Zahn, R., Comas, M.C., and Klaus, A. (Eds.), 1999
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 161

41. PLIOCENE–PLEISTOCENE OCCURRENCE OF SAPROPELS IN THE WESTERN MEDITERRANEAN SEA AND THEIR RELATION TO EASTERN MEDITERRANEAN SAPROPELS[1]

Anne Murat[2]

ABSTRACT

Sedimentological and organic geochemical analyses of sediments along five Leg 161 drill sites document the occurrence of sapropels throughout the Western Mediterranean Sea. Two hundred and seventeen well-dated sapropel events are found at these sites ranging in age from 0.01 to about 3 Ma. Total organic carbon (TOC) content has a wide variation, ranging from <0.1% to maximum values of >6%. The highest sapropel TOC values are found in the Tyrrhenian Sea. Sapropel TOC values decrease to the west and are lowest in the Alboran Sea. In contrast, background TOC in nonsapropel sediments increases from east to west, with values ranging from 0.1%–0.3% in the Tyrrhenian Sea to 0.3%–0.5% in the Alboran Sea. In view of this TOC variability, sapropels in this study are defined as sediment horizons with higher-than-background TOC concentrations. Sapropels that comply with this definition can often be recognized by distinctive color changes. That is, rather than using a narrowly defined, minimum TOC value as a cutoff line for defining sapropels, the concept of using color changes and above-background TOC levels allows to detect sapropel events in much better detail. This is especially true for the western Mediterranean, where sapropels are sometimes less distinctive in the sedimentary record than in the eastern Mediterranean. Applying this concept and using detailed oxygen isotope stratigraphies (Pierre et al., Chap. 38, this volume; von Grafenstein et al., Chap. 37, this volume) and high-resolution biostratigraphy (de Kaenel et al., Chap. 13, this volume) show that most sapropels in the eastern and western Mediterranean are well correlated. Exceptions to this observation point to the importance of local phenomena such as hydrological and productivity fronts that are associated with the Atlantic inflow and wind-driven meso-scale gyres in the western Mediterranean. From the Leg 161 paleoceanographic studies it must be concluded that sapropels are Mediterranean-wide phenomena. This warrants revision of our views about the origin of sapropels and their paleoceanographic and paleoclimatic implications.

INTRODUCTION

Drilling in the western Mediterranean was part of a trans-Mediterranean drilling transect at 16 sites, which were drilled during Legs 160 and 161. The paleoceanographic objectives of both legs were aimed at documenting of Mediterranean-wide environmental conditions during the late Cenozoic, with special emphasis on periods of sapropel deposition, to better constrain the various factors that may have caused sapropel formation in the eastern Mediterranean.

Studies to understand the origin and temporal distribution of sapropels so far have almost exclusively been undertaken in the Eastern Mediterranean. Various models have been proposed to explain the enrichment in organic carbon during the sapropel events. In general, two types of models have been proposed: (1) a stagnation model that explains the elevated TOC levels of sapropels by enhanced organic matter preservation under oxygen-deficient deep-water conditions; (2) a productivity model that links the occurrence of sapropels to increased marine biological production in the photic zone.

The stagnation model explains anoxic bottom conditions by water column's increasing density stratification, which ultimately inhibits convective overturning and ventilation of the deeper water column (Shaw and Evans, 1984; Anastasakis and Stanley, 1986; Ganssen and Troelstra, 1987). Enhanced buoyancy of the surface layer could have been brought about by two mechanisms: (1) warm climatic conditions (Mangini and Dominik, 1982; Thunell et al., 1984) or (2) formation of a low-salinity surface layer (Vergnaud-Grazzini et al., 1986; Ten Haven et al., 1987; Fontugne et al., 1989; Troelstra et al, 1991; Tang and Stott, 1993). Low-salinity surface layers in turn could be explained through imported meltwaters from decaying Eurasian ice sheets during deglaciation (Ryan, 1972; Cita et al., 1977; Stanley, 1978; Thunell and Lohmann, 1979) or by enhanced precipitation and resultant increases in river runoff to the Mediterranean from the Nile river and rivers from the northern Mediterranean borderlands (Adamson et al., 1980; Rossignol-Strick, 1985; Rohling and Gieskes, 1989). Another possible mechanism is an increased low-salinity Atlantic water inflow (Müller, 1973). Changes in the circulation of the semi-enclosed Mediterranean Sea resulting in decreased water exchange across the Sicily-Tunisia Strait that inhibits deep-water circulation and oxygenation of the eastern Mediterranean basin deep waters would be a further factor determining the ventilation of the deep Mediterranean (Béthoux, 1984; 1993).

Increased biological productivity within the photic zone as a primary cause of sapropel formation has been proposed by several authors (Calvert, 1983; Jenkins and Williams, 1983/84; Lourens et al., 1992; Calvert et al., 1992; Van Os et al., 1994). These models were built on the recognition that organic carbon flux to the seafloor in today's Eastern Mediterranean Sea would not be sufficient to produce sapropels, even if extensive water column stratification and complete bottom-water anoxia would occur.

More recently, a model for sapropel formation that combines increased productivity with decreased deep-water formation has been proposed by Rohling and Gieskes (1989) and has been further refined by Rohling (1991). In this model, shoaling of the pycnocline to a depth within the euphotic layer would lead to increased nutrient availability to the lower euphotic layer. This enables the development of a deep chlorophyll maximum (DCM) below the pycnocline and a concomitant increase in the downward flux of organic matter from the euphotic zone (export production). According to this model, shoaling of the pycnocline could have occurred in response to an enhanced freshwater flux to the Mediterranean's surface layer, in conjunction with the development of an anti-estuarine circulation pattern. In such a case, the intensity of exchange-transport across the Sicilian sill would be reduced to about 70% of the present.

[1]Zahn, R., Comas, M.C., and Klaus, A. (Eds.), 1999. *Proc. ODP, Sci. Results,* 161: College Station, TX (Ocean Drilling Program).
[2]Intechmer, BP 324, F 50 103, Cherbourg Cedex, France. mearmura@intechmer.cnam.fr

Before Leg 161, it was believed that basin-wide sapropel formation occurred only in the eastern Mediterranean. Development of the sapropel models, therefore, has been driven by sapropel studies in the Eastern Mediterranean. Leg 161 drilling, however, retrieved a full suite of sapropels from throughout the western Mediterranean. The new data show that sapropel formation occurred throughout the entire Mediterranean, from the Eratosthenes Seamount in the far eastern Mediterranean to the Alboran Sea, immediately east of the Strait of Gibraltar.

In this study, I use TOC values from all Leg 161 drill sites to document the spatial and temporal pattern of sapropel formation in the western Mediterranean. Only Site 978 in the Alboran Sea was excluded, because the upper part of the sediment column was washed out without coring down to 213 meters below seafloor (mbsf).

METHODS

Total Organic Carbon

In this study I use shipboard and shorebased TOC data. Analytical techniques for the shipboard TOC measurements are described in the Leg 161 “Explanatory notes” chapter (Shipboard Scientific Party, 1996a).

For the postcruise TOC analyses, samples were freeze dried. Dried sediment aliquots of 100 mg were then weighed, decalcified with 1M H_3PO_4 and dried on a hot plate at ~50°C. The organic carbon concentration was determined by combustion in a LECO CS 300 carbon sulfur analyzer. Reproducibility of the TOC measurements was ± 0.02% as indicated by duplicate analyses of 35 samples.

Shipboard and shorebased TOC values are in good agreement with each other, as is indicated by a similar range of the results.

Grain-Size Analysis

Grain-size distributions of about 50 samples were determined using a SediGraph 5000 Particle Size Analyzer. A 2-g subsample of the sediment fraction <40 µm was dispersed in a 0.1% hexametaphosphate solution using an ultrasonic bath. Size distribution of particles was inferred applying Stoke’s law on the settling particles. The analyzer produces directly cumulative mass percentage curves.

CD-ROM Tables of Results

Tables with TOC data and lithologic codes for each site are on CD-ROM (Tables 1 to 5). In the tables, shipboard TOC analyses are marked by an asterisk (*).

For Hole 976B, sapropel occurrence was documented with color slides. It was thus not possible to obtain sufficient lithologic detail. Therefore Table 3 (Site 976) presents TOC data only.

RESULTS AND DISCUSSION

Sedimentary Characteristics

Continuous pelagic to hemipelagic sedimentary sequences were recovered at the drill sites under study in this paper. There was no occurrence of major turbiditic sequences. The following section provides a site-by-site description of the lithologies at the different sites.

Site 974

Site 974 is located in the central Tyrrhenian Sea, on the lowermost eastern continental margin of Sardinia, in a small basin more than 3400 m deep (Table 6). Lithostratigraphic Units I and II (0–200 mbsf) consist of Pliocene to Pleistocene pelagic to hemipelagic sediments. The major lithologies are nannofossil-rich clay, nannofossil-rich silty clay to nannofossil ooze, and the <2-µm fraction is about 65%–70%. The mean sedimentation rate for these two lithostratigraphic units is about 35 m/m.y. The slightly higher sedimentation rate found in Unit I probably reflects an increasing volcanic component to sediments during this time period (Shipboard Scientific Party, 1996d).

Site 975

Site 975 is located on the South Balearic Margin at a water depth of 2416 m (Table 6). Lithostratigraphic Unit I (0–306 mbsf) consists of Pliocene to Pleistocene open-marine sediments (nannofossil or calcareous clay, nannofossil or calcareous silty clay, and nannofossil ooze). The <2 µm-fraction exhibits a wider and lower range of values, in comparison to Site 974, from 30%–55%. The mean sedimentation rate is about 60m/m.y., two times greater than for Site 974 (Shipboard Scientific Party, 1996e).

Sites 976, 977, and 979

These three sites are located in the Alboran Sea (Table 6). From east to west:

1. Site 977 is situated in the Eastern Alboran Basin to the south of Al-Mansour Seamount at a water depth of 1984 m;
2. Site 979 was drilled in the South Alboran Basin, a narrow depression between Alboran Island and the Moroccan coast, at a water depth of 1062 m; and
3. Site 976 is located in the Western Alboran Sea, about 110 km east of the Strait of Gibraltar at a water depth of 1108 m.

Lithostratigraphic Unit I of each site comprises Pleistocene to Pliocene sequences with an open-marine hemipelagic facies (nannofossil-rich clay, nannofossil clay, and nannofossil silty clay; Site 976: 0–363 mbsf; Site 977: 0–533 mbsf; Site 979: 0–571 mbsf). The <2-µm-fraction ranges from 50% to 65%.

Table 6. General data from Sites 974, 975, 976, 977, and 979.

Site	974	975	976	977	979
Latitude	40°20.360′N	38°53.795′N	36°12.32′N	36°01.907N	35°43.427′N
Longitude	12°08.520′E	04°30.595′E	04°18.760′W	01°57.319W	03°12.353′W
Water depth (m)	3454	2416	1108	1984	1062
Sedimentation rate (m/m.y.)	36	59	112	104	188
% TOC median	0.33	0.26	0.58	0.49	0.68
% TOC mode	0.18	0.09	0.54	0.47	multiple
% TOC max	6.27	2.90	1.85	2.08	2.02
Number of samples	190	238	270	411	232
Number of sapropels	33	36	28	52	68

For Site 976, lithostratigraphic Units II and III were not analyzed because Unit II contained of high amounts of sand that likely are of turbiditic origin.

Sedimentation rates at all three sites in the Alboran Basin are higher than those of Sites 974 and 975. They range from 104 m/m.y. for Site 977 to 188m/m.y. for Site 979 (Shipboard Scientific Party, 1996f, 1996g, 1996h).

TOC Content and Variability: Leg 161 Sapropel Definition

TOC contents along the Leg 161 drill sites display a wide range of values from less than 0.1% to more than 6% (Fig. 1). Sites 974 and 975 have a median TOC of 0.3% (Table 6), which is considered typical of open-ocean oxic environments (Stein, 1990). The different sites of the Alboran Basin are very similar with a higher TOC median and lower TOC maximal value (about 2%).

To interpret TOC variability, sapropel and nonsapropel TOC values are distinguished in Fig. 2. Lithologic code 2 corresponds to a sapropel; code 1 to transitional sediments between the sapropel and surrounding gray muds; code 0 regroups all other samples and indicates the TOC background value.

There is an increase in the TOC background value for the Alboran Basin Sites (0.3%–0.5%) in contrast to that found at Sites 974 and 975 (0.1%–0.4%). However, the contrast between maximum sapropel TOC and nonsapropel background TOC is much smaller in the Alboran Basin (maximum TOC of about 2%) than at Sites 974 (maximum TOC of 6.27%) and 975 (maximum TOC of 2.90%). Sites 974 and 975 show a clear distinction of TOC content between sapropel and surrounding sediments. It is noteworthy that an apparent gap in the TOC distribution exists between 0.6%–0.8% (Fig. 3). The TOC distribution is much less variable (0.3%–2.0%) for the Alboran Basin sediments. Disparate data distribution between Sites 977 and 979 (Fig. 2) can be explained by inadequate sampling because organic-rich sediments are generally oversampled so that samples with background TOC values are under-represented for Site 979 (only 60 samples total compared to 200 samples for Site 977). The disparate sampling would also explain the high value of TOC median at Site 979 (Table 6; Fig. 1).

The term “sapropel” has been used in the literature to describe marine sediments with elevated organic carbon content. Traditionally, a minimum TOC cut-off line has been applied to this definition, between 0.5% and 2.0% (Kidd et al., 1978; Hilgen, 1991).

The shipboard scientific parties of Legs 160 and 161 choose different definitions for sapropels. During Leg 160, Hilgen’s (1991) definition has been applied in that a minimum TOC 0.5% was used to separate sapropels from normal background sediments. In contrast, the Leg 161 party chose to call these intervals “Organic-Rich Layers” (ORL) while waiting for a detailed study of these deposits.

Kidd et al. (1978) defined a sapropel as being a discrete layer, deposited in an open marine environment, and consisting of more than 2% TOC. However, this limit appears to be too high even for sediments in the Eastern Mediterranean Basin. For example, maximal TOC content of sapropel S1 ranges from 1.0% to 3.5% depending on water depth. By this criteria, only sediments deposited deeper than 1400 m would be identified as the S1 sapropel in the eastern Mediterranean. A study of the last eight sapropels based on 84 cores collected across the Eastern Mediterranean Sea from the Ionian Basin to the Nile Delta, including the Sea of Crete and the Levantine Basin, has demonstrated that 1% appeared to be the more relevant value for sapropel definition (Murat, 1991). This revised definition also took into consideration the lack of TOC values between 0.6%–1.0% (Fig. 3). The present study strongly supports the re-definition of sapropels that is, to use the TOC contrast in conjunction with sediment color changes between sapropels and the surrounding sediments as a better means to define a sapropel rather than by applying a strict measure of minimum TOC that has to be met by a sapropel.

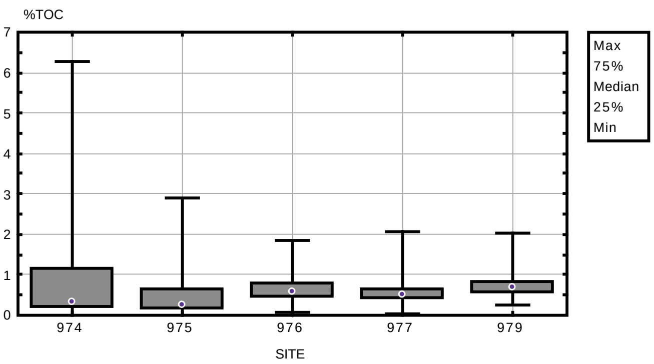

Figure 1. Total organic carbon wt% distribution for Sites 974, 975, 976, 977, and 979. Diagram shows maximum, minimum, median (solid circle within shaded area), and the range where 25%–75% of the data occurs (shaded area).

Using this sapropel definition, the temporal distribution of sapropels in the western Mediterranean can be compared to that observed in the eastern Mediterranean (Fig. 3). Sites 974 and 975 show a distribution similar to that of eastern Mediterranean sites, except for the fact that the sapropel TOC content is as low as 0.8%. The distinction between sapropels and normal sediments is far more difficult at the sites in the Alboran Basin. There, because the higher sedimentation rates, the TOC contrast is much more gradual, continuous, and less distinct. It is more difficult, therefore, to determine upper and lower boundaries of the sapropels. Hilgen’s (1991) lower limit of 0.5% TOC is difficult to apply because the background mode in the Alboran Sea is about 0.4%–0.5% TOC; this value can also be found for background sediments at Sites 974 and 975 (Fig. 2) and in the eastern Mediterranean Sea (Fig. 3; Murat, 1991; Shipboard Scientific Party, 1996c; e.g., Site 964). The minimal TOC content used to define a sapropel for Leg 161 was 0.8% which corresponds to the minimal value found for Sites 974 and 975 sapropels.

Organic carbon content variability within an individual lithologic layer constitutes a further difficulty when defining a sapropel because in some sapropels TOC values range from 0.7% to 1.2%.

If one must define a sapropel, then this study would define a sapropel as an organic-rich lithologic layer deposited in open sea, with at least one TOC value equal to or higher than 0.8%.

Sapropel Stratigraphy

Lists of sapropels for each site and hole (with correlations between the different holes) are given in Tables 7 to 11 on CD-ROM. Synoptic sapropel stratigraphic lists for each site are given in Tables 12 through 16.

The first digit of the Key Bed Number for each sapropel consists of the last digit of the site where it occurs (4 for 974, 5 for 975, and so on); the last two digits is the sequential numbering of the layer from top to base of the lithologic column.

The total number of sapropels varies from 28 for Site 976 to 68 for Site 979 (Table 6). Oxygen isotope stratigraphies for Sites 975, 976, and 977 (Pierre et al., Chap. 38, this volume; von Grafenstein et al., Chap. 37, this volume), as well as biostratigraphic marker events (de Kaenel et al., Chap. 13, this volume) allow us to trace the pattern of sapropel formation in the time domain (Fig. 4). According to the

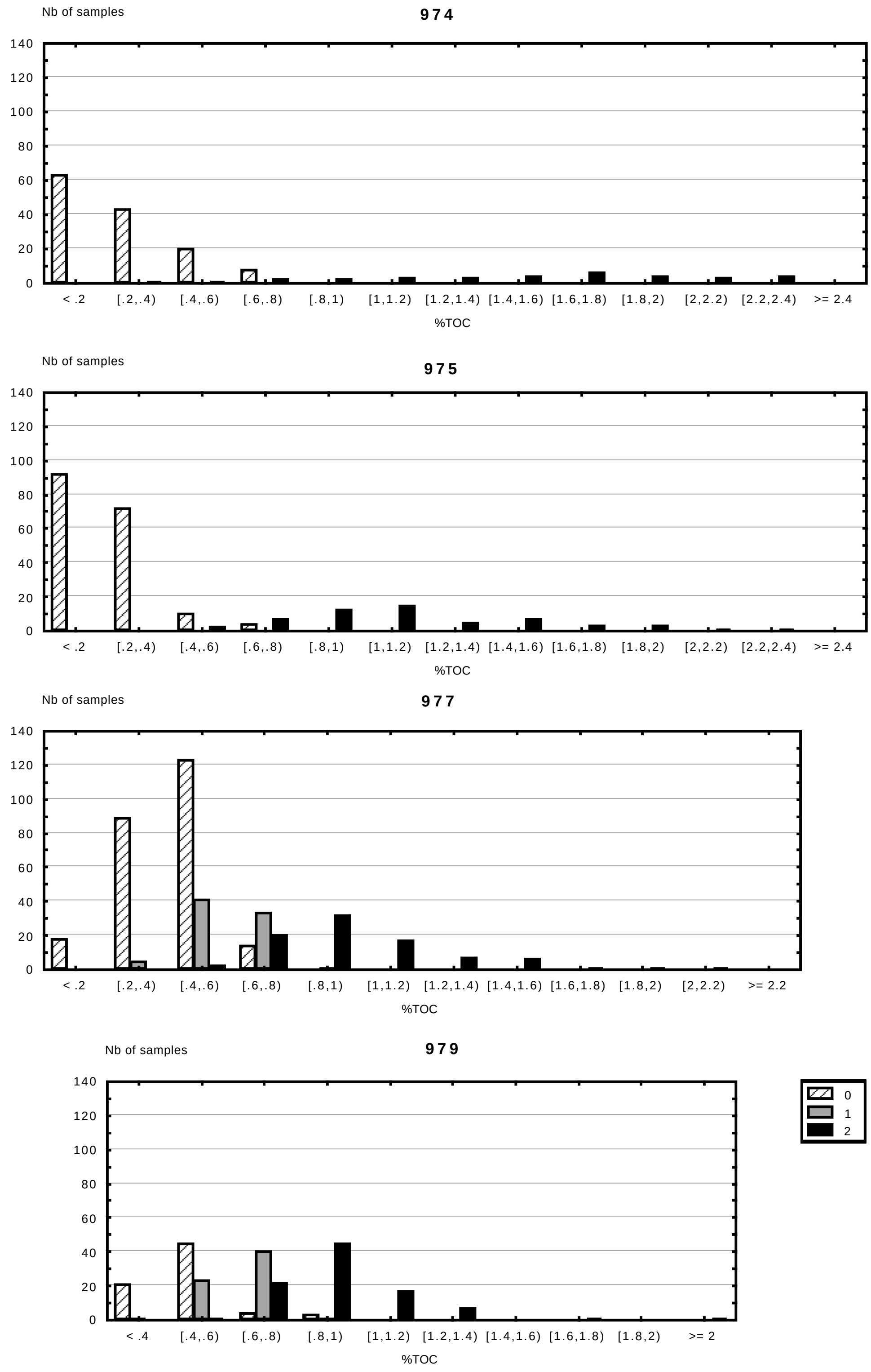

Figure 2. TOC content of sapropel and nonsapropel sediments, Sites 974, 975, 977, and 979. 0 = background; 1 = transitional sediment between sapropel and surrounding gray muds (Alboran Sea); 2 = sapropel.

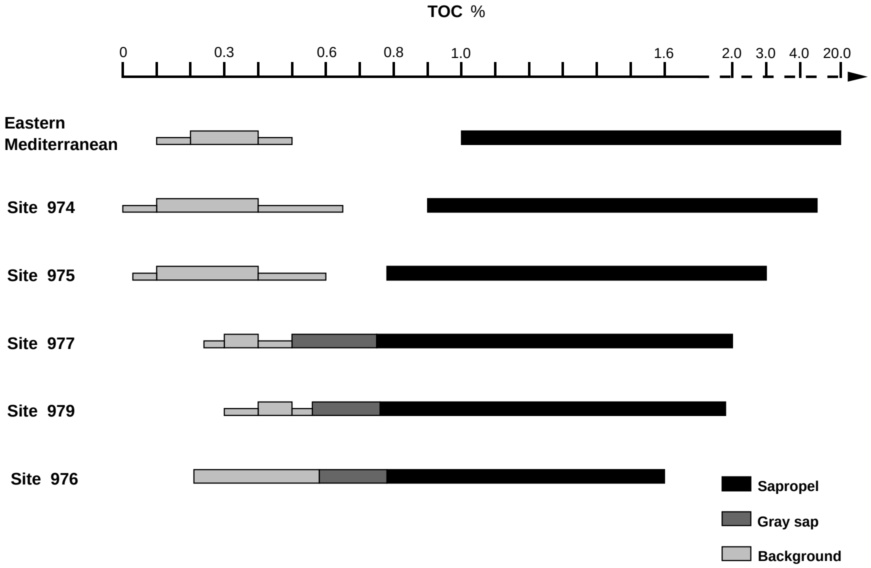

Figure 3. TOC variability of the different Mediterranean basins (differences in thickness reflect frequency variability).

Table 12. Sapropel stratigraphic list, Site 974.

Site 974							
Key bed number	Top (mcd)	Bottom (mcd)	Thickness (cm)	Age (ka)	TOC max (%)	Type	Class
401	6.670	6.730	6.0	239	1.71	II	CB
402	20.620	20.680	6.0	405	1.51	II	CB
403	27.485	27.590	10.5	525	2.07	I	CB
404	33.290	33.400	11.0	597	1.58	II	CB
405	34.020	34.220	20.0	618	1.97	II	C
406	38.075	38.220	14.5	669	3.15	I	CB
407	39.415	39.450	3.5	695	2.92	I	C
	39.515	39.605	9.0				
408	41.830	41.850	2.0	731	1.05	II	CB
409	53.870	53.945	7.5	954	4.56	I	CB
410	54.035	54.075	4.0	955	1.40	II	H
411	55.165	55.215	5.0	975	4.31	I	H
412	55.300	55.315	1.5	977	0.87	III	CB
413	56.125	56.210	8.5	998	2.93	I	CB
414	57.375	57.430	5.5	1028	3.48	I	H
415	58.985	59.060	7.5	1070	6.43	I	CB
416	64.485	64.505	2.0	1163	2.54	I	CB
417	65.200	65.235	3.5	1183	3.04	I	H
418	69.730	69.735	0.5	1281	1.37	II	H
419	69.850	69.905	5.5	1282	1.29	II	C
420	73.260	73.320	6.0	1356	3.91	I	CB
421	75.530	75.570	4.0	1428	2.20	I	C
422	76.780	76.810	3.0	1470	2.67	I	CB
423	80.225	80.250	2.5	1564	1.87	II	H
424	81.830	81.840	1.0	1603	1.52	II	H
425	83.070	83.080	1.0	1642	1.16	II	H
426	85.350	85.370	2.0	1695	1.71	II	H
427	86.215	86.300	8.5	1715	2.72	I	CB
428	87.070	87.095	2.5	1736	1.82	II	C
429	87.740	87.750	1.0	1757	2.38	I	H
430	89.995	90.020	2.5	1808	1.79	II	C
431	90.290	90.400	11.0	1829	2.38	I	C
432	91.730	91.765	3.5	1851	2.95	I	CB
433	93.230	93.250	2.0	1872	2.61	I	CB

Notes: Type: I = >2% TOC, II = 1%–2% TOC, III = 0.8%–1% TOC. Class: CB = color banded, H = homogeneous, C = composite (one or more gray layers/laminae within).

stratigraphic records, the following sapropel pattern evolves for the western Mediterranean sites:

1. Abundant sapropel occurrence (21 to 50 sapropels) is documented between 0–1.5 Ma; only exception is Site 974 where sapropels do not occur during the past 0.5 Ma;

Table 13. Sapropel stratigraphic list, Site 975.

Site 975							
Key bed number	Top (mcd)	Bottom (mcd)	Thickness (cm)	Age (ka)	TOC Max (%)	Type	Class
501	9.470	9.635	16.5	122.50	1.54	II	CB
502	15.370	15.415	4.5	163.50	1.10	II	H
503	15.810	15.915	10.5	169.27	1.15	II	CB
504	16.000	16.025	2.5	171.12	1.66	II	CB
505	16.150	16.270	12.0	175.79	1.52	II	CB
506	17.720	17.800	8.0	194.84	1.72	II	H
507	20.200	20.250	5.0	238.15	0.92	III	H
508	27.960	28.020	6.0	331.14	0.97	II	H
509	35.540	35.645	10.5	405.05	1.42	II	CB
510	40.480	40.525	4.5	464.96	0.89	III	C
511	43.510	43.585	7.5	481.50	1.90	II	CB
512	47.220	47.355	13.5	525.40	1.36	II	C
513	49.345	49.360	1.5	574.28	1.09	II	H
514	50.770	50.870	10.0	597.32	2.90	I	C
515	51.790	51.830	4.0	614.26	1.54	II	CB
516	51.940	52.030	9.0	617.01	1.61	II	CB
517	54.705	54.755	5.0	643.66	1.10	II	CB
518	61.335	61.355	2.0	732.20	0.95	II	H
519	73.245	73.260	1.5	907.89	2.20	I	H
520	76.775	76.885	11.0	949.91	1.47	II	C
521	77.120	77.240	12.0	957.29	1.00	II	C
522	78.380	78.430	5.0	978.61	1.00	II	CB
523	79.600	79.660	6.0	1000.02	2.59	I	H
524	81.060	81.140	8.0	1028.14	1.33	II	CB
525	83.745	83.825	8.0	1073.21	2.69	I	CB
526	84.730	84.740	1.0	1091.62	1.06	II	CB
527	85.820	85.855	3.5	1112.94	1.38	II	C
528	90.655	90.675	2.0	1185.10	2.02	I	H
529	92.435	92.480	4.5	1221.61	1.99	I	C
530	101.520	101.550	3.0	1332.40	1.08	II	CB
531	105.560	105.585	2.5	1398.63	1.59	II	H
532	106.640	106.660	2.0	1409.68	0.84	III	CB
533	112.400	112.485	8.5	1524.62	0.99	II	C
534	126.470	126.480	1.0	1715.02	1.06	II	C
535	127.870	127.880	1.0	1737.86	1.11	II	CB
536	131.270	131.285	1.5	1807.85	0.90	III	H

Notes: Type: I = >2% TOC, II = 1%–2% TOC, III = 0.8%–1% TOC. Class: CB = color banded, H = homogeneous, C = composite (one or more gray layers/laminae within).

2. From 1.5 to 2.0 Ma, sapropels occur only at Sites 974, 975, and 979; sapropel occurrence is best documented at Site 974 during this interval;
3. Between 2.0 and 2.5 Ma, there is only one sapropel at Site 979; and

Table 14. Sapropel stratigraphic list, Site 976.

Site 976						
Key bed number	Top (mcd)	Bottom (mcd)	Thickness (cm)	Age (Ka)	TOC Max (%)	Type
601	3.640	4.950	131.0	12.62	1.13	II
602	14.020	14.830	81.0	37.82	1.10	II
603	18.430	22.870	444.0	54.36	1.08	II
604	26.010	28.690	268.0	71.55	1.10	II
605	32.510	32.650	14.0	95.09	1.19	II
606	40.400	41.600	120.0	127.96	1.85	II
607	49.930	50.430	50.0	183.59	1.18	II
608	56.330	56.580	25.0	210.76	1.04	II
609	60.660	61.360	70.0	224.18	0.95	III
610	66.230	67.350	112.0	241.28	1.28	II
611	90.610	93.270	266.0	328.04	1.18	II
612	113.180	118.130	495.0	422.24	1.16	II
613	135.110	136.100	99.0	501.37	1.61	II
614	142.480	144.520	204.0	526.67	0.96	III
615	162.460	163.960	150.0	604.75	1.25	II
616	180.410	180.570	16.0	701.96	1.09	II
617	182.570	184.220	165.0	714.56	0.84	III
618	187.070	188.070	100.0	728.21	0.85	III
619	190.020	190.590	57.0	735.04	0.95	III
620	219.450	220.390	94.0	835.38	1.58	II
621	241.920	241.970	5.0	951.60	1.07	II
622	242.490	243.320	83.0	955.88	0.87	III
623	257.930	258.770	84.0	1055.04	0.91	III
624	264.895	264.930	3.5	1108.30	1.34	II
625	269.740	269.750	1.0	1144.90	0.97	III
626	296.005	296.890	88.5	1331.60	1.37	II
627	297.350	298.150	80.0	1342.80	1.07	II
628	326.760	327.180	42.0	1528.74	0.77	III

Note: Type: I: >2% TOC, II: 1-2% TOC, III: 0.8-1% TOC

4. Before 2.5 Ma, Site 979 is the only site in the western Mediterranean with a continuous record of sapropels. At Site 977, two sapropels have been observed around 2.7 Ma. Sapropels do not occur at the other sites during this time period.

Comparing the sapropel occurrence at the western Mediterranean sites with that at Site 964 in the eastern Mediterranean (Howell et al., 1997) shows some similarity between 0 and 2 Ma (Fig. 4). In both basins, highest TOC contents are found around 1 Ma (Shipboard Scientific Party, 1996c). Before this time interval, sapropels in the western basin occur less frequently. Only the sapropel record of Site 979 is similar to that of Site 964.

Comparison with the timing of the more recent type-sapropels in the eastern Mediterranean indicates a good correlation. Sapropels S4 to S11 (S4: 97–100 ka, S5: 117–126 ka, S6: 170–180 ka, S7: 194–200 ka, S8: 215–225 ka, S9: 240–242 ka, S10: 325–328 ka, and S11: 406–409 ka [Murat, 1991]) have been recognized in the western basin even in the Alboran Basin (Tables 12 to 16). Some layers exhibit a very good correlation between all the sites, as is the case for sapropels S5, S6, S9, and S10. Other sapropels occur only in the Alboran Basin. These on occasion correspond to a more grayish layer indicative of reduced conditions. For some of these sapropels, no equivalent exists in the eastern Mediterranean (e.g., the sapropel at 31–38 ka).

Most interestingly, the youngest sapropel in the western Mediterranean occurs before the S1 sapropel in the eastern Mediterranean. According to the oxygen isotope stratigraphies, the uppermost sapropel at Sites 976 and 977 occurs between 10.7–14.5 ka and appears to be associated with the Younger Dryas. The youngest sapropel in the eastern Mediterranean, sapropel S1, is dated to begin at 9 ka lasts to at least 7.5 ka (Murat, 1991). At Site 976, TOC content remains high (>0.8%) until ~8 ka.

Further detailed studies on the western Mediterranean sapropels will provide important and new insight into the origin of sapropels and concomitant environmental conditions. As a result of Leg 161 data, it must now been taken into account that sapropels are Mediterranean-wide phenomena.

Table 15. Sapropel stratigraphic list, Site 977.

Site 977						
Key bed number	Top (mbsf)	Bottom (mbsf)	Thickness (cm)	Age (ka)	TOC Max (%)	Type
701	1.930	2.240	31.0	11.54	0.87	III
702	5.730	7.780	205.0	31.15	1.02	II
703	9.050	12.400	335.0	49.96	1.07	II
704	18.370	18.535	16.5	96.91	0.93	III
705	19.755	19.950	19.5	104.54	1.13	II
706	20.710	21.080	37.0	109.68	0.88	III
707	23.330	23.635	30.5	122.25	1.13	II
708	23.890	24.360	47.0	126.33	0.79	III
709	30.465	30.635	17.0	173.24	1.13	II
710	32.840	33.155	31.5	194.71	1.26	II
711	38.925	39.050	12.5	237.47	1.07	II
712	39.340	39.600	26.0	241.36	0.91	III
713	41.850	42.350	50.0	263.52	0.87	III
714	52.120	52.570	45.0	329.15	0.87	III
715	52.705	53.390	68.5	333.89	0.86	III
716	67.120	67.240	12.0	425.58	0.80	III
717	71.330	71.380	5.0	462.54	0.80	III
718	77.230	77.450	22.0	502.63	1.71	II
719	79.750	80.300	55.0	517.27	0.80	III
720	81.345	81.750	40.5	525.53	1.18	II
721	84.610	84.890	28.0	551.99	1.01	II
722	89.710	89.810	10.0	575.38	1.26	II
723	92.250	92.380	13.0	597.02	1.39	II
724	94.350	95.030	68.0	617.17	2.08	I
725	102.820	104.170	135.0	665.23	0.87	III
726	108.995	109.025	3.0	688.96	1.13	II
727	109.220	112.845	362.5	697.83	0.82	III
728	114.065	118.090	402.5	719.99	1.50	II
729	118.310	118.860	55.0	732.27	0.88	III
730	123.620	123.845	22.5	765.87	0.77	III
731	140.510	141.550	104.0	862.14	1.47	II
732	153.805	154.380	57.5	937.02	1.42	II
733	156.240	156.340	10.0	957.15	1.82	II
734	159.120	159.320	20.0	977.5	1.20	II
735	162.800	162.940	14.0	995.78	1.14	II
736	163.680	163.850	17.0	999.75	1.56	II
737	170.830	171.100	27.0	1028.14	1.25	II
738	173.000	174.380	138.0	1044.53	0.82	III
739	174.790	174.870	8.0	1052.27	0.96	III
740	177.200	177.290	9.0	1070.11	0.78	III
741	185.150	187.050	190.0	1148.89	0.76	III
742	188.440	189.250	81.0	1165.7	0.80	III
743	194.110	194.220	11.0	1188.4	1.34	II
744	202.800	203.100	30.0	1279.84	0.88	III
745	204.560	204.730	17.0	1297.87	1.50	II
746	206.460	206.580	12.0	1314.87	>0,71	III
747	210.450	211.040	59.0	1348.89	0.78	III
748	215.090	215.235	14.5	1395.68	0.99	III
749	223.910	224.275	36.5	1481.86	0.96	III
750	226.940	227.230	29.0	1494.07	0.96	III
751	386.700	387.030	33.0	2670	0.94	III
752	390.700	391.550	85.0	2686	0.94	III

Notes: Type: I = >2% TOC, II = 1%–2% TOC, III = 0.8%–1% TOC.

Geographical Variability

Sapropels at the Leg 160 and 161 drill sites display a regional pattern of various sedimentary and lithologic features:

1. Upper and lower boundaries of the sapropels are generally sharp and well defined at all sites, with the exception of those in the Alboran Basin where the boundaries are more subtle and gradual both in color and TOC. This most likely is the result of the high sedimentation rates at the Alboran Sea sites. At Site 977 at the eastern part of the Alboran Basin, sapropels with sharp and gradual upper and lower boundaries occur.
2. Maximum TOC values decrease towards the west along the trans-Mediterranean drilling transect. Maximum TOC at the Eastern Mediterranean sites is above 20% (Shipboard Scientific Party, 1996c), whereas maximum TOC in western Mediterranean is around 6% in the Tyrrhenian Sea (Site 974), 3% in the Balearic Sea (Site 975), and 2% at the Alboran Sea Sites (Table 6).

Table 16. Sapropel stratigraphic list, Site 979.

Site 979						
Key bed number	Top (mbsf)	Bottom (mbsf)	Thickness (cm)	Age (ka)	TOC Max (%)	Type
901	2.180	4.210	203.0	9	1.37	II
902	8.550	10.550	200.0	31	1.36	II
903	10.780	14.770	399.0	57	1.65	II
904	16.890	18.300	141.0	80	0.91	III
905	19.690	21.300	161.0	104	0.85	III
906	22.780	25.720	294.0	124	0.90	III
907	30.375	31.290	91.5	173	0.93	III
908	42.320	43.200	88.0	216	0.81	III
909	44.135	44.200	6.5	217	0.80	III
910	52.190	52.730	54.0	239	1.15	II
911	53.230	53.770	54.0	240	1.02	II
912	53.960	54.330	37.0	241	1.10	II
913	54.590	57.010	242.0	264	1.20	II
914	70.970	71.650	68.0	332	0.94	III
915	89.000	89.120	12.0	405	0.82	III
916	90.370	90.800	43.0	406	1.09	II
917	104.960	106.860	190.0	462	0.84	III
918	106.100	114.820	872.0	482	1.17	II
919	125.600	127.260	166.0	525	0.91	III
920	141.300	141.700	40.0	597	0.84	III
921	144.200	144.500	30.0	617	1.97	II
922	146.000	146.700	70.0	619	0.82	III
923	150.640	151.880	124.0	645	1.31	II
924	157.760	158.835	107.5	669	1.00	II
925	159.490	160.390	90.0	694	1.25	II
926	160.910	161.960	105.0	696	1.02	II
927	163.670	163.990	32.0	711	0.82	III
928	167.530	168.490	96.0	731	1.13	II
929	169.820	170.005	18.5	747	2.02	I
930	170.725	170.995	27.0	749	1.27	II
931	176.800	179.020	222.0	785	1.01	II
932	188.490	189.690	120.0	862	2.18	I
933	196.320	196.510	19.0	882	0.89	III
934	205.420	206.390	97.0	933	0.88	III
935	206.520	208.500	198.0	955	0.85	III
936	231.330	231.540	21.0	1070	0.78	III
937	234.100	234.200	10.0	1091	0.89	III
938	240.450	240.760	31.0	1144	0.98	III
939	242.490	242.990	50.0	1163	0.83	III
940	259.190	259.360	17.0	1281	0.89	III
941	266.130	268.030	190.0	1356	1.09	II
942	269.810	270.690	88.0	1377	0.78	III
943	283.890	284.130	24.0	1450	0.90	III
944	301.440	301.915	47.5	1525	1.66	II
945	307.940	309.420	148.0	1564	0.80	III
946	326.000	326.710	71.0	1642	0.78	III
947	337.930	340.280	235.0	1715	0.84	III
948	356.980	358.460	148.0	1808	0.99	III
949	364.150	364.470	32.0	1829	0.98	III
950	375.500	376.320	82.0	1851	1.20	II
951	396.540	397.600	106.0	1944	0.78	III
952	438.350	440.780	243.0	2136	0.85	III
953	482.660	484.930	227.0	2600	0.81	III
954	485.040	486.200	116.0	2621	0.80	III
955	489.500	491.770	227.0	2651	0.78	III
956	492.570	493.130	56.0	2656	0.82	III
957	500.610	501.290	68.0	2688	0.92	III
958	503.460	504.130	67.0	2699	0.88	III
959	506.100	509.600	350.0	2715	1.01	III
960	510.580	512.340	176.0	2729		V
961	515.000	516.310	131.0	2746	0.98	III
962	521.400	523.490	209.0	2773	0.82	III
963	529.150	531.450	230.0	2813	0.94	III
964	542.250	542.620	37.0	2879	0.91	III
965	544.010	544.840	83.0	2890	0.85	III
966	552.430	553.270	84.0	2936	0.90	III
967	563.200	564.380	118.0	2995	0.91	III
968	568.600	569.110	51.0	3023	0.83	III

Notes: Type: I = >2% TOC, II = 1%–2% TOC, III = 0.8%–1% TOC, V = TOC unknown.

3. The observed gradient towards decreasing maximum TOC at the western Mediterranean drilling sites parallels the decrease in water depth of the locations of Sites 974 (3454 m), 975 (2416 m), 977 (1984 m), and 976 and 979 (1100 m). A similar positive correlation between increasing water depth and increasing TOC has also been observed for eastern Mediterranean sapropels (Murat, 1991).

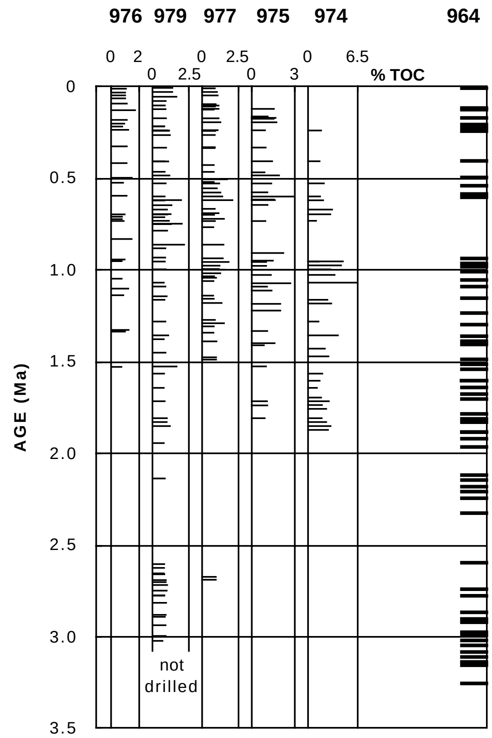

Figure 4. Stratigraphic sapropel occurrence and maximum TOC content in the different Mediterranean basins. Eastern Mediterranean Site 964 age data from Howell et al. (1997); Site 975 ages from oxygen isotope data (Pierre et al., Chap. 38, this volume); Sites 976 and 977 ages from oxygen isotope data (von Grafenstein et al., Chap. 37, this volume) except sapropels 751 and 752; Sites 974 and 979 ages from calcareous nannofossil biostratigraphy (Kaenel et al., Chap. 13, this volume) except sapropels 953 to 968; ages of sapropels 751, 752, and 953 to 962 are from on-board biostratigraphy and ages of sapropels 963 to 968 are extrapolated from sedimentation rate (Comas Zahn, Klaus, et al., 1996).

4. Sedimentation rates increase from average rates of 20 m/m.y. in the Eastern Mediterranean (Ryan, 1972; Cita et al., 1977; Murat and Got, 1987) to 36 m/m.y. at Site 974, 59 m/m.y. at Site 975, 104 m/m.y. at Site 977, and 188 m/m.y. at Site 979 (Table 6). The much higher sedimentation rates in the Alboran Sea can be an important factor to explain the higher TOC background values there.

A similar correlation between shallow water depth (470 m), high sedimentation rate (140 m/m.y.), enhanced TOC background (0.3%–0.5%), decreased maximum TOC of sapropels (0.7%–1.5%), and more gradual upper and lower sapropel boundaries is documented at Site 963 in the Strait of Sicily (Leg 160, Shipboard Scientific Party, 1996b).

As a result, Alboran Basin sediment layer characteristics are not as distinct as their eastern counterparts, and are, instead, probably a consequence of the sedimentological environment rather than its position between the Mediterranean Sea and the Atlantic Ocean.

CONCLUSIONS

Paleoceanographically, one of the most important outcomes of Leg 161 was retrieving a full suite of sapropels in the western Mediterranean. Based on detailed oxygen isotope stratigraphies (Pierre et al., Chap. 38, this volume; von Grafenstein et al., Chap. 37, this volume) and high-resolution biostratigraphy (de Kaenel et al., Chap. 13, this volume), it can be demonstrated that a good correlation exists between most western and eastern Mediterranean sapropel events. However, exceptions do occur and point to the importance of local phenomena such as hydrological and productivity fronts that are associated with the Atlantic inflow and wind-driven meso-scale gyres in the western Mediterranean.

Geographical variability of sapropel and background TOC occurs along the trans-Mediterranean drilling transect of Legs 160 and 161 and appears to be closely correlated with the depth location of and sedimentation rate at individual drill sites.

Sapropels are less distinctive in the westernmost Mediterranean, the Alboran Sea. There, enhanced sedimentation rates resulted in higher background TOC than is typically encountered in the Mediterranean Sea, and in more gradual upper and lower boundaries of the sapropels. Abundant occurrence of sapropels that do not correlate in timing with the eastern Mediterranean type-sapropels imply the existence of climatic and hydrographic variability in the Alboran Sea that is linked to North Atlantic climatic variability (von Grafenstein et al., Chap. 37, this volume). Nevertheless, from the Leg 161 paleoceanographic studies, it must now be concluded that sapropels are Mediterranean-wide phenomena that warrant revision of our views about the origin of sapropels and their paleoceanographic and paleoclimatic significance.

ACKNOWLEDGMENTS

Thanks are expressed to Paul Belanger for reviewing the manuscript and to Mike Howell for age data from Site 964. Special thanks are due to the on-board team for their contribution in data acquisition: Paul Belanger, Winton Cornell, Eric de Kaenel, Heidi Doose, Hitoshi Fukusawa, Silvia Maria Iaccarino, Peter Ippach, Kathleen Marsaglia, Philip Meyers, William Siesser, Gregory Skilbeck, Jane Tribble, Roy Wilkens, and Rainer Zahn. I gratefully acknowledge the assistance of Marie-Paule Ville and Stéphanie Lerouvillois. Grain-size analyses were performed in the Laboratoire de Sédimentologie et Géochimie marines (Université de Perpignan, France). The analyses in France were supported financially by the Institut National des Sciences de l’Univers of CNRS (INSU grant no. 96 “Géosciences Marines”).

REFERENCES

Adamson, D.A., Gasse, F., Street, F.A., and Williams, M.A.J., 1980. Late Quaternary history of the Nile. *Nature,* 288:50–55.

Anastasakis, G.C., and Stanley, D.J., 1986. Uppermost sapropel, Eastern Mediterranean: paleoceanography and stagnation. *Nat. Geogr. Res.,* 2:179–197.

Béthoux, J.P., 1984. Paléo-hydrologie de la Méditerranée au cours derniers 20000 ans. *Oceanol. Acta,* 7:43–48.

————, 1993. Mediterranean sapropel formation, dynamic and climatic viewpoints. *Oceanol. Acta,* 16:127–133.

Calvert, S.E., 1983. Geochemistry of Pleistocene sapropels and associated sediments from the Eastern Mediterranean. *Oceanol. Acta,* 6:225–267.

Calvert, S.E., Nielsen, B., and Fontugne, M.R., 1992. Evidence from nitrogen isotope ratios for enhanced productivity during the formation of eastern Mediterranean sapropels. *Nature,* 359:223–225.

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

Comas, M.C., Zahn, R., Klaus, A., et al., 1996. *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program).

Fontugne, M.R., Paterne, M., Calvert, S.E., Murat, A., Guichard, F., and Arnold, M., 1989. Adriatic deep water formation during the Holocene: implication for the reoxygenation of the deep Eastern Mediterranean Sea. *Paleoceanography,* 4:199–206.

Ganssen, G.M., and Troelstra, S.R., 1987. Paleoenvironmental change from stable isotopes in planktonic foraminifera from Eastern Mediterranean sapropels. *Mar. Geol.,* 75:210–218.

Hilgen, F.J., 1991. Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary. *Earth Planet. Sci. Lett.,* 107:349–368.

Howell, M.W., Thunell, R.C., Sprovieri, R., and Di Stefano, E., 1997. Stable isotope chronology and paleoceanographic history of ODP Sites 963 and 964, Eastern Mediterranean Sea. *Proc. Int. Conf. Neogene Paleoceanogr., Erice, Sicily,* 35.

Jenkins, J.A., and Williams, D.F., 1983/84. Nile Water as a cause of Eastern Mediterranean sapropel formation: evidence for and against. *Mar. Micropaleontol.,* 9:521–534.

Kidd, R.B., Cita, M.B., and Ryan, W.B.F., 1978. Stratigraphy of eastern Mediterranean sapropel sequences recovered during DSDP Leg 42A and their paleoenvironmental significance. *In* Hsü, K.J., Montadert, L., et al., *Init. Repts. DSDP,* 42 (Pt. 1): Washington (U.S. Govt. Printing Office), 421–443.

Lourens, L.J., Hilgen, F.J., Gudjonsson, L., and Zachariasse, W.J., 1992. Late Pliocene to early Pleistocene astronomically forced sea surface productivity and temperature variations in the Mediterranean. *Mar. Micropaleontol.,* 19:49–78.

Mangini, A., and Dominik, J., 1982. The problem of missing sapropels in SW Ionian Sea sediments (core TR171–20). *Mar. Geol.,* 45:M1–M8.

Müller, C., 1973. Calcareous nannoplankton assemblages of Pleistocene-Recent sediments of the Mediterranean Sea. *Bull. Geol. Soc. Gr.,* 10:133–144.

Murat, A., 1991. Enrégistrement sédimentaire des paléoenvironnements Quaternaires en Méditerranée Orientale [Ph.D. dissert.]. University of Perpignan, France.

Murat, A., and Got, H., 1987. Middle and late Quaternary depositional sequences and cycles in the eastern Mediterranean. *Sedimentology,* 34:885–899.

Rohling, E.J., 1991. A simple two-layered model for shoaling of the Eastern Mediterranean pycnocline due to glacio-eustatic sea level lowering. *Paleoceanography,* 6:537–541.

Rohling, E.J., and 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., Palaeoecol.,* 49:237–263.

Ryan, W.B.F., 1972. Stratigraphy of late Quaternary sediments in the Eastern Mediterranean. *In* Stanley, D.J. (Ed.), *The Mediterranean Sea:* Stroudsburg, PA (Dowden, Hutchison and Ross), 149–169.

Shaw, H.F., and Evans, G., 1984. The nature, distribution and origin of a sapropelic layer in sediments of the Cilicia Basin, northeastern Mediterranean. *Mar. Geol.,* 61:1–12.

Shipboard Scientific Party, 1996a. Explanatory notes. *In* Comas, M.C., Zahn, R., Klaus, A., et al., *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program), 21–49.

————, 1996b. Site 963. *In* Emeis, K.-C., Robertson, A.H.F., Richter, C., et al., *Proc. ODP, Init. Repts.,* 160: College Station, TX (Ocean Drilling Program), 55–84.

————, 1996c. Site 964. *In* Emeis, K.-C., Robertson, A.H.F., Richter, C., et al., *Proc. ODP, Init. Repts.,* 160: College Station, TX (Ocean Drilling Program), 85–123.

————, 1996d. Site 974. *In* Comas, M.C., Zahn, R., Klaus, A., et al., *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program), 55–111.

————, 1996e. Site 975. *In* Comas, M.C., Zahn, R., Klaus, A., et al., *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program), 113–177.

————, 1996f. Site 976. *In* Comas, M.C., Zahn, R., Klaus, A., et al., *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program), 179–297.

————, 1996g. Site 977. *In* Comas, M.C., Zahn, R., Klaus, A., et al., *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program), 299–353.

————, 1996h. Site 979. *In* Comas, M.C., Zahn, R., Klaus, A., et al., *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program), 389–426.

Stanley, D. J., 1978. Ionian Sea sapropel distribution and late Quaternary palaeoceanography in the eastern Mediterranean. *Nature*, 274:149–152.

Stein, R., 1990. Organic carbon/sedimentation rate relationship and its paleoenvironmental significance for marine sediments. *Geo-Mar. Lett*., 10:37–44.

Tang, C.M., and Stott, L.D., 1993. Seasonal salinity changes during Mediterranean sapropel deposition 9000 years B.P.: evidence from isotopic analyses of individual planktonic foraminifera. *Paleoceanography,* 8:473–493.

ten Haven, H.L., Baas, M., de Leeuw, J.W., and Schenck, P.A., 1987. Late Quaternary Mediterranean sapropels, I. On the origin of organic matter in sapropel S_7. *Mar. Geol.,* 75:137–156.

Thunell, R.C., and Lohmann, G.P., 1979. Planktonic foraminiferal fauna associated with eastern Mediterranean quaternary stagnations. *Nature*, 281:211–213.

Thunell, R.C., Williams, D.F., and Belyea, P.R., 1984. Anoxic events in the Mediterranean Sea in relation to the evolution of late Neogene climates. *Mar. Geol.,* 59:105–134.

Troelstra, S.R., Ganssen, G.M., Van der Borg, K., and De Jong, A.F.M., 1991. A late Quaternary stratigraphic framework for eastern Mediterranean sapropel S1 based on AMS ^{14}C dates and stables oxygen isotopes. *Radiocarbon,* 33:15–21.

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

Vergnaud-Grazzini, C., Devaux, M., and Znaidi, J., 1986. Stable isotope “anomalies” in Mediterranean Pleistocene records. *Mar. Micropaleontol*., 10:35–69.

Date of initial receipt: 7 May 1997
Date of acceptance: 8 April 1998
Ms 161SR-244