Z. Geomorph. N.F.	Suppl.-Vol. 137	147 – 158	Berlin · Stuttgart	March 2005

Holocene morphology of the Thessaloniki Bay: Impact of sea level rise

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with 5 figures and 1 table

Summary. Both ancient and modern City of Thessaloniki are located on the north end of Thessaloniki Bay. A smooth hilly terrain on either side of which lay two low and flat areas characterizes the surrounding morphology. These areas represent ancient and modern river deltas where both the Holocene transgression and excessive sediment deposition have had significant impacts. Data extracted from seventeen (17) boreholes around the bay and near the present shoreline together with results of carbon dating of five (5) samples were used to create a sea level rise curve for the last 10.000 yr BP for the entire area. The results suggest the existence of a smooth, nonoscillating curve, initially characterized by rapid sea level rise from −30 m at 10 kyr to −5 m at 5 kyr, while lower sea level rise rates have been observed for the last 4 kyr. Prehistoric settlement debris (4 kyr) found at −4 m further support the curve smoothness. Holocene marine transgression resulted in inundation of these low and flat areas but during late Holocene excessive delta deposition filled the inundating lands and shifted the shoreline further offshore. Accordingly, human activities over the past 23 centuries have resulted in not only keeping the seafront stable, but also in extending both the city and the harbour seawards as has been proved by ancient debris deposited on top of marine sediments.

Zusammenfassung. *Morphologie der Bucht von Thessaloniki im Holozän, Einfluß von Meeresspiegel-Anhebung.* Die antiken und die modernen Stadtteile von Thessaloniki sind auf hügeligem Gelände gebaut, zwischen zwei tiefliegenden ebenen Gebieten, die durch Transgressionen und deltaischen Ablagerungen während des Holozän besonders beeinflußt wurden. Die Profile von siebzehn Bohrungen nahe der heutigen Küstenlinie der Bucht und die Ergebnisse von fünf Karbon-Altersbestimmungen wurden korreliert, um die Anhebungskurve des Meeresspiegels der letzten 10.000 Jahre zu bestimmen. Daten zeigen eine glatte nicht schwingende Kurve, welche eine rapide Anhebungsrate für den Zeitraum zwischen 10 Ka und 5 Ka, von −30 m zu −5 m nachweist. Die rezenten 4 Ka weisen geringere Anhebungsraten auf. Prähistorische Siedlungsreste 4 Ka entdeckt im Niveau −4 m untermauern den nicht schwankenden Aspekt. Meerestransgression zog in die flachen Gebiete ein, aber die nachfolgenden deltaischen Ablagerungen setzten die Küstenlinie zurück. Auch die menschlichen Aktivitäten während der letzten 23 Jahrhunderte der Stadtgeschichte haben die Küstenlinienfront nicht nur stabil gehalten, sondern die Stadt und ihr Hafen haben sich Richtung Meer ausgebreitet, wie die Befunde von antiken Resten auf marinen Sedimenten nachweisen.

1 *Introduction*

The Bay of Thessaloniki comprises the northeast part of the broader Thermaikos Gulf. Cape Megalo Emvolo on the east and the present delta of Axios River on the west, separate the Bay of Thessaloniki, from Thermaikos Gulf. (Fig. 1) The old city of Thessaloniki has been built on the hilly terrain on the north end of the Bay, around a smaller embayment occupied by the harbour and the seafront of the modern city. Cape Mikro Emvolo on the east and Galikos river delta on the west bound this smaller bay. Generally, the morphology of the surrounding area is characterized by a smooth hilly terrain on the north while two lowland areas lay on both sides of the hills;

0044-2798/05/0137-0147 $ 3.00

one on the west and the other on the east side. The western lowlands are an integral part of the big deltaic complex formed by the propagating deltas of the rivers Axios and Galikos. The east lowland, bounded by the capes Mikro Emvolo and Megalo Emvolo comprises the lower part of the Anthemuntas basin.

1.1 *Geomorphological background*

The present geomorphologic characteristics of the broader area of the Thessaloniki Bay – Thermaikos Gulf have evolved since Lower Miocene. It is generally accepted (Psilovikos & Vavliakis 1982/83: p.8) that before Miocene the area of Macedonia exhibited a "planation surface" morphology that has been evolved on Mesozoic and Palaeozoic crystalline rocks. During early – Middle Miocene intense tectonism (Psilovikos 1977, Karystineos 1984) affected the entire region of Macedonia forming a pattern of elongated tectonic depressions with NNW-SSE direction.

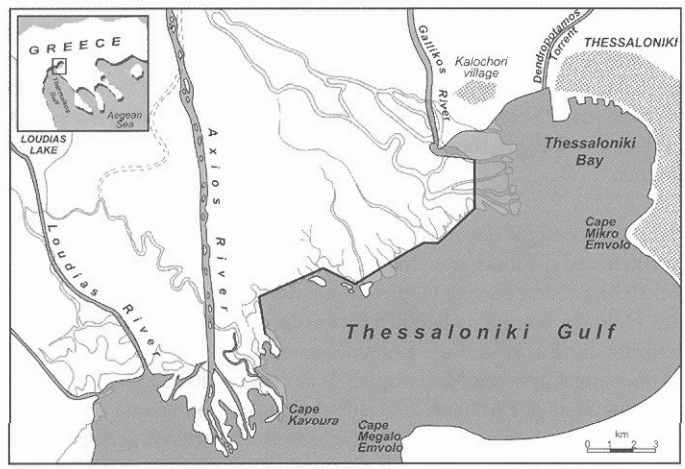

Fig. 1. Changes of the coastline in the Bay of Thessaloniki during the 20th century (Albanakis et al. 1994: 319–323).

An elongated basin was formed in this way in the area of Lower Axios Valley – Thessaloniki plain – Thermaikos Gulf. Similar tectonic depressions in both size and orientation have been also formed. Examples include the Florina – Ptolemais – Elassona basin, on the west and Strymon – Strymonikos Gulf on the east.

During Neogene and Pleistocene the tectonic depression of Lower Axios Valley – Thessaloniki plain – Thermaikos Gulf was gradually filled with clastic sediments up to a total thickness of 3.500 m in the center of the basin (Faugeres & Robert 1976: 209). The filling process was not uniform both in space and time. According to Syrides (1990: 202–212) stratigraphical analysis of deposited Neogene-Quaternary sediments revealed various depositional palaeoenvironments.

Deposition began during Lower – Middle Miocene with thick layers of coarse clastic sediments of fluvial origin representing humid palaeoclimatic conditions up to Upper Miocene. During Upper Miocene (Valesian – Lower Turolian) a warm terrestrial palaeoenvironment phase dominated the area with palaeosoils and redbeds containing a rich savannah type fossil mammalian fauna. In the uppermost Miocene (Pontian) an extensive brackish lake covered the area, attributed to a Paratethyan invasion in northern Aegean Sea. During that phase deposition of fine grained silty-clayed fossiliferous sediments as well as fine sands and fossiliferous limestones took place.

The Pliocene was characterised by deposition of fluvial, and clastic sediments while massive marly limestone beds were deposited into small shallow lakes. During upper Pliocene – Pleistocene redbeds were deposited in an extensive terrestrial palaeoenvironment characterised by arid climatic conditions. Intense tectonic action during Middle Pleistocene modified the area creating grabens that either remained terrestrial (Mygdonia, Anthemoundas) or were inundated by the sea (Thessaloniki plain – Thermaikos Gulf, Toroneos Gulf, Siggitikos Gulf). The formation of the hilly and mountainous terrain of the entire region that is seen at present took place during that phase of intense tectonic activity. Pleistocene palaeoclimatic conditions together with a fluctuating sea level regime favoured terrestrial and fluvial clastic sedimentation and locally palaeosoil and redbed deposition. The last "Wurmian" glaciation lowered the sea level by approximately 120 m. Thus, an extensive lowland almost flat area, was formed in the area of present day Thessaloniki – Thermaikos Gulf and Thessaloniki plain. The coast and the deltas of Axios, Aliakmon, Gallikos rivers were shifted southwards. This pre Holocene terrain was mainly developed on Neogene sediments (northern margins) and covered by Pleistocene clastic sediments.

1.2 *Holocene transgression*

Detailed references about the stages of sea-level rise and the evolution of the palaeo-coastline of the study area have not been published yet and the entire region is under investigation. Chronis (1986: 199) has reported that sea level was –28 m near Epanomi at 8360 +/– 130 BP. The only existing information about the condition of the old landscape during ancient times derived from ancient historians and archaeological record. Based on those reports, several authors tried to reconstruct the ancient landscape (Astaras & Sotiriadis 1988: 109).

It is generally accepted that during Historical times (500 BC, or 2500 BP) the coastline was 40 km inland from its present position. The ruins of Pella, the capital town and the main port of ancient Macedonia are now 25 km inland. Therefore, the transgression covered not only the present depression of Thermaikos Gulf but it also extended 30 - 40 km inland to the NW. During the period of reduced rates of the sea-level rise, the deltas of the two main rivers Aliakmon to the south and Axios to the north gradually filled the NW part of that ancient inundated bay forming initially a lagoon and later a lake in its centre. This landscape was preserved until the first quarter of 20th century. By that time the deltas of Axios and Galikos Rivers formed an extended fluvial plain with marshes that reached the west side of Thessaloniki harbour. After 1930 a series of human interventions took place which completely reformed the landscape by draining the old lake, canalising the rivers with dykes and shifting the mouth of Axios River 25 km to SW so that to avoid harbour siltation.

1.3 *Geography of the Coastal Environments*

The relief surrounding the city of Thessaloniki has always been a hilly terrain between two low and flat areas (Axios & Anthemoundas basins). The research area has been divided into three sectors with different landscape characteristics:

West Sector: A coastal flat of former marshland areas between west margin of the city of Thessaloniki and Kalochori village. Until the first quarter of 20th century the evolution of the area was affected significantly by the deposits of Dendropotamos torrent (to the north), as well as by the east part of Gallikos river delta, forming extensive marshlands. After the second half of 20th century the expansion of city of Thessaloniki transformed the area into a wide industrial zone with extensive land reclamation, significant debris deposition and rapid built up of industrial facilities. As a result Gallikos River was canalised. Accordingly, Dendropotamos torrent which was initially draining the hilly terrain west of Thessaloniki was subjected to changes. The expansion of the city occupied a great part of its drainage basin so that the torrent has been transformed to a close covered sour while its branches have become roads diminishing the present-day sediment load.

Central sector: Includes the coastal area of the city of Thessaloniki from the port up to cape Mikro Emvolo. It comprises a dense populated area and its morphological characteristics have hardly been affected during time. Thessaloniki was founded at 315 BC and for more than two millennia it has been evolved between walls (Christaras 1988: 1182). The coastal zone of the city covers the area from present harbour up to the White Tower. The landscape from White Tower to cape Mikro Emvolo was rural with a dense pattern of small torrents that formed small deltaic fans along the coastline. The White Tower was built on a small promontory and was the eastward end of the city for many centuries.

During the last century and particularly the last 80 years a rapid evolution and expansion of the city outside walls changed dramatically the landscape. The city now occupies the former rural areas to the SE. The torrents have been cut-off and directed into an artificial channel around the perimeter of the city to avoid flooding. A new artificial coastline was constructed during 1960–1970 between the White Tower and cape Mikro Emvolo. This manmade coastline extended 200 m from the old shore, and straightened up the former jigsaw coastal pattern.

South-Southeast sector: It is an area of low relief starting from the hilly terrain of the NW side of Anthemoundas graben and extends to the centre of the graben in an area of extensive marshes around Thessaloniki airport. A prehistoric settlement, Toumba Gona, is situated in the transitional zone between the hilly terrain and the marshlands.

2 *Materials and methods*

2.1 *Borehole drilling – Core sampling*

In order to obtain a better understanding of the pre-Holocene morphology of the Thessaloniki bay margins, we supervised the drilling of seventeen (17) boreholes around the bay and near the present-day shoreline (Fig. 2). Boreholes covered all three (3) sectors: West sector (nine boreholes), Central sector (three boreholes) and South-Southeast sector (five boreholes). Borehole drilling and coring recovered numerous core samples that were placed into storing boxes. Detailed core descriptions permitted the construction of lithostratigraphic columns for each borehole.

2.2 *Core analysis*

Collected core samples were transported to the laboratory of the School of Geology for further analysis. Representative core samples were subjected to textural and paleontological analyses for determination of main sediment types and fossil mollusk fauna. Analyses were focused mainly on the samples containing mollusks.

Samples with mollusks were soaked and washed with de-ionized water into a 0.125 mm wire mesh sieve to remove the silt and clay fractions. The dry residue was hand selected with steel forceps under a binocular microscope and the recovered shells were sorted for further palaeontological determination. Special attention was paid to the non-characteristic mollusk fragments that were carefully collected in aluminum containers and aluminum foil for carbon dating.

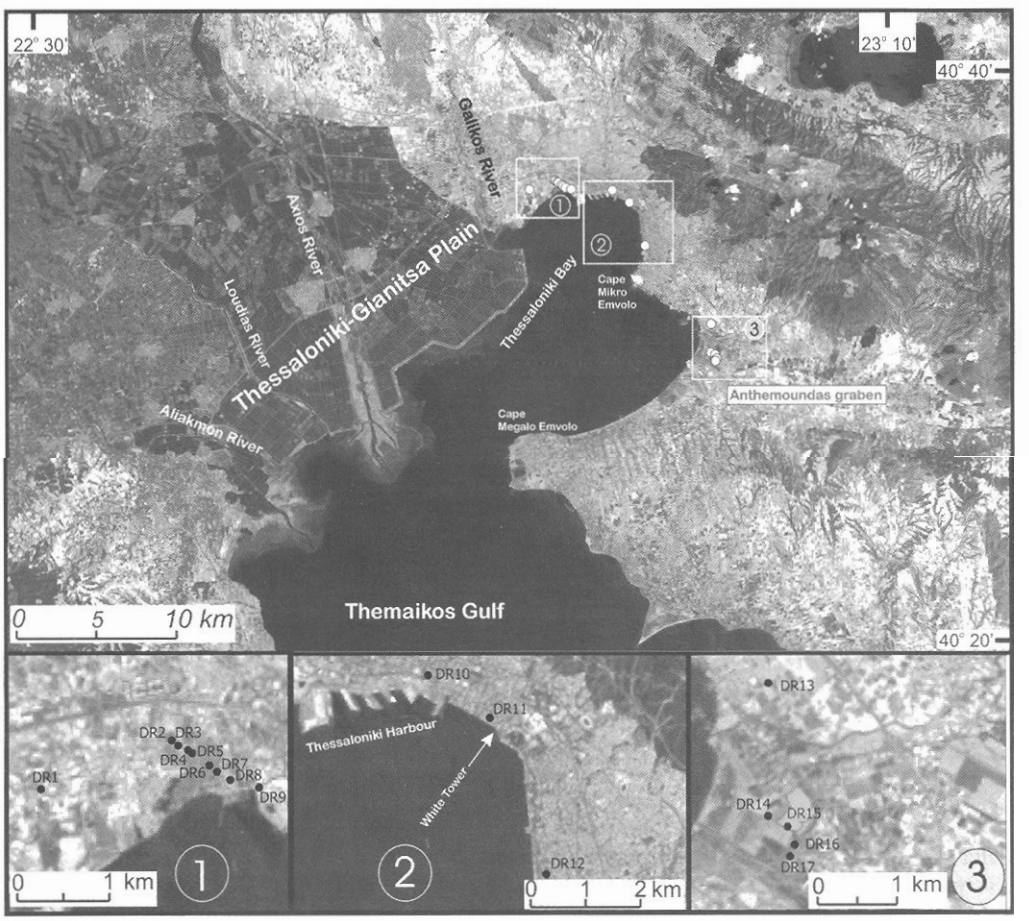

Fig. 2. Borehole positions in a recent (1997) LANDSAT satellite image.

2.3 *Carbon dating*

Three representative samples of the isolated mollusk fragments were sent to Leibniz – Laboratory for Radiometric Dating, Kiel University, in Germany for standard 14C dating.

Two more samples were carbon dated in Paris VI University in collaboration with Dr. A. Drivaliari.

3 *Results From Boreholes*

3.1 *Holocene Stratigraphy*

Following the core samples analyses lithological columns of the boreholes were constructed (Fig. 3). The penetrated sediments were distinguished into four different groups (D, C, B & A) from older to younger.

D group consists of terrestrial, fluvial Pleistocene sediments and locally Neogene deposits that existed into the area before the Holocene marine transgression. Its contact with the C group represents the PreHolocene land surface.

C group consists of fossiliferous clastic marine sediments, mainly dark coloured, grey-blackish silty-clayed sands as well as sandy clays that were deposited after the Holocene transgression in a shallow (up to 40 m depth) marine environment. Sedimentation rate of group C varies spatially. In the vicinity of the river (Axios, Gallikos) and torrent (Anthemoundas) deltas, sedimentation rates are greater and coarse grained in comparison with other areas characterised by restricted supply of clastic material. Numerous marine shells were recovered from these sediments.

B group consists of terrestrial, fluvial and locally marsh deposits. These deposits overlay the marine sediments and represent riverine – torrential discharge and land progradation following the reduction of rate of sea-level rise.

A group includes human debris of various ages, e.g. modern trash debris in the area of Kalochori – Dendropotamos (Boreholes DR1-DR9), Ancient debris of Hellenistic – Roman – Byzantine – Ottoman age along the coast of old city (boreholes DR10, DR11). Debris containing prehistoric pottery and food litter around the prehistoric settlement Toumba Gona, near Thessaloniki airport (Boreholes DR15, DR16) and modern debris used for foundation of buildings (DR12, DR17).

3.2 *Relationships between the three sectors*

West Sector: All nine (9) boreholes (DR1-DR9) drilled in this sector penetrated marine sediments (group C) and terminated into the underlain terrestrial sediments (group D). On the top human debris (group A) up to 3–4 m thick where found, while at four boreholes fluvial sediments (group B) existed above the marine sediments. These sediments may have originated from the former delta of Galikos River and Dendropotamos torrent.

The contact between marine sediments (group C) and the underlying terrestrial sediments (group D) is located between −15.5 m (DR9) and −18 m (DR2) while at DR1 it is more profound −29 m. This implies a gradual lowering of the Preholocene palaeorelief from east to west. Holocene transgression transformed the area into a shallow bay more profound on the west.

Central sector: Boreholes (DR10, DR11 and DR12) drilled in this sector were located along the coastal area of the city of Thessaloniki. A surface layer of human debris (group A) up to 8 m thick (DR10) was revealed on top of marine sediments of group C. Marine sediments of group C overlay older terrestrial deposits of group D. Contact between Group A and Group C sediments is situated below present sea level at −4 m DR10, −3 m DR11, −1,8 m DR12. It is remarkable that sediments of group B were not found in these boreholes; but marine sediments are covered immediately by human debris of various ages (Hellenistic – Roman – Ottoman – recent). This suggests that the shoreline was initially inshore and shifted offshore due to debris deposition. The human impact was focused primary on the seafront of the old city of Thessaloniki (from the harbour to White Tower). Borehole DR10 is situated just outside the walls of the ancient city in the area of the former Roman – Byzantine harbour. Today's shoreline from this site is 350 m southwards. The artificial seaward migration of the seafront gradually diminishes at the eastern site of the ancient city (borehole DR11) up to a small promontory, consisting of group D sediments, where the White Tower was built.

South-Southeast sector: Boreholes DR14, DR17 drilled in this sector penetrated fluvial and marshy deposits of Group B, marine sediments of Group C (−3 m up to −5 m in DR14, −9 m up to −13 m in DR17) and terminated into the underlying terrestrial sediments of Group B. On top of these 3 m of DR 17 recent human debris was also found. Boreholes DR15, DR16 penetrated up to −2 m and −1 m respectively sediments rich in prehistoric pottery and food litter (group A). Between −2 m and −3,5 m in DR15, and −1 m and −5 m in DR16 marshy sediments with fresh water fauna were penetrated and then the boreholes terminated into the underlain terrestrial sediments of Group D. The absence of marine sediments in the last two boreholes indicates that in this location the palaeorelief was not reached by the marine transgression. Borehole G13 was drilled 2 km northern of Toumba Gona at 17 m a.s.l. on a low hilly landscape. The area is dominated by reddish terrestrial sediments (group D) and the borehole penetrated exclusively these sediments up to 20 m depth (−3 m b.s.l.).

3.3 *Results on Holocene fossilized fauna and carbon dating*

Numerous fossil mollusks were recovered from the core samples of Group C sediments. Palaeontological determination revealed a rich fauna:

BIVALVES: *Nucula, Nuculana, Ostrea, Chlamys, Acanthocardia, Cerastoderma, Corbula, Mytilus, Modiolus, Tellina, Venus, Venerupis, Dosinia, Lucina, Abra, Mactra, Spisula*

GASTROPODES : *Gibbula, Caliostoma, Retusa, Rissoa, Alvania, Cerithium, Bittium, Turitella, Ringicula, Murex, Nassarius*

SCAPHOPODA : *Dentalium*

VERMES: *Serpula*

FORAMINIFERA: *Elphidium, Nonion, Triloculina*

CORALS: *Cladocora*

DECAPODA: Crab fragments

ECHINOIDEA: Test fragments and spines of regular and irregular echinoids.

Synthesis of the fauna indicated typical shallow marine palaeoenvironment of normal salinity. The majority of shells has originated from the lower part of Group C sediments. In all sec-

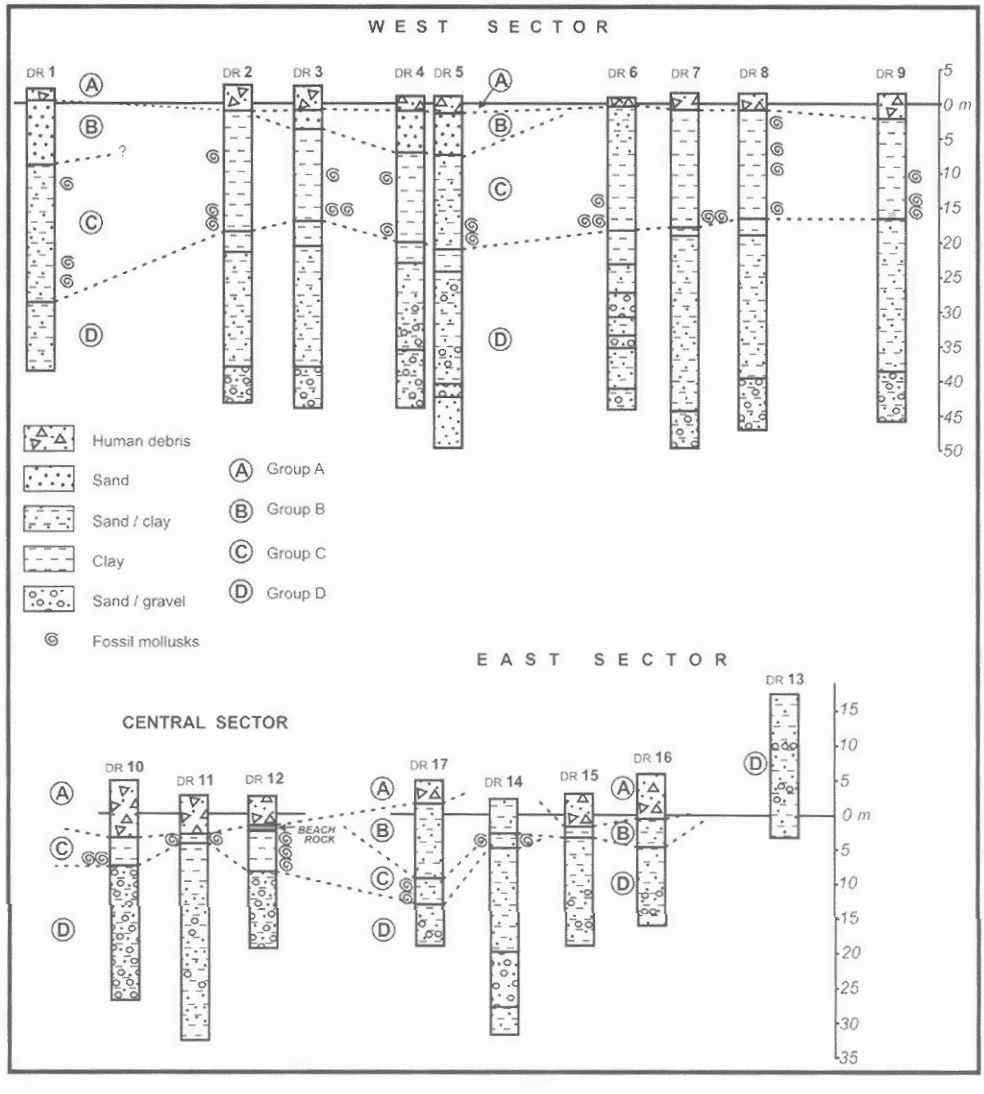

Fig. 3. Columns of the boreholes drilled along the coastal area of Thessaloniki bay. Synthesis includes: distribution into geographical sectors, absolute altitudes, lithology - fossils, places and ages of C14 samples, and sediment group correlation. (Horizontal distance between boreholes not in scale).

tors (West, Central, South-southeast) boreholes penetrating marine sediments revealed almost the same fauna from the lower part of Group C. In contrast, along the west sector (Boreholes DR1-DR9) the upper part of Group C sediments is characterized by a monotonous fauna with few euryhaline genera (Loripes, Abra) indicating a fluctuating salinity. This possibly indicates the dominance of a shallower marine palaeoenvironment, being restricted due to the existence of Axios and Gallikos deltas.

Selected mollusk shells from the core samples were carbon dated. In each sample the mollusk fauna was determined. Synthesis of the fauna from each sample permitted estimations of the marine palaeodepth that such fauna lived (Table 1).

Table 1. Carbon dating results.

Sample No.	Borehole	Depth m	Age BP	Type of material	Depth-range of the fauna/material
1	DR1	−29.00	9453 ±360	Marine mollusks	Coastal
2	DR2	−18.00	6838 ±115	Marine mollusks	Shallow water ~ (5 to 10m)
3	DR9	−15.50	7533 ±80	Marine mollusks	Coastal
4	DR17	−13.00	5715 ±35	Marine mollusks	Shallow water ~ (<5m)
5	DR16	−4.50	4020 ±80	Marshy sediment	1 – 2m a.s.l.

3.4 *Reconstruction of sea level rise curve for Thessaloniki Bay*

From the five available carbon datings only two (DR9, DR1) represent low energy beach environment as inferred from the existence of beach worn shell fragments and flat rounded pebbles. The two other datings (DR2, DR17) of shells representative of shallow water fauna were found in loamy matrix (Table 1), determining the depth range of the fossilised fauna.

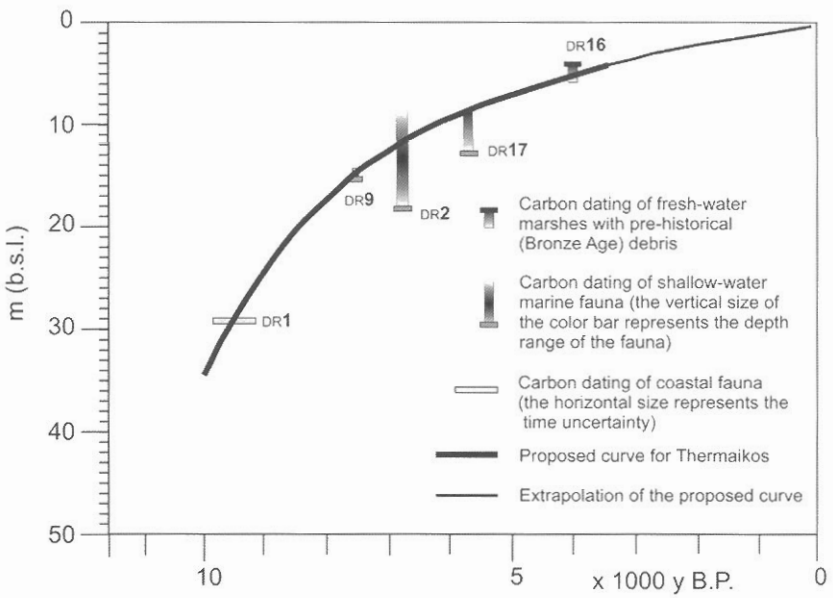

Fig. 4. Proposed sea level curve for Thessaloniki Bay – Thermaikos Gulf.

The fifth dating from DR16 suggests terrestrial conditions 4000 BP at a depth of −4.5m. Correlation between the location of DR16 with the other boreholes location and stratigraphy (Fig. 3), suggests that 4000 years ago marshes existed in the region. These marshes around Antemoundas River were both salt marshes that extended seawards and fresh water occupying the area near the prehistoric settlement of Tumba Gona. Prehistoric human debris found in DR16 was retrieved from depth similar to that of the carbon dated sediment. This confirms the accuracy of the dating despite it was made on carbon material from a marsh. Therefore DR16 dating represents fresh water marshland approximately 1–2 m above the sea level during 4000 BP.

All five datings were used to construct the sea level rise curve for Thessaloniki Bay (Fig. 4). The derived curve was compared with similar curves (Fig. 5) from Peloponnese (van Andel & Lianos 1984) and several other places across the Mediterranean, the Black Sea and the World (Pirazzoli 1996: 90–92)

4 *Conclusions*

Carbon datings of five samples were used to reconstruct the sea level rise curve during past last 10000 years in Thessaloniki Bay. Despite the small number of the available datings (5), the distribution of the estimated ages over time and the relatively small amount of time error allowed the construction of the curve.

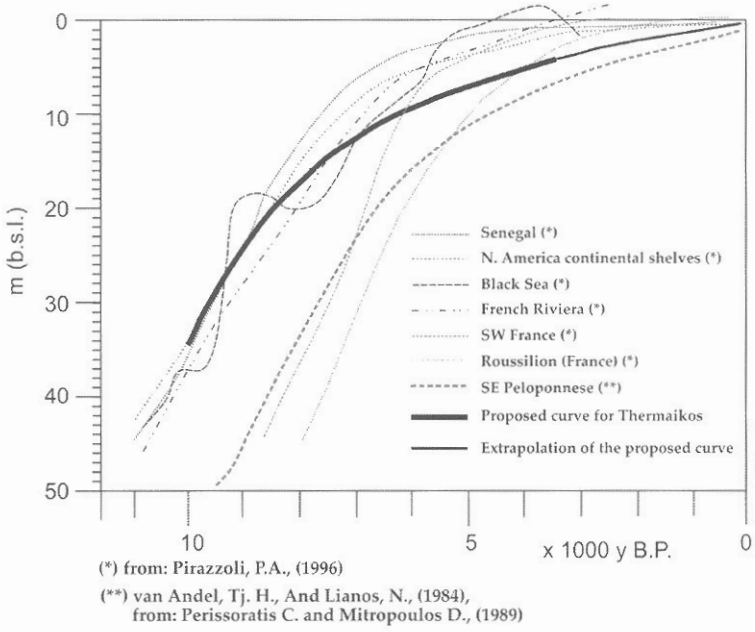

Fig. 5. The sea level curve of Thessaloniki bay in comparison with other data.

The results suggest a smooth, nonoscillating sea level rise similar to the "Shepard Curves" (Bruse et al. 2001: 27). The reconstructed curve suggests that 10000 y BP the sea level was about 29 m below its present value and rose rapidly up to –5 m with an average rate of 4 m per millennium. During the past 4000 years the rate dropped to an average value of 1 m per millennium. As a result the low coastal areas around Thessaloniki Bay were inundated by the rising sea. More specifically the two almost flat areas E and SW of the hilly terrain where Thessaloniki City is located were totally covered by sea-water. Marine sedimentation dominated the phase of rapid sea level rise. Following the reduction of the sea level rise rate, excessive sedimentation of the progressing river deltas covered the marine sediments and shifted the present shoreline seawards to its present day position. Human debris of ancient and recent origin has been deposited on top of the fluvial sediment sequence. In contrast, along the central sector, where the city of Thessaloniki has evolved as a harbour for more than 23 centuries, ancient and recent human debris lies directly on top of marine sediments. The coastline along the central sector, in the absence of significant sedimentation from river input, should have been inshore its present position as transgression proceeded. But borehole data suggested that human activity over the centuries not only kept the seafront stable but both the city and the harbour extended seawards in order to provide more space to the inhabitants. The Thessaloniki case provides a good example of how humans were protected from increasing sea level and can be used as a reference for future reaction of major cities to sea level rise.

Acknowledgements

We are grateful to Dr. A. Drivaliari that allowed us to use unpublished data from a forthcoming paper (Syrides & Drivaliari. Geoarchaeological research in the area of the prehistoric settlement of Toumba Gona, near Thessaloniki airport).

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