10. LATE NEOGENE PALEOENVIRONMENT: QUANTITATIVE MICROPALEONTOLOGY

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The present investigation was initiated to further reconstruct the climatic record of the last several million years, by means of quantitative studies on planktonic foraminiferal assemblages in Cores 397-1 to 397-39. Our research was motivated by the necessity (1) to calibrate the detailed carbonate curve obtained from these cores (see Cita and Spezzibottiani, this volume) and thereby check its value as a climatic indicator, and (2) to have a paleontological basis for making comparison with oxygen and carbon isotope curves (see Shackleton and Cita, this volume).

Because of time restrictions, the amplitude of the interval considered, and the difficulty of extrapolating procedures to lengthy time intervals (procedures usually only applied to the late Pleistocene), we concentrated our efforts on four discrete test intervals, ranging from the late Quaternary to the early Pliocene.

The paleoclimatic record of the late Neogene section continuously cored at Site 397, as expressed by variations in fossil assemblages, has some problematic aspects. The faunal changes result from the interaction of the following factors: (1) temperature changes in the superficial water masses induced by temperature changes of the lower layers of the atmosphere; (2) temperature changes related to changes in the gyre margin currents, which in the area under discussion are clockwise cool currents (Canary Current); (3) changes related to upwelling, which is presently active in the area; and (4) changes related to dissolution at depth. The first factor (atmosphere-induced temperature changes) is considered "the signal"; the other three factors are considered "noise."

MATERIAL

The intervals selected for quantitative studies are from sediment cores where disturbances were minimal, as determined by visual observations on the ship and a careful examination of core photographs.

Each test interval includes nine samples, one per section, which means one approximately every 1.5 meters (samples were consistently taken from 50 to 52 cm from the top of each section). The average sedimentation rate for the late Neogene succession is 7 cm/1000 years; consequently, we have a data point every 20,000 years on the average. This frequency certainly is inadequate to detect all the climatic cycles, but is sufficient to identify the main trends.

From top to bottom, the four test intervals are as follows:

Test interval 1: from Samples 2-2, 50 to 52 cm to 3-4, 50 to 52 cm. Most of the data points of the carbonate curve in this interval (late Quaternary, Brunhes Epoch) lie above the mean value calculated for the 260 points (57.2%); several low amplitude and a few high amplitude cycles are recorded (high amplitude isotopic cycles).

Test interval 2: from Samples 7-6, 50 to 52 cm to 9-2, 50 to 52 cm. In this interval (early Quaternary, upper Matuyama Epoch), most of the data points of the carbonate curve lie below the mean value, and a number of sharp troughs and peaks are recorded in the carbonate as well as in the isotopic curve.

Test interval 3: from Samples 21-5, 50 to 52 cm to 23-1, 50 to 52 cm. This interval represents the late Pliocene (Piacenian), M Pl 5 foraminiferal zone, lowermost part of the Matuyama Epoch, including the Gauss/Matuyama boundary. All the data points, but one, in this interval lie above the mean value of the carbonates, and a well-defined cycle is recorded. A marked isotopic change is also recorded with $\delta^{18}O$ becoming more positive upwards, whereas $\delta^{13}C$ shows an upwards change to more positive values (Shackleton and Cita, this volume).

Test interval 4: from Sample 38-1, 50 to 52 cm to 39-5, 50 to 52 cm. This interval represents the early Pliocene (Zanclean), *Globigerina nepenthes* interval zone, lower part of the Gilbert Epoch. Strong disturbances in the pelagic realm are recorded, such as high amplitude carbonate and isotopic cycles, accompanied by a reversal in the trend towards downhole increasing carbonate values, and by the first (downhole) evidence of strong dissolution.

PROCEDURES

We examined the sediment fraction >200 µm. From a sample size of 300 to 400 foraminifers, specimens were identified down to the species level, counted, measured, and/or observed following the procedures described below. These procedures differ in part between Quarternary (test intervals 1 and 2) and Pliocene (test intervals 3 and 4) sediments.

Procedure A

The first procedure is similar to that adopted by CLIMAP workers (see McIntyre et al., 1976). Following Thiede (1977), we considered five faunal assemblages. Plates 1 and 2 illustrate the most characteristic taxa for a precise reference.

1) tropical with the species *Globigerinoides ruber, G. gomitulus, G. sacculifer, Hastigerina siphonifera, Globorotalia menardii,* and *Pulleniatina obliquiloculata;*

2) subtropical with the species *Globorotalia truncatulinoides, G. inflata, Globigerina falconensis,* and *G. calida;*

3) polar with *Globigerina pachyderma* (left-coiling);

4) subpolar with *Globigerina pachyderma* (right-coiling), *G. bulloides,* and *Globigerinita glutinata;*

5) gyre margin with the species *Pulleniatina obliquiloculata, Globorotalia menardii, G. inflata, Globigerinoides sacculifer,* and *G. tenellus.*

This procedure was modified in part for test intervals 3 and 4, as discussed below.

Procedure B

We used a second procedure, which has been recently applied with success by Bé et al. (1973) in the Indian Ocean, at latitudes comparable to those at DSDP Site 397 (26°). Studies on living and bottom populations of *Orbulina universa* (Hecht et al., 1976) showed that the mean and maximum values of the diameter of *O. universa* bear a definite relationship to the temperature of superficial water masses, hence with latitude. Large forms indicate warmer superficial waters than small forms: the mean value <450 μm is considered characteristic of latitudes ranging from 32° to 45°S. Bé and Duplessy (1976) showed a definite positive correlation between the isotopic curve and the mean diameter of *O. universa,* with lighter δ^{18}O values and larger diameters being recorded in intervals interpreted as "interglacials."

This procedure, unlike the former, could be applied without any modification to all four test intervals because *O. universa* is always present.

The diameter of the last-formed, spherical chamber of all the specimens of *O. universa* contained in the counted fraction was measured, and mean values calculated.

Procedure C

The coiling direction of *Globorotalia truncatulinoides* is known to have changed during the Quaternary, but the climatic message of this change is still controversial. Reference is made to Ryan et al. (in preparation) for a thorough discussion of the problem. On the basis of the study of six deep-sea cores from the North Atlantic, the South Atlantic, and the Indian Ocean, they interpret the climatic record of the Holocene. In these cores, left-coiling specimens dominate during warm periods. According to Bé et al. (1976): "the brief periods in which left-coiling *G. truncatulinoides* was prevalent in the tropical Atlantic Ocean apparently indicate cooler subtropical conditions similar to those found today at latitudes about 30°N or 30°S."

G. truncatulinoides is consistently recorded in all our Quaternary samples. This procedure is by far the easiest and the fastest to apply among those attempted. We, therefore, decided to use this technique to evaluate the Quaternary climatic record, i.e., for test intervals 1 and 2.

RESULTS AND DISCUSSION

Reference Sample

Lacking a sediment sample from the surface at DSDP/IPOD Site 397, we employed the above procedures, to study the topmost sample (1-1, 8-10 cm). Its foraminiferal fauna is considered a reference point, ideally representing the present climatic situation.

Tropical assemblage:	
G. ruber	2.2%
G. gomitulus	2.2%
G. sacculifer	7.0%
H. siphonifera	5.5%
G. menardii	1.0%
P. obliquiloculata	5.8%
Total	23.7%
Subtropical assemblage:	
G. truncatulinoides	18.8%
G. falconensis	0.2%
G. inflata	16.8%
G. calida	1.0%
Total	36.8%
Subpolar assemblage:	
G. pachyderma dextral	1.0%
G. bulloides	3.5%
G. glutinata	0.2%
Total	4.7%
Polar Assemblage:	
G. pachyderma sinistral	0%
Gyre margin assemblage:	
P. obliquiloculata	5.8%
G. menardii	1.0%
G. inflata	16.8%
G. sacculifer	7.0%
G. tenellus	0%
Total	30.6%
Orbulina universa	7.1%
others (*G. trilobus, G. quadrilobatus, G. elongatus,* etc.)	27.5%

The "faunal signal" (subtropical + tropical − subpolar) for this reference sample is +59.3. The coiling ratio of *Globorotalia truncatulinoides* is 26.7 per cent dextral (which means dominantly sinistral).

Test Interval 1

The data recorded from Cores 2 and 3 are reported in Figure 1. The polar fauna is either absent from the >200 μm sediment fraction, or present in low percentages ($<1\%$). The tropical assemblage (B) is not well represented either. The subtropical (C), subpolar (D), and gyre margin (E) assemblages are present in variable abundances.

A positive correlation of the carbonate curve (A) with the tropical and subtropical assemblages (percent-

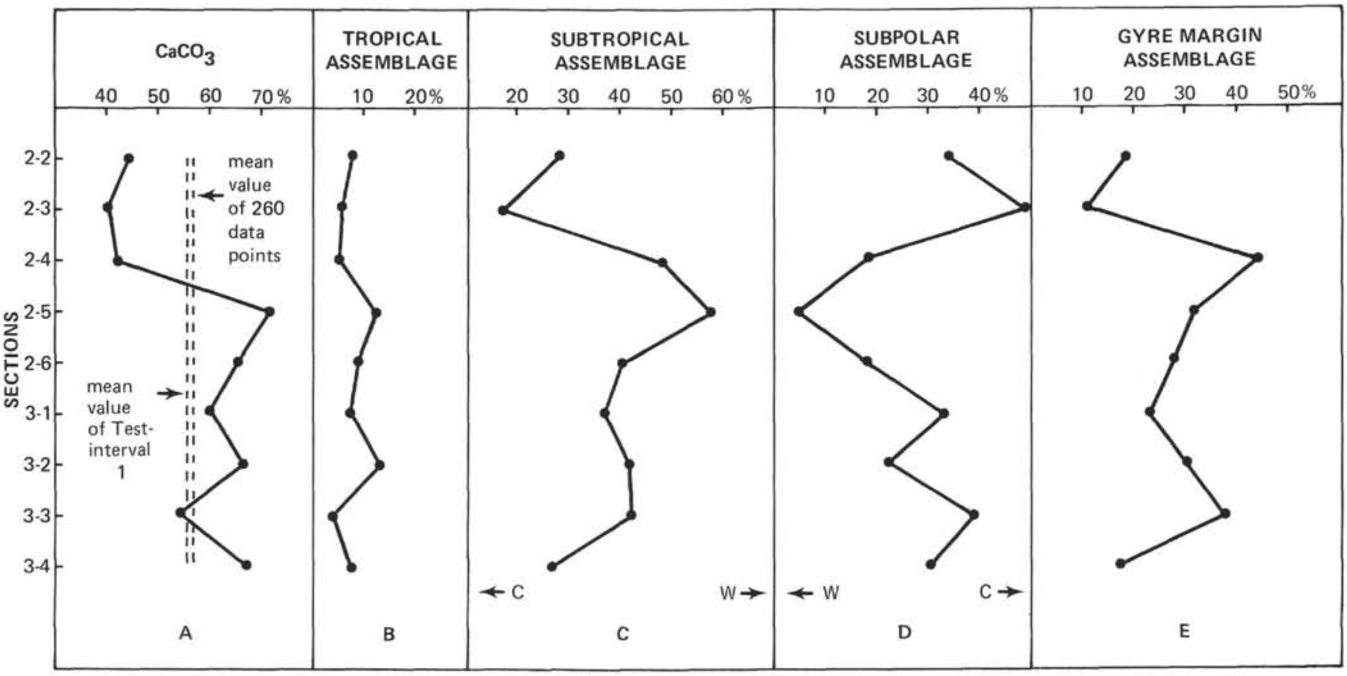

Figure 1. *Changes in percentages recorded in (A) carbonate content, (B) tropical assemblage, (C) subtropical assemblage, (D) subpolar assemblage, and (E) gyre margin assemblage in nine samples from Cores 2 and 3, Site 397. W and C refer to warm and cold, respectively.*

ages) is clearly expressed in Figure 1, whereas the correlation of the gyre margin assemblage is less obvious.

The changing patterns of the gyre margin currents are considered as a "noise" affecting the faunal "signal" (see above). Consequently, we plotted (Figure 2) the carbonate curve against a composite faunal curve (F), resulting from the sum of the tropical and subtropical assemblages, minus the subpolar assemblage.

It is noteworthy that none of the taxa characterizing the three faunal assemblages (B), (C), and (D) is present in more than one group. We separately plotted the percentages of the gyre margin assemblage (E) to test whether or not they acted as "noise." The faunal signal curve amplifies the positive correlation with the carbonate curve (Figure 1).

We also plotted (Figure 2) the coiling ratio of *Globorotalia truncatulinoides* (G): though the signal is in part obscure, right-coiling specimens seem to dominate in warm intervals.

Figure 3 shows the data obtained after applying Procedure B. The second column shows the percentages of *Orbulina universa,* so that the reader can evaluate the reliability of the mean values, which in some instances have been derived from a limited number of specimens.

Changes in the mean diameter seem to correlate with the carbonate curve, and inversely with the percentages of the subpolar assemblage, however the changes recorded are small. The same is true for the maximum diameter. The opposite trend, shown by these two parameters between Sections 2-3 and 2-4 and between Sections 3-1 and 3-2, is attributable to the small number of specimens measured.

Figure 4 shows changes recorded in oxygen isotopes values measured on benthic foraminifers isolated from the same sediment fraction (> 200 μm) used to make quantitative micropaleontological studies. It compares these values to the faunal signal, and to the maximum diameter of *O. universa.* The correlation seems quite good.

Test Interval 2

The data recorded in the second set of samples investigated for the test are plotted in Figures 5 to 8. As shown in Figure 5, the positive correlation of the carbonate curve (A), with tropical assemblage curve (B), and subtropical assemblage curve (C) still exists. However, it is partly obscured by the gyre margin "noise," curve (E), which is here much more pronounced than in the first test area. Indeed, seven out of nine data points contain percentages in excess of 40 per cent of gyre margin assemblages, which coincides closely with the percentages of *Globorotalia inflata,* the dominant taxon in the sediment fraction examined.

The "faunal signal" expressed in Figure 6 has a trend in part similar to that of the carbonate curve. The climatic message of *G. truncatulinoides* (coiling ratio) is contradictory. Indeed, the four lower data points have a striking similarity with the "faunal signal" (F); whereas, the five higher data points have no apparent relationship with that parameter.

As shown by Figure 7, the mean value of the diameter of *Orbulina universa* shows minor changes, whereas the maximum diameter varies considerably. Taking into account that the percentages of the taxon are small (~5%, or about 20 specimens out of nearly 400 counted), the means are not really significant.

The clear relationship between carbonate curve and the maximum diameter of *O. universa* (positive correla-

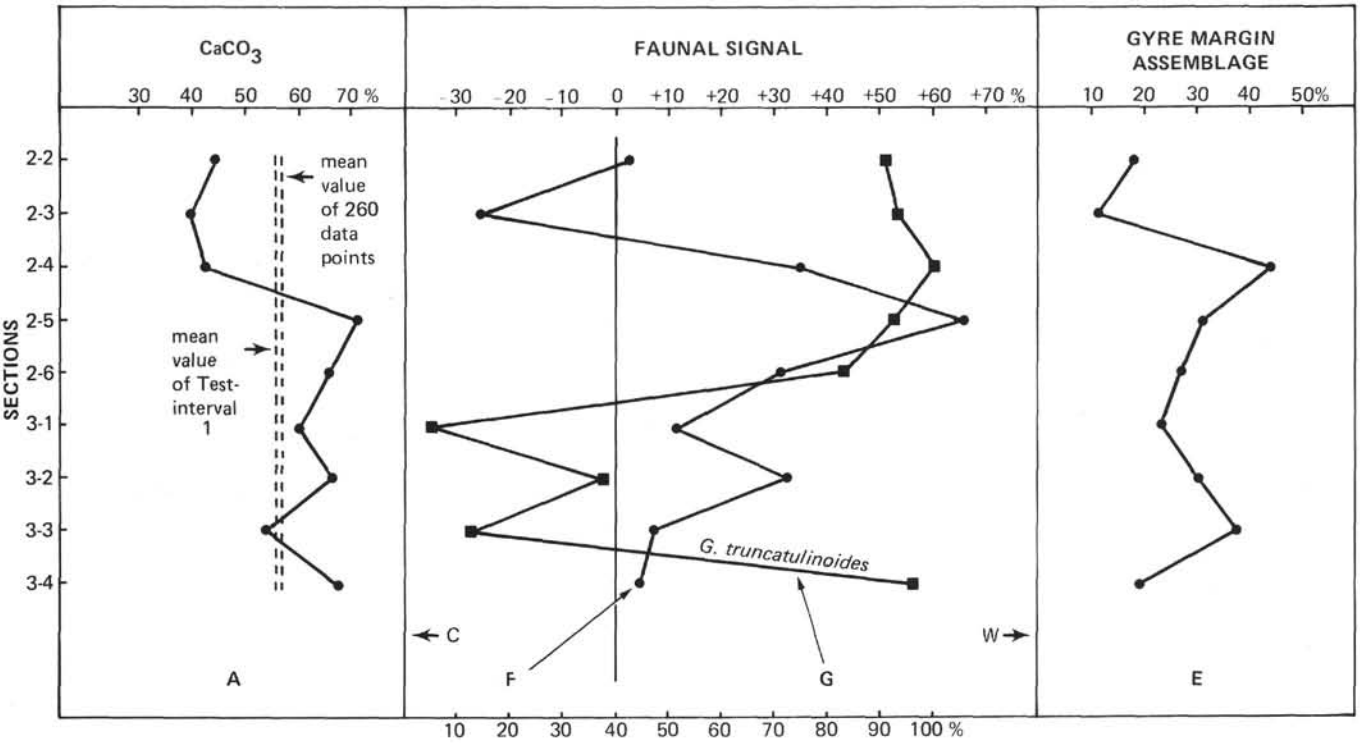

Figure 2. *Changes in percentages of (A) carbonate content, (E) gyre margin assemblage, (G) right-coiling* Globorotalia truncatulinoides *in the same nine samples considered in Figure 1. The faunal signal (F) is the sum of the tropical assemblage (B), plus the subtropical assemblage (C), minus the subpolar assemblage (D) as plotted in Figure 1.*

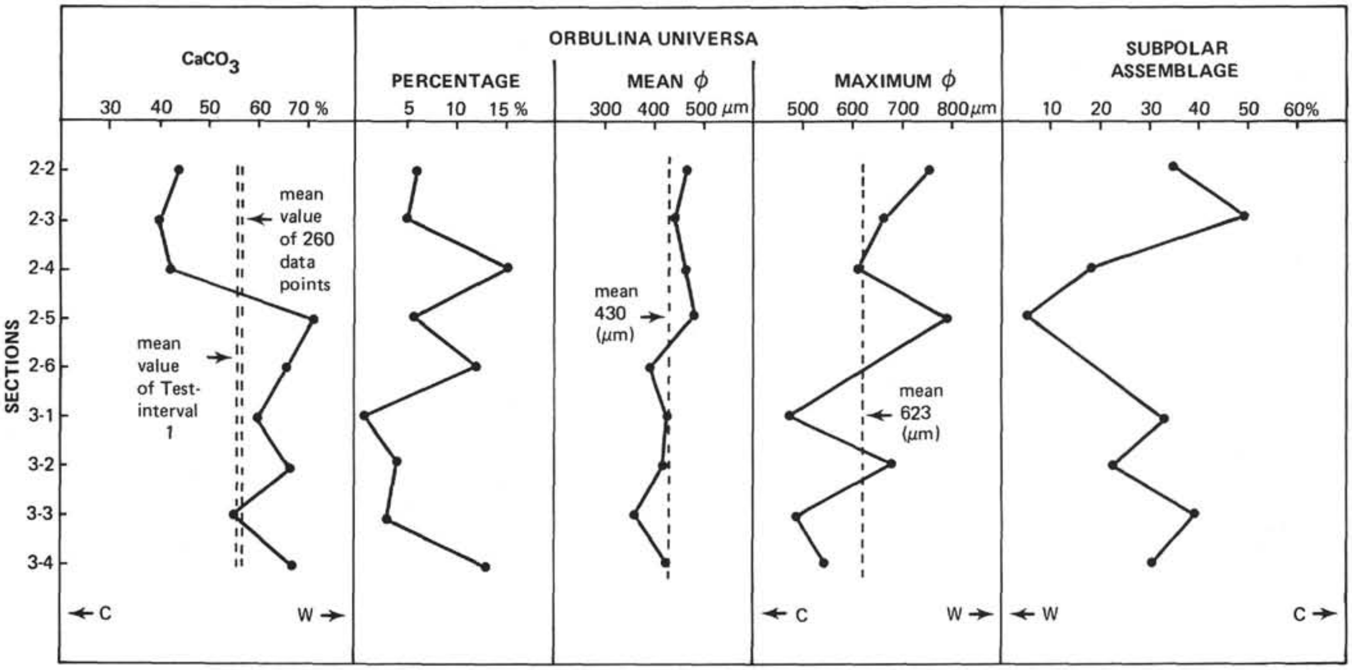

Figure 3. *Changes in percentages of carbonates (column one),* Orbulina universa *(column two), and subpolar assemblage (column three). The two remaining columns are plots of the mean and maximum diameter measured in* O. universa *(last-formed chamber).*

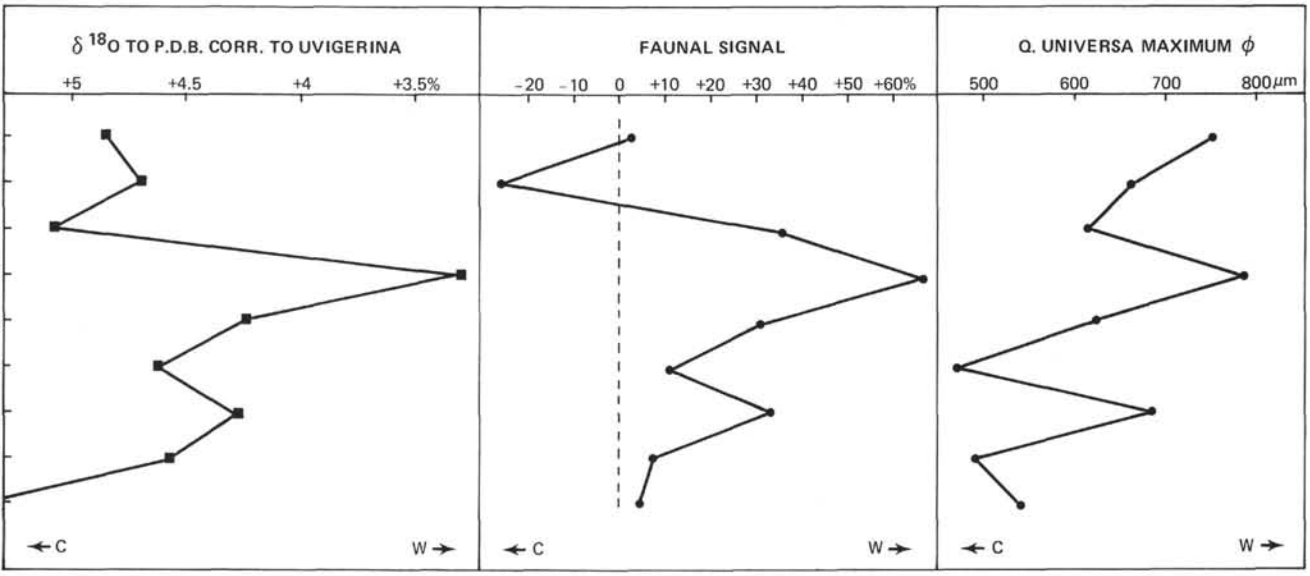

Figure 4. *Correlation between isotopic signal in* Uvigerina *(after Shackleton and Cita, this volume), faunal signal, and maximum diameter of* Orbulina universa *in nine samples from Cores 2 and 3. Test interval 1.*

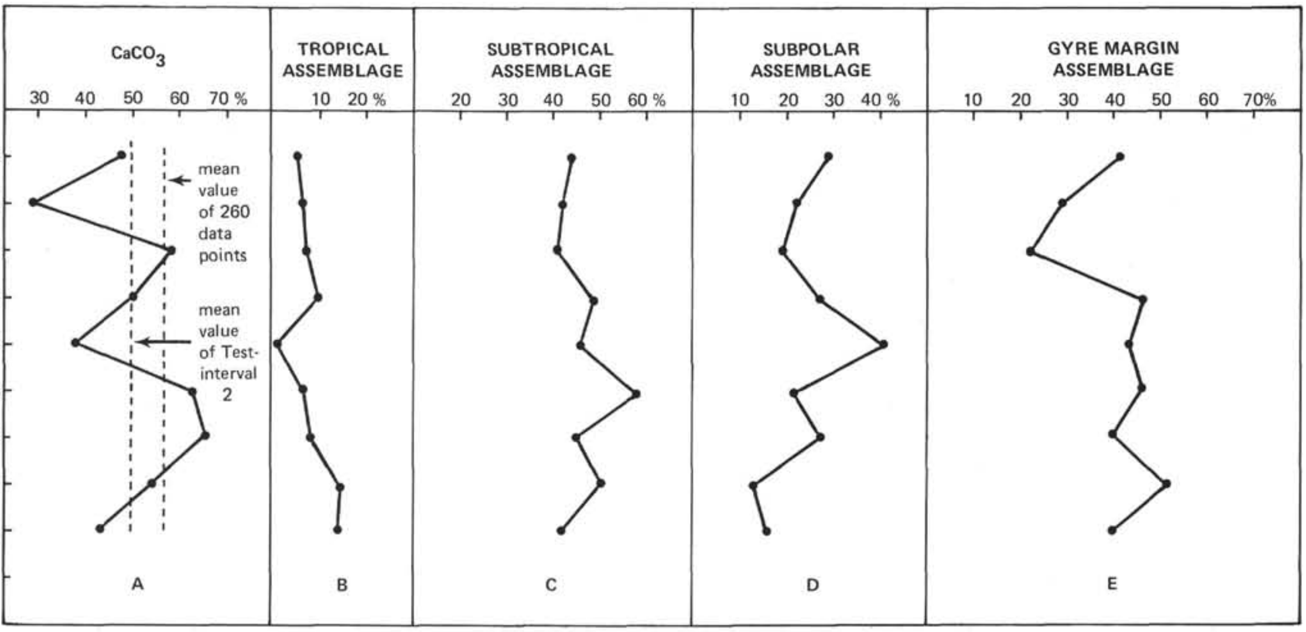

Figure 5. *Changes in percentages of (A) carbonate content, (B) tropical assemblage, (C) subtropical assemblage, (D) subpolar assemblage, and (E) gyre margin assemblage in nine samples from Sections 7-6 to 9-2, Site 397.*

tion), and percentage subpolar fauna (percentage) versus the maximum diameter of *O. universa* (negative correlation) recorded in test interval 1 are not observed here.

Figure 8 shows the isotopic signal imprinted in benthic foraminifers (after Shackleton and Cita, this volume) relative to the "faunal signal" and the maximum diameter of *O. universa*. Correlation of the first two parameters is fairly good, even though the amplitude differs.

We plan further investigations on both the test size and the shell porosity of *O. universa* from test intervals 1 and 2 to determine whether and where a definite change in trend is recorded. Indeed, the perfectly spherical shape of the last-formed chamber of *O. universa* is interpreted as an adaptative response to a pelagic habitat and could have different derivations (Blow, 1969). As in test interval 1, the trends shown by the mean and maximum diameter differ sometimes, this is attributed to the small number of specimens measured.

Test Interval 3

Portions of the preceding procedures had to be modified slightly for test interval 3, which is late Pliocene in age (M Pl 5 foraminiferal zone). Procedure C had to be abandoned because *Globorotalia truncatulinoides* had not yet evolved below Core 15. In addition

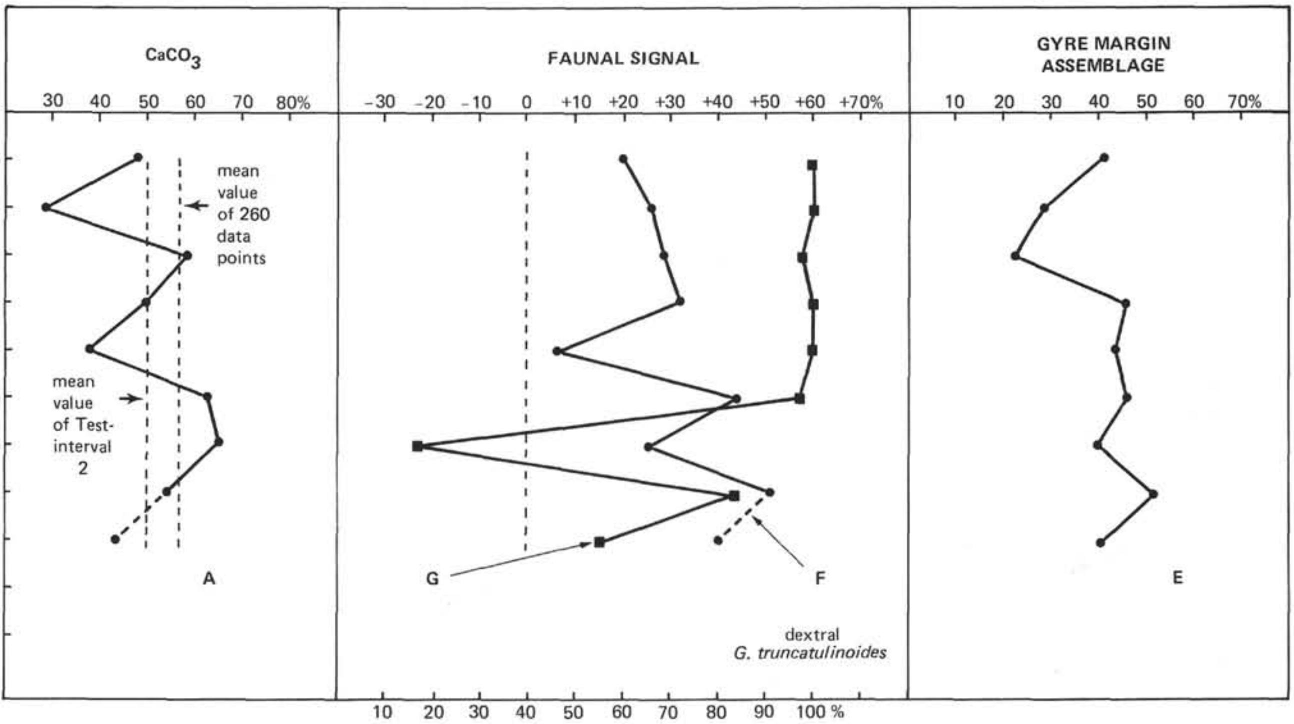

Figure 6. *Changes in percentages of (A) carbonate content, (E) gyre margin assemblage, (G) right-coiling* Globorotalia truncatulinoides *in the same nine samples considered in Figure 5. The faunal signal (F) is the sum of the tropical assemblage (B), plus the subtropical assemblage (C), minus the subpolar assemblage (D), as plotted in Figure 5.*

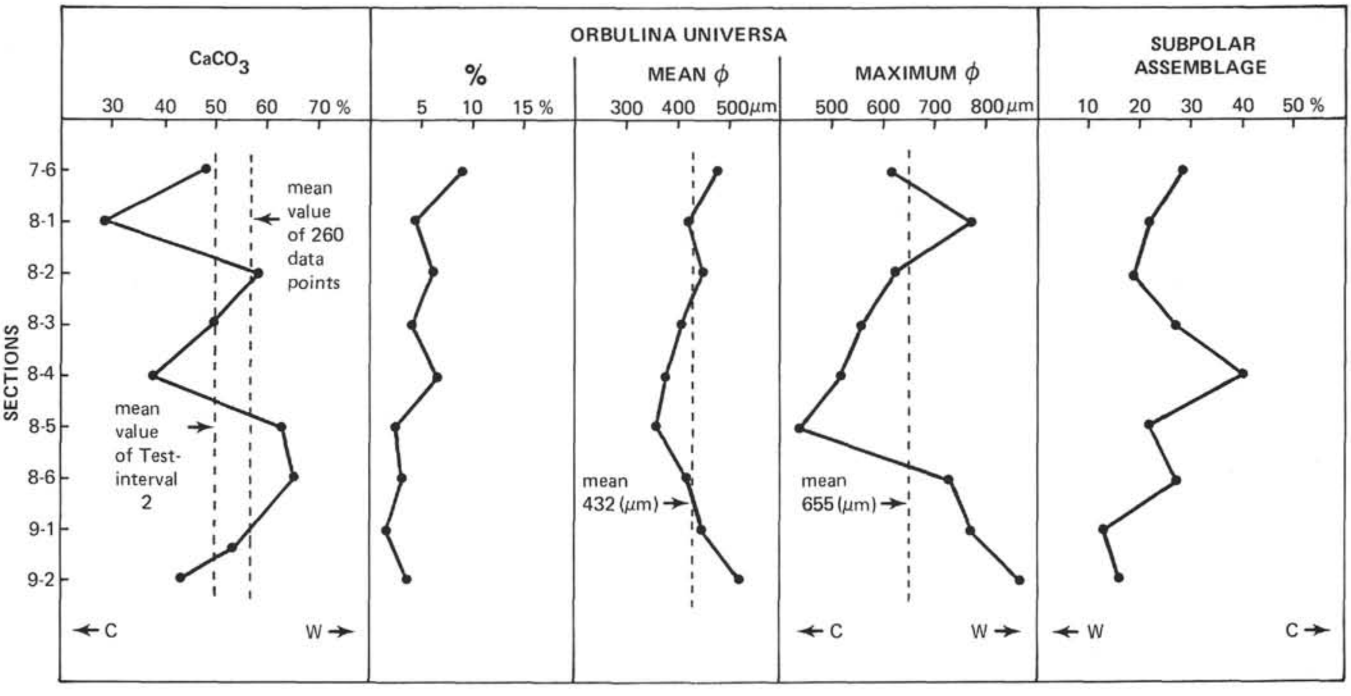

Figure 7. *Changes in percentages of carbonates (column one),* Orbulina universa *(column two), and subpolar assemblage (column three). The two remaining columns show the mean and maximum diameter of* O. universa. *W and C refer to warm and cold, respectively. The nine sets of data points are from Sections 7-6 to 9-2.*

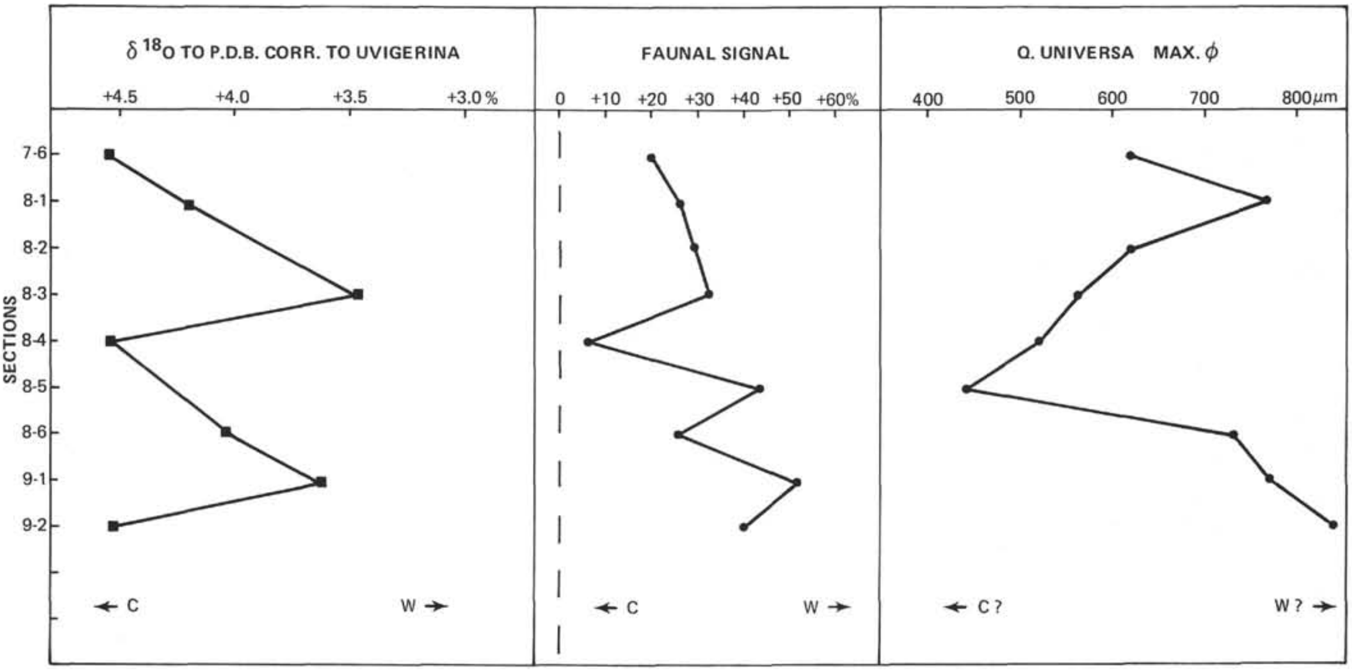

Figure 8. *Correlation between isotopic signal in* Uvigerina *(after Shackleton and Cita, this volume), faunal signal, and maximum diameter of* Orbulina universa *in nine samples from Sections 7-6 to 9-2, Site 397. Test interval 2.*

to *G. truncatulinoides*, other species counted in test intervals 1 and 2, but not recorded in test interval 3 include *G. inflata, Globigerina calida,* and *Globigerinoides tenellus.* Moreover, the plexus of *Globorotalia menardii,* which is only represented by one species in the Quaternary, includes several species in the late Pliocene, e.g., *G. miocenica, G. exilis, G. multicamerata,* and *G. cultrata limbata* (see Plate 3).

Consequently, Procedure A was modified by the introduction of some substitute species, and adding to the list of climatically significant taxa some species which, according to our previous experience on the Pliocene deep-sea record, could be considered meaningful.

In summary, we counted the relative abundance of the following species[1]:

Tropical assemblage:

Globigerinoides obliquus extremus (±)
G. ruber
G. gomitulus
G. sacculifer
Hastigerina siphonifera
Globorotalia miocenica (+)
G. multicamerata (+)
G. exilis (+)
G. cultrata menardii
G. cultrata limbata (+)
Pulleniatina obliquiloculata

Subtropical assemblage:

Globorotalia crassaformis
Globigerina falconensis
Globorotalia muncticulata (+)
G. hirsuta (=)
G. aemiliana (+)
Globigerinoides conglobatus (=)

Subpolar assemblage:

Globigerina pachyderma dextral
G. bulloides
G. apertura (±)
Globigerinita glutinata

Gyre margin assemblage:

Globigerinoides sacculifer
Globorotalia puncticulata (+)
G. menardii and associated forms (+)
Pulleniatina obliquiloculata

A few comments follow:

Tropical assemblage: *G. menardii* has been replaced by a group of keeled globorotalias belonging to the same plexus (*G. miocenica, G. multicamerata, G. exilis, G. cultrata menardii,* and *G. cultrata limbrata*), whose latitudinal distribution in the fossil record is suggestive of tropical conditions. *Globigerinoides obliquus extremus,* which is a pre-Pleistocene species preferring low to middle latitudes, was added to the list of tropical indicators.

Subtropical assemblage: *Globorotalia truncatulinoides* has not been replaced by its direct ancestor, *G. tosaensis,* which is sparse and quantitatively insignificant in the late Pliocene succession of Site 397. The latter has been replaced in turn by *G. crassaformis,* a species which is considered phylogenetically related to *G. truncatulinoides* (Blow, 1969; Hays and Berggren, 1971). *G. crassaformis* is also recorded in low abundances in test intervals 1 and 2, but it was not counted there. The same holds true for *Globorotalia hirsuta* and

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[1] (+) = Species not recorded in test intervals 1 and 2; (=) Species recorded in test intervals 1 and 2, but not counted there.

Globigerinoides conglobatus, which rarely are recorded in test intervals 1 and 2, and have been added to the subtropical assemblage. We also considered *Globorotalia aemiliana* in this group a species not recorded in test intervals 1 and 2, which is phylogenetically related to *G. crassaformis* (Colalongo and Sartoni, 1967).

Globorotalia inflata was tentatively replaced by *G. puncticulata,* a species whose morphology is similar to that of *G. inflata,* and which is generally considered its direct ancestor (e.g., see Cita, 1973). In principle, one should expect that species phylogenetically related share the same habitat. Since *G. inflata* is considered by CLIMAP workers[2] and especially by Thiede (1977) in the eastern North Atlantic as a member of the subtropical assemblage, we initially considered *G. puncticulata* as its substitute. However, the curves constructed using *G. puncticulata* as a member of the subtropical assemblage are so inconsistent with other parameters (see Figures 9 and 10), that we moved this species to the subpolar assemblage. That *G. puncticulata* prefers intermediate waters is suggested from studies on Pliocene sediments of the Mediterranean area (M. A. Chierici, personal communication, 1977, in the subsurface of the Po Plain, northern Italy; Vismara Schilling and Stradner, 1978, with reference in the "Trubi" Formation of Sicily). In Sicily, it has been shown that the relative abundance of *Globorotalia puncticulata* has a definite inverse correlation with the relative abundance of the extant species *Globigerinoides sacculifer* and *G. ruber,* both members of the tropical assemblage.

We therefore concluded that *G. puncticulata* behaves as a temperate-cool water species, characteristic of the transitional zone (sensu Bé and Tolderlund, 1971). We plotted *G. puncticulata* in two different ways (see Figures 9 and 10): as a warm indicator (subtropical assemblage) and as a cold temperate indicator (subpolar assemblage). The resulting faunal signal strongly differs in samples where *G. puncticulata* is the dominant species, with percentages up to 30 per cent. In Plate 4, we also constructed a third curve of the faunal signal (F''') without considering *G. puncticulata.* This one (F''') seems to have the best correlation with the carbonate curve.

Subpolar assemblage: We maintained the three species used in the upper test intervals, and added *Globigerina apertura* (absent in the Quaternary, presumably behaving as *G. bulloides*). Reference is made to the previous discussion for the problem of *G. puncticulata.*

Gyre margin assemblage: The only species maintained are *Globigerinoides sacculifer* and *Pulleniatina obliquiloculata,* both extremely rare in this interval. *Globorotalia inflata* has been replaced by *G. puncticulata,* and *G. menardii* by the group of keeled *Globorotalia* (*G. miocenica, G. exilis, G. multicamerata,* etc.).

Polar assemblage: Not recorded.

All the taxa used as climatic indicators for test interval 3 and not recorded, or not used in the higher test-intervals are illustrated with SEM photographs in Plates 3 and 4.

The data recorded from Sections 21-5 to 23-1 are shown in Figure 9. A positive correlation of the carbonate curve (A) with the tropical assemblage curve (B) is clearly expressed. The curves of the subtropical (C) and subpolar (D) assemblages were created in two ways, as previously discussed. Since *Globorotalia puncticulata* displays strongly variable abundances in this interval, with peaks in excess of 30 per cent in Sections 22-2 and 22-4 (24% in 23-1), the resulting curves are also strongly different, with opposite trends. The gyre margin assemblage (E) is also dominated by *G. puncticulata.* The curves where this taxon is used as an element of the subpolar assemblage are considered more realistic.

Figure 10 compares the carbonate curve (A), the faunal signal (F), and the relative abundance of the gyre margin assemblage (E) as recorded in test interval 3. Curve F has been constructed in three ways: F' with *G. puncticulata* as a member of the subpolar assemblage; F'' with *G. puncticulata* as a member of the subtropical assemblage; and F''' without *G. puncticulata* altogether.

Figure 11 compares the mean diameter of *Orbulina universa* (column one) with the maximum diameter (column two, notice change of scale) and with the carbonate curve (column three). The first two curves correlate positively, especially in the later (upper) part of the test interval. A sharp difference in behavior between the *Orbulina* size (mean and maximum diameter) and the carbonate content is recorded near the transition from Cores 22 to 21. In the upper part, the correlation is negative, as it was in the lower part of test interval 2 (see Figure 7); in the lower part, no correlation is evident. It is noteworthy that at approximately the same level, a strong shift is recorded in the carbon isotopic signal, with a strong upwards increase in the isotopic signal. This is interpreted by Shackleton (in Shackleton and Cita, this volume) as a response to increased forestation on the continent (pluvial).

Figure 12 compares the mean diameter of *O. universa* (column one) with the relative abundance of members of the subpolar assemblage (with *Globorotalia puncticulata,* column two). The correlation of the two curves is almost perfect. The third column plots the faunal signal, also constructed with *G. puncticulata* as a subpolar element (F'). The negative correlation with the first two curves is excellent. Curve F''', constructed without *G. puncticulata,* also shows a negative correlation with the mean diameter of the *Orbulina universa* curve.

The last column in Figure 12 plots the $\delta^{18}O$ values recorded in test interval 3 (after Shackleton and Cita, this volume). Only a few data points are available, so the correlation cannot be perfect. However, a positive correlation with the faunal signal and a negative correlation

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[2] In classical works on Pleistocene micropaleontology, however, *G. inflata* was consistently considered as a cool indicator (see for instance Parker, 1958), also with reference to its present-day distribution (Bé and Tolderlund, 1971).

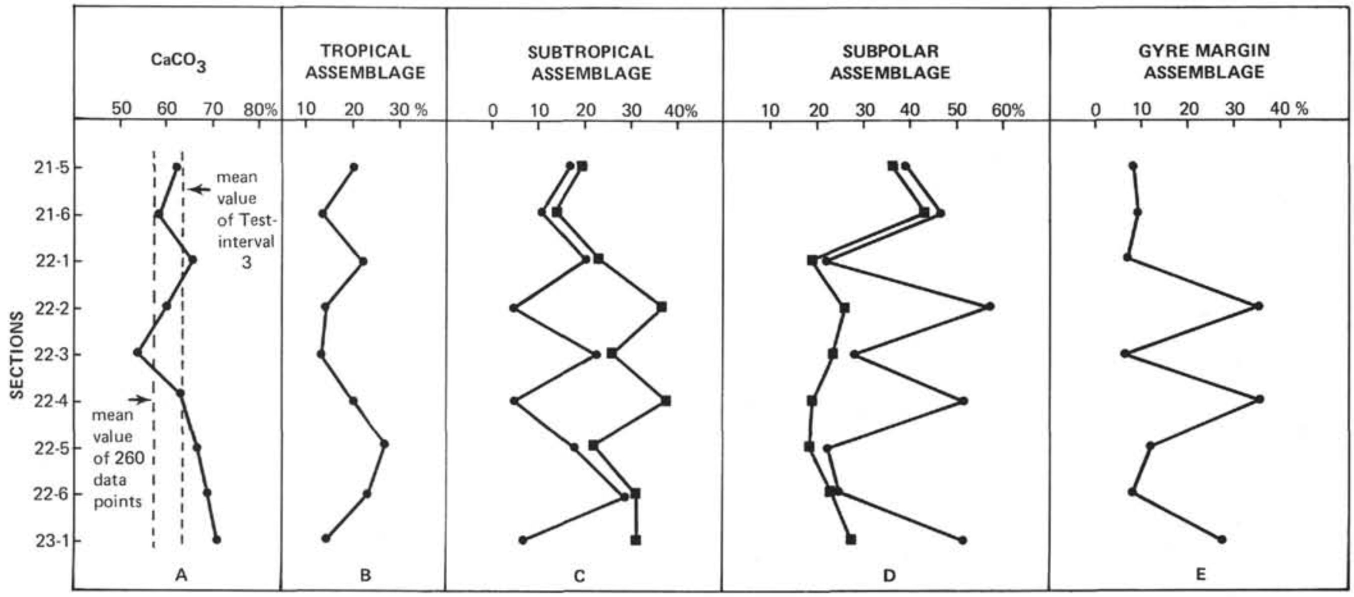

Figure 9. *Changes in percentages recorded in (A) carbonate content, (B) tropical assemblage, (C) subtropical assemblage, (D) subpolar assemblage, and (E) gyre margin assemblage in nine samples from Sections 21-5 to 23-1 (test interval 3). In columns (C) and (D), the solid line is constructed considering* Globorotalia puncticulata *as a member of the subpolar assemblage, whereas the dashed line is constructed considering this same taxon as a member of the subtropical assemblage.*

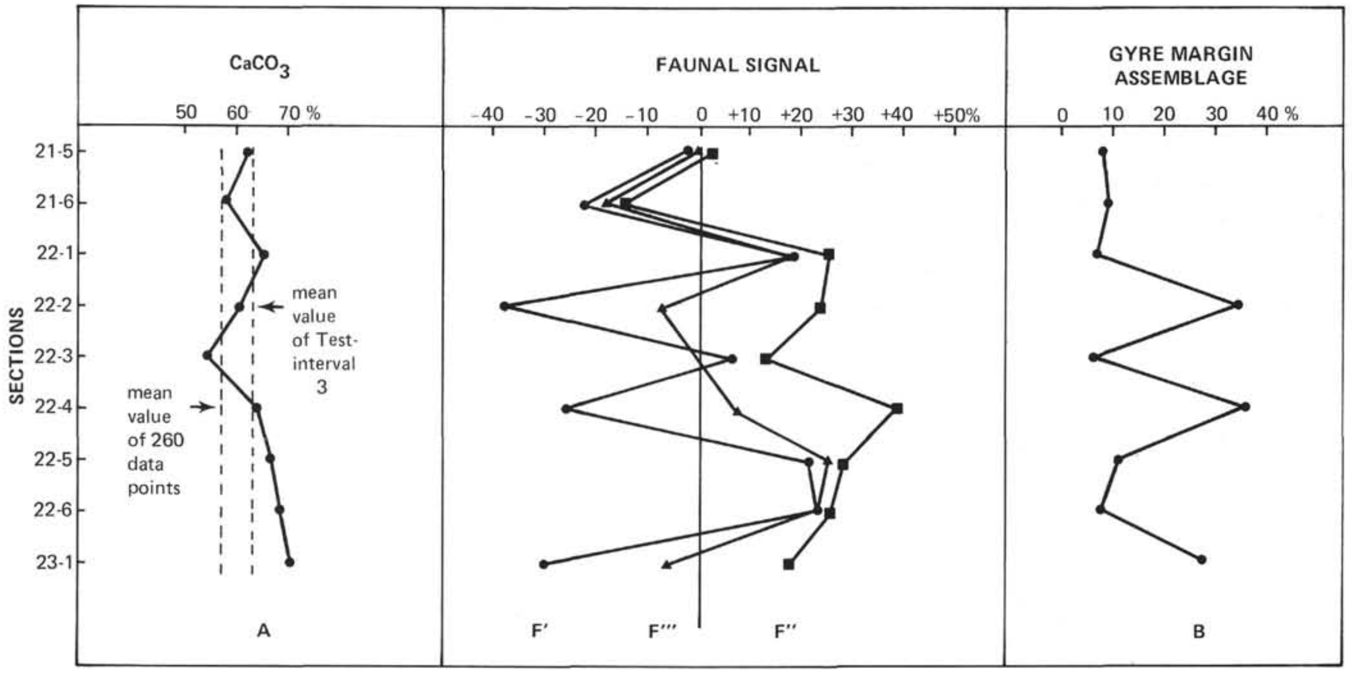

Figure 10. *Changes in percentages of (A) carbonate content, and (B) gyre margin assemblage in the same nine samples considered in Figure 9. The faunal signal (F) is the sum of the tropical assemblage (B), plus the subtropical assemblage (C), minus the subpolar assemblage (D), as plotted in Figure 9. (F') considers* Globorotalia puncticulata *as a member of the subpolar assemblage; (F'') considers the same species as a member of the subtropical assemblage, as discussed in the text; (F''') is constructed without consideration of* G. puncticulata.

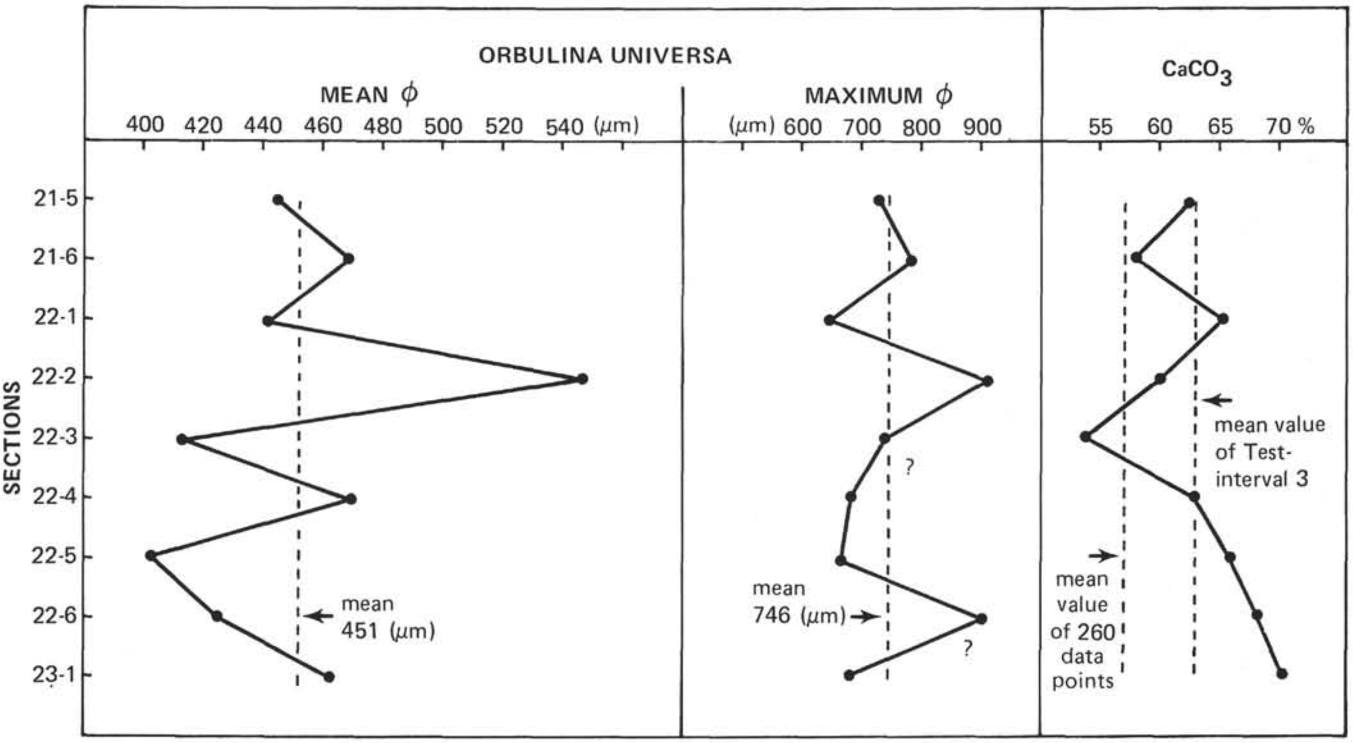

Figure 11. *Plot of the mean value of the last chamber diameter measured in* Orbulina universa *versus the maximum diameter (notice change of scale) and versus the carbonate content in the nine samples of test interval 3.*

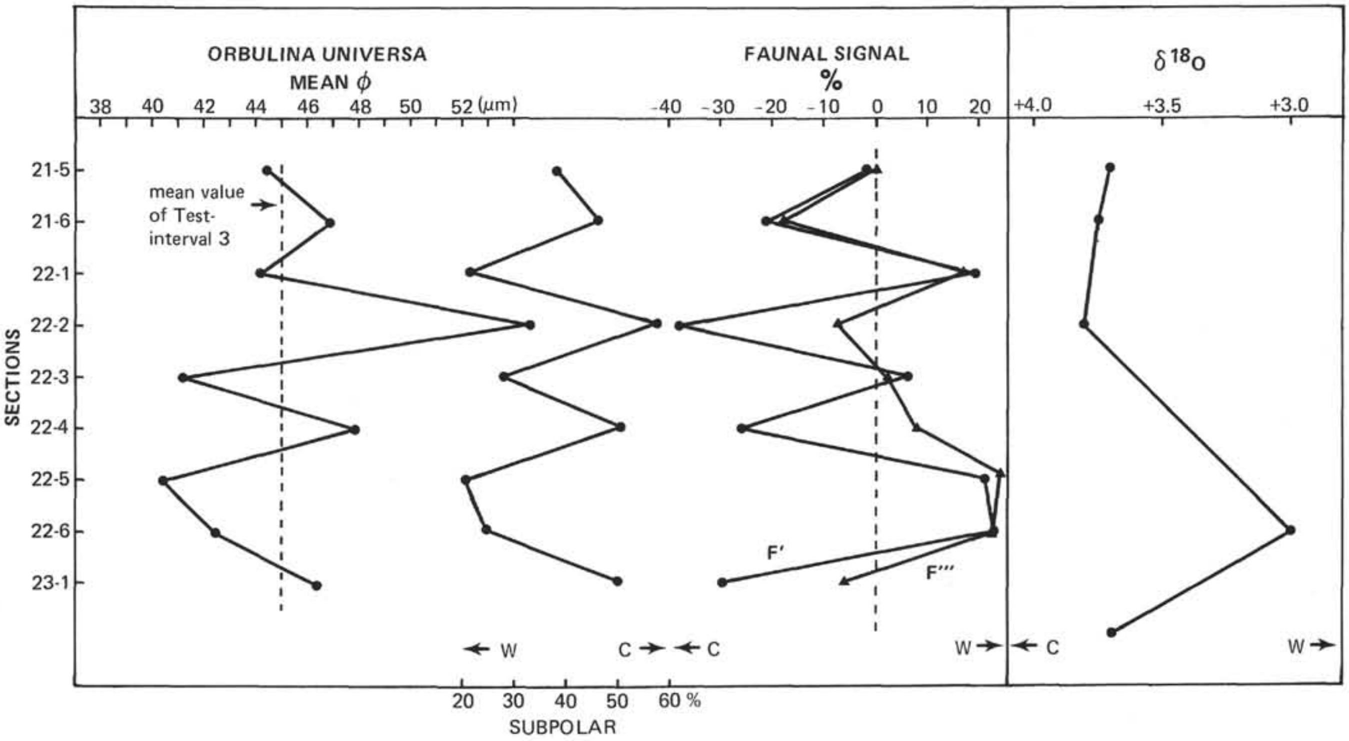

Figure 12. *Correlation of the mean diameter of* Orbulina universa, *percentage of subpolar assemblage, faunal signal (with* Globorotalia puncticulata *considered as a member of the subpolar assemblage [F'] and without* G. puncticulata *[F''']) and isotopic signal (after Shackleton and Cita, this volume) in the nine samples from test interval 3.*

with the curves plotting the mean diameter of *Orbulina universa* is apparent, as is the relative abundance of the subpolar assemblage (always with *G. puncticulata*).

Test Interval 4

Procedure A had to be further modified for the early Pliocene test interval 4 (*Globigerina nepenthes* interval zone of Salvatorini and Cita, this volume). The modification was necessitated by the disappearance of several test interval 3 species, including *Globorotalia crassaformis, G. aemiliana, G. hirsuta,* and *G. puncticulata.* All these species belong to the gyre margin assemblage and to either the subtropical or to the subpolar ones (see previous discussion). Sparse or altogether absent in this fourth test interval are additional elements of the subtropical assemblage such as *Pulleniatina obliquiloculata, Globigerina falconensis, Globigerinoides gomitulus,* and *G. elongatus.*

We introduced the following taxa as substitutes of the species stratigraphically excluded:

Globorotalia margaritae s.l. (including the subspecies *G. margaritae margaritae, G. margaritae primitiva,* and *G. margaritae evoluta*)

Subtropical and gyre margin. The reason for this substitution is the latitudinal distribution of the species, which is widely distributed at middle and low latitudes (being originally described from the Caribbean), as well as its shape, which resembles that of the extant *G. hirsuta.*

Globigerina nepenthes is considered as an element of the tropical assemblage. The species, originally described from the subequatorial Pacific, is widely distributed at low latitudes and appears to be climatically controlled at medium latitudes.

Globoquadrina altispira is considered an element of the tropical assemblage, along with *Sphaeroidinellopsis seminulina, S. subdehiscens,* and *Sphaeroidinella dehiscens.* All these taxa were also present in test interval 3, but have not been used to construct the faunal curves there, although counted. Their relative abundance was too small to be statistically significant. Since they were represented by fairly abundant specimens here, we used them to build the curve of tropical elements.

In summary, the species used in test interval 4 are as follows:

Tropical assemblage:
- *Globigerinoides obliquus extremus*
- *G. ruber*
- *G. sacculifer*
- *Hastigerina siphonifera*
- *Globorotalia menardii* and associated (*G. miocenica, G. limbata*)
- *Globigerina nepenthes*
- *Globoquadrina altispira*
- *Sphaeroidinellopsis seminulina* and related forms

Subtropical assemblage:
- *Globorotalia margaritae* s. l.
- *Globigerina falconensis*
- *Globigerinoides conglobatus*

Subpolar assemblage:
- *Globigerina bulloides*
- *G. apertura*
- *G. pachyderma* dextral
- *Globigerinita glutinata*

Gyre margin assemblage:
- *Globigerinoides sacculifer*
- *Globorotalia margaritae*
- *G. menardii* and associated forms

Polar assemblage:
- Not represented.

Globorotalia margaritae (Plate 5, Figures 4-6) is an important foraminiferal constituent in test interval 4, along with *Globigerinoides obliquus extremus:* both species reach percentages > 24 per cent in some samples from the upper part of the interval.

Globigerina pachyderma (Plate 5, Figures 12-14) is still recorded, though not so abundantly as in the Quaternary. This species has a wider stratigraphic range in the open ocean than in the Mediterranean, where it first appears in the latest Pliocene.

Specimens belonging to taxa not considered climatically significant are fairly abundant in test interval 4, representing more than 20 per cent in all samples except Section 39-2. The maximum percentage of "other species" (55%) is recorded in Section 39-2. The best represented species of this group is *Globorotalia acostaensis* which we did not use as a climatic indicator because of the many ambiguities concerning its significances. Originally described from a tropical area (Venezuela), the species has a wide geographic distribution in low and middle latitudes, including temperate to cool areas. Its presence in the Mediterranean during times of restricted circulation suggests its tolerance to stress conditions (Cita et al., 1978). Besides originating the phyletic lineage leading to *G. humerosa* via *G. humerosa praehumerosa* (see Salvatorini and Cita, this volume), we considered it likely that *G. acostaensis* also gave rise to *G. pachyderma.*

Globigerinoides ruber is poorly represented in all samples from test interval 4. We think that *Globigerinoides obliquus extremus,* which is very abundant here with percentages up to 24 per cent, occupied the ecologic niche that was subsequently populated by *G. ruber* and other extant species.

In test interval 4, we noticed for the first time evidence of dissolution at depth. This might act as a disturbing factor on the foraminiferal climatic message. In the lowermost sample from Core 38 (38-6, 50-52 cm), the sediment fraction >200 μm was so small that we counted all the specimens in the sample (278) without reaching the number usually used in this investigation. Also, we counted all (553) the specimens present in Sample 39-3, 50-55 cm.

The relative abundance of *Globigerina nepenthes* and of representatives of the genus *Sphaeroidinellopsis* is very high in these two samples (12.2% in Section 38-6 and 29.0% in Section 39-3, *G. nepenthes;* 10.9% in Section 39-3, *Sphaeroidinellopsis* spp.). Since all these forms have been used as members of the tropical assemblage, they are responsible for the very high tropical signal in these samples (see second column in Figure 13). Both *G. nepenthes* and *Sphaeroidinellopsis* are known as species highly resistant to solution. Therefore, we believe that the faunal signal of the lower part of test interval 4 is overestimated, inasmuch as *Globigerina pachyderma* disappears at this point of the stratigraphic column.

Figure 13 compares the carbonate curve (A) with the tropical (B), subtropical (C), subpolar (D), and gyre margin (E) assemblage curves. The positive correlation between carbonate curve and tropical assemblage curve consistently recorded in all test intervals is here limited to Core 38. In Core 39, dissolution at depth interacts in two ways: it decreases the carbonates and increases the relative abundance of some solution-resistant taxa here considered as tropical elements (*Globigerina nepenthes, Sphaeroidinellopsis* spp.). The high signal of the gyre margin assemblage (curve [E] in Figures 13 and 14) in the three first samples of test interval 4 is attributable to *Globorotalia margaritae.*

The faunal signal (F) of Figure 14 is less disturbed by the dissolution "noise"; essentially, the lower three data points are not well correlated with the carbonate curve.

Figure 15, plotting the measurements on the size of *Orbulina universa,* is interesting because it shows a fairly clear positive correlation between carbonate curve and mean diameter. The negative correlation of the mean diameter curve with the subpolar assemblage curve is less convincing. The low values recorded in the lowest samples are attributable to dissolution at depth. Indeed, the large specimens of *Orbulina* are thin shelled and display large pores; thus, they easily disaggregate when subject to undersaturated waters. The average values (of mean and maximum diameter) for test interval 4 are also affected by the dissolution "noise."

Figure 16 shows a good correlation of the isotopic signal and faunal signal. The only exception is Section 39-3, where the tropical assemblage is overestimated as a result of dissolution effects. Changes recorded in the maximum diameter of *O. universa* are at the noise level, and are not considered climatically meaningful in this test interval.

Comparison Among the Four Test Intervals and General Discussion

Some of the parameters considered and previously discussed for each discrete interval are plotted together in Figures 17 and 18.

The relative abundance of the subpolar assemblage (A) in Figure 17 clearly shows that the climatic cycles recorded in the Quaternary (test intervals 1 and 2) are wider in amplitude and longer in duration than those of the Pliocene (test intervals 3 and 4). The maximum excursion is recorded in test interval 1 (from 5% in Section 2-5 to 49% in Section 2-3).

The tropical assemblage (B), which is poorly represented in test intervals 1 and 2, is much more abundant in test interval 3. Indeed, the minimum values recorded there are consistently higher than the maximum values recorded in test intervals 1 and 2. This result is in good agreement with the indications given by the carbonates (Cita and Spezzibottiani, this volume) and by the stable isotopes (Shackleton and Cita, this volume). Both suggest higher paleotemperatures in the Pliocene than in the Quaternary and less-pronounced cyclic variations (see Figure 18, column D).

The variations recorded in the mean diameter of *Orbulina universa* are comparable in magnitude as well as in frequency in the four test intervals. This parameter correlates positively with the relative abundance of the subpolar assemblage in test interval 3, whereas it tends to correlate negatively in the Quaternary.

The mean size of *O. universa* steadily increases from test intervals 1 through 3. The mean value of the mean

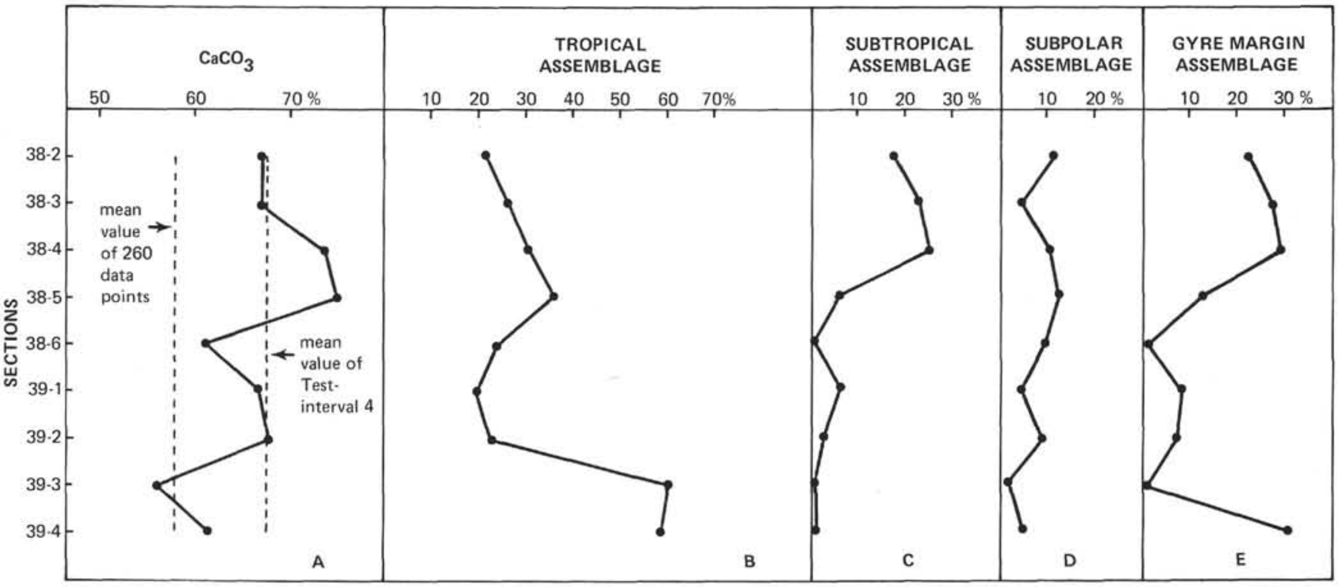

Figure 13. *Changes in percentages recorded in (A) carbonate content, (B) tropical assemblage, (C) subtropical assemblage, (D) subpolar assemblage, and (E) gyre margin assemblage in nine samples from Cores 38 and 39, Site 397.*

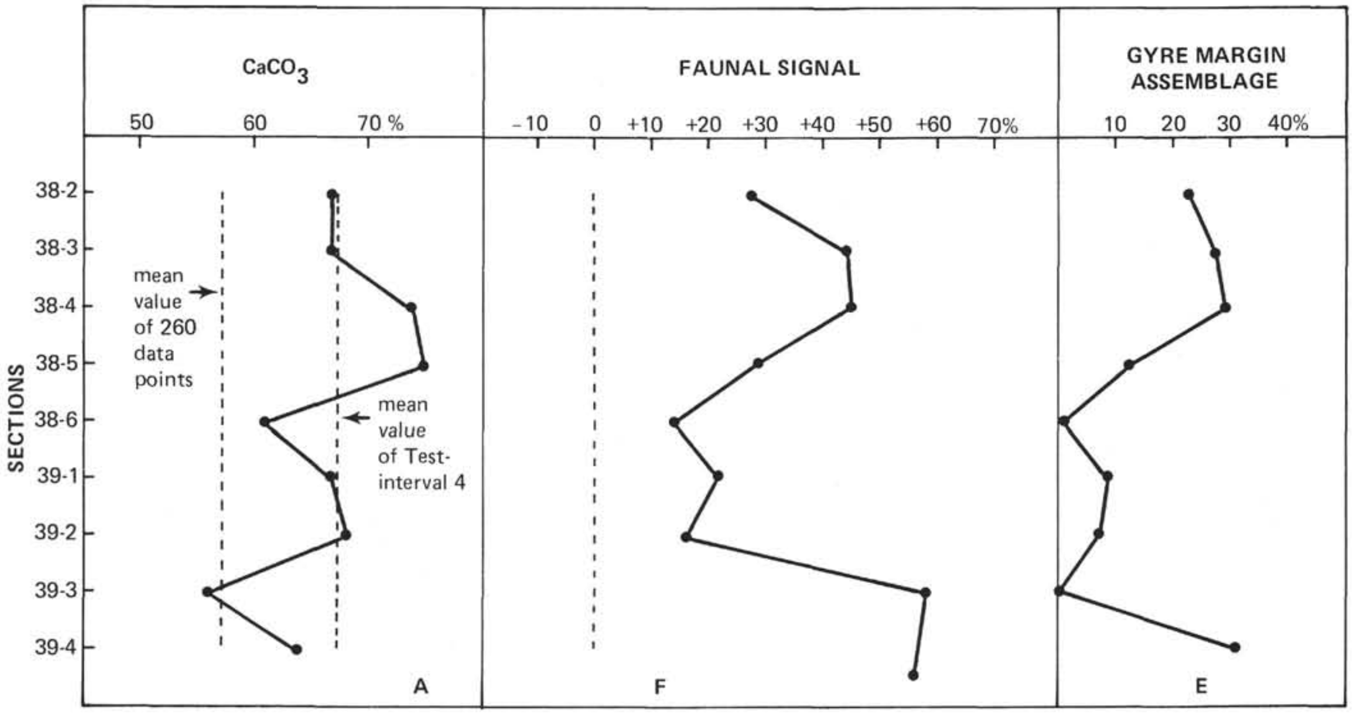

Figure 14. *Changes in percentages of (A) carbonate content, (E) gyre margin assemblage, and (F) faunal signal. (F) is the sum of the tropical assemblage (B), plus the subtropical assemblage (C), minus the subpolar assemblage (D), as plotted in Figure 13.*

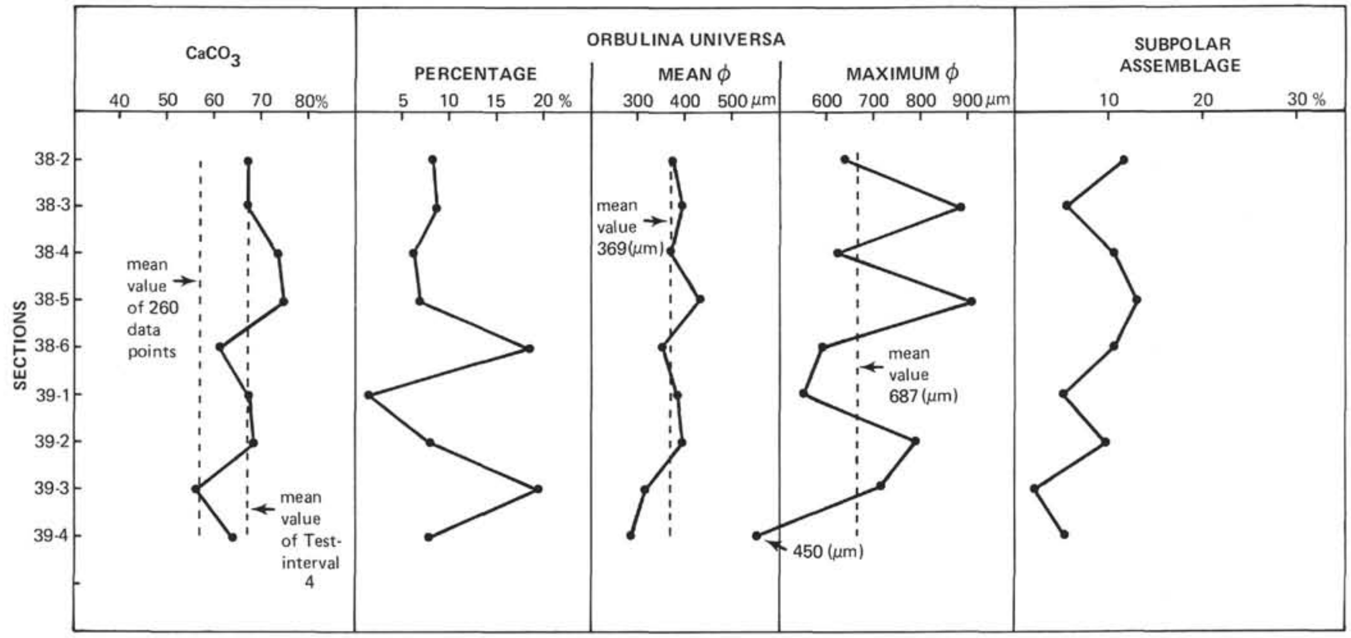

Figure 15. *Changes in percentages of carbonates (column one), of* Orbulina universa *(column two) and subpolar assemblage (column three). The two remaining columns plot the mean and maximum diameter measured in* O. universa.

diameter is 430 µm in test interval 1, 432 µm in test interval 2, and 451 µm in test interval 3. Also, the mean value of the maximum diameter steadily increases from test interval 1 (623 µm) to test interval 2 (655 µm) to test interval 3 (746 µm); see Table 1. The lower values recorded in test interval 4 (mean of mean diameters = 369 µm; mean of maximum diameter = 678 µm) is attributable to the disturbance induced by dissolution at depth.

The faunal signal (Column E of Figure 18) clearly shows the difference between the high amplitude, long, and pronounced cycles of the "glacial" Quaternary (test interval 1) and the small amplitude, shorter cycles of the

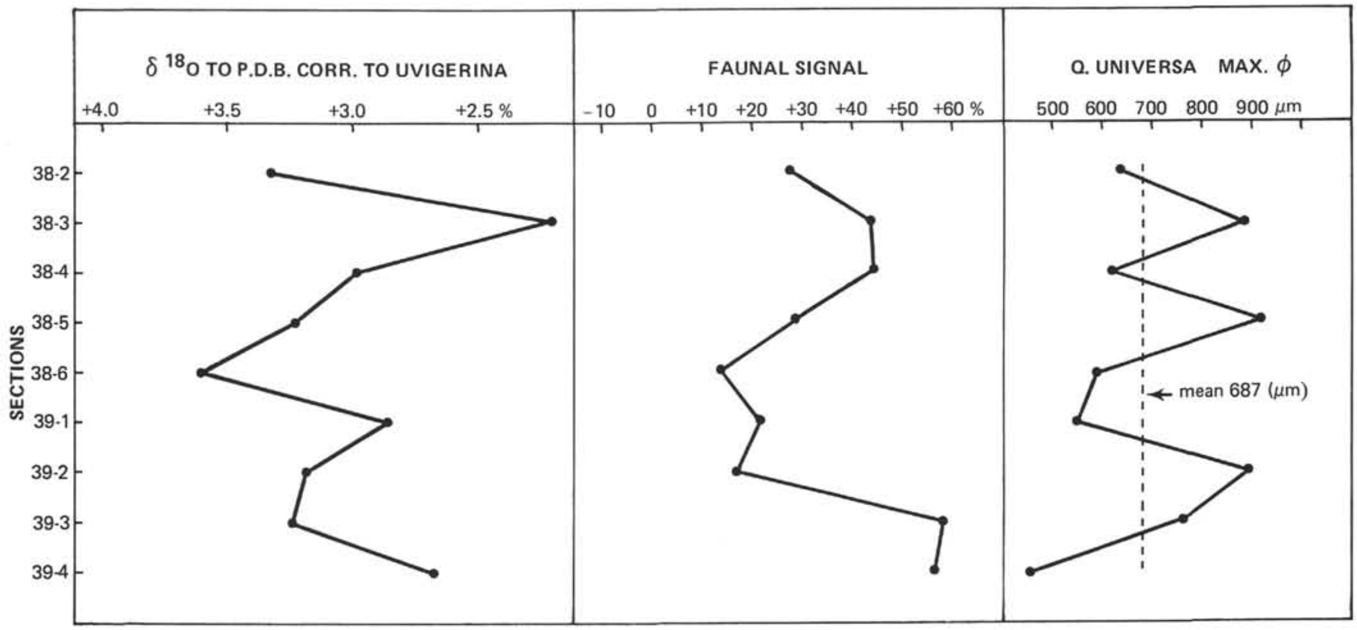

Figure 16. *Correlation between isotopic signal (after Shackleton, in Shackleton and Cita, this volume), faunal signal, and maximum diameter of* Orbulina universa *in test interval 4.*

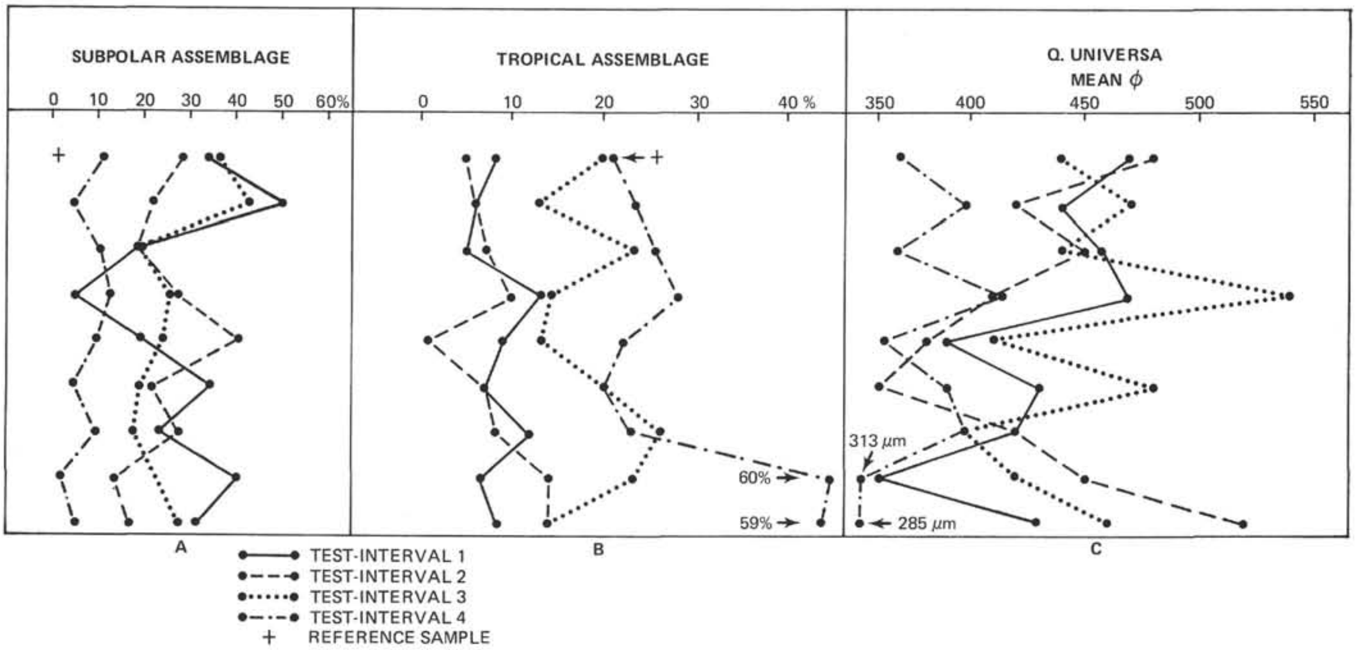

Figure 17. *Comparison of the trends shown by (A) relative abundance of taxa characteristic of the subpolar assemblage, (B) relative abundance of taxa characteristic of the tropical assemblage, and (C) mean diameter of the last-formed chamber of* Orbulina universa *in the four test intervals investigated quantitatively. See text for discussion.*

"pre-glacial" Quaternary (test interval 2). The pronounced cycles, however, are devoid of extreme values in the late Pliocene (test interval 3, see curve F''' of Figures 9 and 10). In the early Pliocene, these cycles are comparable in magnitude to those of the late Pliocene, but they indicate consistently warmer oceanic waters during that time (test interval 4).

SUMMARY OF MAJOR CONCLUSIONS

The results of our investigations on four selected test intervals ranging in age from the late Pleistocene to the early Pliocene can be summarized as follows:

1) It is possible to apply conventional techniques to extend the climatic record of the late Pleistocene back in

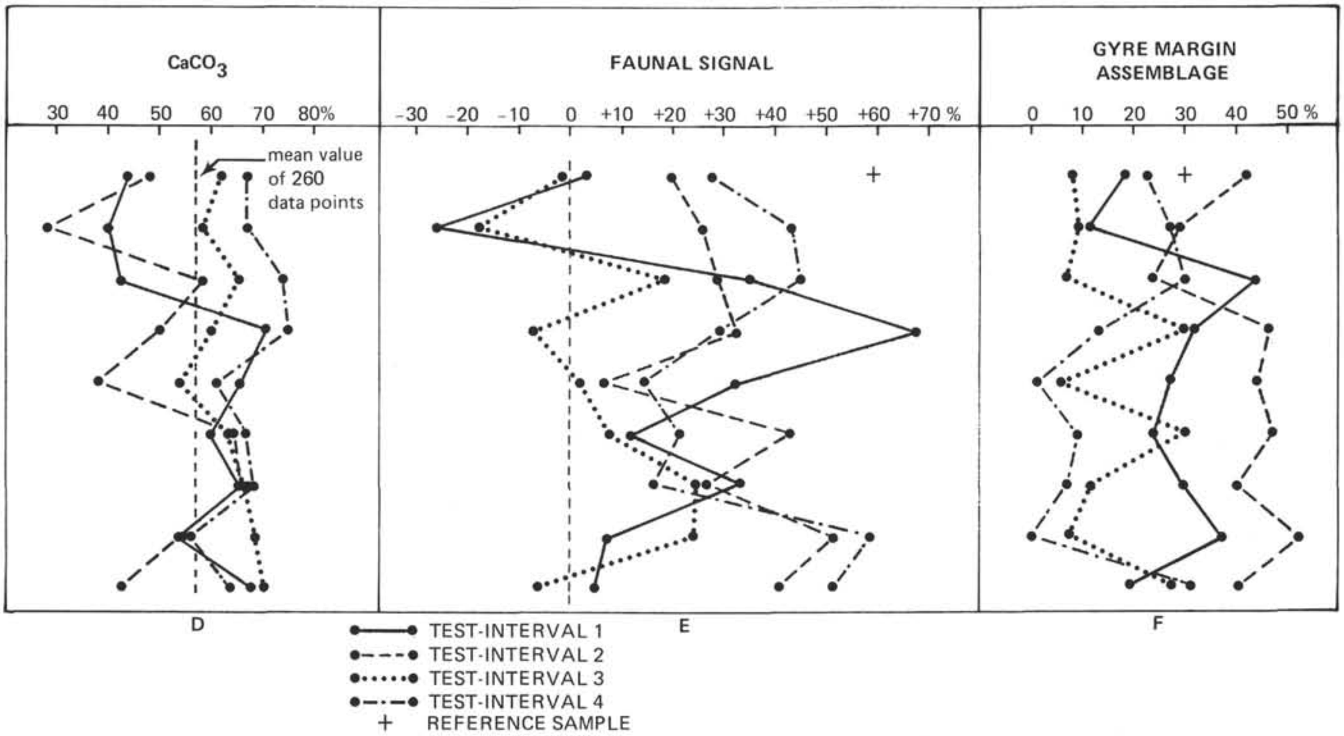

Figure 18. *Comparison of the trends shown by (D) carbonate content (%), (E) faunal signal (= subtropical assemblage % + tropical assemblage % - subpolar assemblage %), and (F) the relative abundance of taxa characteristic of the gyre margin assemblage in the four test intervals investigated. Discussion in text.*

TABLE 1
Variations Recorded in Averages of Mean and Maximum Diameter of *Orbulina universa* in the Four Test Intervals

Test Interval	Mean ϕ (μm)	Maximum ϕ (μm)
1	430	623
2	432	655
3	451	746
4	369	687

time by using substitute species for climatic indicators, which had not yet appeared in the fossil record.

2) The validity of our interpretations, and climatic faunal curves, is established by direct correlation with physical parameters such as carbonate content and composition in stable isotopes measured on benthic foraminifers from the same set of samples.

3) The average of the mean diameter of *Orbulina universa* steadily increases from test intervals 1 through 3, then it decreases in test interval 4. The latter record is attributable to dissolution at depth, which is obvious in Core 39, and eventually masks the climatic signal.

4) The correlation of the maximum diameter of *O. universa* with other variables considered here changes drastically from test interval 1 (late Pleistocene, Brunhes Epoch) to test interval 2 (early Pleistocene, Matuyama Epoch). Further investigations on intervening levels are planned to eventually understand the meaning of this change, which could be taxonomically significant.

5) A change in the trend of mean diameter of *O. universa* versus that of the carbonate curve is recorded in Core 22 (late Pliocene, Matuyama Epoch) at approximately the same level where a strong isotopic change is recorded (i.e., with isotopic ratios of carbon decreasing upwards).

6) *Globorotalia truncatulinoides* is dominantly dextral in most of the levels investigated from test intervals 1 and 2, however strong fluctuations in the coiling ratio are recorded. They are not obviously correlated with either temperature changes, or with the circulation pattern, as expressed by the relative abundance of the gyre margin faunal assemblage.

7) Climatic changes were recorded in all four test intervals. Taking into account the average distance between consecutive samples (1.5 m) and the average sedimentation rate (7 cm/1000 yr), the time between consecutive samples is approximately 20,000 years. As a consequence, only cycles longer than 20,000 years can be detected. Some of those recorded are much longer than this (approximately 100,000 years).

8) The subpolar assemblage tends to decrease from test intervals 1 through 4. Also decreasing downwards are the fluctuations recorded in its abundance.

9) By contrast, the tropical assemblage increases in abundance from the Pleistocene to the early Pliocene.

10) The gyre margin assemblage tends to decrease in abundance from test intervals 1 to 4, being particular-

ly well represented in test interval 2 and displaying strong fluctuations in test interval 3.

11) The faunal signal (sum of relative abundances of tropical assemblage + subtropical assemblage − subpolar assemblage) display very accentuated fluctuations in the late Pleistocene (test interval 1), less pronounced but evident fluctuations in the early Pleistocene (test interval 2) and the late Pliocene (test interval 3). A warming trend of superficial water masses is recorded in the early Pliocene (test interval 4).

12) Values of the faunal signal as high as or higher than the present one (reference sample) are recorded in a single level (Section 2-5) of the late Pleistocene, and in two levels from the early Pliocene.

13) This result is different from, but not contradictory to the results obtained from isotopic geochemistry. The investigations carried out on benthic foraminifers do not provide information on the paleotemperature of the superficial waters, but measure the glacial influx in ocean water. They indicate a steady decrease of this glacial influx in the early Pliocene. All but one of the data points from test interval 4 are isotopically lighter than the reference sample.

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PLATE 1

Representatives of the Subpolar (1-4); Polar (5, 6); and Gyre Margin (7, 8) Assemblages From Test Intervals 1 and 2

Figure 1	*Globigerina pachyderma* (Ehrenberg), spiral view, Sample 3-4, 50 cm.
Figure 2	*Globigerina pachyderma* (Ehrenberg), umbilical view, Sample 3-4, 50 cm.
Figure 3	*Globigerina bulloides* d'Orbigny, umbilical view. Sample 2-4, 50 cm.
Figure 4	*Globigerinita glutinata* (Egger), umbilical view. Sample 7-6, 50 cm.
Figure 5	*Globigerina pachyderma* (Ehrenberg), left-coiling specimen in spiral view. Sample 7-6, 50 cm.
Figure 6	As above, in umbilical view.
Figure 7	*Globigerinoides tenellus* Parker, umbilical view. Sample 3-2, 50 cm.
Figure 8	As above, in spiral view. Sample 2-4, 50 cm.

PLATE 1

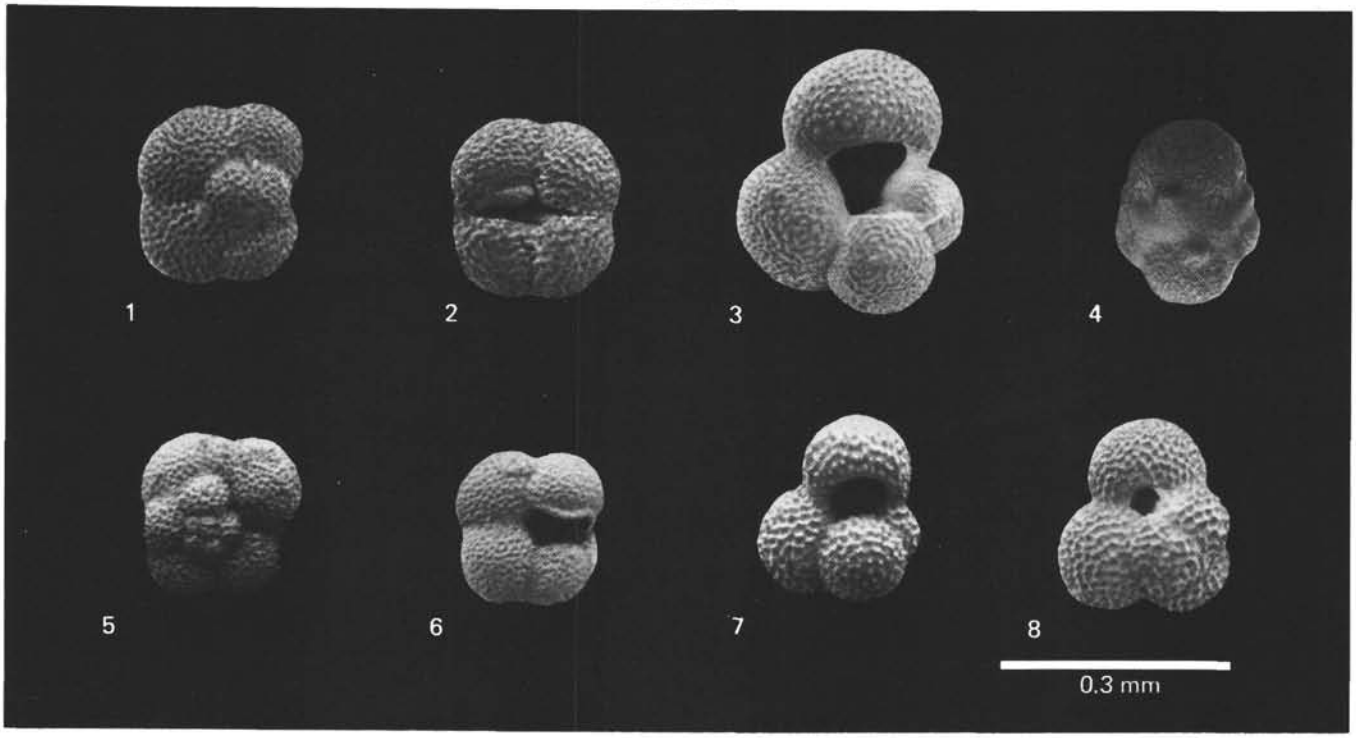

PLATE 2

Representatives of the Tropical Assemblage (1-11, above) and of the Subtropical Assemblage (1-10, below) From Test Intervals 1 and 2

Tropical Assemblage

Figure 1	*Globigerinoides ruber* (d'Orbigny), umbilical view. Sample 2-6, 50 cm.
Figure 2	As above, in spiral view. Sample 2-5, 50 cm.
Figure 3	*Globigerinoides gomitulus* (Seguenza), umbilical view. Sample 2-6, 50 cm.
Figure 4	As above, in spiral view. Sample 2-3, 50 cm.
Figure 5	*Globorotalia menardii* (d'Orbigny), umbilical view. Sample 9-1, 50 cm.
Figure 6	*Hastigerina siphonifera* (d'Orbigny), side view. Sample 2-4, 50 cm.
Figure 7	As above, apertural view. Sample 2-2, 50 cm.
Figure 8	*Globigerinoides sacculifer* (Brady), umbilical view. Sample 1-1, 10 cm.
Figure 9	As above, spiral view. Sample 9-1, 50 cm.
Figure 10	*Pulleniatina obliguiloculata* (Parker and Jones), apertural view. Sample 9-2, 50 cm.
Figure 11	As above, side view. Sample 9-1, 50 cm.

Subtropical Assemblage

Figure 1	*Globorotalia truncatulinoides* (d'Orb.), umbilical view. Sample 2-5, 50 cm.
Figure 2	As above, spiral view, same sample.
Figure 3	As above, apertural view, same sample.
Figure 4	*Globigerina calida* Parker, umbilical view. Sample 3-2, 50 cm.
Figure 5	As above, umbilical view. Sample 1-1, 10 cm.
Figure 6	*Globorotalia inflata* (d'Orbigny), umbilical view. Sample 2-4, 50 cm.
Figure 7	As above, spiral view, same sample.
Figure 8	As above, apertural view, same sample.
Figure 9	*Globigerina falconensis* Blow, umbilical view. Sample 3-1, 50 cm.
Figure 10	As above, umbilical view. Sample 3-2, 50 cm.

PLATE 2

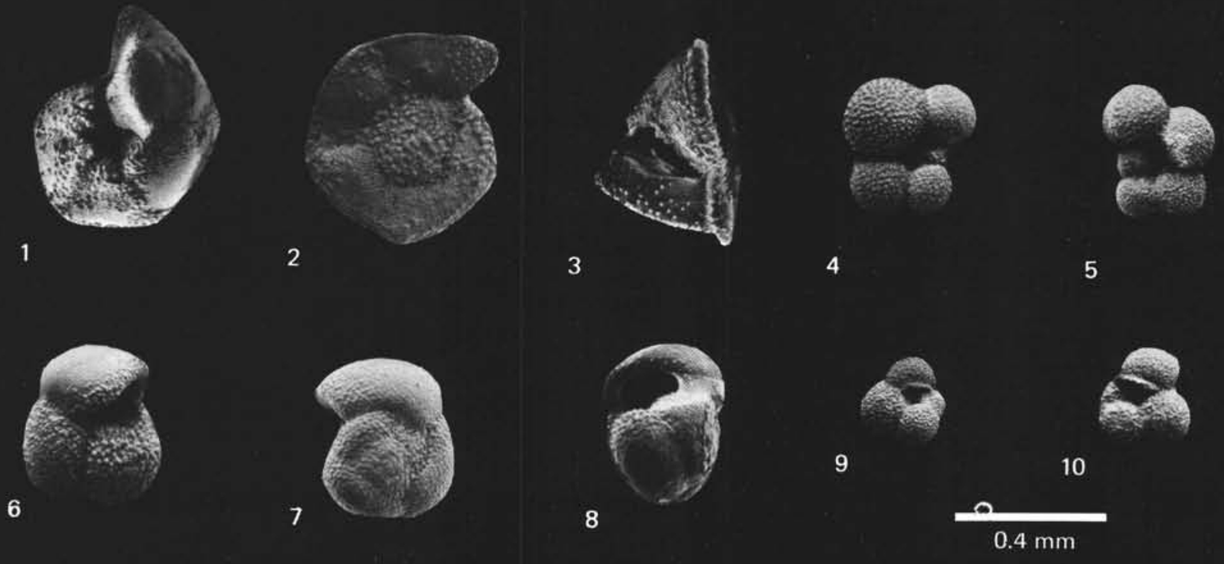

PLATE 3

Representatives of the Tropical (1-10) and Subtropical (11-18) Assemblages in Test Interval 3

Figure 1	*Globorotalia limbata* (Fornasini ex d'Orbigny), spiral view. Sample 22-5, 50 cm.
Figure 2	As above, apertural view, same sample.
Figure 3	*Globorotalia multicamerata* Cushman and Jarvis, umbilical view. Sample 22-5, 50 cm.
Figure 4	As above, spiral view. Sample 22-6, 50 cm.
Figure 5	As above, apertural view. Sample 22-5, 50 cm.
Figure 6	*Globorotalia exilis* Blow, spiral view. Sample 22-1, 50 cm.
Figure 7	*Globorotalia miocenica* Palmer, apertural view. Sample 22-6, 50 cm.
Figure 8	As above, umbilical view. Sample 22-5, 50 cm.
Figure 9	As above, spiral view, same sample.
Figure 10	As above, apertural view. Sample 22-1, 50 cm.
Figure 11	*Globigerinoides conglobatus* (Brady), umbilical view. Sample 23-1, 50 cm.
Figure 12	*Globorotalia crassaformis* (Galloway and Wissler), apertural view. Sample 22-5, 50 cm.
Figure 13	As above, spiral view. Sample 22-6, 50 cm.
Figure 14	As above, umbilical view. Sample 23-1, 50 cm.
Figure 15	*Globigerinoides conglobatus* (Brady), spiral view. Sample 23-1, 50 cm.
Figure 16	*Globorotalia hirsuta* (d'Orbigny), apertural view. Sample 21-5, 50 cm.
Figure 17	As above, spiral view, same sample.
Figure 18	As above, umbilical view, same sample.

PLATE 3

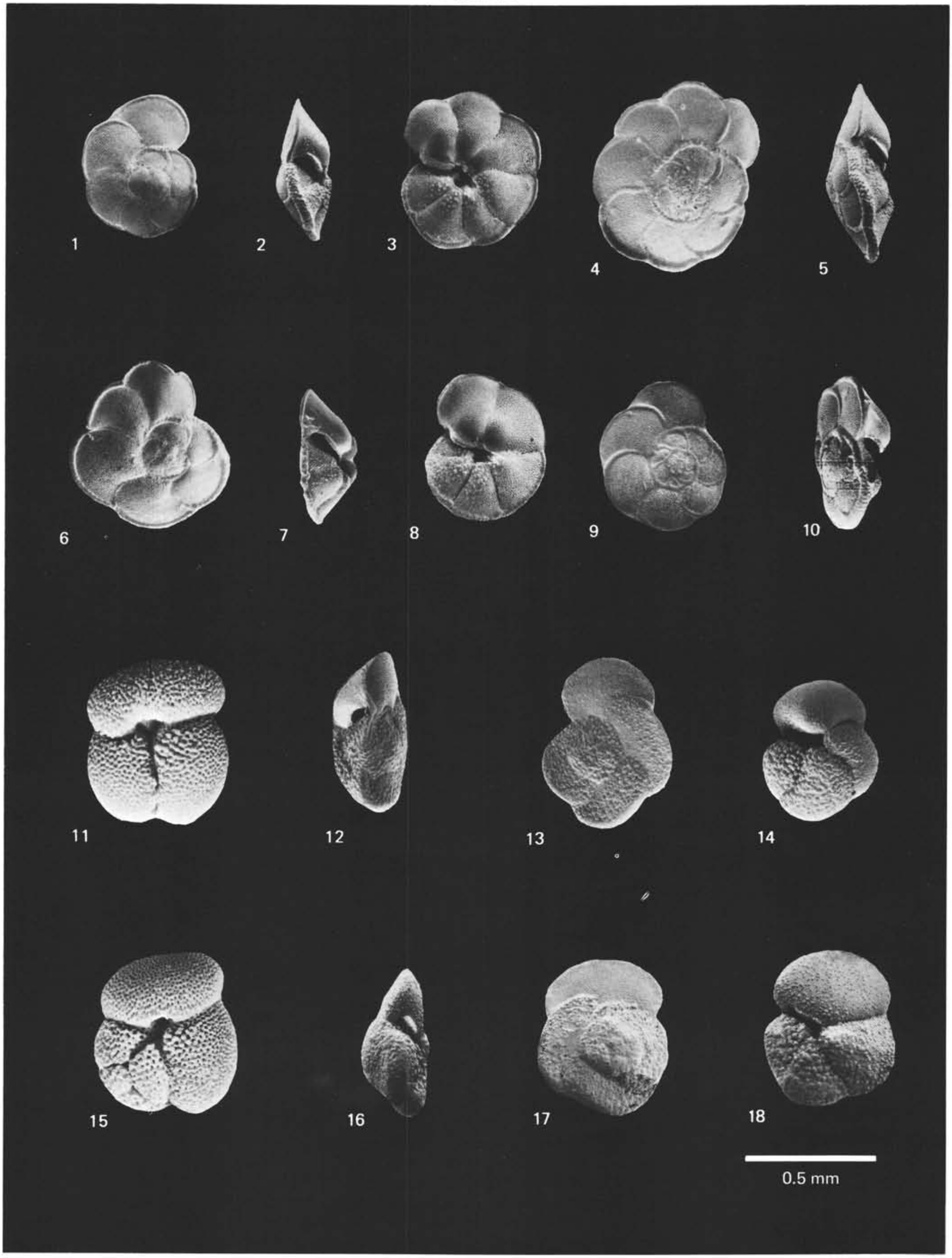

PLATE 4

Representatives of the Tropical (1-3), Subpolar (4), and Subtropical (8-10) Assemblages in Test Interval 3 (for the paleoclimatic significance of *Globorotalia puncticulata* [5-7], see discussion in text)

Figure 1	*Globigerinoides obliquus extremus* Bolli, umbilical view. Sample 23-1, 50 cm.
Figure 2	*Globorotalia cultrata menardii* (Parker, Jones, and Brady), umbilical view. Sample 23-1, 50 cm.
Figure 3	*Globigerinoides obliquus extremus* Bolli, spiral view. Sample 22-5, 50 cm.
Figure 4	*Globigerina apertura* Cushman, umbilical view. Sample 22-2, 50 cm.
Figure 5	*Globorotalia puncticulata* (Deshayes), spiral view. Sample 22-2, 50 cm.
Figure 6	As above, umbilical view, same sample.
Figure 7	As above, apertural view, same sample.
Figure 8	*Globorotalia aemiliana* Colalongo and Sartoni, spiral view. Sample 21-5, 50 cm.
Figure 9	As above, umbilical view, same sample.
Figure 10	As above, apertural view, same sample.

PLATE 4


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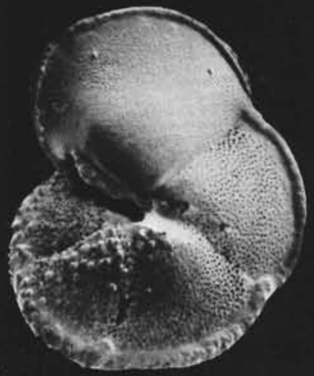
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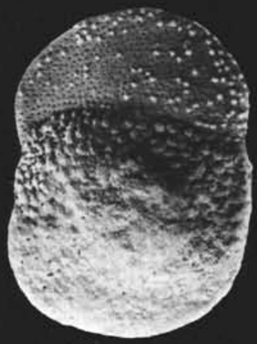
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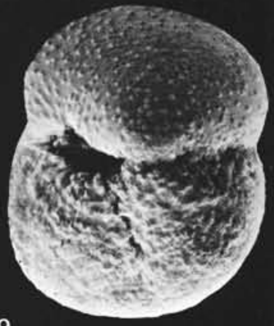
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PLATE 5

Representatives of the Tropical (1-3, 7-11), Subtropical (4-6), and Subpolar (12-14) Assemblages in Test Interval 4

Figure 1	*Globoquadrina altispira*, umbilical view. Sample 38-5, 50 cm.
Figure 2	As above, side view, same sample.
Figure 3	*Sphaeroidinellopsis seminulina* (Schwager), umbilical view. Sample 39-3, 50 cm.
Figure 4	*Globorotalia margaritae* Bolli and Bermudez, umbilical view. Sample 38-4, 50 cm.
Figure 5	As above, spiral view, same sample.
Figure 6	As above, apertural view, same sample.
Figure 7	*Sphaeroidinellopsis subdehiscens* Blow, umbilical view. Sample 39-3, 50 cm.
Figure 8	*Globigerina nepenthes* Todd, umbilical view. Sample 39-3, 50 cm.
Figure 9	As above, umbilical view, same sample.
Figure 10	As above, umbilical view. Sample 38-6, 50 cm.
Figure 11	*Sphaeroidinella dehiscens* Parker and Jones, side view. Sample 39-3, 50 cm.
Figure 12	*Globigerina pachyderma* (Ehrenberg), spiral view. Sample 39-2, 50 cm.
Figure 13	As above, umbilical view, same sample.
Figure 14	As above, spiral view, same sample.

PLATE 5