UPPER QUATERNARY CLIMATIC CYCLES AS EVIDENCED BY LITHOFACIES ASSOCIATIONS AND PLANKTONIC FORAMINIFERA CONTENTS OF SapropeL SEQUENCES IN THE OUTER PERIPHERY OF THE HELLENIC ARC

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ABSTRACT

The East Mediterranean Upper Quaternary sediments record persistent and time-repetitive periods of basin anoxia resulting in the deposition of organic rich sediments, the so-called sапропел. Cores retrieved from carefully selected structural highs on the outer periphery of the South Aegean Island Arc have revealed the presence of many (up to five) organic rich sequences contained within the uppermost three meters of Quaternary sediments. This represents the most extensive record of numerous stagnation layers which occur in minimal water depths of around 300 m. Moreover, short cores collected on the Gavdos shelf demonstrate a new uppermost limit for sапропел deposition in the Ionian and Levantine seas.

Planktonic foraminifera data suggest the following paleoclimatic scenario during the deposition of sапропел: a) the uppermost sапропел S5 was deposited during the warming trend from the last glacial to the present interglacial; b) the lower sапропел S4 also records a minor warming interval within the general cooling trend of the interglacial towards the last glacial period; c) S5 clearly records a very cold interval; d) the underlying sапропел S4 was deposited during a pronounced climatic warming; e) the lowest sапропел S3 was clearly deposited during the coldest interval recorded in this region.

Detailed sedimentological and micropaleontological analyses demonstrate that the cyclothemic developments associated with the sапропел lithofacies are correlative between cores over a wide region. This indicates a consistent and major change of environmental factors affecting the entire Eastern Mediterranean during the deposition of the uppermost five Quaternary sапропел sequences.

INTRODUCTION

Over the past dozen years or so, numerous publications have focused on the East Mediterranean Upper Quaternary organic rich layers, the so-called sапропеLs. Thus, the reader is directed to several recently published studies for details on fossil CITA et al., 1977; THUNEILL and LOHMAN, 1979; MULLINEAUX and LOHMANN, 1981; oxygen isotope strati-
graphy. EMILLIANI, 1955; VERGAUD-
GRAYZOTTI et al., 1977; THUNELL et al.,
1982; THUNELL et al., 1982). geochemistry
DOMINIK and MANGINI, 1979; CALVERT,
1983) and sedimentological aspects of sapropels
(ANASTASAKIS and STANLEY, 1980; 1986).
Despite the fact that sapropel was considered
by Bradley (1938) to have flowed from glacial
episodes during the deposition of Upper Qua-
terary Mediterranean sediments there is still
much controversy in regard to the causative
factors leading to the anomalous conditions. Most
workers link sapropel formation to episodes of
lowered surface water salinities and subsequent
stagnation of the deeper waters. Many attribute
the formation of this low-salinity surface layer
to fresh-water input from the Black Sea
(OLASON, 1961; RYAN, 1972; THUNELL
et al., 1977; VERGAUD-GRAYZOTTI et al.,
1977; STANLEY AND BLAOMP, 1981; BUCK-
LEY et al., 1982). More recently, it has been
proposed that excess fresh water from the River
Nile, coincident with extensive flooding of the
Nile and a warm humid "pluvial" in tropical Af-
rica, triggered stagnation (ROSSIGNOL-
STRICK et al., 1982; ROSSIGNOL-STRICK,
1983). However, ANASTASAKIS AND STAN-
LEY (1986) in a basin-wide investigation of
numerous cores suggested that the uppermost
sapropel S was deposited due to stagnation
resulting from the mixing of less saline waters
of variable origin (Nile, Black Sea and Atlantic
meltwaters flowing through the western Me-
diterranean). Moreover, no dominant freshwater
input triggering stagnation could be identified.
The aims and scientific targets of the Tyro 87/2
mission were to focus on the recovery of
undisturbed cores in the outer periphery of the
South Aegean Island Arc. Knowledge gained
from previous missions suggested that a more
condensed and complete stratigraphic record is
normally encountered on topographic highs
(ANASTASAKIS and STANLEY, 1986). It is
well established that in the East Mediterranean
cores recovered from regions dominated by
hemipelagic sedimentation (deposition of sedi-
ment by settling through the water column) are
likely to yield the most reproducible evidence for
the complete range of oceanographic con-
ditions affecting the hydrography of the basin
(ANASTASAKIS and STANLEY, 1986). The
Tyro 87/2 cruise was to focus on three (Fig. 1)
target areas: a) the strait between E. Kriti and
Kavos-Karpaz; b) the structural highs (Chrysi Ridge and Gavdos Ridge) south of Kriti; c) the strait between W. Kriti and Pelo-
ponnesos. Areas (a) and (c) are crucial, from the
paleoceanographic point of view, in that they
form the narrows through which the exchange
of water masses between the Aegean and East
Mediterranean takes place. Area (b) was se-
lected to permit comparisons with areas subject
to relatively stable conditions, unaffected by
drastic changes in circulation.

![Map of core locations](image)

**Fig. 1. Location map of cores T87-2-13, T87-2-20, T87-2-27 and the other cores discussed in the text.**

**MATERIALS AND METHODS**

During the Tyro 87/2 mission a total of 24 piston and gravity cores were retrieved from the outer periphery of the South Aegean Island Arc. In order to verify lithostratigraphic de-
velopment at least two cores were retrieved from
each station. The cores were split and then
X-radiographed. Core logs were constructed to
record the Bathysciics associations. A dense
sampling network was established along the
cores for a detailed sedimentological and micro-
faunal analysis. Results from three cores,
representative of the three regions studied in
detail, are reported here (Fig. 2). Some 200
samples from three cores (Fig. 2) have been
studied for their planktonic foraminiferal content
in the size fraction 150 to 255 µ. Carbonate
concentrations were analyzed by a volumetric
method (MULLENK and GASTNER, 1971) while organic
carbon contents were determined with a LECO
combustion system.
RESULTS

Core C3 was recovered from the east margin of Kriti at a water depth of 306 m (Fig. 1). This core consists of repetitions of successive organic rich lithofacies. Each of the sapropel (organic carbon >2%) and/or sapropelic (organic carbon from 0.5% to 2%) lithofacies forms the central unit of a sequence (ANASTASAKIS and STANLEY, 1984).

The uppermost sapropelic lithofacies (S, in core C3, Fig. 2), consists of a greyish olive mud (SY 5/2) with organic carbon contents around 1% (Table 1). Carbonate contents are lower in the sapropelic layer and increase significantly below it. This organic-rich sequence is separated from the underlying sapropelic layer $S_2$ (Fig. 2) by a silty sand interbedded within a sandy silt unit. The silty sand and sandy silt contain gastropod and bivalve tests, indicative of a shallower water environment. The sapropelic layer $S_2$ (Fig. 2) is composed of an olive gray (10Y 5/2) mud with organic carbon...
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<tr>
<th>Core No and sample depth in cms</th>
<th>Organic C%</th>
<th>S%</th>
<th>Carbohydrates %</th>
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TABLE I

contents ranging between 1 and 2% (Table I). Nearby (about 18 cm lower than S↓3) another sapropel sequence is developed (Fig. 2). This S↓3 organic rich lithofacies displays a similar organic carbon content to the S↓3 layer, ranging between 1 and 2%. Carbonate contents are slightly reduced in the S↓3 and S↓4 layers. Below the S↓4 another sapropel layer (over 60 cm thick) is developed (S↓5 in Fig. 2). Colours in the organic rich lithofacies range from a greyish olive (S↓3 5/2) at the base to olive black (10V 3/1) in the upper part. Organic carbon contents range between 1 and 2% in the greyish olive basal part; reach values of up to 11% in the olive black central part of the layer and fall to 2% in the uppermost part of this lithofacies. Especially in the upper part of this layer extensive oxidized gas-escape structures are present while carbonate contents show an increase in the trend to the organic carbon contents (Fig. 2). The reduced carbonate contents are matched by a concomitant increase in the siliciclastic biogenic components such as diatoms. The organic ooze and gray mud, which usually underlies the organic rich lithofacies (A nathan- sakis and Stanley, 1984), is represented by a gray (7.5Y 7/2) sandy silt unit with organic carbon contents ranging between 0.3-0.5%.

Core 20 was retrieved from the west-south-west margin of Anakynthos Island at a water depth of 607 m (Fig. 1). The lithofacies associations of the uppermost sapropel sequence is of the gray mud-organic ooze-sapropel-oxidized layer type. The organic rich lithofacies as an olive black colour (7.5Y 3/2) and organic carbon contents range between 2.5 and

by an organic ooze and gray mud lithofacies association. At about 140 cm below this organic-rich lithofacies a similar sapropel layer of olive gray mud (10Y 5/2) with organic carbon content around 3%, is developed (S↓3 in Fig. 2). This is also underlain by an organic ooze and gray mud association. The mud intervening between S↓3 and S↓4 is fine grained and was deposited in a tranquil environment, with some bioturbation. Further down sequence there is a thin sapropel layer of olive grey mud (10Y 5/2) with organic carbon content around 2%, which in turn is underlain by an organic ooze and gray mud S↓4 in Fig. 2). This sequence passes down into another thick sapropel sequence S↓5 in Fig. 2). The sapropel lithofacies consists of more than 30 cm of olive black (5Y 2/2) sediment, with organic carbon contents reaching their maximum of 14.5% in the middle part of the layer, while the upper and lower parts of this unit display organic carbon contents of around 6.5% (Fig. 2). Carbonate contents within this sapropel show a reverse relationship to the organic carbon layer. This character is attributed to an absence of siliciclastic tests such as diatoms. The upper part of this lithofacies contains gas-escape oxidized structures.
3.2% Carbonate contents are drastically reduced within the organic-rich lithofacies. About 1.5 m further down in this core there is another sapropel sequence displaying upward a gray mud-organic ooze-sapropel-organic ooze lithofacies association. The sapropel lithofacies (S, in core 2, Fig. 2) has a grayish olive color (5Y 5/2) and organic carbon contents range between 2.5 and 3%. Below this sequence a peculiar isolated organic ooze lithofacies of light gray (5Y 7/1) colour is present, which displays somewhat enhanced organic carbon levels (around 0.4%). This is underlain by a well developed sapropel sequence (S) displaying a gray mud-organic ooze-sapropel-organic ooze lithofacies association. The sapropel lithofacies is grayish olive (5Y 4/2) in colour at the base becoming olive black (5Y 3/2) in the middle, and passing up into a grayish olive (5Y 5/2) chromatic variation at the top of this layer. Organic carbon contents relate well to the observed colour changes in this layer and range from around 5% at the base, up to 15-15.5% in the middle and 2.5% at the top of the sapropel lithofacies. Carbonate contents generally are reduced within the organic-rich lithofacies and this layer is also characterised by enhanced siliceous test contents. At the bottom of this core traces of another sapropel sequence have been recovered below the S.

Two other short cores (GYR-15 and TYY-16, Fig. 1 and Table 1) retrieved on the east Gudov shelf at water depths around 230 m are significant because they recovered the uppermost sapropelic sequence at water depths shallower than any previously established water depths (ANASTASAKIS and STANLEY, 1986). The organic carbon contents of the sapropelic layer in both these cores are around 0.9% (Table 1).

MICROPALEONTOLOGY AND CORRELATION OF THE SAPROPEL SEQUENCE

Some 200 samples from 3 gravity cores (Fig. 2) have been studied for their planktonic foraminiferal contents in the size fraction 150 to 525 μ. A marked difference exists between the uppermost sapropel S, which is nearly devoid of Neogloboquadrinids, and the other sapropels which generally contain high abundances of this group. At times of deposition of the other sapropels recovered in the cores shown in Fig. 2, Neogloboquadrinids were highly abundant, indicating favourable growth conditions. On the contrary sapropel sediments are characterised by the near absence of benthic foraminifera, especially in the lowermost organic-rich sapropel lithofacies. Altogether, 16 species have been quantified, among which G. ruber, G. sphenodera, G. trilobatus, G. rubescens, O. unversa, G. digitata, G. troхотus and H. pelagica are considered to be warm water species (THUNELL, 1979; THUNELL et al., 1977; THUNELL and WILLIAMS, 1983; TOLDERLUND and BE, 1971). The cumulative percentages of these warm water species are plotted per total planktonic foraminifera minus G. batavus and neogloboquadrinids (whose frequency distributions are primarily controlled by a nutritional setting). The resultant plots are considered to approximate sea surface temperature changes through time, and are correlated with a Mediterranean reference oxygen isotope record (VERGNAUD-GRAZIINI et al., 1977; VERGNAUD-GRAZIINI, 1965) to assess the chronology of the sapropel sequence (Fig. 2).

The uppermost sapropel in all three cores can be identified as S, which has been deposited in early Holocene time. The three older sapropels are also associated with interglacial conditions, and are correlated with the three sapropels underlying the S layer in the reference core CMA-181 (Fig. 3). S seems to be deposited in a relatively cold interval within the isotopic stage-5 interglacial according to the present generally accepted correlation scheme (Fig. 3). This emphasises that sapropel formation may occur during both warm and cool/cold periods, as exemplified especially by Sb which developed in fully glacial conditions (e.g., CITA et al., 1977; MUEJDDER and KENNEDY, 1984; THUNELL et al., 1983; 1984; VERGNAUD- GRAZIINI, 1983).

DISCUSSION

The first to propose an East Mediterranean basin wide stratigraphy for the Upper Quaternary sapropel was Ryan (1972). This basin wide correlation was based on the assumption that the deposition of the organic-rich lito-
Fig. 3. Plots of the cumulative frequencies of *G. ruber*, *G. sipholina*, *G. tenera*, *G. rubescens*, *O. universa*, *G. digitata*, *G. tribula* and *H. pelagica* versus *G. antiqua*, *G. scitula*, *G. inflata*, *G. truncatofusca*, *G. phaeostigma* and *G. antennata* for cores T87/2/130, T87/2/270 and T87/2/205. These plots are considered to approximate the surface water temperature (though time). They are compared with the oxygen isotope profile of *G. ruber* in core RC9-181 (modified after Verburg-Grassini, 1985) for assessing the chronology of the sapropel sequence. Dots = sapropel, Hatch = sapropelic.

Facies (the sapropels) is climatically controlled throughout the basin and not dependent on local conditions. This is the principal reason for considering sapropel layers should be time-synchronous and correlateable throughout the entire East Mediterranean Sea. The correlations with the generalized paleotemperature curve (EMILIANI, 1955) proposed by this author are on the whole still valid but with a few modifications in the correlation schemes (CITA et al., 1977; ROSSIGNOL-STRICK et al., 1983; VERGNAUD-GRAZZINI, 1985). The correlation of sapropels in the Mediterranean with climatic cycles (STANLEY and MALDONADO, 1979) was significantly advanced by ROSSIGNOL-STRICK (1983) who related the sapropels to orbital insolation monsoon index over Africa (ROSSIGNOL-STRICK, 1983). The orbital variation-stagnation association followed the original idea suggested by HAYS et al. (1976),
that variations in the pattern of incoming solar radiation, with a succession of Pleistocene ice ages and thus represented the major mechanism for changing global climate on fine scales between 10,000 and 100,000 years. The correlation between the ‘orbital tuning’ and the Quaternary palaeocli- mate worldwide, as evidenced by stacked oxygen-isotope stratigraphy, is nowadays well established and accepted (PETRAS et al., 1984; MARTINSON et al., 1987). However the connection of the orbital variation with the East Mediterranean stagnation layers clearly requires much more information regarding the timing, spatial distribution, correlation and composition of sapropel layers across the entire basin. This is related to the fact that sediment reworking due to the contemporaneous tectonics in the East Mediterranean results in numerous discontinuities, repetitions and modifications of the original sediment deposited by suspension set- ting processes (ANASTASAKIS and STAN- LLEY, 1984). Thus the oxygen isotopic record that is important, stratigraphically, on a long time scale, suffers from significant shortcomings for fine scale work in the East Mediterranean (VIRGNIAT and GRAZZINI, 1985). This point is amply demonstrated by the differences observed in the morphology of isotopic curves in some stages, such as numbers 2 and 5 (Fig. 3). The most reasonable explanation for such differences is that they record the combined effects of temperature, evaporation, freshwater runoff, and meltwater on the ice volume signal in planktonic foraminifers plus the reworking-induced effects on the isotopic signal.

The correlation of the sapropel sequences recovered in the three cores discussed here in detail (Fig. 2) is based on both sedimentologi- cal-compositional criteria as well as micro- paleontological data (Fig. 3). The total faunal analysis utilised in this study (Fig. 3) uses an a priori knowledge of the temperature preferen- ces of all species to compare warm and cool water assemblages, in order to establish the palaeoclimatic framework during each sapropel horizon. The uppermost sapropel (S3 in Fig. 2) in all cores has been deposited with a warming trend from the last glacial to the present interglacial. Organic carbon contents in this lithofacies never exceed the 3.2% which falls well within the East Mediterranean basin- wide limits established by ANASTASAKIS and STANLLEY (1984). The uppermost sapropelile lithofacies (Table 1) in cores retrieved from water depths of around 230 m on the Gavdos shelf (Fig. 2) establishes a new superposed bathymetric limit for S3 deposition in water depths of less than 230 m in the Levantine and Ionian Seas. The shallowest of the studied cores (Core 13 in Fig. 2), containing the appropriate stratigraphic interval, clearly records in its lithological and textural parame- ters the maximum fall of sea level during the last glacial regression at around 18,000 yrs BP (BERGER et al., 1985). This regression-trans- gression cycle is texturally recorded in the sandy silt-silty sand-sandy silt association of core 13 (Fig. 2). The fact that this interval is faunistically not as cold as in cores 27 and 20 (Fig. 3) is clearly due to the incorporation of reworked elements from the nearby east Cretn shelf during the maximum sea level drop of approximately 120 m (VAN ANDEL and LIANOS, 1984). The lower sapropel S2 (Fig. 3) records also a warming interval within the general cooling trend of the interglacial towards the last glacial. The smoothening of this signal in core 13 is probably due to bioturbation. The uppermost carbon contents range between 1.3-3.2% (Fig. 2 and Table 1) and are similar to those in S3. The next lower sapropel S3 (Fig. 3) clearly records a very cold interval which is well expressed in all three cores. Organic carbon contents in this organic-rich lithofacies vary between 1 and 2.2% and are comparable to those in S2. It is important to note that this S3 layer is stratigraphically represented by an organic ooze in core 27 (Fig. 2) which, however, records the same faunistically-climatic signal as the S2 sequence in the other two cores (Fig. 3). The lowest sapropel S3 was deposited during a phase of pronounced climatic warming (Fig. 3). This lithofacies is characterised by the highest organic carbon contents, up to 15.5%. This is also the only sapropel lithofacies in which very high abundances of siliceous tests (mostly diatoms) are noted. Carbonate contents clearly show an inverse relationship to the organic carbon and diatom contents, indicating that during the deposition of this organic lithofacies there was a dramatic palaeoclimato- graphic change marked by a pronounced in- crease in the productivity. This is amply
demonstrated by a special opal assemblages study of cores recovered in deeper waters south of Crete (SCHRADER and MATHIERE, 1981). The faunal data on the organic ozeo lithofacies underlying the S1 (core TYR-13 and TYR-27 in Figs. 2 and 3) indicate that a strong cooling trend prevailed during the deposition of the S1 sapropel sequence. The fact that in core TYR-13 this ozeo is represented by a coarse sandy silt layer suggests that during the deposi-
tion of this unit there was a dramatic increase in the course silt supply of the region due to a marked pleistocene phase enhancing the sediment load of the east Crete drainage system.

The stratigraphic continuity and correlation scheme of the cores presented in this study coincides well with the stratigraphy and the deduced climatic variations of cores recovered from deeper regions south of Crete (THUNELL et al., 1977; WILLIAMS and THUNELL, 1979). The correlation of the sapropel(s)-rich sequences in cores recovered from the outer periphery of the Aegean Sea, the northwest Levantine Sea and the middle west Ionian Sea clearly demonstrates that stagnant phases are basin-wide phenomena.

This furthermore indicates a consistent and major change of environmental factors affecting the entire East Mediterranean during the dep-
osition of the organic-rich layers and contra-
dicts views (MANGINI and DOMINIK, 1982) that stagnation events were not basin wide phenomena. Missing sapropel lithofacies in most cases are the result of removal by erosion and reposition (ANASTASAKIS and STANLEY, 1984). With low energy repositioning processes it is possible indeed to remove a section of fine grained sediment without leaving any obvious structural sedimentological evidence (i.e. ob-
vious laminations) at the affected site. This is amply demonstrated by the missing sapropel S1 in core 27 where the organic-rich lithofacies is not present and the entire organic-rich sequence is represented only by an organic core. Although early diagenetic alteration (such as a downward progressing oxidation front, which migrates slowly in organic-rich sediments, re-
sulting in a sharp redox front and pronounced colour change) is possible and there is no obvious indication for such a process in core 27. The time-equivalent horizon to the S1 organic core layer displays not the slightest chromatic hue variation, indicative of such a process and the macrofaunocology has not the resulting power to identify such a small stratigraphic hiatus. However planktonic for-
minal data indicate the general climatic trend which may be correlated with time-equi-
ivalent layers in other cores (Fig. 3).
REFERENCES


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