COMPARISON WITH RESULTS FROM THE DEEP SEA

The Palaeogene/Neogene Boundary in the equatorial Pacific Ocean (Fig. 1—5; Pl. 46—50). (G. Keller).

Abstract. Planktic foraminiferal datum events and assemblage changes have been investigated across the Palaeogene/Neogene boundary in the equatorial and subtropical Pacific Ocean DSDP Sites 296, 292, 55, 289, 71, 77B and 495. Over 30 isochronous datum events have been identified in Zones P22 and N4 and tied to the paleomagnetic time scale.

Investigation of the proposed alternative datum planes for the Palaeogene/Neogene boundary, *Globorotalia kugleri* FAD and *Globoquadrina dehiscens* FAD, indicates that the latter datum may be preferable. The *Globoquadrina dehiscens* datum plane is associated with nine other planktic foraminiferal datum events. This major evolutionary pulse provides an easily recognizable datum plane even in the absence of the marker species. The *Globorotalia kugleri* datum plane, however, does not include reliable secondary datum events and is often associated with a short hiatus and increased carbonate dissolution making this a less desirable datum plane for the Palaeogene/Neogene boundary.

Revision of Blow (1969) Zones N4 and P22 are proposed to provide greater stratigraphic control: a) restrict Zone N4 to the range of *Globorotalia kugleri*, b) subdivide Zone N4 (emended) into subzones a, b and c based on FAD *Globigerinoides trilobus* s.l. and FAD *Globoquadrina dehiscens*, and c) subdivide Zone P22 into subzones a, b and c based on FAD *Globorotalia mendacis* and FAD *Globorotalia pseudo-kugleri*.

Introduction.

The stratigraphic position of the Palaeogene/Neogene boundary was set at the base of the stratotype Aquitanian (Chattian/Aquitanian boundary) by the Comité du Néogène in 1969. In the stratotype this interval is marked by the first occurrence of *Globigerinoides* (Jenkins, 1965) and hence the "*Globigeri-noides* datum" has since been recognized as marking the P/N boundary in planktic foraminiferal biostratigraphy. The *Globigerinoides* datum, however, has not proved to be an optimally useful datum because *Globigerinoides* is dissolution susceptible and the first evolutionary appearance (*Gs. primordius*) is now placed within the latest Oligocene (Lamb & Stainforth, 1976; Hardenbol & Berggren, 1978). Stratigraphers have therefore searched for other criteria to identify the P/N boundary and to provide a datum plane that can easily be recognized by workers of different microfossil groups. In recent years alternative datum planes have been investigated by the Working Group on the Palaeogene/ Neogene Boundary (IUGS) and proposals have been made to place the P/N boundary at the first appearance of *Globorotalia kugleri*, or at the first appearance of *Globoquadrina dehiscens* (see also Srinivasan & Kennett, 1981a; Keller, 1980; Berggren et al., in press). There are pros and cons for the *Globigerinoides* datum as well as the newly proposed alternative datum planes.

This report addresses the P/N boundary problem in teh equatorial and subtropical Pacific Ocean based on population studies of planktic foraminifers in DSDP Sites 296, 292, 289, 55, 71, 77B and 495 (Fig. 1). Earlier population

studies of Keller (1980, 1981a,b,c,d) and Srinivasan and Kennett (1981a,b) are summarized in addition to new data on Sites 292 and 77B (Oligocene) and Site 495. These sites combined represent an east-west transect across the equatorial Pacific Ocean and hence provide a unique opportunity to study faunal provincialism and to test isochroneity of datum events.

The main problems addressed in this study are: 1) stratigraphic succession of species across the P/N boundary, 2) isochroneity of datum events, 3) correlation of datum events to the paleomagnetic time scale, 4) revision of existing zonation to improve stratigraphic correlation, 5) recognition of faunal provincialism as determined by quantitative analyses, and 6) pros and cons for placing the P/N boundary at the *Globigerinoides* datum, FAD *Globoquadrina dehiscens* or FAD *Globorotalia kugleri*.

Datum Events across the Palaeogene/Neogene Boundary.

Stratigraphic succession of species across the P/N boundary is illustrated in Site 292 which represents one of the best preserved Oligocene to early Miocene sequences in the Pacific Ocean (Fig. 2). A complete sedimentary sequence
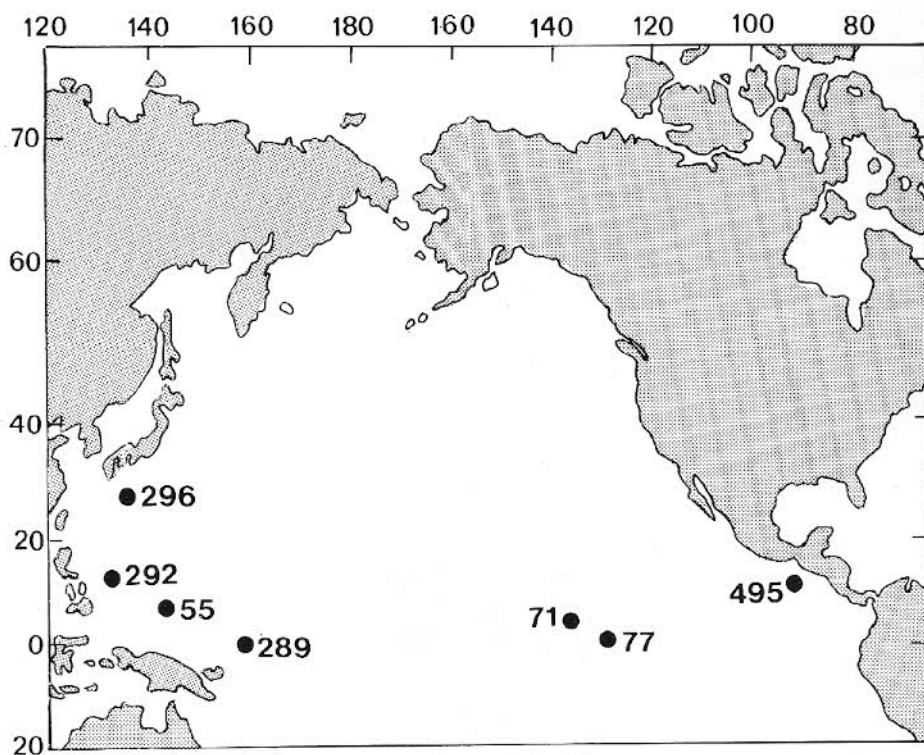

Fig. 1 — Location map of DSDP sites examined.

Table 1 — Planktic foraminiferal datum events in the equatorial Pacific.

Planktic Foraminifer Datum Events (age:Ma) Equatorial Pacific		296	292	55	289	77B	71	495	best age
FAD	*Gl. miozea*	19.2							19.2*
FAD	*Gl. praescitula*	19.5							19.5*
LAD	*Gl. acrostoma*	19.7							19.7*
FAD	*Gl. pseudomiozea*	19.9							19.9*
FAD	*Gl. birnagae*		19.9	21.2		20.5	20.0		unreliable
LAD	*Gs. primordius*		21.5	18.4	18.7		19.5	20.2	unreliable
LAD	*Gs. altiaperturus*			19.4	16.8		20.0		unreliable
FAD	*Sph. disjuncta*	21.0	20.2						21.0*
LAD	*Gl. kugleri*		20.1	20.1	20.2	20.4△	20.1	20.1	20.1
**	*Gg. angustiumbilicata*		20.6		20.5	20.6	20.5		20.6
FAD	*Gq. altispira*		20.7	20.7	20.7	20.8	20.6	20.6	20.7
**	*Gg. ciperoensis*		20.8	21.1		21.0	21.0		21.0
FAD	*Gs. quadrilobatus*		20.8	20.5	20.6				20.7
FAD	*Gs. sacculifer*		20.8	20.5	20.6			20.1	20.7
FAD	*Gs. altiaperturus*		21.0	20.9	21.0				21.0
FAD	*Gl. z. incognita*	21.0	21.1	21.1		20.8	21.0	21.3	21.1
FAD	*Gl. zealandica* ss		21.4	21.7		21.3	21.2		21.5
FAD	*Gq. dehiscens*	21.3	21.3	21.2	21.2	21.2	21.1	21.2	21.2
FAD	*Gl. acrostoma*		21.3	21.7	20.5	21.8	21.7		21.7
FAD	*Gg. bollii*		21.3	20.9	20.0			19.7	unreliable
FAD	*Gs. subquadratus*		21.3		21.6		21.0	20.2	21.6
FAD	*Gs. trilobus* ss	21.2	21.4			20.6△△	21.4		21.4
FAD	*Gg. parawoodi*		21.5	21.5					21.5
LAD	*Gl. mendacis*		21.4	21.7		21.2	21.0	21.1	21.1
**	*Gl. kugleri*		21.4	21.4	21.3	21.4	21.4	21.3	21.4
FAD	*Gs. sac. irregularis*		22.0						22.0
FAD	*Gs. tril. bullatus*		22.1				22.0		22.0
FAD	*Gs. tril. immaturus*		22.1		22.1		22.0		22.1
LAD	*Gl. pseudokugleri*		22.3			22.4	22.4	22.4	22.4
***	*Gl. kugleri*		22.2		22.1	22.2			22.2
FAD	*Gg. woodi*		22.8					21.2	unreliable
FAD	*Gl. kugleri*		23.6			23.6	23.2△	23.6	23.6
FAD	*Gg. connecta*	22.2	23.7			26.4			unreliable
FAD	*Gs. primordius*		23.7		22.4	20.6△△			unreliable
FAD	*Ga. glutinata*		24.7						?
FAD	*Gl. pseudokugleri*		24.7			24.8	23.2△		24.7
FAD	*Gq. praedehiscens*		26.5						?
FAD	*Gl. mendacis*		26.5			26.6			26.6
FAD	*Gl. siakensis*		26.9						26.9
FAD	*Gg. ciperoensis*		27.4			27.5			27.5
FAD	*Gl. cf. siakensis*		28.9						28.9
FAD	*Gg. angulisuturalis*		28.0			28.5			28.5
FAD	*Gg. cf. angulisuturalis*		28.8						?
FAD	*Gg. cf. ciperoensis*		28.4						28.4
FAD	*Gl. cf. mendacis*		30.4			30.4			30.4
FAD	*Gl. munda*		29.4			26.4			unreliable

* mid latitudes
** last abundance peak
*** first abundance peak

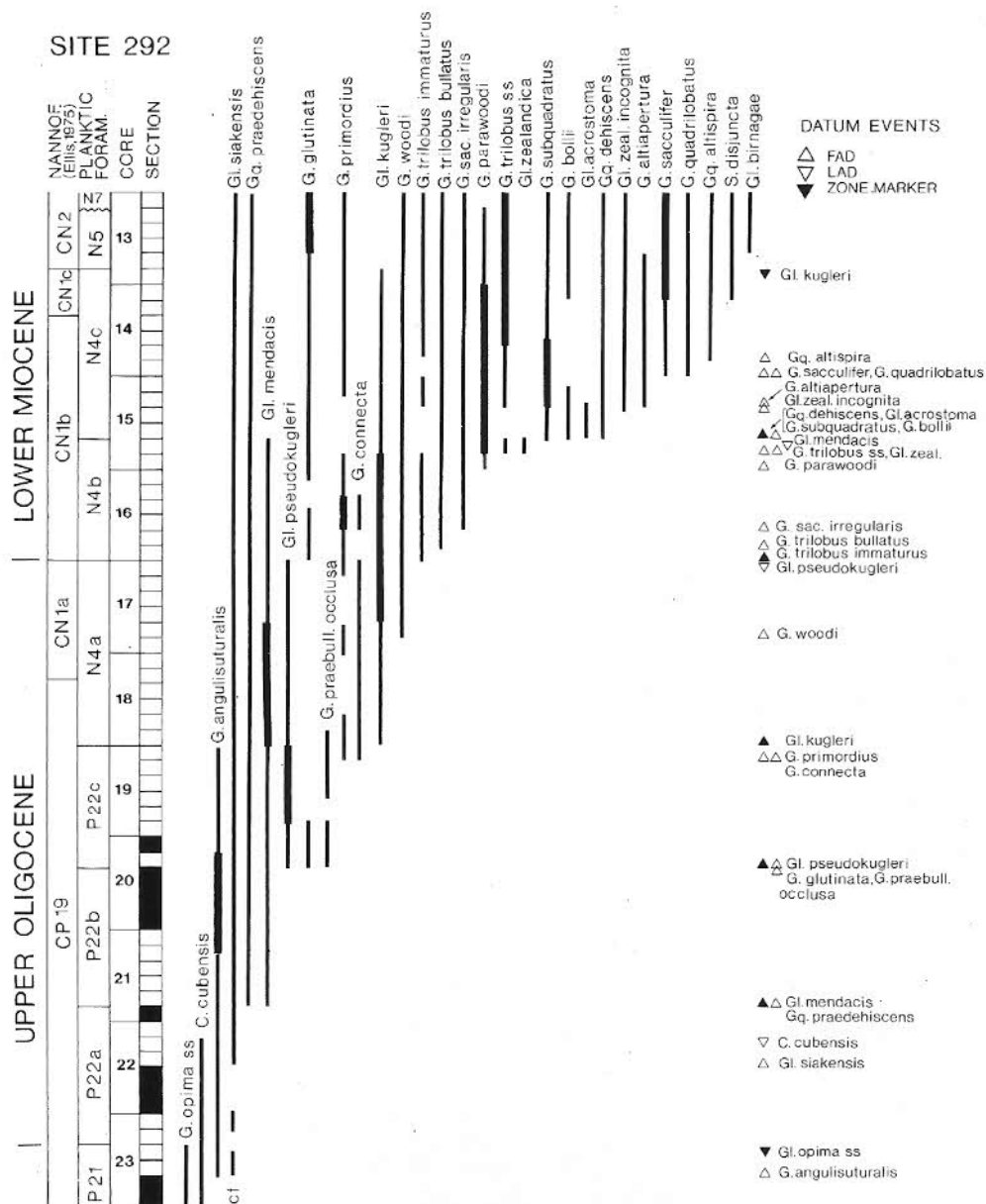△ hiatus
△△ dissolution
? insufficient data

Fig. 2 – Range chart of stratigraphically important species in Site 292, west equatorial Pacific. Thick lines mark intervals where species are common to abundant. Wavy line marks hiatus. Black intervals in core-section indicate no recovery of sediment.

is present between the base of Zone P22 and the top of Zone N4. Species which are biostratigraphically significant in the P22 through N4 interval are illustrated in Figure 2, where species which define Zone or subzone boundaries are marked by black triangles. First and last appearances of species in Zone N4 in Sites 292, 55, 77B and 71 and their isochroneity in the equatorial and subtropical Pacific have been discussed in Keller (1980, 1981a,b,c). Datum events in Zone P22 are based primarily on Sites 292 and 77B (this study) and unpublished data from Site 242 (Indian Ocean) and Site 94 (Gulf of Mexico). The first and last appearance datums (FAD and LAD) of species across the P/N boundary in Site 292 are generally consistent with the same species datums in Sites 289, 55, 71, 77B and 495. Therefore, Site 292 serves as a reference section for this interval.

Age and Isochroneity of Datum Events.

The isochroneity of datum events has been tested based on a) comparison of multiple microfossil stratigraphies at each site (planktic foraminifers, nannofossils, radiolarians and diatoms where available) and b) absolute age estimates extrapolated from the sediment accumulation curve of each site. Sediment rate curves were constructed based on paleomagnetically calibrated radiolarian, diatom, nannofossil and foraminifer datum levels (Westberg & Riedel, 1978; Theyer et al., 1978; Burckle, 1978; Berggren et al., in press; Barron et al., in press). The revised paleomagnetic time scale of Berggren et al. (in press) has been followed for absolute age dates.

Age estimates of 46 datum events are listed in Table 1 for each DSDP site investigated and the best age for each datum event is indicated. Datum events of species whose first and last appearance differ widely from site to site are considered unreliable, these include *Globigerina woodi* FAD, *Globigerinoides primordius* FAD and *Globigerinoides bollii* FAD. For some datum events insufficient data is available to test the isochroneity. About 36 datum events, however, appear reliable marker species between 19 and 30 Ma in the equatorial and subtropical Pacific Ocean. Four of these datum events are based on first and last abundance peaks of *Globorotalia kugleri*, *Globigerina ciperoensis* and *Gg. angustiumbilicata* as will be discussed later.

In a well preserved section such as Site 292 nearly 30 planktic foraminiferal datum events are useful stratigraphic markers in Zones P22 and N4 yielding a high resolution age control. In less preserved section dissolution susceptible species (most *Globigerinoides*) will not be reliable stratigraphic markers. Nevertheless, datum events of dissolution resistant species (*Globorotalia* and *Globoquadrina*) still provide a higher resolution biostratigraphic control than the use of Blow Zones would indicate. Therefore, a revision of Blow Zones P22 and N4 is here proposed.

Revision of Blow Zones (1969).

Species which define zone boundaries should ideally be easily identifiable, dissolution resistant and the datum event should be isochronous in a given oceanic regime. Unfortunately, many zonal marker species, including *Globigerinoides primordius* FAD, which to date defines the P/N boundary as well as the base of Blow Zone N4, do not fit this criteria. In fact, *Gs. primordius* has proved to be a most unreliable marker species because of its diachronous occurrence due to ecologic control and carbonate dissolution. Revision of the widely used zonal scheme of Blow (1969) to reflect the increased knowledge of the geologic record is long overdue.

A redefinition of Blow's (1969) Zone N4 is proposed to limit this zone to the range of *Globorotalia kugleri*. This revision would return Zone N4 to its original definition of Banner and Blow (1965) and makes it equivalent to Bolli's (1957) *Gl. kugleri* Zone. Zone P22 thus becomes equivalent to Bolli's *Globigerina ciperoensis* Zone. Moreover, it is proposed to subdivide Zone P22 into subzones a, b and c based on the first appearance of *Globorotalia mendacis* and *Gl. pseudokugleri* respectively. Zone N4 has been recently subdivided into subzones a and b based on the first appearance of *Globoquadrina dehiscens* by Srinivasan and Kennett (1981a). A further subdivision is proposed here based on the first appearance of *Globigerinoides trilobus* s.l. *(Gs. trilobus immaturus, Gs. trilobus bullatus)* which has been used to mark the P/N boundary whithin Zone N4 (Keller, 1981a,b). This subdivision divides Zone N4 into subzones a, b and c with the earlier subzones a and b of Srinivasan and Kennett equivalent to subzones b and c.

The species proposed here for subdivision of Zones N4 and P22 are easily identifiable, isochronous, dissolution resistant (except for *Globigerinoides trilobus* s.l.) and upon their first evolutionary appearance are consistently present until they become extint. Therefore, they are considered reliable stratigraphic markers and their inclusion in the zonal scheme is well justified.

Zone N4 emended:

Synonym: *Globorotalia kugleri* Zone, Bolli, 1957.
Globorotalia kugleri Zone, Banner & Blow, 1965.

Globigerinoides primordius/Globorotalia kugleri concurrent range Zone of Blow (1969) here emended.

Definition. Interval from the first evolutionary appearance of *Globorotalia kugleri* to the last evolutionary appearance of *Gl. kugleri*.

Age. Latest Oligocene to Early Miocene. Base of Zone N4 coincides with nannofossil Zone boundary CP19b/CN1a and top of radiolarian Zone *Dorcadospyris ateuchus* and correlates to the upper part of Chron 23 of the paleomagnetic time scale.

Reference sections. DSDP Sites 292, 298, 77B equatorial Pacific.

Subzone N4a.

Definition. Interval from the evolutionary first appearance of *Gl. kugleri* to the evolutionary first appearance of *Globigerinoides trilobus* s.l. (*Gs. trilobus immaturus, Gs. trilobus bullatus*).

Age. Latest Oligocene to P/N boundary as marked by *Gs. trilobus* s. l. FAD, nannofossil subzone boundary CN1b/CN1c and radiolarian boundary *Lychnocanoma elongata/Cyrtocapsella tetrapera* and lower part of Chron 21, paleomagnetic stratigraphy.

Subzone N4b.

Synonim: N4a Srinivasan & Kennett, 1981a.

Definition. Interval from the evolutionary first appearance of *Globigerinoides trilobus* s.l. *(Gs. trilobus immaturus, Gs. trilobus bullatus)* to first evolutionary appearance of *Globoquadrina dehiscens.*

Age. Early Miocene: top of subzone correlates to within the lower part of nannofossil subzone CN1c and near the radiolarian *Cyrtocapsella tetrapera/Stichocorys delmontensis* Zone boundary and the diatom *Rocella paleacea* a/b subzone boundary. Subzone N4b spans from the base of paleomagnetic polarity Chron 21 to the base of Chron 20.

Subzone N4c.

Synonym: N4b Srinivasan & Kennett, 1981a.

Definition. Interval from the first evolutionary appearance of *Globoquadrina dehiscens* to the last evolutionary appearance of *Globorotalia kugleri.*

Age. Early Miocene: top of subzone N4c correlates to within nannofossil subzone CN1c and radiolarian Zone *Stychocorys delmontensis* and near the diatom *Rocella paleacea/C. elegans* Zone boundary. Subzone N4c spans from the base of paleomagnetic polarity Chron 20 to the lower half of Chron 19.

Zone P22 emended.

Synonym: *Globigerina ciperoensis ciperoensis* Zone Bolli, 1957.

Globigerina angulisuturalis partial-range Zone here emended.

Definition. Interval from the last evolutionary appearance of *Globorotalia opima opima* to the first evolutionary appearance of *Globorotalia kugleri.*

Age. Late Oligocene: base of Zone P22 correlates with the nannofossil CP19a/b subzone boundary and falls within the radiolarian *Dorcadospyris ateuchus* Zone, and within the diatom *Rocella vigilans* Zone. The top of Zone P22 correlates with nannofossil Zone boundary CP19b/CN1a, and falls near radiolarian Zone boundary *D. ateuchus/L. elongata* and within diatom Zone *Rocella gelida.* Zone P22 spans from the top of paleomagnetic polarity Chron 9 to the upper half of Chron 23.

Reference section. Site 292, west equatorial Pacific.

Subzone P22a.

Definition. Interval from the last evolutionary appearance of *Globorotalia opima opima* to the first evolutionary appearance of *Globorotalia mendacis*.

Age. Late Oligocene: top of subzone P22a correlates to within nannofossil subzone CP19b, radiolarian Zone *D. ateuchus* and falls near the base of diatom Zone *Bogorovia veniamini*. Subzone P22a spans from the top of paleomagnetic polarity Chron 9 to the top of Chron 7A.

Subzone P22b.

Definition. Interval from the first evolutionary appearance of *Globorotalia mendacis* to the first evolutionary appearance of *Globorotalia pseudokugleri*.

Age. Late Oligocene: top of subzone P22b correlates to within nannofossil subzone CP19b, to the upper part of radiolarian Zone *D. ateuchus*, and near the top of diatom Zone *Bogorovia veniamini*. Subzone P22b spans from the top of paleomagnetic polarity Chron 7A to the lower half of Chron 6C.

Subzone P22c.

Definition. Interval from the first evolutionary appearance of *Globorotalia pseudokugleri* to the first evolutionary appearance of *Globorotalia kugleri*.

Age. Latest Oligocene: top of subzone P22c correlates to nannofossil Zone boundary CP19b/CN1a and radiolarian boundary *D. ateuchus/L. elongata* and falls within the diatom Zone *Rocella gelida*. Subzone P22c spans from the lower half of paleomagnetic polarity Chron 6C to anomaly 6C of Chron 6C.

Abundance Distribution.

Variations in species abundance through Early Miocene time are indicative of paleoclimatic and paleoceanographic changes (Keller, 1981d). Recognition of relative abundance changes in the dominant species not only provides paleoceanographic information, but also aids biostratigraphic interpretation. In certain species (such as *Globorotalia kugleri*, *Globigerina angustiumbilicata*) the first and last abundance peaks are reliable stratigraphic markers and have been used successfully throughout the equatorial and subtropical Pacific region (Keller, 1981c).The succession of species in Site 292 is illustrated in Figure 3. Site 292 demonstrates that the rapid succession of dominant species across the P/N boundary can provide stratigraphic control. For instance, *Globigerina angulisuturalis* reaches the highest abundance peak in P22b, *Gl. pseudokugleri* in P22c, *Gl. mendacis* in N4a, *Gl. kugleri* in N4b, and *Globigerinoides* becomes first abundant near the top of N4c along with the first occurrence of *Globoquadrina altispira*. This relationship generally holds across the equatorial and subtropical Pacific although relative abundances vary between the east and west equatorial Pacific.

Abundance variations of dominant species are illustrated in Figure 4 in an east-west equatorial transect. Quantitative data for Zone N4 are more complete

than for Zone P22 because of availability of deep-sea sections and completed population analyses. Correlation lines mark the first appearance of *Gl. kugleri*, *Gs. trilobus* s.l. and *Globoquadrina dehiscens*. In Site 77B, due to dissolution, the first appearance of *Gs. trilobus* occurs in subzone N4c, therefore the N4a/b boundary has been tentatively set in core 33-2 (dashed line, Fig. 4) based on the secondary marker species *Globorotalia acrostoma* FAD. The presence of hiatuses (zig-zag lines, Fig. 3,4) is discussed below.

East-west faunal provincialism in the equatorial Pacific is noted primarily in the decreasing abundances eastward of *Globigerina angustiumbilicata*, *Gg.*
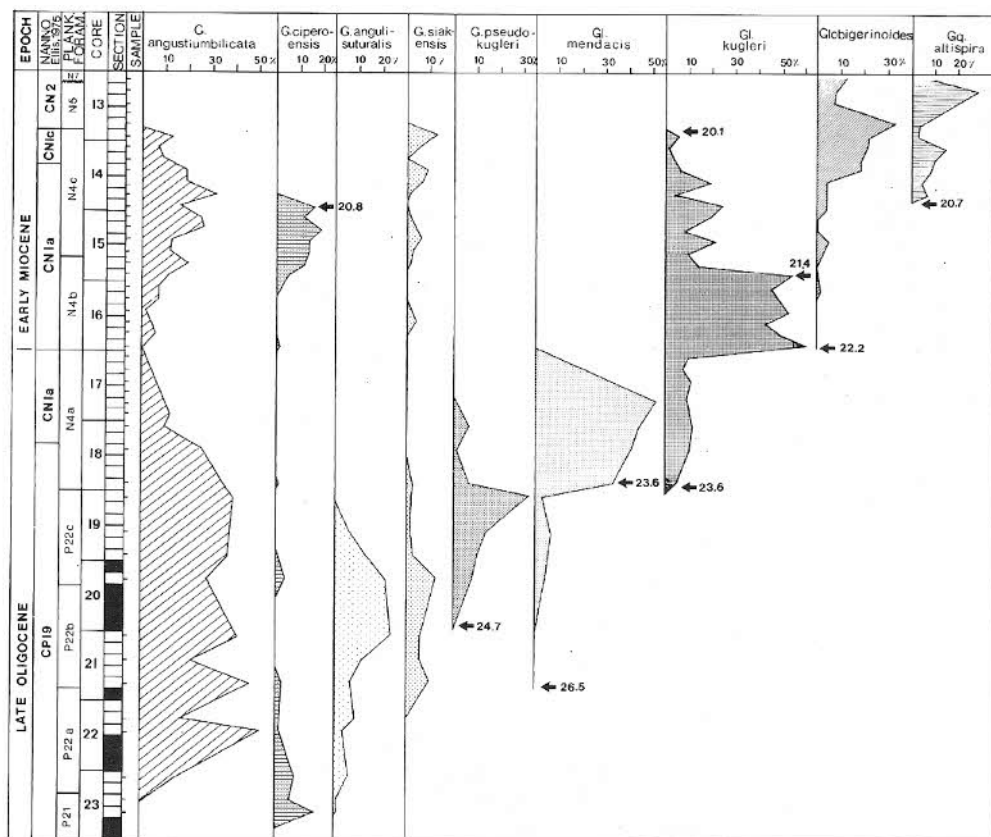
SITE 292

Fig. 3 — Abundance distribution of dominant planktic foraminiferal species at Site 292, west equatorial Pacific. Ages for stratigraphically useful abundance changes are based on extrapolation from the sediment accumulation curve.
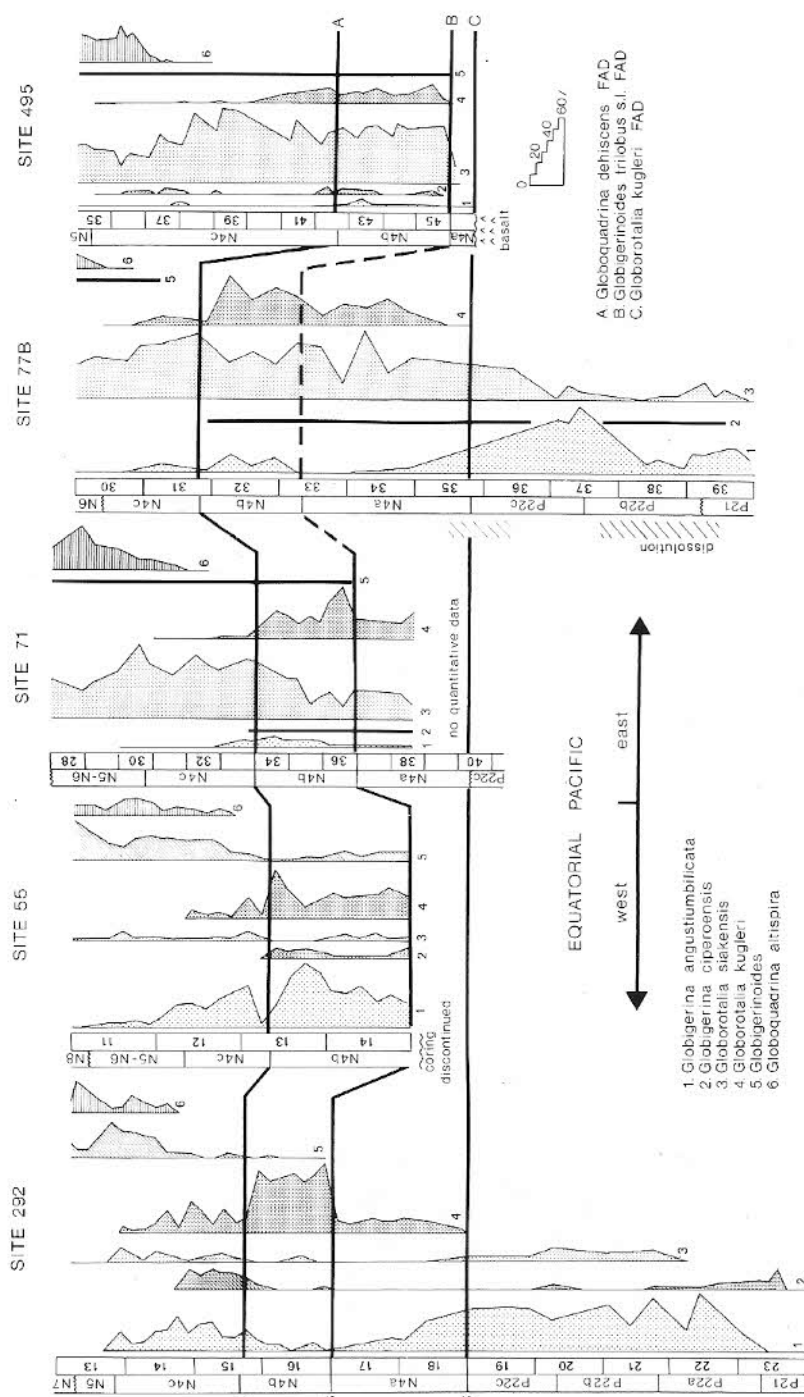
Fig. 4 – Abundance variations of dominant planktic foraminiferal species in an east-west equatorial Pacific transect. Wavy lines mark hiatuses.

ciperoensis, Globorotalia kugleri, and *Globigerinoides,* and the increasing abundance eastward of the *Globorotalia siakensis-Gl. mayeri* group (see also Keller, 1981c). This east-west faunal provincialism reflects the equatorial current circulation with cooler surface temperatures in the east equatorial region due to upwelling and transport of cooler water by the Peru-Chile Current (Burckle et al., 1982; Barron, 1982; Keller, in press). Despite this pronounced east-west faunal provincialism most datum events (FAD and LAD) are isochronous (Table 1) and can be used reliably throughout this region.

Hiatuses.

In most deep-sea sequences there appears to be a nearly continuous sedimentary record between the base of Zone P22 and the top of Zone N4 with the exception of a short hiatus (Palaeogene hiatus PH1) at the Zone P22/N4 boundary. At this interval (*Gl. kugleri* FAD) 0.5 to 1.0 m.y. is typically missing and assemblages are affected by dissolution as for instance at Sites 71 and 289. At Site 77B the Zone P22/N4 boundary is in core 35 which was not recovered. Another hiatus, PH2, is commolly present in Zone P21 in shallow or nearshore marine sections (Site 242, Indian Ocean and Site 94, Gulf of Mexico).

The first Neogene hiatus (NH1) occurs near the base of Zone N5 (Fig. 4). This hiatus is widespread in deep-sea sections of the Pacific, Atlantic and Indian Oceans as discussed in Keller and Barron (1983) and typically removes the stratigraphic interval between the base of Zones N5 and N7. In regions of high sedimentation this hiatus is often represented by two erosional pulses NH1a at the base of Zone N5 and NH1b near the N6/N7 boundary. It is notable that there are practically no mid-latitude Early Miocene sequences in the North Pacific (except Site 296) due to major erosive events and a similar paucity of Early Miocene sequences is observed in the mid-latitude Indian and Atlantic Oceans (Keller & Barron, 1983).

The Palaeogene/Neogene Boundary.

Correlation of microfossil zonations, planktic foraminiferal datum events and occurrence of widespread hiatuses across the Palaeogene/Neogene boundary are illustrated in Figure 5 along with the revised paleomagnetic time scale of Berggren et al. (in press). Early Miocene nannofossil, radiolarian and diatom events and age determinations based on this paleomagnetic time scale are listed in Barron et al. (in press). Important planktic foraminiferal marker species are illustrated in Plates 46-50.

Besides the currently accepted P/N boundary based on the first appearance of *Gs. trilobus* s.l., there are two proposals for setting this boundary at either the *Gl. kugleri* FAD or at the *Gq. dehiscens* FAD. There are pros and cons for each of these datum planes. Some workers argue that these species are diachronous in some regions. Unfortunately, the strong latitudinal provincialism inher-

ent in all microfossil groups preempts the possibility of finding a synchronous datum event between high and low latitudes. However, boundaries should be defined in low latitude sequences where the most diverse and best preserved assemblages are present and hence can provide the best age control. Correlation can then be made to mid and high latitude sequences to find reliable datum events in these regions that are equivalent in time. To insure time equivalency
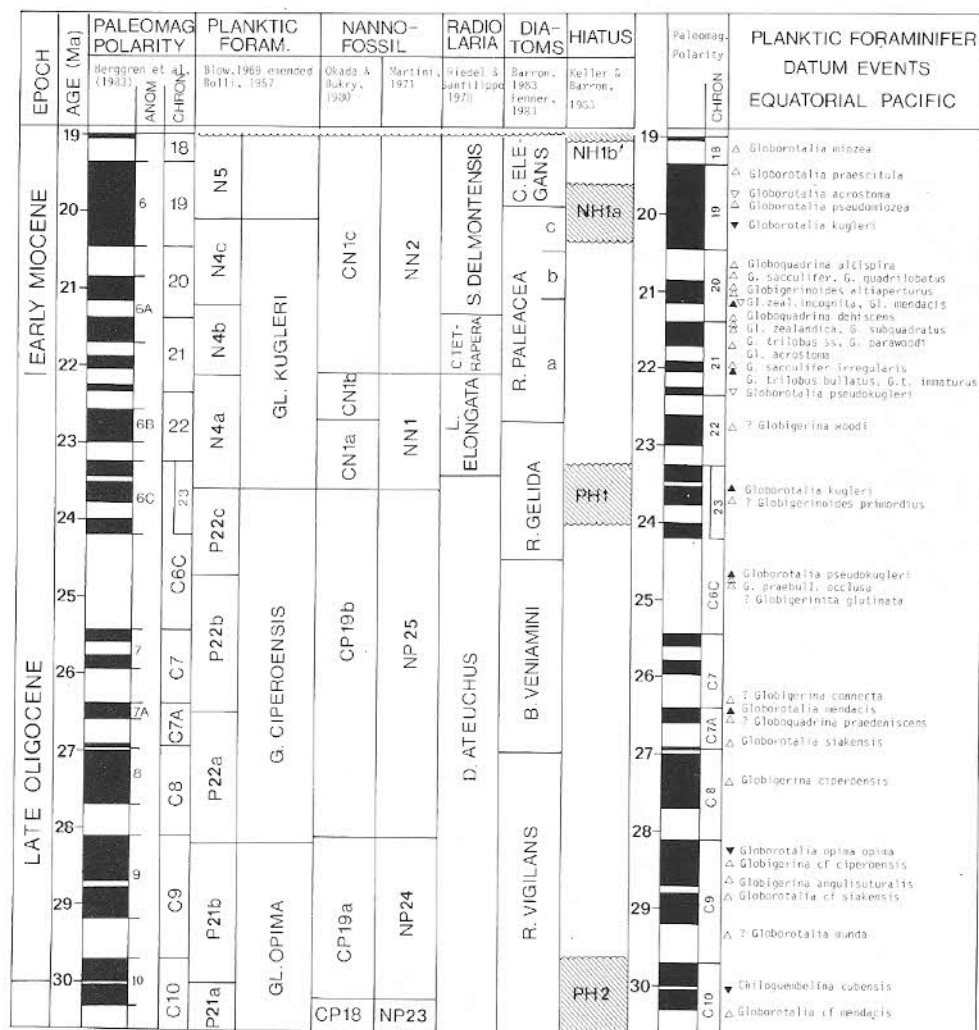

Fig. 5 — Correlation of microfossil zonations, planktic foraminiferal datum events and occurrence of widespread hiatuses across the Oligocene/Miocene boundary in the equatorial Pacific tied to the paleomagnetic time scale of Berggren et al. (in press). Open triangles mark first and last appearances of species; black triangles indicate zone and subzone marker species; ? marks datum events which are questionable (G. primordius), or need further study to establish isochroneity.

such correlations should probably be based on paleoclimatic analyses in addition to first and last appearances of species. The pros and cons of the proposed datum planes for the P/N boundary with respect to the equatorial to temperate Pacific Ocean are discussed below. No evaluation of the P/N boundary in the mid to high latitude North Pacific can be made due to the lack of sequences containing an Early Miocene record.

FAD Globigerinoides trilobus s.l., base N4b, 22.1 Ma.

The P/N boundary as originally identified by the first appearance of *Gs. primordius* is highly unreliable due to diachronous first appearance and dissolution susceptibility of the species. The P/N boundary is currently recognized by the first appearance of *Gs. trilobus* s.l. including *Gs. trilobus immaturus* FAD and *Gs. trilobus bullatus* FAD (Keller, 1981a). *Globigerinoides sacculifer irregularis* also first appears at this interval. Secondary marker species are *Globorotalia pseudokugleri* LAD and *Gl. acrostoma* FAD below and above the *Gs. trilobus* s.l. datum respectively (Fig. 5).

Pro: The *Gs. trilobus* s.l. datum is isochronous in low latitude regions and coincides with the radiolarian boundary *Lychnocanoma elongata/Cyrtocapsella tetrapera* and the nannofossil Zone boundary NN1/NN2 of Martini (1971) and the subzone boundary CN1b/CN1c of Okada and Bukry (1980). Using the *Gs. trilobus* s.l. datum for the P/N boundary, no change is necessary from the currently accepted boundary.

Con: Species of *Globigerinoides* are dissolution susceptible and in the earliest part of the range, species occurrence is thus often sporadic. Therefore, in dissolution affected sequences the boundary can not be placed accurately.

FAD Globorotalia kugleri, base N4a, 23.6 Ma.

The proposed P/N boundary identified by the first appearance of *Gl. kugleri*. There are no other reliable planktic foraminiferal datum events near this interval.

Pro: *Globorotalia kugleri* is relatively dissolution resistant, easily identified, and after its evolutionary first appearance it develops rapidly and becomes common to abundant. The *Gl. kugleri* datum coincides with nannofossil Zone boundaries NP25/NN1 of Martini (1971) and CP19b/CN1a of Okada and Bukry (1980) and nearly coincides with the radiolarian boundary *D. ateuchus/L. elongata*.

Con: *Globorotalia kugleri* appears to be restricted to the tropical and subtropical regions and there are no reliable secondary datum events near the *Gl. kugleri* FAD. Furthermore, increased carbonate dissolution and a short hiatus (PH1) commonly mark this interval.

FAD Globoquadrina dehiscens, base N4c, 21.2 Ma.

The proposed P/N boundary identified by the first appearance of *Globoquadrina dehiscens*. Secondary marker species at this interval are *Gl. mendacis*

LAD, *Gl. zealandica incognita* FAD, just below this interval *Gl. zealandica* ss FAD, *Globigerinoides subquadratus* FAD, *Gs. trilobus* ss FAD, *Gg. parawoodi* FAD, and just above this interval *Gs. altiaperturus* FAD, *Gs. sacculifer* FAD and *Gs. quadrilobatus* FAD (Fig. 5).

Pro: The *Globoquadrina dehiscens* datum is isochronous in tropical, subtropical and temperate regions and the species is easily identified and dissolution resistant. The large number of secondary datum events (9 datum events) occurring near the *Gq. dehiscens* datum insure correct identification of this time horizon even in the absence of the marker species. Moreover, the *Gq. dehiscens* datum occurs just above the final abundance peak in *Globorotalia kugleri* which provides an additional faunal marker. In correlation with other microfossil groups, the *Gq. dehiscens* datum occurs just above the radiolarian Zone boundary *C. tetrapera/S. delmontensis*, and just below the *Rocella paleacea* a/b diatom subzone boundary, and in the lower part of nannofossil Zone NN1 of Martini (1971) and subzone CN1c of Bukry and Okada (1980).

Con: A minor negative aspect associated with the *Gq. dehiscens* datum may be identification. *Globoquadrina dehiscens* evolves from *Gq. praedehiscens* and the transition occurs in N4a-b. The *Gq. dehiscens* datum refers to the first evolutionary appearance of typical *Gq. dehiscens* and hence transitional forms should not be included under this name. However, even if the first appearance of *Gq. dehiscens* is questioned by some workers, the secondary datum species can resolve this problem.

FAD Globoquadrina dehiscens or FAD Globorotalia kugleri?

There are strong arguments in favor of changing the P/N boundary to either the *Gq. dehiscens* or the *Gl. kugleri* datums, especially since both datum planes can be easily identified in other microfossil groups also. *Globorotalia kugleri* FAD may be preferable in that it marks an early development in the evolution of the Neogene fauna. This datum plane however lacks secondary marker species and, more importantly, often coincides with a short hiatus. The *Globoquadrina dehiscens* datum, however, is not associated with a hiatus and coincides with a multitude of secondary datum events which mark the major evolutionary pulse in the development of the early Neogene fauna. For these reasons, identification of the P/N boundary based on the *Gq. dehiscens* FAD is preferable.

Summary and Conclusions.

Investigation of planktic foraminiferal datum events across the P/N boundary in the equatorial and subtropical Pacific Ocean indicate a multitude of isochronous datum events in Zones N4 and P22. These datum events provide a high resolution age control and reveal viable alternative datum planes, such as *Gl. kugleri* FAD and *Gq. dehiscens* FAD, to the current P/N boundary based on the dissolution susceptible "*Globigerinoides* datum". Major new results of this investigation are:

1) Over 30 datum events are identified in Zones P22 and N4 and tied to the paleomagnetic time scale of Berggren et al. (in press). Age determinations for datum events are based on extrapolation from the sediment accumulation rate curves.

2) Quantitative faunal analyses indicate rapid succession in the dominant species groups during Zones P22 and N4. First and last abundance peaks of some species (*Gl. kugleri, Gg. ciperoensis, Gg. angustiumbilicata*) appear isochronous and are useful stratigraphic markers.

3) Among the newly proposed datum planes for the P/N boundary the *Gq. dehiscens* FAD appears preferable. This datum plane is associated with 9 secondary datum events providing an easily recognizable datum plane even in the absence of the marker species.

4) The *Gl. kugleri* FAD is a less desirable datum plane for the P/N boundary because there are no reliable secondary datum events and this interval is frequently associated with a short hiatus and increased dissolution.

5) Revision of Blow Zones (1969) N4 and P22 are proposed based on easily identifiable and isochronous datum events which provide a much improved age control. The following revisions are proposed: a) restrict Zone N4 to the range of *Gl. kugleri*, b) subdivide Zone N4 (emended) into subzones a, b, and c based on *Gs. trilobus* s.l. FAD and *Gq. dehiscens* FAD, and c) subdivide Zone P22 into subzones a, b, and c, based on *Gl. mendacis* FAD and *Gl. pseudo-kugleri* FAD.

Acknowledgements.

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PLATE 46

All specimens from Site 292, scale bar represents 100 um.

Fig. 1,2 — *Globigerinoides primordius* Blow & Banner. Sample 16-6 (140 cm), Zone N4b.

Fig. 3,4 — *Globigerinoides trilobus bullatus* Chang. Sample 16-5 (102 cm), Zone N4b.

Fig. 5,6 — *Globigerinoides trilobus immaturus* (Le Roy). 5) Sample 16-4 (102 cm), Zone N4b; 6) Sample 15-6 (90 cm), Zone N4b.

Fig. 7,8 — *Globigerinoides sacculifer irregularis* (Le Roy). Sample 15-1 (90 cm), Zone N4c.

Fig. 9-12 — *Globigerinoides parawoodi* Keller. 9,11) Sample 15-6 (90 cm), Zone N4b; 10) Sample 14-4 (90 cm), Zone N4c; 12) Sample 14-5 (86 cm), Zone N4c.

Fig. 13,14 — *Globigerinoides subquadratus* Brönnimann. Sample 14-6 (90 cm), Zone N4c.

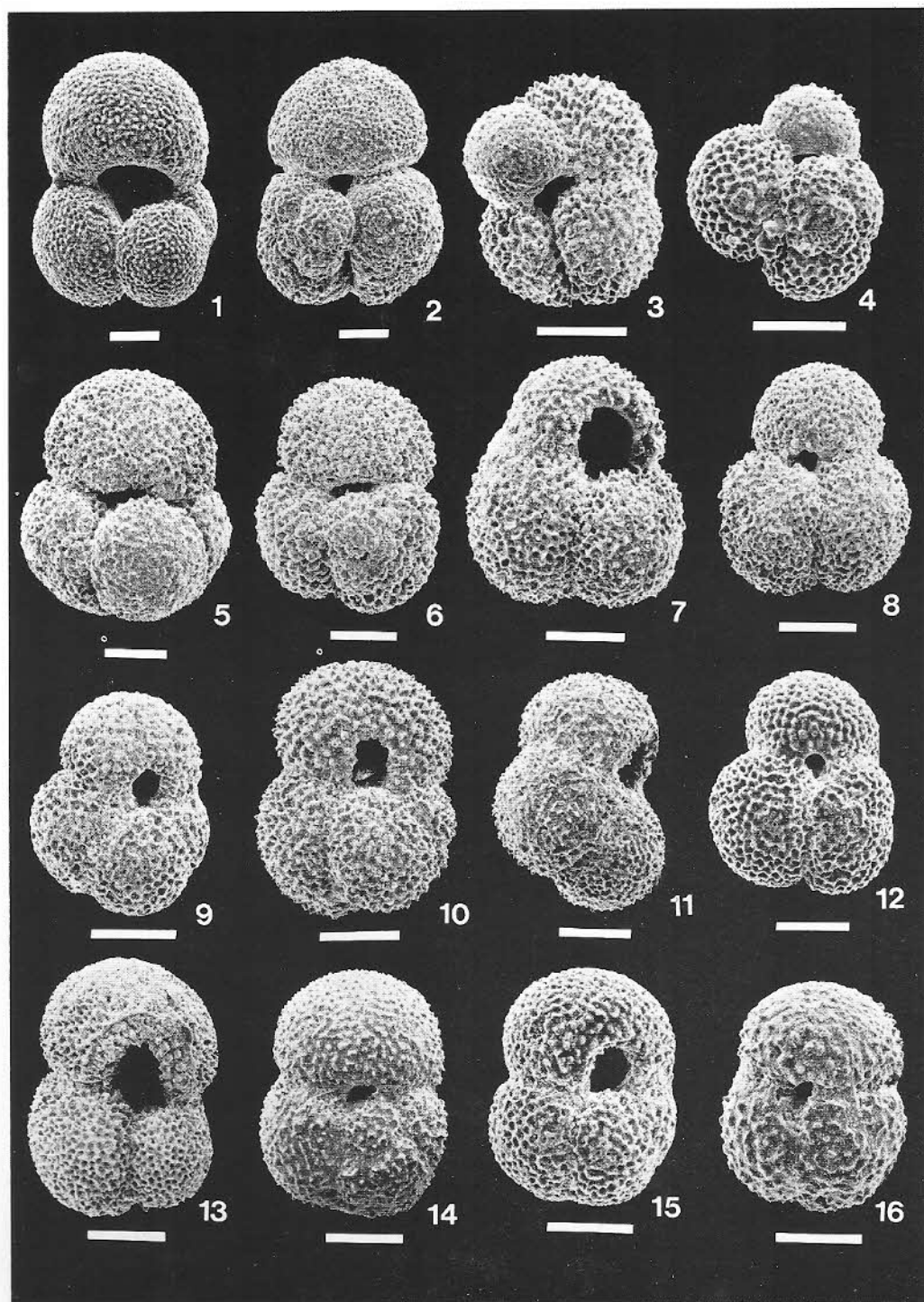Fig. 15,16 — *Globigerinoides bollii* Blow. Sample 13-1 (90 cm), Zone N7.

PLATE 47

All specimens from Site 292, scale bar represents 100 um.

Fig. 1-3 — *Globigerinoides altiaperturus* Bolli. Sample 14-3 (87 cm), Zone N4c.

Fig. 4 — *Globigerinoides quadrilobatus* (d'Orbigny). Sample 14-1 (90 cm), Zone N4c.

Fig. 5-7 — *Globigerinoides trilobus* (Reuss). Sample 13-5 (90 cm), Zone N5.

Fig. 8-10 — *Globigerinoides sacculifer* (Brady). Sample 14-1 (90 cm), Zone N4c.

Fig. 11,12 — *Globigerina woodi* Jenkins. Sample 16-5 (90 cm), Zone N4b.

Fig. 13,14 — *Globigerina praebulloides occlusa* Blow. Sample 19-6 (58 cm), Zone P22c.

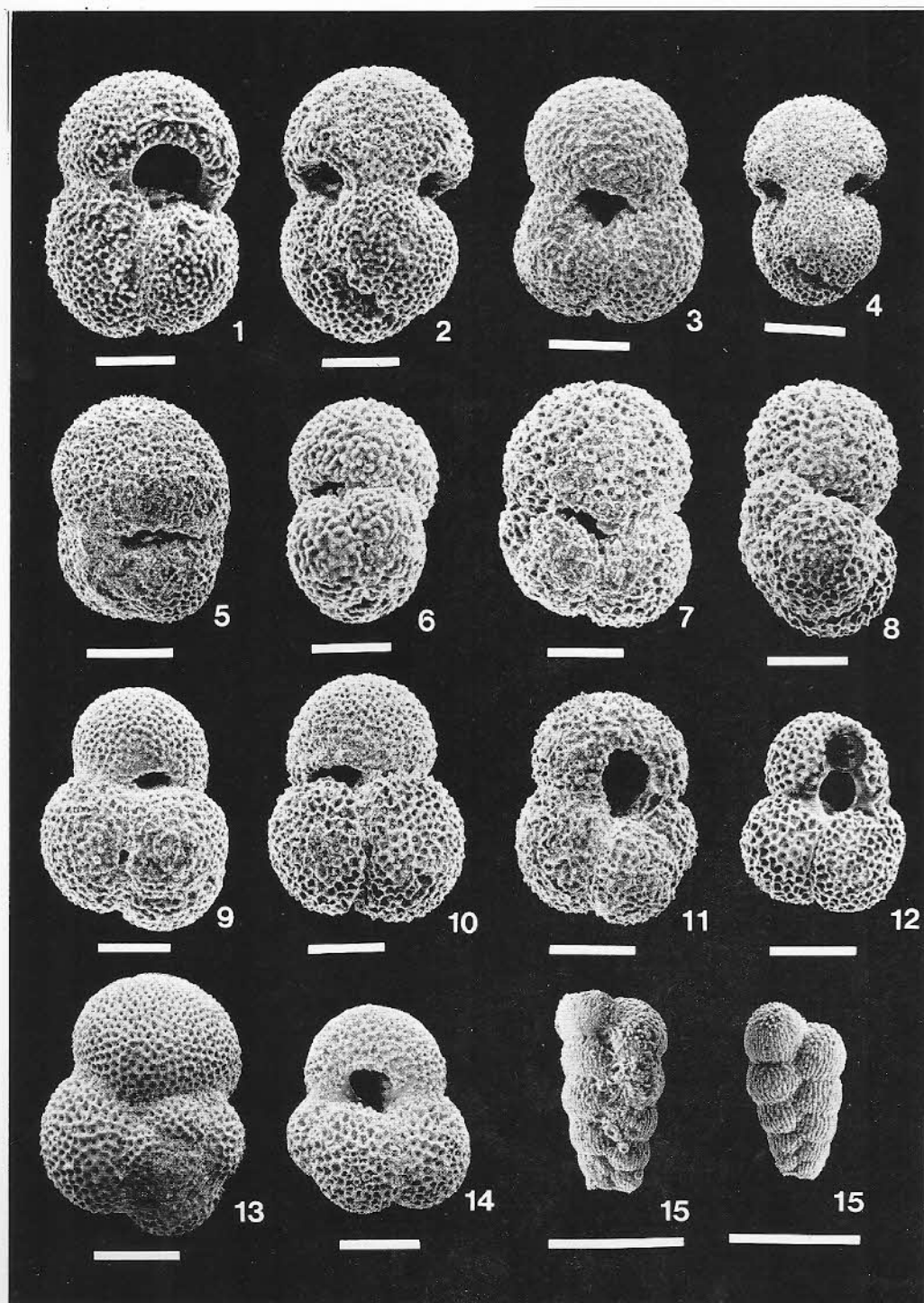Fig. 15,16 — *Chiloguembelina cubensis* (Palmer). Sample 22-3 (58 cm), Zone P22a.

G. *Keller*

PLATE 48

Scale bar represents 100 um.

Fig. 1-3 — *Globorotalia praescitula* Blow. Site 296, Sample 31-5 (88 cm), Zone N5-6.

Fig. 4-6 — *Globorotalia pseudomiozea* Walters. Site 296, Sample 32-2 (32 cm), Zone N5-6.

Fig. 7-9 — *Globorotalia miozea* Finlay. Site 296, Sample 31-4 (100 cm), Zone N5-6.

Fig. 10,11 — *Globorotalia* cf. *miozea* Finlay. Site 296, Sample 31-4 (100 cm), Zone N5-6.

Fig. 12,13 — *Globorotalia zealandica incognita* Walters. Site 296, Sample 32-4 (41 cm), Zone N5-6.

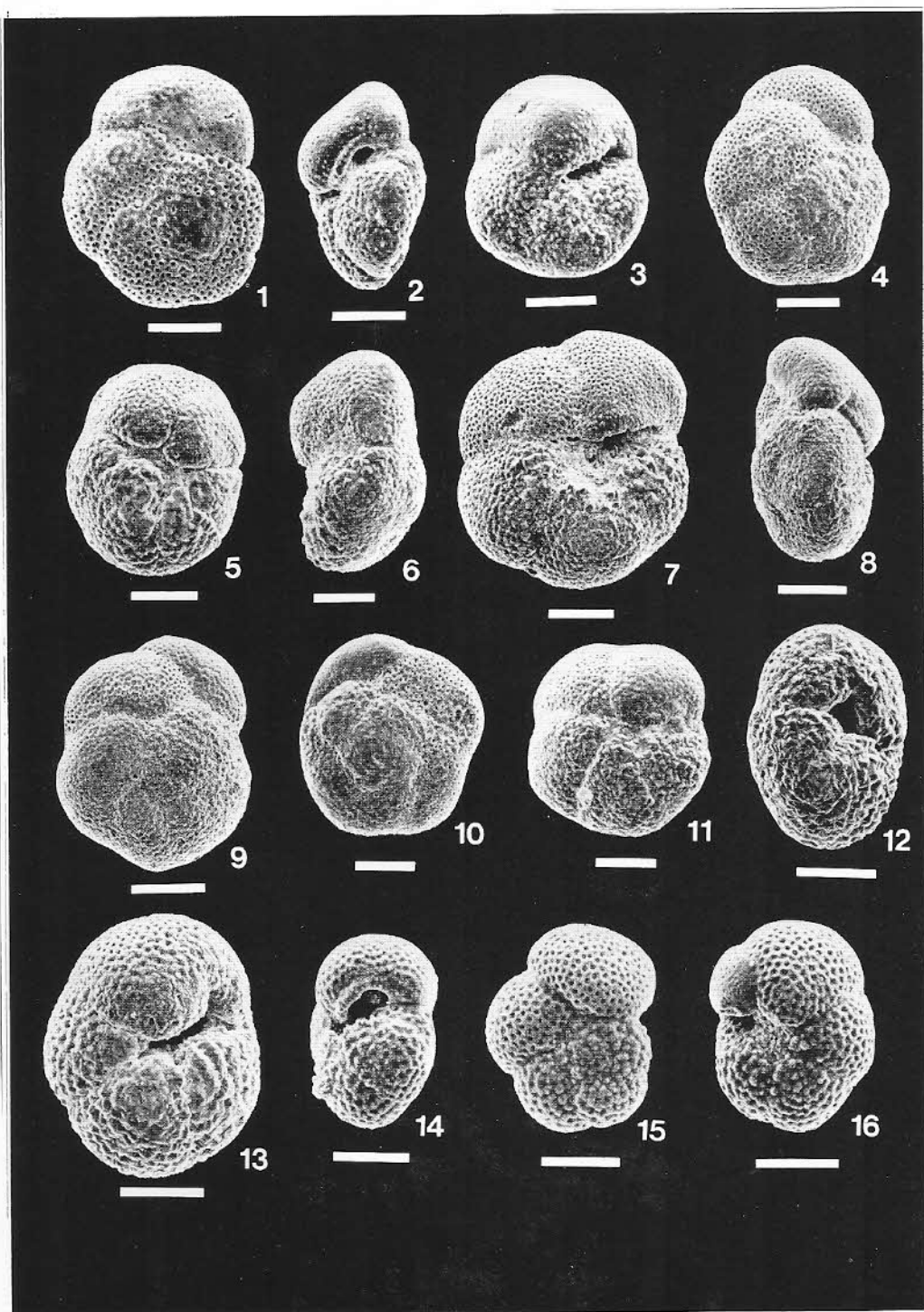Fig. 14-16 — *Globorotalia zealandica incognita* Walters. Site 292, Sample 15-3 (90 cm), Zone N4c.

PLATE 49

All specimens from Site 292, scale bar represents 100 um.

Fig. 1,2   — *Globorotalia zealandica* Hornibrook (early forms). Sample 15-1 (90 cm), Zone N4c.

Fig. 3-5   — *Globorotalia acrostoma* Wezel. Sample 15-3 (90 cm), Zone N4c.

Fig. 6-9   — *Globorotalia kugleri* Bolli. 6-8) Sample 16-2 (100 cm), Zone N4b; 9) Sample 17-5 (103 cm), Zone N4a.

Fig. 10,11 — *Globorotalia mendacis* Blow. Sample 17-5 (103 cm), Zone N4a.

Fig. 12,16 — *Globorotalia mendacis* Blow. Sample 18-1 (9 cm), Zone N4a.

Fig. 13   — *Globorotalia pseudokugleri* Blow. Sample 19-1 (107 cm), Zone P22c.

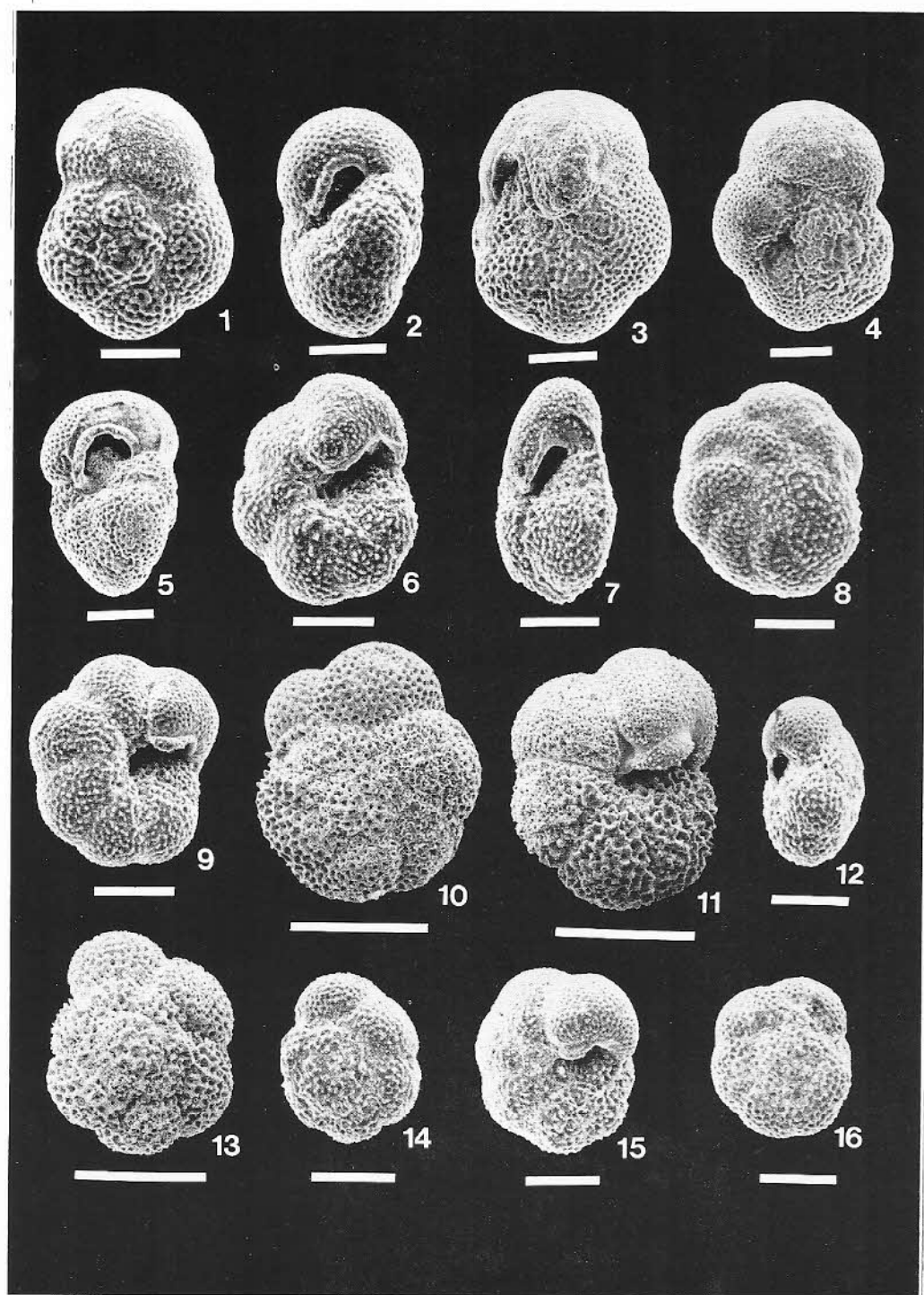Fig. 14,15 — *Globorotalia pseudokugleri* Blow. Sample 18-1 (9 cm), Zone N4a.

PLATE 50

Scale bar represents 100 um.

Fig. 1-3   — *Globorotalia siakensis* Le Roy. Site 292, Sample 19-1 (107 cm), Zone P22c.

Fig. 4,5   — *Globorotalia pseudocontinuosa* Jenkins. Site 292, Sample 22-3 (58 cm), Zone P22a.

Fig. 6-8   — *Globigerina angustiumbilicata* Bolli. Site 292, Sample 18-1 (9 cm), Zone N4a.

Fig. 9   — *Globigerina angulisuturalis* Bolli. Site 292, Sample 19-4 (58 cm), Zone P22c.

Fig. 10   — *Globoquadrina altispira* Bermudez. Site 292, Sample 13-5 (90 cm), Zone N5.

Fig. 11,12 — *Globoquadrina dehiscens* (Chapman, Parr & Collins). Site 292, Sample 13-5 (90 cm), Zone N5 (early forms).

Fig. 13,14 — *Globoquadrina dehiscens* (Chapman, Parr & Collins). Site 71, Sample 31-4 (88 cm), Zone N4c (early forms).

Fig. 15,16 — *Globoquadrina dehiscens* (Chapman, Parr & Collins). Site 71, Sample 23-1 (88 cm), Zone N8 (more typical forms).
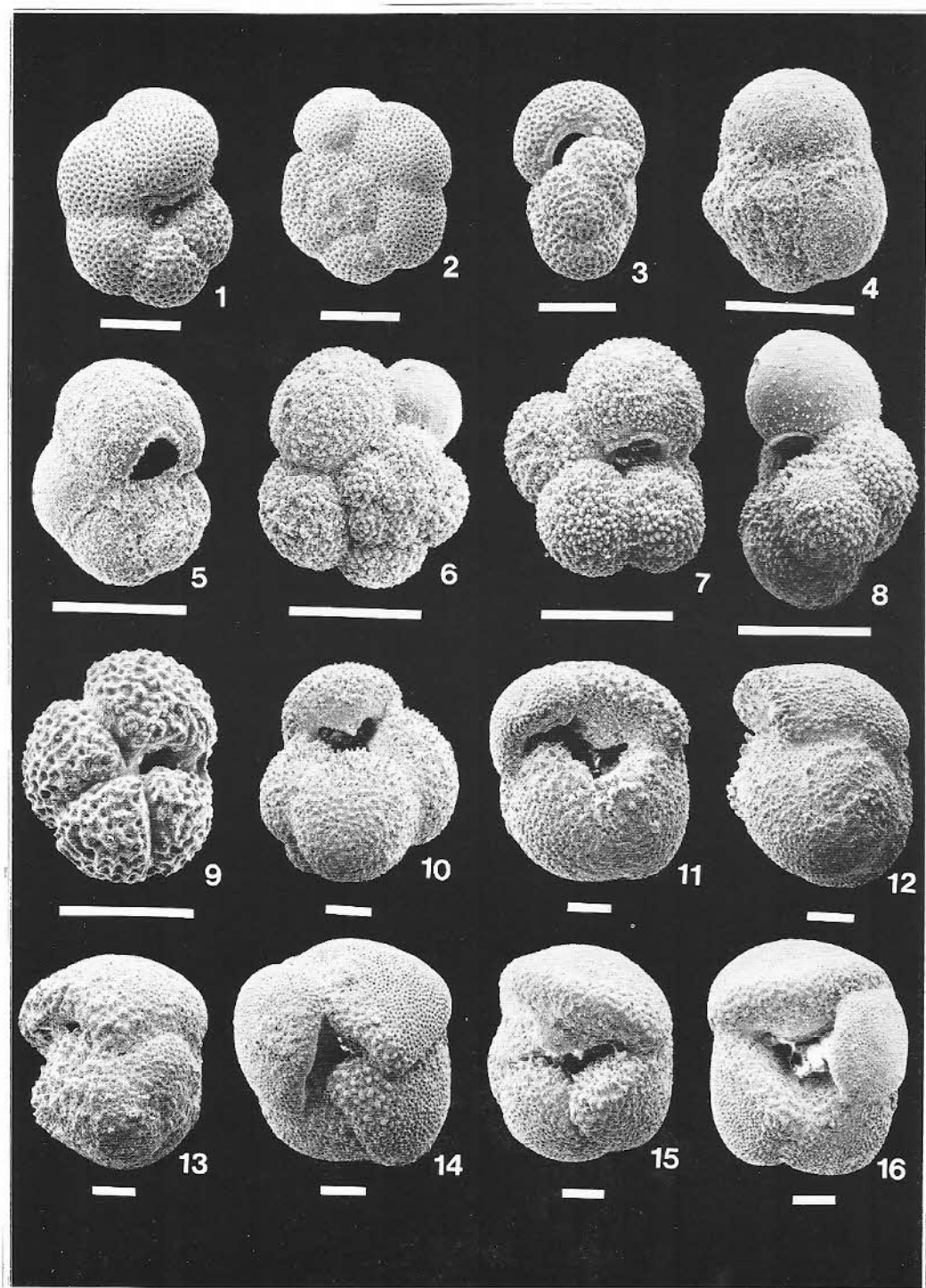
THE NATURE AND THE EFFECTS OF ENVIRONMENTAL CHANGES
IN THE PALAEOGENE/NEOGENE BOUNDARY INTERVAL

Changes in planktonic foraminifera and their environmental meaning (Fig. 1). (G. Bizon).

Abstract. A compilation of the Late Oligocene and Early Miocene planktonic foraminifera shows a gradual trend towards increasing temperature values of the sea surface, with some fluctuations which may explain the isotopic instability in this interval. There are some other ecologic factors including those resulting from the tectonic activity in the Mediterranean area.

Between the Late Oligocene and the Early Miocene, there are a renewal of many groups of fossils and a diversification of several planktonic foraminiferal species, some of them have persisted throughout the Neogene. Paleoclimatic and paleoceanographic changes led to the evolution of the assemblages. One of the most useful development is the first appearance of the genus *Globigerinoides* and *Globoquadrina*. Evolution of *Globorotalia kugleri* may be used, through with caution, as this species is climatically controlled in the Mediterranean area.

Ranges of the main species recognized in the Oligocene/Miocene sections of the Mediterranean area are shown in Fig. 1. Our purpose is to differentiate the epipelagic from the meso-or bathypelagic species, and the cold from the warm-water species. Modern distribution of planktonic foraminifera are used to derive paleoclimatic and paleoceanographic information.

Globorotalia opima opima is absent in the shallow-water sediment. It was probably a deep-water species. The general cooling known during this period of the Middle Oligocene is in favour of a cold-water species. The low diversity of the assemblages is due to a reduced circulation in the oceans.

Globorotalia mayeri is considered to be indicative of relatively warm-water conditions. Its first appearance in the upper part of the *Globorotalia opima* Zone is related to a minor modification of the climate system.

Globigerinita dissimilis is absent in the shallow-water sediments and was probably a deep water species. Its cosmopolitan distribution in the oceans from the late Middle Eocene to the Early Miocene does not indicate any paleoclimatic trend.

Globigerinita glutinata is common in subtropical waters in the present-day northern hemisphere but appears to be cold tolerant. The first occurrence of quite small-sized specimens in the range of the *Globorotalia kugleri* group is indicative of a warming of the sea-surface.

Globigerina angulisuturalis is present in shallow or deep-water sediments. Rare or absent in high latitude Oligocene assemblages, this is probably an effect of dissolution rather than a response to a climatic change.

Globorotalia kugleri is a warm and deep species known from the tropical areas. The small-sized specimens of the Mediterranean area are possibly due to a more temperate climate or to the influx of terrigenous material.

Globoquadrina dehiscens is a meso—or deep—water dweller. The abrupt appearance and exceptional abundance of this species in all the investigated sections may indicate a global change in the environment. Evolutionary grada-tion from *Globigerina tripartita* or *Globigerina globularis* are not observed and possibly have been located in warmer water-masses. Small-sized specimens are present which become larger in the Langhian - Serravallian sediments. The spe-cies is not frequent in the assemblages of the *Globigerinoides altiaperturus* Zone which indicates a possible reduction of the water depth.

In the present-day oceans, high latitude areas are generally characterized by abundant *Globigerina* and *Globigerinoides* are restricted to the transitional and low latitude areas. Most of the *Globigerinoides* species are epipelagic dwell-ers; *Globigerina* species are epi and mesopelagic dwellers. The evolution of *Globigerinoides* from *Globigerina* occurs at different times of the stratigraphical interval in question. First specimens are to be found in the *Globigerina cipero-ensis* Zone. Different ecophenotypes are involved with a small supplementary aperture and a nearly closed umbilicus. They are rare and not present in all the samples. This anagenetic evolution is iterative and probably depends of the warmer surface currents. The major radiation of *Globigerinoides* species (cla-
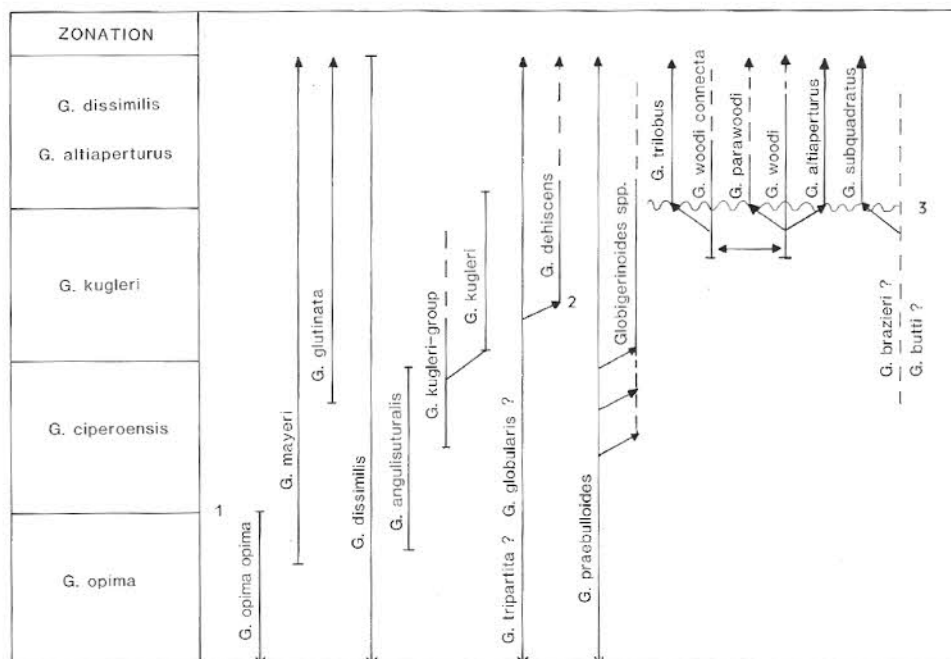

Fig. 1 — Suggested evolutionary lineages of significant planktonic foraminifera at the Palaeo-
gene/Neogene boundary.

dogenesis) is observed near the end of the *Globorotalia kugleri* Zone. The evolutionary rate is slow in the *Globigerina ciperoensis* Zone and goes faster at the end of the *Globorotalia kugleri* Zone.

Globigerina woodi is a cosmopolitan species. Similar specimens with a high arched aperture developed at different period of the Cenozoic record: *Globigerina frontosa* (Late, Early - Early, Middle Eocene), *Globigerina ampliapertura* (Late Eocene - Early Oligocene), *Globigerina apertura* (Tortonian, Pliocene). Their environmental meaning is not known. Two *Globigerinoides* evolved from *Globigerina woodi* : *Globigerinoides parawoodi* and *Globigerinoides altiaperturus*. *G. parawoodi* is probably an ecophenotype of *G. altiaperturus*. In the shallow-water sediments, *G. parawoodi* is more frequent than *G. altiaperturus*, this is the case for the Saucats Pont-Pourquey faluns of the Burdigalian of south-western France.

Globigerinoides subquadratus evolved from *Globigerina brazieri* or *Globigerina butti* or from some other unknown ancestor. In a population of *Globigerinoides* from the Early Burdigalian, there are interrelation between *G. altiaperturus* and *G. subquadratus*. If *G. altiaperturus* gave rise to *G. subquadratus* by a reduction in chamber number in the final whorl, or *G. subquadratus* gave rise to *G. altiaperturus* by acquisition of a fourth chamber in the final whorl is a problem not solved.

Globigerinoides trilobus evolved from *Globigerina woodi connecta* by acquisition of supplementary apertures on the dorsal side.

In conclusion, three major events are observed in the Mediterranean area which are related to paleoenvironmental changes.

— Event 1 (extinction of *Globorotalia opima opima*) is related to a first warming trend (iterative occurrences of *Globigerinoides* spp.), followed by a better circulation of the water-masses (occurrences of deep-dwellers such as *Globorotalia kugleri* group and *Gl. kugleri* sensu stricto).

— Event 2 (first appearance of *Globoquadrina dehiscens* followed by first appearance of *G. woodi*) indicates some global changes in the environmental and possibly a cool oscillation of the sea-surface.

— Event 3 (appearances of *Globigerinoides trilobus, G. altiaperturus, G. subquadratus*) is related to a general warming of the surface water and a reduction of the water depth in some sections of the Mediterranean area (last appearance of the deep-dweller *Gl. kugleri*, scarcity of *Gq. dehiscens*). The development of these different species of *Globigerinoides* is exactly not synchronous in the world and will depend of the paleogeography of the different basins and the surface currents direction.

The evolution in planktonic foraminifera has been the process of adaptation to changing environments. Microfaunas reflect the gradual trend towards increasing temperature values with some fluctuations. This may explain the instability of isotope data in this interval. We have also to keep in mind that tectonic activity is important in the Mediterranean area during this time : turbiditic layers, hiatuses, major changes in the lithology with increasing carbonate layers, mainly in event 3. This is not ideal for an environmental reconstruction.

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Paleoecological interpretation of micromammal faunal successions in the Upper Oligocene and Miocene of Spain (Fig. 2,3). (R. Daams & J. van der Meulen).

Abstract. The relative abundance of rodent families in the Late Oligocene to Miocene sections in Northern Spain is used to reconstruct humidity and temperature curves in this time interval. The trend of temperature curve derived by micromammal associations duplicates in general the trend of temperature curves derived from marine biotas by various method.

Continental sediments of Tertiary age are well-represented in Spain. In the past seven summers R. Daams and M. Freudenthal have focused their study at the Calatayud-Teruel basin in order to obtain detailed documentation of the type Aragonian (roughly Middle Miocene). Some 52 faunas have been found, of which a large number could be correlated lithostratigraphically. The biozonation used is an informal one (Fig. 2) as the detailed study of the faunas has
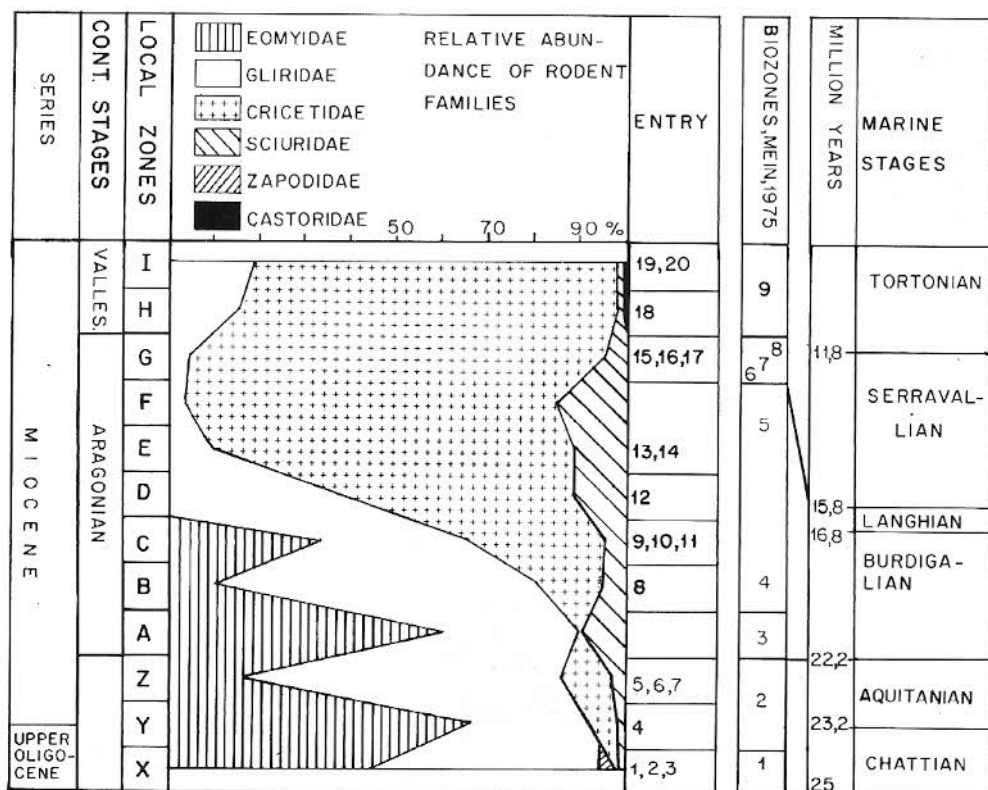

Fig. 2 — The relative abundance of rodent families in the Upper Oligocene and Miocene of North Spain. The correlations between MN zones of Mein (1975), marine stages and absolute time-scale are after Rögl and Steininger (1983).

not been finished yet. For the lower part the letters X, Y, and Z refer to new pre-Aragonian zones, the zones A to I for the Aragonian and Lower Vallesian are the same as published in Daams & Freudenthal (1981).

The correlation of the Spanish zones to the MN zones of Mein (1975) has been done on the basis of our own observations. The correlation of the MN zones to the marine stages, and the absolute datings of the latter, are from Rögl & Steininger (1983).

Van de Weerd & Daams (1978) interpreted the succession of Spanish Neogene mammal faunas in terms of dry and wet biotopes. They used three main criteria to interpret rodent associations paleoecologically:

1) *Eomyidae* (an extinct family) were forest-dwellers;
2) Beavers (*Castoridae*) require streams permanently filled with water;
3) Groundsquirrels (*Sciuridae*) live in dry open country.

Our rodent faunas have been found in river and lake deposits. Alongside these waters we envisage woods and farther away the open-country. Increase and decrease of the relative numbers of the eomyids in successive zones are interpreted to indicate expansion and retreat of the forest which in turn is thought to reflect increase and decrease of the humidity of the climate. On the whole the climate was wetter during the interval covered by zones X to C, and drier during the interval covered by zones D to F. In the latter period ground-squirrels reach their highest frequency. In zone G eomyids, different from the earlier ones, return in very small numbers (not shown in Fig. 2) and towards the end of this zone beavers return (very low numbers of beavers are known from zone Y). In the same interval (G) the groundsquirrels drop significantly in numbers. These observations are thought to indicate an increase of humidity during the interval covered by zones G to I. In addition to the main trend distinct changes of the relative frequency of the eomyids are present in the interval covered by zones X to C. The relative changes of humidity are summarized in Fig. 3.

Additionally we have studied the changes in the glirid fauna. Most of these dormice in our sections are thought to have been open-country dwellers by extrapolating the known ecology of living representatives (Van der Meulen & De Bruijn, 1982). The changes in the *Gliridae* appear to give two different signals. Faunas with abundant *Eomyidae* contain few specimens of *Armantomys* and *Praearmantomys*. On the other hand faunas with few *Eomyidae* contain relatively many specimens of *Armantomys* and *Praearmantomys*. If the *Armantomys/Praearmantomys* - group, giving the first cyclic signal, is left out of the total sum of the glirids, other trends become apparent. For instance, *Peridyromys murinus* decreases in number in the interval covered by zones Z to C, whereas *Microdyromys* increases in number, regardless the changes of humidity. We interpret the trends in *P. murinus* and *Microdyromys* as a second signal, indicating a change of temperature. The former is thought to have tolerated lower, the latter warmer temperatures. One of our arguments is that the first appearance of apes in Europe, is in MN zone 5, which correlates with our zones E/F with abundant *Microdyromys*. The microfauna of Sansan (Gers, France,

lower part of zone G) is dominated by *Microdyromys complicatus*, and the macrofauna of this locality contains apes (*Pliopithecus* and *Plesiopliopithecus*).

On the basis of the relative frequencies of *P. murinus* and *Microdyromys*, we drew the relative temperature curve of Fig. 3. In our model the Late Oligocene and Earliest Miocene appear to be relatively cool, with a peak of higher temperatures in our zone Y (MN zone 2a, Oligocene/Miocene boundary interval). There is a peak of high temperatures in zones E/F, which correlates with MN zone 5 (Langhian, Early Serravallian). It appears also that changes in temperature do not always coincide with changes in humidity.

Our temperature curve shows a remarkable resemblance with the one of Mueller (1983) for surface waters of Mediterranean and North Atlantic based on nannoplankton and planktonic foraminiferal assemblages.
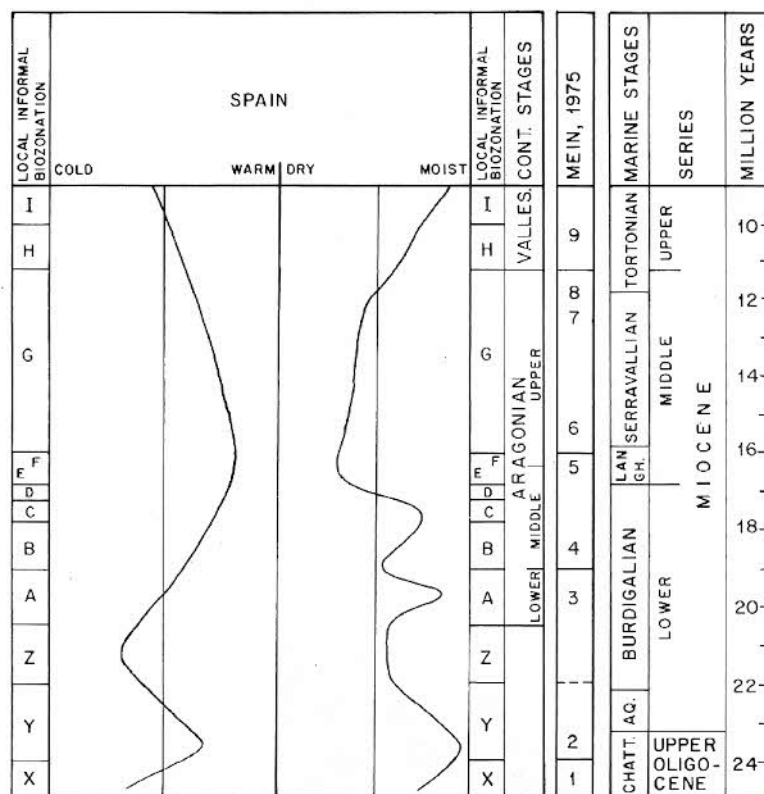

Fig. 3 – Humidity and temperature curves on basis of rodent associations in the Late Oligocene and Miocene of North Spain. Correlations from the marine stages to series and absolute time-scale are after Rögl and Steininger (1983).

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