ELSEVIER

Marine Geology 153 (1999) 337–343

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

Eastern Mediterranean sapropel S1 interruption: an expression of the onset of climatic deterioration around 7 ka BP

S. De Rijk *, A. Hayes, E.J. Rohling

University of Southampton, Department of Oceanography, Waterfront Campus, Southampton, SO14 3ZH, UK

Received 15 June 1997

Abstract

We discuss the palaeoclimatic interpretation of unprecedented high-resolution micropalaeontological studies of short-term (2 to 4 centuries) interruptions within early Holocene organic-rich layer (sapropel) S1 from the eastern Mediterranean. Results for cores from the Adriatic and Aegean seas that contain 'double' S1 sapropels indicate that these interruptions, which are centred roughly around 7000 years $^{14}C_{nc}$ BP, are genuine and related to climatic deterioration. This interpretation is endorsed by a coeval dry event recorded in terrestrial records and indications of climatic deterioration affecting human migration patterns and early societies in Egypt. The presence of sapropel interruptions in the two major source areas of deep water for the entire eastern Mediterranean likely implies that similar intervals may be found throughout the basin, provided that sedimentation rates and sampling resolutions allow the detection of events with a duration of only several centuries. Moreover, our results show that the 'sapropel mode' of circulation comprises a delicate balance between reduced ventilation and enhanced productivity, which is easily disturbed through surface water cooling triggering a short time of improved deep water ventilation.

Keywords: palaeoceanography; Mediterranean Sea; Holocene; sapropel interruption; climate change; planktonic foraminifera

1. Introduction

Up to 80 intervals enriched in organic carbon (sapropels) have been found in the eastern Mediterranean sedimentary sequence since the Early Pliocene (Emeis et al., 1996). Processes invoked to explain their formation range from deep water stagnation to massively increased productivity, and combinations of these extremes (see Rohling, 1994, for overview). Interruptions within sapropels add new information, concerning stability of the 'sapropel mode' of circulation in the basin. Stanley et al. (1978) suggested that sapropel interruptions might be the result of dilution by high sediment input from gravity flows. Rohling et al. (1993) documented an interruption of roughly 900 year duration in Upper Pliocene sapropel C2, as characterised by repopulation of low-oxygen tolerant benthic foraminiferal species in between barren intervals reflecting persistently anoxic bottom water conditions. This repopulation was interpreted in terms of improved deep water ventilation.

Interruptions within the youngest (early Holocene) sapropel S1 have been frequently documented in the past (e.g., Thunell et al., 1977; Cita

* Corresponding author. Fax: +44 (1703) 593059; E-mail: sder@mail.soc.soton.ac.uk

0025-3227/99/$ – see front matter
PII: S0025-3227(98)00075-9

et al., 1984; Vismara Schilling, 1984; Perissoratis and Piper, 1992), but few studies concentrated on their nature. The first comprehensive high-resolution study of an interruption within sapropel S1 concerns core IN68-9 (Fig. 1) from the Adriatic Sea (Rohling et al., 1997). This study indicates that 1000 years of increasing productivity and oxygen depletion preceded the onset of sapropel formation around 8300 years $^{14}C_{nc}$ BP ($^{14}C_{nc}$ = radiocarbon years not corrected for reservoir age). Sapropel formation in the Adriatic was found to have ended around 6300 years $^{14}C_{nc}$ BP, and the interruption was found between 7100 and 6900 years $^{14}C_{nc}$ BP.

Benthic foraminifera in the pre-sapropel phase in IN68-9 (9300–8300 years $^{14}C_{nc}$ BP) mark increasing low oxygen conditions. The lower sapropel unit (S1a) lacks autochthonous benthic foraminiferal fauna, indicating persistent bottom water anoxia. The interruption between the lower (S1a) and upper (S1b) units shows rapid repopulation by a diverse benthic foraminiferal fauna indicative of distinctly improved oxygenation with ongoing enhanced productivity. The upper unit S1b shows a return of poor bottom water oxygenation. Towards the top of S1b, bottom water oxygenation seems to have gradually improved, culminating in a rapid repopulation by diverse benthic faunas at the end of S1 formation. Ongoing enhanced productivity levels are reflected in the benthic fauna until about 5500 years $^{14}C_{nc}$ BP, after which time more or less present-day conditions seem to have prevailed (Rohling et al., 1997).

The planktonic foraminiferal record of core IN-68-9 suggests that the onset of S1 formation and the deposition of the lower part of S1a coincided with warmest surface water conditions, followed by gradual cooling that culminates in the interruption of S1. Return of warmer conditions is found at the base of S1b, again followed by a cooling trend, changing back into a warming trend at the final end of S1 formation (Fig. 2). The observed planktonic and benthonic faunal changes in Adriatic core IN68-9 are suggestive of a causal relationship between surface water cooling and bottom water oxygenation, through convective overturn of the water column. This interpretation may be validated using similar high sedimentation rate cores from the Aegean Sea, as surface cooling and related convective overturn in both the Adriatic and Aegean seas are governed by a more or less similar process of cold and dry polar air incursion in the wake of Atlantic depressions passing north of the Alps.

Perissoratis and Piper (1992) found interrupted S1 sapropels in a variety of sites experiencing high sedimentation rates in the N. Aegean Sea. Linear interpolation of their AMS^{14}C results suggests that the interruption is of about the same age as that in Adriatic core IN68-9. Detailed research on the nature of the interruption is currently being initiated using the N. Aegean cores, while micropalaeontological work has been completed for S. Aegean core LC21 (Fig. 1) and is presented in this paper.

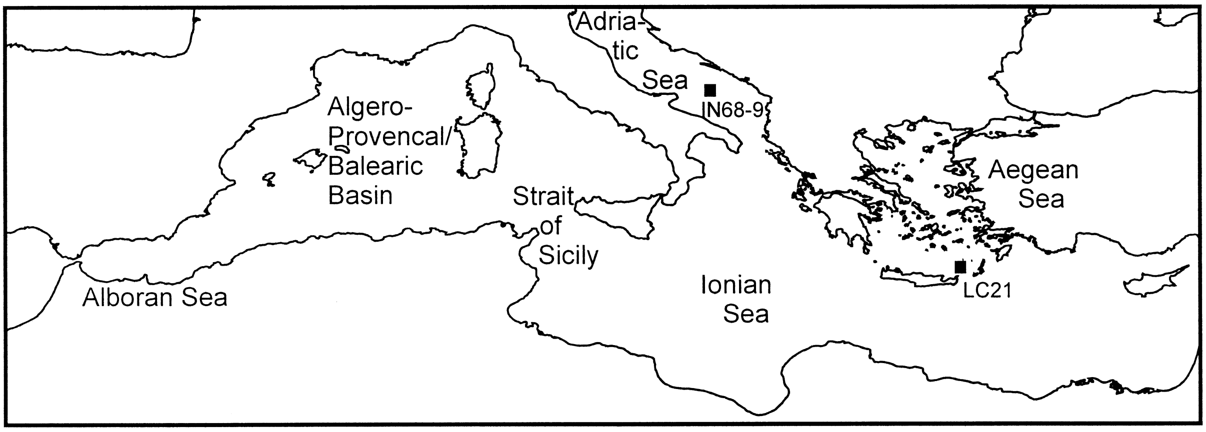

Fig. 1. Map of the Mediterranean Sea showing the location of cores IN68-9 and LC21.

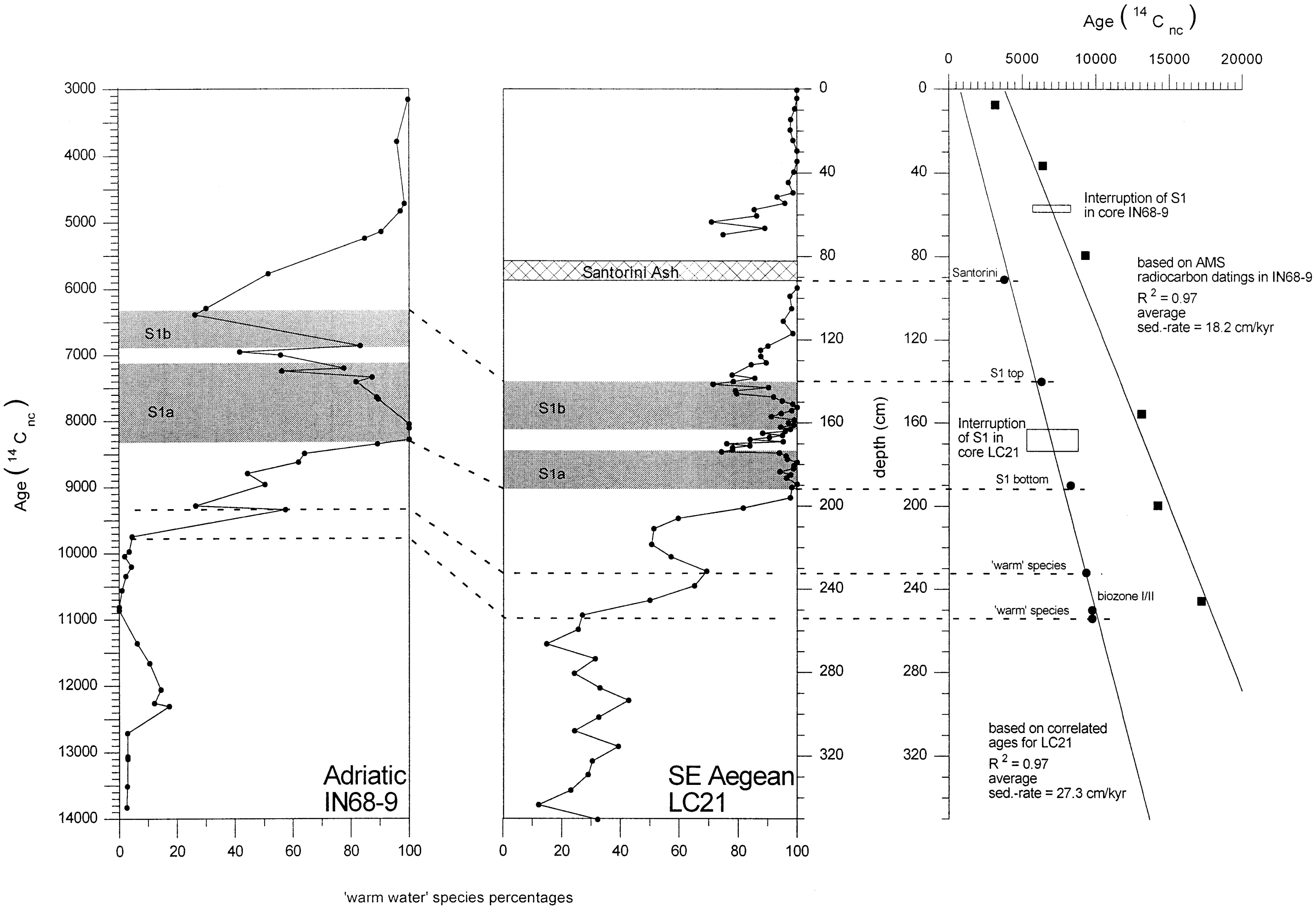

Fig. 2. Two plots on the left show percentages of warm water species in core IN68-9 and LC21 (warm water species is total of *G. ruber*, *G. rubescens*, *G. tenella*, *G. siphonifera*, *G. sacculifer*, *O. universa* and *G. digitata* versus *T. quinqueloba*, *G. scitula*, *N. pachyderma* and *G. inflata*). Vertical axe for IN68-9 indicates age (years $^{14}C_{nc}$ BP), while the other two axes represent depth below surface (cm). Last 3000 years is missing for core IN68-9. Age–depth plots are shown on the right; squares represent the AMS radiocarbon datings in IN68-9 (Jorissen et al., 1993), while correlated ages for LC21 are indicated by dots. The Santorini ash layer in LC21 is dated at 3356 ± 18 years ^{14}C BP (Housley et al., 1990; Friedrich et al., 1990; Bruins and Van der Plicht, 1996); correlation with uncorrected ^{14}C ages forced us to add 400 years.

2. Results

2.1. Time frame

Core LC21, recovered from 1522 m water depth during EC MAST-2 programme Paleoflux (Rothwell, 1995), contains a distinct S1 sapropel interrupted by a lighter grey coloured interval. Since age of sapropel formation may vary with water depth (Troelstra et al., 1991) we date the top and bottom of LC21 sapropel S1 using the AMS^{14}C results of Adriatic core IN68-9 from a similar water depth, 1234 m (Fig. 2). Correlation of S1 top and bottom is further validated by the similar planktonic foraminiferal development in both cores as shown in the next paragraph and in Fig. 3. The dating for the top of S1

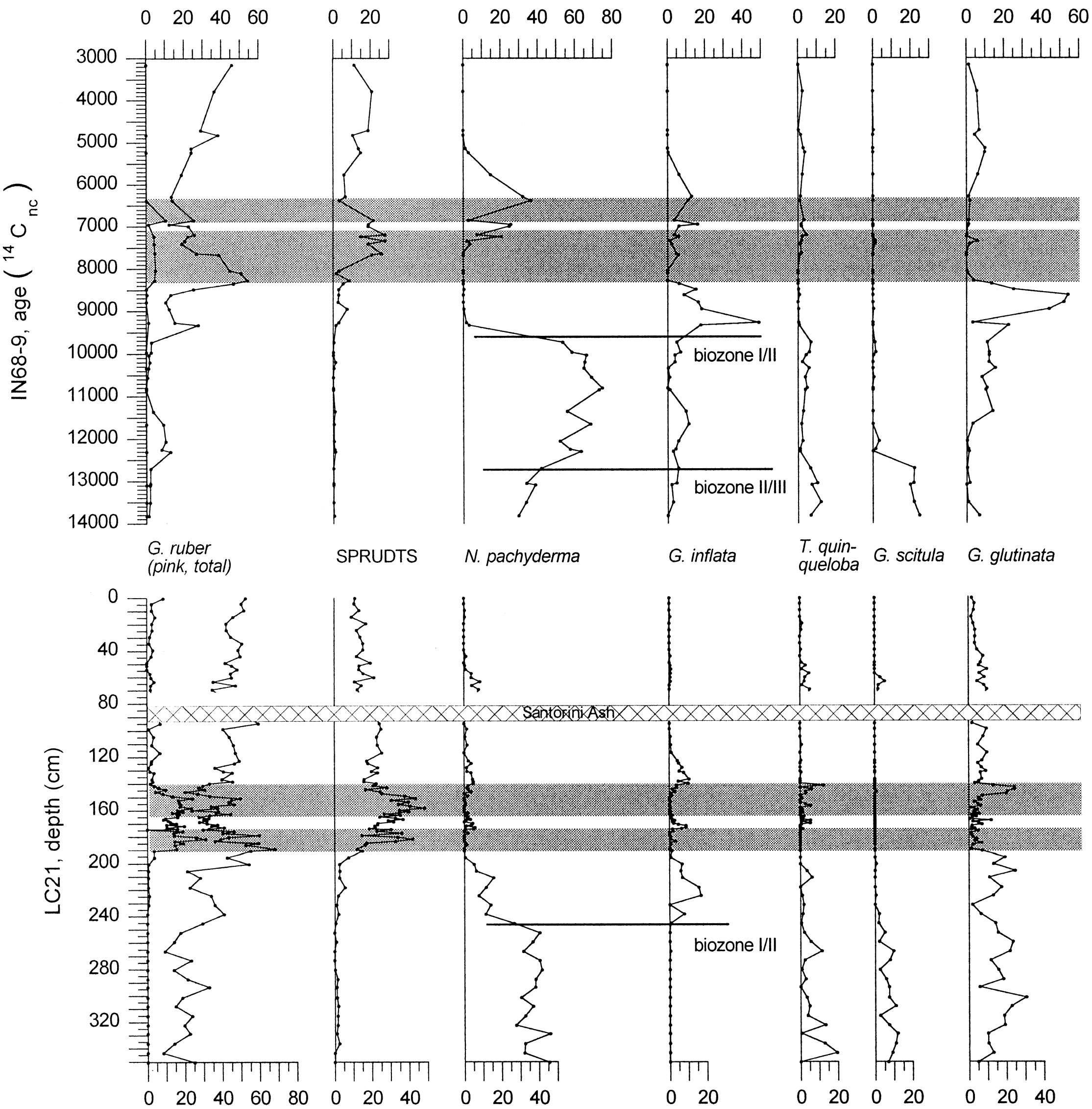

Fig. 3. Relative abundances of the main species of planktonic foraminifera in cores IN68-9 (top) and LC21 (bottom). Grey horizons indicate sapropel S1a and S1b, the Santorini ash layer in LC21 is shown by hatched bar. Biozone I/II as defined by Jorissen et al. (1993) is shown in both records, while biozone II/III is only recognised in core IN68-9.

is used under the assumption that re-oxidation of S1 after re-establishment of oxygenated bottom water conditions (De Lange et al., 1989; Higgs et al., 1994) is of little importance in the high sedimentation rate settings reported on in this paper.

Fig. 3 shows the resemblance between the planktonic foraminiferal records from the Adriatic Sea and the Aegean Sea. Applicability of central Mediterranean biozones defined by Jorissen et al. (1993) into the Aegean Sea has been demonstrated by the AMS^{14}C dated results of a core from the western central Aegean Sea (Zachariasse et al., 1997). Biozone boundary I/II, characterised by a decrease of *Neogloboquadrina pachyderma* and increase of *Globorotalia inflata*, is clearly recognised in LC21 (Fig. 3). Increases of *N. pachyderma* and *Globigerinoides ruber* mark biozone II/III (Fig. 3), but is not recorded in core LC21, which means that the here presented interval is probably younger than 13,000 years $^{14}C_{nc}$ BP. Distinct similarities between plots of 'warm' water species for IN68-9 and LC21 provided approximate ages for two additional levels in core LC21 (Fig. 2).

Besides the biostratigraphy, the Santorini ash layer at 91 cm depth in LC21 gives us an average age of 3356 ± 18 years ^{14}C BP (Housley et al., 1990; Friedrich et al., 1990; Bruins and Van der Plicht, 1996). The significant linear fit through the thus derived age–depth data for core LC21 suggests that the inferred time-frame is fairly accurate (Fig. 2). At this stage, our data are not yet conclusive as to whether both the observed interruptions are synchronous or not, but it is obvious that each has a duration in the order of a couple of centuries (Fig. 2). The approximate ages for the S1 interruptions in the Aegean and Adriatic seas are centred around the equivalent of 7000 years $^{14}C_{nc}$ BP, which is supported by interpolation of AMS^{14}C datings on S1 in north Aegean cores suggesting an age range of about 7000 to 6700 years $^{14}C_{nc}$ BP (Perissoratis and Piper, 1992).

2.2. Palaeoclimatic interpretation

Both around and within S1, the planktonic foraminiferal record of LC21 shows a remarkably similar succession of warmer and cooler faunas to that described for Adriatic core IN68-9 (Fig. 2). Similar cooling events are found to be associated with the endings of the S1a and S1b units. In other words, the Aegean results corroborate the palaeoclimatic fluctuations during sapropel formation inferred for Adriatic core IN68-9.

It is furthermore important to emphasise that, similar to the Adriatic results, the Aegean record also shows a distinct faunal difference between the two sapropel units, and between both sapropel units and the interruption (Fig. 3). Combined with (1) the lack of size-dependent sorting and other familiar sedimentological phenomena associated with turbidites and slumps, and (2) inorganic geochemical results for LC21 which will be presented elsewhere (D. Mercone, pers. commun., 1997), our faunal data provide evidence that the double sapropel feature is genuine and not a result of resedimentation or slumping.

Just before sapropel deposition a short cooling event is noted in both cores disrupting the general warming trend towards the onset of sapropel S1 (Fig. 2). According to the ^{14}C AMS dated core IN-68-9, the cooling event is centred around 9500 years $^{14}C_{nc}$ BP. This may be a local expression similar to the so-called Younger Dryas-II event found in high-latitude North Atlantic records (Koç Karpuz and Jansen, 1992). In core LC21 planktonic foraminifera indicate an decrease of 'warm' water species right after the Santorini event, approximately 3000 years $^{14}C_{nc}$ BP.

3. Discussion and conclusions

As the Adriatic and Aegean seas are important source areas of new deep water for the entire eastern Mediterranean (Roether et al., 1996), the inferred surface water cooling events and resultant convective reventilation of bottom waters in these basins may —to a yet unknown extent— have caused reventilation during S1 formation throughout the eastern Mediterranean. We suggest, therefore, that biological and chemical indicators of (limited?) reventilation may be found in S1 outside the Adriatic and Aegean seas, provided that sedimentation rate and sampling resolution are high enough to allow detection of such short-lived events.

We propose that sapropel S1 occurrences from areas with relatively high sedimentation rates should be investigated in great detail, with continuous sampling methods and up to 0.5 cm resolution, to allow detection of possible interruptions and definition of their nature, and spatial and temporal extent. Such investigation of the S1 interruption within a core from the SW Aegean Sea (Myrtoon Basin) has delivered preliminary faunal results similar to those for IN68-9 and LC21 (Geraga et al., 1997).

As we cannot yet discern whether or not the interruptions are synchronous between the Adriatic and Aegean seas, there are two alternative explanations:

(1) the interruption of S1 formation occurred simultaneously in both basins, and so represents a single phase of climatic cooling of several centuries duration, centred around 7000 years $^{14}C_{nc}$ BP;

(2) formation of sapropel S1 is intermittently interrupted in both basins, with each responding at times individually —and at times possibly together— to short-term climatic instabilities over the NE Mediterranean region.

In view of a similar cooling event coinciding with the termination of S1 formation, both these alternatives suggest that around 7000 years $^{14}C_{nc}$ BP a trend towards deteriorating climate developed, following the optimum conditions reflected within the base of S1. The onset of the climatic deterioration at about 7000 years $^{14}C_{nc}$ BP inferred from the Adriatic and Aegean sediment cores IN68-9 and LC21 coincides with a short dry spell, characterised by reduced winter precipitation, recorded in Lake Tigalmamine, Morocco (Gasse and Van Campo, 1994; Lamb et al., 1995). Simultaneously, the transition to current hyperarid conditions in continental Egypt started to affect human migrations and early societies (Hassan, 1997). The 7000 years $^{14}C_{nc}$ BP arid event has been attributed to changes in freshwater balance related to reduced oceanic heat transfer and reduced North Atlantic deep water formation associated with cooler sea surface temperatures in the North Atlantic (Street-Perrott and Perrott, 1990; Birchfield et al., 1994; Lamb et al., 1995).

Other dry spells recorded in Lake Tigalmamine are dated around 11000–9500 years BP and 3000–4000 years BP (Gasse and Van Campo, 1994), coinciding again with cooling trends of the foraminiferal records (Fig. 2). These correlations between a high-resolution terrestrial record and Mediterranean marine records strengthen the hypothesis that dry spells are generally correlated with lower temperatures over the Atlantic and Europe. Our results suggest that the formation of the studied sapropels resulted from a delicate balance between reduced bottom water ventilation and increased productivity (De Lange and Ten Haven, 1983; Rohling and Gieskes, 1989; Howell and Thunell, 1992). This balance was easily disturbed by temporarily improved deep water ventilation related to surface water cooling (Fig. 2), even when relatively high-productivity conditions continued to prevail (Rohling et al., 1997; and Aegean geochemical results: D. Mercone, pers. commun., 1997).

Acknowledgements

We thank F. Jorissen, M. Paterne, J. Thomson, D. Mercone, and F. Hassan for interesting discussions. R. Hale, N. Ampstead, and R. Abu-Zied are thanked for their efforts in the lab and involvement in the ongoing investigations on LC21 that include benthic foraminiferal abundance variations, multiple AMS^{14}C datings, inorganic geochemistry, and stable O and C isotopes, in cooperation with J. Thomson, I. Croudace and M. Paterne. Core LC21 was taken during the Marion Dufresne cruise 81 (PALAEOFLUX-MAST2) and is stored in the SOC core repository BOSCOR. This study contributes to EC Mast-3 project Climatic Variability of the Mediterranean Palaeo-Circulation (CLIVAMP; MAS3-CT95-0043).

References

Birchfield, E.G., Wang, H., Rich, J.J., 1994. Century/millennium internal climate oscillations in a ocean–atmosphere–continental ice sheet model. J. Geophys. Res. 99 (C6), 12459–12470.

Bruins, H.J., Van der Plicht, J., 1996. The Exodus enigma. Nature 382, 213–214.

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.

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

De Lange, G.J., Middelburg, J.J., Pruysers, P.A., 1989. Discussion: Middle and Late Quaternary depositional sequences and cycles in the eastern Mediterranean. Sedimentology 36, 151–156.

Emeis, K.C., Robertson, A.H.F., Richter, C. et al. (Eds.), 1996. Proceedings of the Ocean Drilling Program. Init. Rep. 160,

U.S. Government Printing Office, Washington, DC, 971 pp.
Friedrich, W.L., Wagner, P., Tauber, H., 1990. Radiocarbon dated plant remains from the Akrotiri excavation on Santorini, Greece. In: Hardy, D.A., Renfrew, A.C. (Eds.), Thera and the Aegean World III, Vol. 3. Chronology. Thera Foundation, London, pp. 188–196.
Gasse, F., Van Campo, E., 1994. Abrupt post-glacial climate events in West Asia and North africa monsoon domains. Earth Planet. Sci. Lett. 126, 435–456.
Geraga, M., Tsaila-Monopolis, S., Tripsanas, E., Papatheodorou, G., Ferentinos, G., Hasiotis, K., Seymour, St., Ioakim, H., 1997. Paleoceanographic and paleoclimatic changes in Central Aegean Sea (Myrtoon basin) during Holocene–Late Pleistocene, preliminary results. Proceedings of 5th Hellenic Symposium on Oceanography and Fisheries I, Greece, pp. 213–216.
Hassan, F., 1997. Geomorphic dynamics and evolution of the Egyptian Sahara: the late Quaternary in the eastern Mediterranean. Programme and Abstracts, INQUA, Ankara, 1–4 April.
Higgs, N.C., Thomson, J., Wilson, T.R.S., Croudace, I.W., 1994. Modification and complete removal of eastern Mediterranean sapropels by postdepositional oxidation. Geology 22, 423–426.
Housley, R.A., Hedges, R.E.M., Law, I.A., Bronk, C.R., 1990. Radiocarbon dating by AMS of the destruction of Akrotiri. In: Hardy, D.A., Renfrew, A.C. (Eds.), Thera and the Aegean World III, Vol. 3. Chronology. Thera Foundation, London, pp. 207–215.
Howell, M.W., Thunell, R.C., 1992. Organic carbon accumulation in Bannock Basin: evaluating the role of productivity in the formation of eastern Mediterranean sapropels. Mar. Geol. 103, 461–471.
Jorissen, F.J., Asioli, A., Borsetti, A.M., Capotondi, L., de Visser, J.P., Hilgen, F.J., Rohling, E.J., van der Borg, K., Vergnaud-Grazzini, C., Zachariasse, W.J., 1993. Late Quaternary central Mediterranean biochronology. Mar. Micropaleontol. 21, 169–189.
Koç Karpuz, N., Jansen, E., 1992. A high resolution diatom record of the Last Deglaciation from the SE Norwegian Sea: documentation of rapid climatic changes. Paleoceanography 7 (4), 499–520.
Lamb, H.F., Gasse, F., Benkaddour, A., El Hamouti, N., Van der Kaars, S., Perkins, W.T., Pearce, N.J., Roberts, C.N., 1995. Relation between century scale Holocene arid intervals in tropical and temperate zones. Nature 373, 134–137.
Perissoratis, C., Piper, D.J.W., 1992. Age, regional variation and shallowest occurrences of S1 sapropel in the Northern Aegean Sea. Geo-Mar. Lett. 12, 49–53.
Roether, W.R., Manca, B., Klein, B., Bregant, D., Georgopoulos, D., 1996. Eastern Mediterranean deep waters found in an entirely new state. Science 271, 333–335.
Rohling, E.J., 1994. Review and new aspects concerning the formation of eastern Mediterranean sapropels. Mar. Geol. 122, 1–28.
Rohling, E.J., Gieskes, W.W.C., 1989. Late Quaternary changes in Mediterranean intermediate water density and formation rate. Paleoceanography 4 (5), 531–545.
Rohling, E.J., Jorissen, F.J., Vergnaud-Grazzini, C., Zaalberg, R., 1993. Temporary repopulation by low-oxygen tolerant benthic foraminifera within an Upper Pliocene sapropel: evidence for the role of oxygen depletion in the formation of sapropels. Mar. Micropaleontol. 22, 207–219.
Rohling, E.J., Jorissen, F.J., De Stigter, H.C., 1997. 200 year interruption of Holocene sapropel formation in the Adriatic Sea. J. Micropalaeontol. 16 (2), 97–108.
Rothwell, R.G., 1995. Marion Dufresne Cruise 81, Cruise report — Mediterranean giant piston coring transect. 17th January–9th February. Marseille, France – Limassol, Cyprus. Southampton Oceanography Centre, 70 pp. and appendices (unpubl. manuscript).
Stanley, D.J., Knight, J., Stuckenrath, R., Catani, G., 1978. High sedimentation rates and variable dispersal patterns in the western Hellenic trench. Nature 273, 110–113.
Street-Perrott, F.A., Perrott, R.A., 1990. Abrupt climate fluctuations in the tropics: the influence of Atlantic Ocean circulation. Nature 343, 607–612.
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.
Troelstra, S.R., Ganssen, G.M., Van den Borg, K., De Jong, A.F.M., 1991. A late Quaternary stratigraphic framework for eastern Mediterranean sapropel S1 based on AMS^{14}C dates and stable oxygen isotopes. Radiocarbon 33, 15–21.
Vismara Schilling, A., 1984. Holocene stagnation event in the eastern Mediterranean. Evidence from deep-sea benthic foraminifera in the Calabrian and western Mediterranean ridges. Benthos' 83. 2nd International Symposium Benthic Foraminifera, Pau and Bordeaux, April, 1983, pp. 585–596.
Zachariasse, W.J., Jorissen, F.J., Perissoratis, C., Rohling, E.J., Tsapralis, V., 1997. Late Quaternary foraminiferal changes and the nature of sapropel S1 in Skopelos basin. Proceedings of 5th Hellenic Symposium on Oceanography and Fisheries I, Greece, pp. 391–394.