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Range and stratigraphic significance of the *Globorotalia crassaformis* plexus

Distribución y significado estratigráfico de *Globorotalia crassaformis* plexus

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Abstract

Study of DSDP sites and piston cores from the Northern Atlantic Ocean provided new knowledge of the range and distribution of the *Globorotalia crassaformis* plexus. The following subspecies are differentiated: *Globorotalia crassaformis crassaformis, G. crassaformis ronda, G. crassaformis hessi, G. crassaformis viola,* and *G. crassaformis imbricata* and are described and illustrated. A similar sequence of FADs and LADs of the plexus was recorded in different climatic realms. *G. crassaformis crassaformis* appeared at 5.06 Ma in the subtropical region and at 4.62 Ma in the boreal realm. It was then followed by other subspecies in a specific succession. At all sites *G. puncticulata* appeared slightly later than the earliest members of *G. crassaformis* ss. Its first occurrence data range from 4.88 to 4.54 Ma in different realms. The stratigraphic significance of the plexus is considerably greater than has formerly been recognized and it may be recommended for wider use in the Pliocene–Quaternary zonations.

Keywords: planktonic foraminifera, *Globorotalia crassaformis,* Atlantic Ocean, biostratigraphy, zonations, FADs and LADs.

Resumen

El estudio de las localidades y testigos, del DSDP, del Oceano Atlántico Norte proporciona nuevos conocimientos sobre la distribución del plexus de *Globorotalia crassaformis.* Se diferencian las siguientes subespecies: *Globorotalia crassaformis crassaformis, G. crassaformis ronda, G. crassaformis hessi, G. crassaformis viola* y *G. crassaformis imbricata*. Se han constatado secuencias similares de las primeras y últimas apariciones de los componentes del plexus en diferentes regiones climáticas. *G. crassaformis crassaformis* apareció hace 5,05 Ma en la región subtropical y 4,62 Ma en la boreal. Fue seguida por otras subespecies en un cierto orden. Así *G. puncticulata* lo hizo en todos las localidades algo más tarde que las primeras *G. crassaformis crassaformis*. Su primer registro se data entre 4,88 y 4,54 Ma según la región. Las subespecies estudiadas se describen e ilustran. El significado estratigráfico del plexus es considerablemente mayor del que se había reconocido y puede ser recomendado para un uso más amplio en la zonación del Plio-Cuaternario.

Palabras clave: foraminíferos planctónicos, *Globorotalia crassaformis,* Oceano Atlántico, bioestratigrafía, zonaciones, primera aparición, última aparición.

1. Introduction

The species *Globorotalia crassaformis*, first described by Galloway and Wissler (1927), is widespread throughout the World Ocean and, along with *Globorotalia puncticulata* and *G. inflata,* commonly defines the specific character of Pliocene and Quaternary planktonic foraminiferal assemblages. Subsequently the following subspecies of *Globorotalia crassaformis* were described: *G. crassaformis oceanica* (Cushman and Bermudez, 1949),

G. crassaformis ronda (Blow, 1969), *G. crassaformis viola* (Blow, 1969), *G. crassaformis hessi* (Bolli and Premoli Silva, 1973) and *G. crassaformis imbricata* (Bylinskaya *et al*., 2002). The attribution of these forms to subspecific rank is controversial and some authors regard them as separate species (Saito *et al.,* 1981). In this paper the author considers these forms as subspecies, holding the viewpoint of Bolli (Bolli and Saunders, 1985, p. 156): "As regards the inclusion of species, we have had to make a choice. Practical use over the years has led to this choice but, again, it is a personal one as is the degree of subdivision to subspecific level and the grouping of such subspecies; stratigraphic utility is the ultimate aim."

It should be noted that the stratigraphic significance of the forms of *G. crassaformis* is so far not widely recognized. For instance, Blow (1969) reported the occurrence of all taxa of the group from the Late Miocene–Early Pliocene to the Holocene thus not distinguishing them as stratigraphic markers. Stainforth *et al.* (1975) considered the distinctions between these forms as weak and insignificant, recognizing only *G. crassaformis, G. aemiliana,* and *G. ronda.* Summarizing different standpoints, Bolli wrote: "The use and acceptance of taxa of the *crassaformis* plexus as index forms in biostratigraphy thus remains incompletely understood, controversial, and largely limited to restricted areas, such as the Mediterranean or the Caribbean." (Bolli and Saunders, 1985, p. 230). However, *G. crassaformis viola* and *G. crassaformis hessi* were used for the zonal subdivision of Quaternary sediments in the Indian Ocean (Rögl, 1974), North (Krasheninnikov, 1979) and South Atlantic (Pflaumann, 1988). Our investigations (Bylinskaya *et al*., 2002) showed that the subspecies of *G. crassaformis* are widespread in oceanic sediments, have clear morphologic distinctions, and therefore that they can be used as marker forms for subdivision of the Pliocene and Quaternary .

I distinguish the following subspecies: *Globorotalia crassaformis crassaformis, G. crassaformis ronda, G. crassaformis hessi, G. crassaformis viola,* and *G. crassaformis imbricata* (Krasheninnikov and Bylinskaya, 1994, 1999; Bylinskaya *et al*., 2002). The aim of this work was to trace the occurrence of these subspecies of *Globorotalia crassaformis* in various climatic realms and to study their distribution throughout the Pliocene–Quaternary section.

This research is based on a thorough study of DSDP samples kindly provided by the Deep Sea Drilling Project and piston cores of the R/V "Akademik N. Strakhov". Over 1500 samples from 14 DSDP sites (Fig. 1), were studied and all of them yielded specimens of *G. crassaformis*. The total area of investigation covers the North Atlantic from the equator to subpolar latitudes.

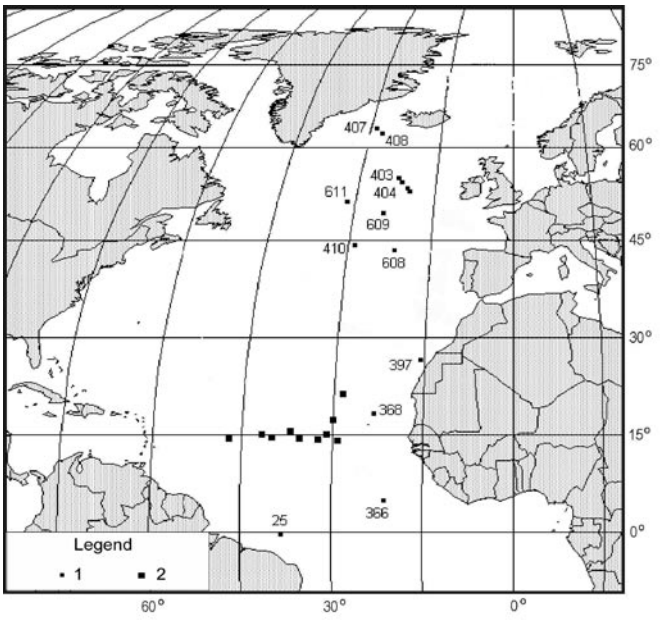


Fig. 1.- Location of the studied DSDP Sites and piston cores. 1 – DSDP sites; 2 – stations of the R/V "Akademik N. Strakhov".
Fig. 1.- Situación de los pozos DSDP y testigos estudiados. 1 - pozos DSDP; 2 - estaciones del R/V "Akademik N. Strakhov".

2. Methods

The samples were washed through a 100-μm sieve and the residues were studied under a light microscope and SEM. The complete residues of each sample (an average of several thousand specimens) were looked through in order to trace all rare species that can be overlooked on cursory examination.

The DSDP holes and piston cores with the available paleomagnetic record (von Rad *et al*., 1979) were most thoroughly investigated. An important aim was to estimate the absolute ages of FADs and LADs of the *G. crassaformis* plexus. The absolute ages were calculated using sediment accumulation rates and calibrated against the time scale of Berggren *et al.* (1995).

3. Results on distribution of the *Globorotalia crassaformis* plexus in the Pliocene–Quaternary sediments of the Atlantic Ocean

As the holes discussed below are characterized by a similar pattern of stratigraphic distribution of the *Globorotalia crassaformis* members, their range is shown in Figure 2 using Site 397 as an example. The sites are described from the south to the north.

DSDP Site 25 (0º 31' S, 39º 31' W) is the southernmost hole among those discussed in this paper (Fig. 1). In studies of its Pliocene–Quaternary sediments our purpose was to reveal the degree of representation of the *Globorotalia*

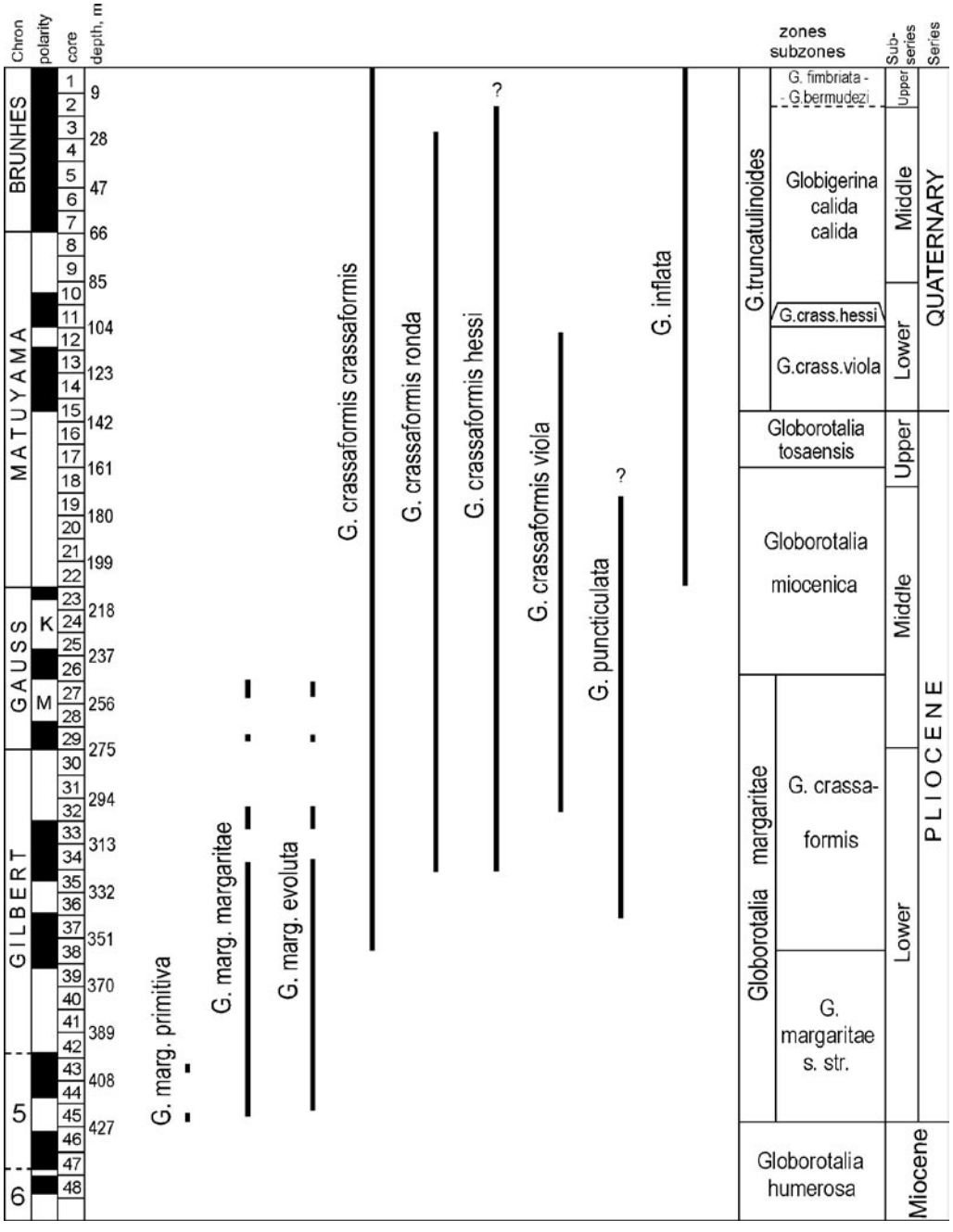


Fig. 2.- Range of the *Globorotalia crassaformis* subspecies in the Pliocene–Quaternary interval of DSDP Site 397, 26º 50' N, 15º 10' W. Paleomagnetic records after von Rad, U., Ryan, W.B.F., et al., (1979). K–Kaena Subchron; M–Mammoth Subchron.

Fig. 2.- Distribución de las subspecies de *Globorotalia crassaformis* en el intervalo Plioceno-Cuaternario del pozo 397 DSDP, 26º 50' N, 15º 10' W. Registro paleomagnético según von Rad, U., Ryan, W.B.F., et al., (1979). K–Subcron Kaena; M–Subcron Mammoth.

crassaformis plexus in the equatorial realm. This group is widespread in almost all climatic realms of the Atlantic Ocean and represents an important instrument for the zonal subdivision of deep-sea sediments. At the same time its subspecies had not yet been reported from the equatorial region. My investigation revealed that the subspecies *G. crassaformis crassaformis, G. crassaformis viola, G. crassaformis hessi,* and *G. crassaformis ronda* occur in all studied samples of Site 25. In the upper part of the section *G. crassaformis imbricata* was recorded (Sample 25-1-1, 80-82 cm). In cores 25-1 and 25-2 I have recognized Bolli's Quaternary *Globorotalia crassaformis viola, Globorotalia crassaformis hessi, Globigerina calida calida, Globigerina bermudezi,* and *Globorotalia fimbriata* Subzones (Bylinskaya *et al.,* 2002).

DSDP Site 366 located in the tropical Atlantic (5º 41' N, 19º 51' W) is characterized by the following successive appearances of the forms of *Globorotalia crassafor-*

mis: *G. crassaformis* s.l. (=*G. crassaformis crassaformis*) appeared in the middle part of the Lower Pliocene in the *Globorotalia margaritae* Zone (Sample 366A-8-4, 71-73 cm), and close to the top of the zone the first occurrences of *Globorotalia puncticulata* and *G. crassaformis viola* were recorded. First specimens of *G. crassaformis hessi* were encountered in the Upper Pliocene *Globorotalia tosaensis* Zone (Sample 366A-4-4, 62-64 cm). At the top of the section *G. crassaformis imbricata* was found (Sample 366A-1, CC).

The piston cores obtained by the R/V "Akademik N. Strakhov" in the tropical Atlantic along 15º N recovered mainly Quaternary sediments, thus only the youngest data of members of the *Globorotalia crassaformis* plexus were traced. In core 32T2 the last occurrence of *G. crassaformis ronda* was recorded at 0.64 Ma and that of *G. crassaformis hessi,* at 0.19 Ma. *G. crassaformis imbricata* appeared within the Brunhes Chron at 0.58 Ma (Fig. 3).

Site 397 (26º 50' N, 15º 10' W) located nearby the northwestern coast of Africa at a depth of 2900 m, is characterized by a thick section of Upper Cenozoic sediments accumulated at a high deposition rate. The reliable paleomagnetic record obtained in Leg 47, permitted the re-estimation of FAD and LAD ages of planktonic foraminifera (Bylinskaya, 1999). The samples studied were taken every 1.5 m, which corresponds to a resolution of 0.02 m.y. First specimens of *Globorotalia crassaformis crassaformis* (Fig. 2) were recorded in the middle part of the Lower Pliocene *Globorotalia margaritae* Zone (Sample 397-38-3, 18-22 cm), within the Thvera Subchron of the Gilbert Chron at 5.06 Ma. This datum is considerably older than was previously estimated (Berggren *et al*., 1995). Next after *G. crassaformis crassaformis,* specimens of *G. crassaformis ronda* and *G. crassaformis hessi* were encountered upward in the section at Site 397 (Sample 397-34-7, 25-29 cm). They first appeared within the Nunivak Subchron at 4.5 Ma. Thus the FAD of the latter subspecies is older than in tropical and temperate regions. The FAD of *G. crassaformis viola* was recorded near the top of the Cochiti Subchron of the Gilbert Chron at 4.0 Ma (Sample 397-32-3, 20-24 cm). Its last occurrence marks the top of the Lower Quaternary subzone of the same name. At Site 397 this was recorded in Sample 397-12-1, 59-63 cm. The LADs of *G. crassaformis ronda* and *G. crassaformis hessi* correspond to the Upper Quaternary (Samples 397-3-5, 70-72 cm and 397-2-1, 79-83 cm, respectively). *Globorotalia puncticulata* appeared at Site 397 at the top of the Sidufjall Subchron, 4.88 Ma (Sample 397-37-1, 18-22 cm), above the FAD of *G. crassaformis*.

DSDP Site 608 (42º 50' N, 23º 05' W) was drilled on the southern flank of the King's Trough, eastwards the Mid-Atlantic Ridge. The members of *Globorotalia crassaformis* plexus and *G. puncticulata* appeared in the middle part of the *Globorotalia margaritae* Zone (Bylinskaya *et al.,* 2002). *G. crassaformis crassaformis* first occurred in Sample 608-16-5, 95-97 cm; slightly above (Sample 608-16-3, 96-98 cm) the appearance of *G. crassafomis ronda* and *G. puncticulata* are recorded. *G. crassaformis viola* starts from Sample 608-15-2, 95-97 cm, and still higher (Sample 608-13-6, 97-99 cm) *G. crassaformis hessi* appears. As seen from the foregoing, *G. crassaformis hessi* appeared later at higher latitudes than in subtropical regions. However, all these FAD events occurred in the Lower Pliocene. The LADs of *G. crassaformis ronda* and *G. crassaformis hessi* are recorded in the Upper Quaternary, as at Site 397 (Fig. 2).

DSDP Site 410 (45º 31' N, 29º 29' W) is located on the western flank of the Mid-Atlantic Ridge. At this site *G. crassaformis crassaformis* also appeared in the Lower Pliocene (Sample 410-19-3, 49-51 cm), upwards through the section it is followed by *G. puncticulata* and *G. crassaformis viola* (Sample 410-18-1, 99-101 cm) and still higher, by *G. crassaformis ronda* (Sample 410-16-4, 134-136 cm) and *G. crassaformis hessi* (Sample 410-15-3, 73-75 cm). Unfortunately, the studied samples from this site provide a comparatively low resolution and hence the actual FADs could differ slightly.

DSDP Site 609 is situated at 49º 53' N, 24º 14' W in the southern part of the boreal climatic realm. The Pliocene and Quaternary sediments at this site are about 350 m thick and have a reliable paleomagnetic record. The appearance of *Globorotalia crassaformis* s.l. (Sample 609-29-5, 100-102 cm) was recorded in the upper part of the *Globorotalia margaritae* Zone (upper Lower Pliocene) at 4.62 Ma (Fig. 3). Slightly above (Sample 609-29-3, 100-102 cm) I registered the first occurrence of *Globorotalia puncticulata* (Bylinskaya and Golovina, *in press*). *G. crassaformis ronda* and *G. crassaformis hessi* appeared at 4.51 Ma (Sample 609-29-2, 100-102 cm) and *G. crassaformis viola* at 4.18 Ma (Sample 609-28-1, 99-101 cm). The LAD of *G. crassaformis viola* was recorded in the mid-Matuyama Chron at 1.48 Ma (Sample 609-11-1, 105-107 cm). In the Upper Quaternary *G. crassaformis ronda* and *G. crassaformis hessi* successively disappear.

DSDP Site 611 was drilled in the boreal Atlantic at 52º 50' N, 30º 19' W. The thick Pliocene–Quaternary sequence recovered by the hole yields numerous but low-diversity planktonic foraminiferal assemblages. The first occurrence of the *Globorotalia crassaformis* members also corresponds to the upper Lower Pliocene. *G. crassaformis crassaformis* was recorded in Sample 611-

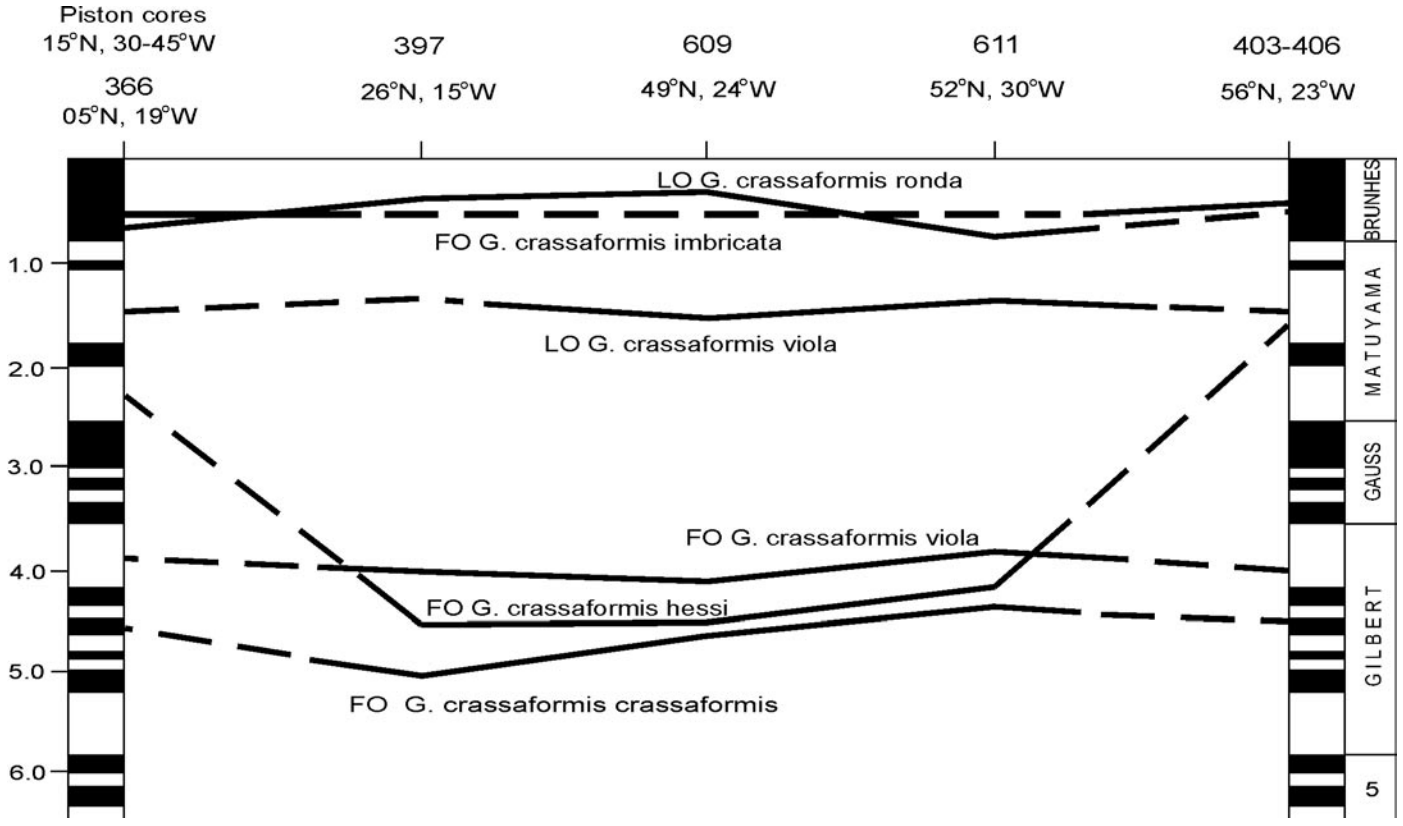


Fig. 3.- First and last appearance datums of the *G. crassaformis* members in the North Atlantic. Magnetochronological scale after Cande and Kent (1995).
Fig. 3.- Datos de primera y última aparición de los miembros de *G. crassaformis* en el Atlántico Norte. Escala magnetocronológica según Cande y Kent (1995).

24-5, 94-96 cm, together with *G. crassaformis ronda. G. crassaformis hessi* appeared slightly higher (Sample 611-23-2, 68-70 cm) and was followed by the first occurrence of *G. crassaformis viola* (Sample 611-22-1, 104-106 cm). All these events are within the upper part of the Gilbert Chron and of the *Globorotalia margaritae* Zone. Accordingly, in these sections the pattern of successive appearances of members of the *Globorotalia crassaformis* plexus remains unchanged from low-latitudes to the boreal Atlantic realm (Fig. 3).

DSDP Sites 403-406 are located on the Hatton-Rockall Plateau, 55º–56º N. The Lower Pliocene *Globorotalia margaritae* Zone is marked by the appearance of *G. crassaformis crassaformis* (Sample 403-12-3, 116-118 cm), *G. crassaformis ronda* (Sample 403-12-2, 8-10 cm) and *G. crassaformis viola* (Sample 403-8-5, 78-80 cm). *G. crassaformis hessi* appeared in the Quaternary (Sample 403-4-1, 90-92 cm) (Fig. 3). Approximately in the middle of the Pleistocene *Globigerina calida calida* Subzone the first occurrence of *Globorotalia crassaformis imbricata* was recorded. Upwards in the section this event is followed by the LADs of *G. crassaformis ronda* and *G. crassaformis hessi* (Krasheninnikov and Bylinskaya, 1994).

4. Discussion

4.1. The use of Globorotalia crassaformis *subspecies in biostratigraphical zonations*

Globorotalia crassaformis subspecies have been repeatedly used as index forms for subdivision of Quaternary sediments (Rögl, 1974; Krasheninnikov, 1979; Pflaumann, 1988). The listed researchers used for this purpose the low-latitude zonation of Bolli and Premoli Silva (1973) or Bolli and Saunders (1985), which includes the *Globorotalia crassaformis viola* and *Globorotalia crassaformis hessi* Subzones in the Lower Quaternary interval (Fig. 4). Berggren (1977) also used *G. crassaformis* in his zonal scheme. He used the event of its first occurrence to define the boundary between units PL1b and PL1c (Fig. 4), though he did not distinguish the subspecies. In so doing he considered that *G. puncticulata* (Fig. 5, 1-3) appeared earlier than *G. crassaformis.*

Subsequently Bolli's zonation was slightly supplemented and modified (Bylinskaya *et al*., 2002). We have changed the criterion for the boundary between the *Globorotalia crassaformis viola* and *Globorotalia crassaformis hessi* Subzones. It is defined not by the first

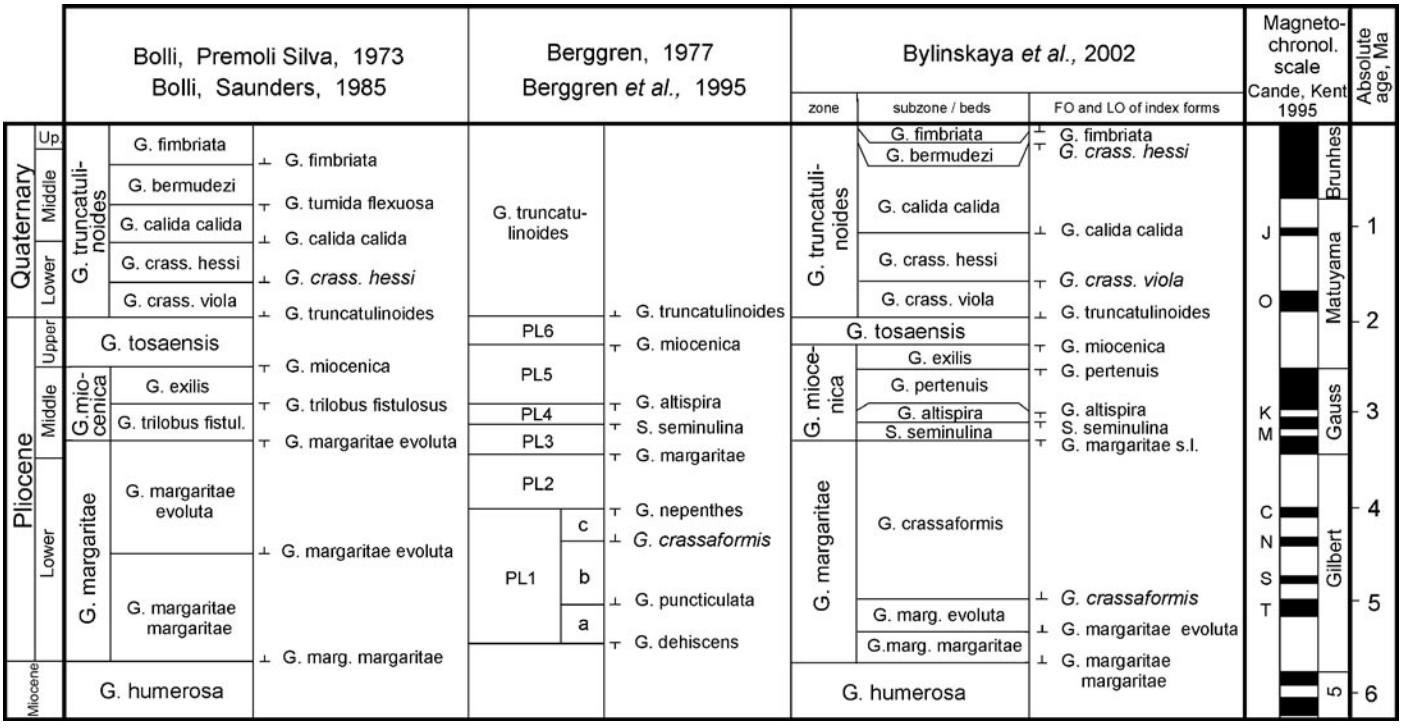


Fig. 4.- Zonations that use the *Globorotalia crassaformis* plexus. Paleomagnetic subchrons: J–Jaramillo; O–Olduvai; K– Kaena; M–Mammoth; C–Cochiti; N–Nunivak; S–Sidufjall; T–Thvera.

Fig. 4.- Zonaciones que usan el plexus *Globorotalia crassaformis*. Subcrones paleomagnéticos: J–Jaramillo; O–Olduvai; K– Kaena; M–Mammoth; C–Cochiti; N–Nunivak; S–Sidufjall; T–Thvera.

occurrence of the latter taxon but by the extinction of *G. crassaformis viola.* Along with the more detailed subdivision of the Middle Pliocene sediments within the *Globorotalia miocenica* Zone, we suggested an additional unit in the Lower Pliocene, i.e. the *Globorotalia crassaformis* Subzone, the base of which is marked by the first appearance of the plexus members (Fig. 4). Therefore, a considerably wider use of the taxa in stratigraphic zonations is possible.

As our studies confirmed, the members of the *Globorotalia crassaformis* plexus are widely distributed in Pliocene–Quaternary deep-sea sediments from the equatorial to the boreal realm. The northernmost point where I have recorded single specimens of *G. crassaformis crassaformis* and *G. crassaformis hessi,* is DSDP Site 408 at 63º N, i.e. in the subarctic region. As for the quantity of *G. crassaformis* specimens, they are usually relatively scarce, however, in some samples they constitute up to 2.6% of the total assemblage.

4.2. First occurrence of the Globorotalia crassaformis *plexus members and* Globorotalia puncticulata

The problem of the first occurrences of *Globorotalia crassaformis* and the morphologically close *Globorotalia puncticulata* is still not clearly understood. There are different viewpoints on this issue in the literature. Initially it was uniquely considered that *G. puncticulata* appeared earlier (Berggren, 1972, 1977; Poore and Berggren, 1975, Dowsett, 1989), but other researchers marked that: “These two species, however, have almost identical FADs in the Leg 94 sites...” (Weaver and Clement, 1986). The problem is in fact that *G. crassaformis* at early stages of its development is represented by rare and small specimens, which are not always recorded by a researcher. Questions arise as to the distinctions between *G. crassaformis* and *G. puncticulata* and as to which of them actually appeared earlier.

Figure 5 illustrates the early *G. puncticulata* (Fig. 5.1-5.3) and *G. crassaformis* (5.4-5.6) encountered in the same sample. It is obvious that they are extremely similar in size and morphology of the umbilical and spiral sides. The only feature that permits the distinction between them is the aperture shape: a high arch in *G. puncticulata* and a low slit sometimes bordered by a rim-like lip in *G. crassaformis*. Since the aperture of small tests is often filled with organic matter and is not always clearly distinguishable, this may partly explain the contradictions as to the question on first occurrences of these species: they can be confused on cursory examination.

My data based on a vast material (see Results) indicate that *G. crassaformis* appeared somewhat earlier than *G. puncticulata* and both FADs are diachronous in different climatic zones. Their earliest appearance data are marked in the subtropical realm. *G. crassaformis* at early stages of evolution is significantly smaller than *G. crassaformis crassaformis* specimens found in younger sediments, so I called it *G. crassaformis* s.l. However, their morphology is identical.

Our studies of planktonic foraminifera in the Pliocene–Quaternary interval in the Atlantic revealed that the *G. crassaformis* subspecies follow the same distribution pattern throughout most of climatic realms (Fig. 3). Berggren *et al.* (1995) placed the first occurrence of *G. crassaformis* within the Nunivak Subchron (4.50 Ma) and in the Mediterranean, at the Gilbert–Gauss boundary (3.58 Ma), respectively. The same age (4.50 Ma) is reported by Spencer-Cervato (1999). Dowsett (1989) dated this event as 4.70 Ma in the southeastern Atlantic. We recorded the earliest appearance of *G. crassaformis* s.l. (=*G. crassaformis crassaformis*) in the subtropical North Atlantic at 5.06 Ma and in the boreal realm, at 4.62 Ma (Fig. 3). According to our data, *G. puncticulata* first occurred in these regions at 4.88 Ma and 4.54 Ma, respectively.

In all the holes discussed the first occurrence of *G. crassaformis crassaformis* is followed by that of *G. crassaformis hessi* and *G. crassaformis ronda*. It should be noted that *G. crassaformis hessi* was originally described in the Caribbean as the index form of the Lower Quaternary *Globorotalia crassaformis hessi* Subzone (Bolli and Premoli Silva, 1973). Berggren (1995) reported the corresponding age of 0.75 Ma. According to our data, at the Rockall Plateau and further northwards it actually appeared in the Lower Quaternary (Krasheninnikov and Bylinskaya, 1994). However, in Hole 366A (5º 40' N) it occurs in Upper Pliocene sediments and at Site 368 (17º 30' N), still lower, in the Pliocene *Globorotalia miocenica* Zone. As evidenced by our records, in the subtropical Site 397 (26º 50' N) the oldest first occurrence of *G. crassaformis hessi* is recorded at 4.5 Ma, i.e. in the upper Lower Pliocene. Thus we conclude that it appeared in the Pliocene, whereas the Quaternary *G. crassaformis hessi* Subzone is actually the acme zone of this form, as it is most abundant and is represented by large typical specimens in these deposits. The first occurrence of this subspecies is a strongly diachronous event in different climatic realms (Fig. 3). *G. crassaformis hessi* last occurred in the Upper Quaternary at 0.1–0.2 Ma; this event marks the top of the *Globigerina calida calida* Subzone (Fig. 4). The extinction of *G. crassaformis ronda* is another marker event in the Quaternary and may serve as an additional tool for detailed subdivision of sediments. In all holes studied it is recorded close to the last occurrence of the nannofossil *Pseudoemiliania lacunosa* in the mid-Brunhes Subchron 0.5–0.6 Ma (Fig. 3).

The first occurrence of *G. crassaformis viola* corresponds to the top of the Cochiti Subchron of the Gilbert Chron at about 4.0 Ma, in the upper part of the Lower Pliocene *Globorotalia margaritae* Zone (Fig. 2). It should be noted that in almost all holes studied *G. crassaformis viola* appeared at a similar level, which is also confirmed by other researchers (Bolli and Saunders, 1985). The last findings of the taxon in the holes discussed were recorded at 1.45–1.5 Ma and mark the upper boundary of the Lower Quaternary *Globorotalia crassaformis viola* Subzone. Thus we infer that both events, i.e. the appearance and extinction of the subspecies, are most likely reliable data for biostratigraphy.

Finally in the equatorial, tropical, and boreal realms of the North Atlantic the appearance of *G. crassaformis imbricata* was recorded at approximately 0.5–0.6 Ma, in the lower half of the *Globigerina calida calida* Subzone (Fig. 3).

4.3. Some remarks on Globorotalia aemiliana *as a related taxon*

In the Mediterranean another related taxon, *Globorotalia hirsuta aemiliana,* was described (Colalongo and Sartoni, 1967), which was considered by the authors as transitional between *G. hirsuta* and *G. crassaformis.* It is now identified as a separate species, *G. aemiliana.* It is regarded to be of stratigraphic significance. The corresponding unit is included in Mediterranean zonations (Bizon, 1979; Iaccarino, 1985). Judging from the illustrations by Colalongo and Sartoni (1967, Fig. 2; Pl. 30, 31), it is distinctly closer to *G. crassaformis* than to *G. hirsuta.* Several forms illustrated by latter authors (Pl. 30, fig. 2a-c; Pl. 31, fig.3) were subsequently synonymized with *G. crassaformis* (Valleri, 1984, p. 388). As may be inferred from the illustrations of Colalongo and Sartoni (1967), *G. aemiliana* closely resembles *G. crassaformis crassaformis* (Pl. 30, figs. 1a-c, 3a-c; Pl. 31, figs. 1a-c) and *G. crassaformis viola* (Pl. 30, figs. 2a-c; Pl. 31, figs. 3a-c, 4a-c). However, if they are identitical, the name *G. aemiliana* has priority.

5. Conclusions

Members of the *Globorotalia crassaformis* plexus follow the same stratigraphic distribution pattern throughout most climatic realms in the North Atlantic. The earliest

form *G. crassaformis crassaformis* appeared at 5.06 Ma in the subtropical region and at 4.62 Ma in the boreal area. In the mid-Lower Pliocene it was followed by *G. crassaformis ronda, G. crassaformis hessi* (4.5 Ma), and *G. crassaformis viola* (4.0 Ma). The latter disappeared at approximately 1.45-1.5 Ma in the Lower Quaternary. *G. crassaformis ronda* and *G. crassaformis hessi* had their LADs at 0.5-0.6 and 0.1-0.2 Ma, respectively. The subspecies *G. crassaformis imbricata* first occurred in the Upper Quaternary at 0.58 Ma.

The problem of the first occurrences of *Globorotalia crassaformis* and *G. puncticulata* is still not clearly understood. Our data indicate that *G. crassaformis* appeared earlier in all sections studied. Specimens of *G. puncticulata* were first recorded at 4.88 Ma in the subtropical region and at 4.54 Ma in the temperate latitudes.

The stratigraphic significance of the *Globorotalia crassaformis* plexus which hitherto remained incompletely understood and controversial, is in my opinion proved. It is considerably greater than formerly recognized and *Globorotalia crassaformis* may be more widely used in the Pliocene-Quaternary zonations.

6. Systematic descriptions

In describing the studied planktonic foraminifera I followed the classification of Stainforth *et al.* (1975) and Bolli and Saunders (1985). The figured specimens and the collections studied herein are deposited in the Geological Institute, Russian Academy of Sciences, Pyzhevskii 7, Moscow 119017, Russia.

Order Foraminifera Eichwald, 1830
Family Globorotaliidae Cushman, 1927
Genus ***Globorotalia*** Cushman, 1927

Globorotalia crassaformis crassaformis
(Galloway and Wissler**)**
(Figs. 5.7 - 5.9)

Globigerina crassaformis Galloway and Wissler, 1927, p. 41, pl. 7, fig. 12.
Globorotalia hirsuta aemiliana Colalongo and Sartoni, 1967, p. 267, pl. 30, figs. 3a-c, pl. 31, figs. 1a-c.
Globorotalia crassaformis crassaformis (Galloway and Wissler) – Pflaumann and Krasheninnikov, 1978, p. 891, pl. 6, figs. 1-3, pl. 7, figs. 5-7.
Globorotalia crassaformis crassaformis (Galloway and Wissler) – Bolli and Saunders, 1985, p. 233, fig. 36.6-7.
Globorotalia crassaformis oceanica Cushman and Bermudez – Bolli and Saunders, 1985, p. 233, fig. 37.11.

Diagnosis and description: A low-trochospiral test, medium in size, with four chambers in the final whorl. The peripheral margin is distinctly lobate from the spiral side, subacute to acute, in some specimens showing an imperforate rim. Chambers from the spiral side, ovate to subquadrate, from the umbilical side, subtriangular, moderately inflated, sutures depressed. The spiral side flat to slightly convex. Aperture interiomarginal, umbilical-extraumbilical, a low slit, sometimes bordered by a rim-like lip.

Remarks: G. crassaformis crassaformis differs from *G. crassaformis hessi* and *G. crassaformis ronda* in the strongly lobate and subacute peripheral margin and less inflated umbilical side. Its last chamber is always larger than the previous one.

Distribution: G. crassaformis crassaformis is a cosmopolitan form distributed as far as the northern boreal Atlantic. It ranges from mid-Lower Pliocene (upper half of the N18 Zone [Blow, 1969]) to Recent. The lowest occurrence was recorded in the subtropical realm at 5.06 Ma.

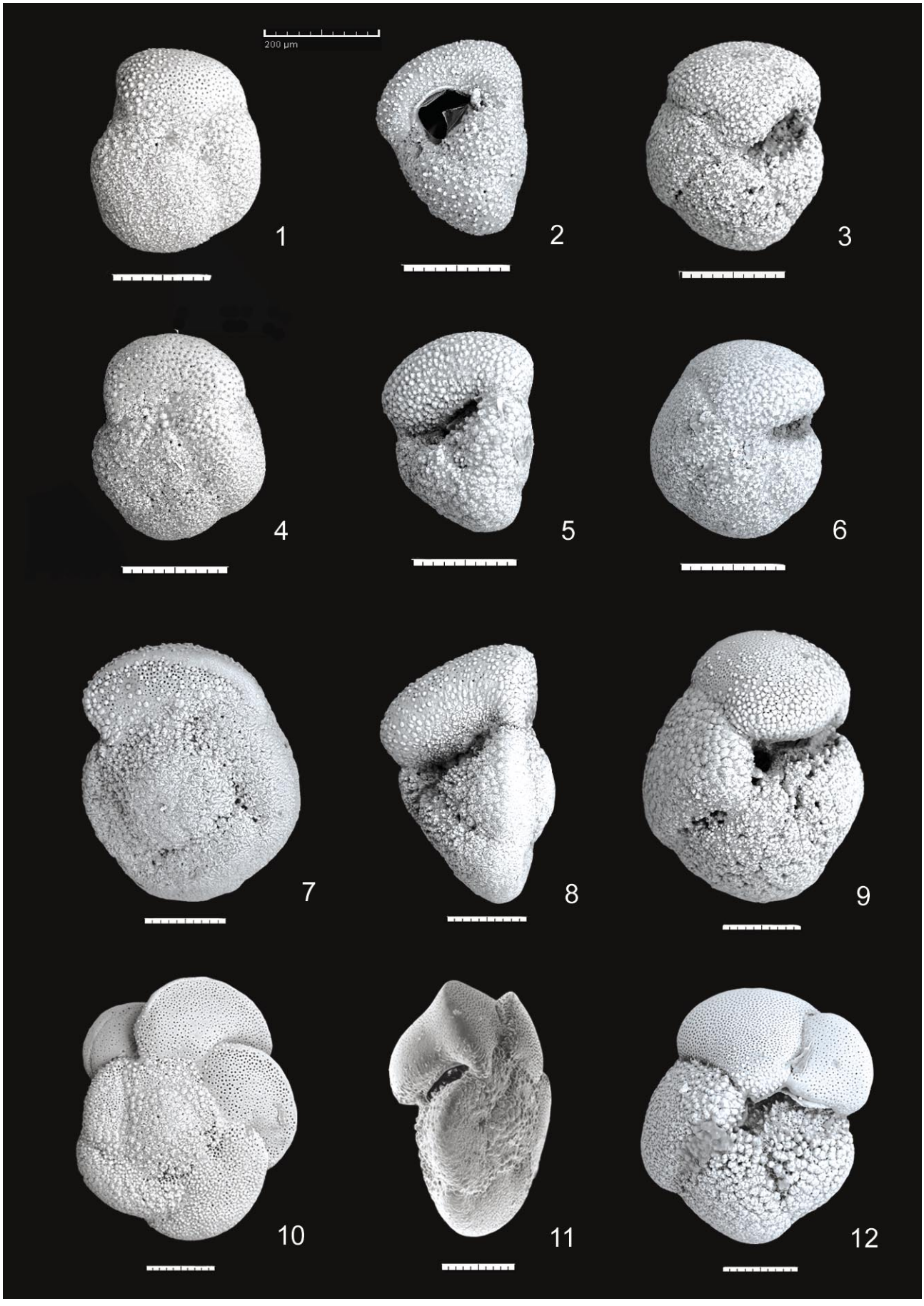
Globorotalia crassaformis hessi Bolli and Premoli Silva
(Figs. 6.1 - 6.3)

Globorotalia hessi Bolli and Premoli Silva, 1973, pp. 476-477.
Globorotalia crassaformis hessi Bolli and Premoli Silva – Bolli and Saunders, 1985, p. 233, figs. 36.3-5.
Globorotalia hessi Bolli and Premoli Silva – Saito, Thompson, and Breger, 1981, p. 127, pl. 42, fig. 2a-c.

Diagnosis and description: Test medium to large in size, low-trochospiral, with four chambers in the final whorl. The peripheral margin is rounded to subacute in the final chamber. Chambers from the spiral side are subelliptical and flat, from the umbilical side, subtriangular, commonly strongly inflated, sutures slightly curved, depressed. The last chamber is slightly offset downwards. Aperture interiomarginal, umbilical-extraumbilical, slit-like, with a thin lip. The umbilical side is covered with large irregular pustules.

Fig. 5.- (next page) *1–3. Globorotalia puncticulata;* Sample 397-34-5, 46-50 cm. *4–6. Globorotalia crassaformis* s.l.; Sample 397-34-5, 46-50 cm. *7–9. Globorotalia crassaformis crassaformis; 7, 8*. Sample 397-11-4, 72-76 cm. *9.* Sample 397-11-2, 62-66 cm. *10–12. Globorotalia crassaformis imbricata; 10, 12.* Piston core 32T2, 15 cm. *11.* Sample 404-1-3, 129-131 cm. Scale bar = 200 μm.

Fig. 5.- (pág. sig.) *1–3. Globorotalia puncticulata;* Muestra 397-34-5, 46-50 cm. *4–6. Globorotalia crassaformis* s.l.; Muestra 397-34-5, 46-50 cm. *7–9. Globorotalia crassaformis crassaformis; 7, 8*. Muestra 397-11-4, 72-76 cm. *9.* Muestra 397-11-2, 62-66 cm. *10–12. Globorotalia crassaformis imbricata; 10, 12.* Testigo 32T2, 15 cm. *11.* Muestra 404-1-3, 129-131 cm. Escala gráfica = 200 μm.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Remarks: G. crassaformis hessi differs from other subspecies in the distinctly quadrangular outline and large, robust test.

Distribution: It is recorded from the equatorial to high-boreal area, ranging from the mid-Lower Pliocene to the Upper Quaternary. The earliest appearance was recorded in the subtropical realm at 4.5 Ma.

Globorotalia crassaformis imbricata Krasheninnikov and Bylinskaya (Figs. 5.10 - 5.12)

Globorotalia crassaformis ssp. – Pflaumann and Krasheninnikov, 1978, p. 891, plate 7, figs. 3, 4.

Globorotalia crassaformis imbricata Krasheninnikov and Bylinskaya – Bylinskaya, Golovina, and Krasheninnikov, 2002, p. 131, pl. 12, figs. 1-3.

Holotype: DSDP Site 368, Core 1, core catcher (17°30′ N, 21° 21′ W, 3366 m), Upper Pleistocene.

Diagnosis and description: The subspecies is characterized by a slightly trochospiral test with 5-6 chambers in the final whorl, considerably overlapping on the dorsal side. Test medium in size, with a strongly lobate outline, 5–5.5 (up to 6) chambers in the final whorl, periphery subacute but no true keel. Spiral side flat, sometimes slightly convex. The 3 or 4 last chambers of the final whorl are characterized by a specific "imbricated" arrangement from dorsal view. Chambers, from the spiral side, lunate to subquadrate, flat, with strongly curved sutures; from the ventral side, subtriangular, strongly inflated, with well-depressed curving sutures. Umbilical area open, depressed. From the umbilical side, three early chambers of the final whorl are covered by irregularly disposed pustules. Aperture interiomarginal, umbilical-extraumbilical, a low arch to slit, commonly bordered by a thin lip. Wall calcareous, finely perforated, non-transparent.

Variability: Principal characters of the subspecies are constant. Only dimensions of specimens and shape of the spiral side (flat, slightly convex) can vary insignificantly.

Remarks: G. crassaformis imbricata differs from other subspecies of the *G. crassaformis* group by a greater (5-6 as against 4) number of chambers in the final whorl and their specific "imbricated" overlapping. From our standpoint there are forms transitional from *G. crassaformis hessi* to *G. crassaformis imbricata.* A similar form with the same stratigraphic range was recorded in the Indian Ocean (Rögl, 1974).

Distribution: We recorded *G. crassaformis imbricata* in the tropical Atlantic and on the Rockall Plateau (piston cores from the Cape Verde Basin, DSDP Sites 25, 366, 368, 403-405). It appeared in the lower part of the *Globigerina calida calida* Subzone about 0.5–0.6 Ma.

Globorotalia crassaformis ronda Blow (Figs. 6.4 - 6.6)

Globorotalia (Turborotalia) crassaformis ronda Blow, 1969, p. 388, pl. 4, figs. 4-6.

Globorotalia ronda Blow – Saito, Thompson, and Breger, 1981, p. 132, pl. 44, figs. 2,3.

Globorotalia crassaformis ronda Blow – Bolli and Saunders, 1985, p. 233, fig. 37.10.

Diagnosis and description: A low-trochospiral test, small to medium in size, with four chambers in the final whorl. The peripheral margin is rounded, in equatorial view the test is almost circular. Chambers from the spiral side, subquadrate, moderately inflated, closely arranged; from the umbilical side, almost triangular and strongly inflated. Aperture interiomarginal, umbilical-extraumbilical, a low slit fringed by a thin lip. Early chambers of the final whorl are covered with coarse pustules.

Remarks: G. crassaformis ronda is marked by circular outline, tight coiling and rather small dimensions.

Distribution: It ranges from the mid-Lower Pliocene to the Upper Quaternary, disappearing at about 0.6 Ma.

Globorotalia crassaformis viola Blow (Figs. 6.7 - 6.11)

Globorotalia (Globorotalia) crassula viola Blow, 1969, p. 397, pl. 5, figs. 4-6.

Globorotalia hirsuta aemiliana Colalongo and Sartoni, 1967, p. 267, pl. 30, figs. 2a–c, pl. 31, figs. 4a–c.

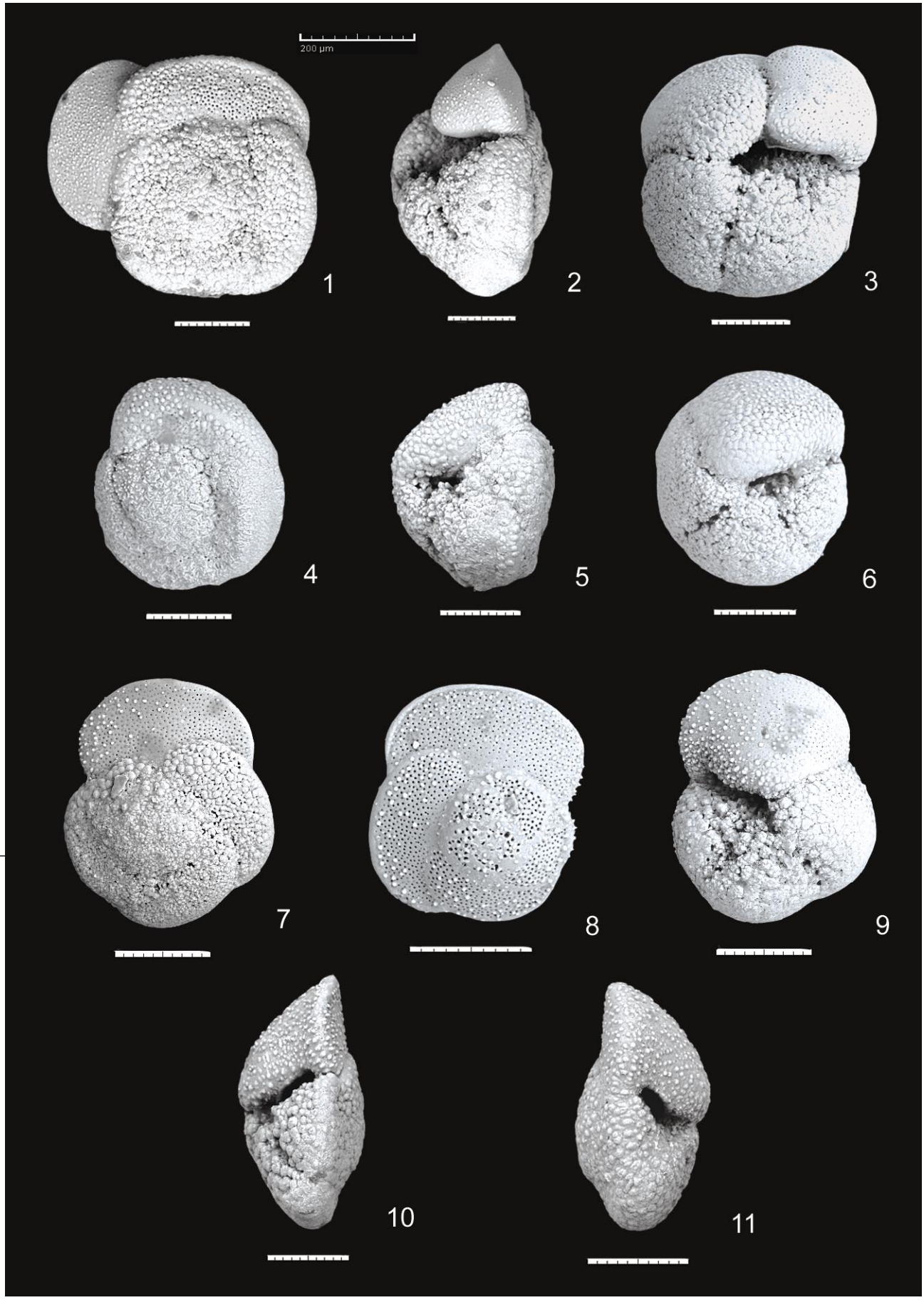
Globorotalia viola Blow – Saito, Thompson, and Breger, 1981, p. 134, pl. 45, figs. 3, 4.

Globorotalia crassaformis viola Blow – Bolli and Saunders, 1985, p. 234, fig. 36.1.

Diagnosis and description: A very low-trochospiral test, small to medium in size, with four chambers in the final whorl, with a peripheral keel. Spiral side is convex though less than the umbilical part. Chambers, from the spiral side, lunate to subquadrate, flat, with curved su-

Fig. 6.- *1–3. Globorotalia crassaformis hessi; 1, 3.* Sample 397-11-4, 72-76 cm; *2.* Sample 397-11-2, 62-66 cm. *4–6. Globorotalia crassaformis ronda; 4, 6.* Sample 397-11-4, 72-76 cm; *5.* Sample 397-11-2, 62-66 cm. *7–11. Globorotalia crassaformis viola;* Sample 397-21-4, 69-71 cm. Scale bar = 200 μm.

Fig. 6.- *1–3. Globorotalia crassaformis hessi; 1, 3.* Muestra 397-11-4, 72-76 cm; *2.* Muestra 397-11-2, 62-66 cm. *4–6. Globorotalia crassaformis ronda; 4, 6.* Muestra 397-11-4, 72-76 cm; *5.* Muestra 397-11-2, 62-66 cm. *7–11. Globorotalia crassaformis viola;* Muestra 397-21-4, 69-71 cm. Escala gráfica = 200 μm.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tures; from the ventral side, subtriangular, slightly inflated. Aperture interiomarginal, umbilical-extraumbilical, a low arch to slit, bordered by a thin lip.

Remarks: Typical forms, mainly in the low latitude area, have a complete peripheral keel and less convex spiral side. Specimens from the temperate realm are more biconvex, somewhat smaller, and possess a less distinguishable keel. Both ecophenotypes differ from other subspecies of *G. crassaformis* by a lower trochospiral and smaller tests, and by the presence of a keel.

Distribution: Globorotalia crassaformis viola was recorded from the uppermost Lower Pliocene to the Lower Quaternary. Its range is from 4.0 to approximately 1.5 Ma.

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