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14. BIOSTRATIGRAPHY AND PALEOCEANOGRAPHY OF THE PLIOCENE AT SITES 975 (MENORCA RISE) AND 976 (ALBORAN SEA) FROM A QUANTITATIVE ANALYSIS OF THE PLANKTONIC FORAMINIFERAL ASSEMBLAGES[1]

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ABSTRACT

The Pliocene assemblages of planktonic foraminifers at Sites 975 and 976 were studied quantitatively to obtain data both on the biostratigraphy and on the paleoceanographic conditions prevailing in the western Mediterranean during the Pliocene. Some significant changes in the composition of the assemblages could be used to complement the biochronology of hemipelagic marine sedimentation in the western Mediterranean. Using modern analog techniques, paleoceanographic conditions were assigned to the Pliocene assemblages. The results suggest that during most of the Pliocene the western Mediterranean was characterized by conditions equivalent to those prevailing today in the western Mediterranean and in the North Atlantic, between the parallels of Cape Finisterre and the Canary Islands, although interspersed with episodes both of subpolar and subtropical conditions. In the latest Pliocene, there were frequent subpolar conditions, presaging the entry of polar fauna that marks the beginning of the Pleistocene.

INTRODUCTION

Consider two assemblages, one recent and the other fossil, composed of organisms of the same species and that are quantitatively similar. If the environmental requirements of the species have not changed over time, we can retrieve paleoenvironmental information from the fossil assemblage. A fossil assemblage that is unaffected by severe taphonomic processes would reflect paleoenvironmental conditions similar to those of the biocoenoses from which the similar present-day assemblage is derived (Hutson, 1979; Prell, 1985; Le, 1992; Pflaumann et al., 1996; González-Donoso and Linares, 1998).

The above assumption poses no great problems when applied to the Pleistocene, as all the Pleistocene species of planktonic foraminifers live in present-day oceans. Numerous studies based on these organisms have been used for reconstructions of the paleoceanographic conditions of the western Mediterranean, especially for the last few thousand years (Blanc et al., 1976; Thunell, 1976, 1978, 1979; Loubere, 1981; Vergnaud-Grazzini, 1985; Pujol and Vergnaud-Grazzini, 1989; Thunell et al., 1991; Vergnaud-Grazzini and Pierre, 1991).

The qualitative composition of the assemblages of Neogene planktonic foraminifers, however, becomes progressively differentiated from that of those of the Quaternary as the time gap enlarges. Therefore, the paleoceanographic results obtained that were based on Neogene assemblages (Thunell, 1979; Vergnaud-Grazzini, 1985; Zachariasse et al., 1990; Dowsett et al., 1996) should be taken with caution, and particularly so in the case of the older assemblages. The validity of the results would largely depend on the treatment applied to noncommon species. For species that are not represented today, it would be possible to assume oceanographic requirements similar to those of the present-day species that are morphologically and/or phylogenetically closest to them (Thunell, 1979; Dowsett and Poore, 1990; Dowsett, 1991). On the other hand, those present-day species not represented in older epochs should be ignored. In this case, the relations between present-day assemblages and oceanographic conditions should be restated as if these species did not exist. The results obtained will depend on the influence exercised by these species on the inferences made on present-day environmental conditions. In any case, the inferences about paleoceanographic conditions become less accurate as older environments are examined and as the number of noncommon species increases.

This study examines the variations in the qualitative and quantitative composition of assemblages of planktonic foraminifers, throughout the Pliocene sediments at Sites 975 (Menorca Rise) and 976 (Alboran Sea). The objective was to detect significant changes in the composition of the assemblages to reveal ecostratigraphic events that might be extensible to, at least, the western Mediterranean. Of these events, the most characteristic might complement the biostratigraphy of planktonic foraminifers for the Pliocene of the Mediterranean Domain. At the same time, we intended to infer the paleoceanographic conditions of the Pliocene in the Alboran Sea and to the south of Menorca by comparing them with present-day areas of the North Atlantic and the Mediterranean in which similar assemblages exist.

MATERIALS AND METHODS

Site 975 was studied mainly from Hole 975B, which includes Pliocene sediments at depths of 108 to 302 mbsf. The samples were taken at intervals of about 1 m, except the interval 146.79–186.60 mbsf, where recovery was poor and only one sample (170.61 mbsf) could be studied. This gap was reduced with 12 samples from Hole 975C, taken between 176.40 and 185.60 mbsf (Table 1, CD-ROM, back pocket, this volume).

At Site 976, Hole 976B bored Pliocene sediments from 359 to 572.9 mbsf, but between 367 and 518 mbsf it traversed a section of fine sands, with very poor recovery. In the intervals of 359–367 mbsf and 518–572.9 mbsf, approximately one sample per meter was taken, but in the interval of 367–518 mbsf, it was only possible to obtain 12 irregularly distributed samples (Table 2, CD-ROM, back pocket, this volume).

Some Pleistocene samples were incorporated into the database, to achieve a quantitative characterization of the Pliocene/Pleistocene boundary. Samples in the text, figures, and tables are identified by their depth in mbsf.

The treatment applied to the samples for washing and picking foraminifer tests followed the protocol described in Linares et al. (Chap. 35, this volume). For the quantitative study, the large fraction of 0.15

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mm was divided up to produce an amount estimated to contain more than 300 foraminifer tests.

Because the list of species is different from that of the present-day and varies according to the Pliocene interval considered, it was necessary for the mathematical processing to group morphotypes and species (Table 3) and to make certain assumptions:

1. *Globorotalia inflata* (d'Orbigny), apart from being the possible descendent, is the present-day ecological equivalent of *Globorotalia puncticulata* (Deshayes)–*Globorotalia bononiensis* Dondi. This assumption is supported by the coexistence of the three morphotypes with their morphological transitions in the upper Pliocene (see also González-Donoso and Porta, 1977).
2. *Globigerinoides obliquus* Bolli, *Globigerinoides extremus* Bolli and Bermúdez, *Globigerinoides ruber* (d'Orbigny), *Globigerinoides elongatus* (d'Orbigny), and *Globigerinoides conglobatus (*Brady) are combined into a single group with the assumption that their oceanographic requirements are similar. To justify this grouping, it should be noted that during the Pliocene, the *G. obliquus–G. extremus* group was substituted by the *G. ruber–G. elongatus* group. In the middle part of the Pliocene, the two groups coexisted in significant proportions, and morphological transitions have been observed between one and the other. From the morphological standpoint, it might be reasonable to equate the *G. obliquus, G. extremus,* and *G. conglobatus* with the present-day *G. conglobatus*, but while *G. obliquus* and *G. extremus* are abundant in the lower part of the Pliocene, *G. conglobatus* is very scarce in both present-day seas and Pliocene sediments. Attempts at the paleoceanographic reconstruction of the lower part of the Pliocene by treating *G. obliquus* and *G. extremus* as if they were *G. conglobatus,* and separating them from *G. ruber,* produced results that were difficult to sustain. Furthermore, in present-day seas, *G. conglobatus* shows a high degree of correlation with *G. ruber.*
3. *Sphaeroidinellopsis* and *Sphaeroidinella* have not been differentiated, with the same environmental conditions assumed for both.
4. *Globorotalia hirsuta* (d'Orbigny), not including *Globorotalia aemiliana* Colalongo and Sartoni, is the present-day ecological equivalent of *Globorotalia margaritae* Bolli and Bermúdez.
5. *Globigerina rubescens* Hofker has been considered the present-day ecological equivalent of *Globigerina apertura* Cushman–*Globigerina decoraperta* Takayanagi and Saito–*Globigerina nepenthes* Todd. This implies a certain degree of distortion, as the *G. apertura* group was more abundant during the Pliocene than is *G. rubescens* today, but this problem has no objective solution.
6. *Globigerinoides bulloideus* Crescenti has been considered the present-day ecological equivalent of *Globigerinoides tenellus* Parker.
7. *Neogloboquadrina atlantica* (Berggren) and *Neogloboquadrina pachyderma* (Ehrenberg) have not been differentiated.
8. *Globoquadrina* has not been integrated into the database. Nevertheless, the percentages of *Globoquadrina* in the assemblages were always very low and, therefore, its influence on the results must be very small.

It was also necessary to make following modifications to the data set of 605 present-day core-top samples from the North Atlantic and Mediterranean by Gardner and Hays (1976), Kellogg (1976), Kipp (1976), Balsam and Flessa (1978), Thunell (1978), Brunner (1979), Pujol (1980), and Loubere (1981), compiled by González-Donoso and Linares (1998).

Table 3. List of species, morphotypes, and groups of species considered in the quantitative analyses.

- *Globigerina bulloides* group
  - *Globigerina bulloides* d'Orbigny
  - *Globigerina riveroae* Bolli & Bermúdez
  - *Globigerina umbilicata* Orr & Zaitzeff
- *Globigerina calida* Parker
- *Globigerina falconensis* Blow
- *Beella digitata* (Brady)
- *Globigerina apertura* group
  - *Globigerina apertura* Cushman
  - *Globigerina decoraperta* Takayanagi & Saito
  - *Globigerina nepenthes* Todd
  - *Globigerinoides bulloideus* Crescenti
- *Globigerinoides obliquus* group
  - *Globigerinoides conglobatus* (Brady)
  - *Globigerinoides extremus* Bolli & Bermúdez
  - *Globigerinoides obliquus* Bolli
- *Globigerinoides ruber* group
  - *Globigerinoides elongatus* (d'Orbigny)
  - *Globigerinoides ruber* (d'Orbigny)
- *Globigerinoides trilobus* group
  - *Globigerinoides immaturus* Leroy
  - *Globigerinoides trilobus* (Reuss)
  - *Globigerinoides sacculifer* (Brady)
- *Neogloboquadrina dutertrei* group
  - *Neogloboquadrina acostaensis* (Blow)
  - *Neogloboquadrina dutertrei* (d'Orbigny)
  - *Neogloboquadrina humerosa* (Takayanagi & Saito)
- *Neogloboquadrina pachyderma* right-coiling group
  - *Neogloboquadrina pachyderma* (Ehrenberg) right-coiling
  - *Neogloboquadrina* ("P-D intergrade") right-coiling
  - *Neogloboquadrina atlantica* (Berggren) right-coiling
- *Neogloboquadrina pachyderma* left-coiling group
  - *Neogloboquadrina pachyderma* (Ehrenberg) left-coiling
  - *Neogloboquadrina atlantica* (Berggren) left-coiling
- *Globorotalia scitula* (Brady)
- *Globorotalia hirsuta-margaritae* group
  - *Globorotalia hirsuta* (d'Orbigny)
  - *Globorotalia margaritae* Bolli & Bermúdez
- *Globorotalia inflata* group:
  - *Globorotalia bononiensis* Dondi
  - *Globorotalia inflata* (d'Orbigny)
  - *Globorotalia puncticulata* (Deshayes)
- *Globorotalia crassaformis* group
  - *Globorotalia aemiliana* Colalongo & Sartoni
  - *Globorotalia crassaformis* Galloway & Wissler
  - *Globorotalia crassacrotonensis* Conato & Follador
  - *Globorotalia crassula* Cushman & Stewart
- *Globorotalia truncatulinoides* right-coiling
- *Globorotalia truncatulinoides* left-coiling
- *Globorotalia cultrata* (d'Orbigny) = *G. menardii* (Parker, Jones & Brady)
- *Globorotalia tumida* group
  - *Globorotalia merotumida* Blow & Banner
  - *Globorotalia plesiotumida* Blow & Banner
  - *Globorotalia tumida* (Brady)
- *Globigerinella*
  - *Globigerinella siphonifera* (d'Orbigny)
  - *Globigerinella obesa* (Bolli)
- *Globigerinita glutinata* (Egger)
- *Pulleniatina obliquiloculata* (Parker & Jones)
- *Sphaeroidinellopsis* group
  - *Sphaeroidinella dehiscens* (Parker & Jones)
  - *Sphaeroidinellopsis seminulina* (Schwager)
  - *Sphaeroidinellopsis subdehicens* (Blow)
- *Turborotalita quinqueloba* (Natland)
- *Orbulina universa* d'Orbigny

For samples above the first occurrence (FO) of *G. puncticulata, Globorotalia truncatulinoides* (d'Orbigny), both left and right coiling, were removed, and *G. rube*r and *G. conglobatus* were combined in the core-top data set. When these modifications were in effect, the relative abundances of the remaining 23 morphotypes, species, and groups of species were recalculated. For the samples below the FO of *G. puncticulata*, we also removed *G. inflata* from the core-top data set and recalculated the relative abundances of the remaining 22 morphotypes, species, and groups of species.

More strictly, it also should have been necessary to separate the interval above the FO of *G. truncatulinoides* to include this species in the data set and to remove the *Globorotalia crassaformis* Galloway and Wissler group in the interval between the FO of *G. puncticulata* and FO of *G. crassaformis.* But, given their low rates of occurrence and scant influences on the quantitative analyses (correlations were not used), the results should not be significantly affected.

These modifications made it necessary to create a different matrix for each interval and site. For the pre-FO of the *G. puncticulata* interval, one matrix was formed with 50 objects (samples) × 22 variables (species) for Site 975, and another with 53 × 22 for Site 976. For the post-FO of the *G. puncticulata* interval, matrices were created with 123 × 23 (Site 975) and 17 × 23 (Site 976).

Once the above-mentioned assumptions and modifications had been taken into account, a series of groups in the core-top data set were defined by the *k*-means clustering procedure (Davis, 1986; Wilkinson et al., 1992). Discriminant analyses were used both to test the clustering results and to assign each Pliocene sample to one of these groups. The cosine as a measure of similarity was used to identify the present-day sample most similar to each Pliocene one. To perform these analyses, the programs MATHEMATICA (Wolfram, 1992), SYSTAT (Wilkinson et al., 1992), and SPSS (Norusis, 1990) were used. A more detailed description of the mathematical treatment is made in Linares et al. (Chap. 35, this volume).

RELATIVE ABUNDANCE OF SPECIES AND BIOCHRONOLOGY

Table 4 illustrates the maximum and mean relative abundances of the morphotype and species groups used as variables for each interval. They are ordered according to their optimum temperatures in the North Atlantic and the Mediterranean (González-Donoso and Linares, 1998). It may be seen from Table 4 that *Globigerina bulloides* d'Orbigny and *N. pachyderma* (right-coiling) exceed 10% relative abundance in all Pliocene intervals at both sites. *G. bulloides* is present in greater mean proportions in the Alboran Sea (22.73% and 30.41%) than in the Menorca Rise (16.35% and 18.49%), while *N. pachyderma* (right-coiling) presents more similar mean relative abundances of around 22%, except in the younger interval at the Menorca Rise, where it falls slightly to 17.23%.

G. obliquus–G. ruber added present mean relative abundances ranging from 9.21% in the oldest interval in the Alboran Sea and 21.63% in the younger interval for the same area, with similar values (17.3% and 18.9%) for the two Menorca intervals. The *G. apertura* group exceeded a mean relative abundance of 10% in the older interval for both sites, higher in the Alboran Sea (15.52%) than at the Menorca Rise (11.18%); however, in the younger interval, the mean abundance is lower, 4.15% in the Alboran Sea and 8.24% at the Menorca Rise. The *G. inflata* group presented large differences between the two younger intervals with mean and maximum relative abundances that were much smaller in the Alboran Sea than at the Menorca Rise (1.0% and 7.9%, and 10.1% and 45.2%, respectively). These differences can be determined by the gaps at the Sites. The remaining species in no case reached a mean relative abundance of 10%.

Concerning the maximum relative abundances of nondominant species, but with extreme optimum temperatures, most noteworthy are the 18.3% of *N. pachyderma* (left-coiling) in the older interval in the Alboran Sea (8.5% at the Menorca Rise) and the maxima of *Globigerinoides trilobus* (Reuss) at the Menorca Rise (34.4% and 25.8%) with respect to those in the Alboran Sea (22.9% and 0.0%). The absence of *G. trilobus* from the younger interval of Alboran is strongly influenced by the gaps.

The qualitative and quantitative variations throughout the sedimentary record (Figs. 1 and 2) enable us to monitor the biochronology of the two sites. Significant variations must represent ecostratigraphic events that may complement the biostratigraphic schemes established for the western Mediterranean. In order to date the events, we used the planktonic foraminifer ages from Sprovieri (1993) and calcareous nannofossil ages from Shackleton et al. (1995), as described in Comas, Zahn, Klaus, et al. (1996). Some ages were completed from Berggren et al. (1995).

The zonation of Cita et al. (1975) emended by Sprovieri (1992 and 1993) mark the beginning of the Pliocene by the re-establishment of

Table 4. Mean and maximum relative abundances of those morphotypes, species, or group of species considered in the quantitative analyses, ordered by winter optimum temperatures of their present-day equivalents in North Atlantic and Mediterranean.

		Pre-FO of *G. puncticulata*				Post-FO of *G. puncticulata*			
		Site 976		Site 975		Site 976		Site 975	
	OPTT	MN	MX	MN	MX	MN	MX	MN	MX
PCS	5.03	0.019	0.183	0.017	0.085	0.005	0.020	0.010	0.084
QNQ	8.29	0.004	0.141	0.002	0.013	0.006	0.048	0.005	0.064
PCD	11.13	0.228	0.444	0.218	0.443	0.248	0.537	0.172	0.453
BUL	13.20	0.227	0.436	0.163	0.339	0.316	0.645	0.187	0.619
INF	14.26	—	—	—	—	0.055	0.206	0.099	0.452
SCI	16.50	0.002	0.018	0.007	0.040	0.001	0.010	0.001	0.016
GLT	17.18	0.038	0.105	0.040	0.099	0.042	0.071	0.081	0.305
TRS	17.27	—	—	—	—	0.000	0.018	0.000	0.000
H-M	17.44	0.032	0.137	0.020	0.143	0.000	0.003	0.006	0.181
FAL	18.20	0.084	0.369	0.075	0.233	0.042	0.096	0.032	0.138
UNV	18.97	0.054	0.152	0.064	0.159	0.046	0.105	0.051	0.364
DIG	19.99	0.005	0.063	0.001	0.008	0.002	0.007	0.000	0.008
APE	20.33	0.155	0.461	0.112	0.235	0.031	0.081	0.084	0.258
TRD	20.65	—	—	—	—	0.000	0.003	0.000	0.000
CAL	20.84	0.008	0.037	0.002	0.014	0.009	0.038	0.002	0.022
R/O	20.97	0.092	0.312	0.173	0.398	0.170	0.656	0.189	0.710
BLL	21.02	0.002	0.025	0.001	0.006	0.001	0.004	0.003	0.022
DUT	21.11	0.005	0.022	0.002	0.019	0.001	0.007	0.004	0.024
SPH	21.37	0.012	0.090	0.012	0.064	0.008	0.027	0.018	0.062
OBL	22.35	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CUL	23.13	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000
CRS	23.16	—	—	—	—	0.013	0.044	0.008	0.174
TRL	23.21	0.023	0.230	0.089	0.344	0.001	0.010	0.045	0.258
TUM	25.73	0.003	0.078	0.000	0.000	0.000	0.000	0.000	0.000
SPS	26.05	0.006	0.070	0.002	0.029	0.002	0.016	0.002	0.029

Notes: MN = mean; MX = maximum; OPTT = optimum temperature; PCS = *N. pachyderma* left-coiling; QNQ = *T. quinqueloba*; PCD = *N. pachyderma* right-coiling; BUL = *G. bulloides* group; INF = *G. inflata* group; SCI = *G. scitula*; GLT = *G. glutinata*; TRS = *G. truncatulinoides* left-coiling; H-M = *G.hirsuta–G.margaritae* group; FAL = *G. falconensis*; UNV = *O. universa*; DIG = *G. digitata*; APE = *G. apertura* group; TRD = *G. truncatulinoides* right-coiling; CAL = *G. calida*; R/O = *G. ruber–G.obliquus* group; BLL = *G. bulloideus*; DUT = *N. dutertrei* group; SPH = *G. siphonifera*; OBL = *P. obliquiloculata*; CUL = *G. cultrata*; CRS = *G. crassaformis* group; TRL = *G. trilobus* group; TUM = *G. tumida* group; SPS = *Sphaeroidinellopsis* group.

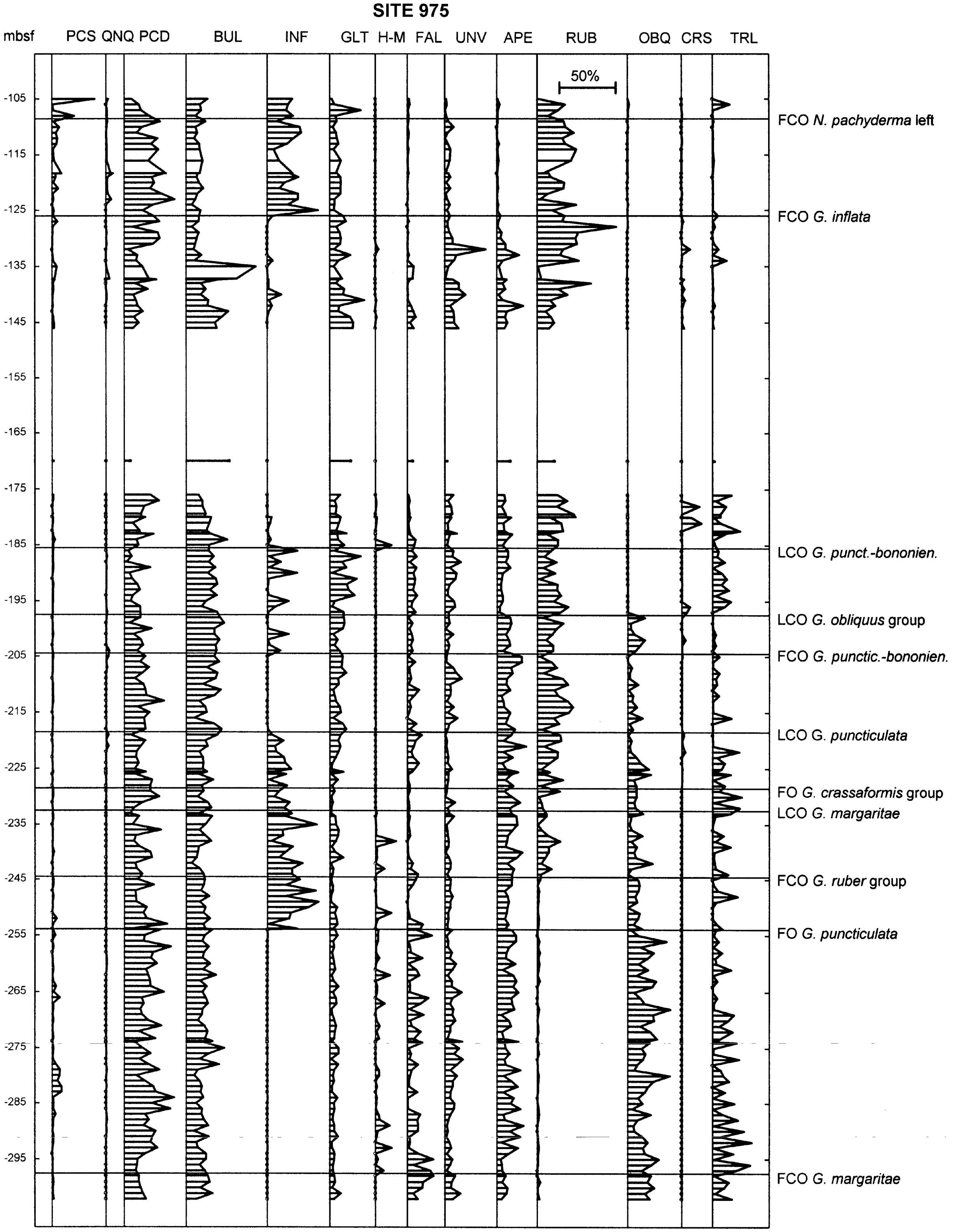

Figure 1. Site 975 relative abundance of the morphotypes and species in the samples analyzed. Only those whose maximum relative abundance exceeds 10% have been represented. PCS = *N. pachyderma* (left-coiling); QNQ = *T. quinqueloba;* PCD = *N. pachyderma* (right-coiling); BUL = *G. bulloides* group; INF = *G. inflata* group; GLT = *G. glutinata;* H–M = *G. hirsuta–G. margaritae* group; FAL = *G. falconensis;* UNV = *O. universa*; APE = *G. apertura* group; RUB = *G. ruber* group; OBQ = *G. obliquus* group; CRS = *G. crassaformis;* TRL = *G. trilobus* group.

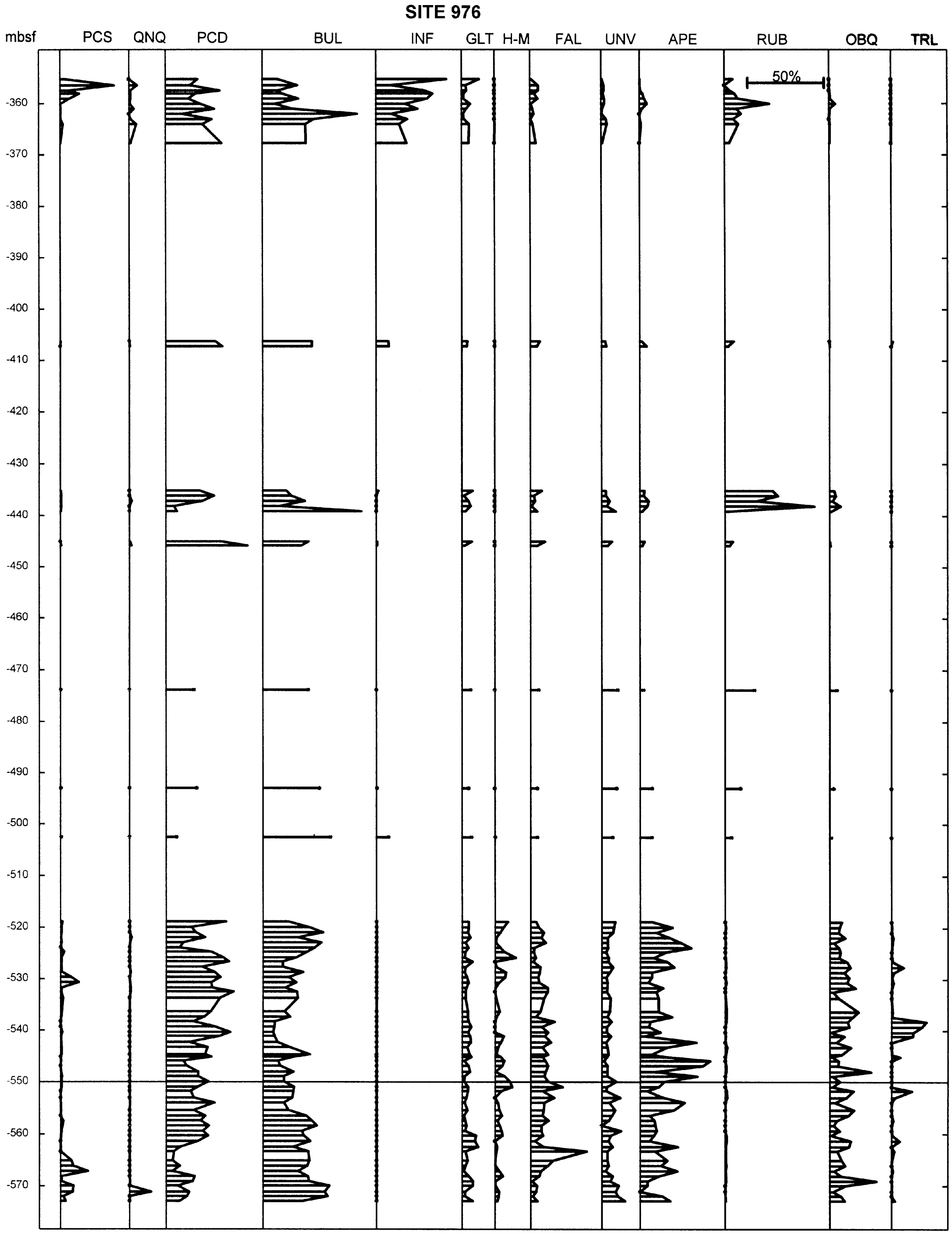

Figure 2. Site 976 relative abundance of the morphotypes and species in the samples analyzed. Only those whose maximum relative abundance exceeds 10% have been represented. PCS = *N. pachyderma* (left-coiling); QNQ = *T. quinqueloba;* PCD = *N. pachyderma* (right-coiling); BUL = *G. bulloides* group; INF = *G. inflata* group; GLT = *G. glutinata;* H–M = *G. hirsuta–G. margaritae* group; FAL = *G. falconensis;* UNV = *O. universa;* APE = *G. apertura* group; RUB = *G. ruber* group; OBQ = *G. obliquus* group; TRL = *G. trilobus* group.

open-marine conditions, dated at 5.33 Ma. The first Pliocene sediments, in zone MPL1, were characterized from the authors by the frequent appearance of *Sphaeroidinellopsis* and by the absence of *G. margaritae,* though, in fact, a very few specimens of *G. margaritae* can be found in these sediments. At Site 975, the basal ~5 m present these characteristics, but at Site 976, Pliocene sedimentation begins with *G. margaritae* regularly present.

The *G. margaritae* zone (first common occurrence, FCO: 5.10 Ma) is clearly identifiable at both sites. The marker species generally appears in the sample fraction analyzed (about 300 individuals). Within this zone, two short episodes are observed, in which *N. pachyderma* (left-coiling) is present in high percentages, exceeding 25% of total *Neogloboquadrina*. At Site 975, the episodes are detected at 283–280 mbsf and at 265 mbsf. Supposing a constant sedimentation rate through the *G. margaritae* zone (74.48 m/Ma), these episodes of increasing *N. pachyderma* (left-coiling) would have occurred 4.91–4.87 Ma and 4.67 Ma, respectively. At Site 976, two correlatable episodes were detected, located at 571–565 mbsf and at 530 mbsf. According to this correlation, Pliocene sedimentation commenced at Site 976 very near the start of the first episode (4.91 Ma), and attained a sedimentation rate of around 173 m/m.y., notably higher than at Site 975.

The first occurrence datum (FOD) of *G. puncticulata* (4.52 Ma) is normally used to identify the base of the upper zone of the lower Pliocene. At Site 975, *G. puncticulata* first appears at 253.8 mbsf, attaining 26.50% of total planktonic foraminifers. At Site 976, it is not clear whether the entrance of *G. puncticulata* is also massive, as there is very poor recovery of the Pliocene sediments above the 518-mbsf level, which is still part of the *G. margaritae* zone. The 518-mbsf level is located a little after the second episode of increasing *N. pachyderma* (left-coiling), at an age of ~4.60 Ma.

At Site 975, above the appearance of *G. puncticulata,* the FCO of *G. ruber* in the Pliocene may be observed. At older levels, only very scarce specimens, always below 3%, are to be found. The FCO of *G. ruber* occurs at 244 mbsf, before the last common occurrence (LCO) of *G. margaritae* (3.94 Ma), the level of which is observed at 233 mbsf. Supposing a homogeneous sedimentation between the FO of *G. puncticulata* and the LCO of *G. margaritae,* the FCO of *G. ruber* must have occurred 4.25 Ma. The LCO of *G. margaritae* has been used to mark the end of the lower Pliocene (Mazzei et al., 1979; Iaccarino, 1985) as this is the closest event to the base of the Piacenzian stratotype, as designated by Barbieri (1967). By this means, the Zanclean/Piacenzian boundary is made to coincide with that between the lower Pliocene and the upper Pliocene (Iaccarino, 1985).

In the upper Pliocene, the FO of *G. crassaformis,* including the *G. aemiliana* form, has been detected at 228 mbsf at Site 975. According to Berggren et al. (1995), this event occurred in the Mediterranean 3.58 Ma.

A little after the FO of *G. crassaformis,* Hole 975B presents an interval occurring between 218 and 205 mbsf from which *G. puncticulata* is virtually absent. Specimens were found in only two samples, and in proportions of less than 1%. Berggren et al. (1995) indicated the absence of *G. puncticulata* between 3.55 and 3.31 Ma. In Comas, Zahn, Klaus, et al. (1996), the LO of *G. puncticulata* was set at 3.57 Ma, but we have observed that when the *G. inflata* group reappears, abundant specimens with the morphology of *G. puncticulata* are found, together with the morphotype *G. bononiensis* and specimens that are very close to *G. inflata* (see also González-Donoso and Porta, 1977). The LCO of the *G. obliquus–G. extremus* group occurs at 198 mbsf, above the reappearance of the *G. inflata* group. This event coincides with the LO of *Sphaeroidinellopsis,* which has been dated at 3.22 Ma.

A new interval, with very slight presence (less than 5%) in the *G. inflata* group, was observed from 185 mbsf, but it was not possible to detect whether this was maintained between 176 and 146 mbsf, because of the nonrecovery of most of the sediments from this section of Hole 975B and to the nonavailability of alternative samples.

In the uppermost Pliocene, a significant decrease in the proportion of the *G. apertura* group was observed, to less than 5% above 131 mbsf (i.e., as is the situation today, in which *G. rubescens* is scarce). However, the most significant event is a strong recovery in the forms of the *G. inflata* group above 126 mbsf. This biohorizon practically coincides with the one considered in Comas, Zahn, Klaus, et al. (1996) as the FO of *G. inflata,* at 2.13 Ma, while Berggren et al. (1995) date the reappearance level of *G. inflata* at 1.99 Ma.

The FCO of *N. pachyderma* (left-coiling;1.79 Ma), marking the Pliocene/Pleistocene boundary, was detected at 108 mbsf at Site 975, where it attained 20% of total planktonic foraminifers (see Linares et al., Chap. 35, this volume). The appearance of *G. truncatulinoides* was detected later within the Pleistocene (106 mbsf).

Hole 976B, above 518 mbsf (zone of *G. margaritae*), mainly traversed fine sands, resulting in very poor core recovery up to 367 mbsf. Some marly intercalations enabled an imperfect biostratigraphic control to be carried out. In the first sample studied from the sandy interval (502 mbsf) *G. margaritae* is no longer found, and, on the contrary, *G. puncticulata* and *G. crassaformis* appear, which indicates that the sample belongs to the upper Pliocene. The levels between 492 and 435 mbsf do not contain the *G. inflata* group, while *G. ruber* and *G. obliquus* frequently occur. Additionally, *G. crassaformis* appears quite regularly, and *Sphaeroidinellopsis* is present in some samples. All these characteristics restrict these levels to a relatively low part of the upper Pliocene, that is, the interval from which *G. puncticulata* is absent (3.55–3.31 Ma; Berggren et al., 1995). A sample from 407 mbsf contains *G. inflata* and *G. truncatulinoides,* indicating the uppermost Pliocene. From 367 mbsf, there is a continuous sedimentary record, and we detected the increase in *N. pachyderma* (left-coiling) from the Pliocene/Pleistocene boundary at 359 mbsf (Linares et al., Chap. 35, this volume).

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In order to establish the modern analogs of the samples after the FO of *G. puncticulata,* five groups (see Linares et al., Chap. 35, this volume) were differentiated by the *k*-means clustering procedure applied to the core-top data set of 23 variables (Fig. 3; Tables 5, 6). These groups (polar, subpolar, intermediate, subtropical-tropical, and equatorial) were practically identical to those differentiated with 26 variables. This result was expected, as *G. conglobatus* is an unimportant element within the core-top data set, with a behavior similar to that of *G. ruber* and a very low *F*-ratio. Furthermore, the *F*-ratios of the two morphotypes of *G. truncatulinoides* are not very high either. When discriminant analysis was applied to the five groups, the results were even better than those obtained for the 26-variable core-top data set: only 10 reassignments change group (1.65% of the total). This result must be credited to the fact that less variables were used.

To locate modern analogs of the samples before the FO of *G. puncticulata* (Fig. 4; Tables 7, 8), the *k*-means clustering procedure is applied to the core-to data set with 22 variables. The results are slightly different to those obtained with 26 variables: 6 samples change group from intermediate to subpolar, 12 samples change from intermediate to subtropical, and 5 samples change from subtropical to intermediate. This was expected, given the high *F*-ratio of *G. inflata* in the *k*-means of 26 variables, and the respective mean and maximum relative abundances in the intermediate group. We consider it important, however, that the geographical areas occupied by the groups remained almost unchanged. Discriminant analysis improves even the above results, with nine reassignments (1.49% of the total).

Figure 5 shows that almost all the samples are included in the intermediate group, except for the uppermost Pliocene. This monotonous pattern suggests an environmental stability, which contrasts with the frequent changes inferred for the Quaternary by means of the same procedure (Linares et al., Chap. 35, this volume).

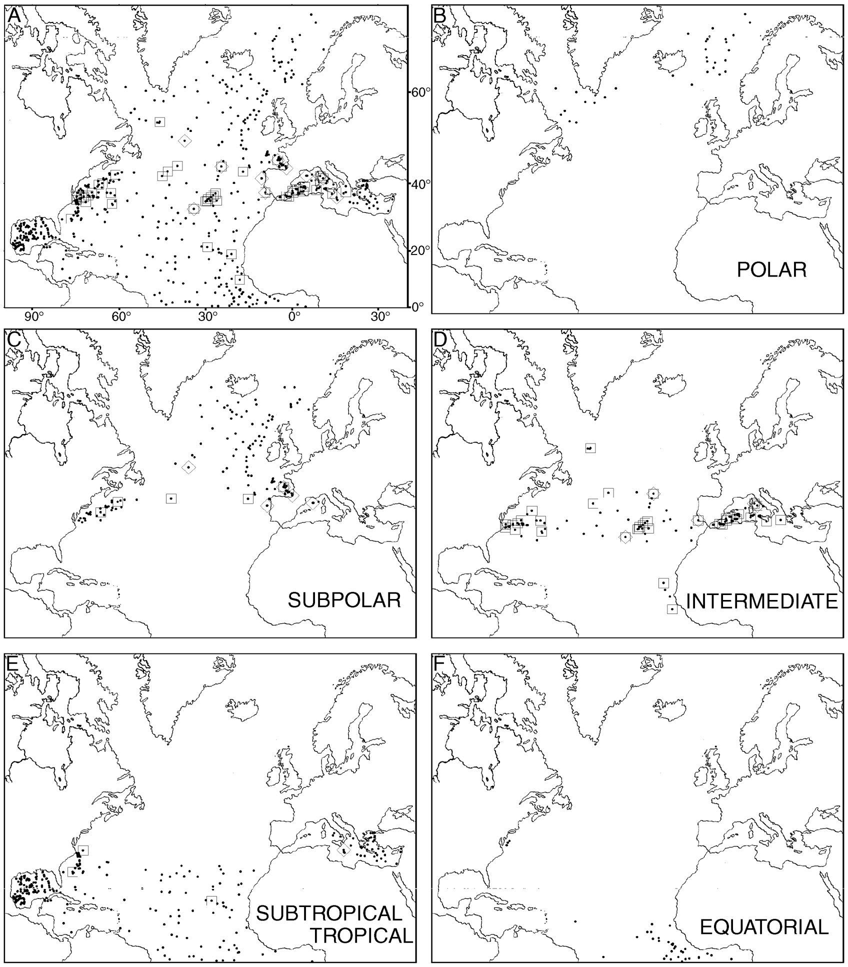

Figure 3. Locations of 605 North Atlantic and Mediterranean core-top samples and groups obtained by *k*-means clustering. Diamonds = modern analogs of the Pliocene post-FO *G. puncticulata* samples from Site 976. Squares: modern analogs of the Pliocene post-FO *G. puncticulata* samples from Site 975. A = all the samples; B = polar group; C = subpolar group; D = intermediate group; E = subtropical-tropical group; F = equatorial group.

Table 5. North Atlantic and Mediterranean 23-variable core-top data set.

	BSS	DF	WSS	DF	FR
PCS	17.219	4	2.491	600	1036.739
PCD	18.288	4	3.008	600	911.966
R+C	25.334	4	4.173	600	910.655
DUT	1.160	4	1.171	600	148.541
SPH	0.224	4	0.253	600	132.924
TUM	1.651	4	1.887	600	131.216
INF	2.849	4	3.365	600	126.984
BUL	3.050	4	3.686	600	124.106
DEH	0.012	4	0.018	600	98.174
CUL	0.446	4	0.766	600	87.360
TRL	1.381	4	2.971	600	69.730
QNQ	0.350	4	0.881	600	59.613
OBL	0.216	4	0.600	600	53.998
CRS	0.010	4	0.031	600	46.618
FAL	0.171	4	0.682	600	37.601
TEN	0.018	4	0.073	600	36.945
HRS	0.021	4	0.109	600	28.315
CAL	0.016	4	0.085	600	27.514
GLT	0.228	4	1.348	600	25.364
RBC	0.014	4	0.123	600	17.660
SCI	0.008	4	0.081	600	14.280
DIG	0.001	4	0.016	600	12.803
UNV	0.014	4	0.241	600	8.646

Notes: Summary statistics for five groups obtained by *k*-means clustering. BSS = between groups sum of squares; DF = degrees of freedom; WSS = within groups sum of squares; FR = F-ratio statistics (one way ANOVA). PCS = *N. pachyderma* left-coiling; PCD = *N. pachyderma* right-coiling; R+C = *G. ruber* plus *G. conglobatus*; DUT = *N. dutertrei*; SPH = *G. siphonifera*; TUM = *G. tumida*; INF = *G. inflata*; BUL = *G. bulloides*; DEH = *S. dehiscens;* CUL = *G. cultrata*; TRL = *G. trilobus*; QNQ = *T. quinqueloba*; OBL = *P. obliquiloculata*; CRS = *G. crassaformis*; FAL = *G. falconensis*; TEN = *G. tenellus*; HRS = *G. hirsuta*; CAL = *G. calida*; GLT = *G. glutinata*; RBC = *G. rubescens*; SCI = *G. scitula*; DIG = *G. digitata*; UNV = *O. universa*.

In the lower Pliocene sediments before the FO of *G. puncticulata,* there is a clear predominance of the samples from the intermediate group. According to the arguments expressed in the "Relative Abundance of Species and Biochronology" section above, the samples from the two episodes with relatively high proportions of polar fauna (*N. pachyderma* [left-coiling]) would be expected to belong to the polar group or, at least, to the subpolar group. This is not so, however. The high percentage of polar forms are counteracted by subtropical-tropical forms (*G. apertura, G. obliquus,* and *G. trilobus* forms), and, therefore, the intermediate group is less important or the attribution to the subtropical-tropical realm is biased. In Hole 975B, however, two samples were observed to belong to the subpolar group, one close to the first episode of polar fauna, and, in Hole 976B, another subpolar sample was found beside the second episode of polar fauna. The three samples were notable for their high percentages of *N. pachyderma* (right-coiling), which produced some doubt as to whether the significance of the two morphotypes of *N. pachyderma* during the lower Pliocene is exclusively thermic (see also Ufkes and Zachariasse, 1993). The climatic variability during the early Pliocene was also detected by Thunell (1979) and Thunell et al. (1991) in the Tyrrhenian Sea. Apart from this, the only noteworthy feature is a sample from Site 975 that is assimilated to the subtropical group, located between the two coldest episodes. Its modern analogue is situated a little to the east of Site 975. However, in the groups that were differentiated by the *k*-means test on the complete core-top data set (26 variables), the sample in question belonged to the intermediate group.

In the interval between the FO of *G. puncticulata* and the younger Pliocene level of increase in relative abundance of *G. inflata* group, almost all the samples from Site 975 belong to the intermediate

Table 6. North Atlantic and Mediterranean 23-variable core-top data set.

	Polar			Subpolar			Intermediate			Subtropical-Tropical			Equatorial		
	Min	MN	Max	Min	MN	Max	Min	MN	Max	Min	MN	Max	Min	MN	Max
BUL	0.00	0.03	0.18	0.00	0.17	0.43	0.02	0.20	0.50	0.00	0.04	0.36	0.00	0.02	0.17
CAL	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.05	0.00	0.01	0.09	0.00	0.00	0.01
CRS	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.08	0.00	0.01	0.04	0.00	0.02	0.07
DEH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.09
DIG	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.04	0.00	0.01	0.03
DUT	0.00	0.00	0.00	0.00	0.02	0.20	0.00	0.03	0.29	0.00	0.04	0.19	0.05	0.20	0.55
FAL	0.00	0.00	0.01	0.00	0.01	0.11	0.00	0.05	0.21	0.00	0.03	0.23	0.00	0.00	0.04
GLT	0.00	0.01	0.08	0.00	0.08	0.36	0.00	0.06	0.17	0.00	0.06	0.32	0.00	0.02	0.10
HRS	0.00	0.00	0.03	0.00	0.00	0.04	0.00	0.02	0.09	0.00	0.00	0.06	0.00	0.00	0.01
INF	0.00	0.01	0.24	0.00	0.12	0.39	0.00	0.19	0.44	0.00	0.02	0.21	0.00	0.03	0.22
CUL	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.01	0.24	0.00	0.05	0.19	0.00	0.11	0.31
OBL	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.01	0.09	0.00	0.04	0.24	0.00	0.07	0.26
PCD	0.00	0.11	0.44	0.16	0.45	0.80	0.00	0.09	0.26	0.00	0.01	0.15	0.00	0.03	0.15
PCS	0.38	0.72	0.98	0.00	0.05	0.40	0.00	0.01	0.34	0.00	0.00	0.03	0.00	0.00	0.01
QNQ	0.00	0.10	0.35	0.00	0.03	0.27	0.00	0.02	0.25	0.00	0.00	0.09	0.00	0.00	0.02
RBC	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.01	0.07	0.00	0.01	0.16	0.00	0.00	0.00
R+C	0.00	0.00	0.00	0.00	0.02	0.14	0.00	0.19	0.39	0.27	0.48	0.85	0.00	0.08	0.23
TRL	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.04	0.17	0.00	0.10	0.42	0.00	0.15	0.51
SCI	0.00	0.00	0.03	0.00	0.01	0.07	0.00	0.01	0.09	0.00	0.00	0.03	0.00	0.00	0.01
SPH	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.02	0.07	0.00	0.05	0.14	0.00	0.02	0.05
TEN	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.01	0.12	0.00	0.00	0.01
TUM	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.06	0.00	0.00	0.06	0.00	0.22	0.84
UNV	0.00	0.00	0.02	0.00	0.01	0.19	0.00	0.02	0.09	0.00	0.02	0.10	0.00	0.02	0.13

Notes: Minimum, mean, and maximum relative abundance of species and morphotypes in the five groups of samples obtained by *k*-means clustering. MIN = minimum relative abundance; MN = mean relative abundance; MAX = maximum relative abundance. Abbreviations of species names as in Table 5.

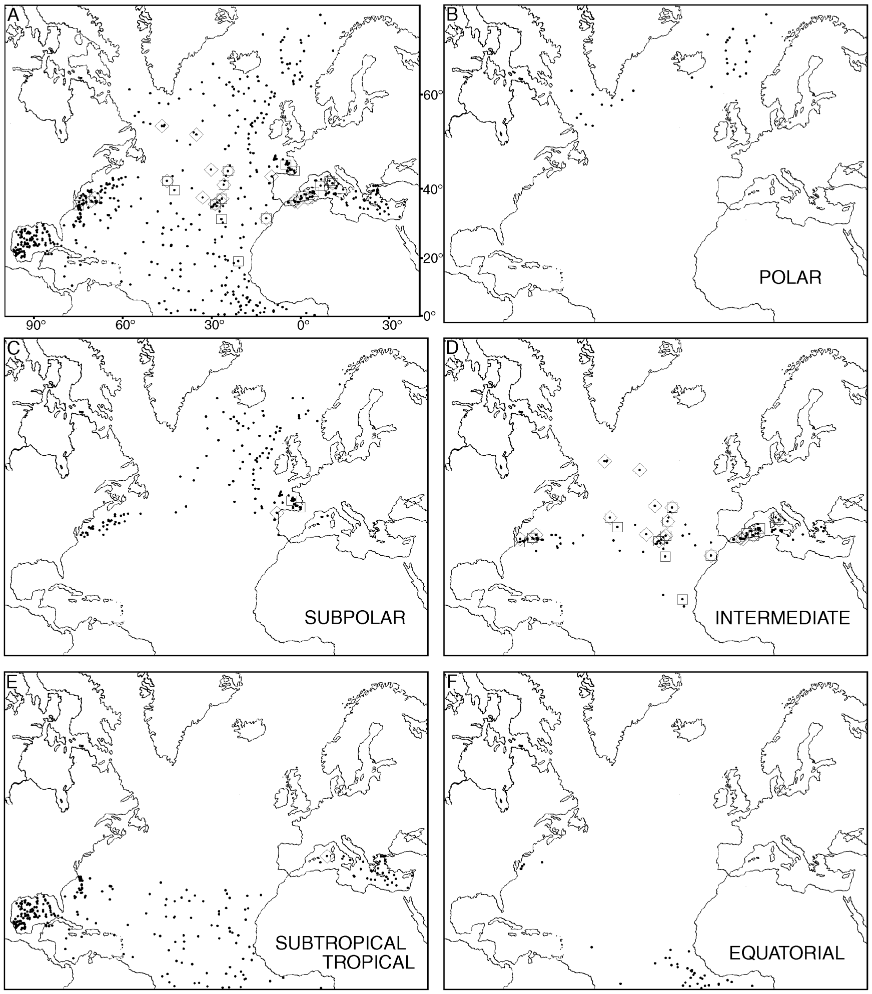

Figure 4. Locations of 605 North Atlantic and Mediterranean core-top samples and groups obtained by *k*-means clustering. Diamonds = modern analogs of the Pliocene pre-FO *G. puncticulata* samples from Site 976. Squares = modern analogs of the Pliocene pre-FO *G. puncticulata* samples from Site 975. A = all the samples; B = polar group; C = subpolar group; D = intermediate group; E = subtropical-tropical group; F = equatorial group.

group. However, there are six assimilated to the subtropical group located in the episodes where *G. inflata* is scarce: Zachariasse et al. (1989) and Thunell et al. (1991) interpreted the vanishing of *G. inflata* lineage as an indication of warming. Another sample, located at the end of the interval, belongs to the subpolar group and is a forerunner of the forthcoming interval. As for Site 976, recovery was very scant, as indicated above, but the presence of two subpolar samples around 445 mbsf should be noted.

Finally, during the interval between the level of increase in the relative abundance of *G. inflata* and the base of the Pleistocene, the situation changed dramatically. At Site 975, there is an alternation of the samples of the subpolar and intermediate groups. At Site 976, there are nine samples in this interval, four belong to the subpolar group and the other five to the intermediate group. This interval shows ecostratigraphic similarities to the basal Pleistocene, even though the increase in polar fauna has not yet been recorded. Climatic variability during the latest Pliocene is not recorded in the Tyrrhenian Sea by Thunell et al. (1991).

Table 7. North Atlantic and Mediterranean 22-variable core-top data set.

	BSS	DF	WSS	DF	FR
PCS	17.546	4	2.530	600	1040.190
PCD	24.135	4	3.684	600	982.798
R+C	25.297	4	4.848	600	782.736
BUL	5.458	4	4.305	600	190.185
DUT	1.304	4	1.549	600	126.252
TUM	1.680	4	2.009	600	125.404
SPH	0.219	4	0.266	600	123.551
DEH	0.012	4	0.020	600	90.620
CUL	0.451	4	0.835	600	81.069
TRL	1.414	4	3.026	600	70.106
QNQ	0.353	4	0.908	600	58.307
OBL	0.219	4	0.622	600	52.664
CRS	0.010	4	0.034	600	44.017
FAL	0.245	4	0.925	600	39.695
TEN	0.018	4	0.077	600	35.382
GLT	0.280	4	1.473	600	28.548
CAL	0.016	4	0.090	600	26.019
HRS	0.022	4	0.163	600	20.290
SCI	0.012	4	0.109	600	16.439
RBC	0.014	4	0.149	600	14.113
DIG	0.001	4	0.018	600	11.013
UNV	0.020	4	0.367	600	8.202

Notes: Summary statistics for five groups obtained by k-means clustering. BSS = between groups sum of squares; DF = degrees of freedom; WSS = within groups sum of squares; FR = *F*-ratio statistics (one way ANOVA). Abbreviations of species names as in Table 5.

CONCLUSIONS

In the Pliocene, at Sites 975 and 976, we detected a succession of datum planes, which are normally used in the biostratigraphy of the Mediterranean Domain, based on planktonic foraminifers: FCO of *G. margaritae,* FOD of *G. puncticulata*, LCO of *G. margaritae,* FO of *G. crassaformis,* LO of *Sphaeroidinellopsis* and FCO of *N. pachyderma* (left-coiling).

Other biohorizons that were used require future evaluation: LO of *G. puncticulata,* FO and LO of *G. bononiensis,* and FO of *G. inflata.* Indeed, in the range charts of planktonic foraminifer species in the Mediterranean Pliocene, there are usually gaps indicated between the ranges of *G. puncticulata, G. bononiensis,* and *G. inflata.* However, the ranges of these morphotypes do not seem to be strictly restricted at the intervals between gaps. The "classical" morphotype range may, therefore, be an oversimplification. Nevertheless, the gaps (or intervals of rare occurrence) themselves may be available events in defining the biostratigraphy of the Pliocene.

Other potentially interesting biohorizons also were detected:

1. Two short intervals of relative abundance of *N. pachyderma* (left-coiling), within Zone MPL-2.
2. The FCO of the *G. ruber* group within Zone MPL-3.
3. The LCO of the *G. obliquus* group, coincident with the LO of *Sphaeroidinellopsis* (198 mbsf at Site 975) and, therefore, at the boundary between Zones MPL-4 and MPL-5. The LCO of *G. obliquus* is more clearly perceptible than the FO the *Sphaeroidinellopsis.* Thus, in the interval 193–203 mbsf at Site 975, *G. obliquus* is present in the five samples beneath its LCO, reaching a mean relative abundance of 8.42% of the total of planktonic foraminifers, while in the five samples above the event, only one specimen was found (0.31%), at 193 mbsf. *Sphaeroidinellopsis* only appeared in two samples within this interval: at 198 mbsf it represented 1.0% and at 200 mbsf it was 1.6%.
4. The LCO of the *G. apertura* group at the highest part of Zone MPL-5B, foretells the sudden reappearance of the *G. inflata*

Table 8. North Atlantic and Mediterranean 22-variable coretop data set.

	Polar			Subpolar			Intermediate			Subtropical-Tropical			Equatorial		
	Min	MN	Max	Min	MN	Max	Min	MN	Max	Min	MN	Max	Min	MN	Max
BUL	0.00	0.03	0.19	0.01	0.45	0.06	0.28	0.63	0.00	0.00	0.04	0.32	0.00	0.02	0.19
CAL	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.01	0.06	0.00	0.01	0.09	0.00	0.00	0.01
CRS	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.08	0.00	0.01	0.05	0.00	0.02	0.07
DEH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.02	0.09
DIG	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.04	0.00	0.00	0.04	0.00	0.01	0.03
DUT	0.00	0.00	0.00	0.00	0.02	0.22	0.00	0.03	0.34	0.00	0.04	0.20	0.05	0.21	0.64
FAL	0.00	0.00	0.01	0.00	0.01	0.13	0.00	0.06	0.28	0.00	0.03	0.25	0.00	0.00	0.05
GLT	0.00	0.01	0.08	0.00	0.09	0.37	0.00	0.06	0.19	0.00	0.07	0.32	0.00	0.02	0.12
HRS	0.00	0.00	0.03	0.00	0.01	0.05	0.00	0.02	0.13	0.00	0.01	0.11	0.00	0.00	0.01
CUL	0.00	0.00	0.00	0.00	0.01	0.10	0.00	0.01	0.27	0.00	0.05	0.19	0.00	0.11	0.33
OBL	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.01	0.08	0.00	0.03	0.24	0.00	0.07	0.26
PCD	0.00	0.12	0.45	0.27	0.51	0.81	0.00	0.10	0.29	0.00	0.02	0.19	0.00	0.04	0.19
PCS	0.38	0.73	0.98	0.00	0.06	0.41	0.00	0.02	0.35	0.00	0.00	0.03	0.00	0.00	0.01
QNQ	0.00	0.10	0.35	0.00	0.03	0.23	0.00	0.02	0.27	0.00	0.00	0.09	0.00	0.00	0.03
RBC	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.01	0.08	0.00	0.01	0.16	0.00	0.00	0.00
R+C	0.00	0.00	0.00	0.00	0.03	0.18	0.00	0.24	0.47	0.27	0.49	0.86	0.00	0.08	0.24
TRL	0.00	0.00	0.00	0.00	0.01	0.10	0.00	0.04	0.14	0.00	0.10	0.42	0.00	0.15	0.51
SCI	0.00	0.00	0.03	0.00	0.01	0.09	0.00	0.01	0.12	0.00	0.00	0.04	0.00	0.00	0.01
SPH	0.00	0.00	0.00	0.00	0.01	0.06	0.00	0.03	0.08	0.00	0.05	0.14	0.00	0.02	0.05
TEN	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.03	0.00	0.01	0.12	0.00	0.00	0.01
TUM	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.07	0.00	0.00	0.07	0.00	0.22	0.85
UNV	0.00	0.00	0.03	0.00	0.02	0.23	0.00	0.03	0.13	0.00	0.02	0.11	0.00	0.02	0.13

Notes: Minimum, mean, and maximum relative abundance of species and morphotypes in the five groups of samples obtained by *k*-means clustering. MIN = minimum relative abundance; MN = mean relative abundance; MAX = maximum relative abundance. Abbreviations of species names as in Table 5.

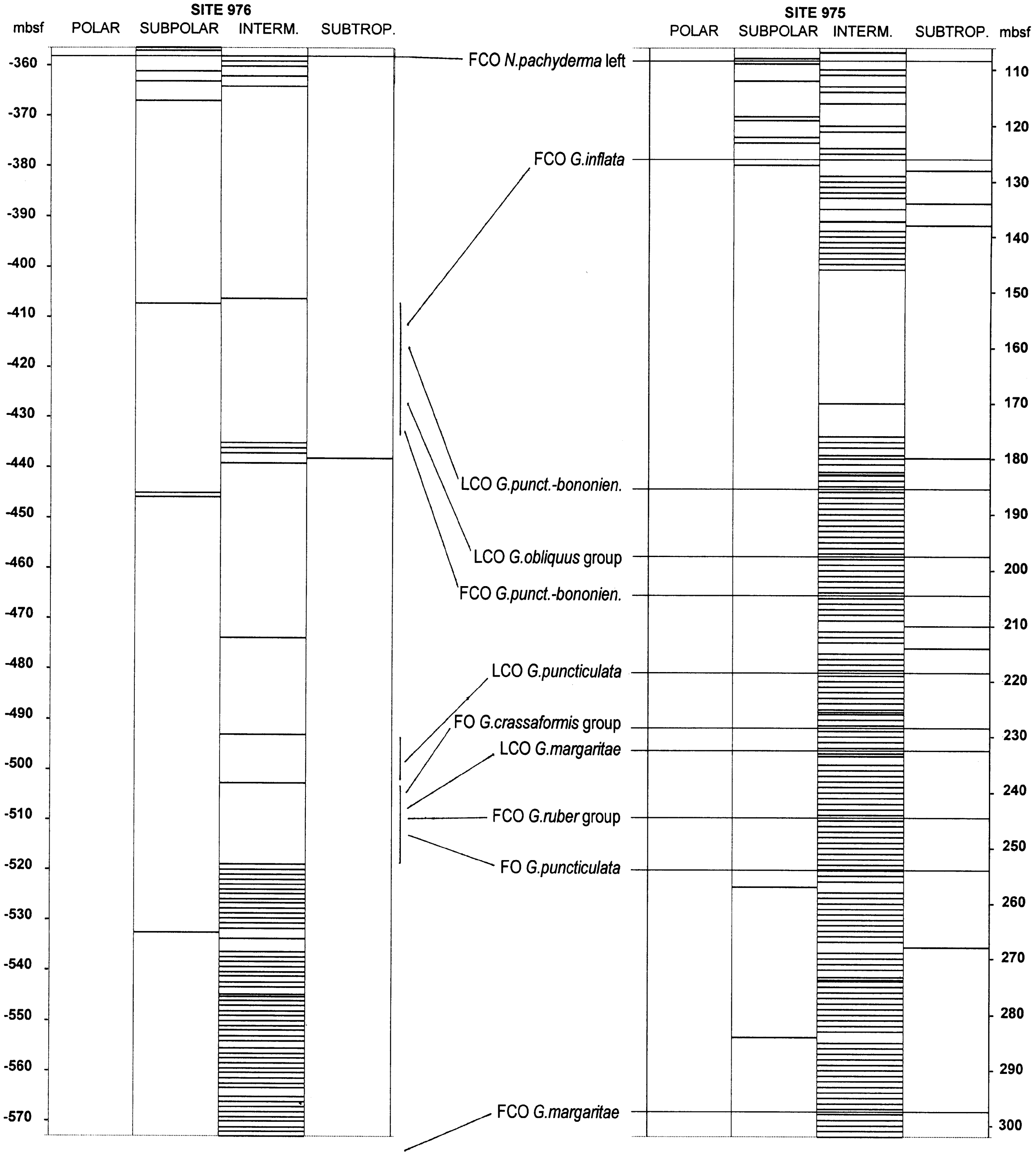

Figure 5. Present-day groups of core-top samples in which Pliocene samples are distributed according to discriminant analysis.

group (FO of *G. inflata* according to Comas, Zahn, Klaus, et al., 1996).

The taxonomic differences between the Pliocene and present-day planktonic foraminifers restricted the accuracy on the paleoenvironmental reconstruction. Accepting this limitation, most of the Pliocene shows a monotonous succession of assemblages whose modern analogs are to be found in present-day waters intermediate between subpolar and subtropical waters. This uniformity is punctuated at the lower part of the sequence by two episodes of subpolar waters, between which is interspersed one of subtropical waters. In the middle part of the sequence, no episodes of subpolar waters were observed, although there were findings of subtropical waters. In the uppermost Pliocene, the paleoceanographic conditions changed to an alternation of subpolar and intermediate episodes, as was to be the predominant pattern during the Pleistocene.

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