13. STUDIES ON SAPROPELS

13.1 STRATIGRAPHY OF EASTERN MEDITERRANEAN SAPROPEL SEQUENCES RECOVERED DURING DSDP LEG 42A AND THEIR PALEOENVIRONMENTAL SIGNIFICANCE

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ABSTRACT

During Leg 42A of the Deep Sea Drilling Project, we recovered over 150 discrete layers of dark colored organic-rich sediment at five sites in the eastern Mediterranean. We consider about two-thirds of these to be sapropels, on the basis of a definition that recognizes a sapropel as "a discrete layer, greater than 1 cm in thickness, set in open marine pelagic sediment and containing greater than 2.0% organic carbon."

This paper includes a catalogue of all the sapropels and sapropelic layers recovered, including analysis of their sedimentary structures, general composition, fossil content, and stratigraphic position.

Sapropels are identified, dating back to the middle Miocene, and a single occurrence is recorded in the Pleistocene of the western Mediterranean. We recognize that the record of sapropel stratigraphy provided by Leg 42A and Leg 13 drilling is incomplete in both time and space. Despite this, we can make tentative basin-wide correlations between individual layers at least back to the early Pliocene, proving that these stagnation events cannot merely be linked to glacial phenomena. Their widespread distribution and the wide range of depths argue against the presence of an "oxygen-minimum layer."

Stagnation of the Mediterranean basins resulted from a number of interacting factors which caused stratification within the water column. This was a transient situation that developed repeatedly since the mid-Miocene when the Mediterranean took on it present configuration. Glacial expansions were primary factors bringing about stratification in the Pleistocene; whereas, similar factors are as yet unidentified in the Pliocene and Miocene sediments.

INTRODUCTION

During Leg 42A of the Deep Sea Drilling Project we recovered more than 150 discrete layers of dark colored organic-rich sediment (sapropels and sapropelic layers) within the sediment columns at five sites drilled in the eastern Mediterranean. We believe these are the sedimentary expression of periods of stagnation of the Mediterranean bottom waters.

Previous studies of similar layers in piston cores have resulted in a correlated sapropel stratigraphy for the Quaternary (McCoy, 1974; Ryan, 1972; Van Straten, 1972). During Leg 13 some of these Pleistocene layers and one upper Pliocene layer was recovered (Ryan, Hsü, et al., 1973). Leg 42A drilling (Figure 1) proved the existence of sapropels and sapropelic horizons in sediments back to the middle Miocene. However, the sapropels occur at relatively few DSDP sites and none is thought to contain a complete sequence of these layers. Consequently our pre-Quaternary record is incomplete in both space and time and we cannot develop a complete Pliocene and Miocene sequence of correlations, as has been done for the Quaternary piston cores. Nevertheless, projected additional analysis of materials from both cruises may result in the correlation of certain pre-Pleistocene horizons within the separate eastern Mediterranean basins. Indeed, this already appears possible for some Leg 42A layers which were cored more than once.

To this end, we present here an inventory of our Leg 42A findings which includes all the observational data in terms of location, structure, general composition, fossil content, and stratigraphic position available to date for each of the sapropels and sapropelic

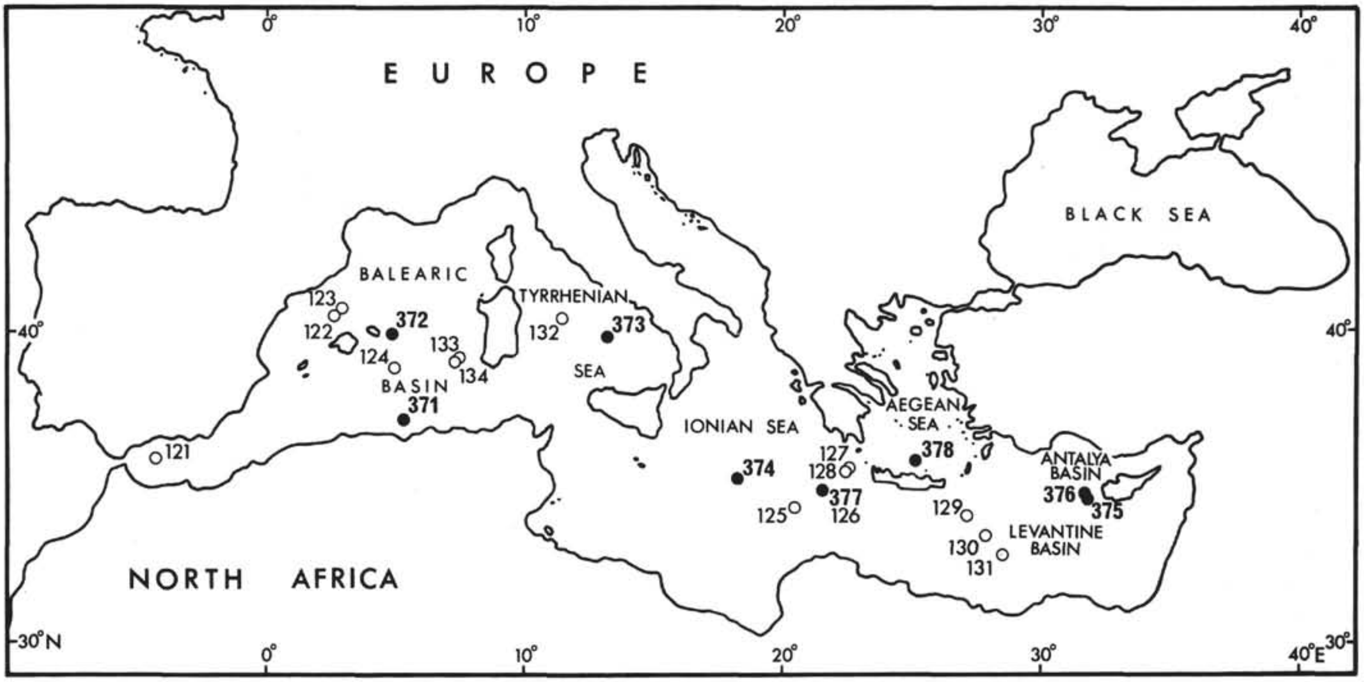

Figure 1. *Index map showing the location of Leg 42A and Leg 13 sites.*

horizons. A discussion follows, which focuses mainly on stratigraphic aspects but also introduces comments on the paleoenvironmental significance of the sequence of layers. This discussion is preliminary in that the observational data are still incomplete and further investigations are foreseen especially with regard to isotopic, organic, and trace element geochemistry. The inventory should nevertheless provide useful data for other scientists interested in oceanic stagnation processes.

TERMINOLOGY OF SAPROPELS

Dark colored layers rich in organic carbon set in marine sequences were first described from eastern Mediterranean piston cores by Kullenberg (1952) and similar horizons were later named "sapropelitic layers" by Olausson (1960). Since that time beds of this type have become known simply as *sapropels.* Loose definition of this term has resulted in some inconsistencies appearing in the literature. Strong variations in organic carbon content exist between layers and, as an aid in environmental interpretation, we need to distinguish between "true sapropels" and the less organic carbon-rich "sapropelic layers." Our Leg 42A terminology, first proposed at a meeting of the shipboard sedimentologists at Lamont-Doherty Geological Observatory in September 1975, defines a *sapropel* as: *a discrete layer, greater than 1 cm in thickness, set in open marine pelagic sediments and containing greater than 2.0% organic carbon by weight.* A *sapropelic layer* is similarly defined, but differs in that it contains between *0.5% and 2.0% organic carbon.* The above definitions mean that, for example, whole sequences as in the Burdigalian of Site 372 with just over 0.5% organic carbon, do not qualify as *sapropelic layers* and similarly, diatomaceous layers rich in organic carbon within the *evaporitic* sediments of Site 374 would not qualify for either term. Of the 74 dark layers encountered on Leg 42A and for which the organic carbon content was determined by the DSDP (La Jolla), Technische Universitat (Munich); and IFP (Paris) shorebases, 54 were designated sapropels.

RECORD OF SAPROPELS AND SAPROPELIC LAYERS RECOVERED DURING LEG 42A

Sapropels and sapropelic layers, ranging in color from black to very dark green and brown, were encountered in all of the eastern Mediterranean sites drilled during Leg 42A. With one notable exception, they were entirely absent from the western Mediterranean sequences (Sites 371, 372, and 373A). This exception is the disturbed lump of greenish black marl recovered in the topmost core of the Tyrrhenian Sea (37A-1-2, 0-5 cm). It contained 2.1% organic carbon and a mixed Pleistocene faunal assemblage.

Tables 1 to 5 catalogue the basic observational data for both the sapropels and sapropelic layers found at Sites 374 through 378, respectively. By definition, all are individual layers at least 1 cm thick, with the exception of some which we term "multiples." These are beds composed of a number of individual layers; some of which are laminae less than 1 cm thick. "Multiples" composed of numerous laminae, *all* less than 1 cm thick, would still be grouped as a single sapropel or sapropelic layer if the layers are obviously interrelated, and if they contain greater than 0.5% organic carbon (Figure 2).

STRUCTURE

Because most of the layers reported here occur in unlithified Pliocene-Quaternary sediments in the upper

TABLE 1
Sapropels and Sapropelic Layers at Site 374

Location					Structure						Composition				Classification			Age		
Core	Section	Top (cm)	Base (cm)	Core Hole Depth (m)	Multiples (No of layers)	Contacts	"Ooze" Layer Above/ Below	Grading (G)	Burrowed (B)	Laminated (X)	Thickness (cm)	Sand Fractions: Abundance	Sand Fractions: Mineralogy	Organic Carbon (max. %)	Sapropels (S)	Sapropelic Layers (SL)	Org. C Unknown (?)	Nanno Zone	Foram Zone	Designation
2	1	165	166	157.0		Sharp above & below					1			?			?			
	2	22	23			Sharp above & below					1			0.6		SL				
	2	51	52			Sharp above & below					1			?			?	NN20	N22	Pleistocene
	2	95	96			Sharp above & below					1			?						
	3	123	127			Sharp above & below	Above				4	High	Mica	2.96	S					
	CC			161.5							?			1.62		SL				
3	1	103	106	208		Sharp disturbed					3	High	Volc. glass, quartz	4.21	S					
	1	121	122			Both sharp	Above				1	Low	Quartz	2.62	S					
	1	125	129			Both sharp					4			4.96	S			NN20	N22	Pleistocene
	1	140	143			Both broken	Above				3	Low	–	8.72	S					
	CC			209							?	Low	Mica, qz. pyrite	0.67		SL				
4	2	56	60	251.5		Both sharp					4	Low	Mica qz.	2.48	S					
	2	62	64			Both sharp					2		Mica qz.,	?			?			
	CC										?	High	pyrite	2.03	S			NN20	N22	Pleistocene
				256.5																
5	2	33	35	297		Both sharp			B	X	2		Mica	1.66		SL		NN19	N22	Pleistocene
	2	38	45		✓ (2)	Sharp curved		G		X	7	Med.	Quartz	3.20	S					
	2	48	51			Disturbed	Above				3			8.99	S			NN18		
	2	121	122			Both sharp					1			1.43		SL				
	3	10	12		?	Both Thin lamina 1 cm below					2	High	–	9.87	S			NN17/ NN16	MPl-5	Late Pliocene
	3	49	51	304		Both faulted top					3	High	–	16.71	S					
6	2	19	20	330.5		Both sharp					1	V. low	Mica	?			?			
	2	42	43			Both sharp					1	High	Mica	9.56	S					
	2	97	98			Both sharp					1	V. low	Mica	1.82		SL				
	3	7	9			Both faulted					2			3.85	S			NN16/ NN17	MPl-5	
	3	50	54			Both sharp					2						?			Late Pliocene
	3	63	66			Both sharp	Above				3	High	–	2.88	S					
	3	124	126			Both sharp					2	High	–	2.77	S					
	5	110	111		✓ (2)	Sharp					1	V. low	–	2.13	S			NN15		
				340.0																
8	3	36	39	349.5 to 359	?	Disturbed					3	V. low	Mica, qz.	?			?	NN13	MPl-3	Early Pliocene
9	2	0	7	359 to 368.5		Sharp disturbed					7	V. low	–	1.93		SL		NN12	MPl-2	Early Pliocene
	3	14	16			Both sharp					2	V. low	–	2.31	S					
10	Part of core catcher Sapropelic																			Early
25	Side wall core – partly Sapropelic																			Pliocene
11	1	91	93	378.0		Sharp faulted			B		2			?			?			
	1	100	101			Both sharp	Layers				1			?			?			
	1	110	111			Both sharp	in				1			?			?			
	2	57	61			Broken	Dolomitic			X	4			?			?		MPl-1	Early Pliocene
	2	112	121			Sharp	L. St.		B	X	9			?			?			
	2	137	150			Base sharp		G	B	X	13			0.72		SL				
				381.5		Top gradnl														

No Sapropels below but dolomitic mudstones (often diatomaceous) have organic carbon values ranging up to 5.3%.

TABLE 2
Sapropels and Sapropelic Layers at Site 375

Location					Structure						Composition				Classification			Age		
Core	Section	Top (cm)	Base (cm)	Core Hole Depth (m)	Multiples (No of layers)	Contacts	"Ooze" Layer Above/ Below	Grading (G)	Burrowed (B)	Laminated (X)	Thickness (cm)	Sand Fraction Abundance	Sand Fraction Mineralogy	Organic Carbon (max. %)	Sapropels (S)	Sapropelic Layers (SL)	Org. C Unknown (?)	Nanno Zone	Foram Zone	Designation
4	4	40	62	245.5 to 252	4 graded units	Sharp base Grad[1] tops		G	B	X	22			7.02	S			NN11	N17	Late Miocene (Tortonian)
5	1	146	147	360		Both sharp					1			?			?			
	2	4	6			Both sharp					2			?			?			
	2	82	88			Both sharp					6			2.3	S					
	3	21	23			Both sharp					2		Rich in detrital mins.	?			?	NN11	N16	Late Miocene (Tortonian)
	3	109	111			Both sharp					2			?			?			
	5	139	141			Both sharp					2			3.72	S					
	CC			369.5							?		Mostly biogenic some pyrite	?			?			
6	3	45	53	461		Both sharp					13			4.31	S					
	3	58	55			Both sharp					2			2.18	S					
	5	48	50			Both sharp					2			0.54		SL		NN10	N16	Late Miocene (Tortonian)
	CC			470							?		Rich in detrital mins.	0.51		SL				
7	2	105	150	565	Multiple	Both sharp			Numer's Laminae		45?			2.54	S					
	4	21	34	to	Multiple	Both sharp					13			0.71		SL		NN10	N16	Late Miocene (Tortonian)
	5	51	52	574.5	Multiple						1			0.51		SL				
8	1	41	44	622 to 631.5		Both sharp					3			2.0	S			NN7	N14/ N11	Middle Miocene (Serravallian)
9	1	100	101	650.5							1			4.10	S		?			
	2	48	49								1			?			?			
	2	88	98		Multiple				Numer's Laminae		10			?			?			
	3	39	56		Multiple						17			3.82	S					
	3	133	134								1			5.06			?	NN6	N12/ N10	Middle Miocene (Serravallian)
	4	16	18								2			3.15	S		?			
	5	7	8								1			2.80			?			
	5	13	14								1			?			?			
	5	113	114	660							1			?				NN5	N9/ N10	

TABLE 3
Sapropels and Sapropelic Layers at Site 376

Location					Structure						Composition					Classification		Age		
												Sand Fraction								
Core	Section	Top (cm)	Base (cm)	Core Hole Depth (m)	Multiples (No of layers)	Contacts	"Ooze" Layer Above/ Below	Grading (G)	Burrowed (B)	Laminated (X)	Thickness (cm)	Abundance	Mineralogy	Organic Carbon (max. %)	Sapropels (S)	Sapropelic Layers (SL)	Org. C Unknown (?)	Nanno Zone	Foram Zone	Designation
1	1	52	80	0	Disturbed prob^{x} graded units (3)	Disturbed		G			?			?			?			
	2	40	146		Disturbed min. (2)	Intensely deformed					?			2.78	S					
	3	13	35		Poss. (3)	Disturbed		G			?			2.21	S					
	3	140	150		Poss. (2)	Disturbed					?			?			?			
	4	3	5			Disturbed					Thickn^{d} Crest (2)			?			?			
	4	10	11.5			Disturbed					Thickn^{d} Crest (1.5)			?			?	NN21	N22	Pleistocene
	4	64	71			Disturbed					Thick n^{d} Crest (7)			5.55	S					
	4	76	77			Disturbed					Thickn^{d} Crest (1)			?			?			
	4	80	89	7.5		Disturbed					Thickn^{d} Crest (8)			2.64	S					
2	1	94	96	7.5		Deformed intensely					?			?			?			
	1	131	150			Deformed					?			?			?			
	2	1	30		Poss. 4 separate layers	Deformed Disturbed					?		Volc. glass	?			?			
	2	120	145			Both sharp					?			5.28	S					
	3	1	2			Both sharp Ints. defmd.					1			1.04		SL		NN20	N22	Pleistocene
	3	3	30			Bounds sharp					?			2.70	S					
	3	86	124		(Poss. 3)	Bounds sharp					?			?			?			
	3	140	148		(Poss. 2)	Bounds sharp					?			1.90		SL				
	4	0	40		(3)	Bounds sharp					?			2.32	S					
	4	70	75	17.0		Highly deformed					?			?			?			
3	2	30	67	17.0 to 26.5	(3)	Intensely deformed					?			3.44	S			NN20	N23/ N22	Pleistocene
5	2	112	115	36.0		Both sharp					3			4.56	S					
	2	120	121			Both sharp					1			?			?	NN19	N22	Pleistocene
	2	138.5	140			Both sharp					1-5			?			?			
	3	68	70			Both sharp					2			?			?	NN18	MPl-5	
	3	145	146			Both sharp					1			?			?			
	4	64	65			Both sharp					1			0.53		SL				Late Pliocene
	4	70	72			Both sharp					2			?			?	NN17/ NN16	MPl-5	
	4	105	111	45.5		Both sharp					6			8.92	S					
6	3	94	97	45.5		Both sharp	Above		B	X	3			1.23		SL		NN19	N22	Pleistocene
	4	55	75	to		Faulted	Above	G		X	20			3.75	S			NN12	MPl-1	Early Pliocene
	4	95	98	55.0	2 thin layers	Sharp, faulted				X	3			?			?			
8	2	0	71	64.5 to 74.0	4 thin layers	Sharp					Up to 2			?			?	NN11	N17	Late Miocene (Messinian)

Organic carbon rich mudstones and graded beds in Cores 9 to 12 – all late Miocene (Messinian)

TABLE 4
Sapropels and Sapropelic Layers at Site 377

Location					Structure						Composition					Classification		Age		
Core	Section	Top (cm)	Base (cm)	Core Hole Depth (m)	Multiples (No of layers)	Contacts	"Ooze" Layer Above/ Below	Grading (G)	Burrowed (B)	Laminated (X)	Thickness (cm)	Sand Fraction Abundance	Sand Fraction Mineralogy	Organic Carbon (max. %)	Sapropels (S)	Sapropelic Layers (SL)	Org. C Unknown (?)	Nanno Zone	Foram Zone	Designation
1	2	140	150	190.5		Gradation'l					10			2.91	S					
	2	10	11			Both sharp					1			4.06	S					
	2	12	13			Both sharp					1			?			?			
	2	28	32			Both sharp	Below?	G		X	4	High		3.47	S			Mixed Pleist.	N22	Pleistocene
	2	97	98	193.5		Sharp- broken into elongated mud pebbles		G?			1	High		3.47	S					

(Marlstone at base of Core 4, Section 3 – organic carbon rich)

TABLE 5
Sapropels and Sapropelic Layers at Site 378/378A

Location					Structure						Composition					Classification		Age		
Core	Section	Top (cm)	Base (cm)	Core Hole Depth (m)	Multiples (No of layers)	Contacts	"Ooze" Layer Above/ Below	Grading (G)	Burrowed (B)	Laminated (X)	Thickness (cm)	Sand Fraction Abundance	Sand Fraction Mineralogy	Organic Carbon (max. %)	Sapropels S	Sapropelic Layers (SL)	Org. C Unknown (?)	Nanno Zone	Foram Zone	Designation
1A	1	61	74	46.0		Disturbed					13?			?			?			
	3	10	15			Disturbed					5?			1.72		SL				
	4	22	30			Top sharp, base gradnl			B		8			?			?			
	4	105	116		At least 3	Both gradnl			B		9?			?			?	NN19	N22	Pleistocene
	4	131	147		Poss. 3	Both gradnl			B		16?			?						
	5	70	89	55.5	At least 4	Both gradnl or base sharp	Below	G?	B		19			2.39	S					
1	1	131	133	84.0		Both? gradnl			B		2			7.15	S					
	2	15	23			Sharp base, top gradnl		G	B	X	8			?			?	NN19	N22	Pleistocene
	2	65	72	93.5		Top gradnl	Above & below	G		X	7			6.98	S					
3	3	112	122	103.0 to 112.5		Both gradnl	Above		B		10			4.08	S		?	NN19	N22	Pleistocene
6	1	144	150	141.0		Disturbed	Above		?		6			?			?			
	2	15	21			Base sharp, top gradnl	Above	G	B	X	6			5.16	S					
	3	81	83			Base sharp, top gradnl	Above & below	G	B		2			4.63	S					
	3	92	95			Base sharp, top gradnl		G	B		3			5.50	S			NN18	MPl-6	Late Pliocene

	3	99	103			Base grad^{nl}, top sharp		B	X	4		?			?			
	3	121	125	150.5		Base sharp, top grad^{nl}	G	B	X	4		?			?			
7	4	69	85	169.5 to 179.0		Both grad^{nl}		B		16		3.22	S			NN16	MPl-5	Late Pliocene
8	1	117	126	217.0 to 226.5		Top grad^{nl}, base sharp	G	B	X	9		3.76	S			NN16	MPl-5	Late Pliocene
	2	3	46			Top grad^{nl}, base sharp	G	B	X	43	Volc. glass	5.17	S					
3A	0	34	43	293.0		Top grad^{nl}	G?	B		9?		?			?			
	1	56	68			Top grad^{nl}, base distrbd.	G?	B		12		?			?			
	2	0	16			Top?, base grad^{nl}		B		16?		?			?			
							Burrows below to 48 cm											
In Sections 2-4 Separate Sapropelic Burrows Between Layers	3	15	20			Both grad^{nl},		B		5		?			?			
	3	52	60			both grad^{nl}		B		8		?			?			
	3	95	100			Both grad^{nl}, distrubed		B		5		?			?	NN13	MPl-3	Early Pliocene
	4	16	25			Top grad^{nl}, base sharp	G?	B				?						
	4	30	43			Both grad^{nl}		B		13		?			?			
	4	70	83			Both grad^{nl}		B		13		?			?			
	4	103	107			Both grad^{nl}, disturbed		B		4		?			?			
	5	72	85			Top sharp, base grad^{nl}		B		13		?			?			
	5	102	111			Both sharp		B		9		?			?			
	5	130	142			Top sharp, base?		B		12		?			?			
	6	40	55			Both sharp		B		15		?			?			
	6	126	137	302.5		Both sharp, disturbed		B		9		?			?			
11	1	144	150	302.5		Disturbed, sharp						?			?	NN14		
	2	1	3			Both sharp				2		4.16	S					
Separate Sapropelic Burrows Between Layers	2	18	32			Both grad^{nl}	G	B	X	14		1.69		SL				
	2	95	106			Both sharp				11		5.01	S					
							Burrows below to 106 cm											
	2	130	144			Both grad^{nl}		B		14		1.51		SL			MPl-3	
	3	18	25			Both grad^{nl}		B		4		?			?			
	3	46	49			Both grad^{nl}		B		3		?			?			
	3	63	66			Both sharp?		B		3		?			?	NN13		
	3	69	75			Both sharp?		B		6		?			?			
	4	9	11			Both sharp			X	2		?			?			Early Pliocene
	4	19	24			Base sharp		B		5		?			?			
	4	37	39			Top grad^{nl}, both sharp				2		?			?			
	4	46	50			Top grad^{nl} Base sharp		B		4		?			?			
	4	63	66			Both grad^{nl}		B		3		?			?		MPl-2	
	4	83	85			Both grad^{nl}			X	2		?			?	NN12		
	4	123	131			Both grad^{nl}	G?	B	X	9		?			?			
	4	133	137	312.0	2?	Both grad^{nl}	G?	B	X	4		?			?			

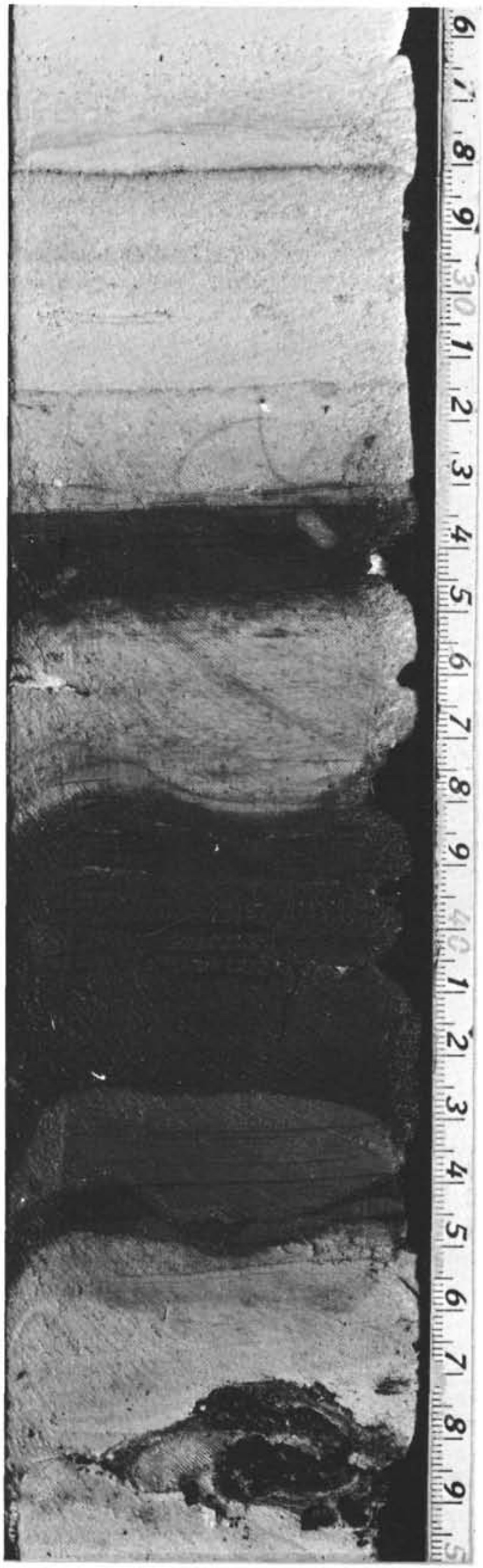

Figure 2. *"Multiple" sapropel horizon at 38 to 45 cm in Core 5, Section 2 of Site 374 (3.2% org.c). Note the relationship of the thin black lamina to the overlying main body of the sapropel. Neither the thin lamina at 28 cm nor the isolated lump of sediment rich in organic carbon at 48 cm was, by definition a sapropel or sapropelic layer. A sapropelic layer is present at 33 to 35 cm. (1.66% org. C). (scale in cm)*

parts of the holes, considerable drilling disturbance is often evident (Figure 3). In these cases, detailed structural analysis is impossible. Although we can recognize discrete layers, flowage upcore caused by the drilling process may result in our recording a somewhat exaggerated thickness.

Although the thicknesses of individual sapropels and sapropelic layers encountered on Leg 42A range up to 45 cm, only a small number–46 out of 150 or more recovered–are greater than 5 cm thick. The thickest layers found at each site were respectively: 13 cm at Site 374, about 45 cm at Site 375, 20 cm at Site 376, 10 cm at Site 377, and 43 cm at Site 378. At Sites 374, 376, and 377, the layers noted above were the only ones greater than 10 cm thick whereas at Sites 375 and 378 beds of this thickness make up over a quarter of those recovered. Consequently we cannot demonstrate a relationship between the occurrence of thick layers and the present environments of the sites; Site 375 was located on the Florence Rise and Site 378 was drilled in the Cretan Basin. Nor can thickness of the individual Leg 42A sapropels be related to sedimentation rate; the thickest layers at Site 374 are recorded in the early Pliocene where calculated sedimentation rates are considerably lower than in the rest of the hole.

Nesteroff (1973), in his study of the Leg 13 cores, identified two main sapropel types, primarily on the basis of structure: "pelagic sapropels," similar to those which had been described in piston cores up to that time, and "sapropelitic turbidites" for those beds encountered during Leg 13 drilling, which showed strong evidence of current deposition. Pelagic sapropels were described as always having sharp contacts with their host sediments, nannofossil oozes. They were made up of a distinct layer of gray marly ooze overlain by a layer of black sapropel and this topped by gray marly ooze or by pure nannofossil ooze. The second type was considered by Nesteroff to be a sapropel-stained current deposit since it had structural characteristics interpreted as cross-bedding and grading, as well as sand-silt laminae and winnowed concentrations of foraminifers. On the basis of these criteria, such beds were considered by Nesteroff to be either sapropel-stained turbidites or contourites. In Tables 1 to 5, structural features were recorded with this general distinction in mind. This proved useful, but also revealed a much greater structural complexity for sapropels than had hitherto been recognized. In addition, the importance of burrows within some sapropels, especially those of the Cretan Basin Site 378, was revealed. Their presence indicates either that a bottom-living fauna existed during the formation of some types of sapropel, or that the post-sapropel population sought out the organic carbon-rich substrate as particularly desirable grazing territory.

Figure 3. *Sapropel layers showing flowage caused by drilling disturbance of soft sediments (376-2-4, 0-25 cm). The location and thicknesses of such layers reported here are those of their crests. (scale in cm)*

We assign most of the Leg 42A sapropels and sapropelic layers to Nesteroff's pelagic group. These have sharp contacts with the host marls and have no internal structure. At Site 374 all but 6 of the 38 layers were of this type. Corresponding figures for the other sites are: Site 375, all except 5 of the 25 recorded and at Site 376 all but 5 of the 32 recorded are of pelagic type. On the other hand, the layers at Site 378 were almost all burrowed throughout and those at Site 377 were difficult to evaluate with at least half seemingly of turbidity current origin. However, the Leg 42A record clearly indicates that there are variations within this pelagic group. Occasionally only one of the contacts is sharp and gradational boundaries can occur at either the top or the base. Also, a thin sapropelic lamina is sometimes present a few centimeters above or below the sapropel bed, separated from it by nannofossil marl (Figure 4). We looked for the association of relatively pure nannofossil ooze layers with the sapropels, as reported by Nesteroff from the Leg 13 sediments, in the Leg 42A cores. We found the association only in a small number of the layers and its occurrence seems entirely random. In most cases a layer of pure nannofossil ooze occurs above the sapropel or sapropelic horizon, but it can also be found below. Also its presence is not confined to layers of the pelagic type; it is also found with clearly current-deposited beds. These observations suggest that the onset and termination of stagnation for deposition of the pelagic-type sapropel was usually a relatively sudden event, but also, that exceptions occurred when unstable conditions prevailed over a more prolonged period, resulting in gradual or oscillatory onsets and terminations.

Sapropels and sapropelic layers which, because of their cross and oblique lamination grading, and/or concentrations of coarse material (Figure 5), we believe to be of current-deposited origin, were encountered at all the Leg 42A eastern Mediterranean sites. This is a total of 41 layers, but half of these are in the Site 378 cores. Site 377, drilled as a continuation of Leg 13, Site 126, contained two sapropels of this type, and confirmed Nesteroff's earlier observations.

Twenty-three of the total 41 current-deposited sapropels recovered were graded, but the exceptions confirm the notion that not all sapropels of this type can be assigned to a turbidity current origin (Figure 5). No clear picture emerges from consideration of their contacts with the host sediment. Almost all in Sites 374 to 377 have sharp basal and upper contacts. But at Site 378 a complete range from "both sharp" through "one or other gradational" to "both gradational" occurs and again the presence of an associated pure ooze layer appears to be random.

The burrow structures that were associated with many of the Leg 42A sapropels and sapropelic layers provide evidence of bottom conditions during, or immediately after, their formation. Leaving aside Site 378 for the moment, burrowing associated with sapropels and sapropelic layers occurs almost exclusively in the current-laminated type. The only exception for Sites 374 through 377 is the bed at Sample 374-11-1, 91-93 cm which contains *Chondrites* burrows throughout and is not laminated. One might expect that the onset and termination of stagnant conditions would be recorded by burrow structures, either below the sapropelic layers, recording the last benthic fauna, or above them, recording the recolonization of the area of sea floor after the stagnation event. Evidence of such occurrences is present in the cores, and Figure 5 shows some examples. On the other hand, there are sapropels and sapropelic layers in which the burrowing occurs within the layer itself. Some, if not all, of this bioturbation could result from organisms recolonizing the seabed after stagnation had ceased and burrowing down into the organic carbon-rich substratum. In some sapropels, the color of the burrow fillings is characteristic of the overlying sediment.

Site 378 represents an extreme case where all but 7 of the 51 layers found there contained burrows actually within the main part of the bed. Indeed, throughout the entire Site 378 sediment column burrow traces were usually most prevalent in association with the sapropels and sapropelic layers (Figure 6). *Chondrites* is the dominant form but *Planolites* is common and a few *Zoophycos* are also present. Possibly Site 378, with its higher levels of burrowing associated with the sapropels, differs from the other eastern Mediterranean sites only because burrowing was restricted to sapropelic beds of current-deposited origin and conditions conducive to this type of deposition were more prevalent in the Cretan Basin. The lack of lamination in many beds may be because primary lamination was disrupted by later activity by benthic fauna. This could also account for the lack of lamination in the bed at Site 374 reported above.

COMPOSITION

Smear-slide analysis was used aboard ship for preliminary determinations of the composition of the sapropels and sapropelic layers. They were generally nannofossil marls which were rich in organic carbon. This richness in organic debris made identification of other components difficult and estimations of their abundances are unreliable. As examples, however, the layers at Site 376 were estimated to contain: 10%-25% fine-grained organic matter, 20%-30% nannofossils, 30%-40% clay minerals, 5%-10% pyrite, and 5%-15% foraminifers, while at Site 378 the estimates were thus: 25%-40% fine-grained organic matter, 15%-50% nannofossils, 0%-30% clay minerals, plus <1% to 5% foraminifers and quartz. The apparent absence of pyrite in the latter may not be accurate inasmuch as dark minerals were frequently undetected in these slides.

Sand fractions, resulting from sieving for microfaunal analyses, were examined for most of the sapropels and sapropelic layers at one of the sites; Site 374 (see Table 1). Unexpectedly, we cannot use these qualitative estimates of sand fraction abundance as criteria with which to make a distinction between the sapropels believed to be of current origin in Core 5 Section 2,

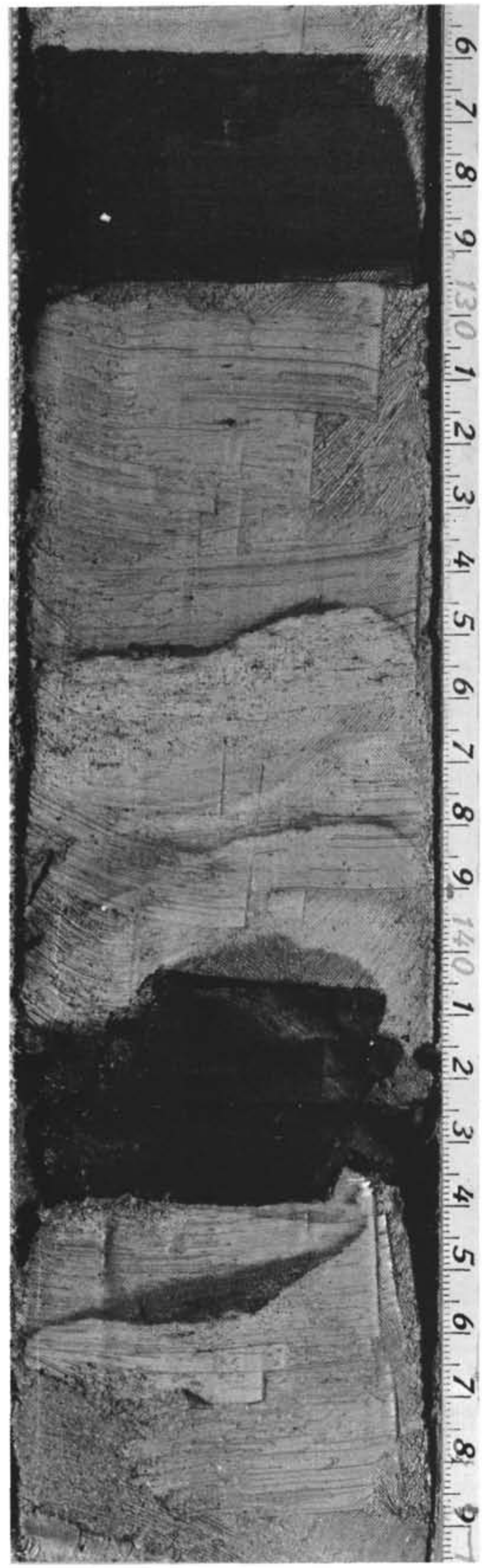

Figure 4. *Three types of relationships of the pelagic sapropel to the host sediment. (Scale in cm.) (A) Sharp contacts above and below (374-3-1, 125-131 cm).*

Figure 4. *(Continued).*
(B) Sharp contacts with sapropelic laminae a few centimeters above (374-3-1, 118-124 cm).

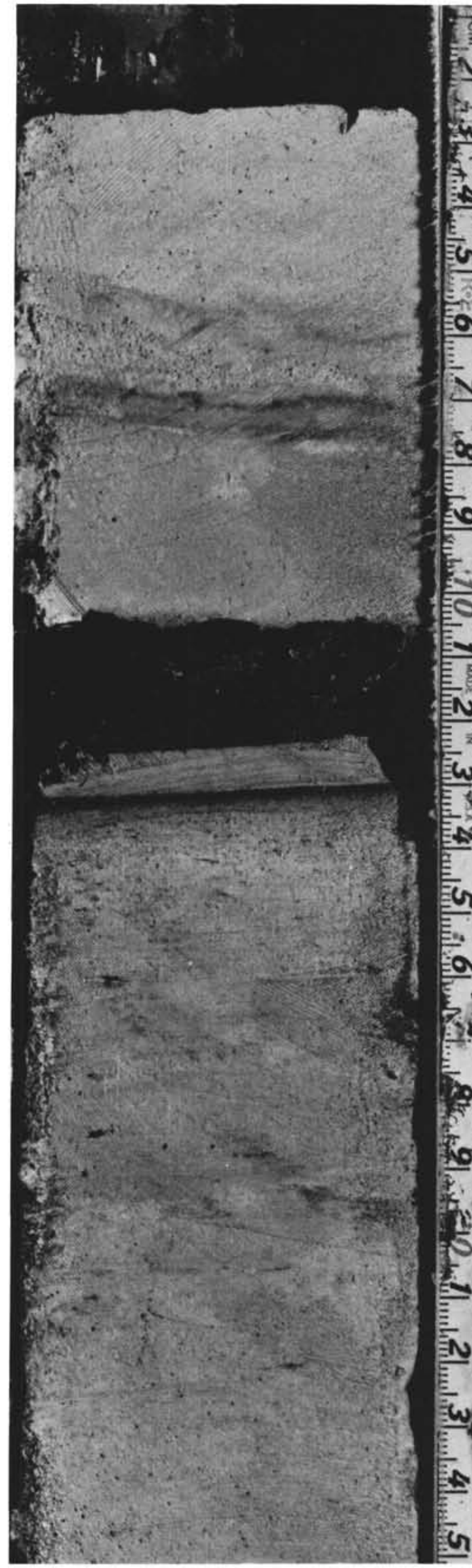

Figure 4. *(Continued).*
(C) Sharp contacts with sapropelic laminae 1 cm below (374-5-3, 6-14 cm).

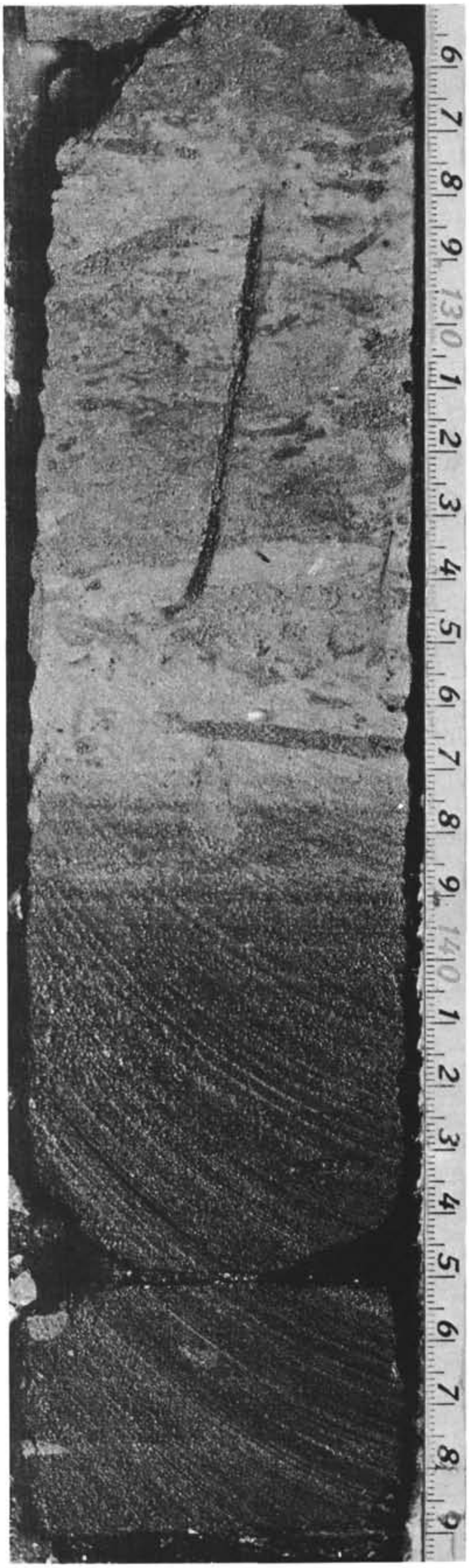

Figure 5. *Three types of current-deposited sapropelic layer. (Scale in cm.) (A) Graded sapropelic layer with lamination and sapropelic burrows above (374-11-2, 125-150 cm).*

Figure 5. *(Continued).*
(B) Non-graded sapropelic layer with lamination and sapropelic burrows above and below (374-11-2, 100-125 cm).

Figure 5. *(Continued).*
(C) Disturbed, but complexly laminated non-graded sapropelic layer. Fine sapropel/marl lamination may be the result of current reworking of the main sapropel.

and those that were of pelagic type. Also, the only sand size minerals recorded were mica, quartz, and pyrite and their distribution is insufficient to suggest variations from layer to layer. Shards of fibrous volcanic glass may have some correlative value, however. These appear in the layer at Sample 374-3-1, 103-106 cm. Others were found at Sample 376-2-2, 1-30 cm (Figure 7), and also as elliptical pockets at Site 378, in its 43-cm-thick layer (Sample 8-2-3, 46 cm). The first two are of similar age (Pleistocene), and the latter is early Pliocene (MPl-3 of Cita, 1975). After some months of storage at the DSDP East Coast Repository, the Leg 42A cores were re-examined for additional ash material. A hitherto, undescribed, non-sapropelic layer, made up almost entirely of ash material was identified in Core 1 of Site 376. This had become more visible after slight drying on the sediment surface of the split core. No additional ash layers were found in the Leg 42A cores, but this finding has allowed tentative correlation with the Leg 13 Site 125 (see later sections).

For detailed petrography and clay-mineralogy of individual sapropel layers, the reader is referred to the contribution by Sigl et al. (this volume) which makes up the second part of this chapter.

The organic carbon analyses made by the shore-based laboratories show clearly the wide variations that exist in organic content between individual sapropel layers. Of those analyzed, that at Sample 374-5-3, 40-51 cm had the highest percentage: 16.71% organic carbon by weight. This is the highest value recorded from any Mediterranean sapropel to date. It is the only one from the Leg 42A cores to exceed 10%, but, on the other hand, a further 12 exceed 5%. One point which is clear from the analyses completed to date is that the pelagic-type layers do not differ from the current-deposited type in percentage organic carbon content. The current-deposited type are not merely "sapropel-stained." All except three of the current-laminated and/or graded layers are true sapropels (2.0%), and include five of those with greater than 5% organic carbon.

FOSSIL CONTENT

All the sapropels investigated are fossiliferous. Planktonic foraminifers encountered in the "normal" sediments are found in similar or greater abundance in the associated sapropels. Giant *Orbulinas*, easily seen on the surface of a split core, are present in the sapropel at Sample 376-6-4, 55-75 cm, of earliest Pliocene age from the Messina Abyssal Plain (Figure 8). Sapropels containing a very high organic carbon content usually do not contain many planktonic foraminifers. This is the case in the Pleistocene sapropel at Sample 374-3-1, 140-143 cm with 8.72% organic carbon and in the late Pliocene sapropel at Samples 374-5-3, 49-52 cm, with its record value of 16.71% organic carbon.

Faunal diversities, in contrast, are usually lower in the sapropels and sapropelic layers than in the host sediments. Discoasters are enriched in the sapropels of Site 376, and similar enrichment is coincident with

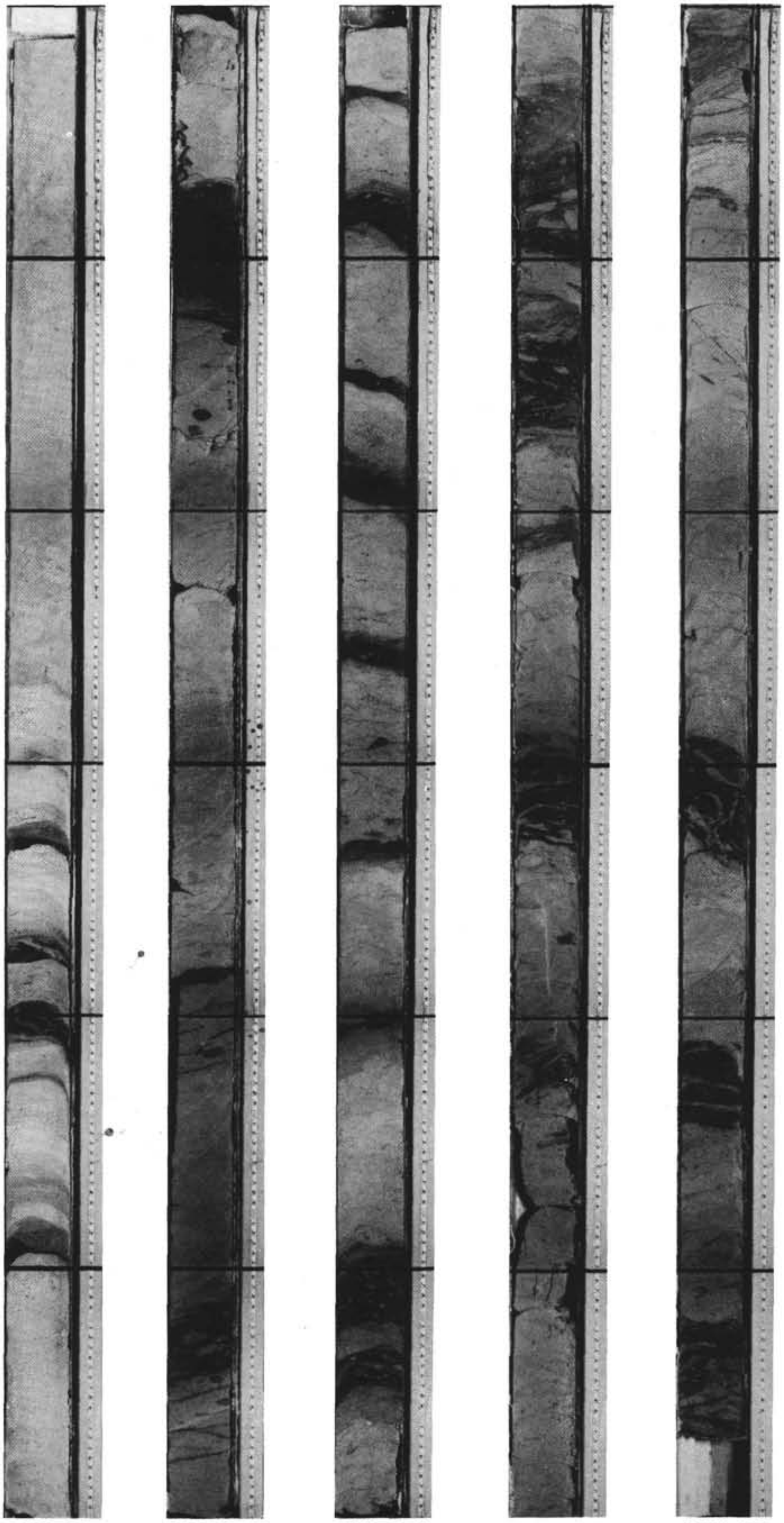

Figure 6. *Several 1.5-meter core sections showing the burrowed sapropels and sapropelic layers at Site 378. (scale in cms)*

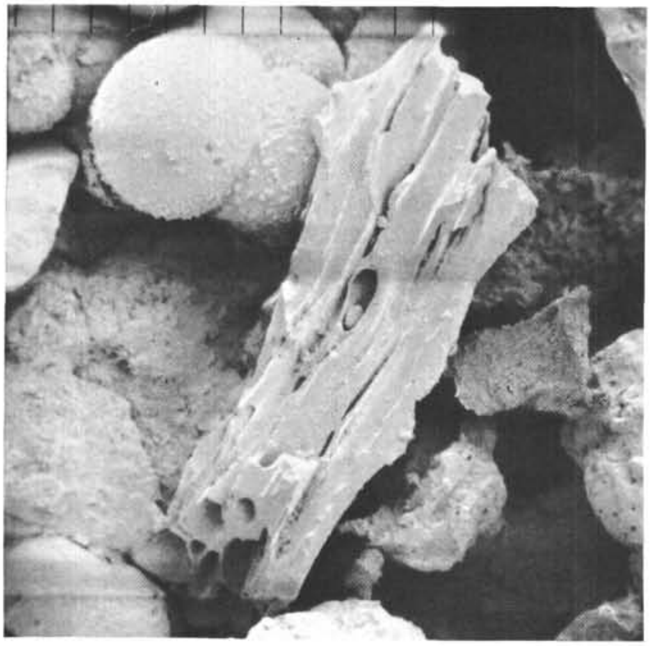

Figure 7. *Scanning electron microscope picture showing a shard of fibrous volcanic glass found in the sapropel at 376-2-2, 1-20 cm. (× 500).*

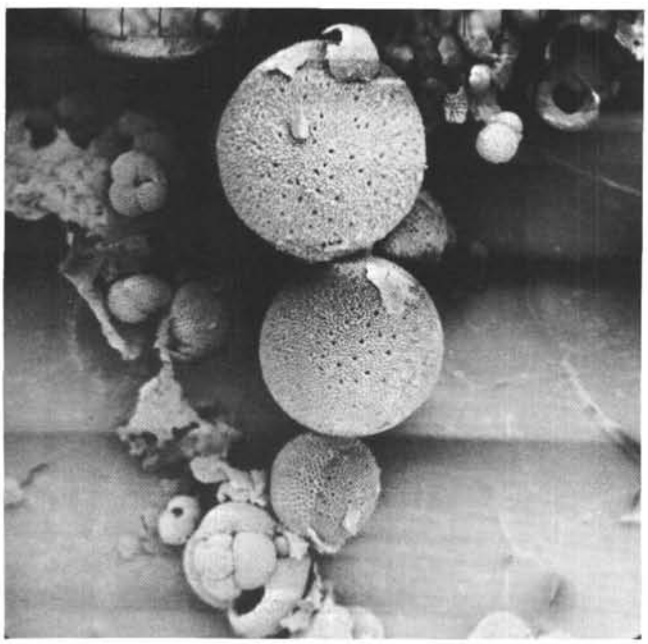

Figure 8. *Scanning electron microscope picture showing giant Orbulinids found in the sapropel at 376-6-4, 55-75 cm. (× 46).*

dissolution of the coccoliths in many of the layers of Site 378 (Müller, this volume). There are also layers obviously enriched in nannofossils with no sign of dissolution and some with large abundances of single species of coccoliths.

Several sapropels yield only species of planktonic foraminifers known to live in the upper layers of the water column (epipelagic). This is the case for the sapropels recorded in the Antalya Basin (376-1-1, 50-80 cm; 376-1-3, 13-16 cm) and in the Cretan Basin (378-6-3, 92-95 cm). Others, however, also contain species of globorotalids which lived between 100 and 500 meters (mesopelagic). This suggests that stagnation here did not affect the structure of the upper water column usually associated with the permanent thermocline.

Deformed specimens of large *Globorotalia truncatulinoides* showing abnormally inflated chambers in the external part of the last formed whorl, were found in the early Pleistocene sapropel at Sample 374-4-2, 56-64 cm of the Messina Abyssal Plain and in the Antalya Basin sapropels at Samples 376-1-1, 50-80 cm, 376-1-2, 116 cm, and 376-2-3, 4-17 cm (Figures 9 and 10). Similar aberrant, deformed specimens of *Globorotalia truncatulinoides* occur in the piston-cored sapropel S7 of the late Pleistocene from the Mediterranean ridge (Cita et al., in press). Since *Globorotalia truncatulinoides* is a well-known mesopelagic species, the development of the laterally inflated forms is interpreted as a response to stress conditions which did occur in the upper water mass.

Highly specialized foraminifer assemblages dominated by populations of the euryhaline species *Globigerina eggeri* and *Globigerina bulloides* (Parker, 1958; Ryan, 1972), were found in the Messina Abyssal Plain sapropels 374-2-3, 123-127 cm; 374-3-1, 103-106 cm; 376-2-2, 20-28 cm; 376-2-3, 4-17 cm; and 376-2-3, 121-146 cm (Figure 11). Similar faunal assemblages were reported in the "Brunhes-Matuyama" sapropels of DSDP Site 125, by Cita et al.' (1973), and in the piston-cored sapropels S6, S9, S11, and S12, by Cita et al. (in press).

Some sapropels, on the other hand, contain foraminifer assemblages indicative of redeposition by currents. For example, one sapropel analyzed from the Tortonian of Site 375 (Sample 5-3, 21-23 cm) was dominated by detrital minerals, but also contained a fairly rich although poorly diversified assemblage of planktonic foraminifers which are consistently small in size. The assemblage is devoid of mesopelagic species but it also contains numerous large spores. Another from the Messinian of Site 376 (Sample 8-2, 7-9 cm), also contained numerous detrital minerals, together with reworked benthic foraminifers, including the innershelf genus *Discorbis*, and sparse, obviously size-sorted, planktonic foraminifers. Intervals, in which diatoms completely dominate the assemblage, were found only in the Cretan Basin sapropels, 378-7-4, 70-76 cm and 378-8-2, 20-40 cm (Figure 12). Both sapropels are late Pliocene (MPl-5, foraminifer zone; NN 16 nannofossil zone) and contain poor foraminifer assemblages which also include species thought to be mesopelagic, such as *Globorotalia puncticulata*.

Palynological investigations were carried out on three sapropels of early Pleistocene, late Pliocene, and early Pliocene age, respectively from the Messina Abyssal Plain Site 374 (Bertolani Marchetti and Accorsi, this volume).

Sapropels are usually very rich in palynomorphs. Strick-Rossignol (1973) demonstrated from the Leg 13

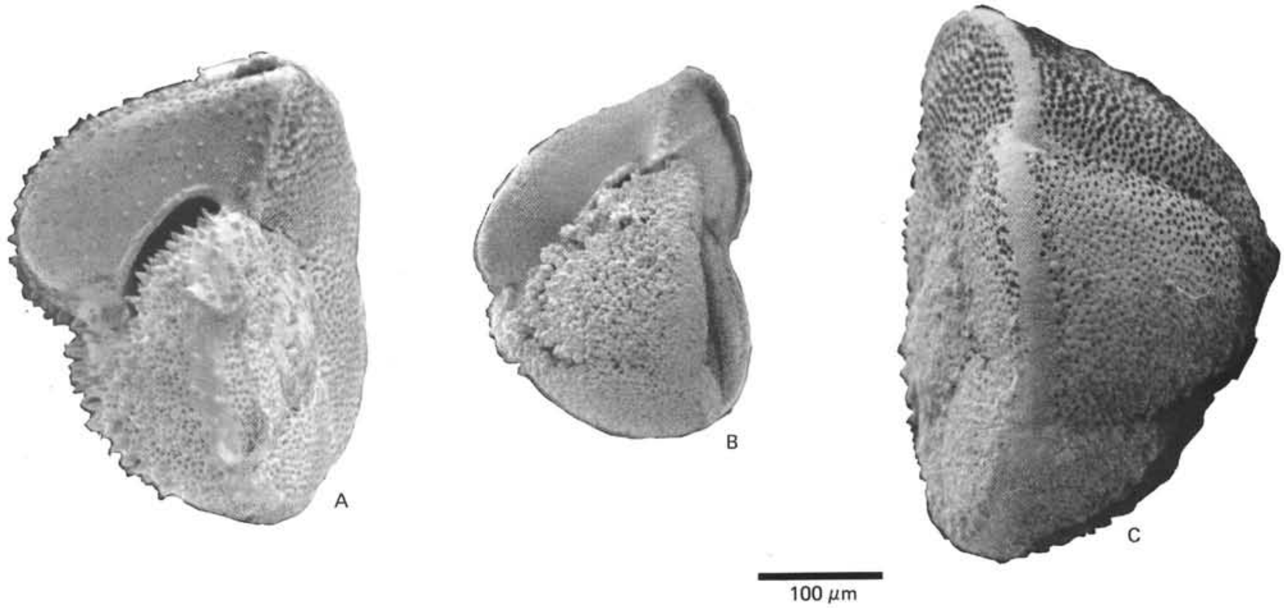

Figure 9. *Scanning electron microscope picture showing three left-coiling specimens of* Globorotalia truncatulinoides *with deformed, laterally inflated chambers in the last whorl. Specimens A and B are from 376-1-1 (52 cm). Specimen C is from 374-4-2 (57 cm). (scale in microns)*

material that two discrete pollen assemblages are represented in the eastern Mediterranean sapropels: one of northern origin dominated by arboreous plants and by *Artemisia*, the other of Nilotic origin dominated by *Graminaceae* and *Cyperaceae*. She suggested three different processes for the transport, dispersal, and sedimentation of the pollen grains:

1) The formation of the resedimented sapropels as found at Sites 130 and 131A is associated with the first process. These sapropels yielded the Nilotic pollen assemblage: *Graminaceae, Cyperaceae*, and Pteridophytes. These pollen, derived from tropical trees, are believed to enter the sea in suspension with the sedimentary discharge and behave as a benthic element.

2) The formation of the finely laminated sapropels containing predominantly biogenic components is associated with the second mechanism in which the sapropel results from wind-transport of pollen over a short distance from the area of vegetation, followed by dispersal by surface currents over a very long distance (pelagic behavior). Note that only northern pollen were found associated with these finely laminated sapropels.

3) The third mechanism of transport is invoked to explain the widespread distribution of certain small-sized non-bladed pollens. This mechanism involves long-distance wind transport of the pollen in the upper atmosphere.

The investigations by Accorsi (Bertolani Marchetti, and Accorsi, this volume) on the three layers from Leg 42A, Site 374, which are of early Pliocene (sapropel layer in 374-9-2), late Pliocene (sapropelic layer in 374-5-2), and Pleistocene (sapropelic layer in 374-4 CC) age, respectively, recorded the northern pollens only. The authors suggest that the remarkable differences found in the percentages of the climatically significant genera *Pinus, Cedrus, Quercus*, of the family *Chenopodiaceae*, and of *Artemisia*, are the result of climatic changes through time.

Investigations by Stradner and Bachmann (this volume), on the silicoflagellates found in the Cretan Basin Site 378, suggest a paleotemperature of 15°-20°C for the sapropel Sample 8-2, 3-46 cm. Their estimate is based on a *Dictyocha/Distephanus* ratio of 1:1.7 recorded at 21 cm. The ratio between the cold water indicator *Dictyocha fibula* and the warm water indicator *Distephanus speculum* is considered climatically significant by Mandra and Mandra (1972). The temperature estimated for this late Pliocene (MP1-5 Zone) sapropel is lower by approximately 5°C than that estimated for the overlying "normal" sediment from Section 1.

Pteropods are common in the Pleistocene sapropels (see, also, Cita et al., 1973). Here, deposition in anoxic, stagnant bottom waters may have enhanced preservation by preventing dissolution (Berger and Soutar, 1970).

Tests of bottom living faunas are generally absent from the sapropels of Sites 374 through 377. Benthic foraminifers, ostracodes, and echinoid spines, which are consistently present in the intervening "normal" host sediments, are rare or absent altogether in the sapropels and sapropelic layers. An exception is the sapropels at Site 378 in the Cretan Basin which contain an epifauna of benthic foraminifers and ostracodes with densities and diversities comparable to those found in the "normal" sediments. These sapropels are the beds that also contain marked structural evidence of burrowing. We are uncertain at present if the benthic tests are from organisms living at the time of sapropel deposition, or whether these tests are alloch-

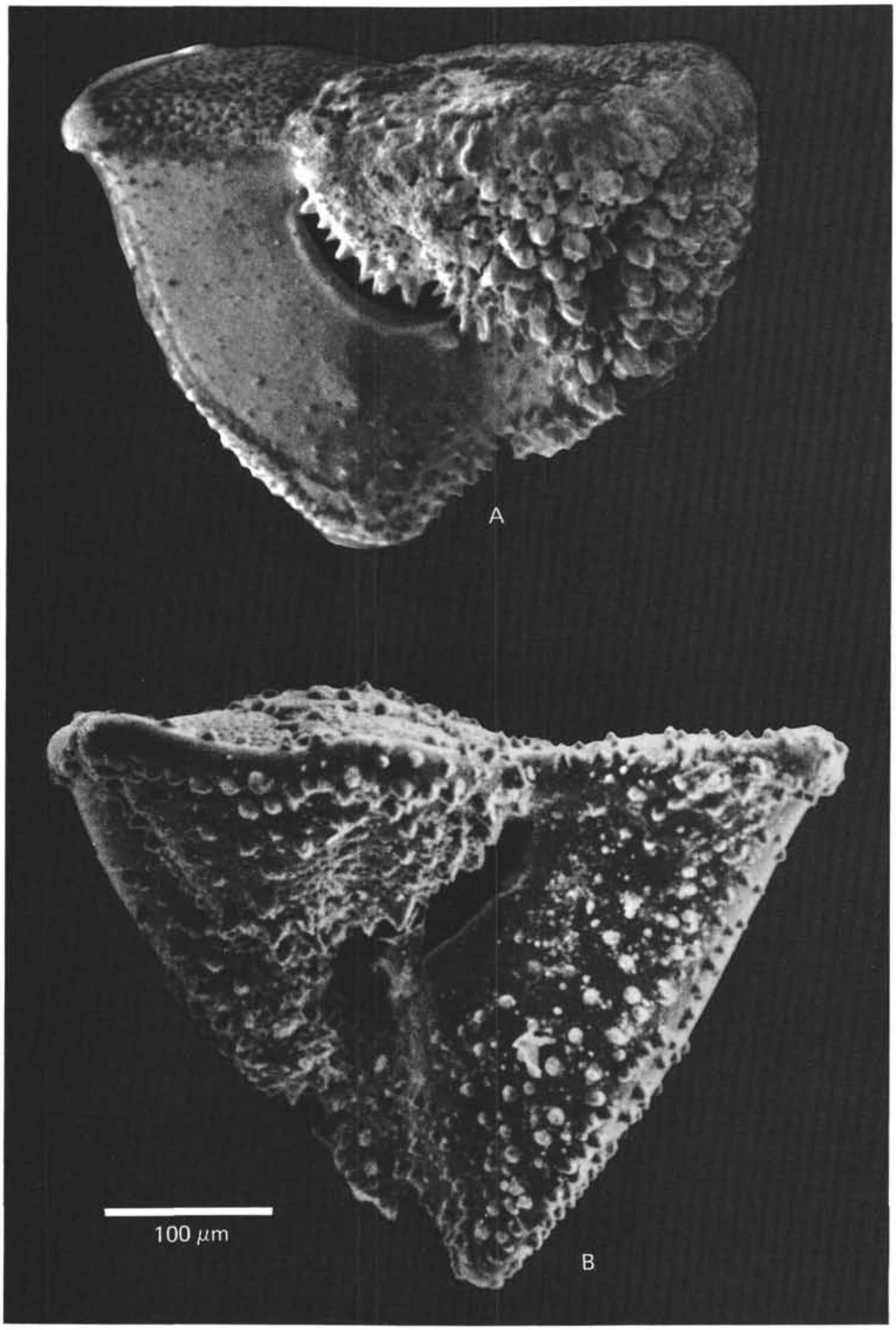

Figure 10. *Comparison between a deformed* Globorotalia truncatulinoides *(A) from 376-1-1 (52 cm) and a normal specimen (B) from 132-3-4 (71 cm), both showing the apertural face. (scale in microns)*

thonous and were carried into the sapropels in the guts of the epifauna which repopulated the seabed with the recommencement of "normal" sedimentation.

STRATIGRAPHIC POSITION

Precise correlations between a large number of Mediterranean cores on the basis of sapropels which were interpreted as "isochronous lithologies" together with others using tephra horizons, have been constructed by Olausson (1961), Ryan (1972), McCoy (1974), and Sigl and Müller (in press).

Nesteroff (1973) used the term "Upper Sapropel" for the DSDP Leg 13 sapropels referred to the *Gephyrocapsa oceanica* Zone (NN 20), and "Lower Sapro-

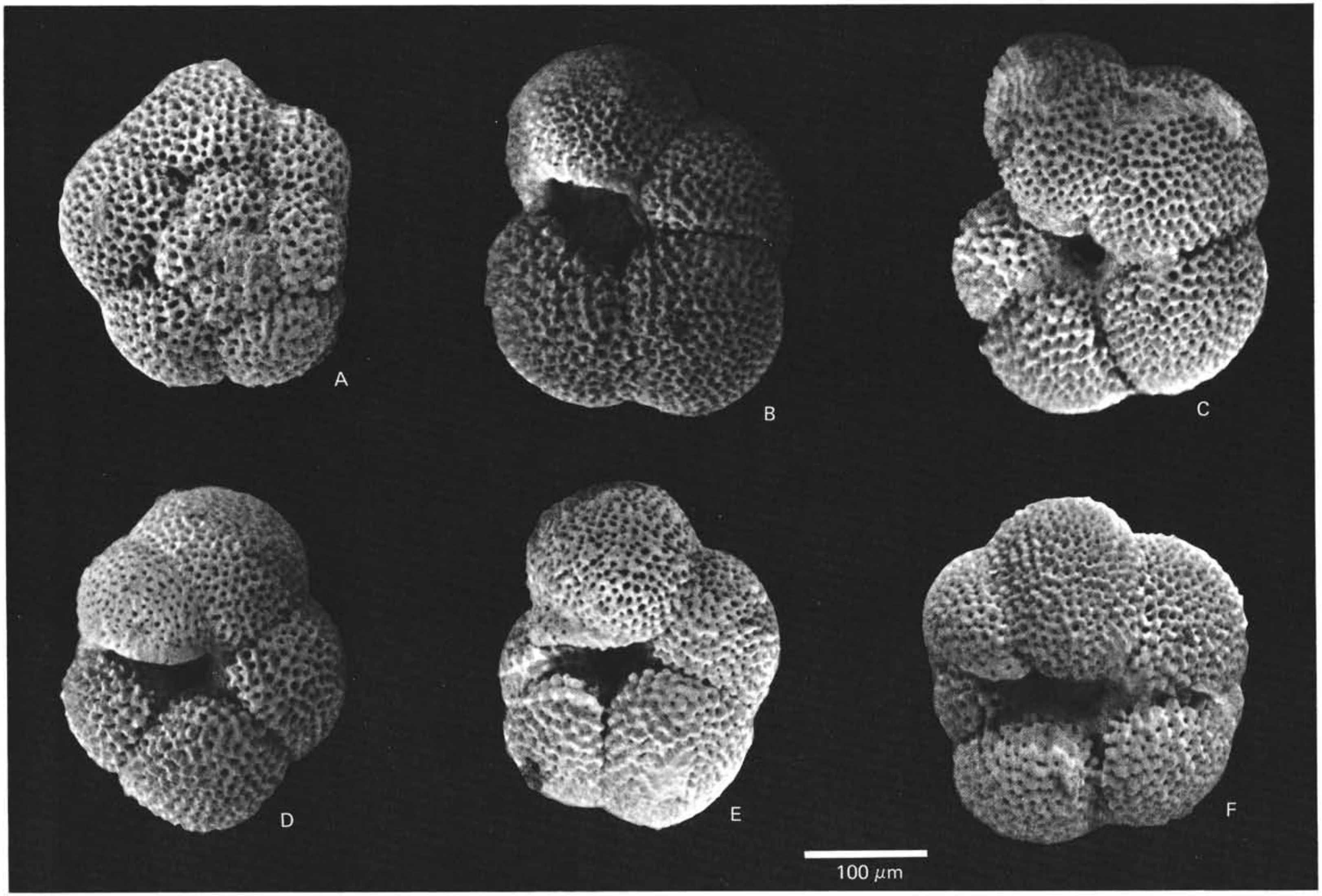

Figure 11. *Specimens of the euryhaline species* Globigerina eggeri *from 374-3-1 (103 cm), whose tests are very thin and fragile. The taxon is also known as* Neogloboquadrina dutertrei. *A = spiral view. B-F = umbilical views. (scale in microns)*

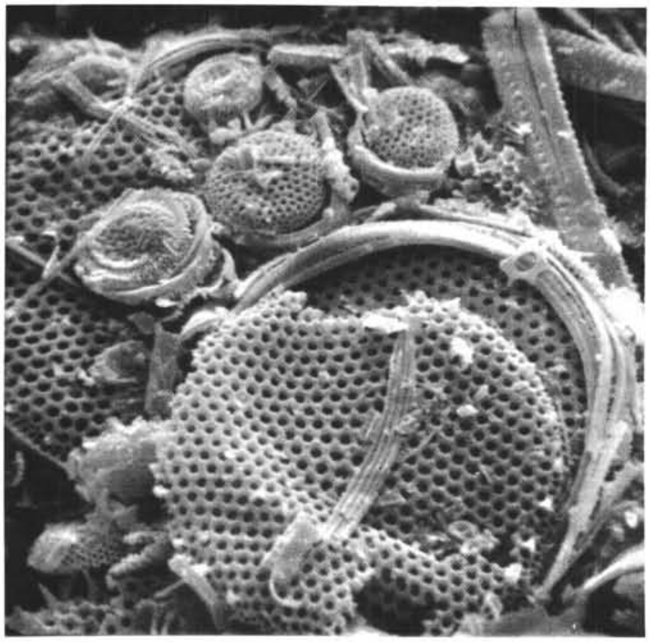

Figure 12. *Scanning electron microscope picture showing a faunal assemblage dominated by diatoms found in the sapropel at 378-8-2, 3-46 cm. (x 1000)*

pel" for those referred to the *Pseudoemiliania lacunosa* Zone (NN 9). Cita and Ryan (1973) proposed a grouping of the same Leg 13 sapropels arranged according to their position with reference to the paleomagnetic time-scale (Ryan, 1972; Cita et al., 1973) as follows: "Brunhes sapropels"; "Brunhes/Matuyama sapropels"; "Matuyama/pre-Jaramillo sapropels"; "Matuyama/pre-Olduvai sapropels".

Sapropels, referable to their "Brunhes" group, have only been recovered in piston cores. They are 12 in all and have been recently numbered independently by several authors (McCoy, 1974; Hieke, in press; Cita et al., in press). The youngest sapropel, S 1, is postglacial, and has been dated several times by the C^{14} method; its absolute age is approximately 8000 yr. B.P. Sapropels referable to this group have not been recovered in any of the DSDP sites.

Details of the stratigraphic record provided by the Leg 42A coring, with reference to that of Leg 13 and to any available piston cores, are summarized below.

Quaternary

The sequence of sapropels and sapropelic layers widely recorded from piston cores (e.g., horizons S 1, through S 12 of Cita et al., in press) were not positively identified in any of the *Glomar Challenger* cores from either Leg 13, Site 125, or Leg 42A, Site 376. These young sapropels extend from isotope stage 1 of Emiliani (1955, 1966), to stage 13 and are dated as ranging back to approximately 0.44 m.y. according to the revised time scale of Emiliani and Shackleton (1974). These layers have been referred to as the "Brunhes sapropels" by Cita et al. (1973).

The most recent stratigraphic horizons in the DSDP cores are those from Core 1 of Site 376 which contain a thick bed of coarse ash of shard texture (non-fibrous and without appreciable inclusions) and index of refraction similar to a bed detected in Section 4 of Core 1, at Site 125 (see Chapter 7 of Ryan, Hsü, et al., 1973). The lithologic correlation of these two ash beds, as shown in Figure 13, is further supported by the presence of the *Globigerina eggeri-Globigerina bulloides* assemblage within these levels at the two sites. Both lines of evidence suggest that the uppermost sapropels in Cores 1 and 2, of Site 376, are the Brunhes/Matuyama sapropels of Cita et al. (1973), and the biostratigraphic assignment to the *E. huxleyi* nannofossil zone in the Site Chapter of 376 is questioned.

Of the eight sapropels recovered from the Pleistocene sequence at Site 374 in the Messina Abyssal Plain, only the highest two from Sample 2-3, 123 cm (160 m subbottom) and Sample 3-1, 103 cm (210 m subbottom) contain the *Globigerina eggeri-Globigerina bulloides* assemblage, perhaps placing these layers also within the group of "Brunhes/Matuyama" sapropels.

The sapropels from the upper part of Core 5 of Site 376 and from Core 4 of 374 are older. From lithologic

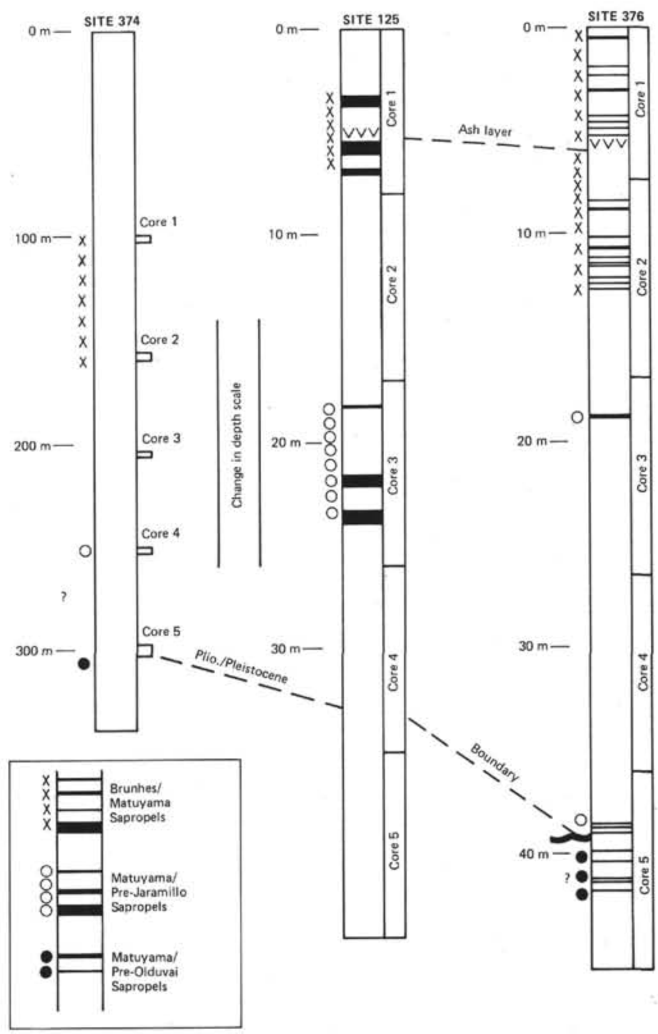

Figure 13. *Tentative correlations of Pleistocene sapropels, between Site 374 (Messina Abyssal Plain) and Sites 125 and 376 (Mediterranean Ridge).*

considerations of textures and colors of the intercalated nannofossil oozes along with bed thickness, this second and older group of sapropels has the greatest physical resemblance to the "Matuyama/pre-Jarmillo" sapropels of Site 125. However, a problem with this proposed correlation is that the Pliocene/Pleistocene biostratigraphic boundary has been identified in Core 5 at both Site 375 and Site 374, where it lies considerably below the sapropels of Core 3 at Site 125. Therefore, the sapropels in the lower part of Core 5 at Site 376 and in Core 5 of Site 374, might be even older and could belong to a "Matuyama/pre-Olduvai" group.

Pliocene

Late Pliocene

Late Pliocene sapropels were first discovered during Leg 13 of the Deep Sea Drilling Project in the crestal area of the Mediterranean Ridge (Site 125A, Core 2-2, approximately 42 m subbottom): they are from a stratigraphic interval referred to the *Globigerinoides obliquus extremus* Interval-Zone (now MPl-5 Zone of Cita, 1975), and to the *Discoaster surculus* Zone (NN 16).

Sapropels from the same biozone were recovered during Leg 42A in the Messina Abyssal Plain, in the Antalya Basin, and in the Cretan Basin.

We propose a correlation which places the jet-black sapropel found in Sample 5-3, 49-51 cm at Site 374 from about 300 meters subbottom as equivalent with the similarly black sapropel found in Sample 5-4, 105-111 cm, from about 45 meters subbottom at Site 376. In addition to having the same biostratigraphic position, these sapropels have the highest organic carbon content of the entire set of eastern Mediterranean sapropels discussed here: the former has a record value of 16.7% and the latter has a value in excess of 8%.

No sapropels were found from either the latest Pliocene (MPl-6 Zone), or from the earliest part of the late Pliocene (MPl-4 Zone) at Sites 374 and 376, although sapropels at this biostratigraphic position were recovered in the Cretan Basin at Site 378.

Early Pliocene

Sapropels of early Pliocene age were first recovered during Leg 42A. They are present in all three foraminifer zones recognized in this stratigraphic interval.

MPl-3 Zone: One sapropel occurs in this biozone at Site 374 (Core 8-3, approximately 360 m subbottom); no sapropels occurred in this biozone at Site 376 (condensed section with omission surfaces). Numerous sapropels were found at Site 378 (up to 15 in Core 3A, Zero Section to Section 6, and up to 10 in Core 11, Sections 1 to 4) all lie between 293 and 307 m subbottom.

MPl-1 Zone: Up to six sapropels occur in this biozone at Site 374 (Core 11, Sections 1 and 2 at approximately 380 m subbottom). Note that Core 11 is diagenetically altered by extensive dolomitization. One thick sapropel occurs at Site 376 (Core 6, Section 4). This biozone is not represented at Site 378.

Miocene

Late Miocene

Diatomaceous sediments rich in organic carbon encountered within the Messinian evaporitic sequence at Sites 374, 375, and 376 are, by definition, excluded from this account of sapropel stratigraphy. However, four thin sapropelic layers occur as a "multiple" in Core 8, Section 2, of the "hemipelagic" ("lago mare" facies) sequence at Site 376.

Fifteen sapropels and sapropelic layers of Tortonian age were recognized in the spot-cored hemipelagic sequence at Site 375; some of these were of the current-deposited type. Seven layers were analyzed for organic carbon content and five of these were designated sapropels (organic carbon ranges 2.18% to 4.31%). Two layers are rich in detrital minerals and contain only a minor biogenic contribution which shows strong evidence of redeposition (375-5-3, 21-23 cm and 375-6, CC). A third however, from 375-6, CC, is predominantly biogenic and framboidal pyrite is its only obvious mineral.

Middle Miocene

Serravallian sapropels, so far the oldest found beneath the Mediterranean deep sea floor, were identified at Site 375 on the Florence Rise. They occur in Cores 8 and 9, and to date all of those analyzed are sapropels containing from 2.8% to 5.06% organic carbon.

DISCUSSION

We consider, at this time, only the Pliocene to Quaternary eastern Mediterranean sapropel stratigraphy and its paleoenvironmental significance because our record becomes distinctly fragmentary even in sediments older than Pleistocene. The interval of time since the end of the Messinian "salinity crisis" is divided into four segments whose sediments were deposited under different conditions of ocean circulation as inferred from their sedimentary and fossil peculiarities. During three of these four intervals we believe that the eastern Mediterranean underwent periods of intermittent stagnation, whereas during the fourth interval it was permanently ventilated.

Late Pleistocene Interval

The "Brunhes sapropels" and "Brunhes/Matuyama sapropels" generally have the following features:

1) They are closely linked to climatic changes (climatically modulated). Many of them occur during global warming trends as deduced from analyses of the microfaunal assemblages and from the studies of the variation in $\delta^{18}/0$ of foraminifers from the Caribbean and Pacific Ocean (Cita et al., in press).

2) They occur in the Mediterranean at levels characterized by a significant lightening of the oxygen isotopic composition (up to 4.8°/₀₀) relative to the intervening periods of effective ventilation and/or enhanced precipitation.

3) They bear (although, not always) a euryhaline faunal assemblage dominated by *Globigerina eggeri* and *Globigerina bulloides* indicating the existence of an upper surface layer of seawater diluted by the run-off of melting glaciers.

4) They are distributed on both structurally elevated regions, such as the Mediterranean Ridge (DSDP Sites 125, 130, and 376), and in the deepest basins (Sites 127, 128, and 374); consequently, the "oxygen minimum" model (Arthur, 1976) cannot be applied. Some of the sapropels in piston cores were found in water depths as shallow as 700 meters (McCoy, 1974) along the upper continental slope.

The "Brunhes" and "Brunhes/Matuyama sapropels" accumulated during the "glacial Pleistocene" (sensu Selli, 1967; Cita el al., 1973) and corresponds to the well-known cyclical glacial expansions in the Alpine-Mediterranean area (Würm, Riss, Mindel, etc.).

Early Pleistocene and Late Pliocene Interval

The so-called "Matuyama/pre-Jaramillop" and "Matuyama/pre-Olduvai" sapropels are only known from the cores of Legs 13 and 42A. Their main characteristics are as follows:

1) They also are climatically modulated and occur during, or near warming trends as recognized in the population of planktonic foraminifers (Cita et al., 1973; Ciaranfi and Cita, 1973). The climatic fluctuations are distinct but not as large as in the "glacial Pleistocene." Warm peaks are recorded, but cold peaks are not comparable in magnitude to those recorded in the later part of the Pleistocene.

2) They do not yield specialized euryhaline assemblages, suggesting that no dilution of the superficial water masses occurred in times before the onset of the Alpine glaciations. If glacio-eustatic changes in the sea level occurred (as postulated by Cita and Ryan, 1973), they were controlled by the Arctic glaciation at high latitudes and did not cause a local dilution of the water masses.

3) They are very rich in organic carbon. The highest values ever recorded from sapropels of any age are to our knowledge from the late Pliocene (MPl-5 foraminifers zone).

4) They are present both on rises and in basins and the "oxygen minimum" model (Arthur, 1976) as is the case for the younger sapropels, cannot be applied to them.

5) High abundances of siliceous plankton occasionally occur in some of these sapropels, as in Cores 6 and 8 of Site 378 in the Cretan Basin.

Early Pliocene Interval

Sapropels of early Pliocene age (the Gilbert sapropels) are different from those previously discussed in several aspects:

1) They are not climatically modulated.

2) They are found only in basins and are absent on ridges.

3) Their content of organic carbon is consistently low (at the limit of the definition of a sapropel).

4) Stagnation is accompanied by a temporary destruction of the epifauna and infauna, as is indicated by the early Pliocene sapropels of Sites 374 and 376, but the benthic fauna is detected throughout the Plio-Quaternary section in the Cretan Basin, Site 378.

Mid-Pliocene Interval Without Sapropels

A time of relatively consistent ventilation without the formation of strata rich in organic carbon occurs throughout the eastern Mediterranean, except in the basins north of Crete, from the early/late Pliocene boundary (ca. 3.3 m.y.B.P.) to the extinction level of the genus *Sphaeroidinellopsis* (ca. 3.0 m.y.B.P.). This interval is entirely within the Gauss Epoch, where the biostratigraphic control is good and includes both the continuously cored sequences at Sites 125 and 376 and the spot-cored sequence at Site 374. Sapropels did, however, form at Site 378.

The Gauss Epoch coincides with the initiation of Northern Hemisphere Arctic glaciation (Laughton, Berggren, et al., 1972) as recorded in sediments of the northern Atlantic by the deposition of ice-rafted material directly on top of deep-sea sediments yielding subtropical faunal assemblages. A cool episode ("brown climatic eposide" of Ciaranfi and Cita, 1973) was recorded both in the eastern and in the western Mediterranean. This episode was correlated (Cita and Ryan, 1973) with the Aquatraversan erosional phase identified on the Tyrrhenian coast of central Italy (Ambrosetti and Bonadonna, 1967).

The maintenance of well-ventilated conditions throughout most of the Mediterranean during the Gauss Epoch, is attributed principally to the vigor that cooling brings to bottom-water generation and circulation.

Comments on the Causes and Durations of Stagnant Episodes

We believe the principal cause of stagnant conditions was the development of a marked density stratification which inhibited sinking of the surface water into deeper levels. This prevented the renewal of dissolved oxygen which was being consumed by the decay and utilization of organic matter. The density stratification may have been in the form of a strong temporary thermocline or simply a lower salinity surface-water layer floating on higher salinity intermediate and deep-water layers as was suggested by Olausson (1961). The development of stratification could have been caused by preferentially greater (and more rapid) heating of the surface-ocean layer than the deep water masses during an episode of regional (or global) climatic warming. In addition, stratification could have been initiated by an influx of fresh water to semi-isolated basins, either as excess rainfall (pluvials), glacial melting, or a combination of the two.

The duration of deposition of the individual sapropels in Mediterranean cores ranged from less than 1000 years to generally no longer than 10,000 years. Ten thousand years is about the time it would take to heat a 1000-meter-thick bottom-water layer by 3°C solely as a result of the geothermal flux through the ocean floor. Large amounts of additional heat would also be supplied by downward advection and conduction from the ocean surface layers. Hence, stratification would be a non-equilibrium transient situation that could only be maintained for long periods of time by a continuous applied perturbation (i.e., the steady inflow and outflow of less dense surface water such as occurs in the Black Sea).

SUMMARY

Of the 150 or more dark colored organic-carbon-rich layers recovered during Leg 42A, about two-thirds are sapropels as defined in this paper. The majority of these are pelagic but a significant number were probably current-deposited on the basis of analysis of their sedimentary structures, detrital mineralogy, and faunal content. These may represent brief incursions of turbidity currents into anaerobic basins analogous to those of the present Californian borderland (Berger and Soutar, 1970).

All the sapropels are fossiliferous, but their faunal diversities are usually lower than in the host sediments. Mesopelagic and epipelagic faunas are present but, as expected, benthic faunas are absent in most of the layers. Aberrant specimens of planktonic foraminifers and large concentrations of diatoms and coccoliths testify to conditions which were adverse to some species but were very favorable (presumably partly due to lack of predators or competition) to others.

We plan to further investigate whether burrow traces and the remains of benthic faunas found *within* some sapropels resulted from the activity of burrowers who recolonized the sediment surface after a period of stagnation or, whether a rich epifauna and infauna did, in fact, live on the sea floor during the time of stagnation. These burrow traces and faunas are characteristic of early Pliocene sapropels but occur throughout the Pliocene and Quaternary at Site 378 in the Cretan Basin. We may need to consider a different mechanism for sapropel formation during the early Pliocene, one which has more recent analogies in the sediment sequences in the basins north of Crete.

Whereas previous studies of piston cores have allowed the correlation of Quaternary sapropels over wide areas of the eastern Mediterranean, the drilling by *Glomar Challenger* on Legs 13 and 42A, although proving the existence of sapropels back to the middle Miocene, provides an incomplete pre-Quaternary record. Despite this, we are able to tentatively correlate the Pliocene and Quaternary sapropel sequences at three of the eastern Mediterranean sites (Figure 13). Such correlations confirm that periods of widespread stagnation took place at least as far back as the lowermost Pliocene, proving that their causes were not merely linked to glacial phenomena (Olausson, 1961). Also, the identification of sapropels in the Serravaillian, at one site (375) suggests that the events have occurred repeatedly over the past 11 million years or more. Furthermore, a sapropel was encountered in the Pleistocene of the Tyrrhenian Sea site (373A) which shows that such stagnation was not entirely confined to the eastern Mediterranean.

Sapropels, considered to be time-synchronous, are found to have been deposited in a wide range of water depths. Consequently, they could not have been formed by the presence of an "oxygen minimum" layer as a function of water depth.

We grouped the Pliocene and Pleistocene sapropels into three categories on the basis of time intervals. We infer that each type of sapropel was developed under different conditions of ocean circulation. Their salient features are summarized in Table 6.

We conclude that basin-wide stagnation within the Mediterranean results from density stratification of the water masses. This is a transient condition that has developed repeatedly since the middle Miocene when the Mediterranean took on its present form with only one outlet to the world ocean (Hsü et al., this volume), and is the result of a number of interacting factors. The main influence on ocean circulation in the late Pleistocene that caused stratification was the repeated Alpine Mediterranean glacial expansions. High latitude Arctic glacial expansions were possibly a prime cause of the early Pleistocene/late Pliocene density stratification. However we are presently unable to identify any outstanding factors which could have caused earlier periods of stratification.

TABLE 6
Salient Features of the Pliocene and Quaternary Mediterranean Sapropels

Time Interval	Distribution	Faunal Assemblages	Relationship to Climate Trends	Oceanic Circulation Influenced by
Late Pleistocene	Both on ridges and in basins	Euryhaline planktonic faunas; benthonic faunas absent	On warming trends; cold peaks distinct	Alpine-Mediterranean glacial expansions
Early Pleistocene/ late Pliocene	Both on ridges and in basins	Planktonic faunas not euryhaline; benthic faunas absent	On or near warming trends; cold peaks less distinct	Arctic high latitude glacial expansions?
Early Pliocene	In basins only	Planktonic faunas not euryhaline; Benthic epifaunas and infaunas may have survived	Not climatically modulated	?

ACKNOWLEDGMENTS

We thank Dr. Steve Calvert of the Institute of Oceanographic Sciences, Wormley, for his critical review of this contribution and for useful suggestions for improvements in the manuscript. Financial support for WBFR was provided by the Division of Ocean Sciences of the U.S. National Science Foundation Grant NSF-OCE-76-0237.

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