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Autor: Konijnenburg, Jan-Henk van / Wernli, Roland / Bernoulli, Daniel

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Tentative biostratigraphy of Paleogene planktic foraminifera in thin-section, an example from the Gran Sasso d'Italia (central Apennines, Italy)

JAN-HENK VAN KONIJNENBURG^{1, 2}, ROLAND WERNLI³ & DANIEL BERNOULLI¹

Key words: Early Tertiary, planktic foraminifera, carbonate base-of-slope sediments, depositional hiatuses, Central Apennines, Italy

ABSTRACT

In well lithified pelagic sediments, the study of planktic foraminifera in thin-section is often the only possibility to perform biostratigraphy and to date the sediment. In contrast to the Late Cretaceous, a biostratigraphic subdivision based on forms described in thin-section has been rarely applied for the Paleogene. In this case study from the Gran Sasso d'Italia, we demonstrate that to a limited extent it is possible to arrive at an acceptable biostratigraphic resolution which, by and large, is in good agreement with zonations obtained elsewhere from isolated forms. Our stratigraphic subdivision of the Paleogene succession of the Gran Sasso d'Italia is based on groups of species (and sometimes species) characterised by their general morphology in axial sections and their wall texture.

The Paleogene pelagic and redeposited limestones exposed in the Gran Sasso d'Italia were deposited on the base-of-slope bordering the Lazio-Abruzzi carbonate platform to the southwest and was adjacent to the Umbria-Marche basin in the north. Submarine erosion and redeposition of material along the base-of-slope caused rapid three-dimensional facies changes and hiatuses which can in part be documented biostratigraphically. Three significant regional hiatuses could be recognised; during the Danian (P1d to P2), in the Early Eocene (P6b to P8) and during the latest Eocene/Early Oligocene (P17 to P19).

The subdivision of the Paleocene part of the succession is nearly as precise as with isolated forms, with the exception of the lower limit of the *M. velascoensis* (P5) biozone. However, the subdivision of the Middle and Late Eocene is by far not as detailed as in the Paleocene and Early Eocene. Only a few discrete evolutionary events are easily identified in our material. For the tentative subdivision of the Middle and Late Eocene we used the evolutionary trend of *Turborotalia cerroazulensis* s.l., but the transitions from one subspecies to another cannot be used as discrete boundaries. Oligocene planktic foraminifera are very difficult to determine in thin-section, and a reliable subdivision of the Oligocene is only possible to a limited extent.

RESUME

Dans les séries carbonatées pélagiques indurées du Paléogène, l'étude des foraminifères planctoniques en sections reste souvent le seul outil biostratigraphique pour la datation. Contrairement au Crétacé supérieur où la méthode est maintenant assez bien rodée, le Paléogène n'a fait l'objet que de très rares tentatives dans ce sens et de surcroît l'illustration d'espèces tertiaires en sections est encore très pauvre dans la littérature. Dans le Gran Sasso d'Italia nous démontrons qu'une bonne analyse géométrique des sections de foraminifères planctoniques et de leur paroi permet une résolution biostratigraphique tout à fait satisfaisante qui approche dans certains cas, celle obtenue ailleurs avec des formes dégagées.

Les subdivisions biostratigraphiques proposées ici pour le Paléogène du Gran Sasso sont basées sur des événements paléontologiques qui sont des apparitions (FO), des extinctions (LO), des acmés ou encore des tendances évolutives d'espèces ou de groupes d'espèces reconnaissables en sections.

Les calcaires pélagiques du Gran Sasso ont été déposés en bas d'une pente bordant la plateforme carbonatée du Lazio-Abruzzi au sud-ouest, et adjacente au bassin Umbria-Marche au nord. Le matériel remanié en bas de pente induit de rapides changements latéraux de faciès ainsi que des lacunes et des discontinuités sédimentaires qui sont maintenant bien cernées par la biostratigraphie. Trois lacunes régionales importantes sont reconnues: Durant le Danien (P1d-P2), dans l'Eocène inférieur (P6b-P8) et à la limite éo-oligocène (P17-P19).

Dans nos séries, la subdivision du Paléocène sur des espèces en sections est presque aussi précise que celle donnée par les formes dégagées, à l'exception de la base de la zone à *M. velascoensis* (P5). Plus haut la subdivision de l'Eocène moyen et supérieur est plus grossière et basée en partie sur l'évolution du groupe de *T. cerroazulensis* s.l. La limite Eocène moyen/Eocène supérieure est bien marquée par l'extinction des *Morozovella* et des *Acarinina*. Dans l'Oligocène les sections de foraminifères planctoniques sont très délicates à interpréter et la reconnaissance des biozones reste limitée.

A côté de ces résultats cette recherche est également une contribution à l'iconographie encore très pauvre des foraminifères planctoniques du Tertiaire en sections.

Introduction

The biostratigraphy of Paleogene planktic foraminifera based on isolated specimens from disaggregated samples is well established (Toumarkine and Luterbacher 1985; Boersma et al.

1987; Premoli Silva & Boersma 1988; Nocchi et al. 1988; Berggren & Norris 1997). However, few biostratigraphic subdivisions based on forms described in thin-section have been

¹ Geologisches Institut, ETH-Zentrum, CH-8092 Zürich

² Present address: SIEP-RTS, Volmerlaan 8, P.O. Box 60, NL-2280 AB Rijswijk

³ Département de Géologie et Paléontologie, Université de Genève, 13, rue des Maraîchers, CH-1211 Geneva 4

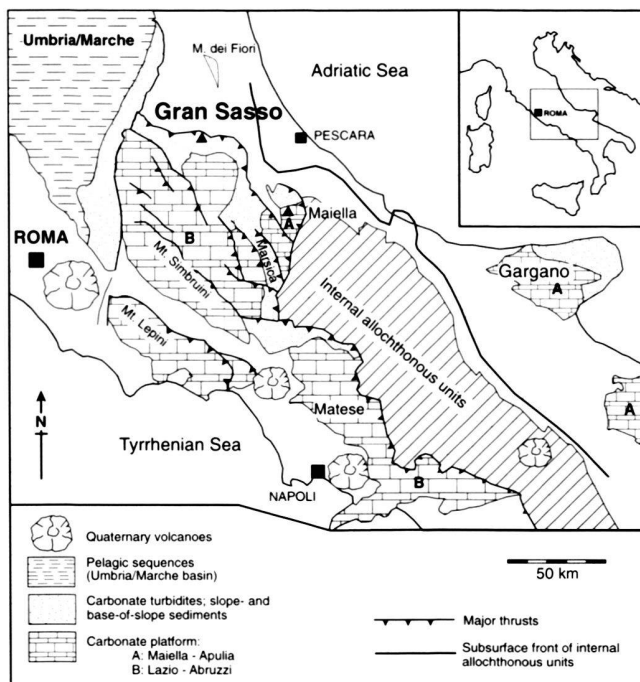


Fig. 1. Regional geology and Upper Cretaceous/Paleogene facies distribution in the central-southern Apennines and location of the Gran Sasso base-of-slope succession (after Eberli et al. 1993).

established for the Paleogene, in contrast to the Late Cretaceous (Renz 1936; Postuma 1971; Caron 1985; Robaszynski et al. 1984; Sliter 1989). Still, in well lithified pelagic sediments, the study of planktic foraminifera in thin-section might be the only possibility to perform biostratigraphy and hence to date the sediment.

This paper presents a case study from the Paleogene of the Gran Sasso d'Italia (Fig. 1), with the aim to demonstrate that, to a limited extent, it is possible to arrive at an acceptable biostratigraphic resolution for planktic foraminifera studied in thin-sections, based on the morphologic characteristics and wall texture of species and groups of species. This resolution can in some cases be nearly as precise as zonal schemes based on isolated specimens. However, identification is based on two-dimensional cross-sections rather than on three-dimensional views, and therefore, some morphologic information will be lost. The taxonomic importance of the wall texture and the surface ornamentation of planktic foraminifera has been extensively debated and is now well established (Li 1987; Premoli Silva & Boersma 1988, 1989; Olsson et al. 1992; Liu & Olsson 1994; Spezzaferri 1994). However, the observation of these characteristics in thin (normal) sections is often problematic and appears not practicable in all cases. Only few attempts in this direction are thus found in the literature.

The biostratigraphic subdivision presented in this paper is largely based on gross morphology and wall structure of co-

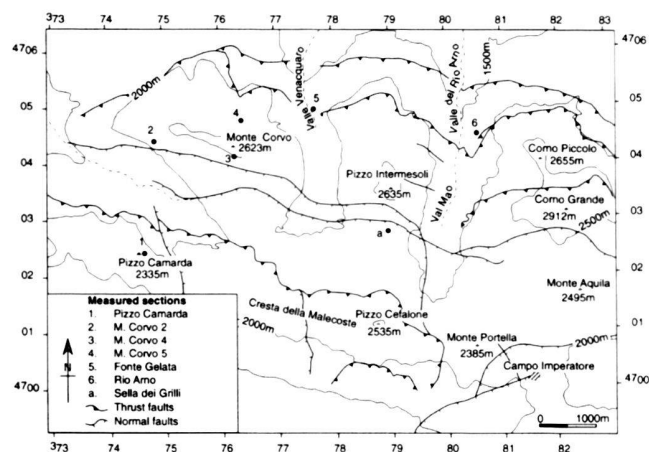


Fig. 2. Schematic tectonic map of the Gran Sasso d'Italia (structural data from Ghisetti & Vezzani 1990). Numbers indicate the location of the measured sections shown in Figure 3.

occurring individual species and groups of species. Because of the homeomorphy of sections of phylogenetically unrelated taxa some species groups are heterogenous. The underlying biozonation is the one proposed by Toumarkine & Luterbacher (1985).

Geological frame and stratigraphy

Samples used in this study are from several measured sections in the Gran Sasso d'Italia (Fig. 2). The Cretaceous to Paleogene limestones of this area represent an ancient base-of-slope succession, which is magnificently exposed in seismic- (km-) scale outcrops (Crescenti 1969; van Konijnenburg et al. in press). These pelagic and redeposited carbonate sediments were deposited along the base of the slopes bordering carbonate platforms situated to the southwest (Lazio/Abruzzi; Accordi & Carbone 1988) and south (Maiella and Apulia, Fig. 1; Eberli et al. 1993; Mutti et al. 1996). This general slope area was adjacent to the Umbria-Marche basin in the north (Fig. 1). Our paper focuses on the Paleogene part of the succession, documented by sections from the northern (i.e. most basinward) part of the Gran Sasso area (Figs. 2, 3). The sedimentology and biostratigraphy of this succession was previously described by Dela Pierre & Bruzzone (1991), Dela Pierre (1992) and Dela Pierre & Clari (1994), and the sedimentology and sequence stratigraphy by van Konijnenburg et al. (in press).

Facies types on the base-of-slope include: (1) breccias and megabreccias, containing a large variety of platform- and slope-derived lithoclasts and minor skeletal fragments; (2) calcareous turbidite beds, with mainly skeletal fragments and minor amounts of smaller lithoclasts; and (3) pelagic/periplatform sediments, i.e. foraminiferal lime mud- and wackestones. Winnowing by contour currents shaped residual deposits (≤ 2 cm thick) with a lag of planktic foraminifera.

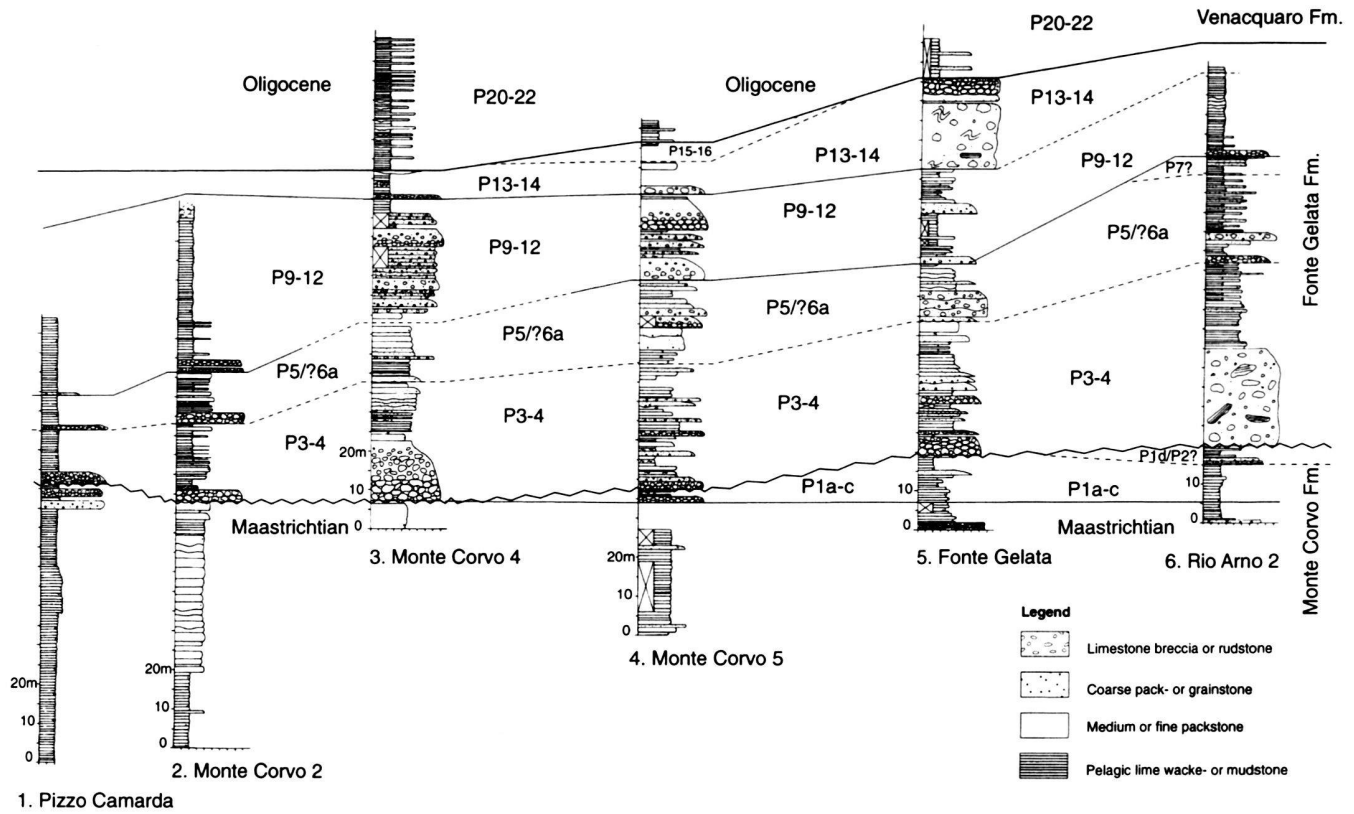


Fig 3. Correlation diagram of the Paleocene to Oligocene parts of the sections located on Figure 2. The breccia bed, which overlies the erosion surface at the lower boundary of the Fonte Gelata Formation, can be traced throughout the Gran Sasso area. The hiatus between the uppermost Thanetian (P5/6a?) and the Upper Ypresian (P9) deposits has no clear sedimentological expression and can only be identified biostratigraphically.

Breccias and turbidite beds have a limited lateral extent and often cannot be followed from one section to the other, despite continuity of the outcrops. Changes in facies associations occur not only down-slope, but also along depositional strike. The bulk of the resedimented material is derived from the adjacent platforms and, therefore, provides additional evidence for platform evolution. Yet, material was also displaced and reworked along the slope by erosion along the base of the gravity-driven mass flows, documented by truncation of the underlying beds, or by slumping of pelagic sediments. The resulting hiatuses can in part be documented biostratigraphically.

The Paleogene deposits of the Gran Sasso d'Italia belong to three formations, the Monte Corvo Formation (Campanian – Lower Danian), the Fonte Gelata Formation (Thanetian – Upper Eocene) and the Oligocene Venacquaro Formation (van Konijnenburg et al. in press). The majority of the Monte Corvo Formation was deposited from the Early Campanian until the end of the Maastrichtian and consists of turbiditic

skeletal pack- to grainstones interlayered with thin pelagic lime wackestone beds and intraclastic breccias. However, the youngest deposits attributed to this formation are pelagic lime wackestone beds of Early Danian age.

The lower boundary of the Fonte Gelata Formation is a marked erosional unconformity, overlain by a basal breccia which cuts up to 3 m into the underlying deposits of the Monte Corvo Formation. The age of the Fonte Gelata Formation ranges from Early Thanetian to latest Bartonian/Priabonian. An important internal depositional hiatus spanning almost the entire Ypresian (P6b to P8) separates the lower from the upper part of the formation (Fig. 3 and Tab. 1). The lower (Paleocene) part of the Fonte Gelata Formation consists of lithoclastic breccias, which up-section are progressively replaced by bioclastic packstones and thin intercalations of pelagic limestones. The upper (Eocene) part of the formation consists of a chaotic interlayering of lithoclastic breccias and bioclastic packstones occasionally interbedded with thin pelagic limestones.

Series	Stages		Planktic Foraminifera Biozones		Planktic Foraminifera Biozones (1985)	Important evolutionary events observed for planktic foraminifera in thin-section
Oligocene	Chattian	Late	<i>G. ciperoensis</i> s.s.	P22/N3	P. eugubina P. pseudobulboides M. uncinata M. angulata group I. pusilla G. chapmani group A. mckannai-nitida group G. pseudomenardii M. aequa M. velascoensis group M. aragonensis group M. subbotinae group P. wilcoxiensis P. pseudosculpta I. broademanni group A. bullbrook group P. meza Globigerinatheka spp. & G. semni M. spinulosa Turonotaloides spp. Herkenna spp. T. cerroazulensis frontosa T. cerroazulensis coccaensis T. cerroazulensis cunalesis Catapsydrax spp. small Turborotalia and Tenutella P. nagaiwachiensis si G. ouachalensis group S. praeterrillina S. gortani G. sellii *G. *ciperoensis farasi?	<ul style="list-style-type: none"> LO <i>Chiloguembelina</i> ▼ ▲ Large globigerinids & lepidocyclinids
		Early	<i>G. ampliapertura</i>	P20/N1		
Eocene	Priabonian	Late	<i>T. cerroazulensis</i> s.l.	P18/19	<ul style="list-style-type: none"> ▼ LO <i>T. cerroazulensis</i> s.l. & <i>Globigerinatheka</i> spp. ▼ LO morozovellids & acarininids ▲ FO <i>T. cerroazulensis</i> s.s. ▲ FO <i>Catapsydrax</i> spp. ▲ FO <i>A. bullbrookii</i> & <i>Globigerinatheka</i> spp. 	
		Early	<i>Gtk. seminivoluta</i>	P17		
	Bartonian	Middle	<i>T. rohr</i>	P16		
		Early	<i>O. beckmanni</i>	P15		
	Lutetian	Middle	<i>M. lehneri</i>	P14		
		Early	<i>Gtk. s. subconglobata</i>	P13		
Ypresian	Middle	Early	<i>H. nuttalli</i>	P12		
		Early	<i>A. pentacamerata</i>	P11		
	Early	Early	not recognized**	P10		
		Early	<i>M. edgan</i>	P9		
Paleocene	Thanetian	Late	<i>M. velascoensis</i>	P8	<ul style="list-style-type: none"> ▲ FO <i>M. velascoensis</i> ▼ LO <i>M. velascoensis</i> ▼ LO <i>M. velascoensis</i> ▼ LO <i>G. pseudomenardii</i>? ▲ FO <i>M. subbotinae</i> group ▲ FO <i>I. pusilla pusilla</i>, <i>G. chapmani</i> & <i>A. mckannai</i> group ▲ FO <i>M. angulata</i> ▲ FO <i>P. pseudobulboides</i> ▲ FO <i>P. eugubina</i> ▼ LO globotruncanids 	
		Middle	<i>G. pseudomenardii</i>	P7		
	Danian	Middle	<i>I. pusilla pusilla</i>	P6a		
		Early	<i>M. angulata</i>	P5		
	Maastrichtian	Early	Early	not recognized*		P4
			Early	<i>P. pseudobulboides</i>		P3
		Early	<i>P. eugubina</i>	P2		
		Early	<i>A. mayaroensis</i>	P1d		
		Early		P1c		
		Early		P1b		
		Early		P1a		

Tab. 1. Stratigraphic correlation diagram for the Paleogene, showing planktic foraminiferal biozonation, and ranges of species and groups of species compiled from the literature (Paleocene and Eocene modified after Toumarkine & Luterbacher, 1985; Oligocene modified after Bolli & Saunders, 1985). Important planktic foraminiferal evolutionary events observed in thin-sections from the Gran Sasso d'Italia are indicated on the right hand side of the table. * P2 is probably, ** P7 possibly preserved in the Rio Arno section.

The lower boundary of the Venacquaro Formation is a paraconformity with a depositional hiatus; no obvious erosional features are observed along the contact. The boundary is easily recognized by the marked lithological change from resedimented limestones to marly hemipelagic lime wackestones. The associated hiatus ranges from the Late Bartonian (P13/14) or Late Priabonian (P15/16) to the "middle" Oligocene (P20–P21?). This formation is "middle" to Late Oligocene in age. Interlayered with the marly pelagic lime wackestones isolated beds of turbiditic bioclastic packstones and grainstones occur. These turbidite deposits are dominantly composed of tests of larger benthic foraminifera (*Lepidocyclina*).

A significant portion of the Paleogene succession is made up by pelagic interbeds (Fig. 3). These interbeds were sampled at 2 to 4 meter intervals.

Biostratigraphy of planktic foraminifera in thin-section

Major biostratigraphic events are associated with planktic foraminifera and are observed in thin-sections from the Gran Sasso d'Italia (Tab. 1). These events are either first occurrences (FO), last occurrences (LO) or, in the case of *Turbotalia cerroazulensis*, evolutionary trends of species or

groups of species (Tab. 1). These diagnostic events are correlated to the zonal scheme of Toumarkine & Luterbacher (1985), which is based on isolated forms. Because of the difficulties in determining planktic foraminifera in thin-section, not all biozones of Toumarkine & Luterbacher (1985) are recognized, however, a stratigraphic subdivision can be established based on the evolutionary events, particularly FO. We also offer additional information on the determination of individual taxa in thin-section. For a complete and systematic description of taxa (including synonymy, authors and stratigraphic distribution) we refer to Toumarkine & Luterbacher (1985).

This study represents the current state of our research and will hopefully be refined in the future. Undoubtedly the analysis of oriented sections across isolated tests following the pioneer work of Postuma (1971) will greatly improve the possibility to determine Paleogene planktic foraminifera in thin-section. For additional reference and illustrations of Paleogene planktic foraminifera in thin-section refer to Luterbacher (1964), McGowran (1968), Postuma (1971), Nocchi et al. (1988), Sartorio & Venturini (1988) and Wernli et al. (1997). The morphogroups of species based on the wall texture are largely derived from the detailed work of Premoli Silva & Boersma (1988, 1989) and Berggren & Norris (1997).

Parvularugoglobigerina eugubina and *Parasubbotina pseudobulloides* (P1a–c) biozones

After the disappearance of larger and evolved Cretaceous species at the K/T boundary, primitive and tiny species like *Guembelitra cretacea* and *Heterohelix globulosa* survived and proliferated, accompanied by the first appearance of *Parvularugoglobigerina eugubina*. Thirty cm higher, *Parasubbotina pseudobulloides* appears together with small calcispheres (van Konijnenburg et al. 1996). The planktic foraminifera in these biozones are generally small (100 to 200 µm) with round chambers and no lateral compression in axial profile. *Parvularugoglobigerina eugubina* is small (≤ 150 µm) and characterized by a low trochospiral (sometimes almost planispiral) coil. *Parasubbotina pseudobulloides* (Pl. 1, Fig. 1), can be distinguished from *P. eugubina* by its larger size (200–220 µm), a flat or even concave spirale side and frequently a well visible aperture. The increase in size of its chambers is relatively rapid; the last chamber is two times larger than the n-2 chamber. This can be observed both in axial as well as in equatorial sections.

Morozovella trinidadensis and “*M.*” *uncinata* (P1d and P2) biozones

Except for one section (Rio Arno), these two biozones could not be identified and are believed to be absent due to erosion associated with the deposition of the overlying lithoclastic breccia at the base of the Fonte Gelata Formation (van Konijnenburg et al. in press).

The FO of “*Morozovella*” *uncinata* (Pl. 1, Figs. 2, 3) indicates the base of biozone P2 and can be recognized in thin-section by its small (~200 µm) delicate, weakly muricate test with subangular chambers. However, in our material it normally occurs higher up at the base of the Fonte Gelata Formation, together with *M. angulata*, and is therefore attributed to the *M. angulata* biozone (P3). However, in the Rio Arno section, where the thickest section of Danian limestones was observed, “*M.*” *uncinata* occurs before the FO of *M. angulata*, probably indicating the “*M.*” *uncinata* biozone (P2).

Morozovella angulata (P3a) biozone

The first appearance of axial sections with muricate walls and (sub)angular chambers marks the beginning of the *M. angulata* zone. The *Morozovella angulata* group (including *M. conicotruncata* and *M. abundocamerata*) is distinguished by its characteristic trapezoidal profile and various degrees of angulation (Pl. 1, Figs. 4, 5).

Igorina pusilla (P3b) biozone

The first appearance (FO) of *Igorina pusilla* (Pl. 1, Figs. 6, 7), is relatively easy to recognize and marks the base of the *I. pusilla* zone. *I. pusilla* has a relatively small (~250 µm) bicon-

vex test. In axial sections it shows a rhombic profile, and on the umbilical side the chambers follow regularly one whorl after another, with flanks subparallel to each other. Unfortunately, its last appearance (LO) cannot be determined, because this species is followed by other taxa which look similar in thin-section.

FO of *Globanomalina chapmani* group

In axial section, this taxon, including *G. ehrenbergi*, is easy to recognize by its large (360 to 500 µm) size, the smooth wall and the slightly biconvex form of the test in equatorial cross-section (Pl. 1, Figs. 8–10). The profile of the chambers is oval-elliptic in primitive specimens and becomes more and more pinched in evolved ones, however, it never develops a true keel.

FO of *Acarinina mckannai-nitida* group

Solid and compact “*Globigerina*”-like forms with muricate-cancellate walls and gently turbinate chambers belonging to the *A. mckannai-nitida* group appear for the first time in this biozone. Their tests are low trochospiral and they generally have a narrow deep umbilicus (cf. *Globorotalia mckannai* in Postuma, 1971). Higher in the series, similar sections may be confused with those of other, unrelated globose *Acarinina*. This type of sections persists until the Middle Eocene and only their FO can be used for dating purposes.

Globanomalina pseudomenardii (P4) biozone

G. pseudomenardii (Pl. 1, Fig. 11) is very similar to *G. chapmani*, but can be distinguished from the latter in axial section by a distinct keel, strongly compressed chambers and a slightly more convex spiral side (cf. McGowran, 1968). However, in thin-section the distinction between *G. chapmani* and *G. pseudomenardii* may be ambiguous, especially since there are numerous intermediate forms between the two species (cf. Pl. 1, Figs. 9 and 10).

FO of *Morozovella velascoensis* group (Pl. 1, Figs. 14, 15)

This group appears at the same time as *G. pseudomenardii* and is readily recognizable. It includes *M. velascoensis* as well as *M. acuta*, which are sometimes difficult to distinguish in thin-section. In axial sections, the height of the chambers is rather uniform in *M. velascoensis*, while in *M. acuta* it increases very rapidly with the last chamber which is very acute and high. The tests of these taxa have a virtually flat spiral and a strongly convex umbilical side, together with a wide, crater-like umbilicus. The muricocarina is strong and the umbilical shoulders of chambers are ornamented by muricae. Because of its distinct form, the FO of this group can be used as a marker for the base of the *G. pseudomenardii* zone. However, care must be taken as these taxa are virtually homeomorphic with the late Early Eocene *M. caucasica*. Only when associated with other species like *G. chapmani* or *G. pseudomenardii* can the *G. pseudomenardii* biozone be ascertained.

FO of *Morozovella aequa* (Pl. 1, Figs. 12, 13)

Morozovella aequa appears shortly after *M. velascoensis*. In axial section, *M. aequa* resembles *M. angulata*, but can be distinguished by its more acute outline, a narrower umbilicus, a weak muricocarina, and a wall completely covered by fine muricae.

Morozovella velascoensis (P5) biozone

The lower boundary of this biozone is difficult to define in our material. Toumarkine & Luterbacher (1985) define it by the LO of *G. pseudomenardii*. However, because of the problems associated with the distinction between *G. pseudomenardii* and *G. chapmani* outlined above, it is not possible to use this datum in thin-section. In our material, the upper boundary of this biozone is marked by the LO of *M. velascoensis* and *G. chapmani*. As *M. acuta* cannot be always distinguished from *M. velascoensis* in thin-section, this event could possibly have taken place in the *M. edgari* (P6a) biozone (Tab. 1).

FO of *Morozovella subbotinae* group (Pl. 1, Figs. 16, 17)

The *M. subbotinae* group, as observed in thin-sections, in which we include *M. subbotinae*, *M. marginodentata* and *M. formosa gracilis* first appears within the *M. velascoensis* zone following Toumarkine & Luterbacher (1985) and Berggren & Norris (1997). We use this FO to determine this biozone, where we do not observe *G. pseudomenardii* with certainty anymore. Representatives of the *M. subbotinae* group have a (slightly) convex spiral and a convex umbilical side, and are in some cases almost symmetrical with respect to the equatorial plane. They have a well developed muricocarina. The chambers have prominent umbilical shoulders, which are rarely ornamented.

The Early Eocene hiatus

In our material, the last appearance of *M. velascoensis* and *G. chapmani* is generally overlain by an association comprising representatives of the *A. bullbrooki* group, *I. broedermanni* group, *M. aragonensis*, *P. pseudoscitula*, *P. wilcoxensis* and *P. micra*, i.e. the *A. pentacamerata* (P9) zone. Therefore, we argue that the *M. subbotinae* to *M. aragonensis* (P6b to P8) biozones are absent in almost all sections. The Rio Arno section forms an exception once again. In this section, an association of *M. subbotinae*?, *M. aragonensis*?, *M. aequa* and *Acarinina* sp. was observed just below the *A. pentacamerata* (P9) biozone, mentioned above, possibly indicating the presence of the *M. formosa formosa*? (P7?) zone in this section (Fig. 3).

Below, we describe several groups of species, the FO of which lies before the *A. pentacamerata* (P9) zone, and which were observed in our material associated with taxa indicating the *A. pentacamerata* (P9) or younger zones.

Igorina broedermanni group (Pl. 2, Figs. 4, 6?, 7?)

In this taxon (= "*Acarinina*" *broedermanni* s.l. auct.), the axial section is oval, rounded rhombic, and middle spired with sub-

angular to rounded chambers. The wall is rugose, totally muricate, and the umbilicus is relatively deep and straight. This taxon (sensu Toumarkine & Luterbacher 1985) becomes extinct in the middle part of the Middle Eocene (P12).

Morozovella aragonensis group (Pl. 1, Fig. 18)

In axial sections, these large morozovellids (including *M. caucasica*) exhibit a flat or slightly convex spiral side with a large, crater-like umbilicus (in evolved forms). The chambers are angular, muricate on their umbilical shoulders, and the muricocarina is well developed, whilst the rest of the walls is weakly muricate. These sections are virtually homeomorphic with those of *M. velascoensis* and only the association with other species can resolve the question.

Planorotalites pseudoscitula (cf. Wernli et al. 1997, their Pl. II, Figs. 11, 12)

In axial sections, this small (200–250 µm) lenticular species shows a low trochospiral test with faintly keeled chambers. The chambers are asymmetrical, being more convex umbilically than spirally, and the walls are rather smooth, or slightly pitted in the last chambers (cf. *Globorotalia renzi* in Postuma 1971).

Pseudohastigerina wilcoxensis (Pl. 1, Figs. 19, 20)

This small (150–180 µm) species is the first planispiral form observed in our material. It has distinctly round chambers, which makes it easily distinguishable from the equatorially compressed *P. micra*.

Acarinina pentacamerata (P9) biozone

This biozone is characterized by the FO of the *Acarinina bullbrooki* group, *Globigerinatheka* spp., *Pseudohastigerina micra* and the *Turborotalia cerroazulensis* group.

Acarinina bullbrooki group (Pl. 2, Figs. 1, 2)

This group of species includes *Acarinina bullbrooki*, *A. matthewsae* and *A. spinuloinflata*; of these, the last species appears somewhat later. The axial sections of their tests are subtriangular to hemicircular, compact and solid. The spiral side is flat to slightly convex, the umbilical side strongly convex. The chambers are subangular to triangular and their walls are thick with well developed muricae. The umbilicus is deep and narrow.

Globigerinatheka spp. (Pl. 1, Figs. 23, 24)

In thin-section the genus *Globigerinatheka* can be recognized by its circular outline, its thick wall, which in many cases is crustose, and the final enveloping chamber covering the primary aperture. In some cases small bullae covering secondary sutural apertures can be observed as well (cf. *Globigerinatheka barri* in Postuma 1971). "*Globigerinatheka*" (= "*Globigerina*" auct.) *senni* first appears in the P9 biozone whereas the other globigerinathekids are rare in P10 and become frequent only in the P11 biozone.

Pseudohastigerina micra (Pl. 1, Figs. 21, 22)

This planispiral species is easy to recognise in axial sections. The chambers are laterally compressed and may increase rapidly in size. Sometimes the lip bordering the broad interior-marginal aperture can be recognized. This species is slightly larger (up to 300 µm) than *P. wilcoxensis*.

Morozovella spinulosa (Pl. 2, Fig. 3)

The axial sections of this species are similar to those of the *M. aragonensis* group, but differ in their walls which are covered with muricae, by more delicate tests and smaller size (~300 µm). Their periphery is "keeled" and the transition from the "keel" to the umbilical shoulders of the chambers is slightly concave.

Turborotalia cerroazulensis frontosa

See comments on *Turborotalia cerroazulensis* s.l. below.

Truncorotaloides spp. (Pl. 2, Figs. 6, 7?)

Plano-convex sections with oval slightly turbinate chambers and spinose walls are attributed to *Truncorotaloides* spp. (excluding *T. topilensis*). The sutures are depressed on the spiral side which shows a small apex of the juvenile whorls in some species (cf. *Truncorotaloides rohri* in Postuma 1971). Sometimes, a discrete secondary aperture can be distinguished (Pl. 2, Fig. 6).

Truncorotaloides topilensis can be distinguished by its flat spiral side, strongly convex umbilical side and characteristic angular (triangular) profile of the last chamber, accentuated by muricae. Although this species is typical for the Middle Eocene, it was rarely encountered in our material.

Hantkenina nuttalli (P10) zone

The FO of the genus *Hantkenina* (Pl. 2, Fig. 8) marks the Early/Middle Eocene boundary. Unfortunately this genus is only very rarely observed in our material. It is therefore difficult to precisely date this boundary in our area.

Middle Eocene

The subdivision of the Middle Eocene is very difficult in the studied area. There are few evolutionary events which can be recognized in thin-section. We strongly rely on the evolutionary lineage of *Turborotalia cerroazulensis* s.l., which is relatively abundant in our material. Additionally, the FO of *Catapsydrax*-like species indicates a *post-G. subconglobata* s.s. (P11) age.

Turborotalia cerroazulensis group (Pl. 2, Figs. 9–11)

The *Turborotalia cerroazulensis* group, in the sense of Toumarkine & Bolli (1970), is rather easy to determine in thin-section. The tests are low trochospiral, with a flat or slightly convex spiral side and a distinctly convex rounded umbilical side. The walls of its chambers are not spinose, and relatively

smooth and flat. The last chamber is typically large compared to the others, ample and overlying a closed umbilicus.

In the initial evolutionary stages of *T. cerroazulensis* s.l., the chambers are inflated (*T. cerroazulensis frontosa*). In the following stages, the chambers become continuously more acute and compressed (*T. cerroazulensis cerroazulensis* and *T. cerroazulensis cocoaensis*), culminating in *T. cerroazulensis cunialensis* with very acute and compressed chambers and a faint "keel" (also compare the series of axial profiles given by Toumarkine & Luterbacher 1985, their Figs. 35 and 36; Wernli et al. 1997, their Pl. 2, Figs. 1–10; and Nocchi et al. 1988). However, *T. cerroazulensis cunialensis* was never observed in our material.

Turborotalia cerroazulensis frontosa

(cf. Wernli et al. 1997, their Pl. II, Fig. 9)

The general axial profile strongly resembles that of a *Globigerina* to which this subspecies was originally attributed. The spiral side is still slightly convex. However, the last chamber occupies about one half of the entire test, with a circular outline when the n-2 chamber (radially facing the last) is slightly turbinate. The FO of this subspecies is in the *A. pentecamarata* (P9) zone.

The two subspecies *Turborotalia cerroazulensis pomeroli* and *Turborotalia cerroazulensis possagnoensis* have not been determined in our material.

Turborotalia cerroazulensis cerroazulensis

(cf. Wernli et al. 1997, their Pl. II, Fig. 4)

T. cerroazulensis cerroazulensis differs from *T. cerroazulensis frontosa* by its virtually flat spiral side and subangular chambers. It appears after *T. cerroazulensis frontosa*, probably in the *Orbulinoides beckmanni* zone. However, because of the numerous intermediate forms between *T. cerroazulensis frontosa* and *T. cerroazulensis cerroazulensis*, it is difficult to exactly determine the FO of the latter.

Turborotalia cerroazulensis cocoaensis (Pl. 2, Figs. 9–11)

The axial profile of *Turborotalia cerroazulensis cocoaensis* is clearly triangular in outline, with subangular to angular chambers. *T. c. cocoaensis* becomes relatively abundant after the P14/15 boundary, but again intermediate forms between *T. c. cerroazulensis* and *T. c. cocoaensis* make it difficult to exactly determine the FO of the latter.

Turborotalia cerroazulensis cocoaensis-cunialensis transitional form (cf. Wernli 1997, their Pl. II, Fig. 5)

The test of this subspecies is smaller, more flattened with a triangular axial section and a more delicate wall. The chambers are clearly angular and have developed a faint keel. In our material, it is the last subspecies of the *Turborotalia cerroazulensis* lineage we observe and its last appearance coincides with the end of Eocene sedimentation in the Gran Sasso d'Italia (P16).

Catapsydrax spp. (Pl. 2, Fig. 13)

In axial sections, the low trochospiral *Globigerina*-like forms with a honey-comb wall and an umbilical bulla are attributed to the *Catapsydrax* spp. Species of *Catapsydrax* become more frequent in the late Middle Eocene and younger strata. Other globigerinids (for example high-spired subbotinids) can sporadically also exhibit an umbilical bulla, but they have a higher spire and appear later in the record.

Globigerina ouachitaensis group (Pl. 2, Figs. 18, 20, 21?)

This group comprises small (100–170 µm) “*Globigerina*” with a thin, smooth wall, including *G. officinalis* and *Tenuitellinata angustiumbilicata*. Their tests are medium trochospiral and subequatorial sections often show an internal polygonal pattern on their walls. The chambers in the last whorl are rounded and the last four chambers increase moderately in size. Although these forms appear in the late Middle Eocene, they become abundant only in the Late Eocene and Early Oligocene.

The Globigerinatheka semiinvoluta and Turborotalia cerroazulensis s.l. (P15–16) biozones

The beginning of the Late Eocene (*Globigerinatheka semiinvoluta* zone) is marked by the abrupt disappearance of all *Acarinina*, *Morozovella* and *Planorotalites* species. *Globigerinatheka* spp. and species belonging to the *Turborotalia cerroazulensis* group (*T. cerroazulensis cocoaensis* and intermediate forms to *T. cerroazulensis cunialensis* in particular) persist, and large *Globigerina* (for example *G. corpulenta*, *G. tripartita*, and *G. eocaena*) become more abundant as well as species belonging to the *G. ouachitaensis* group. *Pseudohastigerina micra* persists and is accompanied by small (~ 150 µm), compact, planispiral species with spherical chambers which we attribute to *P. naguewichiensis* s.l. These two species persist throughout the P20 biozone (Spezzaferri & Premoli Silva 1991).

Small *Turborotalia* and *Tenuitella* (Pl. 2, Figs. 15–17)

Small sections which are low trochospiral, have a flat spiral side and well rounded chambers with a smooth wall are attributed to this group.

The Eocene-Oligocene boundary

In our area, the end of Eocene sedimentation is marked by the last appearance of the *Turborotalia cerroazulensis* lineage, *Globigerinatheka* spp. and *Hantkenina* spp. The last appearance of planispiral forms of the genus *Pseudohastigerina* also occurs at the top of the Fonte Gelata Formation. We never observed a form we could confidently attribute to *T. cerroazulensis cunialensis*. We would therefore argue that the topmost part of the Eocene (P17 of Berggren and Van Couvering 1974 and Blow 1969) is missing.

High-spired subbotinids (*S. praeturritilina*-*S. gortanii* group) (Pl. 2, Fig. 12)

Large (400–600 µm) high trochospiral *Subbotina* species can serve to define in thin-section the onset of the Oligocene. These forms have axially elongated chambers, with relatively thin, honey-comb walls. A small, bulla-like feature frequently covers the umbilicus. When large numbers of these tests are present, the Eocene-Oligocene boundary can be recognized, based on their size. The smaller (≤ 450 µm) forms are attributed to *Subbotina praeturritilina*, and characterize the Late Eocene. The onset of the Oligocene is indicated by the appearance of larger (≥ 500 µm) tests attributed to *Subbotina gortanii*. In our material, only *Subbotina praeturritilina* was rarely observed, but *Subbotina gortanii* could never be confirmed. We therefore conclude that not only the uppermost Eocene but also the lowermost Oligocene is missing.

The Oligocene

Oligocene planktic foraminifera are very difficult to determine in thin-section, and a reliable subdivision of the Oligocene is only possible to a limited extent. The Oligocene strata in the Gran Sasso d'Italia are dominated by large globigerinids (*Subbotina* spp., “*Globigerina*” *venezuelana*, “*G.*” *tripartita*, “*G.*” *rohri*), *Globoquadrina*, *Catapsydrax*, beside small “*Turborotalia*” and *Tenuitella*, all rounded forms difficult to discriminate in thin-sections. Some of these forms can be very large (≥ 500 µm).

Among the benthic foraminifera, both *Lepidocyclina* (*Eulepidina*) sp. as well as *Lepidocyclina* (*Nephrolepidina*) sp. occur in large amounts in turbidite deposits in this part of the series (van Konijnenburg et al. in press). These *Lepidocyclina* are associated with *Heterostegina* sp., *Amphistegina* sp., *Operculina* sp. and *Rotalia* sp., indicating a maximum age of “middle” to Late Oligocene (De Mulder 1975; equivalent to zone P20–21 of Blow 1969).

Globoquadrina sellii (Pl. 2, Fig. 14)

This group is characterized by low trochospiral tests and a compact test shape. The walls of the chambers are pitted and rugose. *Globoquadrina sellii* has a typically flattened rather smooth apertural face on the last chamber. Only when this flat apertural face is observed, can this taxon be positively identified.

“*Globigerina*” *ciperoensis fariasi*? (Pl. 2, Figs. 19, 21?)

Small (100 to 150 µm) high trochospiral globigerinids with a medium thick cancellate wall are tentatively attributed to *Globigerina ciperoensis fariasi*. This species appears in the P21b biozone (see Spezzaferri & Premoli Silva 1991, their Pl. 4, Fig. 6b, and Spezzaferri 1994).

Chiloguembelina (Pl. 2, Fig. 5)

The small biserial tests of *Chiloguembelina* are easy to recognize in thin-section and relatively abundant in our material.

The last appearance of these forms indicates the P21a/b boundary.

Regional hiatuses

A compilation of the data from the entire area shows significant regional hiatuses during the Danian (P1d to P2), in the Early Eocene (P6b to P8) and during the latest Eocene/Early Oligocene (P17 to P19). In the Rio Arno section, the Late Danian P2 biozone is probably present below the Late Danian–Early Thanetian erosional unconformity. This is also the longest section of Lower Danian limestones observed, and erosion before deposition of the overlying sediments seems to have removed less material along this part of the base-of-slope.

Dela Pierre (1992) and Dela Pierre and Clari (1994) stated that the hiatus in the Lower Eocene includes also the *M. velascoensis* (P5) biozone. However, we observed the co-occurrence of *M. velascoensis* and *G. chapmani*, together with the early occurrence of the *M. subbotinae* group, after the disappearance of *G. pseudomenardii*. This association indicates the presence of the *M. velascoensis* (P5) and possibly the *M. edgari* (P6a) biozones. In the Rio Arno section, the P7 biozone is possibly present below the Early Eocene hiatus. However, the determination of the different species is in some cases questionable and more samples should be studied to confirm this age.

Since we did not observe *T. cerroazulensis cunialensis*, we argued for the absence of the latest Eocene (biozone P17 of Blow 1969). Dela Pierre (1992) and Dela Pierre and Clari (1994) also documented the absence of the Early Oligocene based on planktic foraminifera observed in thin-section. We never observed the co-occurrence of *Pseudohastigerina* species with large *Globigerina* species, typical for the Early Oligocene interval. Furthermore *Subbotina gortanii* was not identified and the benthic foraminiferal association in the bioclastic turbidites of the Venacquo Formation indicates a minimum age of “middle” to Late Oligocene. Even though most of this evidence is negative, it is in line with the observations of Dela Pierre (1992) and Dela Pierre and Clari (1994). However, as we pointed out, there are serious problems in applying planktic foraminifera biostratigraphy in thin-section to Oligocene strata and it is difficult to precisely date the upper limit of this hiatus.

Conclusions

The previous section shows that it is, to a limited extent, possible to perform biostratigraphy on Early Tertiary planktic foraminifera in thin-sections. The subdivision of the middle to Late Paleocene is nearly as precise as with isolated forms, with the exception of the lower limit of the *M. velascoensis* (P5) biozone. The difficulties with the distinction between *G. chapmani* and *G. pseudomenardii* and the absence of an additional marker species make it difficult to pin point this boundary.

However, the first appearance of the *M. subbotinae* group can assist in confirming the *M. velascoensis* (P5) biozone.

Several species and groups of species making their first appearance within the *M. subbotinae* (P6b) to *M. aragonensis* (P8) biozones were determined together with species indicating the *A. pentacamerata* (P9) biozone. Therefore, we think that biozones P6b to P8 are not represented (cf. Tab. 1), probably due to submarine erosion (van Konijnenburg et al. in press). The lower boundary of the *A. pentacamerata* (P9) biozone is well defined in the limestones of the area, but not the upper limit of this biozone, the Early to Middle Eocene boundary because of the near absence of *Hantkenina* species in our material.

In fact, the subdivision of the Middle and Late Eocene is by far not as detailed as that of the Paleocene and Early Eocene. Only a few minor evolutionary events are easily identified in our material, like the first appearance of the *Catapsydrax* group at the base of P12 and the disappearance of all *Morozovella* and *Acarinina* species at the Middle to Late Eocene boundary. For the tentative subdivision of the Middle and Late Eocene we used the evolutionary trend of *Turborotalia cerroazulensis* s.l., but the transitions from one subspecies to another are rather gradual. However, more extensive documentation of axial sections of subspecies from this lineage could improve its use in thin-section. The disappearance of *M. aragonensis* would potentially be a useful marker for the top of the *Globigerinatheka subconglobata subconglobata* (P11) biozone, but it could not be used because of the low number of *Morozovella* species observed in the Middle Eocene strata. The FAD and LAD of different *Globigerinatheka* species are important markers in conventional planktic foraminifera biostratigraphy but are of no use in thin-section. The top of the Eocene strata is marked by the disappearance of *Globigerinatheka* spp., *Pseudohastigerina* and *Turborotalia cerroazulensis* s.l. in the Gran Sasso d'Italia.

Paleogene planktic foraminifera biostratigraphy in thin-section is not yet as well established and reliable as for Cretaceous foraminifera. Still, we believe it is to a limited extent possible to perform such a stratigraphy using particular sections of several Early Tertiary foraminifera. We hope this work will inspire other authors to document more examples, in order to further refine this stratigraphy.

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Plate 1

All figures show axial sections unless otherwise indicated. The size mentioned corresponds to the largest diameter of the test.

- Fig. 1. *Parasubbotina pseudobulloides*, 220 µm, Rio Arno 2, P2-biozone, J95125, Monte Corvo Fm.
- Fig. 2. "*Morozovella*" *uncinata*, 200 µm, Rio Arno 2, P3a-biozone, J95127, Fonte Gelata Fm.
- Fig. 3. *Morozovella uncinata-angulata*, 250 µm, Rio Arno 2, P3a-biozone, J95127, Fonte Gelata Fm.
- Fig. 4. *Morozovella angulata*, 340 µm, Monte Corvo 5, P3a-biozone, J95093, Fonte Gelata Fm.
- Fig. 5. *Morozovella angulata*, close to *M. abundocamerata*, 200 µm, Rio Arno 2, P3a-biozone, J95127, Fonte Gelata Fm.
- Fig. 6. *Igorina pusilla*, 260 µm, Monte Corvo 5, P3b-biozone, J95093, Fonte Gelata Fm.
- Fig. 7. *Igorina pusilla?*, 270 µm, Monte Corvo 5, P3a-biozone, J95093, Fonte Gelata Fm.
- Fig. 8. *Globanomalina chapmani* group, 360 µm, Rio Arno 2, P3a-biozone, J95128, Fonte Gelata Fm.
- Fig. 9. *Globanomalina chapmani* group, 560 µm, Monte Corvo 5, P4-biozone, J95096, Fonte Gelata Fm.
- Fig. 10. Intermediate form between *Globanomalina chapmani* and *G. pseudomenardii*, 400 µm, Monte Corvo 5, P4-biozone, J95096, Fonte Gelata Fm.
- Fig. 11. *Globanomalina pseudomenardii*, 280 µm, Monte Corvo 5, P4/5-biozone, J95097, Fonte Gelata Fm.
- Fig. 12. *Morozovella aequa* group, 280 µm, Rio Arno 2, P5/?6a-biozone, J95134, Fonte Gelata Fm.
- Fig. 13. *Morozovella aequa* group, 230 µm, Rio Arno 2, P5/?6a-biozone, J95134, Fonte Gelata Fm.
- Fig. 14. *Morozovella velascoensis* group, 280 µm, Monte Corvo 5, P4-biozone, J95096, Fonte Gelata Fm.
- Fig. 15. *Morozovella velascoensis*, 360 µm, Monte Corvo 5, P4/5-biozone, J95097, Fonte Gelata Fm.
- Fig. 16. *Morozovella subbotinae* group, 480 µm, Rio Arno 2, P5/?6a-biozone, J95132, Fonte Gelata Fm.
- Fig. 17. *Morozovella subbotinae* group, 390 µm, Rio Arno 2, P5/?6a-biozone, J95134, Fonte Gelata Fm.
- Fig. 18. *Morozovella aragonensis* (subaxial section), 350 µm, Rio Arno 2, P9-biozone, J95137, Fonte Gelata Fm.
- Fig. 19. *Pseudohastigerina wilcoxensis*, 150 µm, Monte Corvo 2, P9-biozone, J95102, Fonte Gelata Fm.
- Fig. 20. *Pseudohastigerina naguewichiensis?*, 180 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
- Fig. 21. *Pseudohastigerina micra?*, 130 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
- Fig. 22. *Pseudohastigerina micra*, 320 µm, Monte Corvo 5, P9–12-biozone, J95103, Fonte Gelata Fm.
- Fig. 23. *Globigerinatheka* sp., 240 µm, Rio Arno 2, P9–12-biozone, J95142, Fonte Gelata Fm.
- Fig. 24. *Globigerinatheka* sp., 300 µm, Rio Arno 2, P9–12-biozone, J95142, Fonte Gelata Fm.

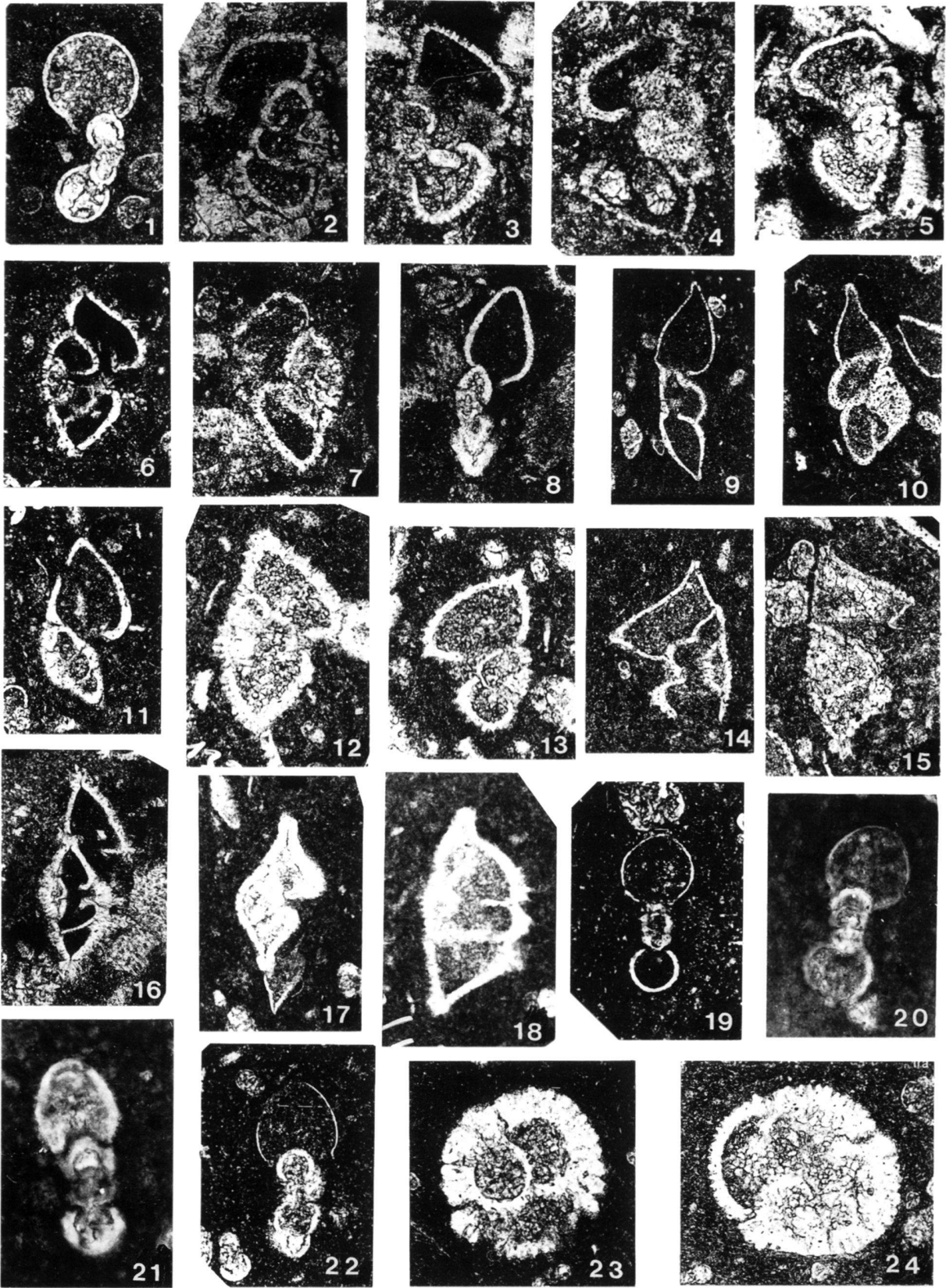
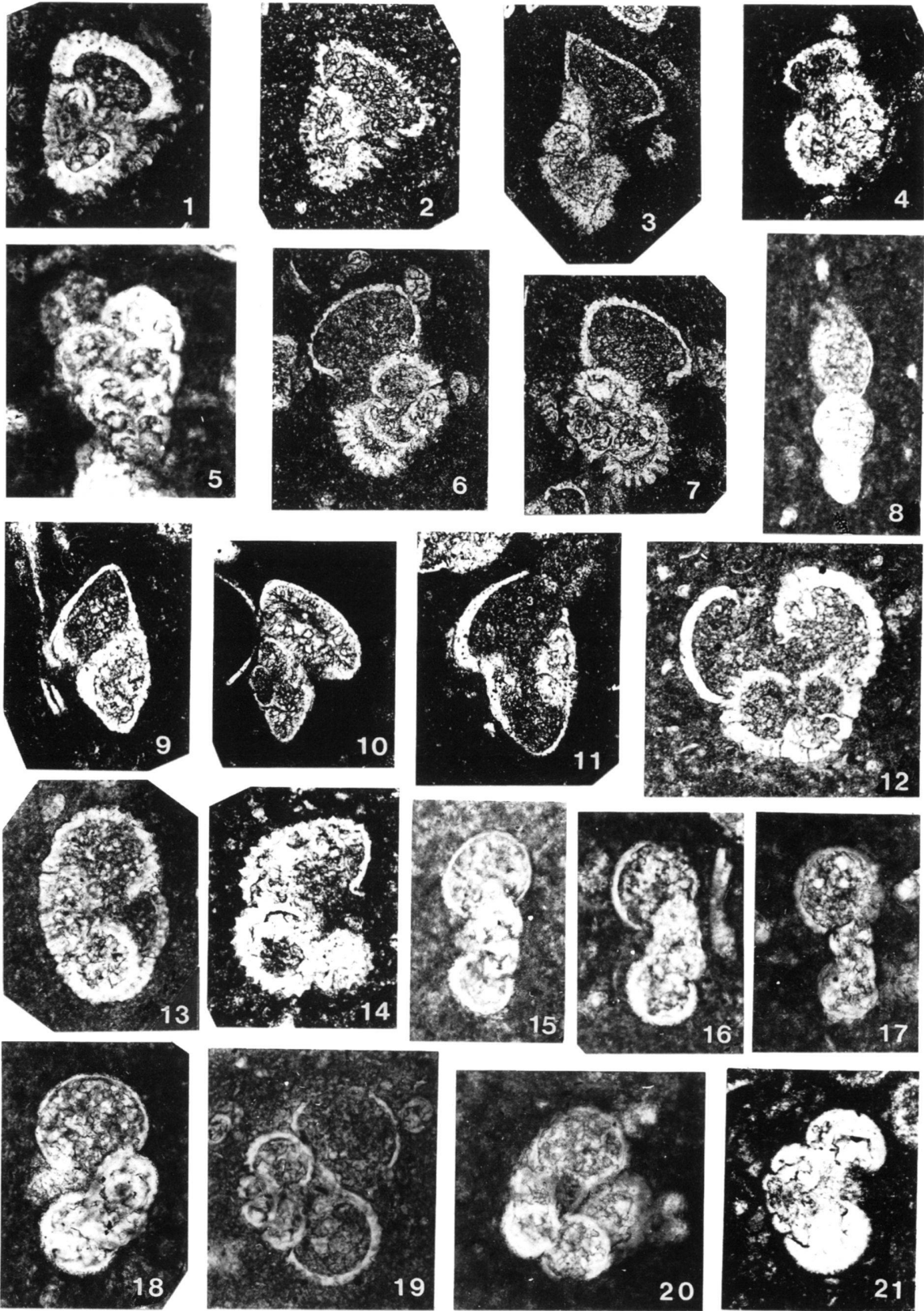


Plate 2

All figures show axial sections unless otherwise indicated. The size mentioned corresponds to the largest diameter of the test.

- Fig. 1. *Acarinina bullbrooki* group, 200 µm, Rio Arno 2, P9–12-biozone, J95140, Fonte Gelata Fm.
Fig. 2. *Acarinina bullbrooki* group, 200 µm, Monte Corvo 5, P9–12-biozone, J95101, Fonte Gelata Fm.
Fig. 3. *Morozovella spinulosa* 630 µm, Monte Corvo 5, P13–14-biozone, J95242, Fonte Gelata Fm.
Fig. 4. *Acarinina* cf. *broedermanni* group, 200 µm, Monte Corvo 5, P9–12-biozone, J95102, Fonte Gelata Fm.
Fig. 5. *Chiloguembelina* sp., 120 µm, Sella dei Grilli, P20–22-biozone, J94156, Fonte Gelata Fm.
Fig. 6. *Igorina broedermanni* group or *Truncorotaloides* sp., 280 µm, Rio Arno 2, P9–12-biozone, J95142, Fonte Gelata Fm.
Fig. 7. *Igorina broedermanni* group or *Truncorotaloides* sp., 240 µm, Rio Arno 2, P9–12-biozone, J95142, Fonte Gelata Fm.
Fig. 8. *Hantkenina* sp., 350 µm, Rio Arno 2, P9–12-biozone, J95141, Fonte Gelata Fm.
Fig. 9. *Turborotalia cerroazulensis cocoaensis*, 240 µm, Monte Corvo 5, P15/16-biozone, J95214, Fonte Gelata Fm.
Fig. 10. *Turborotalia cerroazulensis cocoaensis*, intermediate form to *Turborotalia cerroazulensis cunialensis*, 350 µm, Monte Corvo 5, P15–16-biozone, J95214, Fonte Gelata Fm.
Fig. 11. *Turborotalia cerroazulensis cocoaensis*, 300 µm, Monte Corvo 5, P15/16-biozone, J95214 Fonte Gelata Fm.
Fig. 12. *Subbotina praeturritulina*, 350 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
Fig. 13. *Catapsydrax* sp., 200 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
Fig. 14. *Globoquadrina sellii?*, 240 µm, Monte Corvo 5, P20–22-biozone, J95224, Venacquaro Fm.
Fig. 15. Small *Turborotalia* sp. or *Tenuitella* sp., 110 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
Fig. 16. Small *Turborotalia* sp. or *Tenuitella* sp., 130 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
Fig. 17. Small *Turborotalia* sp. or *Tenuitella* sp., 150 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
Fig. 18. *Globigerina ouachitaensis* group, 170 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
Fig. 19. *Globigerina ciperoensis fariasi?*, 140 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
Fig. 20. *Globigerina ouachitaensis* group, subequatorial section, 140 µm, Sella dei Grilli, P20–22-biozone, J94156, Venacquaro Fm.
Fig. 21. *Globigerina ciperoensis fariasi?*, 100 µm, Monte Corvo 5, P20–22-biozone, J95224, Venacquaro Fm.



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