200 Year interruption of Holocene sapropel formation in the Adriatic Sea

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ABSTRACT - An interruption of Holocene sapropel S1 is found in cores from various subbasins of the eastern Mediterranean. In core IN68-9 from the Adriatic Sea, sapropel S1 is dated between 8300 and 6340 BP; interrupted between 7100 and 6900 BP (14C years uncorrected for reservoir age). Lithology and variations in the foraminiferal faunas suggest that the interruption is genuine, and not the result of resedimentation. The results indicate that S1 was deposited within a period of enhanced levels of productivity (resulting from increased seasonal contrasts) which started around 9300 BP and ended around 5200 BP. The onset, interruption, and final ending of S1 deposition in the Adriatic Sea, however, appear to have been triggered by changes in ventilation of the basin related to changes in sea surface temperature (SST). Although the rough estimates of SST change are relatively small (≤ 2°C), they still are significant when compared with the relative SST changes considered necessary to upset convection in the Adriatic. Moreover, recent studies show that the influence of the inferred temperature changes should be viewed in combination with that of reduced salinities due to (1) the deglaciation, and (2) increased humidity in the eastern Mediterranean area during the deposition of S1. The lithological and benthic foraminiferal evidence that sapropel formation in the Adriatic Sea ended around 6340 BP contrasts with the conclusion from a recent geochemical study that sapropel formation in the open eastern Mediterranean would have ended as late as 5000 BP. More significantly, the results of the present study combined with other reports on sapropel interruptions suggest that the process of sapropel formation is not a very stable mode in the basin, but that it may be relatively easily interrupted in response to subtle rearrangements in the balance between productivity and, especially, deep water ventilation. *J. Micropaleontol.* 16(2): 97-108, October 1997

INTRODUCTION

In the eastern Mediterranean, organic carbon rich, often laminated, intervals (sapropels) have been deposited since at least early Pliocene times (Cita & Grignani, 1982; Thunell et al., 1984; Hilgen, 1991). Sapropel formation has been shown to be astronomically timed, occurring around minima in the precession cycle (Rossignol-Strick, 1985; Hilgen, 1991). The most recent sapropel, S1, was deposited in the early Holocene. AMS 14C dates for S1 range from: 8700-6000 BP (Troelstra et al., 1991; Lander Rasmussen, 1991); 8300-6340 BP (Jorissen et al., 1993) and 9200-6400 BP (Perissoratis & Piper, 1992), which agree with earlier 14C based estimates (Stanley & Maldonado, 1979; Vergnaud-Grazzini, 1985). Higgs et al. (1994) proposed that the formation of S1 ended much later, around 5000 BP, and that postdepositional downward oxidation of the sapropel created an apparent sapropel-top with an older age than the original top. They suggested that the original top resided close to the level of their upper Mn peak (about 5000 BP), but also that this should be verified with benthic foraminiferal faunas.

A pale-coloured horizon interrupts the dark-coloured appearance of S1 in several cases from various subbasins of the central and eastern Mediterranean (Table 1). Sapropels S2 and S3 are also composite (e.g. Cita et al., 1977; Vergnaud-Grazzini et al., 1977; Blechschmidt et al., 1982; Cita & Grignani, 1982; Cita et al., 1984; Vergnaud-Grazzini, 1985). Since these older sapropels are only encountered in long cores, usually from areas with low sedimentation rates, it is hard to study them in sufficient detail to pay special attention to the interruptions. High sedimentation rate cores allow greater resolution, which should enable us to discern whether the interruptions are a sedimentological feature,

| Location                  | Depth range | Sources |
|---------------------------|-------------|---------|
| Adriatic Sea              | 700-1250    | 1-6     |
| Northern Aegean Sea       | 260-425     | 7       |
| Core T171-24 NE off Lybia | 2380        | 8       |
| Cores T36 and M18,        | 1500-2000   | 9       |
| western Hellenic Trench  |             |         |
| Core Medor 75 KS52,       | 3118        | 10      |
| northern Levantine Basin, |             |         |
| Strabo Trench, SE of Crete|             |         |
| Core PC10, central Herodotus| 3198    | 11      |
| Abyssal Plain, off NW Egypt|             |         |
| Core 10, Cobblestone Area 4| 3832    | 12      |

Table 1. Reported occurrence of interruption within Holocene sapropel S1. Sources: 1, Bottema & Van Straaten (1966); 2, Van Straaten (1966); 3, Van Straaten (1970); 4, Van Straaten (1972); 5, Van Straaten (1985); 6, Jorissen et al. (1993); 7, Perissoratis & Piper (1992); 8, Thunell et al. (1977); 9, Stanley et al. (1978); 10, Rossignol-Strick et al. (1982); 11, Cita et al. (1984); 12, Vismara-Schilling (1984).
such as the Adriatic Sea. Within this context, we focus on the nature of the S1 interruption in piston-core IN68-9 from the southern Adriatic Basin (Fig. 1), where S1 was found to be distinctly two-layered at most sites deeper than 800 m (Table 1). The inferred implications for productivity and deep water ventilation in the Adriatic Sea may well be relevant to the entire eastern Mediterranean, since the Adriatic Sea plays a crucial role in the oxygenation of bottom waters in that basin (Pollak, 1951; Wüst, 1961; Mangini & Schlosser, 1986; Malanotte-Rizzoli & Hecht, 1988).

First, a time-stratigraphic framework is constructed for the core, on the basis of AMS14C dating results (Jorissen et al., 1993), verified with an oxygen isotope record (Figs 2 & 3). Then, the overall changes in the planktic and benthic foraminiferal faunas (Figs 3 & 4) are integrated with lithological variations in the upper 310 cm of IN68-9 (about 14000 to 3000 BP). This is followed by a synthesis of key indicator species for (1) sea surface temperature (SST), (2) productivity of the benthic ecosystem, and (3) sea floor oxygenation (Figs 3, 4 & 5), on the basis of which the processes are reconstructed that caused the onset, interruption and ending of S1 formation.

**CORE IN68-9**

**General description**

Core IN68-9 from the southern Adriatic Sea (41°47′5 N, 17°54′5 E; 1234 m water-depth) is used as the standard core in a recently proposed biochronology for the central Mediterranean, its chronology being constrained by 6 AMS14C datings (Jorissen et al., 1993). Previous studies on IN68-9 concerned benthic and pelagic molluscs (Van Straaten, 1970: his core 362A) and - on a much coarser scale - planktic and benthic foraminifera for biostratigraphic and longer-term palaeoceanographic purposes (Jorissen et al., 1993; Rohling et al., 1993a).

For the present study, we strongly increased the detail of the foraminiferal records in the late glacial to Holocene interval (310–0 cm) (Figs 3, 4 & 5). The record through sapropel S1 now averages about one sample per 100–200 years (Table 2). IN68-9 mainly consists of hemipelagic muds, including a dark-coloured laminated sapropel, alternating with several ash-layers and turbidites (Fig. 1). The hemipelagic muds typically contain about 0.5% organic carbon, while values in the sapropel fluctuate between 0.9 and 2.1% (Fig. 5). Sapropel S1 is found between 140 and 54 cm. Within S1, an ash-layer is present between 130 and 128 cm, and a turbiditic interval between 122 and 67 cm. In addition, the sapropel was found to be interrupted by a distinct, lighter coloured and apparently homogeneous interval between 65 and 62 cm. Two samples were taken from this narrow interval, while immediately past its base and top a sample was taken from the adjacent sapropelic sediments (Table 2). Carbonate preservation was observed to be excellent throughout the core, as witnessed also by the continuous presence of aragonitic pteropod shells.

**Age model**

Accelerator mass spectrometer 14C results. Table 2 lists the AMS14C dating results (see Jorissen et al., 1993) and interpolated ages for the various stratigraphic horizons and investigated samples in core IN68-9. After correction of the uncorrected (14C) ages for a reservoir age of about 400 years, giving corrected (14C) ages, the datings could be converted to calendar years (Stuiver et al., 1991; Stuiver & Reimer, 1993).

Since the present study concentrates on the formation of S1 and processes shortly before and after that, and since sample resolution is not much finer than 1 sample per century, the relatively minor Holocene 14C-platforms do not appreciably affect the results. The main platforms influencing 14C, dates occur earlier, around 9600 (calendar-age range 10400-10800 BP) and 10000 BP (calendar-age range 11000-11200 BP) (Stuiver et al., 1991), intervals we do not particularly concentrate on and where, consequently, sample resolution is much lower anyway (1 per 200 to 300 years; Table 2). Figure 2 shows the age versus depth plots for core IN68-9, in two forms: (1) with turbidites and ash-layers included, assuming quasistantaneous deposition for those intervals (cf. Jorissen et al., 1993), and (2) excluding the turbidites and ash-layers. Especially the plot versus calendar years shows an almost straight line since about 15000 BP, suggesting absence of any major non-linearity.
that might upset the (interpolated) time-relations inferred in this paper (cf. Table 2).

Since the offsets between the time-scales of changes expressed in $^{14}$C and calendar-ages (Table 2, Fig. 2) are relatively minor in the early Holocene interval that we concentrate on, we opt for using the primary dating results. We plot and discuss our results in terms of uncorrected $^{14}$C years ($^{14}$C$_{uc}$), instead of correcting them for reservoir age in the Mediterranean, since this reservoir age might be subject to future adjustments from the approximated 400 years.

**Stable oxygen isotope results.** To verify the time-stratigraphic framework based on the radiocarbon datings, a $\delta^{18}$O record has been constructed. This had to be done using the planktic foraminiferal species Globigerina bulloides (Fig. 3), instead of the more commonly used Globigerinoides ruber, because only G. bulloides was found in sufficient numbers throughout the core. Unlike G. ruber, G. bulloides is not a shallow dwelling summer mixed-layer species. Today, it thrives in the western Mediterranean in winter and/or (late) spring (Vergnaud-Grazzini, 1973; Cifelli, 1974; Devaux, 1985; Vergnaud-Grazzini et al., 1986).

Therefore, and since the analysing equipment required > 40 specimens per sample, the $\delta^{18}$O$_{bulloides}$ measurements are crude 'averages' only, influenced by lateral/vertical advection in the water column and by the combination of specimens from various seasons and various years within one measurement. Polynomial smoothing is applied to the record to highlight the major trends, which we do consider to be relatively robust and reliable (Fig. 3).

The smoothed $\delta^{18}$O record (Fig. 3) shows a basically two-step deglaciation, even if no marked (Younger Dryas) return to glacial conditions is found in between. The first step, at the base of the studied section of IN68-9, ends around 12 700 BP (Termination Ia: Mix & Ruddiman, 1985; Bard et al., 1987). Thereafter, the curve levels out until about 10 700 BP, followed by a second trend of depletion until about 7000 BP. The actual measurements show that 60% of this second trend of depletion took place between about 9800 and 9000 BP (Termination Ib: Duplessy et al., 1981; Mix & Ruddiman, 1985; Broecker et al., 1988a). After 7000 BP, the smoothed record shows a very gradual trend of minor enrichment. The similarity between the ages of the major deglaciation steps recorded in the $\delta^{18}$O record of IN68-9, and those of Terminations Ia and Ib in the standard records (Duplessy et al., 1981; Mix & Ruddiman, 1985; Bard et al., 1987; Broecker et al., 1988a), corroborates the age-model for IN68-9 discussed above.

Rossignol-Strick et al. (1992) also constructed a $\delta^{18}$O record for the southern Adriatic, based on G. ruber from core KET8216, along with a detailed pollen record. Compared to our $\delta^{18}$O$_{bulloides}$ record, their $\delta^{18}$O$_{ruber}$ record is similarly indiscriminate concerning the Younger Dryas, although the authors argued that this period is distinctly visible in their (marine) pollen record, as is usually the case in (continental)
Fig. 2. Age versus depth plots for core IN68-9. (1) Turbidites and ash-layers included, assuming quasi-instantaneous deposition for those intervals (cf. Jorissen et al., 1993). (2) Excluding the turbidites and ash-layers. Solid lines are plotted versus uncorrected \(^{14}\)C ages, grey lines versus calendar years (see conversion of ages in Table 2).

pollen sequences from circum-Mediterranean countries (e.g. Guiot, 1987; Magaritz & Goodfriend, 1987; Pons et al., 1987; Rognon, 1987; Lowe, 1992). Our rough planktonic foraminiferal reconstruction of sea surface temperature describes a Younger Dryas-time return of colder conditions as well (see below; Fig 3). As yet, there is no ready explanation for this discrepancy between the distinct Younger Dryas expression in pollen and foraminiferal records, and its poor expression in the Adriatic \(\delta^{18}\)Oubulios and \(\delta^{18}\)Oruber records.

**FORAMINIFERA**

**Planktic foraminifera**

**Individual species: records and interpretation.** Planktic foraminifera (150–595 mm fraction; cf. Jorissen et al., 1993) are present throughout core IN68-9, except within the turbidites. In the upper 310 cm, several large changes occur in the faunal composition (Fig. 3). A minimum of 200 specimens was counted for every sample. The relevant habitat characteristics for the species involved are summarized in Table 3, with references for further information.

Although *Neogloboquadrina pachyderma* (dextral) dominates the pre-12,700 BP interval, *Globorotalia scitula* – a cool to cold water species that occurs to great depth – also is abundant. *Turborotalita quinqueloba*, a species that thrives in cool surface

Fig. 3. Percentages of planktic foraminiferal species versus age in core IN68-9 for the past 14,500 years. Shaded intervals represent the two \(S_1\) subunits. The shaded curve in the \(\delta^{18}\)O record is a polynomial smoothing, to show the general trends. SPRUDTS is a faunal cluster explained in the section *Individual species: records and interpretation* and Table 3; the main species of this cluster are also displayed individually. SST is a Sea Surface Temperature proxy-record constructed and calibrated as discussed in the section *Sea surface temperature record*. Note that the isotopic record is not that presented earlier by Jorissen et al. (1993), but completely new with a resolution similar to that of the faunal analyses. Rather than adding more samples to the Jorissen et al. (1993) record (which actually consisted of two combined sets of analyses already), we chose to avoid any possible calibration problem by running an entirely new set.
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| Species                      | Habitat                                       | Sources   |
|------------------------------|-----------------------------------------------|-----------|
| *G. ruber*                   | Shallow dweller in warm, oligotrophic mixed layer. | 1-10      |
| **SPRUDTS-group =** G. sacculifer, H. pelagica, G. rubescens, O. universa, G. digitata, G. tenella, G. siphonifera** | As a group applicable as warm (subtropical) water indicator, especially when considered in combination with *G. ruber*. Group name based on first letters of species names (Rohling et al., 1993a). | 1, 9-11, 13, 14 |
| *G. inflata*                 | Well-mixed, cool environment with intermediate to high nutrient levels. Dominates in frontal systems. | 1, 2, 4-6, 8, 12 |
| *G. glutinata*              | Both in mixed layer and deeper waters. Wide T and S ranges. Cosmopolitan. | 1, 7, 8-12 |
| *T. quinqueloba*            | Tolerant to fairly low S and indicative of low T and/or enhanced fertility in surficial waters. | 2, 3, 5, 6, 8, 9, 10, 12-15 |
| **Neogloboquadrina**        | Important part of life-cycle in deeper, eutrophic waters, in Deep Chlorophyll Maximum (DCM). Therefore: indicative of stratification in mixed layer The type discussed in the present paper, *N. pachyderma* (dextral) is by far the dominant type in eastern Mediterranean records. Typical *N. dutertrei* types may be found in previous interglacial intervals (esp. stage 5). No substantial numbers of *N. pachyderma* (sinistral) have ever been found in Quaternary eastern Mediterranean records. | 2, 3, 5, 6, 8, 9, 10, 12-15 |
| *G. scitula*                | Down to great depths in cool to cold waters. | 5, 8, 16 |
| *G. bulloides*              | No depth or temperature preference, but highly dependent on enhanced food levels, e.g. by upwelling, strong seasonal mixing, or river input. | 1, 4, 6, 8-10, 12, 16-23 |

Table 3. Summary of main habitat characteristics of the planktonic foraminiferal taxa discussed in this paper (modified after review in Rohling et al., 1993a). Sources: 1, Tolderlund & Bé (1971); 2, Fairbanks et al. (1982); 3, Hemleben & Spindler (1983); 4, Almogi-Labin (1984); 5, Thunell & Reynolds (1984); 6, Bé et al. (1985); 7, Vergnaud-Graziini et al. (1986); 8, Hemleben et al. (1989); 9, Pujol & Vergnaud-Graziini (1989); 10, Van Leeuwen (1989); 11, Hutson (1977); 12, Reynolds & Thunell (1989); 13, Fairbanks et al. (1980); 14, Rohling et al. (1995); 15, Fairbanks & Wiebe (1982); 16, Bé (1969); 17, Kipp (1976); 18, Coulbourn et al. (1980); 19, Duplessy et al. (1981); 20, Thiede (1983); 21, Zhang (1985); 22, Overpeck et al. (1989); 23, Barmawidjaja et al. (1989)

waters, is common in the glacial interval as well, but, unlike *G. scitula*, it continues until about 9600 BP. Globigerinoides ruber, a warm oligotrophic mixed-layer dweller, is common after 12 700 BP, although it displays a brief decrease between 11 000 and 9600 BP. After 9600 BP, a marked increase occurs in the SPRUDTS-group (*Globigerinoides sacculifer, H. pelagica, Globorotalia rubescens, O. universa, Neogloboquadrina digitata,* Globorotalita tenella, and *Globigerinella siphonifera*). These individually low frequency species are grouped because of their tendency to do so in cluster analyses (Rohling et al., 1993a) and form a useful warm, subtropical water indicator, especially when considered in combination with *G. ruber* (Table 3). Note that abundances are probably not directly controlled by temperature, but rather by the degree of development of a persistent seasonal thermocline, separating a warm, oligotrophic mixed layer (habitat of 'warm' species) from cooler and more eutrophic waters below.

The faunal changes in the Adriatic Sea described above suggest ending of truly glacial conditions around 12 700 BP, a poorly developed return to cooler conditions between 11 000 and 9600 BP (corresponding to the Younger Dryas), and a final ending of the glacial period around 9600 BP.

Around 9600 BP, *Globorotalia inflata* shows a sudden increase in dominance following a total decline of *Neogloboquadrina pachyderma* (d). Around 9000 BP, the high abundance of *G. inflata* is rapidly followed by high abundance of *Globigerinita glutinata*.

Since *Neogloboquadrina pachyderma* (d) thrives in eutrophic waters, and is mostly found in association with a deep chlorophyll maximum at the base of the euphotic layer fueled by upward mixing of nutrients from deeper waters (Table 3), its high abundances strongly suggest (seasonally ?) stratified conditions within the euphotic layer. *G. inflata* proliferates in well-mixed, cool environments with relatively high nutrient levels and shows peak abundances associated with strong vertical mixing and distinct frontal systems (Table 3). Hence, the abrupt decline of *Neogloboquadrina pachyderma* (d) in favour of *G. inflata* probably reflects disappearance of a more stably stratified habitat, and increased dominance of strong vertical mixing and/or frontal systems in relatively eutrophic waters. The subsequent change to *G. glutinata* dominance is hard to understand because of its cosmopolitan character (Table 3). Tentatively, we propose that it reflects the next phase in the decline of nutrient availability, to a system with only occasional input of nutrients from deeper waters. According to this interpretation, *Neogloboquadrina pachyderma* (d), *G. inflata*, and *G. glutinata* should have an increasing reproduction-potential, respectively. The inferred highest reproduction-potential of *G. glutinata* would enable it to numerically overwhelm the other species in response to very short-lived
eutrophication events, which might also (partly) explain its observed cosmopolitan character. This proposal needs to be substantiated by further research on the modern characteristics of the species involved.

Globigerina bulloides is abundant throughout the record, but shows a maximum in the sapropel. In the interruption between the two sapropelic subunits, G. bulloides abundances drop to a temporary low. Although the percentages of G. bulloides above S1 show a brief low, they subsequently return to values that are rather similar to those within S1.

G. bulloides is an opportunistic species thriving in any eutrophic setting (Table 3). Plankton tows showed maximum abundance of G. bulloides in winter in the Tyrrhenian Sea (Vergnaud-Grazzini et al., 1986) and in late spring in other western Mediterranean basins (Vergnaud-Grazzini, 1995 pers comm.; Cifelli, 1974). Its peak abundance in especially the lower S1 subunit suggests that sapropel formation coincided with surface water eutrophication. Previously, it has been suggested that part of this eutrophication may be ascribed to increased (Po) river discharge (Rohling et al., 1993a).

Sea surface temperature record. To estimate sea surface temperature (SST) variations, cumulative frequencies of the warm water indicators G. ruber and the SPRUDTS-group are calculated versus the cooler/cold water species T. quinqueloba, G. scitula, G. inflata, and Neogloboquadrina pachyderma (d). A priori grouping is easily performed and gives results comparable to those from more elaborate statistical methods (cf. Cita et al., 1977; Thunell et al., 1977; Rohling & Gieskes, 1989; Rohling et al., 1993a). Note that our record, as all other fauna-based SST records, will be biased to some extent due to the additional dependence on nutrient availability of especially the species on the ‘cool’ side (e.g. Neogloboquadrina pachyderma (d) and G. inflata). In spite of the enhanced detail, the down-core pattern of our a priori grouping strongly resembles that derived previously using Principal Components Analysis, providing an essentially semi-quantitative indicator of ‘cooling’ and ‘warming’ trends (Rohling et al., 1993a). For a better understanding of the order of magnitude of the SST-changes involved, however, we now calibrate the percentage-variations in the a priori grouping to changes in °C as follows:

1. Fossil evidence suggests that last glacial maximum (LGM) winter SST in the Adriatic was about 6°C lower than today (1–3°C less difference in summer) (Bigg, 1994), which is supported by a recent U37N based SST record suggesting about 8°C change in the Alboran Sea (western Mediterranean) (Cacho et al., 1994), and foraminiferal transfer function results suggesting about 5°C change in the Aegean Sea (Thunell, 1979). (2) Modern winter SST in the Adriatic Sea is about 13°C (Levitus, 1982), so that the range of about 100% change in our percentage-plot for SST should correspond to a temperature-range between about 7 and 13°C (winter SST is considered since it is important for deep convection in the Adriatic). (3) Next, the rate of change in the percentage-plot needs to be calibrated to the rate of change in °C. It is unrealistic to use a simple linear relation, since it would imply a 1:4 ratio for the relative proportions of the 14–12 and 10–8 kyr BP winter SST increases, whereas vegetation-based records of winter temperature in southern France (Guiot, 1987) and the U37N based SST record for the Alboran Sea (Cacho et al., 1994) suggest a ratio of about 1:2. We find such an approximate 1:2 ratio when calibrating our percentage-record to °C using a logarithmic relationship. (4) The resultant SST-proxy record is plotted versus age along with the other results (Figs 3 & 5).

Benthic foraminifera

Individual species: records and interpretation. The discussion of benthic foraminifera concentrates on the changes directly associated with, and for some distance below and above S1. Hence, the benthic record shown extends from about 200 cm (11 000 BP) to the very top of the core (Fig. 4). Benthic
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Fig. 5. Summarizing diagram of Sea Surface Temperature (SST), sea floor Oxygen Deficiency Stress (ODS), Benthic Productivity (BPR), Organic Carbon content (C$_{org}$ in %), versus age (yrs BP) in core IN68-9. In the lithological column, both S$_1$ subunits are indicated in black, and the chronostratigraphic positions of ash layers (a) and turbidites (t) are indicated with a shaded band.

foraminifera (150–595 μm fraction; cf. Jorissen et al., 1993) are present up to the very base of S$_1$ (8300 BP). Thereafter, they are absent until 7200 BP, with the exception of the interval between 7400 and 7240 BP, just below the turbidite within the lower S$_1$ subunit. After the lower subunit, benthic foraminifera are present throughout. At least 200 specimens were counted for every sample.

Around 9600 BP, a rather diverse fauna is found with dominant Gyroidina altiformis and Uvigerina mediterranea. This fauna is very similar to that after 5200 BP, which characterizes the relatively oligotrophic conditions of the modern Mediterranean. At about 9300 BP, G. altiformis and U. mediterranea largely disappear, while Gyroidina orbicularis and Bolivina spathulata increase in frequency, as does, somewhat later, Bulimina costata. After 8600 BP, faunal diversity becomes very low and progressively more dominated by Nonion barleeanum, Globobulimina pyrula, Chilostomella czizeki and Cassidulinoides bradyi, while B. costata shows a change in morphology from rather short (inflata) morphotypes with discontinuous costae to elongated (costata) types with continuous costae along the entire test.

The described faunal succession coincides with a significant increase in the organic carbon content after about 9500–9000 BP (Fig. 5), and culminates in complete absence of benthic fauna and preservation of laminae after 8300 BP (base S$_1$), indicating persistent anoxia (Josefson & Widbom, 1988; Bernhard & Reimers, 1991). Combined, these patterns lead us to suggest that the faunal succession resulted from increasing fertility and decreasing oxygenation of the benthic environment. In this scenario, (1) G. orbicularis and B. spathulata would reflect the first stage of ecosystem enrichment; (2) B. costata and N. barleeanum would become dominant through increasing low-oxygen stress while benthic fauna can still profit from high food availability; and (3) G. pyrula, C. czizeki and C. bradyi would reflect very strong dyoxia, possibly even intermittent anoxia. These inferences based on core IN68-9 are supported by previous studies characterizing most of the involved species as indicative of ecosystem enrichment and oxygen depletion (Table 4).

Table 4. Benthic foraminiferal taxa proposed as indicators of ecosystem enrichment and/or oxygen depletion. The cited sources sometimes described the taxa under different names. Sources: 1, Jorissen (1987); 2, Sen Gupta & Machain Castillo (1993); 3, Lutze & Coulbourn (1984); 4, Lutze (1986); 5, Altenbach & Sarnthein (1989); 6, Mackensen et al. (1985); 7, Caralp (1989); 8, Loubere (1994); 9, Miller & Lohmann (1982); 10, Bernhard & Reimers (1991); 11, Alve (1990).

| Taxon                          | Sources |
|-------------------------------|---------|
| Bulimina costata              | 1,2     |
| Uvigerina peregrina           | 3,4,5   |
| Nonion barleeanum             | 1,6,7,8 |
| Globobulimina/Chilostomella   | 2,8,9,10|
| Stainforthia                  | 11      |

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sapropels, which they ascribe to strong low-oxygen tolerance of these taxa. As do other (potentially) infaunal species in the recent Adriatic (Barmawidjaja et al., 1992), these taxa likely follow taxon-specific critical oxygen levels that migrate towards the sediment–water interface when oxygenation deteriorates (e.g. Mackensen & Douglas, 1989), ultimately causing species with the highest tolerance of dysoxia/intermittent anoxia to dominate the fauna, persisting at the sediment surface.

After the sterile base-interval of S1, the first return of benthic foraminifera is found at 7400 to 7300 BP, just below the turbidite. The fauna is very diverse in that interval, containing substantial numbers of Cassidulina carinata, Trifarina angulosa, and Bulimina marginata. These species, virtually absent in the other samples, have a lower depth limit of 800 m in the present-day Adriatic Sea (Jorissen, 1988), so that the 7400–7240 BP environment. The high percentages of Uvigerina orbicularis and G. pyrula with better oxygenated upper slope (200–500 m) faunas. The interruption (7100–6900 BP) suggest admixture of dysoxic lower slope (500–800 m) faunas with better oxygenated upper slope (200–500 m) faunas.

Immediately above the turbidite of 7230 BP, the benthic fauna in the lower S1 subunit is dominated by B. costata, Uvigerina peregrina and N. barleeanum. The interruption of S1 shows an increase of G. orbicularis, and total disappearance of G. pyrula, C. czizeki, C. bradyi. Interpreted in terms of the above explanation for benthic change prior to S1, the fauna after 7200 BP reflects slight reoxygenation of the bottom waters, in a still eutrophic benthic environment. The changes associated with the S1 interruption (7100–6900 BP) suggest substantially improved bottom water oxygenation, while fertility in the benthic ecosystem decreased to levels comparable to those reflected in the last 500 years prior to the onset of sapropel formation.

The onset of the second S1 subunit (6900 BP) corresponds with a return of C. czizeki, and a maximum of B. costata (elongated costata morphotypes), suggesting a return to distinct dysoxia after the reoxygenation represented by the S1 interruption. G. orbicularis and inflata morphotypes of B. costata (encountered also below S1) dominate between 6900 and 6340 BP (second S1 subunit), continuing until 5200 BP. The ensuing frequency drop around 5200 BP suggests that oxygenation and productivity became comparable to the present relatively oligotrophic situation. This date differs completely from that of Fontugne et al. (1989), who argued on the basis of sedimentological evidence that, since the formation of S1, fully oxygenated conditions would only have returned around 1650 BP.

**Summary of benthic productivity and oxygen deficiency stress records.** To summarize the benthic faunal changes, we use the successions observed in IN68-9 to propose a clustering of species that, individually, were previously proposed to indicate ecosystem enrichment and/or oxygen depletion (Table 4). The first group consists of Bulimina costata, Uvigerina peregrina and Nonion barleeanum, characterizing a relatively advanced stage of ecosystem enrichment, where only species with a certain tolerance for low oxygen conditions can profit from the abundance of food ('Benthic Productivity' (BPR) group; Figs 4 & 5). The second group consists of Globobulimina pyrula, Chilostomella czizeki, Cassidulinoides bradyi and Stainforthia sp., characterizing the ultimate stage before totally azoic conditions, tolerating severe low-oxygen stress ('oxygen deficiency stress' (ODS) group; Figs 4 & 5). As yet, it is impossible to fully quantify the ODS and BPR proxies. Concerning the ODS-curve, however, we suggest that the taxa only become present in substantial numbers (ODS score >10%) when bottom water oxygen concentrations become lower than 1.0 ml l−1 (e.g., Sen-Gupta & Machain-Castillo, 1993), while dominance (ODS score >50%) likely reflects virtually anoxic conditions.

The increasing BPR values between 9300 and 8500 BP are followed by an abrupt drop immediately below the sapropel. This sudden decrease likely is an artifact, resulting from an overriding effect of severe low-oxygen stress (ODS peak). Even though the species combined in the BPR record must be fairly tolerant to low oxygen conditions, the progressively increasing oxygen deficiency presumably passed their tolerance limit around 8500 BP, so that only species tolerant of extreme low-oxygen conditions remained. This interpretation is supported by the azoic conditions (persistent anoxia) found only 200 years later (onset of S1; 8300 BP).

**DISCUSSION AND CONCLUSIONS**

**Relation between changes in the planktic and benthic environments**

This section focuses mainly on the relation between the proxy-records of Sea Surface temperature (SST; Figs 3 & 5), Benthic Productivity (BPR; Figs 3 & 4) and sea floor Oxygen Deficiency Stress (ODS; Figs 4 & 5). These records represent changes in long-term average conditions in the basin, even when words like 'abrupt' and 'rapid' are used, since the average sample resolution, relatively high as it may be, is not sufficient to address changes on time-scales smaller than about a century. The winter SST record (Figs 3 & 5) suggests glacial values around 7°C in the southern Adriatic until a first substantial warming around 12 700 BP, followed by a return to near-glacial winter SST conditions between 11 000 and 10 000 BP (Younger Dryas). Thereafter, a second major warming takes place until about 9500 BP, followed by a more gradual increase culminating between 8300 and 8000 BP with near-modern temperatures (13°C). The suggestion that maximum temperatures were reached around 8000 BP is consistent with the vegetation-based palaeotemperature reconstructions for southern France (Guiot, 1987).

The high SST conditions reached around 9300 BP suggest prevalence of a season with a relatively warm and oligotrophic mixed layer in the basin. In addition, the abundance of G. inflata in this interval suggests a well developed rather eutrophic, well-mixed season, while the high abundances of G. glutinata may also be related to a process of eutrophication (section Individual species, records and interpretation). Moreover, although still rather low, G. bulloides abundances start to increase after 9300 BP, suggesting increasingly favourable (eutrophic) conditions, possibly in the form of seasonal blooms. The planktic record, therefore, suggests enhanced seasonal contrasts in temperature and productivity after about 9300 BP, so that the organic flux to the sea floor (export production) must have become increasingly seasonal. Even without a change in the total annual export production, a change from a rather constant flux to a pulsed, seasonal flux would influence benthic life and increase the potential for organic matter burial in the sediment (Berger & Wefer, 1990). Hence, the increases in the Corg content
and the BPR record, indicating enrichment of the benthic environment, support the inferred enhanced seasonal contrasts after 9300 BP (Fig. 5). Additional support comes from the general decrease in 'annual stability' around the Pleistocene/Holocene boundary inferred from planktic foraminiferal faunas in a wider eastern Mediterranean context (Rohling et al., 1993a).

Around 8500 BP, the final increase of winter SST towards the maximum values of 8300–8000 BP coincides with an increase of low-oxygen stress in the benthic community (ODS; Figs 4 & 5), which also culminates around 8300 BP – the onset of S₁ – in complete and persistent anoxia causing azooic conditions at the sea floor until about 7200 BP. During deposition of sapropel S₁ a gradual cooling is suggested, with some minor lows associated with the 7100–6900 BP interruption of S₁. The benthic fauna reflects some improvement of the oxygenation in a still eutrophic environment around 7200 BP, and substantially increased oxygenation between 7100 and 6900 BP. Slight warming at the base of the second sapropelic subunit (6900 BP) coincides with the return of very poorly oxygenated conditions at the sea floor. Continued gradual cooling towards the top of S₁ is accompanied by a change in the benthic fauna reflecting progressive decrease of the stress from oxygen deficiency. Finally, winter SST rises from 6340 to 4500 BP, when modern conditions were established, while around 5200 BP, benthic productivity and oxygenation arrive at present-day levels.

**Ventilation and/or productivity**

The BPR record suggests (well) eutrophicated conditions starting to build up about 9300 BP (1000 years before the onset of S₁), and reaching a likely maximum between 8300 and 7400 BP (considering the high values bordering the azeoic interval, it seems likely that the highly/highest eutrophicated conditions prevailed during deposition of that interval). Then, a rapid decline is suggested between about 6900 BP and 5200 BP, followed by relatively stable oligotrophic conditions. The generally enhanced seasonal contrasts in productivity inferred since about 9300 BP (with a possible end reached around about 5500 BP) also suggests increased organic flux to the sea floor. This coincidence of increased (seasonality of) productivity with sapropel formation would seem to support a recent conclusion that productivity forms the primary control on enrichment of organic carbon in sediments, which was based on recent sapropel formation in the Black Sea (Pedersen & Calvert, 1990; see review in Rohling, 1994).

However, in IN68-9, neither the record of benthic productivity, nor that of the main planktic productivity markers G. bulloides, Neogloboquadrina pachyderma (d), and G. inflata, show patterns suggestive of a causal link between short-term productivity variations and the depositional sequence of two S₁ subunits interrupted by a lighter-coloured homogeneious interval, apart from the overall correspondence of the sapropel to an interval of enhanced productivity. On the contrary, the ODS and SST records do suggest such a direct link with the depositional sequence. Enhanced SST values at the base of both S₁ subunits likely caused lowering of surface water densities, helping to install stable stratification and consequently poor or blocked deep water ventilation in the Adriatic Sea. Subsequent temperature decrease during the deposition of either sapropelic interval would have favoured some improvement of deep water ventilation, allowing benthic forms with sufficient low-oxygen tolerance to repopulate, while the culminated cooling at the end of sapropel deposition caused re-installment of good deep water ventilation and proper sea floor oxygenation.

Summarizing, the data from Adriatic core IN68-9 suggest that within a relatively eutrophic setting – caused by increased seasonal contrasts (and perhaps partly enhanced by nutrient input via river discharge) – the onset, interruption, and final ending of S₁ deposition in the Adriatic Sea were triggered by changes in ventilation of the basin. The coincidence of SST variations with these changes in ventilation suggests a causal relationship. Although the SST changes are of a relatively small magnitude (<2°C), and granted that they may not be very accurately estimated with our simple SST calibration, they still seem significant in terms of the sensitivity of Adriatic Sea ventilation to changes in its density-structure, since even relative temperature increases of the order of only 0.7°C might suffice to upset the basin's vertical circulation, causing onset of sapropel formation (Mangini & Schloesser, 1986). Moreover, the density variations resulting from the inferred temperature changes should be viewed in combination with the underlying influence of 1) a strong salinity decrease in the eastern Mediterranean associated with the deglaciation (Thunell et al., 1987; Thunell & Williams, 1989; Rohling, 1994); (2) increased humidity in the eastern Mediterranean area coinciding with the deposition of S₁ (see review in Rohling & Hilgen, 1991). Our conclusions are similar to those based on benthic foraminiferal evidence in S₂, which identified anoxia resulting from reduced ventilation of deep waters as the critical factor in its deposition, although a surface productivity increase may have occurred immediately preceding and during the deposition of S₂ (Nolet & Corliss, 1990).

**Age of the original top of S₁**

Although the benthic fauna records relatively eutrophic conditions at the sea floor until 5200 BP, it also indicates a return to well oxygenated conditions (also reflected by the disappearance of lamination), i.e. ending of sapropel formation, around 6340 BP in the Adriatic Sea. This contrasts with the conclusion of Higgs et al. (1994) that sapropel formation in the open eastern Mediterranean ended as late as 5000 BP, while the present visible top of the sapropel would (1) represent a geochemical front caused by downward oxidation after the re-installment of oxygenated bottom water conditions and, therefore, (2) appear older than the original top. Similar inferences were made earlier, but, as did Higgs et al. (1994), always using cores with sedimentation rates as low as 2 to 4 cm kyr⁻¹ (De Lange et al., 1989; Lander-Rasmussen, 1991; Rohling et al., 1993a; Pruyser et al., 1991, 1993). The sedimentation rate in the S₁ interval of core IN68-9 is ~15 cm kyr⁻¹, so that post-depositional re-oxidation would not likely be of much importance. This expectation is confirmed by the observed match between the faunal and lithological boundaries of S₁. The 6340 BP age for the very top of S₁ in IN68-9 suggests that it would be the lower, rather than the upper, Mn peak in the records of Higgs et al. (1994) that approximately matches the original top of S₁. This supports the conclusion of a study similar to that of Higgs et al.
placed between 7000 and 6700 BP. Given the inaccuracy and not the result of resedimentation. Van Straaten deep water formation and increased oxygen advection to deep studies that relate the sapropel interruption to a period of was not only significant in the Adriatic Sea, but that improved Sapropel interruption: common or rare? The correspondence between changes in lithology and benthic foraminiferal fauna suggests that both the sapropel interruption, and the second sapropelic subunit in core IN68-9 are genuine, and not the result of resedimentation. Van Straaten

In the northern Aegean Sea, S1 is interrupted in cores from sites deeper than 250 m (Perissoratis & Piper, 1992). These authors dated the top of S1 at 6400 BP, and the base at 9200 BP. By interpolation, the Aegean S1 interruption can roughly be placed between 7000 and 6700 BP. Given the inaccuracy involved in the interpolation of the AMS 14C-dates, the match with the age-range of the Adriatic S1 interruption (7100–6900 BP) is striking. This could indicate that the reoxygenation was not only significant in the Adriatic Sea, but that improved deep water formation and increased oxygen advection to deep waters occurred on a wider scale in the eastern Mediterranean. Since the upper depth limit of S1 in the northern Aegean Sea was much shallower than 250 m (Perissoratis & Piper, 1992), it seems unlikely that the Aegean Sea itself produced deep water, as it may do today. Instead, the Aegean S1 interruption may be primarily related to improved deep water formation in the Adriatic Sea, which potentially caused an eastern Mediterranean wide reoxygnation event. In that case, future research on other high sedimentation-rate cores throughout the basin should show interruption of S1.

Interruptions have not only been found in Quaternary, but also in Pliocene sapropels. High-resolution study of Upper Pliocene sapropel C2 (Singa section, S. Italy) showed an (~900 years) interval containing high abundances of the low-oxygen tolerant benthic foraminiferal species Bulimina marginata inbetween benthic azoic intervals (Rohling et al., 1993b). Planktic foraminiferal abundance variations and stable isotopes suggest that this interval of temporarily improved sea floor oxygenation was preceded by surface water cooling, while the return to persistently anoxic (i.e. azoic) conditions was related to warming. The low diversity benthic fauna in the repopulated interval of C2 indicates continuing low-oxygen stress, whereas the higher diversity fauna in the Adriatic S1 interruption suggests a far more advanced state of reoxygnation. In Pliocene sapropel C2, therefore, the sapropel interruption appears to be caused by a short period of reoxygenation in a relatively stable, anoxic context, whereas the Adriatic record of S1 reflects a long-term trend of progressively improving oxygenation, interrupted by a short relapse that caused the formation of the second S1 subunit. Although the faunal expressions are not exactly alike in the studies of C2 and S1, both suggest a high sensitivity of the process of sapropel formation to short periods of improved deep water formation.

ACKNOWLEDGEMENTS
We thank W. J. Zacharias, R. C. Thunell, A. E. S. Kemp, and an anonymous reviewer for stimulating discussions and critical reviews. A.M. Borsetti kindly enabled us to work with the material of core IN68-9. This study contributes to EU MAST-3 project Climatic Variability of the Mediterranean Paleocirculation (CLIVAMP), and to UNESCO-IUGS project Climates in the Past (CLIP). It is partly funded from Southampton University grant A94/18, and British Council grant JRP235.

Manuscript received June 1996 Manuscript accepted January 1997

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