Palaeogeography, Palaeoclimatology, Palaeoecology 190 (2003) 103–119

PALAEO

www.elsevier.com/locate/palaeo

A dynamic concept for eastern Mediterranean circulation and oxygenation during sapropel formation

J.S.L. Casford[a,g,*], E.J. Rohling[a], R.H. Abu-Zied[b], C. Fontanier[c], F.J. Jorissen[d], M.J. Leng[e], G. Schmiedl[f], J. Thomson[a]

[a] Southampton Oceanography Centre (SOC), European Way, Southampton, SO14 3ZH, UK
[b] Geology Department, Faculty of Science, El-Mansoura University, El-Mansoura 35516, Egypt
[c] Département de Géologie et Océanographie, l'Université Bordeaux, 33405 Talence Cedex, France
[d] Laboratoire de Géologie, Fac. Sciences, Université d'Angers, 49045 Angers Cedex, France
[e] NERC Isotope Geoscience Laboratory (NIGL), Keyworth, Nottingham, UK
[f] Universität Leipzig, Institut für Geophysik und Geologie, Talstraße 35, 04103 Leipzig, Germany
[g] University of Durham, Science site, South Road, Durham, UK

Received 19 March 2002; received in revised form 26 June 2002; accepted 18 October 2002

Abstract

We propose that intermittent bottom water ventilation occurred throughout periods of sapropel deposition, and that the recently reported sapropel 'interruptions' represent centennial-scale episodes of enhanced frequency/intensity of that process. In essence, the modern high-frequency variability in deep water formation (affected by climatic variability over the northern basins on seasonal to longer time scales) prevailed also at times of sapropel deposition, although the overall ventilation state was much reduced. This concept is supported by: detailed multiple-species isotope records for three Aegean cores; the presence of abundant *Globorotalia truncatulinoides* within especially sapropels S7 and S8 in the western Levantine basin; observations of three rapid benthic repopulations within sapropel S6 in the deep western Levantine basin; a report of continuous benthic presence through sapropel S1 at intermediate-deep locations offshore Libya; and further supporting information from the literature. In the Aegean records, concomitant abundance of low-oxygen tolerant benthic foraminifera and presence of the more oxyphilic benthic foraminifer *Uvigerina mediterranea*, with surface-similar $\delta^{13}C$ values, indicate repeated deep water re-oxygenation events throughout the deposition of S1. The observations of a continuous benthic presence through S1 (offshore from Libya) imply that no persistent anoxia developed at mid-depth levels in that region, which is far removed from direct deep ventilation influences. The abundance of deep mesopelagic *G. truncatulinoides* through several sapropels from the western Levantine basin also suggests the presence of bio-available oxygen at many hundreds of meters of depth. Moreover, the rapid/intermittent benthic repopulations within sapropels from the deep eastern Mediterranean imply that bottom water anoxia was spatially restricted and/or of a highly intermittent nature. The short time scales of these repopulation events are incompatible with titration of an extensively anoxic water column and subsequent re-establishment of water-column anoxia. We suggest that where anoxic/azoic conditions were present, they most likely were restricted to a veneer at the sediment/water interface. The extent of such an anoxic 'blanket' depends on the balance between advective oxygen supply into the deep sea, and biological and chemical oxygen demand. The demand functions imply a decoupling of oxygenation from water mass advection, allowing export production and C_{org} posting

---

* Corresponding author. *E-mail address:* j.s.l.casford@durham.ac.uk (J.S.L. Casford).

PII: S0031-0182(02)00601-6

rates to the sea floor to delimit the extent of the anoxic blanket in both space and time. Low-productivity regions would develop no anoxic blanket, allowing for the observed persistence of deep dwelling planktonic and bottom dwelling benthic faunas.

Keywords: eastern Mediterranean; sapropel S1; benthic foraminifera

1. Introduction

The Mediterranean Sea is of particular interest to palaeoceanographers, as it possesses its own thermohaline circulation with deep water being formed in the northern basins (Bethoux et al., 1999). In the eastern Mediterranean, the Adriatic Sea and the Aegean Sea are subject to orographically channelled cold, dry air from high latitudes (Mariolopoulos, 1961; Poulos et al., 1997) similar to the mistral that affects the western Mediterranean (Leaman and Schott, 1991). This drives deep overturn that is known to respond rapidly to climatic variability in both the modern (Theocharis, 1989; Roether et al., 1996) and palaeorecords (Casford et al., 2001; Rohling et al., 2002). We present preliminary observations from RV *Meteor* cruise M51-3 (12 November–11 December 2001) and data from Aegean cores SL-11, SL-21 and SLA-9 (Fig. 1) that suggest that this high-frequency variability may also find expression during times of sapropel formation.

Ever since the first discovery of sapropels in eastern Mediterranean sediments (Kullenberg, 1952) they have been a source of controversy. Although the association between sapropel formation and insolation-driven monsoon maxima is well established (Rossignol-Strick, 1983, 1985), the role of anoxia has become a central issue in the characterisation of processes that underlie sapropel formation. Opinions are divided about the relative importance of two possible processes, either a reduction in ventilation leading to anoxia and hence organic carbon preservation (Olauson, 1961; Cita et al., 1977; Vergnaud-Grazzini et al., 1977; Cita and Grignani, 1982; Vergnaud-Grazzini, 1985), or an increase in primary productivity (DeLange and Ten Haven, 1983; Calvert, 1983; Boyle and Lea, 1989; Pederson and Calvert, 1990; Van Os et al., 1994). Clearly, these scenarios are not mutually exclusive (see Rohling and Gieskes, 1989), as an increase in productivity would enhance export of organic carbon (C_{org}) to the sediment surface and could utilise all the available oxygen, producing anything from dysoxia to anoxia. Increased freshwater influx would enhance nutrient concentrations in the basin that would in turn enhance productivity, especially when there appears to be a potential build-up of nutrients over >1000 years before utilisation (Casford et al., 2002). Observations of high pollen concentrations (Cheddadi and Rossignol-Strick, 1995) provide strong arguments that C_{org} preservation was much improved during sapropel times, compared with the present, and have been used to suggest extensive anoxia. The upper depth limit of sapropel occurrence at ~300 m in the open eastern Mediterranean (Rohling and Gieskes, 1989) and ~125 m in the Aegean Sea (Perissoratis and Piper, 1992), has been used to suggest that anoxia prevailed throughout the water column up to this depth. However, there are no observations to eliminate the possibility that true anoxia only developed as a blanket limited to the sediment/water interface. Indications for this 'Blanket Hypothesis' have been seen in Pliocene sapropel C2 from the Singa section of southern Italy (Rohling et al., 1993). Calvert (1983) implies that low C_{org} sapropels (i.e. those with $\leq 2\%$ C_{org}) such as the Holocene S1 could be produced, without significant increases in primary productivity, i.e. without the development of a Deep Chlorophyll Maximum (DCM) (Rohling, 1994). Mercone et al. (2001) performed a combined micropalaeontological and geochemical study and infer that the presence of an Oxygen Deficiency Stress (ODS, sensu Rohling et al., 1997) assemblage of benthic foraminifera throughout S1 indicates either intermittent anoxia or continuous dysoxia. They further argue that uncertainties in the mechanism of

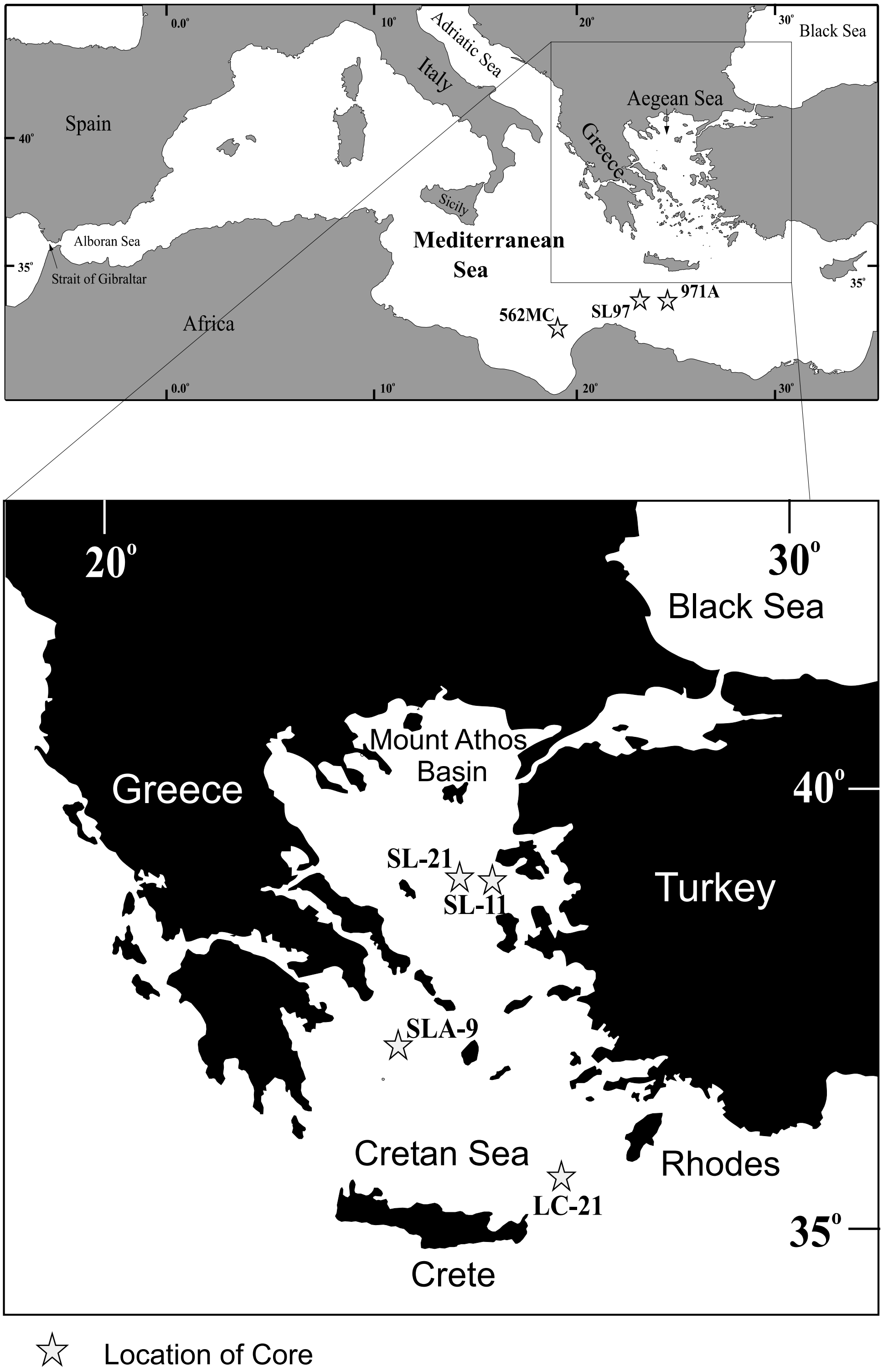


Fig. 1. Map of the Mediterranean Sea showing locations of the cores.

Table 1
Core location and type

Core	Type of core	Length (cm)	Depth below sea level (m)	Sedimentation rates (cm kyr^{-1})	Co-ordinates
LC-21[a]	Piston	–	1522	13.7	35°40′N, 26°35′E
SL-11	Gravity	209	258	9.5	39°06′N, 25°48′E
SL-21	Gravity	273	317	6.8	39°01′N, 25°25′E
SLA-9	Gravity	286	260	12.6	37°31′N, 24°33′E
971A	ODP	5880	2026	–	33°42′N, 24°43′E
SL97	Gravity	640	1879	–	33°43′N, 23°30′E
562MC	Multi-core	27	1390	–	32°46′N, 19°11′E

[a] Hayes et al. (1999); De Rijk et al. (1999); Mercone et al. (2000, 2001); Casford et al. (2001); Rohling et al. (2002).
Sedimentation rates are derived from the GISP II tuned time framework of LC-21 and from Casford et al. (2002).

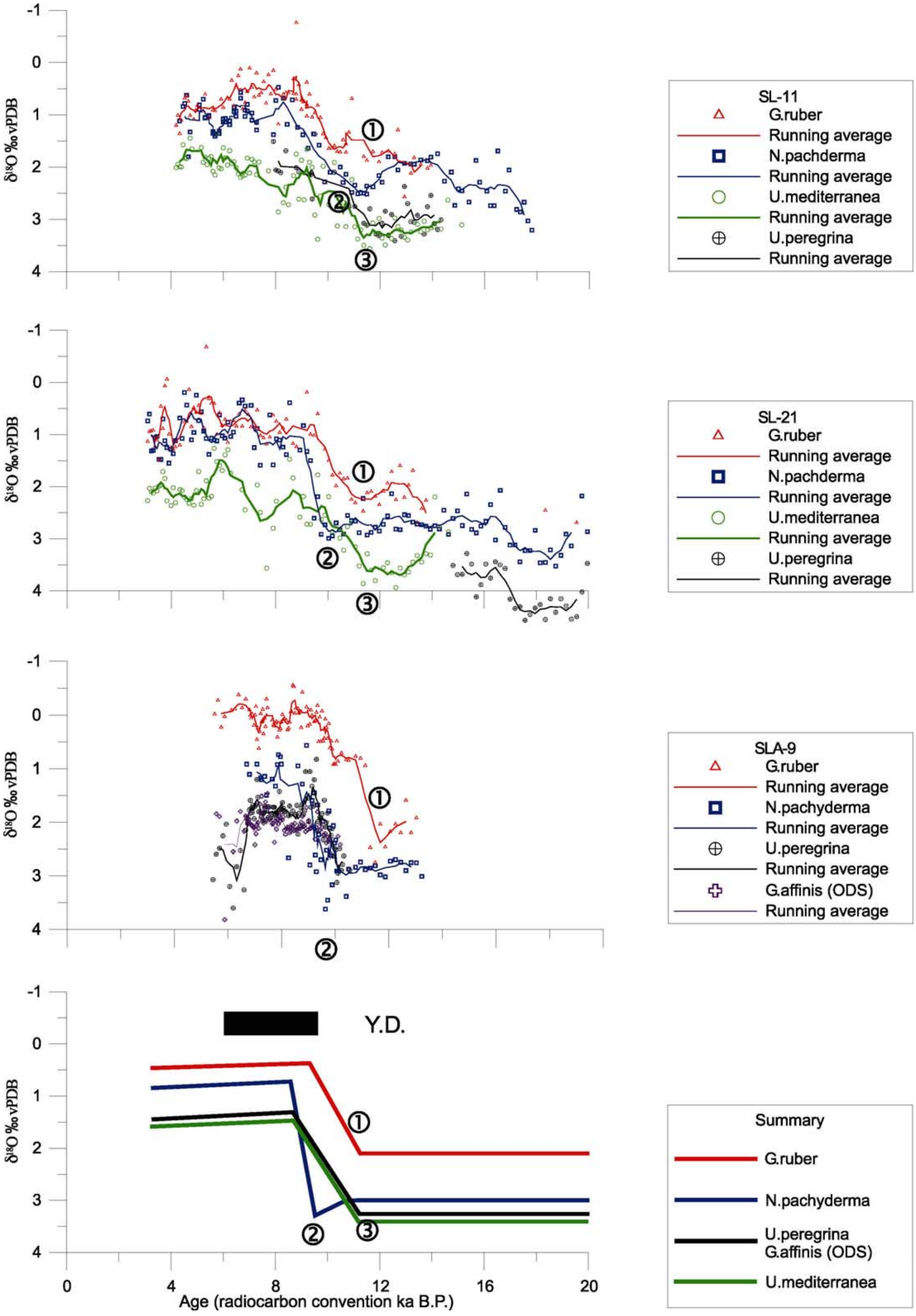
barium uptake in the water column and dissolution processes leave the use of barium as an indicator of palaeoproductivity in S1 open to question. We here offer new observations within the context of previous work to assess whether, at times of sapropel deposition, deep water formation had ceased (or not) and to what extent dysoxic and/or anoxic conditions prevailed. To explain these observations, a new dynamic concept of ventilation and oxygenation is presented.

2. Methods

We present: (1) initial observations from coring on RV *Meteor* cruise M51-3; (2) results from Aegean gravity cores SL-11 and SL-21 (North Aegean) and SLA-9 (South Aegean), which complement previous work on southeast Aegean core LC21 (Mercone et al., 2001; Casford et al., 2001; Rohling et al., 2002); (3) benthic foraminiferal abundance data in sapropel S1 from multicore 562MC off the Gulf of Sirte; and (4) benthic foraminiferal abundance data from sapropel S6 of ODP Hole 971A in the open Mediterranean. These results are placed within the context of observations from the literature. All cores investigated here consist of microfossil-rich hemipelagic ooze, with clearly defined darker bands of sapropel material. Cores SL-11, SL-21, SLA-9, and S6 from ODP Hole 971A were sampled in continuous sequences of 0.5-cm intervals. Given the high sedimentation rates of our cores the 0.5-cm sample interval gives a temporal resolution of between 40 and 75 years (Table 1). Multi-core 562MC was sampled at a 1-cm resolution. These samples were dried, weighed and selected (weighed) subsamples were disaggregated and wet sieved using demineralised water. The sieved fractions were collected on 600-, 150-, 125- and 63-μm mesh sizes. The > 150-μm fractions were subdivided using a random splitter to provide an aliquot of about 200 individual planktonic foraminifera (> 300 for benthics). For multi-core 562MC benthic fauna was analysed on the > 63-μm fraction and between 50 and 100 individuals were counted where present. After sorting and counting, results were expressed as numbers g^{-1} and percentages (see Abu-Zied, 2001; Casford et al., 2002 for the Aegean faunal data). During RV *Meteor* cruise M51-3, core SL97 was sampled to provide an initial biostratigraphy. Several samples were taken from each sapropel and sieved over 150-μm mesh. The faunas were qualitatively assessed on board, using a binocular light microscope.

Detailed monospecific stable oxygen and car-

Fig. 2. Oxygen isotope data from cores SL-11, SL-21 and SLA-9. The main features of these records are summarised in the bottom panel. A solid bar indicates the extent of the sapropel. Explanation: (1) inflection before the depletion into the Holocene from the Younger Dryas (Y.D.) as shown in the record of $\delta^{18}O_{Globigerinoides\ ruber}$; (2) enrichment trend in the *Neogloboquadrina pachyderma* record and the lag in response of $\delta^{18}O_{N.\ pachyderma}$ compared with that of $\delta^{18}O_{G.\ ruber}$; (3) inflection in the benthic $\delta^{18}O$ record, coinciding with the inflection in $\delta^{18}O_{G.\ ruber}$.


δ¹⁸O ‰ vPDB
-1
0
1
2
3
4
①
②
③
SL-11
G.ruber
Running average
N.pachderma
Running average
U.mediterranea
Running average
U.peregrina
Running average
SL-21
G.ruber
Running average
N.pachderma
Running average
U.mediterranea
Running average
U.peregrina
Running average
SLA-9
G.ruber
Running average
N.pachyderma
Running average
U.peregrina
Running average
G.affinis (ODS)
Running average
Y.D.
Summary
G.ruber
N.pachyderma
U.peregrina
G.affinis (ODS)
U.mediterranea
0
4
8
12
16
20
Age (radiocarbon convention ka B.P.)

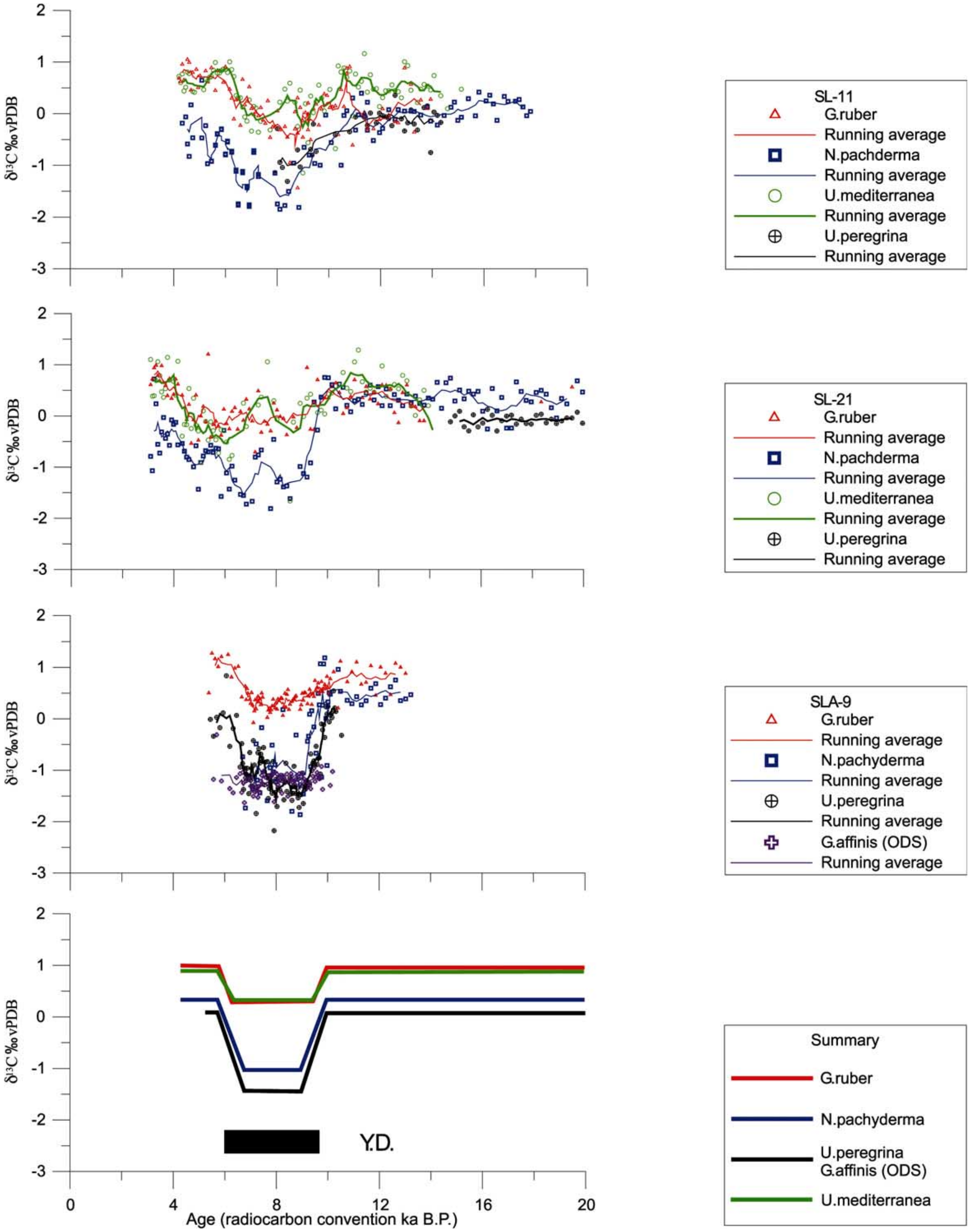


Fig. 3. Carbon isotope data from cores SL-11, SL-21 and SLA-9 showing the marked depletion in $\delta^{13}C$ across sapropel S1. The main features of these records are summarised in the bottom panel with the extent of the sapropel indicated by a solid bar.

bon isotope records were constructed for cores SL-11, SL-21 and SLA-9 with resolutions in the order of 1 cm (Figs. 2 and 3). These were derived from 'alternate' 0.5-cm samples and based on analyses of at least 10 individuals for each chosen species per sample. These chosen species were: the epipelagic (< 50-m) species *Globigerinoides ruber*; the mesopelagic species *Neogloboquadrina pachyderma* (dextral) which thrives in the DCM near the base of the euphotic layer; and the epifaunal/shallow infaunal benthics *Uvigerina mediterranea* (SL-21) and *Uvigerina peregrina* (SLA-9). In core SLA-9 we also analysed the low-oxygen tolerant benthic species *Globobulimina affinis*, which under oxygenated conditions occupies a deep infaunal habitat, at the Redox boundary. The selection of planktonic and benthic species follows global and specific Mediterranean habitat summaries in Hemleben et al. (1989), Rohling and Gieskes (1989), Jorissen et al. (1993), Pujol and Vergnaud-Grazzini (1995), Rohling et al. (1993, 1995, 1997), De Rijk et al. (1999), Hayes et al. (1999), Jorissen (1999), Reiss et al. (2000), and Abu-Zied (2001). The analyses were performed at two separate inter-calibrated facilities: the Europa Geo 20-20, with individual acid bath preparation at the SOC, and the VG-Optima with a common acid bath preparation at the NIGL. Isotope results are reported as ‰, standardised to Vienna Pee Dee Belemnite. External precision is in the order of < 0.06‰ (std).

3. Observations

3.1. High-frequency events in the Aegean Sea

The fact that it is possible to pick mature, clean *Uvigerina mediterranea* in sufficient numbers from all samples of cores SL-11 and SL-21 at a 1-cm resolution indicates that it occurs systematically (if rare) throughout S1 at this locale. This cannot be explained by downslope transport since this species was not found to be systematically associated with other shallow water (sensu De Rijk et al., 1999) faunal elements (Abu-Zied, 2001). In addition, the ridge location of the core sites make downslope transport less likely. Detailed abundance counts of benthic foraminifera in cores SL-31, SLA-9 and LC-21 show that *U. mediterranea* does not correlate with the known low-oxygen tolerant ODS group (Abu-Zied, 2001) and the presence of this group in itself suggests that, in the Aegean at least, deep waters never became persistently anoxic during S1.

The oxygen isotope records (Fig. 2) show obvious depletions into the Holocene, shifting about −2‰ in all species. This reflects a combination of global ice-volume reduction and changing regional climatic conditions as the eastern Mediterranean became warmer and more humid into the Holocene Climatic Optimum following the cooler, drier Younger Dryas (Rohling, 1999b). A clear offset can be seen, however, with the $\delta^{18}O$ of the epipelagic species *Globigerinoides ruber* showing more depleted values than the mesopelagic *N. pachyderma*, both in absolute values and general trends. The $\delta^{18}O$ values of all benthic foraminifera are similar to, or more enriched than, $\delta^{18}O_{Neogloboquadrina\ pachyderma}$. This can be explained in terms of the lower temperatures and higher salinities that characterise subsurface and deep water, relative to the surface mixed layer. Significantly, $\delta^{18}O_{U.\ mediterranea}$ (in cores SL-11 and SL-21) retains the heavy deep water values but inflects to lower values after the Younger Dryas at the same time as the surface-water record of *G. ruber*. This contrasts markedly with the lagged response of $\delta^{18}O_{N.\ pachyderma}$ that suggests an isolation of intermediate waters from surface processes (Casford et al., 2002). The combined data portray a direct link between responses to regional freshwater input in both surface and deepest waters, which is not shared at intermediate levels. We view this as a reflection of the proximity of our cores to an area of active deep water formation, with bottom waters penetrating intermittently below intermediate waters that continuously advect into the Aegean from a remote source area with different $\delta^{18}O$ characteristics (Casford et al., 2002).

The carbon isotope data (Fig. 3) allow further insight into the habitat separations between species. The general $\delta^{13}C$ trend shows relatively constant values before and after periods of sapropel deposition, with depletion in $\delta^{13}C$ values over the

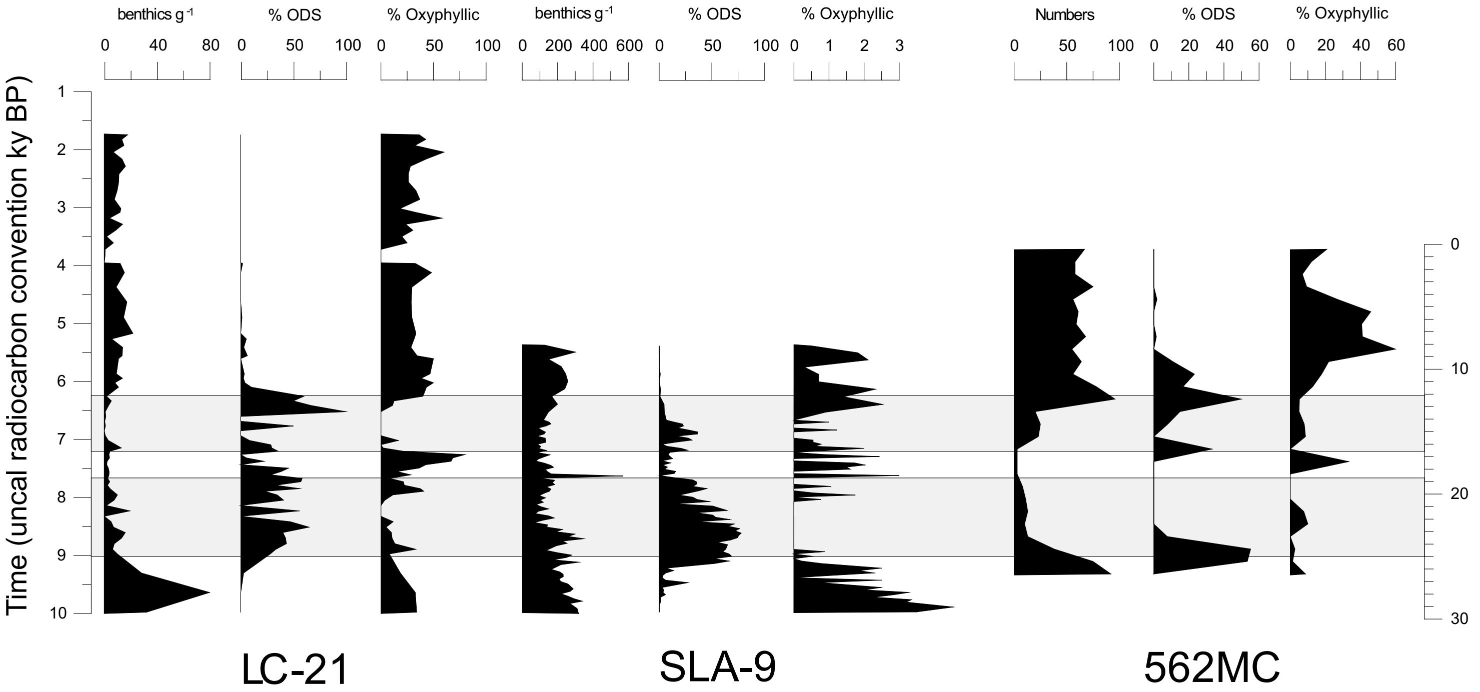


Fig. 4. Summary of (benthic) faunal indicators from cores SLA-9 and LC-21 as well as the preliminary results from multi-core 562MC. Showing numbers of benthic foraminifera per gram in SLA-9 and LC-21, with absolute numbers from 562MC. The % ODS plot indicates the total percentage of the dominant ODS foraminifera *Chilostomella mediterranensis*, *Cassidulinoides bradyi*, *Fursenkoina mexicana*, and *Globobulimina affinis*. The oxyphyllic plots show the total percentage of miliolids, *Cibicides pachydermus* and *Gyroidinoides orbicularis* indicating the presence of oxygen requiring fauna.

sapropel itself. The magnitude of this depletion is greater in the mesopelagic *Neogloboquadrina pachyderma* than in the surface species *Globigerinoides ruber*. The benthic species *Globobulimina affinis* and *Uvigerina peregrina* in SLA-9 (southwest Aegean) show an even stronger depletion than *N. pachyderma*. Since ^{12}C is preferentially taken up during photosynthesis, surface-water Dissolved Inorganic Carbon (DIC) attains relatively high δ^{13}C values, while remineralisation causes relatively light $\delta^{13}C_{DIC}$ values at depth. Hence, benthic and mesopelagic species would normally be expected to show lighter δ^{13}C values than epipelagic species. Vital effects might account for constant offsets between the various benthic and deep planktonic species but the general trends in their records should be similar. Paradoxically, the $\delta^{13}C_{\mathit{U. mediterranea}}$ signal in the northern Aegean cores SL-11 and SL-21 mimics both the trend and values of the epipelagic species *G. ruber* (Fig. 3). Note that SL-11 and SL-21 are both from locations adjacent to an area of deep water production (the Mount Athos basin) and are sited in relatively shallow water (Table 1). Hence, a likely explanation for the anomalous $\delta^{13}C_{\mathit{U. mediterranea}}$ signal is that *Uvigerina mediterranea* lived in newly advected deep water, with a carbon isotope signal that has very recently been 'set' according to air–sea equilibrium, but retaining an oxygen isotope signal that reflects the (cool and saline) deep water signature (Fig. 2). The combination of abundant ODS species (with carbon isotope trends resembling that of *N. pachyderma*) alongside *U. mediterranea*, with an absence of comprehensive repopulation by other species, suggests that advection events were intermittent and short-lived phenomena.

3.2. Centennial-scale sapropel interruptions

'Interruptions' of centennial-scale duration within sapropels have been reported from across the Mediterranean, with examples from the Holocene to the Pliocene (e.g. Van Straaten, 1966, 1972; Thunell et al., 1977; Stanley, 1978; Rossignol-Strick et al., 1982; Cita et al., 1984; Vismara-Schilling, 1984; Perissoratis and Piper, 1992; Rohling et al., 1993, 1997; Mercone et al., 2001). It is important to establish the relationship between the conjectured high-frequency advection events (above) and the longer-term ventilation changes that caused these sapropel interruptions.

First of all, we note that the centennial-scale 'interruption' of S1 in the Aegean core LC-21 shows rapid benthic repopulation, from one sample to the next (i.e. within ∼50 years; Fig. 4). SLA-9 also shows these marked shifts, alternating between ODS species and less low-oxygen tolerant opportunists (Abu-Zied, 2001; Mercone et al., 2001); this is also the case in the Adriatic (Jorissen et al., 1993; Rohling et al., 1997; Mercone et al., 2000). Here, we show similar rapid benthic repopulations, bound by azoic intervals, within S6 (Fig. 5). This is a significant observation because the studied S6 comes from ODP Hole 971A, taken at a deep location (∼2026 m) in the open eastern Mediterranean, rather than within a deep water source region like the Adriatic or Aegean. Clearly deep ventilation improved sufficiently to allow the presence of bio-available oxygen at the sea floor at this very deep site in the open basin, and it happened both repeatedly and abruptly.

Detailed study of the interruption in S1 has linked it to climatic processes. Its benthic foraminiferal repopulations are indicative of re-oxygenation, related to improved deep water formation and while the entire interval lasted several centuries, its onset was very abrupt, within 50 years (Mercone et al., 2001; Rohling et al., 2002). The reventilations were found to be related to 'cold spells' over northern basins of the Mediterranean (Rohling et al., 1997, 2002; Casford et al., 2001; Mercone et al., 2001), which are considered to be periods of increased frequency or intensity of outbreaks of polar/continental northerly air masses from higher latitudes (Mariolopoulos, 1961; Theocharis, 1989; Roether et al., 1996; Poulos et al., 1997). Individual outbreaks are seasonally dependent, normally lasting 1–5 days, concentrated in the winter months, and interannually variable (Saaroni et al., 1996). Intense periods of concentrated outbreaks can dominate over periods of weeks to months; a recent episode started end November 2001 and lasted into January 2002 (see on-board observations RV *Meteor* cruise M51-3 for the first two weeks of the event; Fig.

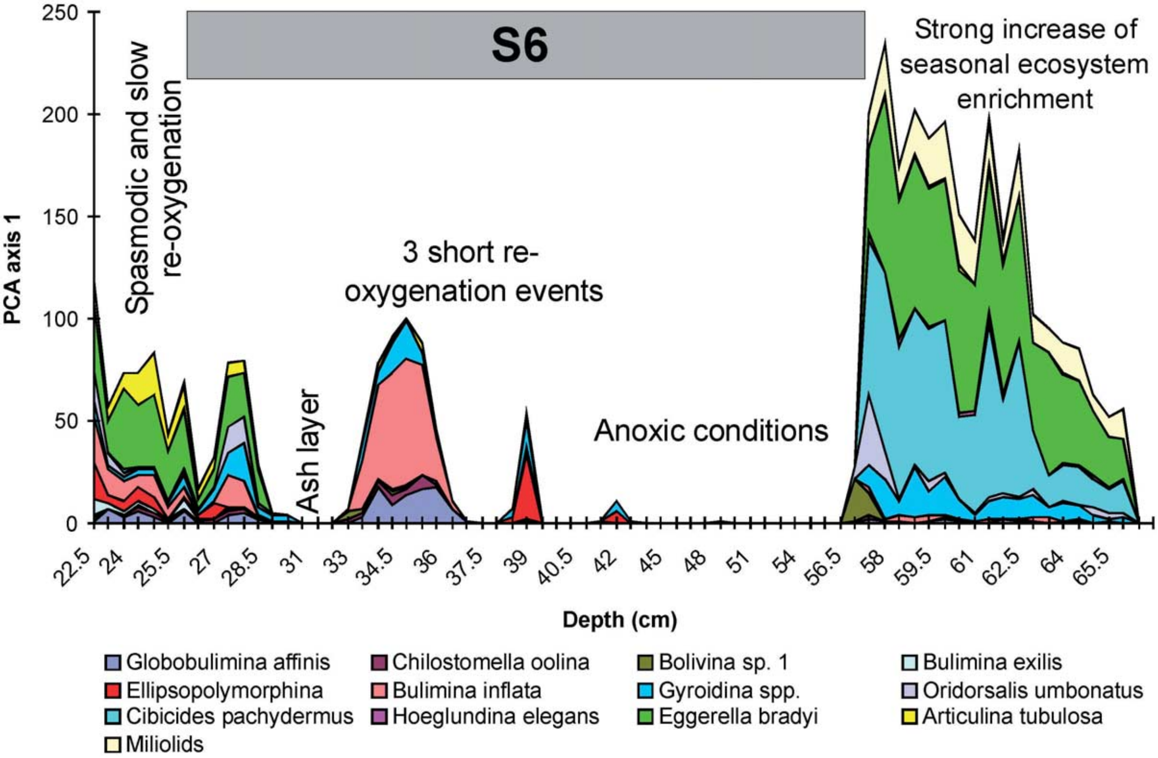


Fig. 5. Core 971 scores on first-principle component for the benthic foraminifera abundance distributions through S6 in ODP Hole 971A, illustrating three abrupt reventilation events in this deep location (2026 m).

6), while a previous episode with particularly intense northerly cooling over the Aegean occurred in the late 1980s–early 1990s (Theocharis, 1989; Roether et al., 1996). Variations in the intensity and frequency of such outbreaks drive variability in the deep water formation rates (Theocharis, 1989; Roether et al., 1996). The Holocene history of centennial-scale cold spells has been linked to the GISP2 ice-core based proxy for intensity of the Siberian High (Rohling et al., 2002). It would appear that the cold spells represent a longer-periodicity 'clustering' of times with particularly abundant and intense northerly outbreaks.

3.3. Other ventilation indicators

A key on-board observation from RV *Meteor* cruise 51-3 relevant to this study concerns the high relative abundances of both right and left coiling morphotypes of the planktonic foraminifer *Globorotalia truncatulinoides*, which we found in several sapropels of core SL97 from the western Levantine basin (especially S7 and S8). This species has been observed in the deepest tows in the Mediterranean at ∼300 m (Pujol and Vergnaud-Grazzini, 1995), but is known from oceanic studies to spend significant parts of its life cycle below these levels, down to ∼1000 m (Hemleben et al., 1989; Lohmann and Schweitzer, 1990). This unprecedented observation of *G. truncatulinoides* suggests that the upper water column remained regularly ventilated to a depth of many hundreds of meters in this region.

A further important observation concerns the presence of benthic foraminiferal faunas reported here, throughout S1 at mid-depths (1391 m) off Libya in core 562MC (Table 1; Fig. 4), similar to such observations through much of S1 in the southern Aegean (Mercone et al., 2001) and the Adriatic (Jorissen et al., 1993; Rohling et al., 1997). Such continuations imply that either intermittent ventilation or continuous dysoxia pre-

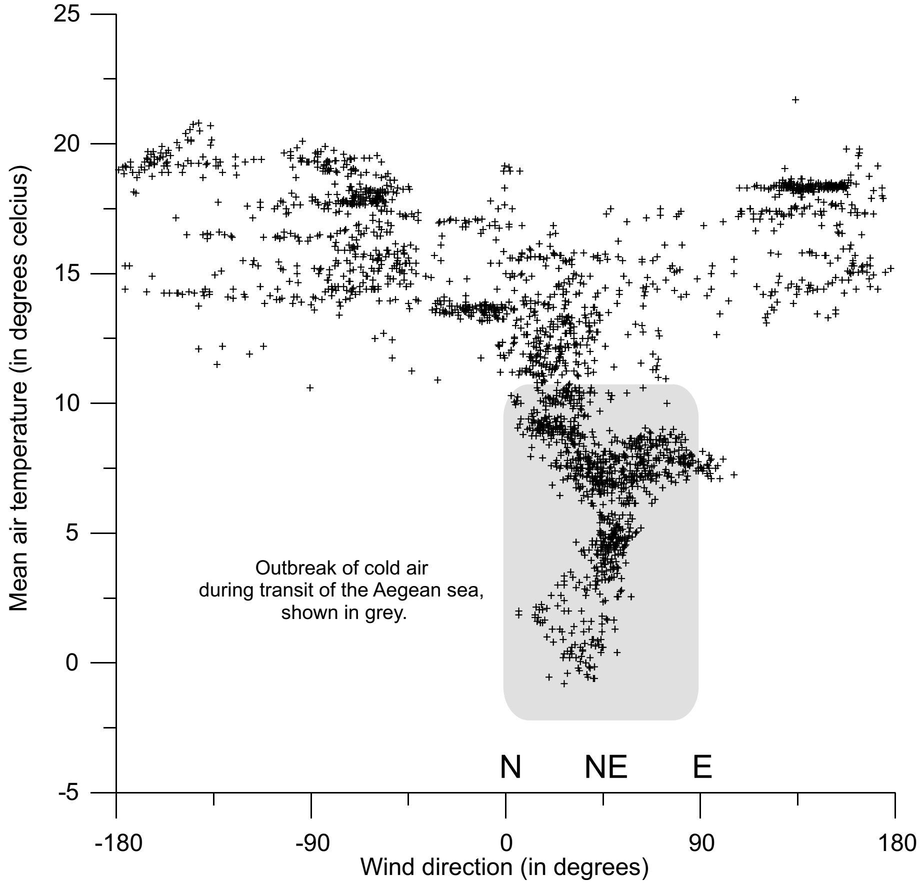


Fig. 6. Plot of wind direction vs. air temperature illustrating the northery flow of the cool/continental air outbreak over the Aegean during RV *Meteor* cruise 51-3 (December 2001).

vailed. The observations off Libya are most surprising because of this area's remote position relative to likely deep ventilation sources.

4. Discussion

Although sample size even in high sedimentation-rate areas limits the temporal resolution of proxy records, some important conclusions can still be drawn from the sedimentary record. The occurrence of *Uvigerina mediterranea* throughout the S1 in the Northern Aegean suggests that it repopulated on a regular basis within our sample resolution. Hence, ventilation must have occurred at least once and possibly several times within the time span of each sample (~50 years). We inferred that the resemblance of the trends in $\delta^{13}C_{U.\ mediterranea}$ to those of the epipelagic species *Globigerinoides ruber* suggests that $\delta^{13}C_{U.\ mediterranea}$ (Fig. 3) reflects DIC values that were recently 'set' at the surface, in agreement with the core's proximity to a sensitive key area of regional deep water production. Hence, intermittent ventilation is suggested throughout S1 within the Aegean (Fig. 7).

The benthic faunas present through S1 off Libya (Fig. 4) also suggest intermittent ventilation, or continuous dysoxia. Similarly, ventilation to a depth of many hundreds of meters is inferred from the abundance of *Globorotalia truncatulinoides* in the open eastern Mediterranean (core SL97) during S7 and S8, while discrete but sustained reventilation events are even observed in

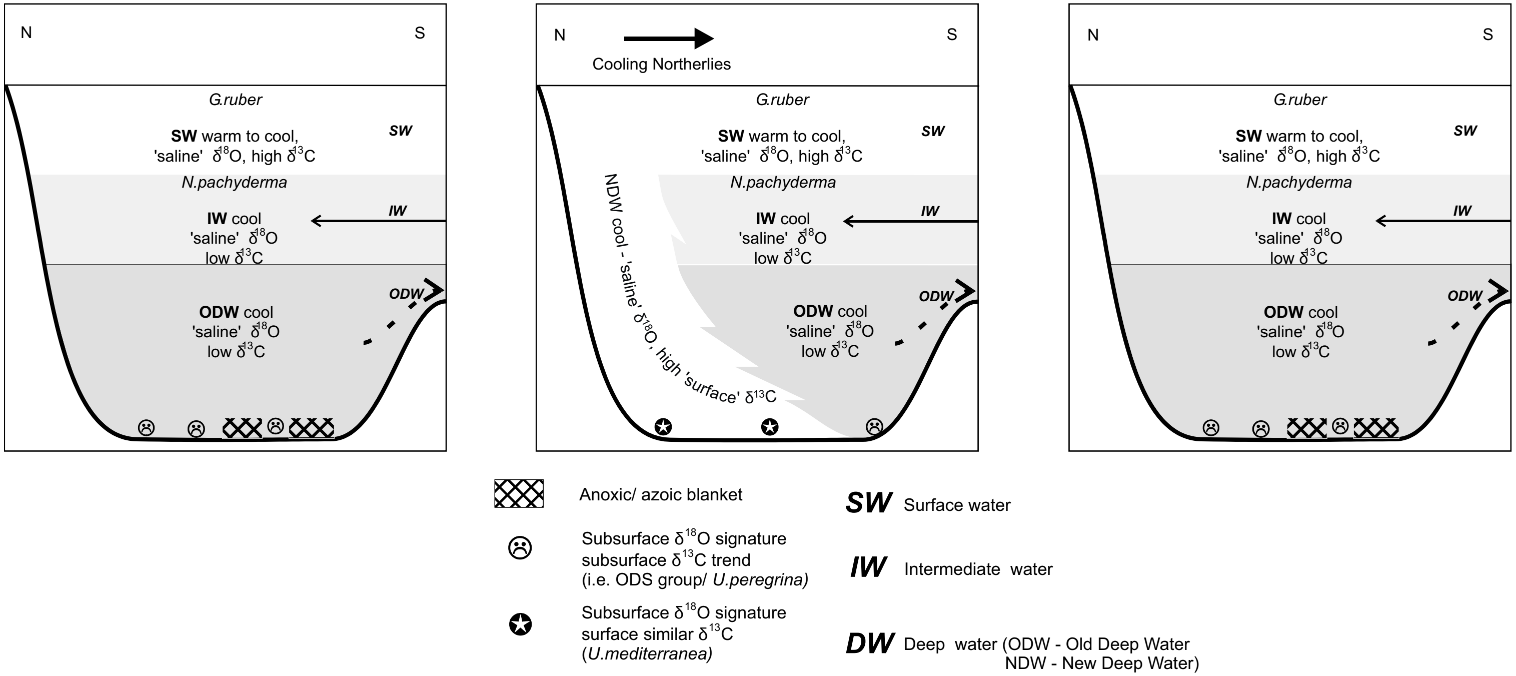


Fig. 7. Three-stage schematic representation of the inferred configuration of water masses before, during and after reventilation in the Aegean Sea. ODW indicates the presence of Old Deep Water; NDW represents the advection of New Deep Water.

the deep water S6 deposit of ODP Hole 971A (Fig. 5).

While persistent ventilation events in small convective regions such as the northern Aegean basin are relatively easy to envision, rapid and sustained repopulations in deep open settings are much more difficult to explain. Such rapid events would require abrupt oxygenation of the bottom waters. This cannot be explained by diffusive oxygen transport, since diffusive mixing operates on time scales >1000 years (~ 450 years e-folding diffusive time scale (Casford et al., 2002). Consequently, the rapid reventilations must have resulted from direct advection of newly formed bottom waters. This advection must have been strong enough to overcome the titration of any reduced chemical species (e.g. Fe^{2+}, Mn^{2+}) both in the water column and at the sediment/water interface. If the entire water column were anoxic, then a very considerable reservoir of such chemical species would need to be titrated. In addition, any Biological Oxygen Demand (BOD) in the water column would need to be overcome, before a finite amount of bio-available oxygen could be present at the sea floor to sustain viable benthic populations.

Using values summarised in Rohling (1994), modern BOD rates alone would require on the order of 640 years to establish water-column anoxia below 1500 m if advective oxygen supply failed completely. More sophisticated model results (Stratford et al., 2000) suggest that it would take nearer to ~ 1500 years to establish anoxia. Today advective oxygen supply outstrips this demand by around five times (~ 2.67 mol O_2 m^{-3} y^{-1}, below 1500 m), so that a re-establishment of today's intensity of advective supply after an anoxic phase would re-oxygenate the water column below 1500 m as rapidly as 1–2 centuries. This is in agreement with Roether and Well (2001) who calculate a figure of 150 years to replace existing deep water. Following the above values for establishment of anoxia and subsequent re-oxygenation, it would require around 740–1700 years which far exceeds the rapid variability observed. Note that this ignores the potential build-up of reduced chemical species in the water column, which would considerably lengthen the calculated recovery period. BOD and chemical titration would remove oxygen from the new deep water resulting in a spatial separation between the oxygenation front and the penetration of the new deep water. Furthermore, these controls will also vary with the strength of export productivity and concentration of reduced species (a function of the degree of anoxia) both of which are likely to show regional and/or spatial variability.

To address the much faster response times observed it would appear much more likely that any anoxia was limited to a thin 'blanket' at the sediment/water interface. Such a 'blanket' would result from remineralisation of organic components that were rapidly posted to the sea floor (e.g. diatom mats; Kemp et al., 1999), and so would reflect the patchy nature of the spatially and temporally variable export productivity distribution.

Observations of deep-living planktonic species (e.g. *Globorotalia truncatulinoides*) and benthics throughout sapropels suggest that they are most common in the more oligotrophic areas of the eastern Mediterranean, e.g. off the Gulf of Sirte. Might this reflect spatial differences in the export productivity levels? Poor ventilation would create dysoxic conditions everywhere, and regions of high export flux developed anoxic 'blankets' whereas oligotrophic regions did not. The patchy nature of such 'blankets' may also allow refugia for certain benthic foraminifera to develop locally, promoting more rapid repopulation.

In addition, there is a clear increase in sedimentary C_{org} concentrations with water depth (Murat and Got, 2000), that appears to conflict with the normal expectations of a mid-depth remineralisation maximum/oxygen minimum. The observed increase with depth may reflect that a remineralisation maximum instead prevailed at the sea floor, presumably due to rapid export/dumping of C_{org}, supporting our proposal that anoxia was constrained to a blanket at the sediment/water interface.

Murat and Got (2000) observations of increasing organic carbon concentrations with depth suggest that deep water isolation also increases with depth. In addition, the probability of significant ventilation in a density-stratified basin decreases with depth. As the indicators, reported here, of (intermittent) bio-available oxygen within sapropels do not include observations from below 2026 m, we cannot exclude the possibility that abyssal depths developed more widespread and persistent anoxia. This uncertainty calls for high-resolution studies in abyssal sites of sapropels that have known reventilation histories in shallower locales.

5. Summary and conclusions: A dynamic ventilation concept

Integrating the various strands of evidence discussed above, we propose a dynamic concept for the relationship between deep water ventilation and oxygenation at sapropel times. The ventilation state we propose is in fact similar to that of today, in that it remained characterised by intermittent climate-related maxima of new deep water formation that were associated with cooling by interannually variable northerly outbreaks of polar/continental air. However, at sapropel times, the ventilation was weakened overall, due to the additional buoyancy gain imposed by the enhanced freshwater influx into the basin. Our dynamic concept of ventilation decouples water mass advection – driven by new formation and internal mixing – from the oxygen concentrations

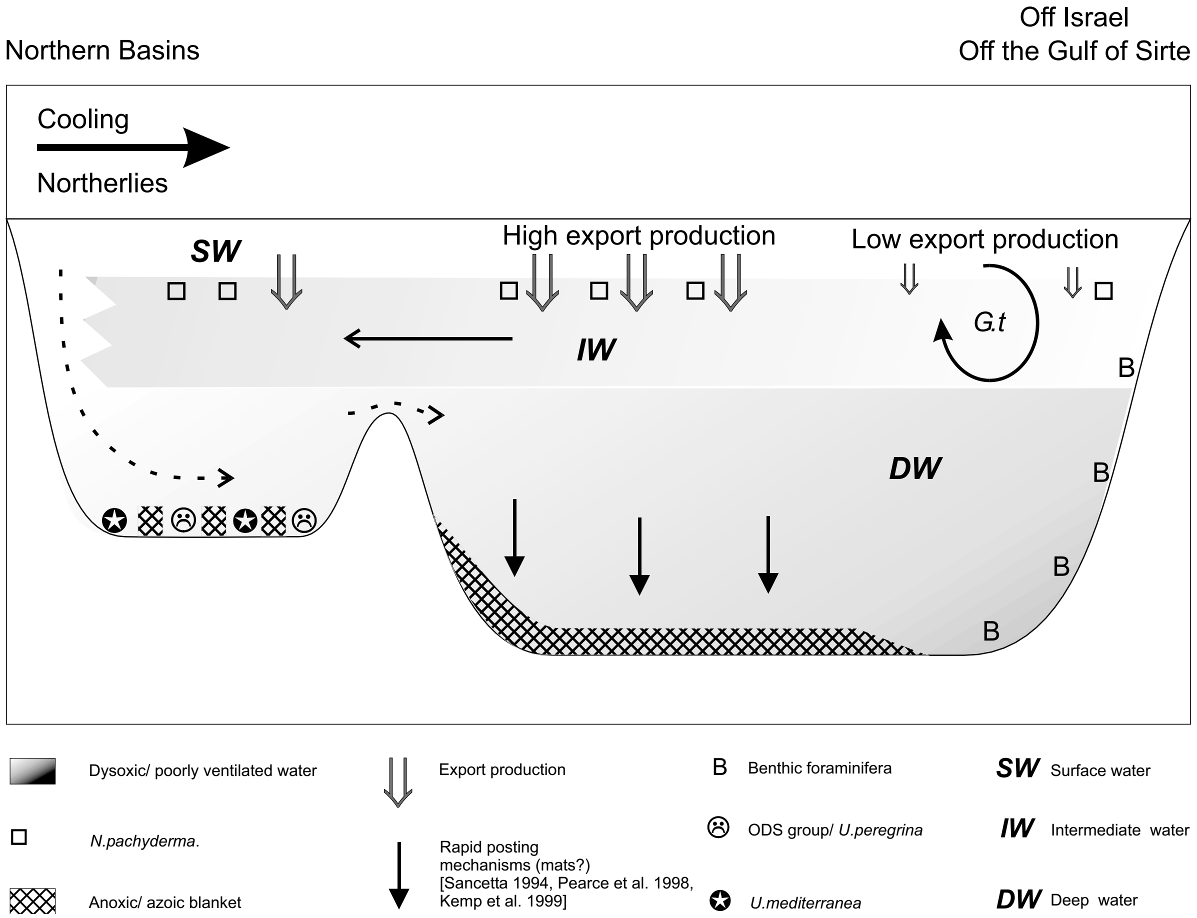


Fig. 8. Schematic 2-D summary of the discussed aspects of deep water advection and oxygenation, based on a compilation of several sapropels. This is intended to represent a hypothetical north–south transect and is therefore not intended to define specific spatial gradients. The letter B in the key represents benthic foraminifera in both the continuous benthic presence off Israel and the rapid repopulation S6. This exemplifies the restricted nature of the anoxic blanket in both space and time.

that are in addition affected by chemical and biological constraints, with their own temporal and spatial variability. This allows for contrasting oxygen concentrations within single water masses, both temporally and spatially.

Fig. 8 aims to summarise these key aspects in a very schematic 2-D representation, which obviously cannot capture all observed 3-D and temporal variability. In addition, this figure does not account for any possible anoxia deeper than 2000 m, as mentioned above. Intermittent ventilation is shown in the north of the profile, as determined throughout S1 in both the Aegean and Adriatic from the presence of benthic faunas and their isotopic composition, in particular contrasting the low-oxygen tolerant species *Globobulimina affinis* and the more oxyphilic *Uvigerina mediterranea*. This deep water ventilation must occur at least once within every sample interval (~50 years), and most probably even more frequently. The graded grey fill illustrates the inferred oxygenation gradient within both deep water and intermediate water masses, and highlights the dissociation of intermediate water from the surface and deep waters in the Aegean Sea (see Casford et al., 2002). A blanket of anoxia develops under areas of higher export production, with the presence of benthic foraminifera in cores from even the deep, southern Mediterranean suggesting the limited extent of these truly anoxic conditions in both space and time. This blanket hypothesis for the development of anoxia removes the requirement to titrate the complete water column upon reventilation, allowing very rapid events of re-oxygenation and return to anoxic conditions seen in the proxy records.

Acknowledgements

We acknowledge the contributions of the scientific team of RV *Meteor* cruise M51-3 (November–December 2001), in particular the chief scientist Professor C. Hemleben. We thank Larry Peterson and Anne Murat for their invaluable comments during review. Additional thanks are also due to S. Cooke and H. Sloane for their technical assistance.

References

Abu-Zied, R.H., 2001. High Resolution LGM-Present Paleoceanography of the N.E. Mediterranean: A Benthic Perspective. Ph.D. Thesis.

Bethoux, J.P., Gentili, B., Morin, P., Nicolas, E., Pierre, C., Ruiz-Pino, D., 1999. The Mediterranean Sea: a miniature ocean for climatic and environmental studies and a key for the climatic functioning of the North Atlantic. Prog. Oceanogr. 44, 131–146.

Boyle, E.A., Lea, D.W., 1989. Cd and Ba in planktonic foraminifera from the Eastern Mediterranean: evidence for river outflow and enriched nutrients during sapropel production. Trans. Am. Geophys. Union 70, 101–134.

Calvert, S.E., 1983. Geochemistry of Pleistocene sapropels and associated sediments from the eastern Mediterranean. Oceanol. Acta 6, 255–267.

Casford, J.S.L., Rohling, E.J., Abu-Zied, R., Cooke, S., Fontanier, C., Leng, M., Lykousis, V., 2002. Circulation changes and nutrient concentrations in the Late Quaternary Aegean Sea: A non-steady state concept for sapropel formation. Paleoceanography (in press).

Casford, J.S.L., Abu-Zied, R., Rohling, E.J., Cooke, S., Boessenkool, K.P., Brinkhuis, H., DeVries, C., Wefer, G., Geraga, M., Papatheodorou, G., Croudace, I., Thomson, J., Lykousis, V., 2001. Mediterranean climate variability during the Holocene. Mediterranean Mar. Sci. 2, 45–55.

Cheddadi, R., Rossignol-Strick, M., 1995. Improved preservation of organic-matter and pollen in eastern Mediterranean sapropels. Paleoceanography 10, 301–309.

Cita, M.B., Grignani, D., 1982. Nature and origin of Late Neogene Mediterranean sapropels. In: Schlanger, S.O., Cita, M.B. (Eds.), The Nature and Origin of Cretaceous Carbon-Rich Facies. Academic Press, London, pp. 165–196.

Cita, M.B., Beghi, C., Camerlenghi, A., Kastens, K.A., McKoy, F.W., Nosetto, A., Parisi, E., Scolari, F., Tomadin, L., 1984. Turbidites and megaturbidites from the Herodotus abyssal plain (Eastern Mediterranean) unrelated to seismic events. Mar. Geol. 55, 79–101.

Cita, M.B., Vergnaud-Grazzini, C., Robert, C., Chamley, H., Ciaranfi, N., d'Onofrio, S., 1977. Paleoclimatic record of a long deep sea core from the eastern Mediterranean. Quat. Res. 8, 205–235.

DeLange, G.J., Ten Haven, H.L., 1983. Recent sapropel formation in the eastern Mediterranean. Nature 305, 797–798.

De Rijk, S., Rohling, E.J., Hayes, A., 1999. Onset of climatic deterioration in the eastern Mediterranean around 7 ky BP; micropalaeontological data from Mediterranean sapropel interruptions. Mar. Geol. 153, 337–3432.

Hayes, A., Rohling, E.J., DeRijk, S., Kroon, D., Zachariasse, W.J., 1999. Mediterranean planktonic foraminifera faunas during the last glacial cycle. Mar. Geol. 153, 239–252.

Hemleben, C., Spindler, M., Anderson, O.R., 1989. Modern Planktonic Foraminifera. Springer, New York, 363 pp.

Jorissen, F.J., 1999. Benthic foraminiferal successions across Late Quaternary Mediterraenan sapropels. Mar. Geol. 153, 91–101.

Jorissen, F.J., Asioli, A., Borsetti, A.M., Capotondi, L., deVisser, J.P., Hilgen, F.J., Rohling, E.J., vanderBorg, K., Vergnaud-Grazzini, C., Zachariasse, W.J., 1993. Late Quaternary central Mediterranean biochronology. Mar. Micropaleontol. 21, 169–189.

Kemp, A.E.S., Pearce, R.B., Koizumi, I., Pike, J., Rance, S.J., 1999. The role of mat-forming diatoms in the formation of Mediterranean sapropels. Nature 398, 57–61.

Kullenberg, B., 1952. On the salinity of the water contained in marine sediments. Medd. Oceanogr. Inst. Göteborg 21, 1–38.

Leaman, K.D., Schott, F.A., 1991. Hydrographic structure of the convection regime in the Gulf of Lions Winter 1987. J. Phys. Oceanogr. 21, 575–598.

Lohmann, G.P., Schweitzer, P.N., 1990. Globorotalia truncatulinoides' growth and chemistry as probes of the past thermocline: 1. Shell size. Paleoceanography 5, 55–75.

Mariolopoulos, E.G., 1961. An Outline of the Climate of Greece. Publ. Meteorol. Inst. Univ. Athens 6, 51 pp.

Mercone, D., Thomson, J., Abu-Zied, R.H., Croudace, I.W., Rohling, E.J., 2001. High-resolution geochemical and micropalaeontological profiling of the most recent eastern Mediterranean sapropel. Mar. Geol. 177, 25–44.

Mercone, D., Thomson, J., Croudace, I.W., Siani, G., Paterne, M., Troelstra, S., 2000. Duration of S1, the most recent sapropel in the eastern Mediterranean Sea, as indicated by accelerator mass spectrometry radiocarbon and geochemical evidence. Paleoceanography, 15, 336–347.

Murat, A., Got, H., 2000. Organic carbon variations of the eastern Mediterranean Holocene sapropel: a key for understanding formation processes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 158, 241–257.

Olauson, E., 1961. Studies of deep-sea cores. Rep. Swed. Deep Sea Exped. 8, 335–391.

Pedersen, T.F., Calvert, S.E., 1990. Anoxia vs. productivity – what controls the formation of organic-carbon-rich sediments and sedimentary-rocks. AAPG Bull. 74, 454–466.

Perissoratis, C., Piper, J.W., 1992. Age, regional variation, and shallowest occurrence of S1 sapropel in the Northern Aegean Sea. Geo-Mar. Lett. 12, 49–53.

Poulos, S.E., Drakopoulos, P.G., Collins, M.B., 1997. Seasonal variability in sea surface oceanographic conditions in the Aegean Sea (eastern Mediterranean) an overview. J. Mar. Syst. 13, 225–244.

Pujol, A., Vergnaud-Grazzini, C., 1995. Distribution patterns of live planktic foraminifera as related to regional hydrography and productive systems of the Mediterranean Sea. Mar. Micropaleontol. 25, 187–217.

Reiss, Z., Halicz, E., Luz, B., 2000. Late-Holocene foraminifera from the SE Levantine Basin. Isr. J. Earth Sci. 48, 1–27.

Roether, W.H., Manca, B.B., Klein, B., Bregant, D., Georgopoulos, D., Beitzel, V., Kovacevic, V., Luchetta, A., 1996. Recent changes in eastern Mediterranean deep waters. Science 271, 333–335.

Roether, W., Well, R., 2001. Oxygen consumption in the Eastern Mediterranean. Deep-Sea Res. I 48, 1535–1551.

Rohling, E.J., Mayewski, P.A., Abu-Zied, R.H., Casford, J.S.L., Hayes, A., 2002. Holocene atmosphere–ocean interactions: records from Greenland and The Aegean Sea. Clim. Dyn. 18, 587–593.

Rohling, E.J., 1999b. Environmental controls on salinity and $\delta^{18}O$ in the Mediterranean. Paleoceanography 14, 706–715.

Rohling, E.J., Jorissen, F.J., DeStigter, H.C., 1997. 200 year interruption of Holocene sapropel formation in the Adriatic Sea. J. Micropaleontol. 16, 97–108.

Rohling, E.J., Den Dulk, M., Pujol, C., Vergnaud-Grazzini, C., 1995. Abrupt hydrographic change in the Alboran Sea (western Mediterranean) around 8000 yrs BP. Deep-Sea Res. I 42, 1609–1619.

Rohling, E.J., 1994. Review and new aspects concerning the formation of eastern Mediterranean sapropels. Mar. Geol. 122, 1–28.

Rohling, E.J., Jorissen, F.J., Vergnaud-Grazzini, C., Zachariasse, W.J., 1993. Northern Levantine and Adriatic Quaternary planktic foraminifera; Reconstruction of paleoenvironmental gradients. Mar. Micropaleontol. 21, 191–218.

Rohling, E.J., Gieskes, W.W.C., 1989. Late Quaternary changes in Mediterranean intermediate water density and formation rate. Paleoceanography 4, 531–545.

Rossignol-Strick, M., 1985. Mediterranean Quaternary sapropels: an immediate response of the African monsoon to variation of insolation. Palaeogeogr. Palaeoclimatol. Palaeocol. 49, 237–265.

Rossignol-Strick, M., 1983. African monsoons, an immediate response to orbital insolation. Nature 304, 46–49.

Rossignol-Strick, M., Nesteroff, W., Olive, P., Vergnaud-Grazzini, C., 1982. After the deluge: Mediterranean stagnation and sapropel formation. Nature 295, 105–110.

Saaroni, H., Bitan, A., Alpert, P., Ziv, B., 1996. Continental Polar outbreaks into the Levant and Eastern Mediterranean. Int. J. Climatol. 16, 1175–1191.

Stanley, D.J., 1978. Ionian Sea sapropel distribution and Late Quaternary palaeoceanography in the Eastern Mediterranean. Nature 274, 149–152.

Stratford, K., Williams, R.G., Myers, P.G., 2000. Impact of the circulation on sapropel formation in the eastern Mediterranean. Glob. Biogeochem. Cycles 14, 683–695.

Theocharis, A., 1989. Deep water formation and circulation in the Aegean Sea. In: Charnock, H. (Ed.), Reports in Meteorology and Oceanography, 40, I, pp. 335–359.

Thunell, R.C., Williams, D.F., Kennett, J.P., 1977. Late Quaternary paleoclimatology, stratigraphy, and sapropel history in eastern Mediterranean deep-sea sediments. Mar. Micropaleontol. 2, 371–388.

Van Os, B.J.H., Lourens, L.J., Hilgen, F.J., Delange, G.J., Beaufort, L., 1994. The formation of Pliocene sapropels and carbonate cycles in the Mediterranean – diagenesis, dilution, and productivity. Paleoceanography 9, 601–617.

Van Straaten, R.M.V.U., 1966. Micro-malacological investigation of cores from the southeastern Adriatic Sea. Proc. Kon. Ned. Akad. Wet. 69, pp. 429–445.

Van Straaten, R.M.V.U., 1972. Holocene stages of oxygen depletion in waters of the Adriatic. In: Stanley, D.J. (Ed.), The Mediterranean Sea: A Natural Sedimentation Laboratory. Dowden, Hutchinson and Ross, Stroudsburg, PA, 631 pp.

Vergnaud-Grazzini, C., 1985. Mediterranean late Cenozoic stable isotope record: Stratigraphic and paleoclimatic implications. In: Stanley, D.J., Wezel, F.C. (Eds.), Geological Evolution of the Mediterranean Basin. Springer, New York, pp. 413–451.

Vergnaud-Grazzini, C., Ryan, W.B.F., Cita, M.B., 1977. Stable isotope fractionation, climate change and episodic stagnation in the Eastern Mediterranean during the Late Quaternary. Mar. Micropaleontol. 2, 353–370.

Vismara-Schilling, A., 1984. Holocene stagnation event in the eastern Mediterranean. Evidence from deep-sea benthic foraminifera in Calabria and Western Mediterranean ridges. Benthos '83,Second Int. Symp. Benthic Foraminifera, Pau, April 1983, pp. 585–596.