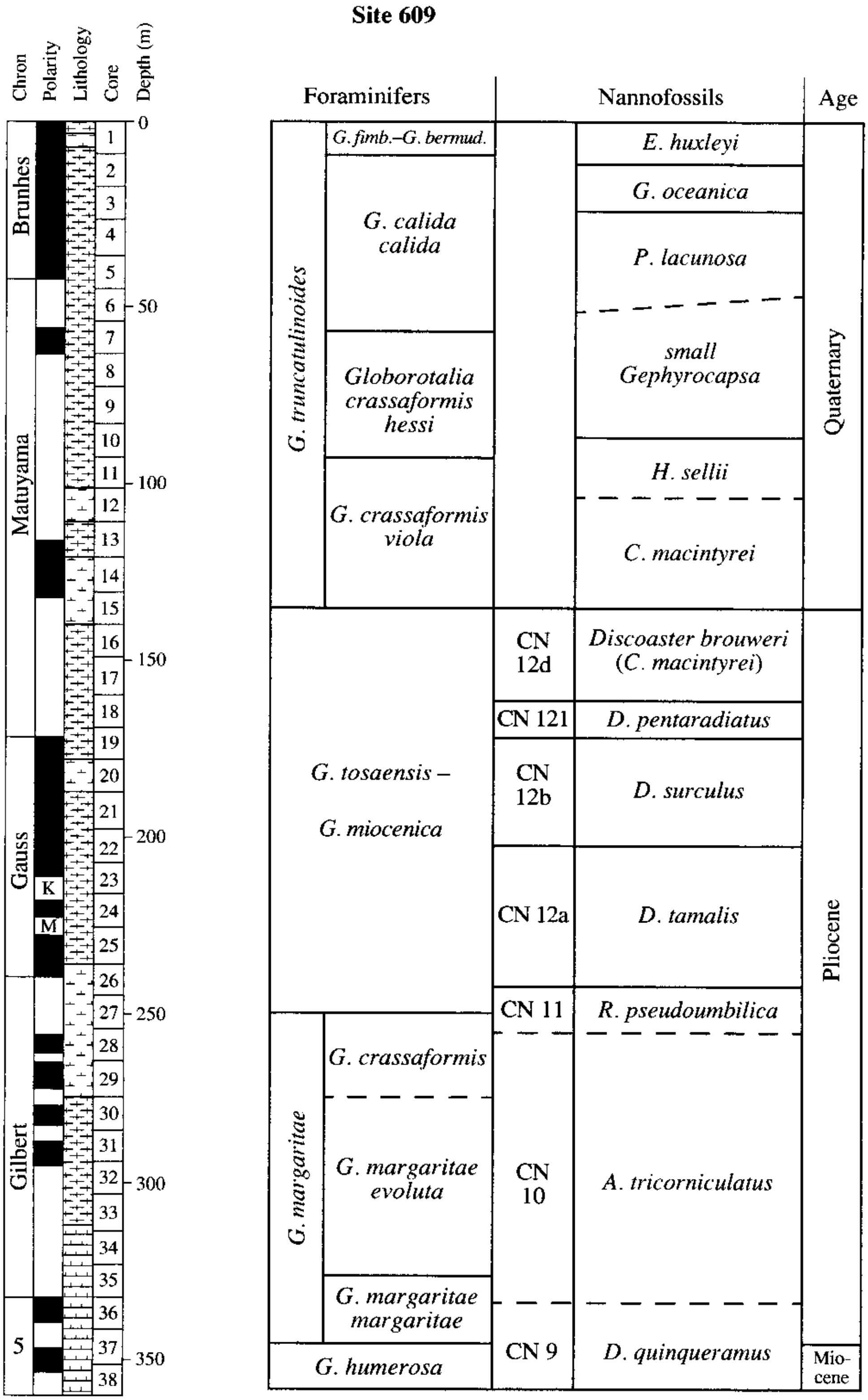

Fig. 4. Pliocene–Quaternary zonal units of calcareous plankton from DSDP Site 609 (symbols as in Fig. 2).

planktonic foraminifers *Globorotalia crassaformis* and *G. puncticulata* is recorded within the zone. The *Reticulofenestra pseudoumbilica* Zone (CN11) is likely reduced at the site (Fig. 4). Like at Site 608, its top is defined in Sample 609-26-6, 98–100 cm, from the lowermost foraminiferal *Globorotalia miocenica* Zone.

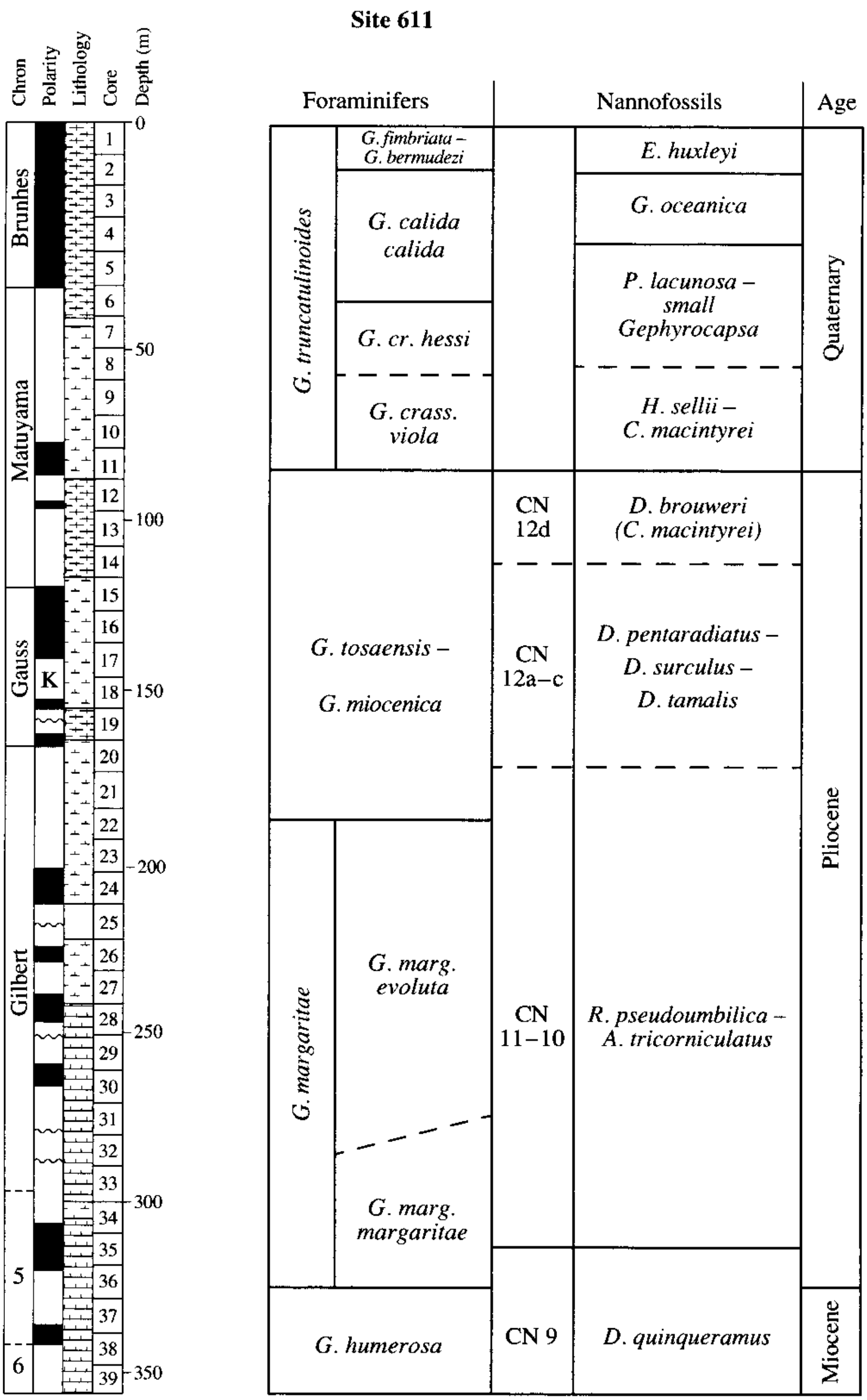

Fig. 5. Pliocene–Quaternary zonal units of calcareous plankton from the DSDP Site 611 (symbols as in Fig. 2).

The last occurrence of *Globorotalia margaritae* recorded within the zone took place at this northern site considerably earlier than in the low-latitude regions.

As in the other studied sections, the undivided interval of the *Globorotalia miocenica* and *Globorotalia tosaensis* foraminiferal zones corresponds to several nannofossil units. The *Discoaster tamalis* Subzone ranges up to Sample 609-22-2, 57–59 cm, and its top is dated at 2.85 Ma. The *Discoaster surculus* Subzone extends up to Sample 609-19-1, 98–100 cm (age level of 2.56 Ma) and the *Discoaster pentaradiatus* Subzone up to Sample 609-18-1, 98–100 cm (age level of 2.43 Ma). The *Discoaster brouweri* (=*Calcidiscus macintyrei*) Subzone CN12d terminates the Pliocene section at Site 609. Its upper boundary in Sample 609-15-4, 103–105 cm, is very close to the extinction level of *Neogloboquadrina atlantica* and to the *Globorotalia truncatulinoides* FO.

As at Site 608, the *Calcidiscus macintyrei* Zone of the lower Quaternary corresponds to a greater part of the *Globorotalia crassaformis viola* Subzone. Its top in Sample 609-12-1, 102–104 cm, is dated back to 1.55 Ma. The *Helicosphaera sellii* Zone is overlapping with the lower half of the *Globorotalia crassaformis hessi* Subzone. The top of the former defined in Sample 609-10-3, 102–104 cm, is 1.38 Ma old. Despite the conventional upper boundary of the *Gephyrocapsa* Zone at the site, it seems to be close to the top of the *Globorotalia crassaformis hessi* Subzone. The *Globigerina calida calida* Subzone includes the *Pseudoemiliania lacunosa* Zone ranging up to Sample 609-3-6, 96–98 cm (age level of 0.45 Ma), and the *Gephyrocapsa oceanica* Zone traceable up to Sample 609-2-3, 103–105 cm. Finally, the undivided interval of the *Globigerina bermudezi* and *Globigerina fimbriata* subzones corresponds to the *Emiliania huxleyi* Zone.

Site 611

DSDP Site 611 located in the Boreal Atlantic is the northernmost one among the others. In distinction from other cases, when we were able to correlate in detail the zonal units established for different groups of calcareous plankton, the microplankton assemblages from Site 611 are so impoverished that it was impossible to divide the recognizable zones and intervals into smaller units (Fig. 5).

The *Globorotalia margaritae* Zone is correlated at the site with the upper part of the nannofossil *Discoaster quinqueramus* Zone CN9 whose top is in the uppermost Chron 5, like at Sites 609 and 397, and with the greater part of zones CN10 and CN11. The upper boundary of the undivided *Amaurolithus tricorniculatus* (CN10)–*Reticulofenestra pseudoumbilica* (CN11) interval is established in the upper part of the Gilbert Chron within the interval of the foraminiferal *Globorotalia miocenica–Globorotalia tosaensis* Zone. This level analogous to its counterpart at Site 609 is dated back to 3.63 Ma based on the last occurrence of *Sphenolithus* forms. It is remarkable that the estimated disappearance time of *Sphenolithus* forms at this northern site coincides with dates established in other climatic belts (Berggren *et al.*, 1995). The rest of the *Globorotalia miocenica–Globorotalia tosaensis* interval includes the *Discoaster* subzones, first the undivided interval of the *Discoaster tamalis* (CN12a), *Discoaster surculus* (CN12b), and *Discoaster pentaradiatus* (CN12c) subzones ranging up to Sample 611-14-3, 101–103 cm, and then the *Discoaster brouweri* (=*Calcidiscus macintyrei*) Subzone (CN12d) ranging up to Sample 611-11-5, 99–101 cm. The top of the latter subzone coincides with the Pliocene–Quaternary boundary that was defined in the studied section at the last occurrence level of *Neogloboquadrina atlantica* and corresponds to the Olduvai Subchron.

The units recognized in the Quaternary part of the section are as follows. The *Globorotalia crassaformis viola* Subzone approximately corresponds to the greater part of the *Calcidiscus macintyrei–Helicosphaera sellii* undivided interval, the top of which conventionally defined in Sample 611-8-3, 103–105 cm, is dated back to 1.25 Ma. The *Gephyrocapsa–Pseudoemiliania lacunosa* undivided interval ranging up to Sample 611-4-5, 98–100 cm, includes the *Globorotalia crassaformis hessi* and, partly, *Globigerina calida calida* subzones. Crowning the section are the *Gephyrocapsa oceanica* and *Emiliania huxleyi* nannofossil zones.

CONCLUSIONS

The analyzed correlation between nannofossil and foraminiferal zones in the Pliocene–Quaternary deposits of subtropical and boreal region of the Atlantic Ocean leads to the following conclusions.

(1) The upper part of the *Discoaster quinqueramus* Zone (CN9) in all studied sections is overlapping with the Lower Pliocene foraminiferal *Globorotalia margaritae* Zone, and its top is close to the base of the Gilbert Chron. The base of the *Globorotalia margaritae* Zone is 6.1 to 6.3 Ma old in the sections, and the top of the *Discoaster quinqueramus* Zone is 5.94 Ma old.

(2) The foraminiferal *Globorotalia margaritae* Zone (N18–N19) is comparable in range with nannofossil zones CN10–CN11 and includes the *Triquetrorhabdulus rugosus* (CN10a), *Ceratolithus acutus* (CN10b), *Ceratolithus rugosus* (CN10c), *Amaurolithus delicatus* (CN10d), *Sphenolithus neoabies* (CN11a), and *Discoaster asymmetricus* (CN11b) subzones after Okada and Bukry (1980). In all studied sections, the top of the *Reticulofenestra pseudoumbilica* Zone (CN11) is established in the lower part of the foraminiferal *Globorotalia miocenica* Zone close to the boundary between the Gilbert and Gauss chrons.

(3) The greater part of the foraminiferal *Globorotalia miocenica* and *Globorotalia tosaensis* (N20–N21) zones corresponds to a succession of *Discoaster tamalis, Discoaster surculus, Discoaster pentaradiatus* and *Discoaster brouweri* (=*Calcidiscus macintyrei*) subzones CN12a–CN12d.

(4) The lower boundary of the foraminiferal *Globorotalia truncatulinoides* Zone corresponds to the base of the Olduvai Subchron and almost coincides

with the top of the *Discoaster brouweri* Subzone at the level of 1.95–2.0 Ma according to our assessment. The Pliocene–Quaternary boundary is thus substantiated based on distribution of nannofossils and planktonic foraminifers. In a narrow belt of the Atlantic Ocean between 42° and 49° N, the Pliocene–Quaternary boundary marks three concurrent events: the extinction of *Discoaster brouweri* and *Neogloboquadrina atlantica* sin and the first appearance of *Globorotalia truncatulinoides*. To the north of the belt, the first occurrence level of latter species is recorded higher, whereas *Neogloboquadrina atlantica* is missing to the south of the belt.

(5) In the Quaternary sequences of all studied sites, similar correlative zonations of two groups of calcareous plankton are observable. The *Calcidiscus macintyrei* Zone (Gartner, 1977) is correlative in this case with the lower (greater) part of the *Globorotalia crassaformis viola* Subzone. Zones of *Helicosphaera sellii* and small *Gephyrocapsa* forms approximately correspond to the *Globorotalia crassaformis hessi* Subzone, and the Jaramillo Subchron is therewith in the second nannofossil zone. The *Pseudoemiliania lacunosa* Zone is included in or overlaps with the *Globorotalia calida calida* Subzone. The *Gephyrocapsa oceanica* and *Emiliania huxleyi* zones correspond to the upper part of the *Globorotalia calida calida* and two overlying subzones.

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REFERENCES

1. W. A. Berggren, D. V. Kent, and J. A. Van Couvering, Neogene Geochronology and Chronostratigraphy, in *The Chronology of the Geological Record*, Ed. by N. J. Snelling (Mem. Geol. Soc., London, 1985), No. 10, pp. 211–260.
2. W. A. Berggren *et al.*, Late Neogene Chronology: New Perspectives in High-Resolution Stratigraphy, Bull. Geol. Soc. Am. **107**, 1272–1287 (1995).
3. H. M. Bolli and J. B. Saunders, Oligocene to Holocene Lowlatitude Planktic Foraminifera, in *Plankton Stratigraphy*, Ed. by H. M. Bolli, J. B. Saunders, and K. Perch-Nielsen (Cambridge Univ. Press, Cambridge, 1985), pp. 155–262.
4. M. E. Bylinskaya, Pliocene–Quaternary Planktonic Foraminiferal Datums in DSDP Site 397 and Comparison of Zonal Stratigraphic Schemes, Stratigr. Geol. Korrelyatsiya **7** (4), 75–84 (1999) [Stratigr. and Geol. Correlation **7**, 377–385 (1999)].
5. M. E. Bylinskaya and L. A. Golovina, Stratigraphy of the Quaternary Sediments of the Tropical Atlantic Based on Foraminifers and Nannofossils, Byul. Komis. Izuch. Chetv. Per., No. 59, 117–128 (1990).
6. M. E. Bylinskaya, L. A. Golovina, and V. A. Krasheninnikov, *Pliocene–Quaternary Zonal Stratigraphy of the Northern Half of the Atlantic by Means of Calcareous Plankton* (Nauchnyi Mir, Moscow, 2002) [in Russian].
7. S. Gartner, Calcareous Nannofossil Biostratigraphy and Revised Zonation of the Pleistocene, Mar. Micropaleontol. **2**, 1–25 (1977).
8. K. Kameo and T. Takayama, Biostratigraphic Significance of Sequential Size Variations of the Calcareous Nannofossil Genus *Reticulofenestra* in the Upper Pliocene of the North Atlantic, Mar. Micropaleontol. **37**, 41–52 (1999).
9. V. A. Krasheninnikov, Significance of Oceanic Deposits for Development of Mesozoic and Cenozoic Stratigraphic Scale (Pacific and Atlantic Oceans), Vopr. Mikropaleontol., No. 21, 42–161 (1978).
10. V. A. Krasheninnikov, Continental and Oceanic Cenozoic Zonal Scale, in *Stratigraphy in Investigations of Geological Institute, AN SSSR*, Ed. by V. V. Menner and V. A. Krasheninnikov (Nauka, Moscow, 1980), pp. 162–207 [in Russian].
11. V. A. Krasheninnikov and M. E. Bylinskaya, Pliocene–Quaternary Stratigraphy and Planktonic Foraminifers of the Low-Latitude North Atlantic, Byul. Komis. Izuch. Chetv. Per., No. 63, 46–64 (1999).
12. V. A. Krasheninnikov, I. A. Basov, L. A. Golovina, *et al.*, *Northeastern Atlantic and Eastern Mediterranean Miocene* (Nauchnyi Mir, Moscow, 1999) [in Russian].
13. M. Kučera, Biochronology of the Mid-Pliocene *Sphaeroidinella* Event, Mar. Micropaleontol. **35**, 1–16 (1998).
14. E. Martini, Standard Tertiary and Quaternary Calcareous Nannoplankton Zonation, in *Proceedings of the II Planktonic Conference, Roma, Italy, 1971* (Roma, 1971), Vol. 2, pp. 739–785.
15. H. Okada and D. Bukry, Supplementary Modification and Introduction of Code Numbers to the Lowlatitude Coccolith Biostratigraphic Zonation (Bukry, 1973, 1975), Mar. Micropaleontol. **5**, 321–325 (1980).
16. U. von Rad *et al.*, *Initial Reports of the Deep Sea Drilling Project*, Vol. 47, Part 1 (US Government Printing Office, Washington, 1979).
17. W. F. Ruddiman, R. B. Kidd, E. Thomas, *et al.*, Site 609, in *Initial Reports of the Deep Sea Drilling Project*, Ed. by S. Orlofsky (US Government Printing Office, Washington, 1987), Vol. 94, Part 1, pp. 247–349.
18. C. Spencer-Cervato, The Cenozoic Deep Sea Microfossil Record; Explorations of the DSDP/ODP Sample Set Using the Neptune Database, Palaeontologia Electronica, Vol. 2, No. 2 (1999).
19. P. P. E. Weaver and B. M. Clement, Synchroneity of Pliocene Planktonic Foraminiferal Datums in the North Atlantic, Mar. Micropaleontol. **10**, 295–307 (1986).