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High-resolution stratigraphic framework for Mediterranean sapropel S5: defining temporal relationships between records of Eemian climate variability

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Abstract

A high-resolution stratigraphic framework is presented for sapropel S5, which represents the low-mid latitude climate optimum of the previous interglacial period (Eemian). The framework is based on three sites along a transect from west to east through the eastern Mediterranean, and is further validated using a fourth site. This method allows expression of S5-based proxy records of Eemian climate variability along a standardised depth scale that offers unprecedented possibilities for assessment of spatial gradients and signal leads and lags in an interval where high-resolution (radiocarbon-style) dating cannot be performed. Our lateral comparison of S5 sapropels suggests that the onset of S5 in ODP site 967C (Eratosthenes seamount) was 1–6 centuries delayed relative to the onsets in more westerly sites. © 2002 Elsevier Science B.V. All rights reserved.

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1. Background

The last decade has witnessed an exponential increase in studies concerned with the processes responsible for the episodic deposition of anoxic sediments (sapropels) in the eastern Mediterranean (extensive reviews in Rohling, 1994; Cramp and O'Sullivan, 1999; Emeis et al., 2000). The only sapropel where such studies may benefit from a tightly constrained time-frame is the most recent one, sapropel S1 from the early Holocene. A synthesis of radiocarbon ages reported in the literature led Strohle and Krom (1997) to conclude that S1 started to be formed at mid depth, and that the anoxic conditions associated with it rapidly expanded to greater depths. Mercone et al. (2000) challenged this compilation of datings, demonstrating that it overlooks the great importance of using a single criterion to determine the onset and ending of sapropel formation for dating. Mercone et al. (2000) instead consistently obtained radiocarbon datings for the onset and ending of the Ba/Al increase associated with sapropel S1 in an array of cores throughout the eastern Mediterranean. Their study shows no systematic

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Fig. 1. Map of the Mediterranean with core locations. Arrows indicate general surface water circulation patterns. On the plotted scale, the ODP 971C site is identical to that of ODP 971A (for exact locations see Table 1).

depth-dependent diachroneity of either the onset, or ending, of S1 formation.

For older sapropels, the issue of synchroneity (or not) cannot be as finely addressed as for the radiocarbon datable S1. However, it is particularly important that the temporal relationship between individual sapropels is determined, since the bottom-water anoxia during sapropel formation caused benthic azoic conditions, precluding bioturbation, so that sapropels are perfect windows for very high-resolution investigation of past climate/ocean variability. Before spatial patterns/gradients can be reconstructed within each sapropel event, a 'standard' time scale or equivalent inter-calibrated scale is needed.

2. Introduction

We here develop a high-resolution stratigraphic framework for sapropel S5, which formed during the previous interglacial maximum, Marine Isotope Stage 5e (Vergnaud-Grazzini et al., 1977; Bar-Matthews et al., 2000). Using three sites from west to east in the eastern Mediterranean (Table 1, Fig. 1), a comprehensive 'master' stratigraphy is developed that offers a standardised depth scale for records through 'normal' S5 sapropels, and that allows a direct evaluation of temporal and spatial gradients. The broader applicability of our stratigraphic framework is tested by applying it to an 'anomalous' laminated, opalrich, high accumulation rate S5, which has a visible slump/fold in its basal section and a top that is obscured by obvious resedimentation (ODP 971C; Table 1, Fig. 1).

Development of a 'master' stratigraphy on the basis of correlations has to be approached with great care in the absence of high-resolution datings, because of the lack of primary information on the diachronous or synchronous nature of the correlation levels. We address the issue of syn-/diachroneity of the correlations by: (1) selecting correlation levels from records of proxies that reflect different environmental processes (planktonic foraminiferal abundance records, and δ^{18} O and δ^{13} C records for both shallow and deep-living species); (2) using only unambiguous events as correlation levels (e.g. last or first zero abundance levels); (3) carefully avoiding circular reasoning through assessment of all potential correlations without any a priori assumption of synchroneity; and (4) restricting the application of our correlation framework to a basin of rather limited dimensions – the open eastern Mediterranean. Next, the levels of the correlation markers in the various cores are plotted against

Table 1Details of the cores used in the present study

| Latitude | Longitude | Depth |
|------------|--|---|
| 38°11.86'N | 18°08.04'E | 2384 m |
| 24°41′N | 33°43′E | 2026 m |
| 24°41′N | 33°43′E | 2141 m |
| 34°04.27'N | 32°43.53'E | 2554 m |
| | Latitude 38°11.86'N 24°41'N 24°41'N 34°04.27'N | LatitudeLongitude38°11.86'N18°08.04'E24°41'N33°43'E24°41'N33°43'E34°04.27'N32°43.53'E |



Sapropel S5

Fig. 2 (Caption overleaf).

90

one-another. Highly significant regressions in these plots demonstrate that all sites show a virtually identical sequence of major events, with remarkably similar event durations and spacings. It is not realistic to explain this in terms of systematically diachronous relationships between the records, since that would imply (a) that proxies reflecting a variety of biological and physicochemical parameters would all have responded with identical phase shifts, and (b) that there also were identical phase relationships between surface and subsurface signals. The much more logical alternative explanation is that the sequences simply reflect virtually synchronous major events between all sites, and within this context the regressions suggest synchroneity for not only the very major isotope shifts around S5, but also for numerous other unambiguous, but less dramatic, isotopic and faunal events. Note that a (virtually) synchronous nature for the major isotope events can hardly be contested, since such shifts represent events of fundamental hydrographic significance within a basin of rather limited size (cf. Rohling, 1999).

3. Methods

We present planktonic foraminiferal abundance data and species-specific δ^{18} O and δ^{13} C records for *Neogloboquadrina pachyderma* (right coiling; 350–400 µm) and *Globigerinoides ruber* (white variety; 400–450 µm) through S5 in four cores (Figs. 2, 3). The faunal data are based on species identification and counting of random sample splits containing ~200 specimens in the 150–600 µm size fraction. The isotope results have been obtained on a Europa Geo2020 mass spectrometer with individual acid bath carbonate preparation line, and are expressed in ‰ deviations from Vienna-PDB using the international NBS-18 and NBS-19 standards, and Southampton's H1 laboratory standard. The data are presented in plots versus depth (cm) from the top of the relevant ODP core sections in holes 971A, 967C and 971C, and versus total down-core depth (cm) for KS205 (Figs. 2, 3).

Figs. 2 and 3 show the positions of the event markers used for correlation purposes (further details in Table 2). Faunal markers represent welldefined faunal events that leave little room for ambiguity (e.g. zero abundance levels, or sharply defined peaks). Markers in the main species were assigned primary confidence, and are used in establishing the correlations. Markers for minor species or slightly less well-defined events are assigned secondary confidence, and are used for validation purposes only. The isotopic markers represent levels of narrowly defined peaks, or levels preceding or following major changes. Of course, sampling resolution affects the accuracy of the depth assignment for the various markers, and this is why we have sought a practically feasible optimum resolution. For KS205, 971A, and 971C, sample spacings down to 0.5 cm were feasible. For S5 in ODP 967C we used existing samples taken on a 1 cm spacing. In the isotopic work, the resolution also depends on the target species' presence (or not) in the relevant size window. Neogloboquadrine pachyderma (right coiling) is very rare in some intervals, especially in the basal part of S5, which leads to a loss of resolution, which in turn causes some isotopic peaks (i11 and i12) to be less accurately constrained. These peaks are therefore used only to validate, i.e. not to constrain, the correlation frameworks. The study of our four sapropels comprises a total of roughly 360 faunal abundance counts and 980 stable isotope analyses (including replicates and standards). The average resolution-imposed precision of the depth assignments for the correlation markers is about ± 1 cm.

Fig. 2. Planktonic foraminiferal relative abundance patterns (%) for cores ODP 971A, KS205, ODP 967C, and ODP 971C. Labelled arrows indicate correlation markers (Table 2). Shaded bands indicate extent of dark colouration for S5. The colour changes are not used as correlation criteria. Black block indicates position of the slump/fold in the basal part of ODP 971C. Cmbsf stands for cm below sea floor, and the 1H-5, 2H-3, and 1H-3 codes indicate the segment containing the studied sapropels in the ODP cores.

| Correlation point | Species/stable isotope | Definition | Confidence | KS205 | 971A | 971C depth967C | |
|--------------------|---------------------------------|--|------------|--------|-------|----------------|-------|
| - | | | | depth | depth | | depth |
| il | N. pachyderma $\delta^{13}C$ | prominent isotopic depletion peak at sapropel cessation | primary | 482.25 | 39.25 | _ | 73.5 |
| f1 | G. scitula faunal | last sample before species reappears in detectable quantities | primary | 482.75 | 40.75 | 84.75 | 74.5 |
| i2 | N. pachyderma δ ¹³ C | second prominent isotopic enrichment peak | primary | 486.75 | 45.75 | - | 81.5 |
| f2 | G. sacculifer faunal | last sample before species reappears in detectable quantities | primary | 491.25 | 48.75 | 103.75 | 87.5 |
| i3 | N. pachyderma δ ¹³ C | prominent isotopic depletion peak between i1 and i11 | primary | 491.25 | 49.75 | - | 88.5 |
| f3 | O. universa faunal | last sample before species reappears in detectable quantities after short absence | primary | _ | 51.25 | 111.75 | 88.5 |
| i4 | G. ruber δ^{18} O | prominent shoulder of isotopic depletion after maximum enrichment within sapropel | primary | 492.25 | 52.75 | - | - |
| f4 | G. scitula faunal | species no longer present in detectable quantities (zero abundance) | primary | 493.25 | 53.25 | 121.75 | 88.5 |
| i5 | N. pachyderma $\delta^{13}C$ | first prominent isotopic enrichment peak | primary | 495.75 | 53.75 | _ | 90.5 |
| i6 | G. ruber δ^{18} O | prominent shoulder before sharp enrichment trend | primary | 498.75 | 56.25 | _ | _ |
| f5 | G. sacculifer faunal | species no longer present in detectable quantities (zero abundance) | primary | 499.25 | 57.75 | 135.75 | 101.5 |
| f7 | O. universa faunal | species no longer present in detectable quantities after large abundance at sapropel base | primary | _ | 59.75 | 130.75 | 97.5 |
| f6 | N. pachyderma faunal | last sample before species reappears in detectable quantities after short absence | primary | 502.25 | 60.25 | - | 100.5 |
| f8 | G. inflata faunal | species no longer present in detectable quantities (zero abundance) | primary | 503.75 | 61.75 | 162.25 | 102.5 |
| i7 | G. ruber δ^{18} O | mid-point of isotopic depletion at sapropel onset | primary | 506.25 | 62.25 | 162.75 | 106 |
| i8 | G. ruber $\delta^{13}C$ | peak before isotopic depletion | primary | 507.25 | 63.25 | 167.75 | _ |
| f9 | pink G. ruber faunal | last sample before species appears in detectable quantities | primary | 506.75 | 63.75 | 166.75 | 107.5 |
| f10 | <i>N. pachvderma</i> faunal | prominent peak below sapropel preceding sharp drop in abundance | primary | 509.25 | 65.25 | 171.25 | _ |
| f11 | N. pachyderma faunal | lowest abundance of species after sapropel formation | secondary | 477.25 | 31.25 | 77.75 | _ |
| i9 | G. ruber δ^{13} C | prominent peak in isotopic enrichment after sapropel | secondary | 479.75 | 31.25 | _ | _ |
| f12 | G. sacculifer faunal | last sample before species reappears in detectable quantities after short dramatic decline | secondary | 488.25 | 43.75 | 87.75 | 82.5 |
| i12 | N. pachyderma $\delta^{18}O$ | first major depletion | secondary | 500 | 55.75 | _ | 95.5 |
| f13 | G. glutinata faunal | species no longer present in detectable quantities (zero abundance) within sapropel | secondary | 498.25 | 57.25 | 134.25 | 92.5 |
| i10 | G. ruber δ^{13} C | shoulder during isotopic depletion in basal third of the sapropel | secondary | 499.75 | 59.25 | _ | _ |
| i11 | N. pachyderma $\delta^{13}C$ | prominent isotopic depletion peak after sapropel onset | secondary | 500.25 | 59.25 | _ | 92.5 |
| f14 | G. siphonifera faunal | last sample before species appears in detectable quantities | secondary | 512.25 | 71.25 | 171.25 | _ |
| Top black | | | n/a | 482.5 | 40.25 | [82] | 74.5 |
| Base black = benth | ic extinction | | n/a | 506 | 63 | 163.5 | 103 |

Table 2 Details of the primary and secondary correlation markers assigned in the present study



Fig. 3. Stable isotope record for cores ODP 971A, KS205, ODP 967C, and ODP 971C. Labelled arrows indicate correlation markers (Table 2). Shading indicates extent of dark colouration for S5. The colour changes are not used as correlation criteria. Black box indicates position of the slump/fold in the basal part of S5 in ODP 971C.



Fig. 4. Linear (solid) and polynomial (dashed) fits through the primary correlation markers (filled symbols), using ODP 971A as the independent variable ('standard scale') and KS205 and ODP 971C as dependent variables. Open symbols represent secondary correlation markers, which are not used to constrain the regressions, but are shown only in evidence of the fits. Big + symbols show positions of main colour changes associated with onset and ending of S5 (not used to constrain the regressions). In the 971A vs. KS205 plot, the linear fit is y=1.067x+438.461 with N=16 and $R^2=0.98$, while the second-order polynomial fit is $y=0.014x^2-0.434x+477.139$ with N=16 and $R^2=0.99$. The polynomial fit is not statistically better than the linear fit, but more closely approximates a visual point-to-point interpolation to relate KS205 to 971A-equivalent units (see text). In the 971A vs. 971C plot, the linear fit for the segment below the (black) slump in 971C is y=2.633x-0.408 with N=5 and $R^2=0.93$, while that for the upper segment is y=3.016x-40.293 with N=5 and $R^2=0.98$.

4. Results and discussion

4.1. Development of stratigraphic framework

Because of its highly organised signals and its central position in the eastern Mediterranean basin, we use ODP 971A as the benchmark record against which the others are compared. Fig. 4 plots the 16 primary S5 correlation marker pairs (filled dots) between cores KS205 and ODP 971A and reveals a highly significant linear regression, with $R^2 = 0.98$. The secondary markers (open dots) score very near to this line as well, corroborating the regression. The maximum deviation of any primary marker from the linear regression line is 2 cm, but the vast majority lies within 1 cm of the line. Although it does not offer a statistically significant improvement over the linear regression, a second-order polynomial regression is also indicated ($R^2 = 0.99$), since it yields a visual improvement of the 'point-to-point' fitting through the markers. The highly significant regression indicates that the succession and spacing of the markers in KS205 are virtually identical to those in 971A. For the purposes of accurately calibrating the depth scale of KS205 to 971A-equivalent units, one could therefore simply interpolate between individual points, and we approximate this procedure by using the relationship given by the second-order polynomial fit.

In the plot of primary S5 correlation marker pairs between ODP 967C and ODP 971A (Fig. 5), the 14 recognisable pairs define a linear regression with $R^2 = 0.97$. Upon close examination, however, there appears to be a 'platform' at about the middle of S5 in ODP 967C, where the record of 967C clearly shows a 'bunching' of markers compared with 971A and KS205. This platform



Fig. 5. Linear fits through the primary correlation markers (filled symbols), using ODP 971A as the independent variable ('standard scale') and ODP 967C as dependent variable. Open symbols represent secondary correlation markers, which are not used to constrain the regressions, but are shown only in evidence of the fits. Big + symbols show position of main colour changes associated with onset and ending of S5 (not used to constrain the regressions). Left-hand panel shows plots based on the observed depth levels for the various markers. Note the platform of markers around 88 cm in ODP 967C. We evaluate this platform by assessing three linear fits: one through all points (y=1.361x+19.253 with N=14 and $R^2=0.97$), one through only the segment below the platform (y=1.669x+0.723 with N=8 and $R^2=0.90$), and one through the segment above the platform (y=1.471x+14.959 with N=5 and $R^2=0.98$). These are considerably different fits, despite their similar slopes, but they can be easily reconciliated by assuming that the platform of values reflects a minor hiatus in ODP 967C. Correction for a 4.5 cm hiatus (right-hand panel) makes the three fits near identical, with a main fit through all primary points of y=1.595x+9.710 with N=13and $R^2=0.98$.

separates two partial regression lines with very similar slopes (1.7 and 1.5 for the regressions below and above the platform, respectively). When it is assumed that this platform represents a hiatus to the equivalent of 4.5 cm thickness within S5 of 967C, a very significant linear regression becomes apparent between 967C and 971A (N=13 and $R^2 = 0.98$, or N = 11 and $R^2 = 0.99$ when ignoring the f5 and f7 outliers). The maximum deviation of a primary marker from the hiatus-corrected regression line is ~ 2 cm for markers f5 and f7, which both concern minor abundance species with warm, oligotrophic mixed layer preferences. The deviations of f5 and f7 from the main trend may highlight that local influences are affecting some minor species' abundance patterns, while regional (basin-wide) changes dominate the isotopic events and those in the main species' abundance patterns. All other markers are typically positioned within 1 cm from the regression line. The linear regression after adjustment of 967C for a 4.5 cm hiatus gives a very reasonable approximation of a point-to-point interpolation through all except f5 and f7, and is therefore used in calibrating the 967C depth scale into 971A-equivalent units.

4.2. Broader applicability of the stratigraphic framework: correlation with an expanded diatomaceous S5

Our results suggest that lateral correlations are possible between S5 sapropels from west to east, to accuracies of order ± 1 cm that are comparable



Fig. 6. Detailed sedimentological log of the sapropel section within hole 971C. The minerogenic material is dominantly redeposited exhudate from the adjacent Napoli mud volcano. Shaded intervals are where successions of lamina were measurable. Studied sediments (Figs. 2, 3) below the logged (sapropel) interval consisted of homogeneous grey hemipelagic mud.

with the sampling/analytical resolution of the records. Having developed this stratigraphic framework, its validity may be tested by applying it to an 'anomalous' S5 record. The anomalous S5 considered here is the laminated, diatom-rich, and very thick (>80 cm; Figs. 2, 3, 6) S5 recovered from the moat of the Napoli mud volcano, site ODP 971C (Pearce et al., 1998; Kemp et al., 1999). The high accumulation rate of this S5 and its exceptionally well-preserved diatom flora provide a window into seasonal to decadal climate/ ocean variability which cannot be assessed from the 'normal', typically ~ 30 cm thick S5 sapropels that contain only highly dissolved or no opaline skeletons (Kemp et al., 1999). This horizon forms the lower, mainly intact section of a 3 m thick slumped sapropel sequence that appears to be duplicated with an upper intensely slump-folded and disrupted section (Pearce et al., 1998, Fig. 4). The base is affected by a small slump fold overlain by the mainly intact section dominantly composed of laminated to intermittently laminated diatom ooze (Fig. 6). The diatom ooze is interrupted by a few graded turbiditic beds ranging from 12 to 0.5 cm thick and by pale thin beds and laminae of terrigenous material interpreted as exudates of the adjacent Napoli mud volcano. The pale sediment is barren while some of the turbiditic beds contain foraminifers in their lower parts and are marked in Fig. 2 by an upwards decrease in the abundance of white Globigerinoides ruber. The basal slump fold and turbidite beds are indicated as 'disrupted stratigraphy' in Fig. 2 since for reasons of exact sample calibration to the ODP core section, the entire interval was sampled. The faunal and isotopic signals of S5 in 971C are much more noisy than in the other S5 sapropels investigated here (Figs. 2, 3). This may well be a function of centennial averaging in the 0.5 cm sampling of a 'normal' S5 versus the (multi-) decadal resolution of such sampling in ODP 971C, while S5 in 971C also contains many micro-turbidites and thin mud volcano layers of barren mud (Pearce et al., 1998). The top of S5 in ODP 971C is obscured by a rapid transition from laminated sapropel below, to jumbled and distorted sapropel material above. If so, might we then use seasonal laminae (varve) thickness (Pearce et al., 1998; Kemp et al., 1999) in combination with our method's assessment of the intact thickness of S5 in ODP 971C to obtain a rough estimate of the duration of S5 deposition?

Comparing sites 971A and 971C, the correla-

tion markers through S5 present two clusters, separated by a blank interval representing the slump in 971C. Below the slump, we identify a linear regression with N = 5 and $R^2 = 0.93$, while the section above the slump shows five primary markers as well, marking a linear regression with $R^2 = 0.98$. The correlation of the upper section is further corroborated by close agreement of two secondary markers with the overall regression (Fig. 4). Note that the slopes of the regression lines below and above the slump are very similar (2.6 and 3.0, respectively), suggesting that the relative accumulation rate at the 971C site compared to the 971A site remained relatively constant. Our correlation between 971A and 971C suggests that the laminated sapropel in 971C represents S5 almost entirely, and that the overlying jumbled sapropel material therefore is an immediately post-S5 slump/turbidite. The emplacement of the slump in the basal part of S5 in 971C appears to have been associated with a loss of original material to the 971A-equivalent thickness of less than 2 cm.

Previous SEM studies of 971C identified a number of intervals where clear lamina couplets could be observed (Fig. 6). These couplets consist of laminae of rhizosolenid diatoms alternating with laminae of mixed assemblages and are interpreted to represent annual deposition or 'varves' on the basis of correlation with the seasonal succession of diatom floras in the Mediterranean (Pearce et al., 1998; Kemp et al., 1999, 2000).

Table 3

Details of our BSEI pilot study of macroscopically well-laminated sapropel i-182 (Lourens et al., 1996; Vrica section, S. Italy)

| | · · | | • • • | | • • |
|---------------------------|-----------------------------------|---|--------------------------------|-----------------------------------|----------------------------|
| Interval (cm from top) | Total sample thickness $(mm) = A$ | No. of triplets (min- max range when uncertain) = B | Triplet thickness $(mm) = A/B$ | Average triplet thickness (mm) | Diatoms visible in BSEI |
| 3.5-4.5 | 7 | 13 | 0.54 | 0.54 | Y |
| 46-48.5 | 16 | 26–33 | 0.61-0.48 | 0.55 | Ν |
| 85–87 | 19 | 32–40 | 0.59-0.48 | 0.54 | Ν |

Importantly, the BSEI work revealed that the lamina couplets observed under the binocular microscope in detail appear to be lamina triplets. Relatively high-density bulky layers (beige laminae under the binocular) comprise clay-rich and silt-rich laminae, and thin low-density layers (brown laminae under the binocular) consist of either diatom-rich or relatively high-porosity, clayey laminae. The high porosity of the thin laminae likely results from an abundance of organic matter. No considerable thickness variation was apparent between varves in the top and basal sections. Diatoms are only present within the upper part of i-182, and include *Thalassionema frauenfeldii*, *Rhizosolenia* spp., *Thalassiosira* spp. and *Chaetoceros* spp. spores. A comparable facies transition between diatom-bearing terrigenous varves and non-diatomaceous terrigenous varves is known from Holocene sediments from the Santa Barbara Basin (Bull and Kemp, 1995), which also has a rather similar bathymetric and near-continental setting to that of Vrica about 2 million yr ago.



Fig. 7. The isotopic data plotted against the standard 971A-equivalent depth axis developed here, for the 'normal' S5 sapropels in KS205, ODP 971A, and ODP 967C. Plots show that besides event correlations, also the general structures of the records correlate very closely, corroborating our method for intercomparison of S5 sapropels.



99

The average varve thickness for all the coherent laminated intervals (comprising 15% of the 971C S5) is 623 ± 482 µm. If this varve thickness was extrapolated to the entire thickness of the relatively intact sapropel observed at 971C, a duration of deposition of just over 1 kyr for S5 would be implied. This is in stark contrast with evidence from other independent sources, namely estimates of: (1) a 2-3 kyr duration for S1 (Mercone et al., 2000); (2) a 4–5 kyr duration of the peak MIS 5e wet phase in Israel (Bar-Matthews et al., 2000); (3) an ~ 6 kyr duration for S5 from comparison of its thickness with that of the complete precession cycle in which it is embedded (using fig. 4 of Lourens et al., 1996), which is supported by similar estimates for well-developed Pliocene sapropels (Wehausen and Brumsack, 1999). It further contrasts with (4) an estimate of ~ 2.5 kyr from a study that we performed on the well-laminated Pliocene sapropel i-182 (Lourens et al., 1996) from the terrestrially influenced Vrica section. Using the binocular microscope, beige-brown lamina couplets with an average thickness of ~ 0.5 mm were found throughout the entire 128 cm thick sapropel i-182, and this couplet thickness was corroborated using back scatter electron microscope imagery (BSEI; Table 3). The ~ 1 kyr duration estimate for S5 in ODP 971C, therefore, is at least a factor two lower than any other estimate for S5 or any other sapropel. Consequently, since our correlation scheme works as well for S5 of ODP 971C as for the other - more 'normal' - S5 sapropels in this study, it seems that we are not justified in extrapolating the varve thickness from 15% to the entire section analysed in 971C. It

may be that only the periods with sufficient flux to differentiate the seasonal signal are preserved as varves, so that there is a cut-off of flux below which the varve signal is not preserved. Alternatively there may be more significant intermittent erosion by some of the intercalated turbidite beds.

4.3. A common depth scale for S5

Using the identified regressions to calibrate the depth scales for the various S5 sapropels, we can plot them against a common depth scale of 971Aequivalent depth units (Figs. 7, 8). Thus, we can align individual S5 records with an accuracy of ± 1 cm, which facilitates the discussion of spatial gradients, and signal leads and lags across the basin. The examples shown in Figs. 7 and 8 show that there are not only good correlations of the main events that define the stratigraphic framework, but also of the basic signal structures. This observation strongly supports the validity of the stratigraphic framework. Stronger deviations are found in several faunal events than in the isotopic events, suggesting that faunal abundance patterns of especially minor species are more strongly affected by local variability than the isotopic records. Especially events f5 and f7 in 967C show considerable local effect among the primary markers, as do f11, 12, 13, and 14 among the secondary markers. This indicates that a purely faunal (biological) correlation scheme would be much less accurate than a combined faunal and isotopic scheme such as that applied here.

We refrain from discussing the top of S5 in too much detail, because the benthic repopulation in

Fig. 8. As Fig. 7, but for some of the main species' abundance records. The upper panel concerns plots of warm species percentages, calculated as $100 \times \text{warm}/(\text{warm}+\text{cool})$. The warm group comprises the photosynthetic symbiont-bearing spinose species *Globigerinoides ruber* (pink+white), *Orbulina universa, Globigerinoides sacculifer, Globigerinella siphonifera, Globoturborotalita rubescens*, and *Globorotalita tenella*, with trace abundances of *Hastigerina pelagica* and *Globigerinella digitata*. Today, these dominate warm and oligotrophic summer mixed layers in subtropical regions, including the easternmost Mediterranean (Hemleben et al., 1989; Rohling et al., 1993; Pujol and Vergnaud-Grazzini, 1995; Reiss et al., 2000). The 'cool' group comprises the non-spinose species *Globorotalia scitula, Turborotalita quinqueloba, Globorotalia inflata*, and *Neogloboquadrina pachyderma* (right coiling). These lack symbionts, show a distinctly herbivorous feeding preference, and thrive in the cool, more eutrophic conditions fuelled by upmixing of regenerated nutrients in winter mixed layers, or in the previous winters' water below the summer thermocline (Hemleben et al., 1989; Rohling et al., 1993; Pujol and Vergnaud-Grazzini, 1995; Reiss et al., 2000). The heavy lines with dots represent the warm species plot determined with *N. pachyderma* included, and the light lines give the warm species plots when *N. pachyderma* is excluded from the calculation.

our records is not fully investigated yet. After the benthic azoic conditions of S5, repopulation would have taken some time even after sea floor oxygenation had improved, and extensive benthic assemblage studies including the very fine fractions are needed to assess exactly where the benthic repopulation started in the records. The top of the black sapropel colour suggests a virtually synchronous ending of sapropel formation, but this conclusion needs validation from the ongoing benthic assemblage study since we cannot exclude that post-depositional oxidation ('burndown') has shifted the colour change (cf. Mercone et al., 2000).

A very intriguing observation can be made however, regarding the onset of the dark S5 colour, which coincides with the extinction level for benthic foraminifera (Fig. 2). In 967C, this occurs some 3 cm above the main oxygen isotope shift (i7) that marks the base of S5 in 971A, KS205, and 971C (Fig. 3), while i7 sits very close to the regression lines in all cases, as supported by the nearly identical relative positions of f8, f9, f10, and i8 in all cores investigated (Figs. 7, 8). We infer that the onset of sapropel-forming conditions was somewhat delayed in the easternmost setting of 967C relative to the other sites. The 3 cm delay compares with an overall S5 thickness of 20-25 cm, and hence would equate very roughly to a time lag of $\sim 10\%$ of the depositional period of S5. For the range of estimates of S5 duration discussed above (1-6 kyr), therefore, the 'delay' in its onset at site 967C would amount to 1-6 centuries.

Although site 967C has the greatest water depth of all sites from which S5 sapropels are studied here, the depth differences with the other sites are small (Table 1). Especially between KS205 and 967C, there is only about 150 m depth difference. Therefore, we contend that the delayed onset of S5 at 967C can not be considered as corroboration of the previously proposed model of slow downward expansion of an oxygen minimum zone (Strohle and Krom, 1997; Stratford et al., 2000). Instead, we suggest that for a yet unknown reason anoxia developed later in the easternmost sector. With the information available to date, we can only speculate on the cause of this delay: it could be due to lower productivity/export production in the easternmost sector, or due to a period of occasional deep ventilation bursts in the easternmost sector (possibly from the Aegean Sea?). To properly address this problem, further highresolution work is needed on S5 from a wide variety of sites, working towards a dense spatial grid of high-quality records that can be related to one another using our proposed framework.

5. Conclusions

Basin-wide correlations of major faunal and stable isotope events through eastern Mediterranean sapropel S5 indicate a near-identical sequence and spacing of main events in sites from the NW Ionian Sea and from the western Levantine Sea (Napoli mud volcano). A high degree of similarity is also observed at a site from the eastern Levantine Sea (Eratosthenes seamount), especially when allowing for a minor hiatus in that record. Such a high degree of similarity in event sequence and spacing implies that a similar succession of major oceanographic changes has affected all three sites, with virtually identical temporal spacing. This can only be reasonably explained in terms of a succession of near-synchronous oceanographic changes throughout the main body of the eastern Mediterranean basin, during the formation of sapropel S5. In the absence of an absolute chronology for events during the last interglacial maximum, therefore, we suggest that our record of S5 in ODP 971A may serve as a 'master' record, against which other S5 records may be calibrated. This enables alignment of the various records along a standard 971A-equivalent depth scale. The standardised depth scale serves the same purpose as a time scale in well-datable sequences (e.g. Holocene), allowing the identification of spatial property gradients and signal leads and lags. We observe an intriguing delayed onset of S5 in the easternmost site (967C) relative to the other, more westerly, sites. The 'delay' amounts to about 3 cm in an S5 thickness of 20-25 cm, which roughly equates to about 10% of the duration of S5 deposition.

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