Internal structure and evolution of the Late Quaternary sequence in a shallow embayment: The Amvrakikos Gulf, NW Greece

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Abstract

The Late Quaternary stratigraphic pattern of the Amvrakikos Gulf in the eastern Mediterranean has been studied on the basis of the analysis of high-resolution seismic profiles and short sediment cores. Lowstand, transgressive and highstand systems tracts have been identified that are configured in a major depositional sequence of a fifth-order sea level cycle. During the last glaciation, when the sea level was lowered by ~55 m relative to its present position (ca. 50 ka BP), the Amvrakikos Gulf was probably emerged, giving rise to: (a) subaerial erosion and fluvial incision in the western shallow part of the Gulf; and (b) development of a paleo-lake in the eastern deepest domain. Until the early phase of the post-glacial transgression (ca. 11–50 ka BP), a paleo-river, characterized by a dense network of V-shaped valleys, was draining the western part of the Gulf and flowing into the Ionian Sea. In the isolated eastern part, lowstand lacustrine deposits (deltaic and prodeltaic units) accumulated within the paleo-lake. At the latter stage of the last post-glacial transgression (ca. 11 ka BP), seawater entered the Gulf and the transgressive systems tract was deposited, consisting of incised-channel fills, beach–shoreface deposits and delta/prodelta wedges. Buried terraces have been identified also within this transgressive tract that reveal a step-like sea level rise. Since ca. 6 ka BP, when the sea level reached its present-day position, a distal prodeltaic unit has been deposited and overlain by prograding deltaic wedges. The spatial distribution of these wedges provides evidence of a continuous shifting of the river mouths during Holocene. The recent sedimentation patterns are related to the terrigenous inputs primarily from the Arachthos River, located in the northeastern part of the Gulf, and secondarily from the Louros River, located in the northwestern part.

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1. Introduction

The stratigraphic architecture of semi-enclosed embayments, receiving riverine water/sediment fluxes, is the result of the interplay between local physiography, hydrodynamic conditions, sea level changes and sediment supply that determine the spatial distribution of sedimentary facies patterns.

In the case of a semi-enclosed embayment, apart of the sediment supply, the geometry (shape) of the receiving basin plays a significant role to subaqueous deltaic sedimentation and delta growth, as the hydro-

Fig. 1. Regional setting of the Amvrakikos Gulf showing: (a) the major rivers flowing into the Gulf and their catchments; (b) the simplified geology of the river basins (after Bonovas and Rondogianni-Tsiambaou, 1983).
dynamic regime is rather weak. In contrast, delta growth in open shelf areas is subjected usually to intensive wave activity and/or high tidal range, which are responsible, primarily, for sediment dispersion and accumulation patterns (Ercilla et al., 1994; Morton and Suter, 1996; Tortora, 1996). In addition, the presence of a sill at the entrance of semi-enclosed embayments may induce a different response to sea level fluctuations (in terms of time period and range) within the embayment, in relation to the adjacent open sea. Furthermore, low gradient of the embayment coastal plains, associated with high sediment supply can contribute significantly to the development of depositional sequences, with different characteristic from those formed in open shelves (Trincardi et al., 1994; Yoo and Park, 2000).

The present study, based on shallow seismic data, investigates the internal structure of the upper sedimentary deposits of the Amvrakikos Gulf, in order to reconstruct the Late Quaternary evolution of the Gulf, which is related mainly to deltaic/prodeltaic sedimentation and relative sea level change. Hence, the conceptual model of sequence stratigraphy, developed by Mitchum et al. (1977), Vail et al. (1977), Posamentier and Vail (1988), and Van Wagoner et al. (1988) has been applied. This model allows the identification of the unconformity-bounded sequence, which represents deposition during a complete cycle of sea level fluctuation (Posamentier et al., 1988; Boyd et al., 1989; Mitchum and Van Wagoner, 1991). Although this stratigraphic framework was developed initially to study depositional sequences corresponding to 1–2 Ma (third order) sea level cycles, its basic principles have been extensively in the study of Quaternary sequences (fourth or fifth-order cyclicity) (Bellotti et al., 1994; Hernández-Molina et al., 1994; Okyar et al., 1994; Barnes, 1995).

### 2. Regional setting

The Amvrakikos Gulf is located in the southeastern Balkan Peninsula, and receives freshwater from numerous rivers and streams, from which the Arachthos and Louros rivers are the major suppliers (Fig. 1). The Arachthos River basin is 1894 km\(^2\), having relatively higher rainfall levels and erodible clastic (flysch, alluvial) formations, whilst the Louros River drains an area of 785 km\(^2\), consisting mainly of carbonate rocks (Table 1). Both the Arachthos and Louros rivers discharge into the northern margin of the Amvrakikos Gulf constructing a joint deltaic plain of 350 km\(^2\) (Poulos and Chronis, 1997). The sediment supply of small rivers and seasonal streams draining the western, southern and eastern catchments of the Gulf is very low and cannot affect significantly the geomorphological evolution of the Gulf (MertzNAS, 1992).

The Amvrakikos Gulf is a shallow (water depths < 65 m) and semi-enclosed marine embayment, communicating with the open Ionian Sea through a narrow (600 m wide) and shallow channel (8.5 m deep), including an artificially dredged navigational channel (Fig. 2). The Gulf can be divided morphologically into two parts: (a) the western part, formed by a number of small basins, with water depths less than 40 m; and (b) the eastern part that is characterised by a

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\(^a\) Values abstracted from Therianos (1974).
\(^b\) Measured values abstracted from Poulos and Chronis (1997).
\(^c\) Estimated values from measured water discharge (Poulos and Chronis, 1997).
deep basin (water depths up to 65 m). The bed of the Gulf is covered mainly with rather uniform mud, with the exception of the Preveza Bay, where sandy mud is dominant (Piper et al., 1982).

The hydrodynamic regime of the Gulf represents a rather calm wave climate, due to limited wave fetches (Poulos et al., 1993), and tidal ranges <30 cm (Tsimpis, 1992). Although the water circulation is weak, it shows a complex pattern that depends on the direction of the dominant winds and the morphometry of the coastline. Thus, in the eastern part of the Gulf, surficial waters circulate clockwise, whilst in the western part of the Gulf, the flow pattern has an anticlockwise direction (Voutsinou-Taliadouri and Balopoulos, 1991). In the narrow Aktion Strait, strong currents (up to 1 m/s) present alternating directions, following the tidal regime.

The Amvrakikos Gulf has been subjected to major morphological changes during Upper Quaternary, as a result of sea level fluctuations and neotectonic activity (Clews, 1989). Thus, it is most likely that during the last post-glacial transgression (earlier than 10 ka BP), seawater from the open Ionian Sea had already entered into the Gulf (Tziavos, 1996; Poulos et al., 2005). Subsequently, sea level continued to rise up to ca. 2 ka BP, whilst over the last 2000 yr, it seems to fluctuate within a range of 1–2 m (Poulos et al., 2005).

Offshore, the Late Quaternary sequence of the Gulf has been studied previously by Poulos et al. (1995). These authors have identified three main depositional phases: (a) the lowest basinward progradational phase composed of clinoforms deposited during Late Pleistocene period; (b) prodeltaic sediments accumulated in a lacustrine environment during the last transgression (ca. 6–18 ka BP); and (c) the uppermost shallow marine phase, which resulted mainly from the rapid deltaic progradation of the Arachthos River that is associated with the Holocene highstand of the sea level (from ca. 6 ka BP to today).
3. Materials and methods

This study is based on the interpretation of 325 km of high-resolution (3.5 kHz) seismic profiles acquired with the R/V Aegaeo (Hellenic Centre for Marine Research) in May 1987, using an O.R.E. subbottom profiling system (Fig. 3). Depth data were simultaneously collected with an echo-sounder (FURUNO). Shipboard navigation was provided by radar, with an estimated accuracy of 50–100 m, depending on the proximity to the shoreline. During profiling, vessel speed was maintained at about 4 knots. An average sound velocity of 1550 m/s was used to calculate the thickness of subsurface sediments and water depth on profiles.

Four gravity cores (of 2.6 m maximum length) were collected to study the Late Holocene deposits (Fig. 3). Grain size analysis was carried out using a particle size analyser (Sedigraph 5000ET), and sediment types were classified according to Folk’s nomenclature (Folk, 1974). Qualitative and semi-quantitative mineralogical observations were carried out with the use of a binocular microscope. Carbonate content was determined by the procedure of ‘Carbonate bomb’ (Muller and Gastner, 1971). In the absence of any absolute dating of the core sediments, the stratigraphic correlation between the various seismic units has been composed on the basis of indirect information, related to local relative sea level change (Lambeck, 1996; Poulos et al., 2005).

4. Results

4.1. Sequence stratigraphy

In the Amvrakikos Gulf, seismic profile analysis provided evidence of a strong and continuous reflector that could be defined as the sequence boundary

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Fig. 3. Location of the high-resolution (3.5 kHz) seismic tracks (solid lines) and gravity cores (black squares). Bold lines refer to the selected profiles shown in subsequent figures.
(SB), separating two distinct seismic sequences (Fig. 4): (a) the upper sequence (US), which is a sedimentary cover with a maximum thickness of 45 m and complex internal structure, including a variety of bounding surfaces and seismic units (described below, from the earliest to latest ones); and (b) the lower sequence (AB) that shows very faint reflectivity and could be defined as the acoustic basement, for the frequency of 3.5 kHz. AB contains locally deformed and/or faulted reflectors, and is eroded at the top.

4.1.1. Sequence Boundary (SB)

The sequence boundary, having a high acoustic impedance contrast, is traced almost throughout the Gulf (Fig. 5). In the western and southern parts of the Gulf, SB shows a strong erosive character, representing an extended hydrographic network of V-shaped incisions (Fig. 4). Near the Aktion Strait, these incisions are narrow (maximum width of 600 m) and deep (maximum depth of 20 m), and may correspond to paleo-valleys, developed by fluvial erosion (Fig. 5). In the western part of the survey area, the maximum depth of the SB was found to be at ~55 m below present sea level (bgs); this implies that when the sea level was lower than ~55 m, the Gulf would be isolated from the open Ionian Sea. In the Salaora Bay, the basal unconformity (SB) forms an elongated basin, with W–E direction and maximum depth of 70 m that is offset by many normal faults, activated since the last transgression (Fig. 6). In the central part of the Gulf, SB appears as a roughened paleo-surface, dominated by shallow V- and U-shaped channels (Fig. 7a). This area has a saddle-like morphology with depths not greater than 50 m, separating the eastern (maximum depth of 69 m) from the western (maximum depth of 75 m) part of the Gulf (Fig. 5). In the eastern paleo-basin, there are some erosional truncations, at depths ranging from 56 to 70 m (Fig. 8). The SB morphology (Fig. 5) suggests that when the sea level was lowered by ~50 m bgs, the paleo-basin in the eastern domain was probably isolated from the other parts of the Gulf, and a lake might have been formed.

4.1.2. Lowstand systems tract (LST)

The lowermost units of the upper sequence (US) constitute the lowstand systems tract (LST), which is identified only in the eastern paleo-basin (Figs. 7b, 8, 9 and 10). The deepest parts of this paleo-lake are
covered partly by a thin (<2 m) and almost transparent seismic unit, consisting presumably of fine-grained material (silt and clay); this unit represents the deep lake deposits (DLD) (Fig. 9). The upper limit of DLD, which is partially eroded, is overlain by another unit that comprises a package of successive strong and faint reflectors (Figs. 8, 9 and 10); the latter unit presents an oblique progradational configuration pattern, which is interpreted as a lowstand deltaic wedge (LDW). This unit is located at depths not shallower than 55 m, implying that deposition occurred when the eastern paleo-basin was isolated from the other parts of the Gulf, and functioned as a paleo-lake. LDW has a maximum thickness of 10 m (Fig. 9), and a NNW–SSE orientation that turns to the east in the deepest part of the paleo-basin (Fig. 11b). The upper limit of LDW is also partially eroded, suggesting fluctuations of the lake level.

4.1.3. Transgressive Surface (TS)

The transgressive surface (TS) represents a stratigraphic discontinuity that separates LST from the overlying transgressive systems tract (TST). TS was formed when seawater entered the Gulf during the last transgression, and can be seen only within the paleo-basin, at depths ranging between 55 and 68 m (Figs. 8, 9 and 10).

4.1.4. Transgressive systems tract (TST)

TST was formed presumably, when sea level rose from ~55 m bpsl to its present position. Four depositional units, comprising the TST, have been identified in the Gulf: (a) the beach–shoreface complex (BSC), (b) incised-channel fill (ICF), (c) transgressive distal prodelta (TDP); and (d) transgressive deltaic wedges (TDW).

BSC is characterised by a hummocky or chaotic pattern, transformed basinwards to subparallel dipping
Fig. 6. 3.5 kHz profile from the Salaora Bay (for location, see Fig. 3) showing faulted incised channel fills (ICF). The transgressive distal prodelta (TDP) unit is bounded below by a ravinement surface (RS), and above by a maximum flooding surface (MFS). The upper highstand units consist of the distal prodelta deposits (HDP) and the intermediate delta wedge (HDW₂). SB, sequence boundary.

Fig. 7. (a) 3.5 kHz profile from the central part of the Gulf (for location, see Fig. 3) showing two different stages of delta deposition: (a) during a first stage, the lower transgressive delta wedge (TDW₁) deposited above the erosional sequence boundary (SB), the incised-valley unit (ICF) and the ravinement surface (RS); and (b) during an earlier stage, the lower highstand delta wedge (HDW₁) is buried within the highstand distal prodelta deposits (HDP). (b) 3.5 kHz profile from the eastern part of the Gulf (for location, see Fig. 3) showing buried terraces. Erosional escarpments from both sides of the paleo-basin are overlain by beach–shoreface complex (BSC) and small transgressive delta wedges (TDWs). Transgressive distal prodelta deposits (unit TDP) cover the sequence boundary (SB) in the deepest parts of the paleo-basin. The highstand unit consists of distant prodelta deposits (HDP) and the upper delta wedge (HDW₃). MFS, maximum flooding surface.
reflections (Fig. 7b). It is located only in the eastern and northeastern margin of the Gulf, at depths ranging between 40 and 55 m bpsl. The upper limit of BSC represents a truncated surface, related probably to coastal processes, whilst the lower limit is associated with the TS.

ICF is a stratified unit that infills: (a) deep and V-shaped paleo-valleys of the Preveza Bay (Fig. 4); (b) wide and asymmetric paleo-channels of the southern Salaora Bay (Fig. 6); and (c) shallow V- and U-shaped channels of the central part of the Gulf (Fig. 7a). This unit has complex fill reflection configuration and contains alternating weak and strong reflectors. The thickness of ICF is variable, but reaches up to 20 m in the central and eastern part of the Preveza Bay. Locally, the top of ICF is overlain discordantly by small packages of strong and subparallel reflectors (perhaps, muddy sand) (Fig. 4).

The upper limits of BSC and ICF are both erosive, and correlate to a ravinement surface (RS) (Figs. 4, 6 and 7a); this unconformity is created by shoreface erosion during the sea level rise. It appears as a high-amplitude and continuous reflection, and lies usually at depths between 46 and 53 m bpsl.

The transgressive distal prodelta (TDP) unit is transparent, with few moderate-amplitude reflections,
representing, possibly, fine-grained deposits. TDP was formed at the basinward extremity of river deltas during the late stage of the last transgression.

Between the promontories Koronisia and Panagia, a transgressive deltaic wedge (unit TDW₁) that presents a hummocky and/or chaotic configuration pattern overlies AB and ICF (Fig. 7a). It has a butterfly-like shape with two distinct depocenters, where the thickness of the deposits reaches 10 m (Fig. 11a).

Another transgressive deltaic wedge (TDW₂), with hummocky and/or chaotic foresets and subparallel bottomsets, is located in the eastern part of the Gulf. TDW₂ is interpreted as a progradational prodeltaic unit, presenting a sigmoid configuration pattern (Figs. 8, 9 and 10). In the deep basin, the continuity of internal high-amplitude reflectors is weakened, evolving to semitransparent facies. The southeastern end of TDW₂ consists of two lobes with similar internal structure and growth. Fig. 10 shows that the upper surface of the western lobe (TDW₂-a) is isochronous with the lower surface of the eastern lobe (TDW₂-b); this implies that when the deposition of the former completed, the latter started to grow. Although there are no data for the landward extension of TDW₂, two depocenters are identified, with maximum thickness <10 m. The upper surface of TDW₂ lies at depths lower than 50 m bpsl (Fig. 11d).

Secondary transgressive deltaic wedges (TDWs), associated with small rivers or streams, are observed in the eastern part of the Gulf. TDWs are found at depths ranging between 30 and 45 m bpsl, and located above BSC (Fig. 7b).

4.1.5. Maximum Flooding Surface (MFS)

The transition from a transgressive to a highstand depositional systems tract is marked by the maximum flooding surface (MFS), which in the case of Amvrakikos Gulf is synchronous to the time of its maximum sea level stand. The MFS is identified as a strong reflector, located at the base of the highstand distal prodelta (HDP) deposits of the Gulf (Figs. 4, 6, 7, 8, 9 and 10). It is usually present at depths ranging from 20 to 60 m bpsl (see Fig. 4), although it cannot be traced, clearly, in the northwestern part of the Gulf. In contrary, MFS in open shelves presents a downlap surface at the base of the highstand progradational wedges (HDW) (Trincardi et al., 1994). This difference is attributed to the geomorphological characteristics of the Gulf, which as a relatively small in size and semi-enclosed basin receives fine-grained sediment continuously since the last seawater intrusion. In addition, onshore and offshore shifting of the river mouths, according to sea level changes and delta growth, is associated with the formation of TDP and HDP, respectively, when the deltaic wedges were being formed much farther.

4.1.6. Highstand Systems Tract (HST)

The uppermost systems tract (HST) was formed during the Holocene highstand. It is a thick package (>35 m) that can be divided into two groups of seismic
Fig. 11. Isopach maps (in milliseconds) of the identified Late Quaternary delta wedges: (a) the TDW₁, (b) the LDW, (c) the HDW₁, (d) the TDW₂, (e) the HDW₂; and (f) HDW₃. The dotted lines are the isochrone contours (in ms) of the upper surface of the wedges.
units: (a) the highstand distal prodelta (HDP) deposits; and (b) highstand deltaic wedges (HDW).

An acoustically transparent unit interrupted by a few reflections of moderate amplitude represents HDP deposits. This unit is likely to consist of fine-grained material (perhaps, clay and mud) and some interposed layers of sandy mud, derived from coastal sources. Its thickness in the Preveza Bay is up to 10 m (Fig. 4) and becomes less than 1 m near the southern shoreline.

Three units, corresponding to three distinct highstand deltaic wedges, can be determined within HST. Stratigraphic correlation between these units, provided by the interpretation of seismic profiles, shows that the oldest wedge is the HDW1 that is located in the central part of the Gulf (Fig. 11c). HDW1 has an

![Graphical representation of sediment cores A-01, A-04, A-07, and A-10 showing vertical changes of lithology, grain size, and carbonate content.](image)

Fig. 12. Vertical changes of lithology, grain size and carbonate content within the sediment cores A-01, A-04, A-07 and A-10, collected by the Amvrakikos Gulf bed, from water depths of 50, 57, 29 and 13 m, respectively (for location, see Fig. 3).
oblique tangential progradational configuration pattern, consisting probably of mud and sandy mud. The thickness reaches 13 m near Cape Koronisia, and increases northwards (Fig. 7a). This unit is partially depicted by the seismic grid, representing probably the distal end of a deltaic prism that had been developed farther to the northeast. In the Salaora Bay, the intermediate wedge (HDW2) comprises a thick package of subparallel inclined reflectors (Fig. 6). It shows an accretional depositional pattern and consists probably of mud and sandy mud alternations. HDW2 could be assumed as an inactive delta wedge, since it is overlain by HDP with maximum thickness of 4.5 m (Fig. 6). Although the lower limit of HDW2 is locally masked by gas, the maximum identified thickness is 40 m at the north, decreasing to the south. The isopach map of HDW2 (Fig. 11e) shows that the system was developed from north to south, and the depocenter is located 3 km to the southwest of Cape Salaora. The distribution of bottomsets shows that HDW2 prograded more than 9 km southwards from the river paleo-mouth. HDW3 is a well-developed deltaic formation, representing the most recent deposits of the Arachthos River. Its internal structure indicates sigmoid progradational configuration, with moderate to high amplitude reflections, and high lateral continuity in proximal settings (Figs. 7b, 8, 9 and 10). HDW3 extends some 8 km basinwards, at water depth of approximately 60 m, whilst some lobe-shaped accumulations are observed downslope (Fig. 10). These lobes are associated with short-lived and independent events of temporal function of secondary river mouths. The depocenter of HDW3 that is located in front of the modern Arachthos River mouth has a maximum thickness of 45 m, decreasing southwards (Fig. 11f). It covers almost the whole eastern part of the Gulf; having, in plan view, a lobate pattern.

4.2. Recent sedimentation pattern

The lithology of the upper depositional units is revealed by the analysis of 4 gravity cores (Fig. 12). Due to their relatively small length (<2.6 m), cores preserve only the recent sedimentary features, formed within the Late Holocene when sea level had already reached its present stage.

Core A-01 has been collected seawards of the present-day mouth of Arachthos River, from the fore-sets of HDW3. The sedimentary facies consist of alternations of thin layers of mud and sandy silt, with low carbonate (<20%) and high terrigenous (>50%) content. Core A-04, recovered from the deepest basin of the Gulf, includes two distinct units: (a) an upper layer (0–90 cm), affected probably by the Arachthos River (prodelta deposits), with many successive laminations of olive gray mud and greenish gray fine sand, and (b) a lower unit (90–150 cm) of almost homogeneous mud, reflecting a calm deep depositional environment. The carbonate content remains low, some 15% in the upper unit and 20% within the lower unit. Core A-07 has been taken from the southwestern margin of the Gulf, and biogenic assemblages are dominant. The carbonate content reaches 67% at a depth of 240 cm below the seafloor, reflecting the abundance of shells and/or shell fragments. Core A-10, located approximately 2 km seawards of the mouth of Louros River, consists of a homogeneous dark olive gray mud with a clay fraction higher than the silt one, and contains some scattered shells (carbonate content ranges from 18% to 20%). This composition reveals deposition of fine-grained riverine/terrigenous sediments, with increased contribution of biogenic material, provided by a river that has a relatively low sediment discharge.

5. Discussion

Interpretation of seismic and core data shows that over the study area, SB represents the irregular surface of the acoustic basement, interpreted as the result of subaerial erosion and fluvial incision during the last glacial period. Poulos et al. (1995) have interpreted SB as the base of Holocene deposits, and the underlying depositional sequences (AB) as consolidated sediments of Plio–Pleistocene age.

Due to lack of seismic data, the exact location of the connection between the Gulf and the Ionian Sea is not established. Nevertheless, the maximum depth of SB in the western extremity of the Preveza Bay is located at a depth of 55 m (Fig. 5), suggesting that the Amvrakikos Gulf was emerged during the last glacial regression. According to eustatic curves, provided by Shackleton (1987), Fairbanks (1989) and Bard et al. (1990) in a global scale, and Lambeck (1996) and Perissoratis and Conispoliatis (2003) in a local
(Greek) scale, the Gulf emergence might have occurred ca. 50 ka BP (Fig. 13). A network of incised paleo-valleys, draining the northern and northwestern catchments of the Gulf, developed afterwards (Fig. 14a). This paleo-river is likely to be a joint hydrographic system of the Arachthos and Louros rivers. In addition, many small rivers or local streams joined the main paleo-river and created lateral incised channels.

However, before the subaerial exposure of the western part of the Gulf, and when the sea level was lowered by ~50 m (ca. 70 ka BP), the eastern paleo-basin was isolated from the other parts of the Gulf, and a paleo-lake was formed. Formation of paleo-lakes during the last glacial regression is common in Greek coasts, and has been confirmed by the analysis of shallow seismic and/or core data, in the cases of the Gulfs of Ierrisos, Strymonikos and Alexandroupolis (Perissoratis and Mitropoulos, 1989), Corinth (Perissoratis et al., 2000), and Saronikos and North Evvoikos (Lykousis et al., 1995). However, in the Amvrakikos Gulf, the acoustic character of the paleo-basin surface implies that significant changes in the sedimentation processes occurred during the initial stage of paleo-lake formation. The unconformity between TST and AB could be explained by a long-term interruption of deposition due to lack of sediment.
Fig. 14. Paleogeographic reconstruction of the Amvrakikos Gulf: (a) during the last regression, when the sea level was lowered by ~55 m (ca. 50 ka BP), an extending network of paleo-rivers developed in the western part of the Gulf, and an isolated lake in the eastern part filled by deep lake deposits (DLD), supplied by minor rivers or streams; (b) from 50 to 11 ka BP, when the Gulf was emerged, the paleo-river still existed, but a tributary of the paleo-river flowed into the paleo-lake forming the lowstand delta wedge (LDW); (c) during the last transgression, when the sea level reached ~55 m bpsl (ca. 11 ka BP), seawater entered the Gulf from the Aktion Strait, and sediments accumulated in the channels and depressions of the western and central part of the Gulf (ICF). On the western side of the Gulf, wave-cut escarpments and beach–shoreface complex (BSC) evidence stillstand periods of sea level. A hummocky transgressive delta (TDW₁) and some other smaller wedges (TDWs) are formed in the central and eastern part of the Gulf, respectively; (d) ca. 9–10 ka BP, when the sea level was 40 m bpsl. A delta wedge with two lobes (TDW₂) and terraces are formed in the eastern part of the Gulf; (e) ca. 6 ka BP, the sea level attained its present position. The mouths of the main rivers retreated some 15 km to the north and only highstand distant prodelta (HDP) deposits settled in the Gulf; (f) since 3–4 ka BP. The shoreline moved to the south due to delta progradation and three highstand delta wedges were developed in the Gulf.
availability or complete desiccation of the lake. This
effect is well documented in some lakes, such as the
Lake Victoria (Stager et al., 2002) and the Lake
Ziway–Shala (Benvenuti et al., 2002), where desicca-
tion has been repeated many times during the Late
Quaternary. Moreover, erosional truncations of SB,
 occurring at depths between 56 and 70 m (Fig. 8),
suggest that the lake base level might have fluctuated,
followings variations in freshwater inputs due to Late
Quaternary climatological changes. Similar features
have been identified within the lakes Titicaca
(D'Agostino et al., 2003), Lisan (Bartov et al.,
2002) and Baikal (Urabe et al., 2004), and have
been attributed also to changes of lake level.

Subsequently, sediment inputs, induced mainly
from small rivers and streams, covered the deepest
part of the paleo-basin with fine-grained material
(DLD) (Fig. 14b). Following the formation of DLD,
the lake level might have been lowered by ~75 m
bpsl; this explanation is based on the observation that
part of the upper limit of DLD was truncated by
subaerial erosion. During a later stage of the paleo-
lake evolution, a progressive delta (LDW) was devel-
oped in the western part of the lake, covering the thin
DLD unit and part of AB. The growth of LDW
stopped by a lake level lowering, resulting in a partial
emergence of the foresets that subsequently, eroded
subaerially (Figs. 9 and 10).

The western part of the Gulf was flooded by sea-
water when the sea level rose ~55 m (ca. 11 ka BP),
whilst seawater entered the paleo-lake, later, when the
sea level reached approximately ~50 m. Over this
period, in the western part of the Gulf, poorly bedded
estuarine fine sands and silts filled the pre-existing
incised valleys that were paved probably by fluvial
coarse-grained materials. In the eastern domain, trans-
gressive deposits covered the lacustrine LST.

Buried marine escarpments found in the eastern
margin of the paleo-basin at depths ranging between
50 and 40 m indicate a step-like rise of the sea level,
during the last transgression. This type of sea level
rise has been observed also in the Gulf of Mexico
(Nelson and Bray, 1970), southwestern Pacific (Cart-
er et al., 1986), Spanish shelves (Hernández-Molina
et al., 1994), Gulf of Cadiz (Somoza et al., 1997;
Lobo et al., 2001), and in Greek shelves (Van Andel
and Lianos, 1984; Chronis et al., 1991). Posamentier
et al. (1992) have studied analogous erosional fea-
tures in the small delta of East Coulee, and point out
that these escarpments may be wave-cut surfaces,
formed during the transgression of the shoreline. In
addition, Trincardi et al. (1994) found large marine
terraces within the Late Quaternary sequence of the
Adriatic Sea, pointing out that the terrace height is
 inversely proportional to water depth; this is based on
the assumption that the hydrodynamic regime (i.e.,
wave energy) increased progressively due to shelf
widening during the sea level rise. In the Amvrakikos
Gulf, the accumulation of the beach–shoreface depos-
its (BSC) over escarpments suggests that short peri-
ods of stillstand or even minor regressions took place
during the last transgression. This step-like rise of the
sea level has been not identified as a local phenom-
emon but a common process affecting many continen-
tal shelves (Evans et al., 1992; Saito, 1994; Duncan
et al., 2000; Lobo et al., 2001). However, subsequent
accelerations of water level rise resulted in rapid
landward migration of the shoreline, which caused
truncation of the uppermost ICF and BSC surfaces.
Above this erosive surface that corresponds to TS, a
transgressive delta wedge (TDW₁) and some small
prograding deltas (TDWs) were formed (Fig. 14c).
TDW₁ overlies the sequence boundary in the central
part of the Gulf and might have deposited during an
earlier stage of the sea level rise and most probably
soon after seawater intrusion into the Gulf. The shape
of TDW₁ was affected by the local paleo-morphology
and the rate of sediment supply. The shallow area
between the capes Salaora and Panagia did not allow
a typical formation of a deltaic prism; but instead,
two lobes were formed to the northwest and south-
east, respectively.

Stratigraphic correlation between the two trans-
gressive delta wedges (TDW₁ and TDW₂) reveals
that the wedge in the eastern part of the Gulf
(TDW₂) may be younger than TDW₁. Presumably,
the river that formed TDW₁, abandoned its course
when the shoreline retreated toward the northeastern,
and shifted eastward to form the TDW₂. On the
northern margin of the paleo-basin (Fig. 14d),
TDW₂ has a normal fan-like shape with two lobes.
Furthermore, the creation of the western lobe followed
the completion of the eastern lobe, suggesting that the
overall sedimentation process was not interrupted.

During this period, all the rivers supplied very fine-
grained material to the submerged Gulf, creating the
transgressive distal prodelta (TDP) unit. Lykousis and Chronis (1989) found analogous acoustically transparent units in the Thermaikos Gulf (Greece), and interpreted them as the most distant delta/prodelta sediments, deposited under calm hydrodynamic conditions (weak currents). In the Amvrakikos Gulf, the TDP overlies parts of SB, ICF, BSC and LDW. Due to its internal uniformity, limited information can be extracted for the exact origin (i.e., which and where was the major sediment supply) and the time period of deposition of this unit.

The rise of the sea level from –40 m (ca. 10 ka BP) to approximately its present position (ca. 6 ka BP) resulted to a farther landward movement of the shoreline. In particular, on the northern margin of the Gulf, where its slope was gentle, the shoreline retreated about 15 km to the north from its previous position (Poulos et al., 2005). During this period, the Arachthos and Louros rivers separated, and their mouths moved independently to the northeast and northwest, respectively. Nevertheless, fine-grained sediments, derived from those rivers, reached the Gulf and formed the uppermost part of TDP.

At ca. 6 ka BP, the stabilization of sea level is delineated by MFS (Fig. 14e), followed by the deposition of the Holocene HST. The rivers Arachthos and Louros supplied sediments to the northern margin of the Gulf, gradually forming the Holocene deltaic complex (Poulos et al., 1995; Tziavos, 1996). In parallel, fine-grained material accumulated in the deepest parts of the Gulf, forming HDP.

The Holocene HDW1 deposited firstly in the central part of the Gulf (Fig. 14f). In the seismic profiles, HDW1 can be traced only at its southeastern extremity, as the river mouth is located farther to the north. The age of this formation is uncertain. However, Poulos et al. (2005), based on micropaleontological and radiocarbon analysis of sediment cores from the deltaic plain and archaeological evidence, suggest that ca. 3–4 ka BP, the mouth of the Arachthos River was located to the west of its present position. Since then, the river shifted towards the south, near Salaora, where it formed a thick deltaic prism (HDW2). The shape, the internal structure and, in particular, the thickness (~40 m) of this wedge ensure the formation of the HDW2 by the Arachthos River, and not by the Louros River that is characterised by much lower sediment fluxes. Subsequently, the Arachthos River mouth moved eastwards, near Paleobouka and formed the western lobe of the HDW3.

Historical charts of the Amvrakikos Gulf confirm that the Arachthos River was discharging at Paleobouka at least from the 17th Century A.D. (Coronelli, 1690) to the end of the 19th Century. Since the beginning of the 20th Century, the mouth shifted to its present position. These charts show also that, at least since 1690, the mouth of Louros River is located at the northwestern extremity of the Gulf, without any significant displacement. During the last 50 yr, human intervention on the deltaic plain, such as artificial diversion and realignment of the lowest course of the Arachthos River, wetlands draining, development of an extended irrigated network, and construction of dams along the main river course, has affected to a great extent the sediment supply, and therefore, the present-day sedimentation patterns.

6. Conclusions

The Amvrakikos Gulf has been subjected to extended geomorphological changes during the Late Quaternary, induced by sea level fluctuations, neotectonic activity and deltaic progradation processes. Due to the presence a sill at the entrance of the gulf and the basin geometry (relatively small size but substantial deep), sediments, mostly associated with fluvial origin, were trapped within the Gulf, forming a thick depositional sequence.

During the last regression, when sea level was lowered by ~55 m (ca. 50 ka BP), the gulf was isolated from the Ionian Sea. The western part of the gulf was exposed to subaerial erosion and incised by a network of paleo-rivers, whilst in its deeper eastern part, a paleo-lake formed, receiving freshwater and sediment inputs. Within the paleo-lake, a thin unit of fine-grained deposits accumulated firstly in the deepest parts, and a lowstand deltaic wedge was formed subsequently, by a small river (most probably, a tributary of the main paleo-river).

Seawater entered the Gulf approximately at 11 ka BP, possibly from the Aktion Strait, and transgressive deposits filled the incised-channels and parts of the eroded bed. Subsequently, during the period from ca. 11 to ca. 9 ka BP the Gulf is characterised by
step-like sea level rise, with many stillstand events. This process is evidenced by the presence of buried terraces, preserved on the eastern margin of the Gulf at water depths ranging from 40 to 50 m. At the achievement of the transgression, two main prograding delta wedges developed within the Gulf, from which the older wedge is located to the southwest of Koronisia, and the younger one in the eastern part of the Gulf.

At the time of maximum flooding (ca. 6 ka BP), distal prodelta highstand deposits covered the Gulf. This is associated with the southward progradation of the northern margin of the Gulf and in particular, the deltas of the rivers Arachthos and Louros. Thus, during the last prehistoric time (ca. 3–4 ka BP), the shoreline reached approximately its present position. Since then, three successive highstand delta wedges deposited, reflecting the changes in the position of the river mouths. The most recent wedge, formed in the eastern part of the Gulf, corresponds to the modern deltaic deposits of the Arachthos River.

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