## Late Quaternary central Mediterranean biochronology

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#### ABSTRACT

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A high-resolution biochronology is presented for the Late Quaternary of the central Mediterranean. In the Late Pleistocene–Holocene successions three assemblage zones are distinguished on the basis of frequency patterns of planktic foraminifera. The age of these zones is determined by Accelerator Mass Spectrometry (AMS) <sup>14</sup>C dating. The zonal boundaries are dated at 12,700 yr B.P. (the end of Termination Ia) and 9600 yr B.P. (the start of Termination Ib), respectively. The AMS dates show that major changes in the planktic and benthic realms occurred synchronously over wide areas, although records of individual species may show important regional differences. In the studied areas, resedimentation processes revealed by anomalous successions of <sup>14</sup>C dates, play a far more important role than indicated by the sedimentological and micropaleontological data. Possibly these processes contribute to the very high accumulation rates in the glacial Zone III. Although the AMS technique has increased the accuracy of <sup>14</sup>C-measurements, admixture of older carbonate may still lead to substantial age differences between areas with different sedimentary regimes.

#### Introduction

The last glacial cycle is one of the best documented examples of abrupt climatic change. Evidence is mainly provided by high-sedimentation cores from open-ocean areas. In the eastern Mediterranean, accumulation rates are generally low, and as a result, only a few detailed studies have focused on the last 15,000 years (e.g. Buckley et al., 1982; Buckley and Johnson, 1988; Caralp, 1988; Vergnaud Grazzini et al., 1988; Pujol and Vergnaud Grazzini, 1989; Troelstra et al., 1991). An exception is the Adriatic Sea, an area with unusually high sedimentation rates, where a large number of high quality piston-cores have been recovered (e.g. Colantoni and Galignani, 1977). Unfortunately, in most studies on these cores, time control is rather poor (e.g. D'Onofrio, 1959, 1973; Cita and Chierici, 1962; Bottema and Van Straaten, 1966; Van Straaten, 1966, 1967, 1972, 1985; Cita and D'Onofrio, 1967; Breman, 1975; Van der Zwaan, 1980).

The primary scope of the present paper is to

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provide a detailed biochronology for the central Mediterranean. The advent of Accelerator Mass Spectrometry (AMS) made it possible to obtain accurate <sup>14</sup>C-ages from very small quantities of calcium carbonate, such as samples of hand-picked foraminifera. This new technique minimalizes the risk of contamination by older carbonates, which may be prevalent in the finest sediment fraction, and which may result in significantly older ages when bulk sediments are dated.

Stanley (1985) opened a paper about the influence of redepositonal processes on mud sedimentation in the Mediterranean by stating that "fine-grained sediments, forming the bulk of unconsolidated Plio-Quaternary series on Mediterranean margins and basins, are largely of redepositional origin." Obviously, much caution is needed when interpreting the faunal assemblages from such sediments. If redepositional processes are already common in the low-accumulation regions in the Mediterranean, then such processes will certainly have influenced sedimentation in the Adriatic Sea. Therefore, it is of primary importance to establish if, and how seriously, the Adriatic Sea sediments are affected by redepositional processes, and to what extent the original faunal signal has been distorted. Unfortunately, most of the sediment cores studied in this paper were sampled in 1968, when the influence of redepositional processes was largely underestimated, and no X-ray radiographs were taken routinely.

In this paper we focus on aspects related to the core stratigraphy. Since the benthic system is much more affected by local environmental parameters than the pelagic system, we base our biozonation on the planktic foraminiferal record (from the southern Adriatic Sea). The successions of benthic foraminifera are used for local refinements of the biozonation. The applicability of our zonation outside the Adriatic Sea is tested in two sediment cores, from the Strait of Sicily and the Tyrrhenian Sea, respectively. The paleoecology of the Late Quaternary planktic foraminiferal assemblages is discussed by Rohling et al. (1993, this volume).

### Material and methods

We selected 11 sediment cores from the Adriatic Sea (Fig. 1; Table 1), for which the core descriptions (Colantoni and Galignani, 1977; UU.OO. Gruppo Bacini Sedimentari, 1979) indicate a minimum of down-slope transport and a maximum of hemipelagic muds. For comparison two cores were selected from the Strait of Sicily and the Tyrrhenian Sea.

Most of the cores consist largely of hemipelagic muds. Those from the central part of the southern Adriatic Sea contain numerous turbidites and ash layers, which have been used successfully for intercore correlations (Van Straaten, 1967, 1985). The Holocene part of the cores contains also a well-developed sapropel  $S_1$ , which consists of two laminated parts, separated by a thin interval of homogeneous mud (Van Straaten, 1972).

In total, we studied some 400 samples. Samples were washed over sieves with meshwidths of 63, 150 and 595  $\mu$ m. The 150–595  $\mu$ m fraction was split in aliquots of at least 200 planktic foraminifera, and 250 benthic foraminifera, respectively. The identified taxa were quantified as a percentage of the total number of planktic or benthic foraminifera. Planktic foraminiferal census data are available on request.

For the planktic foraminifera we largely followed the taxonomic concept of Hemleben et al. (1989). The benthic foraminiferal taxonomy is basically similar to that of Jorissen (1987, 1988).

 $\delta^{18}$ O values of the planktic foraminifer *Globigerina bulloides* were measured in cores IN 68-5, IN 68-9 and IN 68-21. Standard laboratory procedures, as described by Shackleton and Opdyke (1973), were followed, and analyses were performed on a Sira V6 mass-spectrometer. The results are reported as  $\infty$ -devia-

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Fig. 1. Maps showing core localities (a and b) and bathymetry (b).

#### TABLE 1

Core localities; the numbers between brackets refer to the core identification numbers used by Van Straaten (1966, 1967, 1972, 1985). Lithological data can be found in these papers and in Colantoni and Galignani (1977) and UU.OO. Gruppo Bacini Sedimentari (1979). The right-hand columns indicate whether planktic foraminifera (P), benthic foraminifera (B), or both have been studied

Core		Water depth	Latitude	Longitude	Length	Р	В
IN 68-3	(369)	868 m	40°42′8	18°45′3	539 cm	+	+
IN 68-5	(372)	1030 m	41°14′0	18°32'0	643 cm	+	+
IN 68-7	(365)	1225 m	41°56′0	18°14′1	410 cm	+	+
IN 68-9	(362)	1234 m	41°47′5	17°54′5	609 cm	+	+
IN 68-16	(388)	194 m	42°36′9	15°01′3	466 cm		+
IN 68-21	(394)	252 m	42°53′2	14°47′5	719 cm	+	+
IN 68-22	(384)	129 m	42°23′0	15°00′0	544 cm		+
IN 68-23	(381)	64 m	42°11′1	14°55′5	411 cm		+
IN 68-28	(400)	396 m	41°59′5	16°55'3	396 cm	+	
IN 68-29	(401)	797 m	42°00′0	17°08′5	554 cm	+	+
IN 68-38	(404)	716 m	41°07′6	17°34′8	643 cm	+	
CS 73-34		680 m	35° 57' 4	13°25′8	713 cm	+	+
BS 78-12		626 m	42°40′1	9°49′0	585 cm	+	+

tions from the PDB-1 standard (Epstein et al., 1953).

Accelerator Mass Spectrometry <sup>14</sup>C datings were performed on 46 samples. For shallow sites we used carbonate of mixed benthic organisms (foraminifera, molluscs, bryozoans), whereas carbonate of mixed pelagic organisms (foraminifera, pteropods) was used at deeper sites. In order to check whether pelagic and benthic assemblages produce different ages, we dated both types of CaCO<sub>3</sub> in three samples. The biogenic material used for the <sup>14</sup>C dates was hand-picked and pretreated with 4% HCl. The evolved CO<sub>2</sub> gas was reduced to graphite using finely divided iron powder in the presence of excess hydrogen at 920 K (Hut et al.,

1986). Subsequently, the mixture was pressed into a hole of an aluminium holder and the  $^{14}C/^{12}C$  ratio was analyzed, using the Utrecht tandem accelerator (Van der Borg et al., 1987). The <sup>14</sup>C results are expressed in radiocarbon vears, corrected for fractionation according to  $\delta^{13}$ C-values (Stuiver, 1983), and reported with 1- $\sigma$  error including the reproducability and background. The  $\delta^{13}C_{PDB}$  values were routinely measured at the Utrecht Institute of Earth Sciences. No corrections have been made for the mean apparent <sup>14</sup>C-age of surface sea water (reservoir age), which at low and middle latitudes is estimated to be about 400 years (Bard, 1988; Broecker et al., 1988b; Bard et al., 1990).

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## Southern Adriatic planktic foraminiferal zonation

The zonation proposed here is based on major compositional changes in the succession of planktic foraminifera in the southern part of the Adriatic Sea. It consists of three zones, which roughly correspond to the succession of glacial (Zone III), transitional (Zone II) and postglacial (Zone I) phases. A fourth (older) zone may be present in two of our cores, but is not yet well-defined, because both cores show an anomalous succession of <sup>14</sup>C-dates in the critical interval.

The relative frequency patterns of the dominating species in the various cores are shown in Figs. 2 and 3. For reasons explained by



Fig. 2. Relative frequencies of planktic foraminifera plotted against core depth.

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Fig. 3. Relative frequencies of planktic foraminifera plotted against core depth.

Rohling and Gieskes (1989), all morphotypes of Neogloboquadrina are lumped together. The species Globigerinella siphonifera, Hastigerina pelagica, Globoturborotalita rubescens, Orbulina universa, Globigerina digitata, Globoturborotalita tenella and Globigerinoides sacculifer, which show significant positive correlations in a large number of statistical analyses performed on the present data set, will hereafter be treated as one category, termed SPRUDTSgroup (see Rohling et al., 1993, this volume).

Zone I is characterized by the continuous presence (>1%) of the SPRUDTS-group (except for the very basal part of the zone), the (near-)absence of *Globorotalia scitula* (<1%), high relative frequencies of (both white and pink) *Globigerinoides ruber* (>7.5%), and low

numbers of **Turborotalita** quinqueloba (<7.5%). Globorotalia truncatulinoides, which is always scarce, displays a predominantly sinistral coiling. Except for some specific levels around sapropel S<sub>1</sub>, Neogloboquadrina and Globorotalia inflata are absent in Zone I. In our most complete (and most densely sampled) records (IN 68-5 and IN 68-9) there is a clear succession of peak-frequencies in various species around  $S_1$  (Figs. 2-4). A spike of G. inflata at the base of Zone I is followed directly by a peak in Globigerinita glutinata just below  $S_1$ . Higher in Zone I (at the top of  $S_1$ ), a level with abundant Neogloboquadrina and G. in*flata* is followed by raised percentages of G. glutinata. The magnitude of these short-term acmes varies considerably between the cores;



Core IN 68-9

Fig. 4. Overview of interpolated ages of a number of lithological horizons, which Van Straaten (1967, 1985) used for intercore correlations, in cores IN 68-9. probably it is strongly influenced by the sampling interval, which, unfortunately, varies from 1 to 10 cm.

Zone II is characterized by the (near-)absence (<1%) of G. scitula and the sPRUDTSgroup and by high frequencies of Neogloboquadrina (>17.5%). Pink-coloured G. ruber is scarce. In the basal part of the zone the coiling direction of the rare G. truncatulinoides changes from predominantly dextral to predominantly sinistral. The lower part of Zone II shows increased percentages of G. inflata and G. ruber in combination with suppressed numbers of T. quinqueloba and G. glutinata; the reversed pattern is found in the upper part of the zone.

Zone III is characterized by the common occurrence of G. scitula (>1%), the (near-)absence of the SPRUDTS-group (<1%), and relatively high percentages of T. quinqueloba (>3.5%). G. inflata is absent, except for the very top of Zone III. Few to common G. ruber (<22.5%) is always of the white variety. G. truncatulinoides is virtually absent in Zone III.

Since exact presence/absence levels are prone to be influenced by the combination of sediment mixing and differences in sedimentation rate between the studied cores (e.g. in low sedimentation rate cores, even minor bioturbation may cause an artificial "tail" above the original exit-level), we avoided their use for the positioning of zonal boundaries, and used quantitative and sequence criteria instead. The I/II zonal boundary is placed at the very abrupt upward frequency drop of Neogloboquadrina. Generally this event coincides with a sudden increase in G. ruber, and slightly precedes an increase in the SPRUDTS-group (Figs. 2 and 3). The II/III zonal boundary is placed at the strong diminution of G. scitula. Generally, frequencies of this species rapidly fall to zero, but at sites with lower accumulation rates (e.g. IN 68-7) bioturbation resulted in significant upward mixing of G. scitula (Fig. 3). Usually this drop in the abundance of G. scitula is slightly preceded by the re-appearance level of G. in*flata.* The base of Zone III is tentatively placed at the disappearance level of *G. inflata*, which in the southern Adriatic Sea is only found in core IN 68-7.

# <sup>14</sup>C stratigraphy and planktic foraminiferal biochronology

In order to determine the age and synchroneity of our biozones, 46 samples were dated (Table 2). Paired <sup>14</sup>C-dates were obtained for three samples, using benthic foraminifera and pteropods, respectively. Age differences between these pairs are minimal and apparently random, indicating that planktic and benthic organisms are equally suitable for <sup>14</sup>C-dating in this region. In these three cases of "duplicate" dates, we used the younger ages.

The succession of <sup>14</sup>C-ages is very consistent down to 15,000 yr B.P. in all cores (Fig. 5). Below that level the chronology shows major anomalies in cores IN 68-29, IN 68-7 and CS 73-34. These anomalous successions of <sup>14</sup>C ages can only be explained by sliding and redeposition. Core 68-7 shows a turbiditic level between 2.58 and 2.73 m (Colantoni and Galignani, 1977). The sample dated 23,200 yr B.P. (2.5 m) is positioned slightly above this interval and could, therefore, be from the finegrained top of this turbidite. The quick passage from 18,500 yr B.P. at 3.35 m to > 42,000yr B.P. at 4.03 m in the same core suggests the presence of a hiatus. Although there are no clear indications for sliding and redeposition in the other two cores with an anomalous <sup>14</sup>C-stratigraphy (IN 68-29, CS 73-34), we suspect that also here mixing of sedimentary units caused the age discrepancies.

When possible, the ages of the I/II and II/ III zonal boundaries were determined by linear interpolation between <sup>14</sup>C-dates (Table 3). Before interpolating, all ash-layers and turbidites were omitted from the sedimentary record. The maximal differences in the ages of the I/II and II/III zonal boundaries between the various cores are 950 and 1270 years, respectively. In Fig. 4, we show interpolated ages for a number of lithological horizons in core IN 68-9, which Van Straaten (1967, 1972, 1985) used for intercore correlations within the Adriatic Sea (Fig. 5). Remarkably, those ages, as well as those of our zonal boundaries, would turn out to be systematically older, by 300 to even 1400 years, when interpolating between <sup>14</sup>C ages in IN 68-5. However, since the cores IN 68-9 and IN 68-5 are recovered from sites only about 100 km apart, it is hard to imagine that the lithological horizons, or the (bio-)zonal boundaries, would indeed be diachronous, and in the case of ash-layers this would even be highly unlikely. Note that core IN 68-5, recovered from the base of a relatively steep slope (Fig. 1), shows a much higher accumulation rate than core IN 68-9 (Fig. 5). Therefore, the apparently older ages in core IN 68-5 may be the likely result of admixture of reworked foraminifera by down-slope transport.

Since there are a number of processes that may cause an increase in apparent  ${}^{14}C$  ages (e.g. reworking, bioturbation), whereas a decrease in  ${}^{14}C$  ages is very hard to explain, we used the youngest ages for our bioevents. These youngest dates are found in core IN 68-9, which also is the core with the most detailed  ${}^{14}C$ -record. Interpolated ages of the most distinct events in the planktic foraminiferal record of core IN 68-9 are given in Table 4.

The chronology of all other cores (Fig. 6) is based on the ages determined in core IN 68-9 for the I/II and II/III zonal boundaries (9600 and 12,700 yr B.P., respectively) and ash-levels 2 (2800 yr B.P.) and 4 (4900 yr B.P.) of Van Straaten (1985). Below the II/III zonal boundary, where the number of reliable correlative levels is limited, the chronology of the cores is based on the actual <sup>14</sup>C-ages (Fig. 6). In cores IN 68-28 and IN 68-38, which lack <sup>14</sup>Cages, we used ash 8 of Van Straaten (1985), which we dated 17,900 yr B.P. in IN 68-9. In case of anomalous sequences of <sup>14</sup>C-ages below the II/III zonal boundary, we only used the younger ages.

## TABLE 2

<sup>14</sup>C-results. No corrections have been made for the reservoir age. Material: bf=benthic for a minifera, mo=molluscs, pm=plant material, pf=planktic for a minifera, pt=pteropods

Sample number	Laboratory code	Depth in core	Material	Zone	Age (in years B.P.)
Core IN 68-3:					
369-13 •	UTC-904	221.5-224 cm	mo	II/III	13,060±190
369-18	UTC-905	338-340.5 cm	mo	III	$13,400\pm 200$
369-30	UTC-906	524.5-527 cm	bf	III	$16,300 \pm 200$
Core IN 68-5:					
372-1/1A	UTC-899	10-20 cm	bf	I	5800±100
372-5A/3	UTC-900	190-200 cm	pt	1/II	<b>9870</b> ±170
372-9	UTC-901	330340 cm	bf	II	$11,900 \pm 300$
372-12A	UTC-902	460–470 cm	bf	II/III	$13,700 \pm 300$
372-16A	UTC-903	617–626 cm	bf	III	$14,700 \pm 300$
Core IN 68-7:					
365-1	UTC-854	0–5 cm	pf	I	$1290 \pm 120$
365-10	UTC-855	180–185 cm	pf	111	$15,400 \pm 200$
365-12A	UTC-856	248–253 cm	pt	III?	$23,200 \pm 600$
365-16	UTC-857	335-340 cm	pt	IV?	$18,500 \pm 300$
365-19	UTC-858	401–406 cm	pf	IV?	> 42,000
Core IN 68-9:					
362-2	UTC-500	11 - 12  cm	bf	I	$3160 \pm 120$
362-7	UTC-1607	54–55 cm	pf	I	$6390 \pm 60$
362-18	UTC-501	155.5–157.5 cm	bf	I/II	$9280 \pm 180$
362-25	UTC-502	241–242 cm	pf	top III	$13,100\pm 200$
362-30	UTC-503	322–323 cm	pf	III	$14,200 \pm 300$
362-44	UTC-504	510–511 cm	pf/pt	III	$17,200 \pm 300$
Core IN 68-16:					
388-17	UTC-508	255–256 cm	bf	III	$15,100\pm 500$
388-28	UTC-509	461–462 cm	bf/mo	III	$19,900 \pm 400$
Core IN 68-21:					
394-1	UTC-510	0–2 cm	bf	I	$830 \pm 100$
394-10	UTC-511	163.5–165.5 cm	mo/bf	I	$7160 \pm 140$
394-14	UTC-512	244–247 cm	mo	I	$9510 \pm 130$
394-19	UTC-513	439.5–442.5 cm	bf	11/111	$13,300 \pm 400$
394-Sc	UTC-896	700–725 cm	bf	111	15,800±500
Core IN 68-22:		<u>.</u>		_	
384-1	UTC-850	0-1 cm	br	1	1140±90
384-4	UTC-851	58-59 cm	mo	1	$4360 \pm 100$
384-9	UTC-852	197–198 cm	bt	1	6000±140
384-14	UTC-853	321-322 cm	bi	1	8450±130
384-24	010-895	542-543 cm	br/mo	11	9700±160
Core IN 68-23:		<b>A A</b>		Ŧ	100 1 00
381-1	UTC-505	0-2 cm	bt	L	$400 \pm 90$
581-1 281-2	UTC-536	U-2  cm	pm	I	Recent
381-3	UTC-677	41-46 cm	bi	I	$1030 \pm 70$
J01-0 291 10	UIC-0/8	110-121 cm	DI	i T	$2180 \pm 70$
J01-10 201 17	UTC 507	210-221 cm	01 5.6	i T	207UII30
301-17	010-307	3/0-381 cm	DI	1	4390±100

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Sample number	Laboratory code	Depth in core	Material	Zone	Age (in years B.P.)
Core IN 68-2	29:				
401-14	UTC-897	390–397 cm	bf	III?	$27,100 \pm 600$
401-19	UTC-898	542–555 cm	bf	III?	$23,600 \pm 500$
Core CS 73	34:				
CS-5B	UTC-910	29.5-31 cm	bf	I/II	$10,780 \pm 160$
CS-5P	UTC-893	29.5-31 cm	pt	I/II	10,340±150
CS-8B	UTC-911	74.5–76 cm	bf	II/III	$15,070 \pm 190$
CS-8P	UTC-894	74.5–76 cm	pt	II/III	$15,400 \pm 300$
CS-17	UTC-912	274-275.5 cm	pt	III	$21,800 \pm 400$
CS-28	UTC-913	487-488.5 cm	bf	III/IV?	34,200 + 1600 / - 1300
CS-38	UTC-914	696-697.5 cm	bf	IV?	26,000+6000/-4000
Core BS 78-	12:				
BS-9B	UTC-907	146.5-148 cm	bf	I/II	$10,600 \pm 200$
BS-9P	UTC-892	146.5-148 cm	pt	I/II	$10,050 \pm 140$
BS-16	UTC-908	282-283.5 cm	bf	II/III	13,820±190
BS-29	UTC-909	550.5-552 cm	bf	III	$21,100 \pm 400$



Fig. 5. Outline of the biozonation and <sup>14</sup>C-dates of the studied cores. Roman numbers refer to Zones I to III.

The sediment accumulation curves presented in Fig. 6 reveal that accumulation rates are generally lower in Zone I than in Zones II and III. The anomalies in the succession of <sup>14</sup>Cages in three of the cores suggest that the high accumulation rates in Zone III could at least partially result from redeposition of older sediments, and not solely from an increase in the rate of hemi-pelagic sedimentation.

Subsequently, time-abundance plots of the

#### TABLE 3

Core	Locality	I/II zonal boundary	II/III zonal boundary
IN 68-3	Southern Adriatic, sill		12,870 yr B.P. (212.5 cm)
IN 68-5	Southern Adriatic	10,180 yr B.P. (215 cm)	13,590 yr B.P. (455 cm)
IN 68-9	Southern Adriatic	9620 yr B.P. (163.5 cm)	12,680 yr B.P. (233 cm)
IN 68-21	Central Adriatic	10,100 yr B.P. (276 cm)	13,110 yr B.P. (431 cm)
IN 68-22	Central Adriatic	9060 yr B.P. (429 cm)	_
CS 73-34	Sicily Channel	9780 yr B.P. (22.5 cm)	13,610 yr B.P. (75 cm)
BS 78-12	Tyrrhenian Sea	10,330 yr B.P. (157 cm)	13,630 yr B.P. (272 cm)

#### TABLE 4

Interpolated ages (in core IN 68-9) of main events in the planktic foraminiferal record

2nd frequency increase Neogloboquadrina spp. and G. inflata in top $S_1$	6400 yr B.P.
1st frequency increase Neogloboquadrina spp. and G. inflata in top S <sub>1</sub>	7200 yr B.P.
Frequency increase SPRUDTS-group	7800 yr B.P.
G. glutinata Acme at basis $S_1$	8600 yr B.P.
G. inflata Acme in basal part Zone I	9300 yr B.P.
Zone I/II-boundary	9600 yr B.P.
Frequency increase G. inflata in basal part Zone II	11,700 yr B.P.
Change in coiling (from dextral to sinistral) in G. truncatulinoides	11,700 yr B.P.
Zone II/III-boundary	12,700 yr B.P.
Exit G. scitula	12,700 yr B.P.
Re-entry G. inflata in top Zone III	13,700 yr B.P.

most important taxa were constructed for all cores (Figs. 7 and 8). In the southern Adriatic cores, the position of sapropel S<sub>1</sub> has been fixed on the basis of the age range established in standard core IN 68-9 (8300-6300 yr B.P.). Figures 7 and 8 show that in the southern Adriatic Sea, changes in the planktic foraminiferal record are highly synchronous. In most cases, age differences of specific bio-events between cores are less than 500 years. Unfortunately, the temporary disappearance of G. inflata in core IN 68-7, on which we tentatively defined the base of Zone III, could not be dated with certainty, because this bioevent is positioned in a section with anomalous <sup>14</sup>C-ages. However, this temporary disappearance is not found in core IN 68-29, which yields a maximum <sup>14</sup>C-age of 27,100 yr B.P. This suggests that G. inflata disappeared from the central Mediterranean before that time.

## **Benthic for aminiferal biochronology**

The main changes in the benthic foraminiferal record are remarkably coincident with those in the planktic foraminiferal record. Because the number of species is large, and some species occur only in a relatively short timespan, the zonation can easily be adapted, and can locally be refined.

Frequencies of the most time-indicative benthic foraminiferal taxa are plotted versus apparent <sup>14</sup>C-ages in Figs. 9–11. Interpolated ages of the main events in the benthic record are listed in Table 5. In the southern Adriatic Sea, Zone I is characterized by high percentages of Uvigerina mediterranea, Gyroidina altiformis, Gyroidina orbicularis and Hoeglundina elegans. A number of taxa is virtually absent; Bolivina albatrossi, Cibicides wuellerstorfi, Siphotextularia affinis and Trifarina angulosa disappear at or just above the I/II zonal boundary (Table 6; Figs. 9 and 11). These species are generally present in fair numbers below the I/II zonal boundary. The assemblages in and around  $S_1$  are completely different. There, typical low-oxygen tolerant taxa such as *Globobulimina pyrula*, *Chilostomella czizeki*, *Cassidulinoides bradyi*, *Bulimina costata* and *Uvigerina peregrina* prevail, whereas the taxa which are characteristic for the remainder of Zone I may even be absent.

Zone I can be subdivided into 5 successive intervals, each characterized by a specific combination of species:

(1) 9600-8300 yr B.P.: a diversified fauna, in which *Bolivina spathulata*, *B. albatrossi* and *S. affinis* are still present.

(2) 8300-6300 yr B.P.: acmes of C. czizeki, G. pyrula, C. bradyi, B. costata and U. peregrina indicate that the faunas are affected by low-oxygen conditions. In the middle part of  $S_1$  benthic faunas may even be absent.

(3) 6300-4500 yr B.P.: faunas without B. albatrossi, B. spathulata and S. affinis, and with fairly high percentages of G. altiformis, G. orbicularis and Nonion barleeanum. U. mediterranea does not exceed 15%.

(4) 4500-3000 yr B.P.: faunas with abundant U. mediterranea (>20%) and H. elegans. N. barleeanum is virtually absent.

(5) 3000 yr B.P.-Recent (missing interval in most cores): faunas differ from those of the previous interval by raised percentages of *Cassidulina crassa* and by the presence of *Cassidulina subglobosa*.

The I/II zonal boundary (9600 yr B.P.) coincides with a strong upward decline of *Cibicides pachydermus* (Fig. 9). At the same level *T. angulosa* shows an exit (Fig. 11).

In Zone II B. albatrossi, C. wuellerstorfi, S. affinis and T. angulosa are present throughout. Just as in Zone I, Karreriella bradyi is absent







Fig. 6. Control points used for interpolations and accumulation rates for the thirteen cores studied. (a) Southern Adriatic Sea, (b) central Adriatic Sea, (c) Sicily Channel and Tyrrhenian Sea.



Fig. 7. Relative frequencies of planktic foraminifera plotted against time. The  $S_1$ -interval is stippled. The abundance patterns in the basal part of five of the cores are hatched as an indication of poor time control.

(Fig. 12). Bulimina marginata, B. costata, Hyalinea balthica and N. barleeanum are present in fair numbers. Two distinct intervals can be recognized:

(1) 12,700-11,000 yr B.P.; G. altiformis and U. peregrina are relatively abundant, whereas C. pachydermus is scarce or even absent.

(2) 11,000-9600 yr B.P.: C. pachydermus (Fig. 9) shows peak frequencies (up to 70%), and in turn G. altiformis and U. peregrina are scarce or even absent.

The II/III zonal boundary (12,700 yr B.P.) coincides with the exit of *Sigmoilina sellii* and *K. bradyi* (Figs. 10 and 11). *G. altiformis* and

*H. elegans* first occur at this level (Figs. 9 and 10).

In Zone III B. albatrossi, C. wuellerstorfi, S. affinis as well as K. bradyi are present. The assemblages are dominated by B. spathulata, C. pachydermus, U. peregrina and Pyrgo depressa. Two intervals can be distinguished on the basis of the relatively brief presence of S. sellii (Fig. 10):

(1) older than 15,000 yr B.P.: S. sellii is absent.

(2) 15,000–12,700 yr B.P.: faunas with S. sellii.

In core IN 68-7 the exit level of Epistomi-

*nella rugosa* is positioned only one sample below the temporary disappearance of the planktic foraminifer *G. inflata*, on which we tentatively placed the basis of Zone III.

## Applicability of the zonation outside the southern Adriatic Sea

## *Central Adriatic Sea* (cores IN 68-16, -21, -22, -23)

The three zones defined in the southern Adriatic basin can also be recognized in core IN 68-21 from the central Adriatic basin. In this shallow water area (maximum water depth 270 m) relatively deep dwelling taxa such as Neogloboquadrina (scarce in Zones II and III), and G. scitula (absent throughout) are much less frequent than in the southern Adriatic (Fig. 8). The patterns of G. ruber and the SPRUDTSgroup (Fig. 7) are identical to those in the southern Adriatic, and therefore, the position of the I/II zonal boundary can easily be identified. T. quinqueloba is abundant in the basal part of core IN 68-21. Its dramatic decline higher up in the core is thought to be timeequivalent with the II/III zonal boundary in the southern Adriatic. Interpolated ages of the zonal boundaries (10,100 and 13,100 yr B.P., respectively) show a difference of only 500



Fig. 8. Relative frequencies of planktic for aminifera plotted against time. The  $S_1$ -interval is stippled. The abundance patterns in the basal part of five of the cores are hatched as an indication of poor time control.



Fig. 9. Relative frequencies of benthic foraminifera plotted against time. The  $S_1$ -interval is stippled. The abundance patterns in the basal part of three of the cores are hatched as an indication of poor time control.

TABLE 5

Interpolated ages (in core IN 68-9) of main events in the benthic foraminiferal record

Entry Cassidulina subglobosa	Topmost sample	
Exit Bolivina spathulata	6600 yr B.P.	
Exit Siphotextularia affinis	8600 yr B.P.	
Exit Bolivina albatrossi	8600 yr B.P.	
Exit Cibicides wuellerstorfi	9300 yr B.P.	
Exit Trifarina angulosa (I/II-boundary)	9600 yr B.P.	
Acme Cibicides pachydermus	11,000-10,000 yr B.P.	
Exit Karreriella bradyi (II/III-boundary)	12,700 yr B.P.	
Exit Sigmoilina sellii (II/III-boundary)	12,700 yr B.P.	
Entry Sigmoilina sellii	15,300 yr B.P.	

years with the ages of the same levels in our standard core IN 68-9. This strongly suggests that the major turnovers in the planktic foraminiferal record were synchronous throughout the Adriatic Sea.

In the other three central Adriatic cores, the



Fig. 10. Relative frequencies of benthic for aminifera plotted against time. The  $S_1$ -interval is stippled. The abundance patterns in the basal part of three of the cores are hatched as an indication of poor time control.

planktic foraminiferal faunas become very poor due to the shallow water depth. Here the observed synchroneity of the main events in the benthic and planktic foraminiferal records proves to be very useful. Although the benthic foraminiferal faunas from the much shallower central Adriatic are substantially different from those in the deep southern Adriatic, the zonal boundaries can easily be recognized. The I/II zonal boundary is characterized by a very rapid increase in the relative frequency of *U. mediterranea* (Fig. 11), whereas also here the II/III zonal boundary coincides with the exit of *S. sellii* (Fig. 10). As in the southern Adriatic, a number of local subzones can be recognized. These subzones yield a stratigraphic resolution of 1500 to 3000 years.

### Strait of Sicily (core CS 73-34)

The I/II zonal boundary in core CS 73-34 from the Strait of Sicily is characterized by a strong drop in the relative frequency of *Neo*globoquadrina, and a rapid increase of *G. ruber* and the SPRUDTS-group (Figs. 7 and 8). It is dated at 9800 yr B.P. The exit of *G. scitula*, indicative of the II/III zonal boundary, has an interpolated age of 13,600 yr B.P. These ages fall within the range of values found in the southern Adriatic (Table 3), which may sug-



Fig. 11. Relative frequencies of benthic foraminifera plotted against time. The  $S_1$ -interval is stippled. The abundance patterns in the basal part of three of the cores are hatched as an indication of poor time control.

gest that our zonal boundaries are quite synchronous throughout the central Mediterranean. The temporary disappearance level of G. *inflata*, which is tentatively used to define the basis of our Zone III, is in core CS 73-34 found at about 460 cm. Unfortunately, the lower part of this core shows an anomalous succession of  $^{14}$ C dates, just as in core IN 68-7, which is the only other core which contains this exit.

Zonal criteria defined in the benthic record of the southern Adriatic are no longer fully applicable in core CS 73-34. However, the frequency plots of *B. albatrossi*, *S. affinis* and *C. wuellerstorfi* (all with an exit around the I/II zonal boundary) are remarkably similar to those of the southern Adriatic basin. The marker species S. sellii and P. depressa are absent in Zone III, whereas K. bradyi is only found in one sample. Therefore, the II/III zonal boundary is less clear; it seems to coincide with an increase in G. altiformis, G. orbicularis and U. mediterranea. These species are typical for Zone I in the southern Adriatic. It is remarkable that also in core CS 73-34 the exit of E. rugosa is present. As in core IN 68-7 this event, which may well be synchronous in the central Mediterranean, is positioned slightly below the exit of G. inflata.

### Tyrrhenian Sea (core BS 78-12)

In core BS 78-12, our zonal criteria allow the recognition of the I/II zonal boundary at an interpolated age of 10,300 yr B.P. The II/III zonal boundary yields an interpolated age of 13,600 yr B.P. Again, these values fall within the age ranges found in the southern Adriatic. We propose, therefore, that the major changes in planktic foraminifera are fairly synchronous in the Tyrrhenian Sea and the central Mediterranean. We realize, however, that further study is required to assess the validity of this suggestion.

The benthic foraminiferal record of core BS 78-12 shows many similarities with those of the southern Adriatic Sea. The exits of *B. albatrossi* and *S. affinis* coincide with the I/II zonal boundary (Figs. 9 and 11), but the exit of *C. wuellerstorfi* is positioned somewhat earlier, at about 11,500 yr B.P. Rather surprisingly, the Zone III marker species S. sellii and K. bradyi, which were virtually absent in the Strait of Sicily core, are present in small amounts in core BS 78-12 (Fig. 10). As in the southern Adriatic, their exits coincide with the II/III zonal boundary.

## Stable isotope stratigraphy

In Fig. 12,  $\delta^{18}$ O-values of *G. bulloides* are plotted versus time for cores IN 68-5, IN 68-9 (both southern Adriatic Sea) and IN 68-21 (central Adriatic Sea). This figure shows that the three records are highly comparable, although in detail some differences occur due to calibration problems and differences in sample spacing. Between 9800 and 9000 yr B.P. an abrupt shift to lighter values is recorded in all three cores. The age range of this shift indi-



Fig. 12.  $\delta^{18}$ O records of two southern Adriatic (IN 68-5, IN 68-9) and one central Adriatic (IN 68-21) sediment cores. Roman numbers refer to Zones I to III.

cates that this event correlates with Termination Ib (e.g. Duplessy et al., 1981; Mix and Ruddiman, 1985; Broecker et al., 1988a). The position of our I/II zonal boundary at 9600 yr B.P. indicates that this important faunal turnover coincides with the beginning of Termination Ib. The (Younger Dryas) cool period, immediately preceding Termination Ib, is not particularly well reflected in our records, although there are somewhat enriched  $\delta^{18}$ O values in the upper half of Zone II up to the I/II zonal boundary.

In the cores from the southern Adriatic Sea, another shift to lighter values is perceptable between 15,000 and 12,700 yr B.P. (our II/III zonal boundary). Its age range accords well with the youngest ages given in the literature for Termination Ia (e.g. Mix and Ruddiman, 1985; Bard et al., 1987). Apparently our II/III zonal boundary reflects the end of this event.

In core IN 68-21 from the shallow central Adriatic basin, Termination Ia cannot be recognized. In contrast to the other two cores, oxygen isotope values in Zone III are not heavier than those in Zone II (Fig. 12). Tentatively, we infer that at glacial times, when sea level stood some 120 m below the present level (Fairbanks, 1989), core IN 68-21 was positioned directly in front of the Po outlet. At the onset of the last deglaciation, meltwater discharge into the central Adriatic basin would have resulted in a reduction of the surface water salinities and, consequently, in lighter isotope values. If so, the effect of meltwater on the isotope composition in the central Adriatic Sea would have diminished in the course of the deglaciation, as the Po outlet shifted northward to its present-day position with the rise of sea level.

## **Discussion and conclusions**

Major changes in the planktic foraminiferal record at 12,700 and 9600 yr B.P. are used to subdivide the Late Quaternary sequences from the central Mediterranean into three zones. These zones coincide with the pleniglacial, a transitional phase, and the Holocene interglacial. The oxygen isotope record reveals that the break at 9600 yr B.P. corresponds to Termination Ib, whereas the faunal boundary at 12,700 yr B.P. reflects the end of Termination Ia.

Although the main changes in the Late Quaternary planktic foraminiferal record seem to be synchronous in the central Mediterranean, the abundance patterns of some individual species show large differences between the various areas. Cold-water species show the most similar records; the exit of G. scitula, defining our II/III zonal boundary appears to be synchronous in the entire Mediterranean (compare Buckley and Johnson, 1988). Also the strong frequency decrease in T. quinqueloba at our I/II zonal boundary seems to occur in the whole western and central Mediterranean (compare Vergnaud Grazzini et al., 1988). Warm-water species show similar patterns over large areas as well. Both G. ruber (compare Vergnaud Grazzini et al., 1988) and the species of our SPRUDTS-group show a strong increase at the I/II zonal boundary throughout the Mediterranean. An earlier period of raised frequencies of these taxa in the lower part of Zone II (12,700–11,000 yr B.P.) is limited to the eastern part of the Mediterranean (in this case including the Strait of Sicily). The abundance patterns of Neogloboquadrina, and especially those of G. inflata, are more variable. Nevertheless, the significant decrease of Neogloboquadrina at the I/II zonal boundary can be recognized everywhere in the Mediterranean. Also G. inflata, which today is highly frequent in the western Mediterranean, and absent in the eastern Mediterranean, shows a number of correlatable peaks around sapropel  $S_1$ .

Sapropel S<sub>1</sub> was only found in the southern Adriatic Sea, where it consists of two (laminated) intervals. Its interpolated age (8300-6300 yr B.P.) agrees well with the reported ages in the literature (review in Vergnaud Grazzini et al., 1986).

Although different taxa may be involved in different areas, the benthic foraminiferal events are unexpectedly synchronous, and coincide with the major changes in the pelagic record. Minor changes in the benthic records allow a further refinement of the biozonation.

The combined presence of Globorotalia inflata and (the benthic foraminifer) Epistominella rugosa is only found in cores IN 68-7 and CS 73-34. These are the only cores with radiocarbon ages older than 30,000 yr B.P. The fact that both species are completely absent in core IN 68-29, which shows a maximal radiocarbon age of 27,100 yr B.P. suggests that the (for G. inflata temporary) exit of these taxa took place before 27,000 yr B.P. This would be in agreement with the age of 36,000 yr B.P., which Muerdter and Kennett (1984) assigned to the exit of G. inflata.

Anomalies in the successions of AMS<sup>14</sup>C dates suggest that resedimentation processes play a far more important role in the central Mediterranean than is suggested by sedimentological and faunal data alone. An undisturbed record seems to be present down to about 15,000 vr B.P. in all central Mediterranean cores. However, especially at localities at the base of the continental slope, admixture of older foraminiferal tests seems to have resulted in too old <sup>14</sup>C ages. Older parts of the record frequently show anomalous <sup>14</sup>C sequences, indicating that slumping and redeposition took place frequently during glacial times, possibly contributing to the substantially higher glacial accumulation rates.

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