Holocene sedimentation and palaeogeographic reconstruction of the inner Thermaikos Plateau, N.W. Aegean sea (Greece)

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Abstract. A detailed 3.5 kHz profiling survey from the Inner Thermaikos Plateau, located in the NW Aegean Sea, revealed Holocene deltaic sedimentary sequences. These sequences consist of four seismic facies: a) stratified (i.e., foresets of late Holocene); b) transparent (bottom sets); c) reflector C (representing the beginning of the Holocene); and d) reflector D (a pre-Holocene erosional surface). The mean sedimentation rates range from 0.05 to 2.5 m/1000 yrs, while the maximum sedimentation rates (94 mm/yr) are observed in the modern foreset beds of the river Axios. Radiocarbon analyses of corals from shallow marine sediments indicate that there was a transgression of the Inner Thermaikos Plateau around 12.000 yrs B.P.

1. Introduction

The Inner Thermaikos Plateau is located on the inner continental shelf of the N.W. Aegean Sea, extending from the Greek mainland (22° 35' E) to the Chalkidiki Peninsula (23° 00' E), and from 40° 40' N to about 40° 20' N at its southern edge (Fig.1). The southern limit of the study area, between the capes of Kitros and Epanomi, is the transitional area between the inner and outer plateau. Here the inner plateau reaches a maximum depth of about 45 m.

The sedimentology and mineralogy of the area has been investigated by Chronis and Tziavos (1978), Conispoliatis (1979) and Chronis (1986). Large river systems discharge into the area, supplying large quantities of freshwater and fine-grained terrigenous material. The rivers Axios and Aliakmon, with mean annual discharges of 5.031 x 10^3 m^3 and 2.529 x 10^3 m^3 (Therianos, 1974), respectively, are the most important rivers in the area. The complete drainage system which surrounds the Inner Thermaikos plateau (including all the major and minor rivers and

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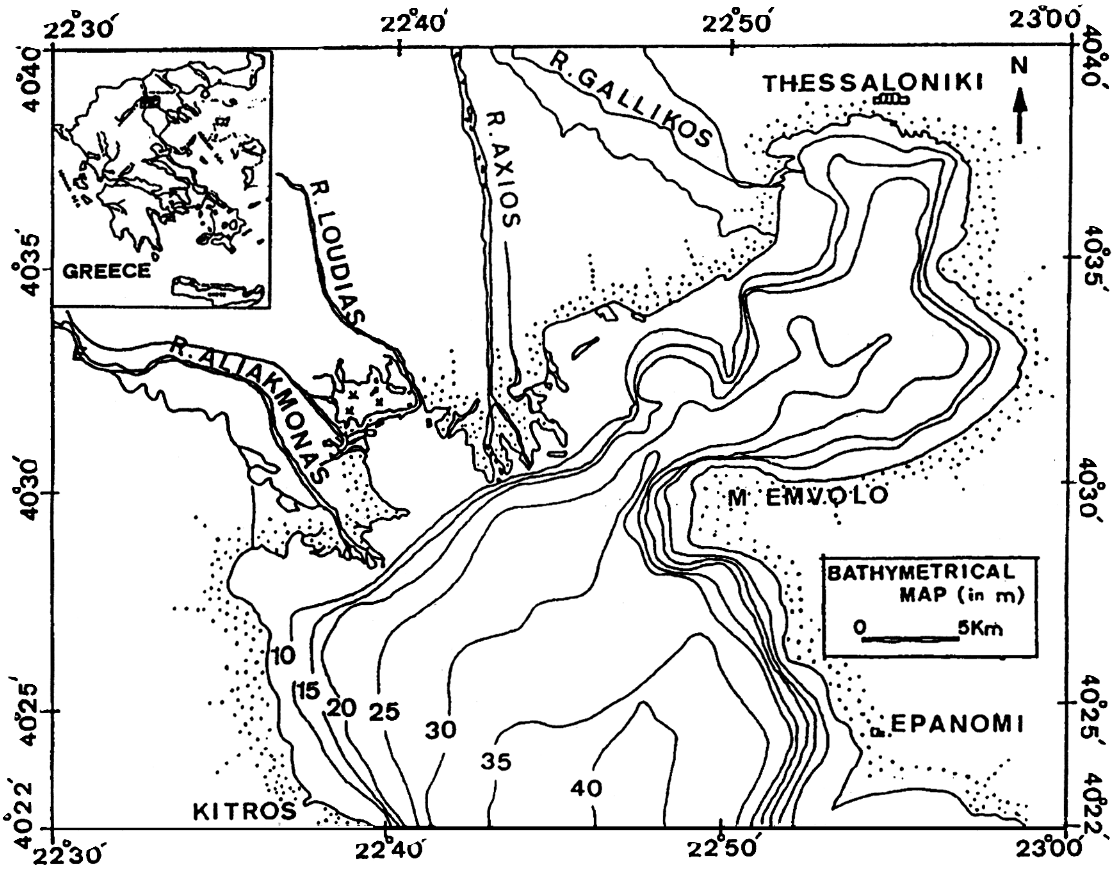

Fig. 1 - Location and bathymetric map (in m) of the Inner Thermaikos Plateau.

ephemeral inputs) has an area of about 29,000 km^2.

Rainfall over the study area is about 800 mm/yr (Karapiperis, 1974). The geology of the surrounding landmass is dominated by Quaternary-Neogene sedimentary rocks, mainly marls, sands, sandstones, and limestones (I.G.M.E., 1983). There is a well defined anti-clockwise water circulation pattern over the entire area (Balopoulos, 1982). Tides are small, with spring and neap ranges of 30 cm and 5 cm, respectively.

This presentation examines the Holocene sediment sequences; the factors which affect the sedimentation over this period; and lastly, evolution of the sedimentation pattern during the Holocene.

2. Methods and materials

Sampling was carried out from boat trawlers. Position fixing was done using a radiopositioning system (Motorola, Mini-Ranger). Shallow seismic profiling lines of about 180 km were obtained (Fig. 2) using an O.R.E 3.5 kHz system. Piston coring sites were selected following

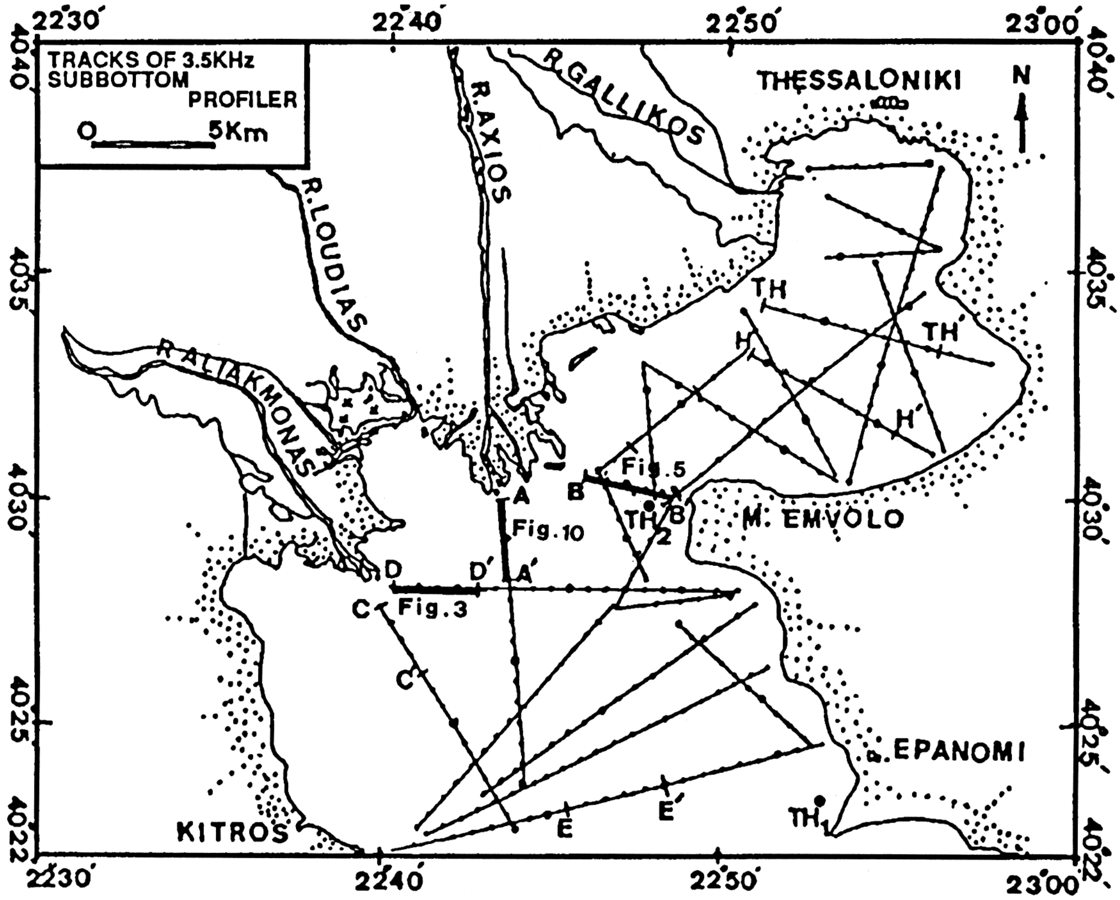

Fig. 2 - 3.5 kHz sub-bottom profiling tracks and sampling sites in the Inner Thermaikos Gulf.

analysis of the 3.5 kHz profiles (Fig. 2). Grain-size analyses were carried out by seive and pipette (Folk, 1974). Moreover, microfaunal assemblages were etermined using a binocular microscope, and representative species were photographed with a scanning electron microscope. Radiocarbon analyses were carried out in the BETA ANALYTIC LAB. (Mass, USA).

3. Results

3.1. Seismic profiles

The seismic facies recognized on the 3.5 kHz profiles can be interpreted from the distribution of surficial sediments in the Inner Thermaikos Plateau (Chronis, 1986), and by comparison with similar data from other Mediterranean deltas (Got et al., 1985; Aloisi, 1986; Chronis et al., 1991).

The acoustic character of the deltaic sequence, corresponding to four main seismic elements,

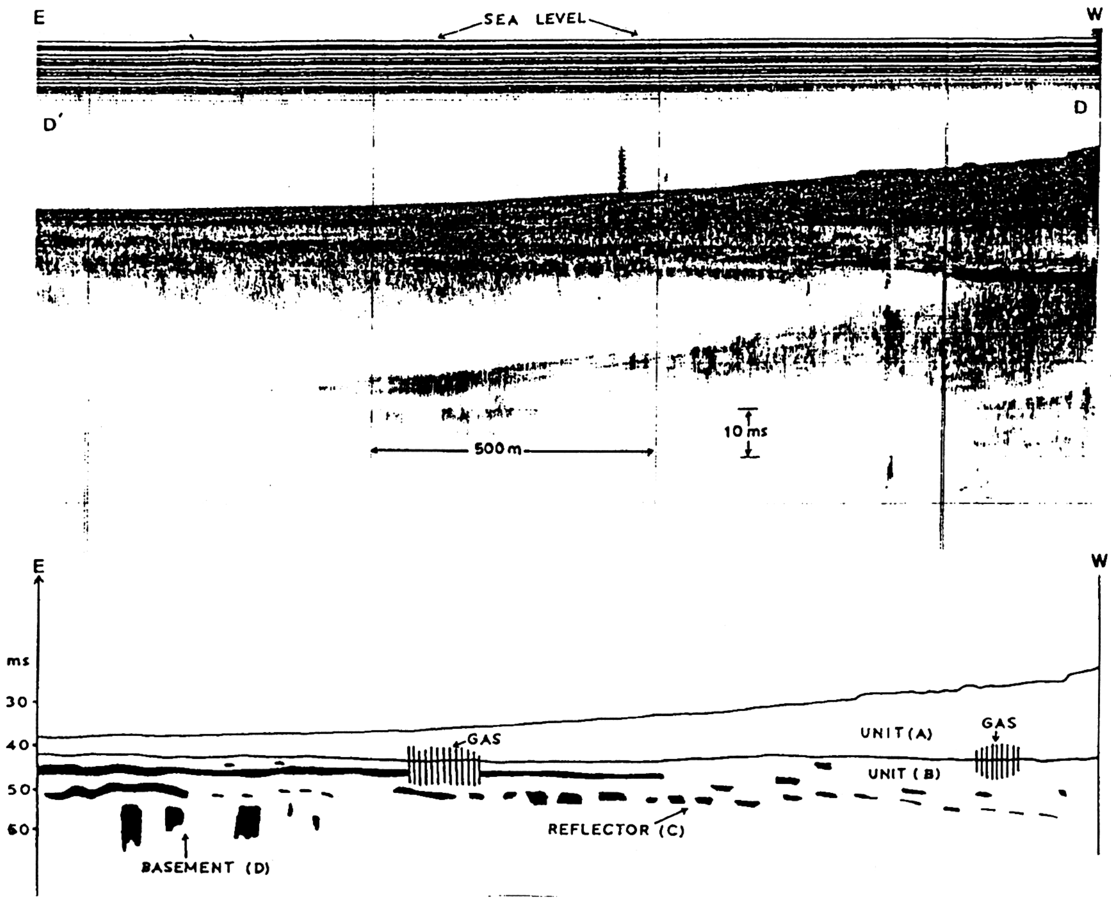

Fig. 3 - Representative 3.5 kHz profile, from the prodelta area of the Aliakmon River.

has been recognized (Fig. 3); these elements extend from the seafloor to a maximum sub-bottom depth of 30 ms, equal to about 25 m, and are described below.

a) Seismic Unit A. This consists of stratified seismic facies, with continuous high-amplitude reflections and a prograding architecture (Fig. 3). It usually appears in profiles relatively close to the river mouths, representing the prograding phase of the delta (foreset beds). Acoustically similar units from the outer Thermaikos Plateau (Lykousis and Chronis, 1989), the western Mediterranean (Aloisi, 1986) and the Gulf of Mexico (Stuart and Gaughey, 1977) consist of muddy sediments with silt and sand laminae. Generally, this acoustic unit is representative of delta front and prodeltaic sedimentation. The deposition mechanism here is characterised by flocculation, superimposed on gravitational processes.

b) Seismic Unit B. This corresponds to an area associated with seismic profiles either free of reflectors or having generally only a few weak reflectors; it is referred to as the transparent facies. This facies occurs below and seawards of the stratified facies, and generally consists of muddy or silty sediments. The sediments in this unit suggest a low energy deposition environment, representing the bottom sets of river delta systems; which discharged further north, during the early Holocene. “Step-like” acoustic masking by gas, extends up into units A and B in the

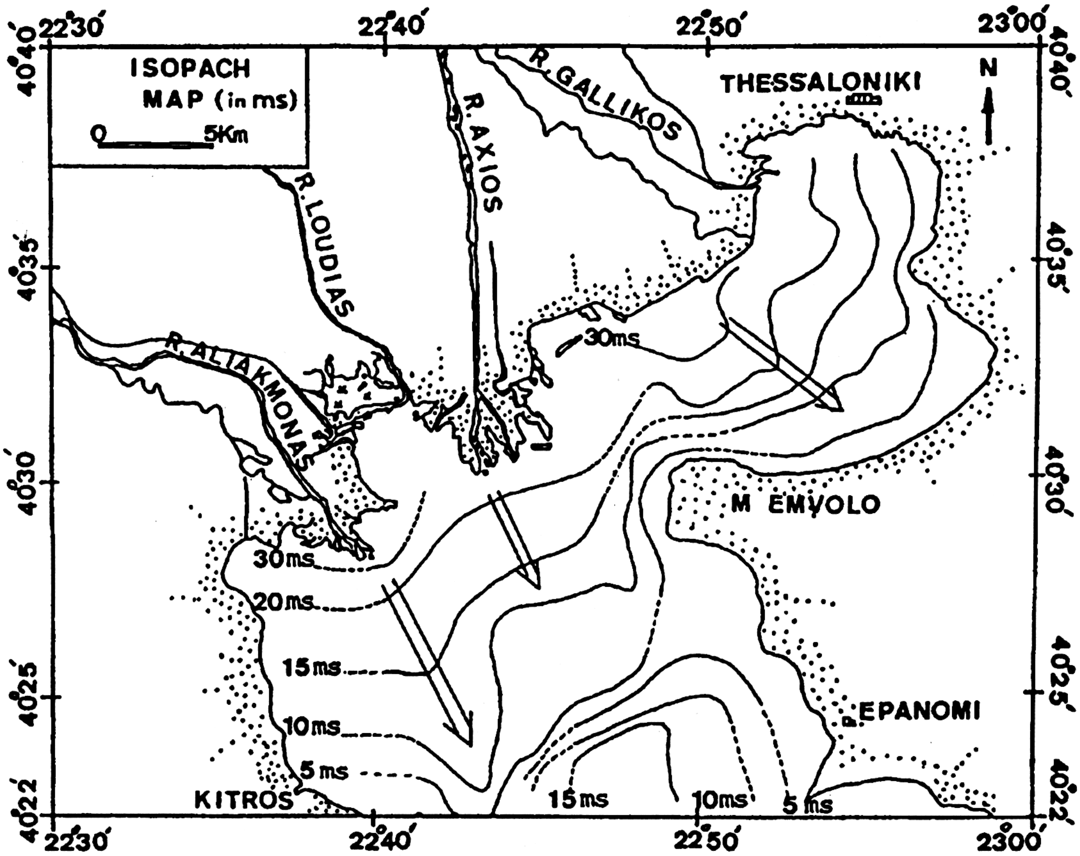

Fig. 4 - Thickness (in ms) of the Holocene sediment sequences over the Inner Thermaikos Plateau.

shallow water delta of the Axios and Aliakmon rivers (Figs. 3 and 5). Gas extends commonly through prodelta sediments (Got et al., 1985; Chronis et al., 1991); and is probably caused by decomposition of organic-rich deposits (Chassefiere et al., 1970; Aloisi et al., 1975).

c) Acoustic basement D. This basement appears, in the profiles from the Inner Thermaikos Plateau, as an irregular erosional surface over which the seismic units A and B lie unconformably. The acoustic basement represents the pre-Holocene substrate and was probably a subaerial surface, before the Holocene transgression took place.

d) Reflector C. This low amplitude relatively strong reflector was found between the acoustic basement (D) and the transparent facies (B). A unit similar to reflector C is well known from other Mediterranean deltas (Aloisi et al., 1975); it has been correlated to a coarse grained stratigraphic unit which indicates the beginning of the Holocene sedimentation.

The whole configuration of these four seismic elements and ultimately, the delta configuration, is a characteristic sigmoid-oblique to slightly sigmoid-oblique progradation patterns (Mitcham et al., 1977). Since reflector C is widespread over the Inner Thermaikos Plateau, it can be concluded that the whole Plateau is covered by Holocene prograding prodelta sediments (mainly foresets and bottomsets). Neotectonic activity during the Holocene has not affected

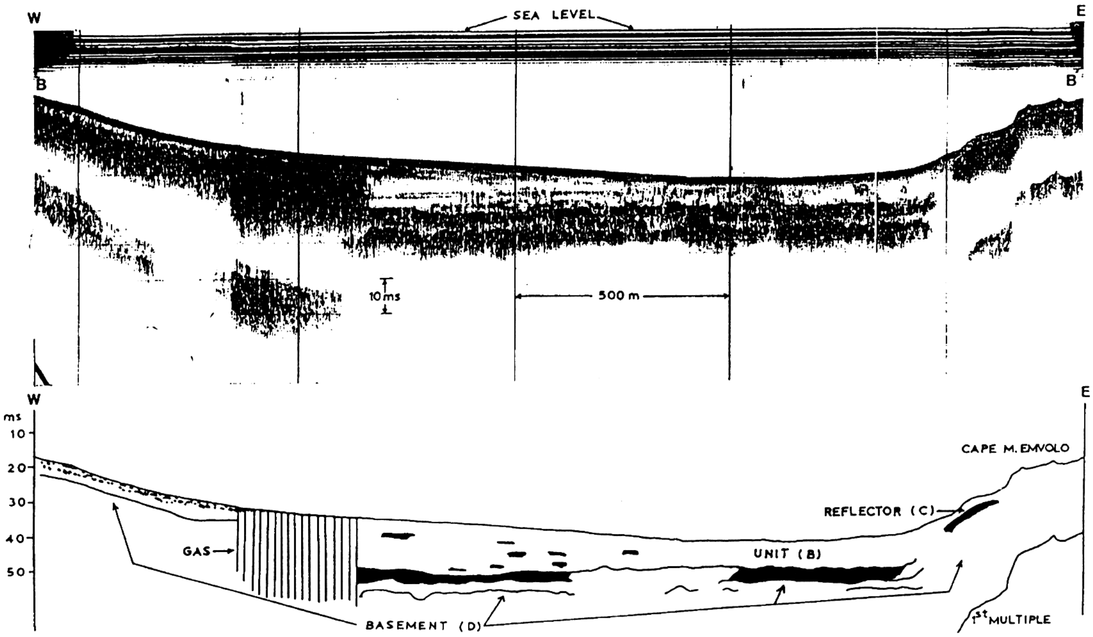

Fig. 5 - Characteristic 3.5 kHz profile from the prodelta of the Axios River, towards Mt. Emvolo.

these seismic-statigraphic units, implying only an indirect interrelationship between Holocene tectonism and sedimentation.

3.2. Holocene sedimentation

The Inner Thermaikos Plateau is covered mainly by prograding Holocene delta sequences, which are up to 25 m thick in areas close to the river mouths, but decreasing in thickness rapidly towards the E and SSE, to a minimum of about 1 m (Fig. 4). These sediment sequences are not affected by neotectonic activity (see above), so any relationship between tectonism and sedimentation is somewhat indirect.

The basic unit of Holocene sedimentation consists of a sedimentary prism, built up during each major change in sea-level stand; it comprises sand and silt in the near shore areas, evolving seawards into muds. The sizes and thicknesses of the Holocene deposits are comparable to those on the various continental shelves of the western and eastern Mediterranean (Aloisi, 1986; Chronis et al., 1991).

There is also a relationship between the prismatic configuration of the Holocene deposits and the actual multilayer system of vertical suspended matter distribution in the water column (Chronis et al., 1989), over the Inner Thermaikos Plateau. This close correlation between the sedimentary prism and the geometry of the nepheloid layer provides information on the sedimentation mechanisms.

The decreasing thickness of the prodeltaic prismatic lobe from west to east, as well as the

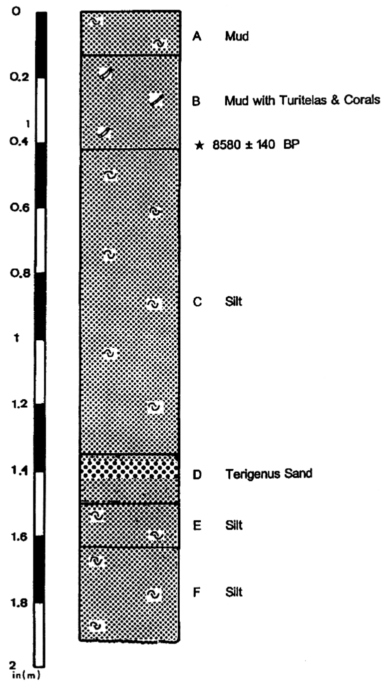

Fig. 6 - Description and radiocarbon dating of core TH-1.

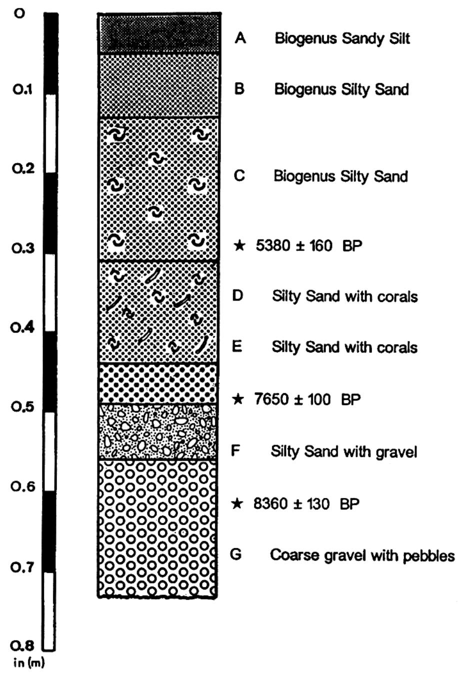

Fig. 7 - Description and radiocarbon dating of core TH-2.

outflow area of the rivers Axios and Aliakmon being towards the outer part of the gulf (south), are in accordance with a decrease in suspended sediment within the near-bed nepheloid layer in the same direction (Chronis et al., 1989). This implies uniform sedimentation during the late Holocene, with similar deposition mechanisms as at present.

3.3. Cores and radiocarbon dating

The thickness of the Units A and B and reflector C, representing Holocene sediment cover over the Inner Thermaikos Plateau, ranges from 5 ms to over 30 ms (Fig. 4). In order to estimate the mean sedimentation rates and the palaeogeographic evolution during the Holocene, by the dating of reflector C, two sediment cores, TH-1 and TH-2, were collected. The cores were taken from the bottom of the eastern part of the Inner Plateau, where reflector C is covered by a thin veneer of fine grained sediments (Fig. 2 and Fig. 5).

Core TH-1, collected at a water depth of 37 m, penetrated 192 cm of mud to silty sand sediment layers. The upper 40 cm of the core (Fig. 6, Section A and B) consists of mud, with minor amounts (<10%) of biogenic sand that consists of mollusc fragments, assemblages of benthonic Foraminifera (dominated by *Elphidium macellum, Ammonia beccarii, Quiqueloculina sp., Rosalina sp. etc.) and Ostracods (Cytheridea neapolitana, Costa edwardsii, Carinicythereis sp.* Loxoconcha agilis, L. rhomboidea, Hiltermanicythere sp. etc.) (Table 1). In section B, the gasteropod *Turitella, Crinoids* and corals *(Cladocor)* appeared for the first time. The benthic fauna

Table 1 - Microfaunal distribution in the cores.

		TH-1					TH-2						
		Depth in cm					Depht in cm						
	Species	0-12	13-40	45-50	73-80	123-130	0-5	5-13	13-25	35-44	44-49	49-56	56-73
FORAMINIFERA	*Amonia becarii*	A	C	-	C	-	AA	A	C	A	A	C	C
	Elphidium maccelum	A	A	R	A	-	AA	A	A	A	A	A	-
	E. edvena	-	-	-	-	-	-	R	R	C	C	A	R
	E. sp	-	R	R	-	-	R	-	C	C	C	A	-
	Quinqueloculina seminulum	A	-	-	-	-	C	-	-	-	R	-	-
	Q. crassa	-	-	-	-	-	C	C	-	-	-	A	-
	Q. costata	-	-	-	-	-	-	-	-	-	C	C	-
	Q. irregularis	-	-	C	-	-	-	-	A	-	A	C	-
	Q. oblonga	-	-	R	R	-	-	-	-	-	-	-	-
	Q. pulchella	-	-	C	-	-	-	-	-	-	-	-	-
	Q. ssp	-	C	A	R	-	A	A	A	A	A	C	-
	Textularia cronica	R	R	C	-	-	-	R	C	A	A	C	C
	Rosalina sp.	-	C	-	-	-	C	C	-	-	C	-	-
	Trioculina trigonula	-	-	A	R	-	C	C	A	A	A	A	-
	Spiroloculina excavata	-	-	-	-	-	C	R	-	-	R	-	-
	S. sp.	-	R	-	-	-	-	-	-	R	C	R	-
	Cibicides sp.	R	-	-	R	-	C	C	C	-	-	-	-
	Massilina sp.	-	-	-	-	-	-	R	R	R	-	-	-
OSTRACODA	*Ciprideis torosa*	-	-	-	-	C	-	-	-	-	-	-	-
	Loxoconcha rhomboidea	R	C	A	R	-	C	A	C	A	AA	A	-
	L. agilis	C	-	-	C	-	C	-	-	-	-	-	-
	Hitermanicythere sp.	C	R	-	-	-	R	-	-	-	-	-	-
	Cytheridea neapolitana	A	C	R	R	-	C	-	-	-	-	-	-
	Pterigocythereis jonesi	R	-	-	R	-	-	-	-	-	-	-	-
	Costa edwardsii	C	R	-	-	-	-	-	-	-	-	-	-
	Carinocythereis carinata	C	C	R	C	-	R	-	-	-	-	-	-
	Propontocypris pyrifera	R	-	-	-	-	-	-	-	-	-	-	-
	Xestoleberis communis	-	R	C	-	-	-	R	-	-	C	R	-
	Bosquetina dentata	R	-	-	-	-	A	-	R	-	-	-	-
	Urocythereis favosa	-	-	-	-	-	-	-	R	R	C	C	-
	Aurila sp.	-	-	-	-	-	-	-	-	R	R	-	-
	Cytheropteron sp.	-	-	-	-	-	-	-	-	R	-	-	-

Legend: AA=Very Abundant, A=Abundant, C=Common, R=Rare.

within this layer seems to represent a shallow marine depositional environment (Tziavos, 1978). Radiocarbon dating of shell fragments and crinoid stems yielded an age of 8580 ± 140 yrs B.P (BETA ANALYTIC INC., Beta-12918).

From 40 to 135 cm below the sea floor (Section C), the sediment appears to be similar to the upper layer but more silty and coarser. Terrigenus material is more abundant while the biogenous declines. The absence of corals and the gradual decrease of the micrifaunal population in species and individuals towards the deeper sections is characteristic of this layer. In the sediment layer near 130 cm, the only microfauna representative seems to be the ostracod *Cyprideis torosa*, a typical inhabitant of brackish water. This sediment layer represents a coastal marine to brackish water environment.

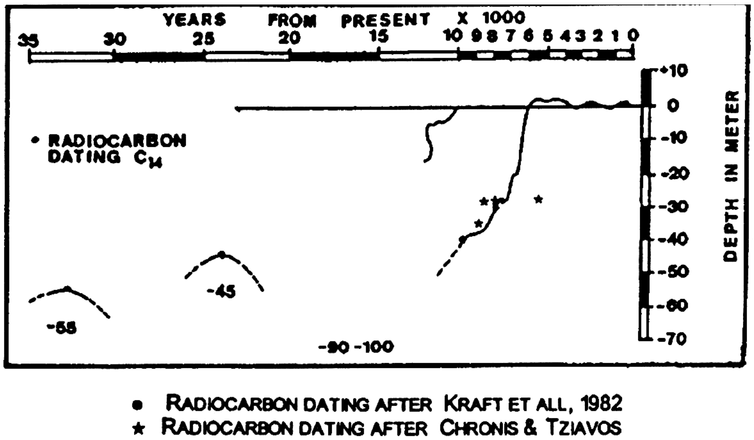

Fig. 8 - Holocene sea-level fluctuation curve for the Aegean Sea (from Kraft et al., 1982), combined with radiocarbon dates from the Inner Thermaikos Gulf.

The sediment layer that extends from 135 to 192 cm below the seafloor (Sections D, E, F) consists of muddy silt, with little or no biogenic fraction. The thin layer of sand in section D represents a terrigenous fraction dominated by quartz, feldspars and micas with small wood fragments. Few small individuals of the foraminiferida *Ammonia beccarii* (brackish water habitat) and charophyte seeds (fresh water habitat) suggest that this layer represents a coastal brackish water environment.

The short core TH-2 (73 cm) was taken at a water depth of 27 m. In contrast to TH-1, TH-2 is very diverse along its length in terms of grain-size and presence of benthic fauna (Fig. 7). The upper 30 cm consists of biogenic sandy silt (Section A) to silty sand (Section B and C). From 30 cm to 50 cm depth in the core (Section D and E), there is a gradual increase in the grain size of the terrigenous fraction (containing sand up to .250 mm in diameter), and in the abundance of the coral fragments (up to 4 mm in diameter). These features indicate a shallower but still marine depositional environment. Radiocarbon analysis of crinoid stems gave a date of 5380 ± 160 yrs B.P. (Beta-12921). Between 50 to 56 cm, there is a significant increase of gravel content in the benthic foraminiferal species present. This sediment layer was deposited in a near shore shallow marine environment. Radiocarbon analysis of crinoid stems and shell fragments gave a date of 7650 ± 100 yrs B.P. (Beta-12919).

Along the whole section, from 0 to 56 cm of the core, there is a large number of benthonic Foraminifera especially *Elphidium macelum, Ammonia becarii*, and varius species of *Quinqueloculina*, but also to a lesser degree, *Triloculina trigonula, Spiriloculina sp., Rosalina sp., Elphidium advena, Textularia cinica* etc. The ostracods are present with the dominant species *Loxoconcha rhomboidea, Bosquetina dentata, Cytheridea neapolitana, Xestoleberis communis, Uricythereis favosa* etc., which are characteristic of a typical marine environment.

Section G in the lower part of the core (56-73 cm) consists of coarse gravel and pebbles (up to 6 cm in diameter). Fragments of molluscs, crinoids and corals are present, but there are no ostracods and very few Foraminifera *(Ammonia, Triloculina)* in this section. Radiocarbon analy-

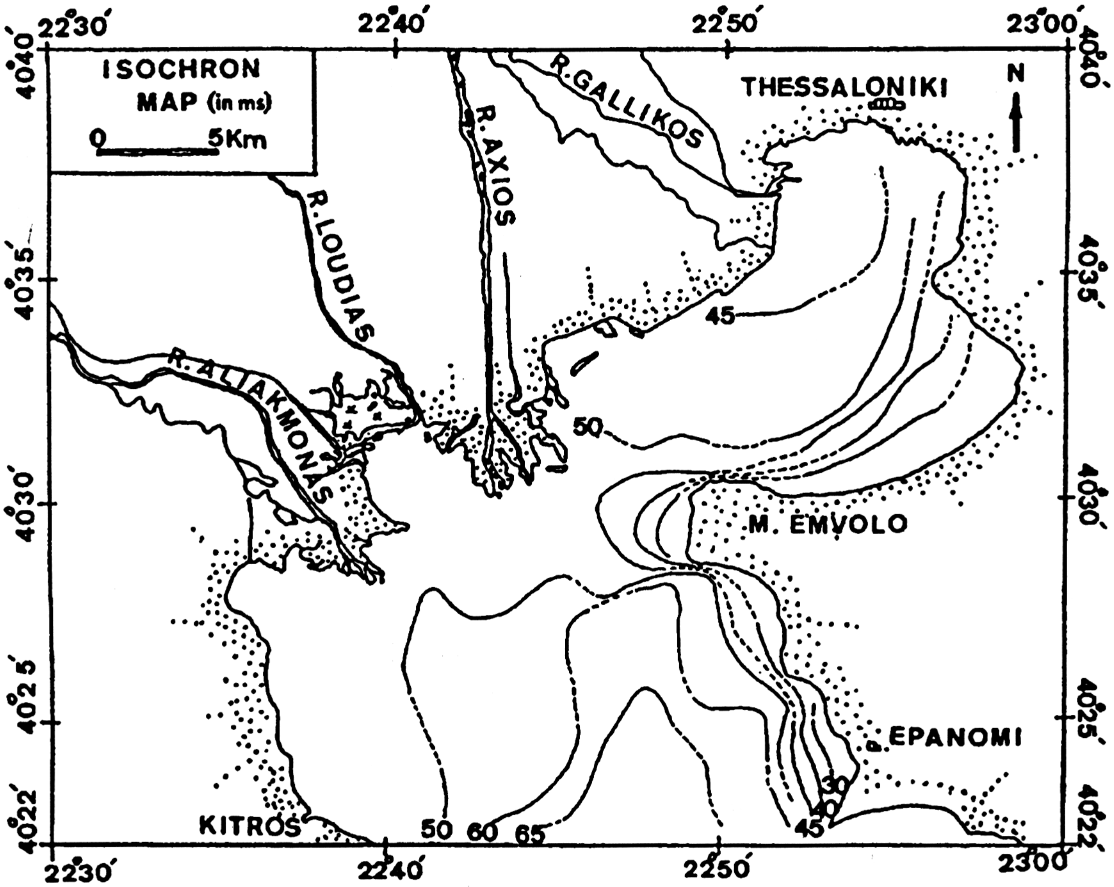

Fig. 9 - Isochron map of the Holocene transgressional surface. Datum plane: sea level.

sis of shells and crinoid stems gave a date of 8360 ± 130 yrs B.P. (Beta-12920). It is likely that this lower part of the core represents a palaeo-shore environment, indicating that sea level at 8.400 yrs B.P. was about 30 m lower than at present.

4. Discussion

4.1. Paleogeographic evolution and sedimentation rates

Our determination of the sea level at 8.400 yrs B.P. is in close agreement with the eustatic curve for the NE Aegean Sea proposed by Kraft et al. (1982) (Fig. 8). Using this curve, in conjunction with the depth of Reflector C and the radiocarbon analyses, it can be concluded that the Holocene sea transgressed onto the southern and deeper part (45 m) of the Thermaikos Plateau around 12000 yrs B.P. Consequently the whole process associated with the Holocene transgression can be easily estimated (Fig. 9), and the Holocene delta sequences have prograded into the present Inner Thermaikos Plateau over the last 8000-9000 yrs B.P., reaching a thickness

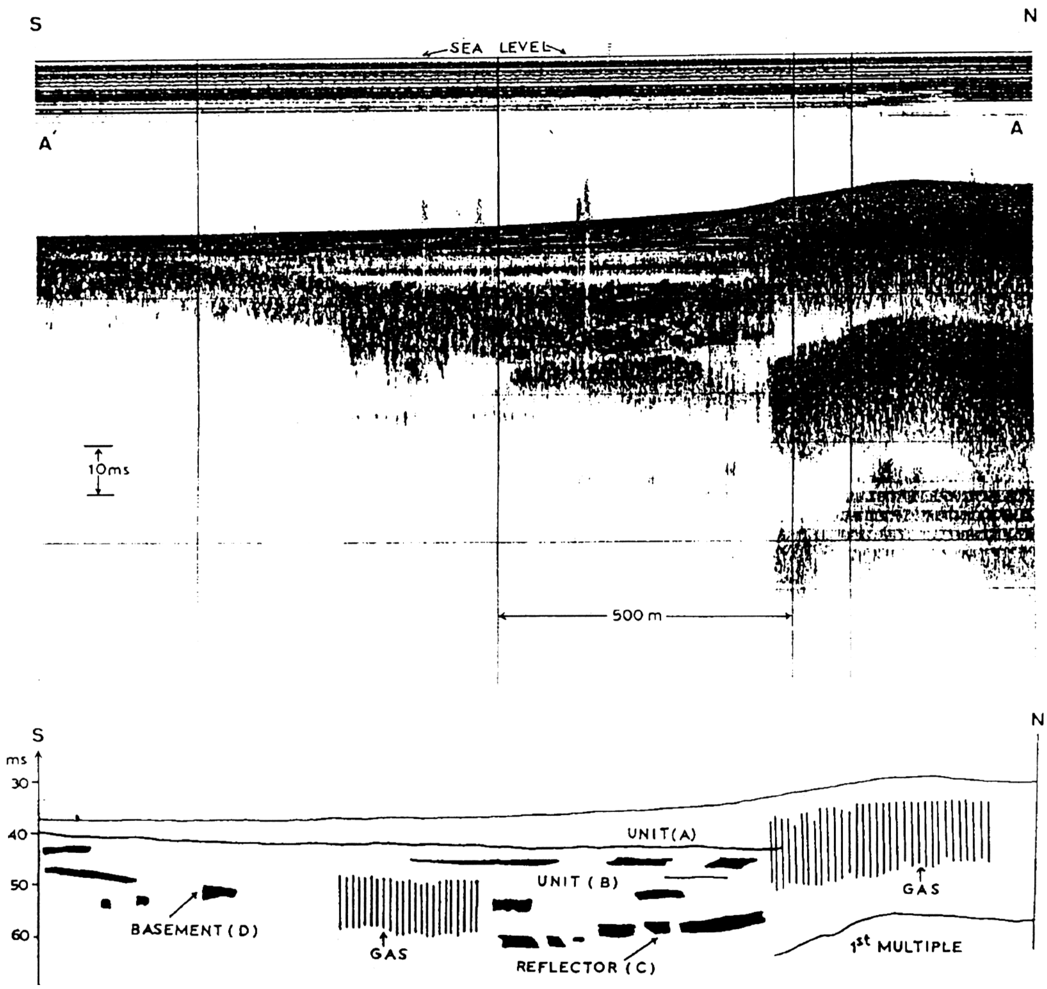

Fig. 10 - 3.5 kHz profile from the recent prodelta sequences of the Axios River.

of 4-25 m. This thickness implies mean sedimentation rates of 0.44-2.5 m/1000 yrs during this period.

The maximum rates of sedimentation have been observed near the river mouths and over the western part of the Inner Plateau; these rates decrease towards the E and SSE. The maximum (mean) sedimentation rate, during the Holocene, is consistent with the maximum values estimated for the prodelta of the Pinios River (~3m/1000 yrs) (Lykousis et al., 1987) which discharges onto the Outer Thermaikos Plateau. Likewise, it is consistent with the maximum values observed in the prodelta of the Evinos, Mornos and Pirros Rivers in western Greece, (~3m/1000 yrs) (Lykousis and Chronis, 1987).

The minimum (mean) sedimentation rates are observed in the eastern part of the Plateau, especially near the Epanomi and Mt. Emvolo headlands. In this area Reflector C is almost reaches the sea-bed, and rates are estimated from the cores to be 0.05-0.085 m/1000 yrs. Although significantly lower mean rates of sedimentation for the Holocene have been observed in the eastern Inner Thermaikos Plateau, particularly high rates have been estimated for the prodelta area of the artificially constructed Axios river mouth (since 1926) (Fig. 10). During the past 60 years, stratified facies of 5.6 m maximum thickness have developed, implying sedimentation rates of 94 mm/year. This value is consistent with the maximum sedimentation rates observed for the rivers of western Greece (40-150 mm/yrs), reflecting the sedimentation rates of a high energy prograding environment (foreset beds) during the evolution of the delta.

5. Conclusions

(a) The Inner Thermaikos Plateau is covered mainly by prograding Holocene delta sequences, up to a maximum thickness of 25 m, close to the river mouths, and thinning rapidly towards the E and SSE to a minimum thickness of about 4 m. These sediment sequences are not affected by neotectonic activity, so any relationship between tectonism and sedimentation is somewhat indirect.

(b) Four seismic elements have been recognised, throughout the Inner Plateau, in the seismic profiles: (i) Reflector D (a pre-Holocene erosional surface); (ii) Reflector C (the beginning of the Holocene sedimentation); (iii) Unit B: a transparent seismic facies (bottomset silts and clays of Early Holocene age); and (iv) Unit A: a stratified seismic facies (foresets, consisting of sandy silts-muds of modern-late Holocene age). The complete configuration of the seismic facies is a slightly oblique-sigmoidal progradation pattern.

(c) During the Holocene, mean sedimentation rates are high adjacent to the river mouths (~2.5 m/1000 yrs); they decrease rapidly eastwards and south-south-eastwards to minimum (mean) values of about 0.05-0.085 m/1000 yrs. Maximum sedimentation rates (94 mm/yr) are identified within deposition of the modern (last 60 yrs) foreset beds of the Axios river.

(d) The Inner Thermaikos Plateau was subjected to marine transgression over its southern and deep water parts, at about 12.000 yrs B.P.

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