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Active faults, deformation rates and Quaternary paleogeography at Kyparissiakos Gulf (SW Greece) deduced from onshore and offshore data

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Abstract

Kyparissiakos Gulf forms a 45 km long zone located at 70–80 km east from the Hellenic trench with a general direction NNW–SSE. Onshore studies show the existence of several neotectonic horsts and grabens bounded by E–W trending normal faults. Thrust sheets of the underlying Hellenides crop out within the horst areas and younger sediments, mostly Lower Pleistocene, have been deposited in the grabens. The age of the marine sediments is mostly Lower Pleistocene. Throw rate on the normal faults varies between 0.7 and >1.0 mm/yr, accommodating extension in the N–S direction. Subsidence rates during Early Pleistocene are between 0.1 and 0.3 mm/yr, whereas uplift rates during Middle Pleistocene–Present are between 0.18 and 0.50 mm/yr. Offshore data were obtained using bathymetric and air-gun litho-seismic profiles. The shelf has been disrupted by active faults with several meters of throw. Average Holocene throw rates are 0.4–0.6 mm/yr, but in some areas adjacent Filiatra and Olympia values greater than 3 mm/yr are detected. Holocene and Upper Pleistocene marine sediments thicken gradually to the north, as do the marine Lower Pleistocene sediments onshore. A NNW–SSE offshore longitudinal fault parallel to the Kyparissiakos coast with throw rate above 3 mm/yr is the dividing structure between the uplifted coastal area and the present-day gulf. This indicates a major change in paleogeography between Early and Middle Pleistocene. Present-day transition from E–W compression in the Hellenic Trench to E–W extension in the Kyparissiakos Gulf and to N–S extension in Western Peloponnesus is discussed. The development of E–W structures in Western Peloponnesus since Latest Pliocene may be related to the Central Hellenic Shear Zone, which accommodates differential GPS rates between Northern Greece and Southern Peloponnesus.

1. Introduction

Kyparissiakos Gulf forms a 45 km long segment of the Ionian coast of central–western Peloponnesus, trending north–northwest and paralleling the Hellenic Trench, which is about 70–80 km to the west (Fig. 1a). The general tectonic trend of the gulf is NNW–SSE, following the geometry of the fold and thrust belt of the External Hellenides (Philippson, 1898; Aubouin et al., 1961; Aubouin, 1977; Jacobshagen, 1979) and of the modern Hellenic arc and trench system (McKenzie, 1972; LePichon and Angelier, 1979). However, neotectonic structures in the area are not oriented parallel to the arc in the NNW–SSE direction. Instead, there are several east–west trending normal faults forming the margins of the post-Alpine basins developed on top of the thrust sheets of the Hellenides, with alternating horst and graben structure (Fig. 1b; Mariolakos and Papanikolaou, 1981, 1987; Mariolakos et al., 1985).

Extended outcrops of marine lower Pleistocene sediments are observed within the grabens along the coastal zone up to 15–20 km distance from the coastline and at altitudes of several hundred meters (Fountoulis, 1994; Mariolakos et al., 1998). This demonstrates the occurrence of significant vertical tectonic movements during the Quaternary, which permitted the deposition of marine quaternary sediments in subsided areas and their subsequent uplift and erosion at their present state. The

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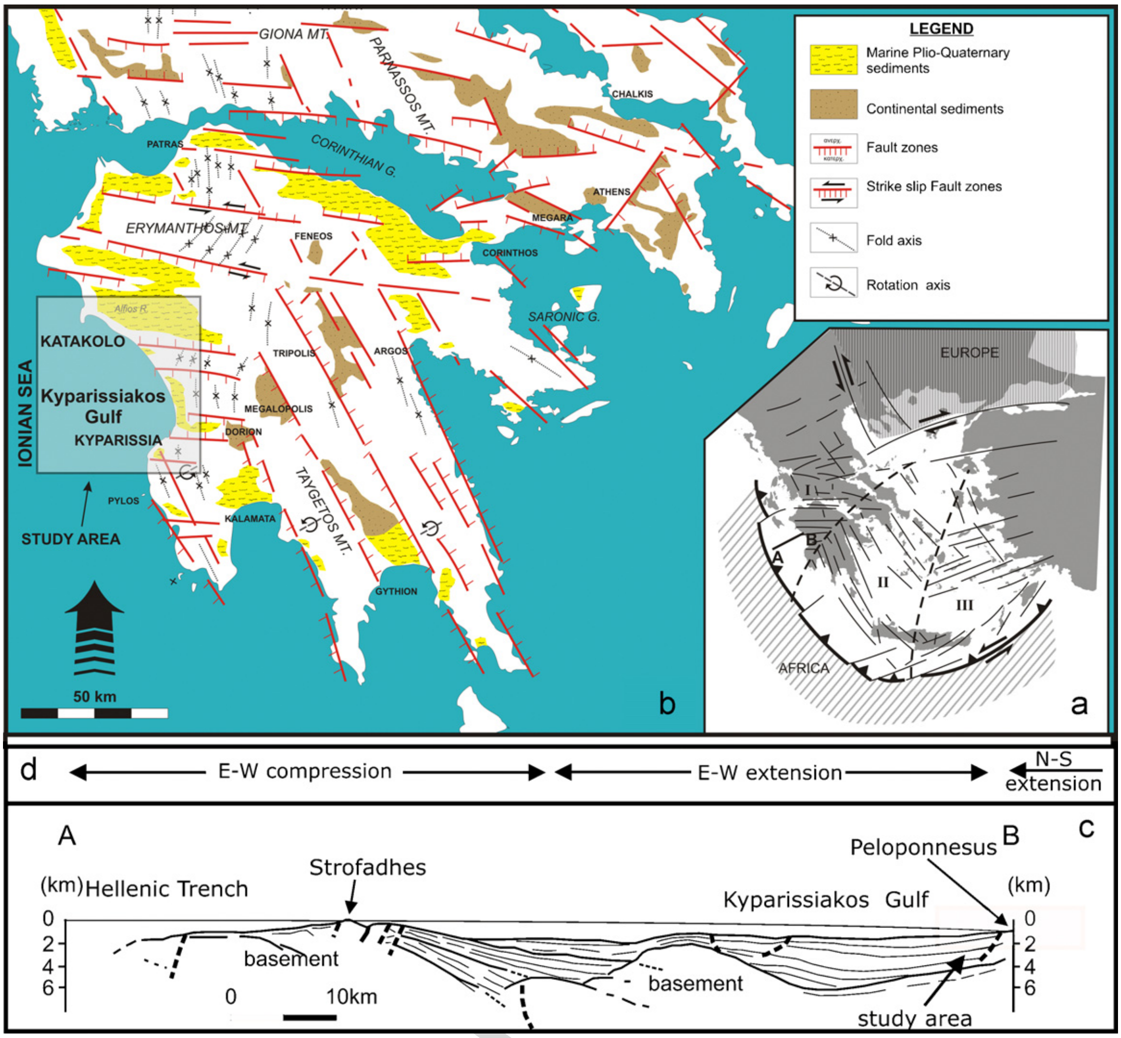

Fig. 1. (a) Structural sketch of the Hellenic arc showing also the distinction of three domains with different neotectonic trends: E–W for I, NNW–SSE for II and ENE–WSW for III. (b) Location of the studied area of Kyparissiakos Gulf within the neotectonic frame of Peloponnesus (after Mariolakos and Papanikolaou, 1981, 1987, modified). (c) The ENE–WSW geotectonic profile from the Hellenic trench through the Strophades islands to Kyparissiakos Gulf including the position of the studied area (after Monopolis and Bruneton, 1982, modified). The trace of the profile is shown in (a). (d) Deformation zones across the geotectonic profile in (c).

extensional character of this tectonism observed near the front of the Hellenic arc and at a few tens of kilometers above the subducting slab of the East Mediterranean basin provides an exceptional opportunity to study the closely spaced transition from compressional to extensional deformation in an evolving arc.

Although the E–W neotectonic faults propagate westwards into the gulf, no studies concerning the offshore geometry have been compiled. The only available data concern the structure and the depositional patterns of the deep sediments near the Hellenic trench (Lequellec et al., 1980; Vittori et al., 1981; Mascle et al., 1982) and one tectonic profile based on geophysical and drilling data through the Strophades islands (Fig. 1c; Monopolis and Bruneton, 1982). A more detailed study of the recent sedimentation relating to the Alfios River outloading in the Kyparissiakos Gulf has been presented more recently (Poulos et al., 2002).

Our study (a) provides unprecedented offshore and onshore data, (b) compares onshore and offshore data of the Kyparissiakos Gulf, in order to test whether the uppermost Pleistocene to Holocene well displayed offshore deformation pattern, is comparable to the Plio-Quaternary history recorded onshore and (c) discusses some paleogeographic implications throughout Quaternary in this area within the general geodynamic evolution of the Hellenic arc.

Onshore fieldwork comprised detailed geological mapping with emphasis on Quaternary marine deposits and active fault zones. The offshore fieldwork was carried out on the R/V AEGEON of the Hellenic Center for Marine Research. The litho-seismic data were obtained using an "AIR GUN 10 in.^{3}" profiling system. Seismic profiles were conducted in a zigzag pattern, with depths ranging from 40 to 50 m near the coast up to several hundred meters in the open sea, so as to trace all active faults near the coast and correlate them with faults mapped along the coastal zone onshore.

2. Onshore structures

Several studies have been implemented in the onshore coastal zone of Kyparissiakos Gulf analyzing the stratigraphy and structure of the post-Alpine sedimentary sequences (Hageman, 1977; Kamberis, 1987; Fountoulis, 1994; Fountoulis and Moraiti, 1994, 1998). These sediments are unconformably overlying the Alpine formations and comprise continental and marine deposits of Pliocene and Quaternary age (Fig. 2). The successive episodes of sedimentation and erosion with respect to the vertical neotectonic movements and the resulting landscapes have been analyzed by Dufaure (1977) within his general study of Peloponnesus.

The Alpine formations mainly belong to the Pindos nappe, which comprises a Mesozoic pelagic sequence and a Paleogene flysch. Thick molassic conglomerates of Miocene age occur at the front of the Pindos nappe in the area south of Kyparissia (Fig. 2). The underlying Gavrovo nappe, comprising Mesozoic to upper Eocene shallow water carbonates and an upper Eocene–Oligocene flysch, occurs at the area of Filiatra in the south, whereas a small outcrop of the more external Ionian nappe

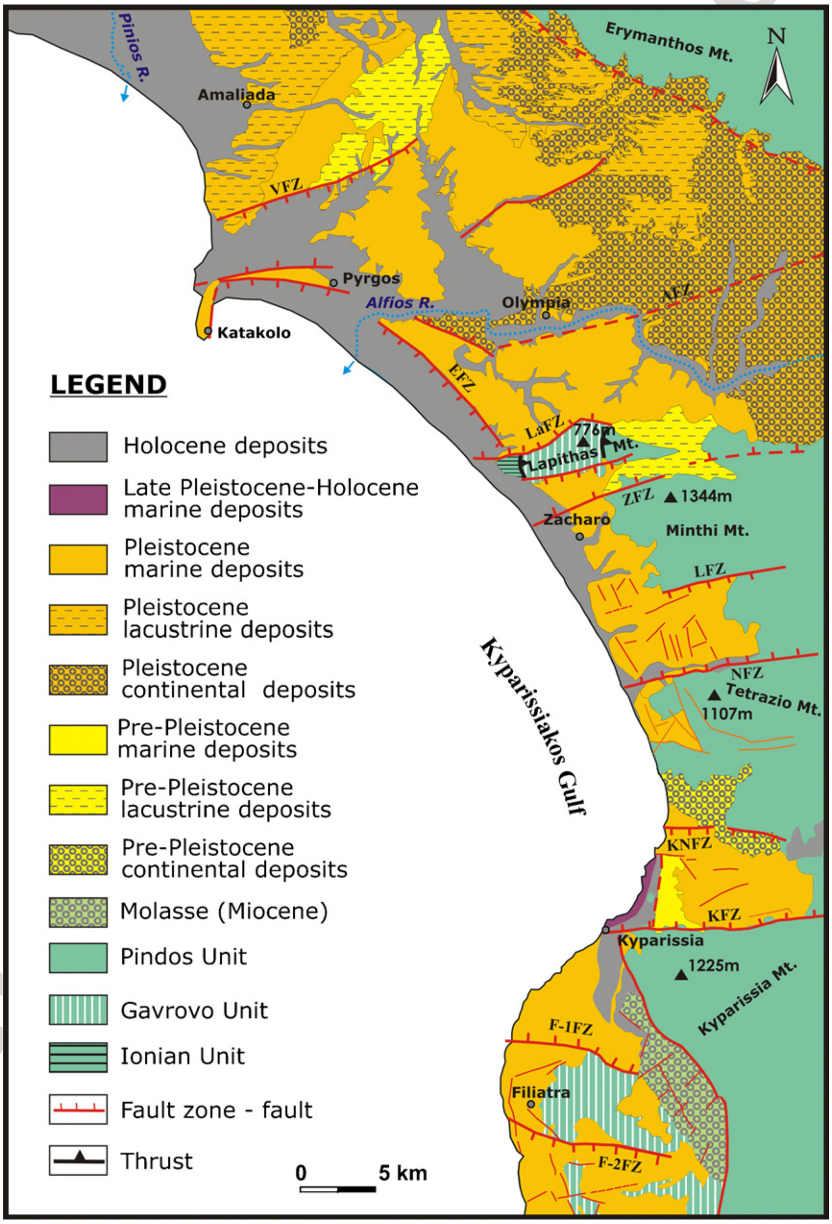

Fig. 2. Simplified geological map of the coastal zone along Kyparissiakos Gulf. F-1FZ: Filiatra-1 fault zone, F-2FZ: Filiatra-2 fault zone, KFZ: Kyparissia fault zone, KNFZ: Kalo Nero fault zone, NFZ: Neda fault zone, LFZ: Lepreo fault zone, ZFZ: Zaharo fault zone, LaFZ: Lapithas fault zone, AFZ: Alfios fault zone, EFZ: Epitalio fault zone, VFZ: Vounargo fault zone (mainly from the neotectonic maps at scale 1/100,000 of Filiatra) (Mariolakos et al., 1998), and Pyrgos–Tropaea (Lekkas et al., 1992).

occurs at the western part of Lapithas Mt. near the Olympia basin at the north (Fig. 2; Fountoulis and Lekkas, 1991).

Continental and lacustrine Pliocene–Lower Pleistocene deposits occur mainly at the eastern part of the Olympia basin (Erymanthos Fm after Hageman, 1977), whereas marine sediments occurring along the coastal zone of the gulf (Vounargon Fm after Hageman, 1977) are mainly of Lower Pleistocene age (Fig. 2).

The neotectonic structure of Kyparissiakos Gulf comprises a number of successive horsts and grabens, extending from the Kyparissia Mt. horst toward the south to the Katakolon peninsula and Vounargon fault zone to the north (see also the Neotectonic Map of Filiatra at scale 1/100,000, Mariolakos et al., 1998; Neotectonic Map of Pyrgos and Tropaea at scale 1/100,000, Lekkas et al., 1992).

Starting southwards the Kyparissia Mt. (1225 m) represents an uplifted neotectonic block and consists of Pindos unit Alpine formations. The E–W trending Kyparissia fault zone (KFZ in Fig. 2) is more than 20 km long and is located along strike the foot-slopes of the Kyparissia Mountain. Its throw is 1.4 km, an estimation based on the offset unconformity between the Alpine and the post-Alpine formations. The same fault has produced also dextral strike-slip motion, as shown by the offset of geological formations and the abrupt change of the Kyparissiakos coastline to the south (Fig. 2).

The tectonic graben of Kyparissia–Kalo Nero extends north of the Kyparissia fault and is bounded to the north by the Kalo Nero fault (KNFZ in Fig. 2). This structure contains, at its base, upper Miocene–Lower Pliocene marine sediments covered unconformably by marine Pleistocene sediments (Fountoulis and Moraiti, 1994). The lower marine sequence is similar to coeval rocks cropping out in the Ionian Islands (e.g., Zakynthos) and is probably involved in the late thrusting of the external Hellenides. The upper marine sequence is of Lower Pleistocene age and similar to other post-Alpine sequences of the central western Peloponnesus. Total thickness of the marine Pleistocene sediments in this basin is 150 m. However, in neighboring basins to the north, thickness exceeds 300 m towards the Neda and Zacharo grabens (Fountoulis, 1994; Fountoulis and Moraiti, 1994, 1998), whereas in the Olympia basin, the thickness of the Pleistocene sediments is estimated to be more than 1 km (Hageman, 1977; Kamberis, 1987). Late Pleistocene (Tyrhennian) and Holocene marine sediments crop out along the coastline from Kyparissia to Kalo Nero (Fig. 2). This outcrop shows that important uplift has occurred during the last few tens of thousands of years in this neotectonic graben.

The following structure northwards is the Tetrazio horst (1107 m), where the thrust sheets of the external Hellenides reappear at the surface (the Pindos unit). The Tetrazio horst is bounded to the north by the Neda fault (NFZ in Fig. 2), that is parallel to the Neda River.

The Neda graben is bounded by the Neda fault in the south and the Lepreo fault (LFZ in Fig. 2) in the north. Marine Pleistocene sediments within this basin are traced up to 12 km distance from the present-day coastline. These sediments abut on the Lepreo normal fault that dips 40–45° southwards. The uppermost marine sediments in Neda basin have been dated as Middle Pleistocene (Fountoulis and Moraiti, 1998).

The Minthi horst (1344 m) extends from the Lepreo fault southwards to the Zacharo fault northwards (ZFZ in Fig. 2). Marine Pleistocene sediments are traced along its western margin, forming a narrow, few-kilometer wide zone.

The Zacharo basin is a narrow graben, a few kilometers in width, located immediately north of the Minthi horst and extending up to the southern boundary of the Lapithas horst. The basin comprises a lower lacustrine sequence of Pliocene age, toward the eastern part that is probably related to the Olympia basin (Hageman, 1977), and an upper sequence of marine lower Pleistocene sediments at the western part. At Lapithas Mt. (776 m), the previously mentioned Pindos unit, cropping out all the way to Kyparissia in the south, is uplifted and the underlying more external Gavrovo and Ionian units crop out (Fountoulis and Lekkas, 1991). The Lapithas fault (LaFZ in Fig. 2) forms the northern margin of the horst and is visible from a large distance as an abrupt cliff above the sediments of the Olympia basin.

North of the Lapithas horst, thrust sheets of the external Hellenides disappear below the thick sedimentary sequences of the Olympia basin. The Kyparissiakos structure ends in the area of Katakolon peninsula, where a small horst structure is observed within the Pleistocene sequences. The Vounargon fault (VFZ in Fig. 2) bounds the marine sedimentary basin of Olympia to the north, with several hundred meters of throw. In the Olympia basin, there are more than 3 km of Plio-Quaternary sediments, including some diapiric structures related to the existence of Upper Miocene evaporites at depth, detected from geophysical prospecting and drilling (Hageman, 1977; Kamberis, 1987; Tsaila-Monopolis et al., 1993). The eastern margin of the Olympia basin is a NW–SE trending fault zone. This fault zone appears to be inactive during the Quaternary as indicated by the continuity of the planation surfaces to the northeast of the zone. The E–W trending active faults in the Pyrgos area within the Olympia basin have been analyzed following the 1993 destructive earthquake (Koukouvelas et al., 1996; Lekkas et al., 2000). An exception as far as the direction of active faults concerns the Epitalion fault (EFZ in Fig. 2) which has a NNW–SSE trend instead of E–W. This fault is observed along the coast of Kyparissiakos along a well-defined linear structure, which separates the Holocene coastal deposits to the west from the uplifted marine Pleistocene sediments to the east.

Fig. 3 displays a NNW–SSE profile about 5 km from the coast cutting across the approximately E–W trending faults

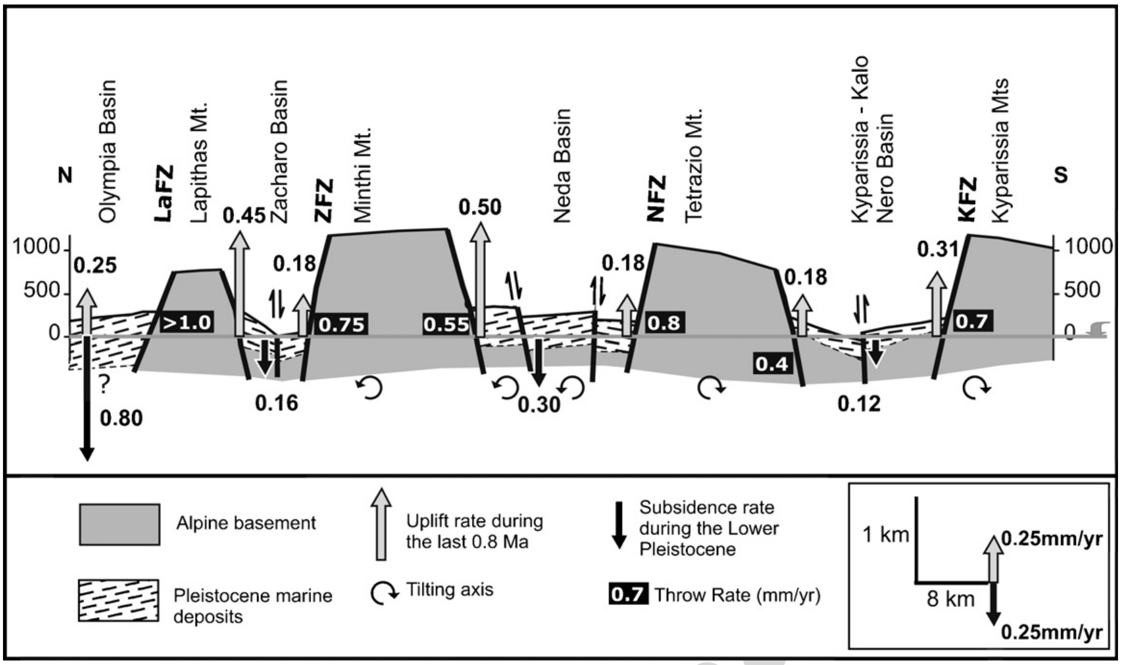

Fig. 3. Schematic cross-section of the neotectonic E–W horst and graben structure of central western Peloponnesus (after Fountoulis, 1994, modified). Indications of the throw rates along the major marginal fault zones for the Plio-Quaternary period, subsidence rates within the Uppermost Pliocene–Lower Pleistocene marine basins and uplift rates of the marine sediments during Middle Pleistocene–Present are shown.

and show the deformation rate pattern. All major neotectonic blocks and their marginal faults are shown, whereas topography has been modeled in each block having either horizontal or inclined planar surfaces. This is based either on the planation surfaces developed over the Alpine formations at the top of the horsts or on the general dip of the bedding of the marine sediments in the grabens. The geological formations are distinguished in Alpine basement (mostly the Pindos nappe) or in marine Lower Pleistocene sediments. Thus, the synthetic profile shows the deformation pattern approximately over the last 2 million years. The topographic difference of the top of the Alpine formations at the horsts with their unconformity below the Pleistocene marine sediments at the grabens gives a minimum estimate of the total throw of the marginal faults of the basins. The deformation can be further divided in two stages: (i) the first stage from Latest Pliocene to Latest Lower Pleistocene (approximately 0.8 my) that lasted about 1.2 my, is characterized by fault activity mainly across the marginal faults of the grabens and subsidence of the basins with sea transgression and deposition of marine sediments. The thickness of the marine sedimentation can provide an estimate of the subsidence rate for this period. (ii) The second stage from the beginning of Middle Pleistocene to Present (about 0.8 my) is characterized by uplift and erosion of the marine Lower Pleistocene sediments. The altitude of the marine outcrops indicates the minimum amount of uplift that can be obtained for this second period.

Quaternary average throw rates differ across the profile with smaller values 0.7–0.8 mm/yr southwards in Kyparissia, Neda and Zacharo fault zones and higher values towards the north with >1.0 mm/yr in the northern marginal fault of the Lapithas horst towards the Olympia basin. Early Pleistocene subsidence rates range between 0.1 and 0.3 mm/yr in the three basins of Zacharo, Neda and Kyparissia–Kalo Nero. On the contrary, a much higher subsidence rate (0.8 mm/yr) is calculated for the Olympia basin. Middle Pleistocene–Present uplift rates range between 0.18 and 0.50 mm/yr, including the uplift rate of the Olympia basin. In general, uplift rates are much higher than subsidence rates and this explains why the marine sediments are now uplifted and eroded even though the period of uplift is almost half than that of the subsidence.

3. Offshore structures

Offshore data analysis includes the study of (a) the bathymetric data focusing on the submarine topography of the continental shelf and slope of Kyparissiakos Gulf and (b) the air-gun litho-seismic profiles of the surveyed coastal zone.

Previous studies of the coastal zone of Peloponnesus in Messiniakos, Lakonikos and Argolikos gulfs (Papanikolaou et al., 1988, 1994, 2001; Pavlakis et al., 1988) have shown that the continental shelf forms a subhorizontal plane with a very low morphological slope of about 1–3% from the coast to a depth of about 110–120 m. At the knick point between the continental shelf and the slope, there is an abrupt increase in slope of about 5–10%, which may be maintained down to the basin at large depths, where it becomes again subhorizontal. The edge of the continental shelf coincides with the horizontal plane of the Holocene transgressive unconformity, produced by the global sea level rise following the last glacial period. The deformed Holocene sediments of the continental shelf provide us with valuable information regarding not only the location of active faults but Holocene throw rates as well. This has been already shown in Messiniakos Gulf, where vertical offsets of several meters have been mapped in the active faults bordering the neotectonic blocks around the gulf (Pavlakis et al., 1988).

The edge of the continental shelf is traced all along the Kyparissiakos Gulf (Fig. 4), except in front of the deltas of the two major rivers of the western Peloponnesus, Pinios and Alfios, where it has been partly buried and distorted,

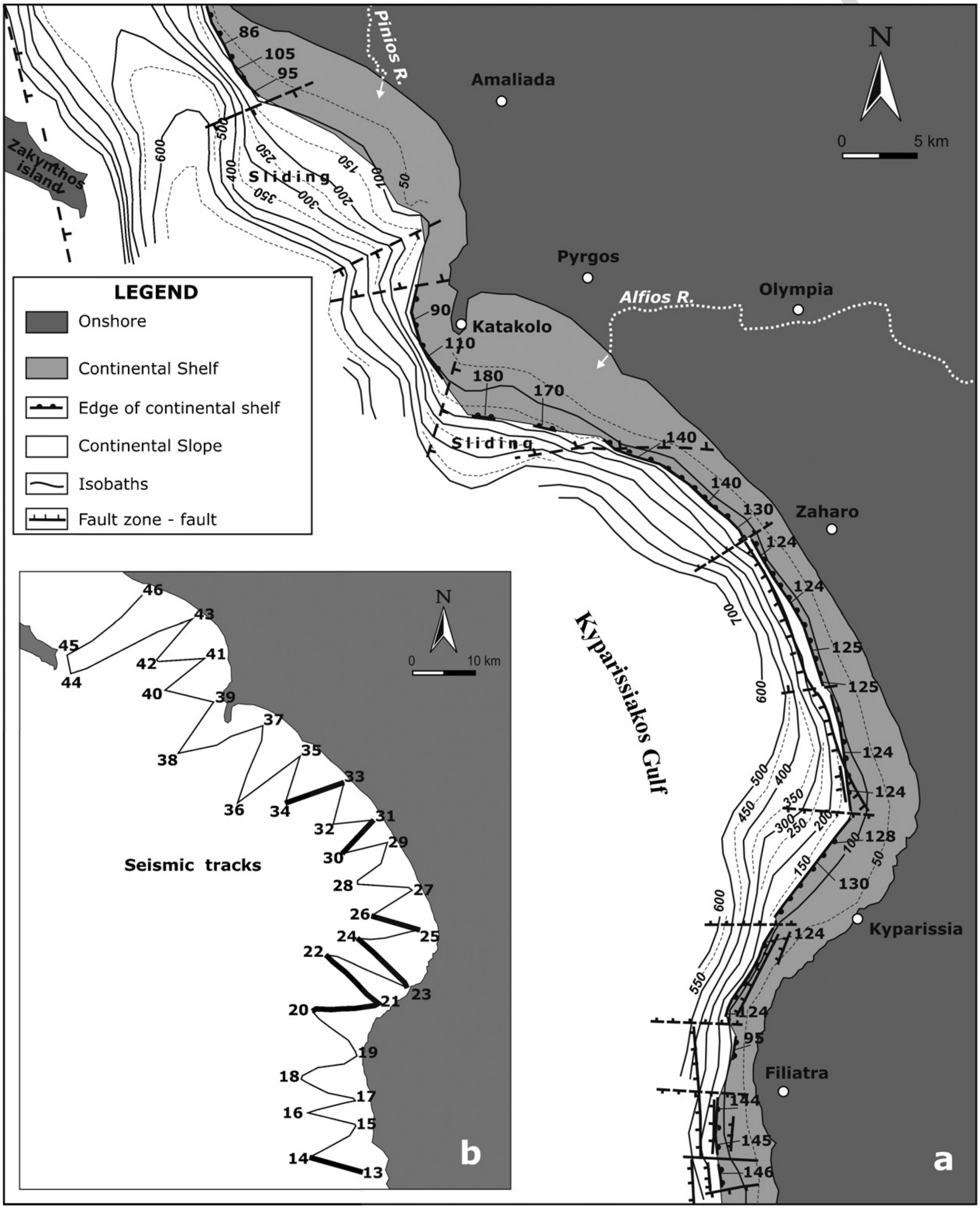

Fig. 4. (a) Submarine map of Kyparissiakos Gulf showing the coastal bathymetry, the geometry and the depth of the edge of the continental shelf and the detected faults. The location of the seismic tracks with R/V Aegaeo is shown in (b). Thick tracks correspond to the profiles given in following figures.

due both to the high sedimentation rates that outpass fault throw rates and the sliding phenomena occurring within the deltaic sediments. The Holocene transgression is clearly reflected by the angular unconformity between the sub-horizontal Holocene strata and the underlying Pleistocene strata dipping to the west (Fig. 5). The upper sequence (H) is very thin with a maximum thickness of about 20–25 m, laterally decreasing down to 1 m near the edge of the shelf, forming a Holocene sedimentary prism. The lower sedimentary sequence (Pst1) has a thickness of more than 50 m with a slight decrease towards the basin and its age is probably Upper Pleistocene. A second angular unconformity is detected below this sequence with a dip similar to the general stratification of Pst1. The sedimentary sequence Pst2 below this second unconformity shows a higher dip of the strata, which are more than 80 m thick and their age is probably Middle Pleistocene. This pattern of litho-stratigraphy can be traced all along the gulf. A systematic change of the thickness of each sedimentary sequence is also observed with an increase towards the north (see Fig. 13). In the area of Pinios basin north of Pyrgos, marine terraces cropping out at about 100–120 m altitude have been dated as Middle Pleistocene (Stamatopoulos et al., 1998).

Contrary to the smoothed development of the shelf shown in Fig. 5, there are segments where the shelf is missing and the continental slope reaches the coastline through a complex structure of a disrupted margin. Fig. 6 shows a seismic profile, taken from the southern part of our study area south of Filiatra, where Holocene sedimentary sequence or unconformity is not observed. In this example, the Alpine basement can be identified within the horsts.

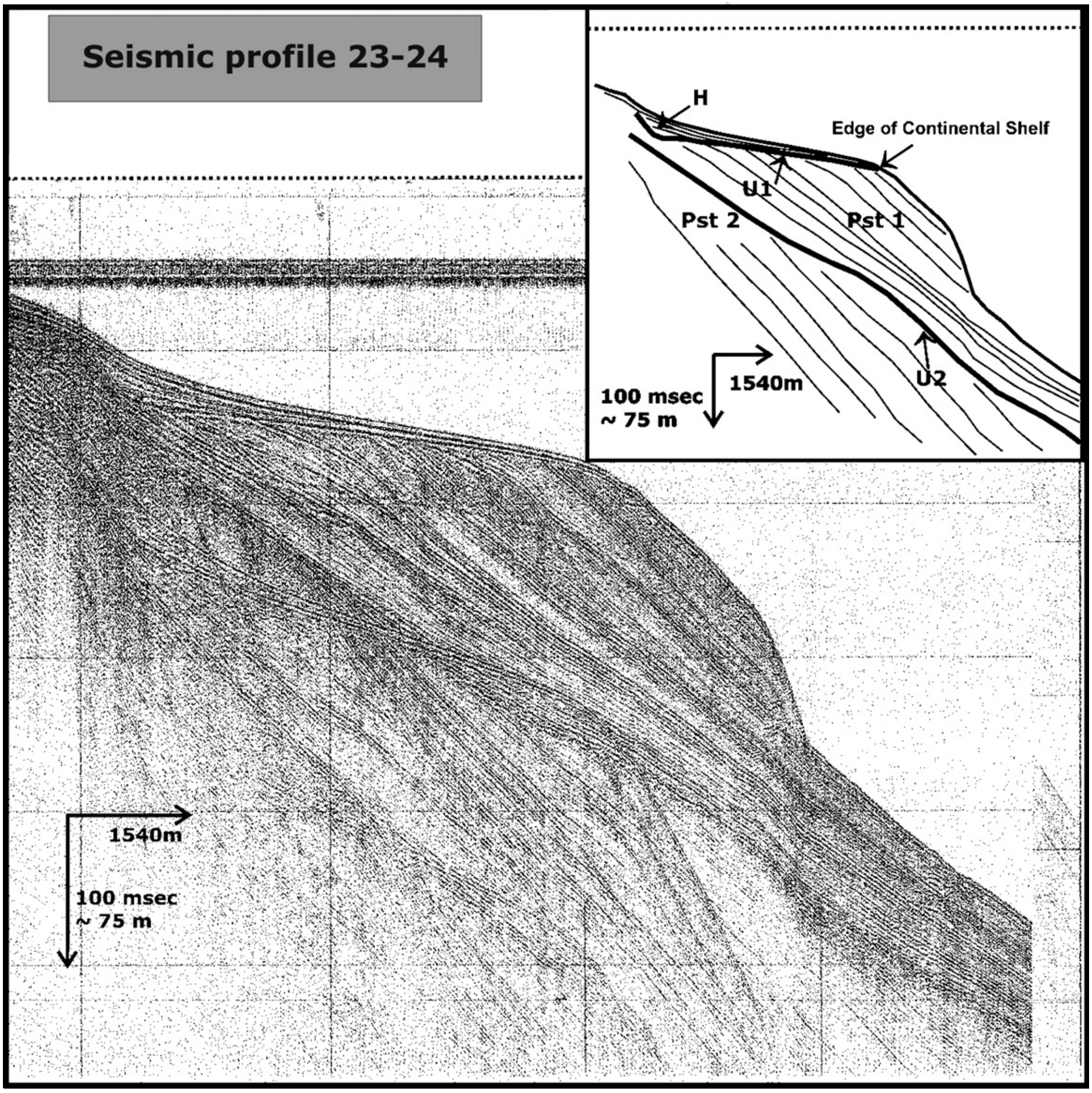

Fig. 5. Litho-seismic profile 23–24 of Kyparissiakos Gulf. The continental shelf is beautifully developed and the Holocene trangressive sequence (H) forms the upper unconformity (U1). A second deeper unconformity (U2) is also nicely detected below the (?) Upper Pleistocene sequence (Pst1) and the underlying (?) Middle Pleistocene sequence (Pst2). No fault is observed across this profile. The edge of the shelf is marked on the sea bottom topography by the subhorizontal surface of the upper unconformity (U1) and the abrupt change of the morphological slope, which parallels the general bedding of the underlying sequence (Pst1).

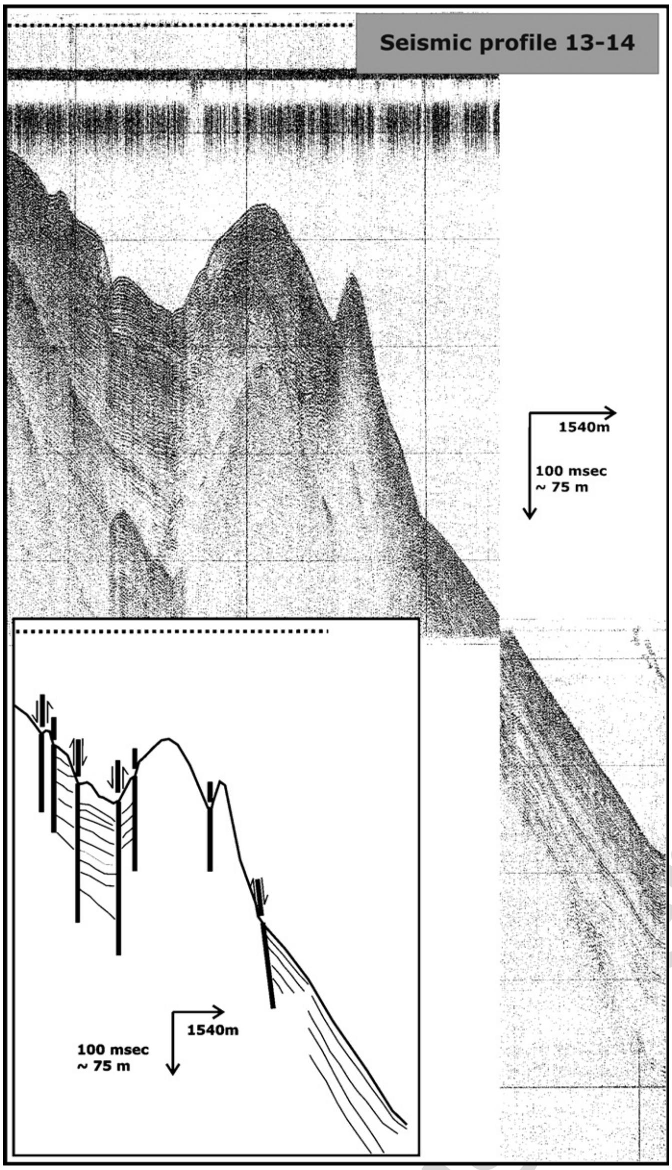

Fig. 6. Litho-seismic profile 13–14 of Kyparissiakos Gulf. The continental shelf is absent and instead a strongly disrupted margin is shown above the geometric development of the slope. The absence of reflectors in the domes/horsts of the margin corresponds to the presence of Alpine basement.

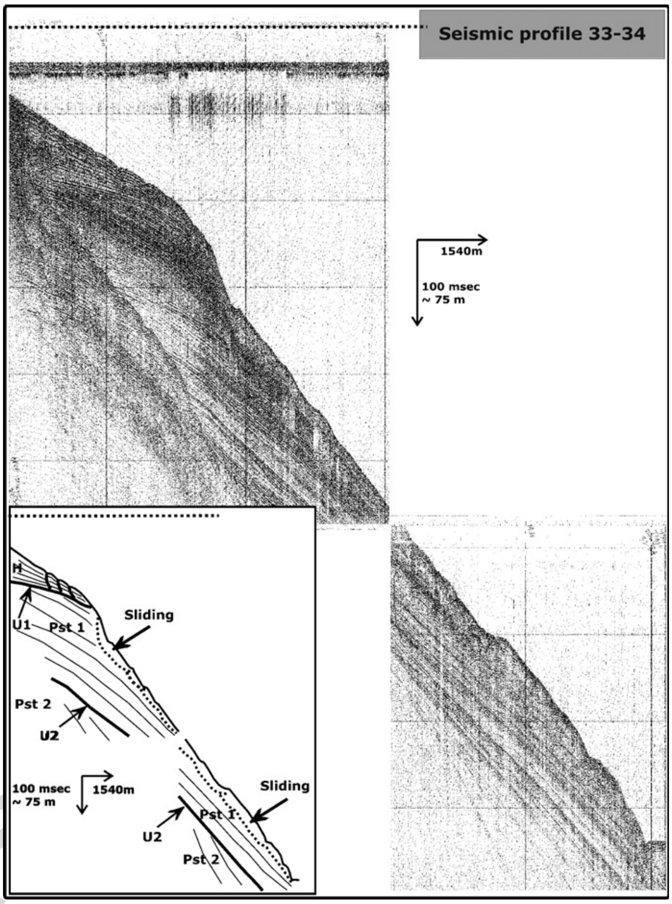

Fig. 7. Litho-seismic profile 33–34 of Kyparissiakos Gulf. Characteristic mass movements with sliding along the continental slope is evident, even though no fault is present. Near the edge of the continental shelf, there are listric surfaces of sliding. Note the increased thickness of the Holocene sedimentary prism (H), unconformably overlying (U1) the (?) Upper Pleistocene sequence (Pst1). The lower unconformity (U2) can be also traced at deeper levels with an angular unconformity between Pst1 and Pst2.

In the profiles near the deltaic structure of the Alfios River, the shelf becomes deeper and unstable (Fig. 7). Sliding occurs immediately below the edge of the shelf involving the upper 15–20 m of sediments. Moreover, rotational sliding surfaces are observed also within the Holocene sedimentary prism above the unconformity. Herein, the thickness of the Holocene sediments increases significantly compared to the south, reaching 60–70 m (compare with profile 23–24 in Fig. 5). The Holocene unconformity over the Upper Pleistocene is clearly reflected, whereas the lower unconformity is weakly traced and the estimated thickness of Pst1 is 140–150 m.

The depth of the edge of the continental shelf has been measured in the bathymetric profiles along the gulf (Fig. 4). Its value ranges from 90 to 95 m west of Katakolo and Filiatra to 140–145 m south of Filiatra up to 170–180 m in the Alfios delta. Nevertheless, the average depth of the edge in the central part of the gulf lies between 124 and 130 m.

The offset edge of the continental shelf is related to the Holocene activity of faults and has been measured in several points along the profile shown in Fig. 8. The faults detected adjacent to the onshore Kyparissia, Kalo Nero and Zacharo faults show an apparent Holocene throw of 6 m, which corresponds to a throw rate of 0.6 mm/yr (based on 10 ky for the Holocene period in the Mediterranean following the establishment of the modern high stand). The faults detected adjacent to the Olympia basin and Filiatra horst show apparent Holocene throws of more than 30 m, corresponding to throw rates of >3 mm/yr (Figs. 4 and 8). Similar high deformation rates for the Holocene period have been detected only in the Kitries fault zone along the eastern margin of the adjacent Messiniakos gulf (Pavlakis et al., 1988).

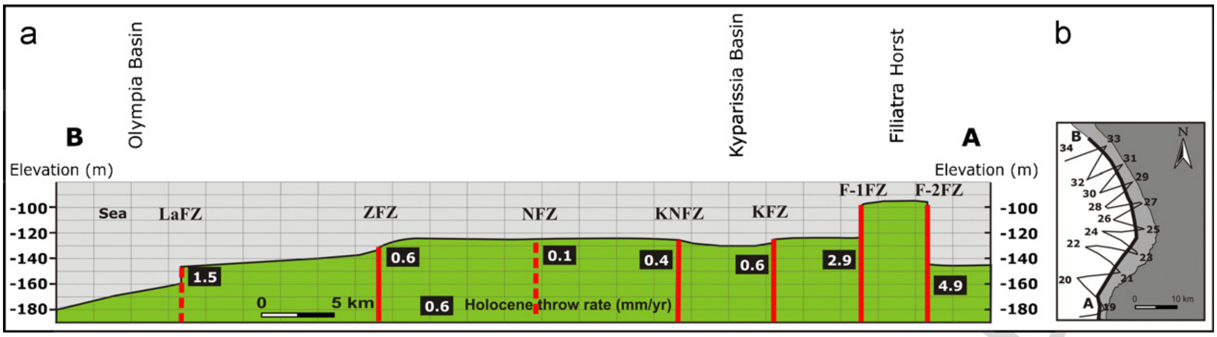

Fig. 8. Longitudinal profile along the edge of the continental shelf of Kyparissiakos Gulf. The disruption of the shelf by the active faults is shown by the differences in depth and the resulted Holocene throw rates (mm/yr). The location of the profile is shown in (b).

The continental shelf is on average 4–5 km wide along the Kyparissiakos Gulf, with a maximum value of 6–7 km adjacent to the Olympia and Kyparissia–Kalo Nero basins and a minimum of 2 km adjacent to the Filiatra horst (Fig. 4).

The observed deformation along the continental shelf and slope of Kyparissiakos Gulf is rather complex. In some segments of the gulf faults disrupt only the shelf, in some others only the slope and in a few others both the shelf and the slope.

At the southern part of the gulf adjacent to the coast of Kyparissia–Filiatra, the few meters thick Holocene sequence of the shelf has been deformed by active faults (Fig. 9). The Holocene fault throw is estimated between 10 and 30 m and the shelf is divided in a number of horsts and grabens. However, the slope has not been deformed by faults.

In the area west of Kyparissia, the shelf is developed better with thicker Holocene deposits (10–12 m thick). In this example, faults disrupt not only the shelf but the slope as well (Fig. 10). In some cases, faults develop against the morphological slope of the sea bottom. This kinematic indication implies that these faults are striking at right angles or highly oblique to the trend of the morphological slope and a strike-slip component might also occur. The location of these faults in the prolongation of the Kyparissia fault zone onshore indicates that they essentially belong to the same fault zone, which thus continues offshore.

Active faults on the continental shelf have not been detected along the seismic profiles from the coast of Kyparissia to the north of the gulf. Instead, very important faults have been detected along the slope (Fig. 11). Herein, a major normal fault is observed immediately below the edge of the continental shelf conformable to the morphological slope. However, a few other faults at deeper levels develop against the morphological slope and may well correlate offshore to the prolongation of the Kalo Nero fault zone onshore. A similar structure is observed also west of Zacharo, where the thicker Holocene sedimentary prism is not affected by faults whereas the slope is highly deformed (Fig. 12). The important fault located along strike the morphological slope is detected again immediately below the edge of the continental shelf. Moreover, there is also a fault zone developed against the slope, probably belonging to the prolongation of the Zacharo fault onshore. It is noteworthy that no faults are detected in the remaining profiles to the north of Zacharo as, for example, in the case of profile 33–34 (Fig. 7).

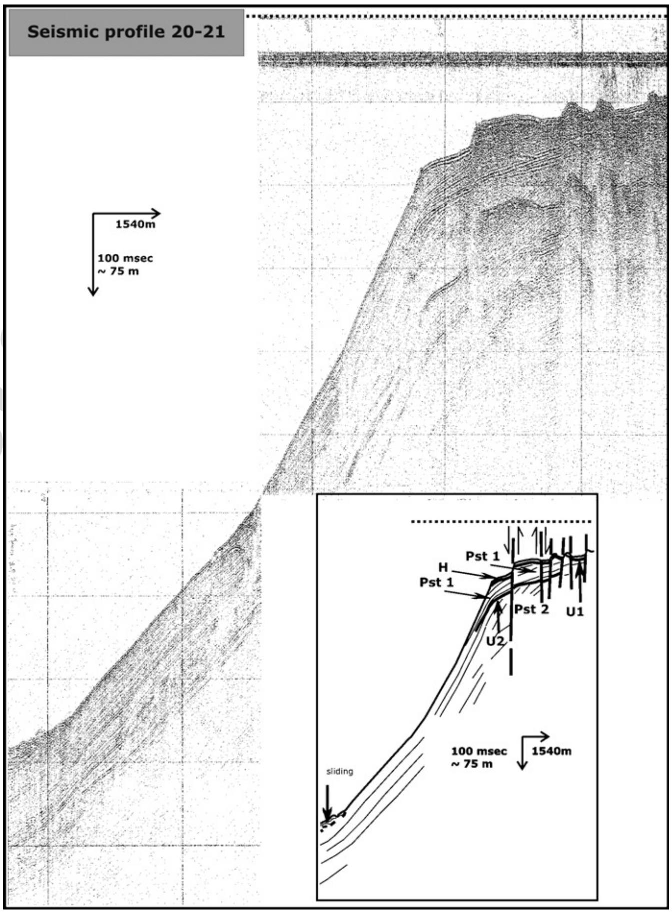

Fig. 9. Litho-seismic profile 20–21 of Kyparissiakos Gulf. A number of active normal faults is shown to deform the shelf and the thin Holocene cover. A reduced (?) Upper Pleistocene sequence (Pst1) is observed below the upper unconformity (U1) and above the lower unconformity (U2) towards the underlying (?) Middle Pleistocene sequence (Pst2).

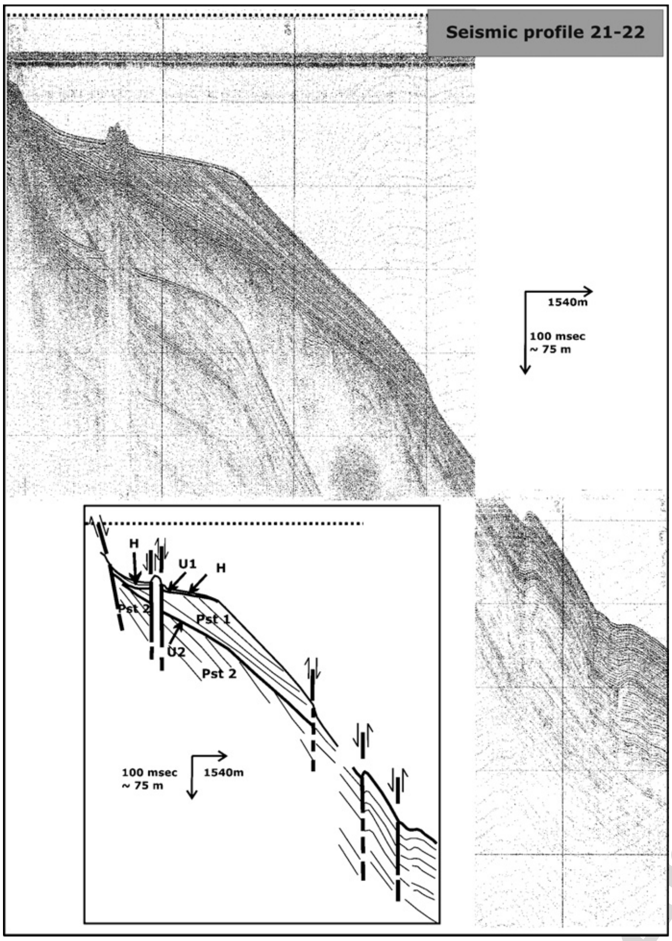

Fig. 10. Litho-seismic profile 21–22 of Kyparissiakos Gulf. Active faults are observed to affect all three sequences H, Pst1 and Pst2 in the continental shelf as well as the continental slope. The opposite to the morphological slope tectonic motion of the two lower faults is probably related to the Kyparissia fault zone onshore which may also display some strike-slip movement.

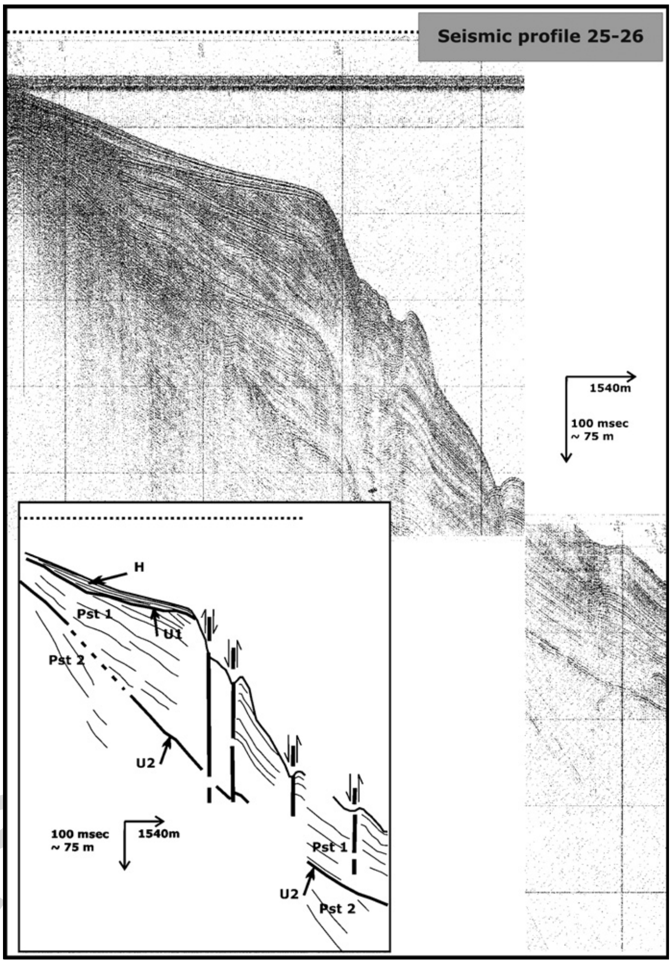

Fig. 11. Litho-seismic profile 25–26 of Kyparissiakos Gulf. The continental shelf is undisturbed by faults whereas the slope is deformed by several faults. The first fault next to the edge of the shelf is longitudinal and contributes to the development of the slope whereas the other three faults have opposite to the slope throws and are probably related to the Kalo Nero fault zone onshore.

Correlation of the litho-seismic profiles along the gulf enables us to examine the thickness variations of the Holocene and the Upper Pleistocene sequences (Fig. 13). The synthetic profile has been drawn approximately along the 50 m isobath and the faults correlated to the onshore faults are also indicated. Both sedimentary sequences of Holocene and Upper Pleistocene show a thickness increase from south to north along the Kyparissiakos Gulf. The increase of the Holocene is from a few meters to more than 130 m and that of the Upper Pleistocene is from 50 m to more than 180 m. Although the change in sediments' thickness is similar for both periods, the gradient is much higher for the Holocene (about 12 times more) than for the Upper Pleistocene (about 3.5 times more). Thus, whatever is the cause for this lateral increase of the rate of sedimentation in the gulf, it has been accelerated in the Holocene. The offshore continuation of the onshore E–W faults along strike on this longitudinal marine profile shows abrupt changes in the thickness of the Holocene sediments, by about 10 m across the Kyparissia and Zacharo faults and about 20 m across the Lapithas fault.

4. Correlation of onshore and offshore structures

Correlating onshore and offshore structures is facilitated by the synthetic map of Kyparissiakos Gulf (Fig. 14). E–W trending faults observed onshore continue in several cases offshore along the central and southern part of the gulf. This is observed from the area of Zacharo to the area south of Filiatra. However, north of Zacharo up to Katakolon, there is no evidence of E–W faults offshore.

N–S to NNW–SSE faults are not observed onshore, with the exception of (i) the Epitalion fault zone (EFZ in Fig. 2), which runs parallel to the coast of northern Kyparissiakos Gulf from Lapithas Mt. to Pyrgos and Katakolon and (ii) the fault separating the Miocene molassic conglomerates from the Pindos nappe along the western slopes of Kyparissia Mt. The fault of western Kyparissia Mt. is inactive, whereas the Epitalion fault is active, bordering the coastal lagoonal Holocene deposits from the uplifted Pleistocene marine sediments.

In the offshore area, it is remarkable that a major longitudinal fault of N–S to NNW–SSE direction has been mapped along the continental slope at the Zacharo–Kyparissia segment (e.g., Figs. 10–12) and along the continental shelf at the Kyparissia–Filiatra segment (e.g., Figs. 6, 9 and 10). Thus, a continuous but segmented longitudinal fault can be traced all along the coastal zone of the Kyparissiakos Gulf from Katakolon to Filiatra. This fault separates the uplifted blocks of the continent in the east from the subsided blocks of the ocean in the west. The Holocene fault throw is several tens of meters in the south, judging from the disruption of the Holocene deposits on the shelf (e.g., the major fault near the edge of the platform in Fig. 9, which shows a 30 m throw), up to more than 60 m in the north. The pre-Holocene throw can be estimated only in a few cases where the Upper Pleistocene sediments are offset but the age of the deformed reflectors is not well known. In any case, the Holocene throw rate of the longitudinal fault is several times higher than those of the E–W faults offshore.

5. Quaternary paleogeography

The onshore and offshore neotectonic pattern presented in the previous sections demonstrates that important changes have occurred during Quaternary in the Kyparissiakos Gulf. The overall paleogeography of the area can be better visualized in two snapshots (Figs. 15 and 16): a first snapshot during Early Pleistocene time, when marine sedimentation progressed landwards for 10–20 km, followed by a second period of the sea regression to about its present-day stand. This shoreline relocation appears to be related to a first N–S phase of extension of the coastal area, the creation of the E–W oriented horsts and grabens, with a subsidence of several hundred meters and deposition of the Lower Pleistocene marine sediments in the grabens (Fig. 15). This period of tectonism is followed by similar tectonic deformation consisting of north–south-directed extension but of smaller intensity. At the same time, the coastal zone was separated from the offshore areas that lie west of the continental shelf (Fig. 16) by the longitudinal fault that has been detected in most of the profiles, usually at the break of slope between the continental shelf and slope. The Epitalion longitudinal fault mapped along the coastal zone of the Olympia basin from Pyrgos to Zacharo probably belongs to the same fault system. Thus, the coastal zone and sedimentary deposits of the Lower

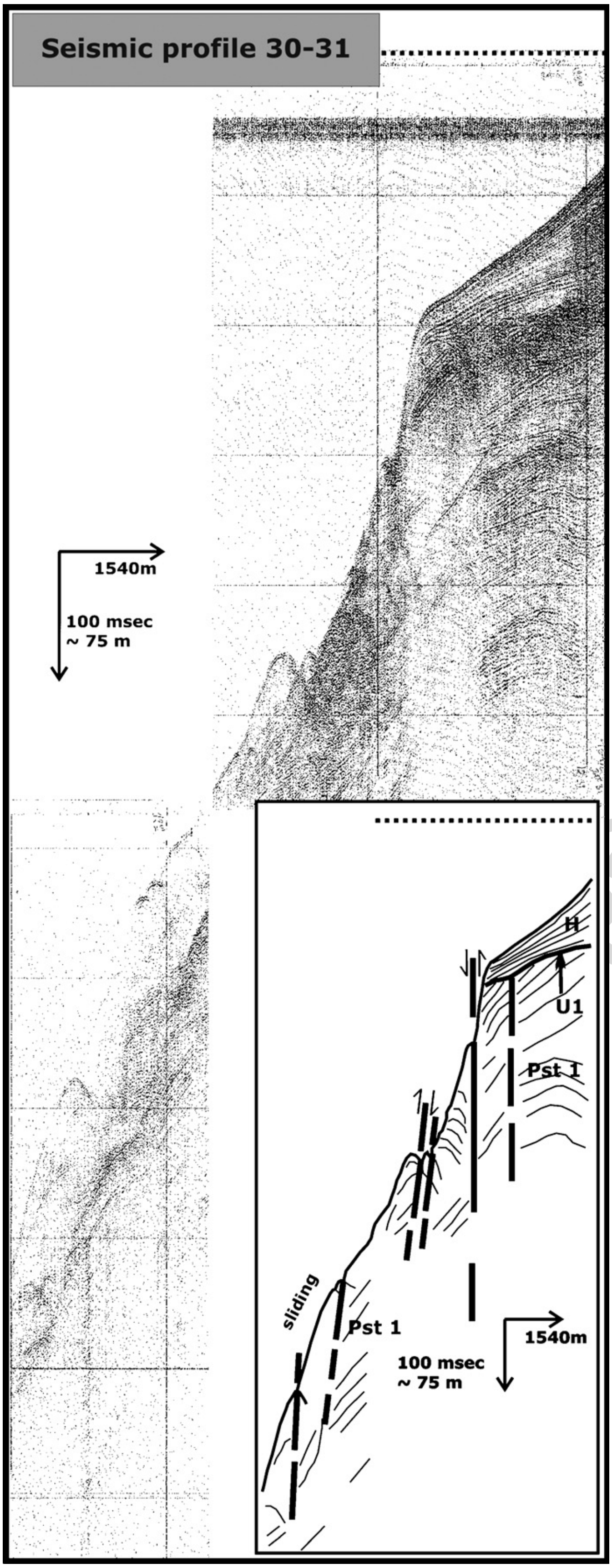

Fig. 12. Litho-seismic profile 30–31 of Kyparissiakos Gulf. The thick Holocene prism (H) is undisturbed whereas the underlying sequence is highly distorted by several faults. The first fault next to the edge of the shelf is the longitudinal fault contributing to the development of the slope. The next fault shows an opposite motion and might be related to the Zacharo fault zone onshore. Sliding occurs at deeper levels.

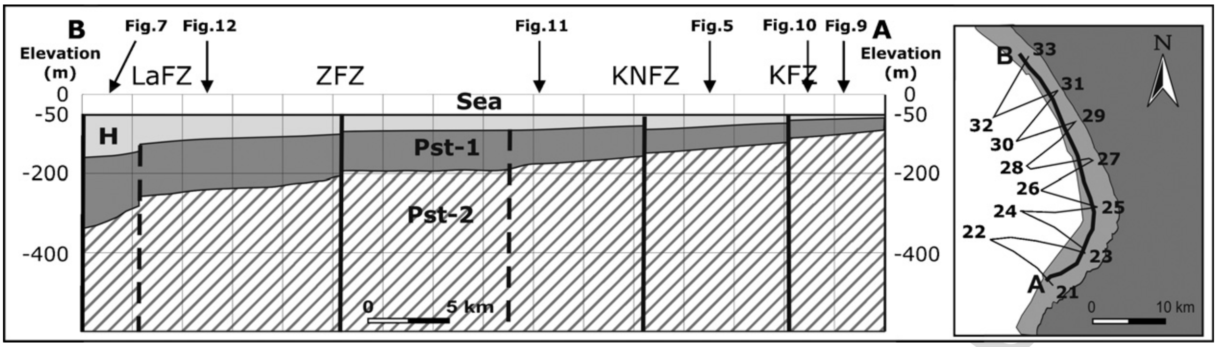

Fig. 13. (A) Schematic cross section along the 50 m isobath of Kyparissiakos Gulf. Its location is shown in (B). The increase of thickness of the Holocene (H) and (?) Upper Pleistocene (Pst1) can be followed from south to north. The traces of the intersecting fault zones are also shown and their effect on the thickness change can be evaluated. The location of the litho-seismic profiles given in Figs. 5, 7, 9, 10–12 is also shown to help follow the increase by the obtained data.

Pleistocene continental shelf were uplifted and eroded during Middle Pleistocene–Present.

In the eastern part of the Olympia basin continental sedimentation occurred during Early Pleistocene, followed by erosion in Middle Pleistocene–Present. During Early Pleistocene, subsidence was moderate in the E–W basins, with higher subsidence rate observed in the Olympia basin to the north, whereas uplift seems more important in the horsts. During Middle Pleistocene–Present uplift dominates all over the eastern block, eroding the uplifted marine sediments. This is demonstrated also by the angular unconformities (U1, U2) observed in the offshore profiles, which show intense peneplaination during the glacial low-stands prior to the sea transgressions during the inter-glacial high stands. In several litho-seismic profiles (e.g., Figs. 5, 10 and 11), the two unconformities merge within the present-day shelf, indicating that uplift and tilt toward the open sea has occurred during the low stand glacial periods.

The dramatic change from Early to Middle Pleistocene described above is not limited in the area of central western Peloponnesus but it is observed more generally to the entire Peloponnesus (Dufaure, 1977). Spectacular morphogenetic impact of this uplift is documented in the northern margin of Peloponnesus from Corinth to Patras but also in the three southern peninsulas of Messinia, Mani and SE Laconia (Kowalczyk and Winter, 1979; Mariolakos et al., 1992, 1994).

6. Discussion

The paleogeographic change described between Early and Middle Pleistocene (Figs. 15 and 16) marks an interruption of the general N–S extension and subsidence that produced the post-Alpine basins of western Peloponnesus from a new phase of general uplift of the area. Although N–S extension continues since Middle Pleistocene, it does not produce any subsidence below sea level and instead the lower Pleistocene marine sediments have been uplifted and sometimes their transgressive unconformity on the Alpine basement too. In some cases like Kyparissia coast even Late Pleistocene and Holocene marine sediments are uplifted. Slip rates on the E–W faults onshore can be estimated only for the Lower Pleistocene period whereas offshore only for the Late Pleistocene and Holocene. A comparison of throw rates onshore and offshore even though involving different time periods (Figs. 3, 8 and 13) shows that in some cases values are comparable whereas in other cases they differ significantly. Thus, Kyparissia, Kalo Nero and Zacharo faults show comparable or slightly smaller values offshore than onshore (about 0.6 against 0.7–0.8 mm/yr). On the other hand, Neda fault was active onshore during Early Pleistocene (0.8 mm/yr) but shows very low activity offshore during Late Pleistocene–Present (0.1 mm/yr). The same result has been reported in the case of the Vounargon fault, which borders the Olympia basin to the north which, based on the drilling data, shows a much higher throw rate of 0.35 mm/yr for the period 3.4–0.7 Ma than the rate of 0.14 mm/yr for the recent period since 0.7 Ma (Koukouvelas et al., 1996).

Subsidence rate during Early Pleistocene is much higher in the Olympia basin (0.80 mm/yr) than in the Kyparissia to the south (0.12 mm/yr) and this is confirmed by the northward increase of thickness of the Upper Pleistocene and Holocene deposits offshore (Fig. 13). The increase of sediments' thickness from south to north throughout the Quaternary period both onshore and offshore shows a systematic subsidence of the Olympia basin, where 3 km of Neogene and Quaternary sediments have been accumulated, of which about 1 km is of Lower Pleistocene (Kamberis, 1987), 200 m of Upper Pleistocene and 130 m of Holocene (Fig. 13). The same area is drained by the Alfios, which is the main river of the Peloponnesus. These observations indicate that the systematic subsidence within the Olympia basin has been accelerated in Late Quaternary.

The subsidence rate of the Zacharo, Neda, Kalo Nero and Kyparissia basins during Early Pleistocene is between 0.1 and 0.3 mm/yr (Fig. 3), which is similar to the subsidence rate of 0.20 mm/yr reported from the Middle Pleistocene marine interglacial sediments in the Elis basin north of Pyrgos (Stamatopoulos et al., 1998), and in the Kalamata basin and Filiatra area (Mariolakos et al., 1992, 1994).

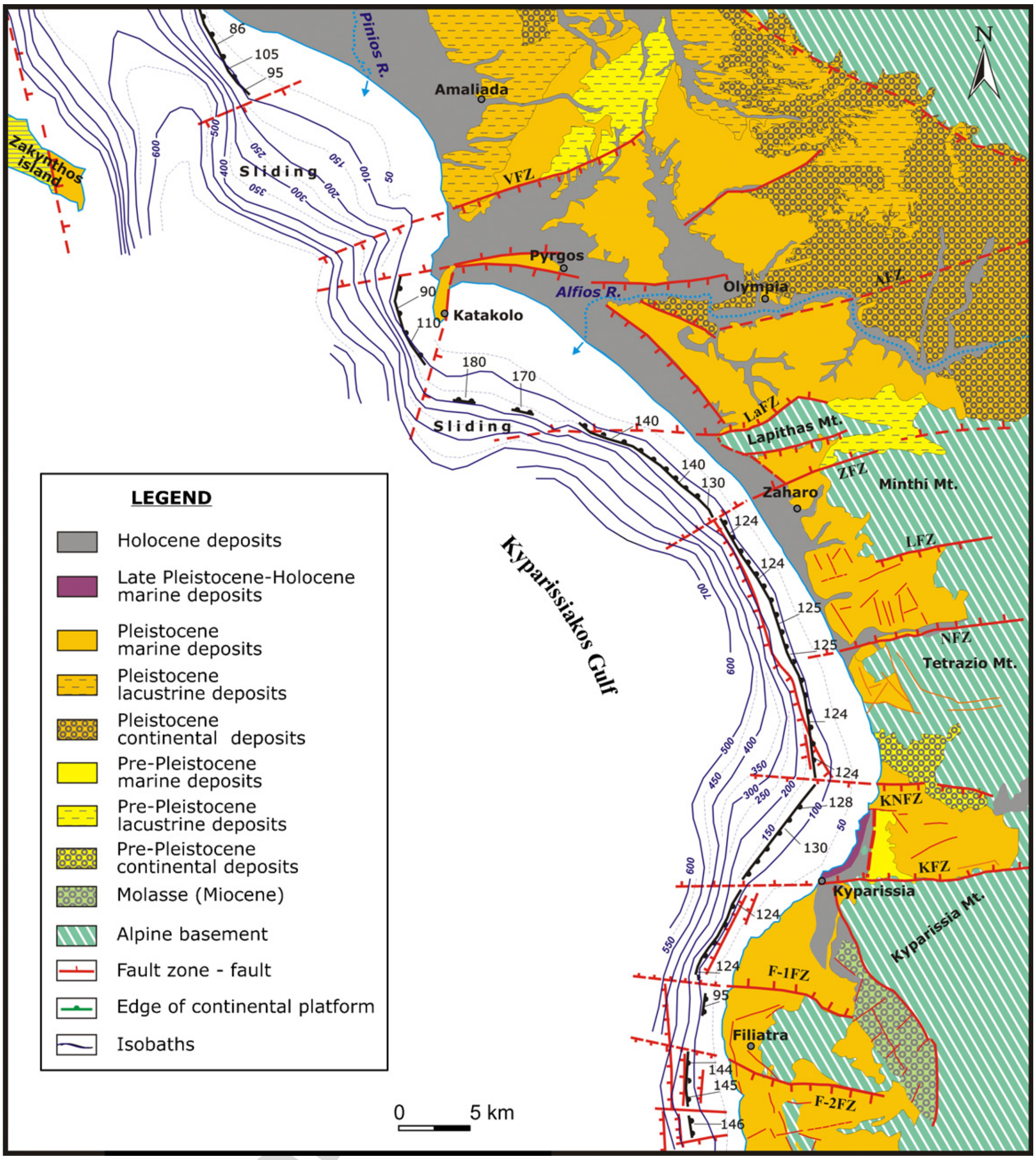

Fig. 14. Synthetic geological map of the Kyparissiakos Gulf together with the offshore data. Probable correlations of the onshore with the offshore faults are shown with dashed lines. F-1FZ: Filiatra-1 fault zone, F-2FZ: Filiatra-2 fault zone, KFZ: Kyparissia fault zone, KNFZ: Kalo Nero fault zone, NFZ: Neda fault zone, LFZ: Lepreo fault zone, ZFZ: Zaharo fault zone, LaFZ: Lapithas fault zone, AFZ: Alfios fault zone, EFZ: Epitalio fault zone, VFZ: Vounargo fault zone.

Onshore uplift rates since Middle Pleistocene are up to 0.5 mm/yr, whereas the throw rate of the NNW–SSE longitudinal fault is more than 3 mm/yr. The latter implies that only a small portion of the fault throw is compensated by the uplift of the (eastern) continental block whereas the major part of the throw is contributing to the development of the continental slope of the gulf towards the subsiding western block. The higher throw rate values in the Holocene offshore are observed in the Filiatra area, where high uplift rates have also been reported onshore, based on the elevation of the Quaternary marine sediments (Kelletat et al., 1976; Kowalczyk and Winter, 1979; Mariolakos et al., 1992). This maximum uplift coincides with the absence of continental shelf (Fig. 6) and the decrease of thickness in the Holocene as well as in the Upper Pleistocene sedimentary sequences (Fig. 13). Comparable uplift rates have been obtained also in the Corinth rift, mainly by coral dating on marine terraces, which show a variation from 0.3 mm/yr in the east (Collier et al., 1992) to 1.2–1.8 mm/yr in the central part (Armijo et al., 1996) and to 0.7–0.8 mm/yr in the west (Houghton et al., 2003).

The north–northwest trending fault zone along the shelf of the Kyparissiakos Gulf is an arc parallel structure accommodating uplift of the crust above the Hellenic

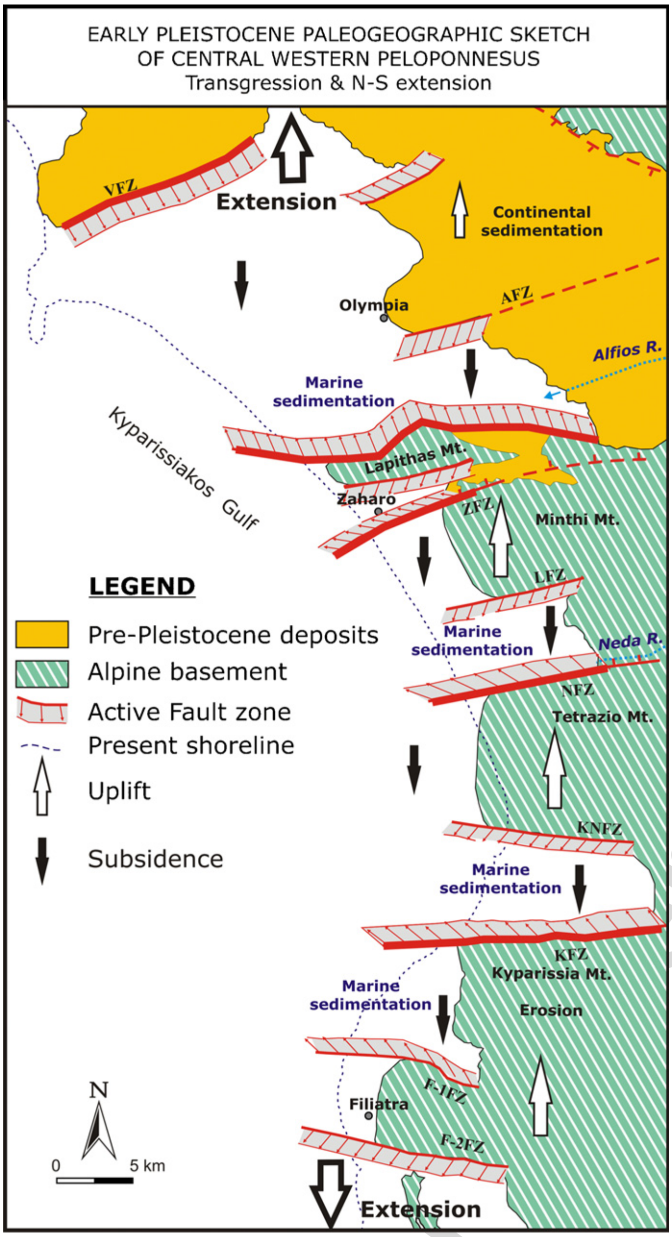

Fig. 15. Paleogeographic sketch of central western Peloponnesus for the Early Pleistocene. A general transgression of the sea is observed into the landscape of the Alpine basement, except in the Olympia basin, which remains continental at its eastern part. N–S extension produces the successive E–W horsts and grabens. Thick fault lines indicate major faults with kilometric order of throw magnitude.

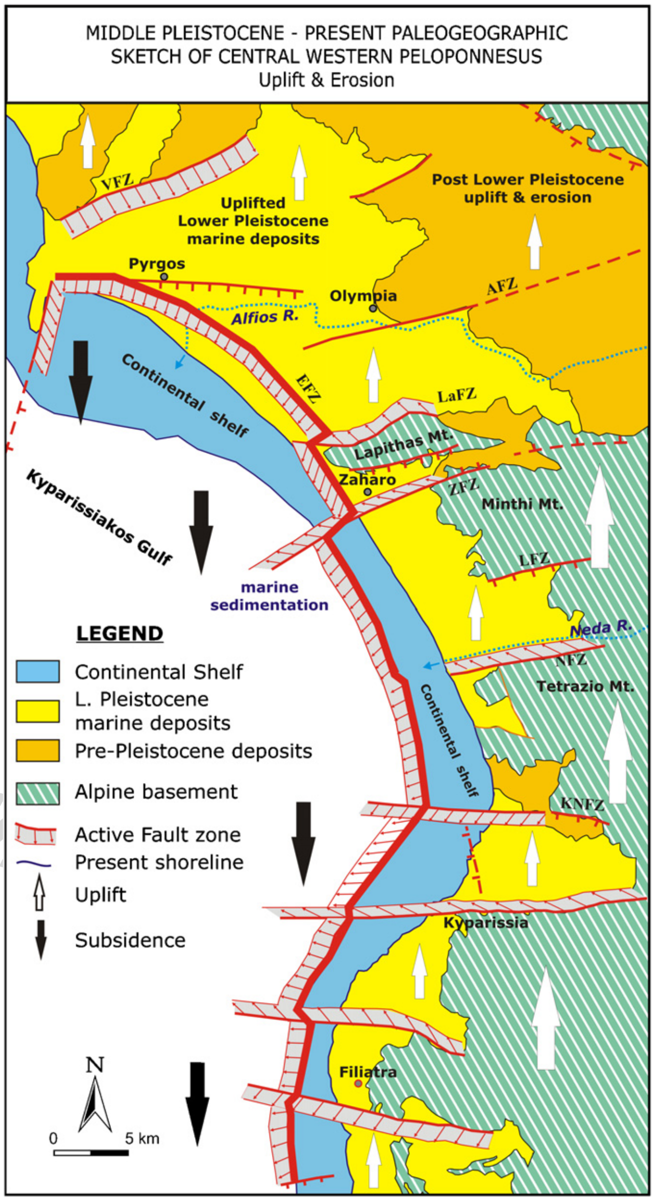

Fig. 16. Paleogeographic sketch of central western Peloponnesus for the Middle Pleistocene–Present. Uplift and erosion of the previously subsided basins is observed with extensive outcrops of the lower Pleistocene marine sediments. The dividing line of the uplift is a sub-parallel to the Kyparissiakos Gulf, longitudinal fault zone of NNW–SSE direction, which disrupts the continental shelf at the southern part, the slope at the central and the coast onshore at the northern part. N–S extension still continues in the former extensional E–W structures but E–W extension prevails along the NNW–SSE direction of the gulf.

subduction zone, which lies at a depth of about 15–20 km (McKenzie, 1972; LePichon and Angelier, 1979; Laigle et al., 2002). This tectonic trend characterizes the fold and thrust belt of the external Hellenides throughout the Neogene but also compressional structures during the Early Pleistocene as in the case of the Ionian islands and more especially of Kephalinia (Mercier et al., 1972; Underhill, 1989) and Kylini peninslula (Dufaure, 1977; Kowalczyk and Winter, 1979). Nevertheless, this active fault has the characteristics of a normal fault accommodating E–W extension, similar to the dominant faults of south–southeast Peloponnesus bordering the Quaternary lignite basin of Megalopolis, the grabens of rivers Pamissos and Evrotas and the horsts of Messinia peninsula, Taygetos Mt/Mani peninsula and Parnon Mt. (domain II of Mariolakos and Papanikolaou, 1981, 1987). Along a transverse profile of the Hellenic Arc from the Ionian to the Aegean Sea, a gradual decrease of the tectonic activity and subsidence rate has been shown across the successive NNW–SSE gulfs/grabens of southeastern Peloponnesus (Messiniakos, Lakonikos, Argolikos, Saronikos)

(Papanikolaou et al., 1988). These arc parallel normal faults accommodate back-arc type extension of the Hellenic arc during the Plio-Quaternary period.

Seismotectonic data (Hatzfeld et al., 1990; Papoulia and Makris, 2004) and in situ stress measurements (Papanikolaou et al., 1990) indicate an E–W compressive stress field in this external zone of the Hellenic arc, probably involving also sinistral stike-slip motion in the Vartholomio–northern Kyparissiakos zone (Roumelioti et al., 2004). Nevertheless, strike-slip focal mechanisms involving E–W faults offshore Kyparissiakos Gulf have been also reported (Kiratzi and Louvari, 2003) as well as focal mechanisms of normal faults trending NNW–SSE, parallel to the Kyparissiakos coast (Papoulia and Makris, 2004).

The east–west trending faults along the central western Peloponnesus are Plio-Quaternary structures accommodating north–south extension of this upper plate crust, similar to that observed in the Corinth rift and in central Greece (domain I of Mariolakos and Papanikolaou, 1981, 1987; Armijo et al., 1996; Roberts, 1996) (Fig. 1a). This N–S extension of the upper plate in the Aegean area cannot be interpreted in terms of the Hellenic arc dynamics (in the west) but must be balanced by N–S shortening in the Hellenic trench (in the south) within the Africa and Europe convergence system (e.g., Jackson and McKenzie, 1988). E–W extension indicated by the roughly N–S normal faulting observed in the Southern Peloponnesus and Crete has been interpreted as the result of the beginning of collision of the southern part of the Hellenic margin with the northern margin of Africa (Armijo et al., 1992). However, NNW–SSE faults prevail in the southern part of the Aegean area (Southern Peloponnesus, Western Crete) with an ENE–WSW extension (domain II in Fig. 1b; Mariolakos and Papanikolaou, 1981, 1987). This E–W extension at the southern part of the Hellenic arc has been proposed to be the result of the beginning of collision of the southern part of the Hellenic margin with the northern margin of Africa (Armijo et al., 1992). On the contrary, E–W faults in Western Peloponnesus have been interpreted as collision structures of the northern part of the Hellenic arc, whereas N–S faults in Southern Peloponnesus and Kythera have been interpreted as subduction-related structures (Lyberis and Lallemant, 1985) assuming a transition from subduction in the south to collision in the north along the arc. However, E–W normal to oblique-slip normal faults can be produced by a transtensional stressfield, which results from the development during Pliocene time of the Central Hellenic Shear Zone (Papanikolaou and Royden, 2007). This zone develops between the northern continental Greece—which converges at a slow rate of 10 mm/yr to the south toward Africa—and the southern Peloponnesus and central–southern Aegean area—which converges at a high rate of 40 mm/yr to the southwest (e.g., McClusky et al., 2000).

Thus, the deformation observed in a cross section from the Hellenic trench through Kyparissiakos Gulf to the western Peloponnesus (Fig. 1c and d) comprises (i) NNW–SSE compressive structures along the Strophades islands, resulting from the subduction and the related convergent zone of the evolving Hellenic fold and thrust belt, (ii) NNW–SSE extensional structures along the axis of the basin and continental slope of the Kyparissiakos Gulf, representing arc parallel structures related to the back-arc extension and (iii) E–W extensional structures along the coastal zone of central Peloponnesus, related to the transtentional stressfield of the Central Hellenic Shear Zone.

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