Title: The tectono-sedimentary evolution of the Lechaion Gulf, the south eastern branch of the Corinth Graben, Greece.

Article Type: Research Paper

Keywords: Corinth rift; assymetric graben; Lechaion Gulf; tectono-sedimentary evolution

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The tectono-sedimentary evolution of the Lechaion Gulf, the south eastern branch of the
Corinth Graben, Greece.

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Abstract

The Gulf of Corinth is the second most active continental rift in the world and thus a
much-studied natural laboratory for analyzing details of rift history. A new detailed offshore
seismic survey combined with previously acquired data in its least studied part, the Lechaion
Gulf shed light on the tectono-sedimentary evolution of the eastern end of the Corinth rift.
This study shows that: (i) the Lechaion Gulf is the submerged northern part of the onshore
Corinth-Nemea basin, (ii) they are both bounded to the south by the north dipping Klenia and
Kenchreai faults, which are considered at present inactive, (iii) both the Corinth-Nemea basin
and the Lechaion Gulf were formed at around between 3.6 to 4 Ma BP (middle to late
Pliocene), at the same time with the Megara basin, (iv) the Lechaion Gulf was submerged and
took its present shape at around between 0.7 to 1.7 Ma BP, at the same time with the Gulf of
Corinth and the Alkyonides Gulf. Furthermore, sequence stratigraphy interpretation of seismic profiles from the Lechaion Gulf revealed: (i) a total post-alpine sediment thickness of almost 3 km below the Lechaion Gulf, (ii) at least 400 m of sediments accumulated during the last 245 ka, corresponding to a mean sedimentation rate of 1 m/ka for the last 245 ka and 2.3 m/ka for the Holocene, (iii) differential vertical movement, in the order of 4.5 km, between the bedrock under the Lechaion Gulf and the adjacent mountains yields an accumulative average slip rate of 0.9 m/ka or less, over the last 4 Ma. Therefore, for estimating more accurately the slip rates, the uplift rates, the extensional rates and the earthquake recurrence interval over the eastern end of the Corinth rift, the presently mentioned tectono-sedimentary evolution of the Lechaion Gulf must be taken into consideration.

Keywords: Corinth rift; assymetric graben; Lechaion Gulf; tectono-sedimentary evolution.

1. Introduction

The Gulf of Corinth is a graben structure that occupies the northern part of the Corinth Rift, representing its present day active component (Fig. 1). It is the second fastest graben in the world, after the Woodlark basin in the Pacific Ocean (Taylor et al., 2009), while its aerial extent (~120 km long x 40 km wide) characterizes it as the smallest, far behind the 800 km wide and more diffused Basin and Range province (Thatcher et al., 1999). In comparison with other regions that undergo continental extension, it is significantly younger, with age almost ten times smaller than other rifts, such as the East African rift (Hayward & Ebinger, 1996) or the Baikal rift (Mats, 1993) (Table 1). Holocene extension rates derived from GPS studies vary from 15±2 m/ka to 10±4 m/ka for the western and eastern parts, respectively (Clarke et al., 1997, 1998; Briole et al., 2000; McCluskey et al., 2000; Avallone et al., 2004). A high
uplift rate of 2.0 m/ka has been measured for the south rift margin in the center, which
decreases to 0.8 m/ka to the west and 0.3 m/ka to the east (Turner et al., 2010).

Rift flank uplift is characterized mostly by vertical tectonic movements along numerous
faults (Stefatos et al., 2002; Moretti et al., 2003; McNeill et al., 2005; Lykousis et al., 2007;
Bell et al., 2008) and is the most seismically active zone in Europe (Papazachos &
Papazachou, 1997; Papadopoulos, 2000). For this reason, great emphasis has been given to
the study of slip rates, total displacement and recurrence intervals of paleo-earthquakes on the
active faults around the Gulf of Corinth, in relation to the past and present day extension rates
and the strain taken by the active faults.

These studies were based mainly on onshore data (e.g. Collier, 1990; Armijo et al.,
1996; Goldsworthy & Jackson, 2001; Morewood & Roberts, 2001; Leeder et al., 2003;
McNeill & Collier, 2004; Westaway, 2007; Roberts et al., 2009; Turner et al., 2010). The
1995 Aigion earthquake increased the interest in the study of the tectono-sedimentary
structure in the marine part of the Gulf, which had already been the subject of earlier studies
(Heezen et al 1966; Brooks & Ferentinos 1984; Papatheodorou & Ferentinos, 1993).

Systematic mapping and numerous marine geophysical surveys have been conducted since
1995 and shed light on the structure of the rift below the seafloor (Lykousis et al, 1998, 2007;
Sakellariou et al., 1998, 2001, 2007; Leeder et al., 2002; Stefatos et al., 2002; Moretti et al.,
2003; McNeill & Collier, 2005; Bell et al., 2009; Taylor et al., 2011) and have shown the
importance of offshore faulting in the understanding of long-term and Holocene vertical
movements in the area and their role in the evolution of the rift.

The purpose of this paper is to study the southeastern branch of the Gulf of Corinth,
known as the Lechaion Gulf (Fig. 1), which is the least studied part of the Corinth Rift.
Furthermore, this study aims to compare the tectono-sedimentary evolution of the Lechaion
Gulf to the evolution of: (i) the Gulf of Corinth and the Alkyonides Gulf and (ii) the Corinth rift and the Megara basin (Fig. 1).

2. Geological setting

The central Hellenic Peninsula represents the classic “basin and range” type extensional area in Greece (Doutsos and Kokkalas, 2001). According to Doutsos & Kokkalas (2001) a series of WNW-trending asymmetric grabens takes up most of the extension in the area (Fig. 1). These are, from north to south, the Almyros, Atalanti, Tithorea, Megara graben and the Corinth rift with the presently active Corinth graben. Roberts & Jackson (1991) suggested that the 150 km wide area between the N Peloponnese and N Euboea has undergone an overall NNE-SSW extension of at least 20-30 km during the last 5 Ma, with present day motion of 10-20 mm/a.

Extensional stresses have been attributed to the following geological processes, such as the back-arc extension due to the roll back of the African plate as it subducts beneath the Aegean plate along the Hellenic Arc (McKenzie, 1972, 1978; Doutsos et al., 1988; Vita-Finzi, 1993), the westward propagation of the North Anatolian fault and the consequent differential velocity of the Anatolian–Aegean plate (Le Pichon & Angelier, 1979; Billiris et al., 1991; Armijo et al., 1996; McClusky et al., 2000), the gravitational collapse of lithosphere thickened in the Hellenic orogeny (Meijer & Wortel, 1996; Hatzfeld et al., 1997; Martinod et al., 2000; Jolivet, 2001; Tirel et al., 2004) or the uplift of the Aegean-Anatolian plate, as the latter overrides the African plate in a zone of low-angle subduction between the Peloponnese (Leeder et al., 2003). A more complex model, based on GPS studies (since 1988), attributes present Aegean deformation to the relative motion of four microplates, Aegean, Central Greece, South Marmara & Anatolia (Nyst & Thatcher, 2004, their figure 5). The Corinth rift coincides with the southern boundary of the Central Greece microplate.
The initiation of the Corinth rift evolved in two stages (Ori, 1989; Doutsos & Piper, 1990) and took place in middle to late Pliocene (Zelilidis et al., 1988; Doutsos & Piper, 1990) or in late Miocene to early Pliocene, according to other authors (Kelletat et al., 1976; Ori, 1989; Papanikolaou & Royden, 2007, Taylor et al., 2011). First stage deposits represent fluvial and shallow lacustrine environments, with most probably no connection to the open sea. During the initial subsidence of the basin no major fault scarp relief developed (Doutsos & Piper, 1990) and the subsidence rate was rather slow, never exceeding the sedimentation rate (Ori, 1989). Onshore field work showed that an angular unconformity separates first stage deposits from the overlain ones (Ori, 1989; Doutsos & Piper, 1990).

During the second stage, a significant increase in basin subsidence versus uplift of the southern margin led to the formation of Gilbert-type deltas in early Pleistocene (Malartre et al., 2004). The Gilbert-type delta deposits are composed of very thick and steeply inclined foresets, indicating a very steep margin and a deep basin. In such a depositional environment the sedimentation is no longer compensated by subsidence (Ori, 1989), while major faults define the basin margins.

As a result of the intense tectonic activity with basinward stepping of the bounding faults, early Pleistocene fan deltas are presently elevated to 1200 m above the present day sea-level along the southern margin of the gulf (Ori, 1989; Doutsos & Piper, 1990; Poulimenos et al., 1993; Dart et al., 1994; Zelilidis & Kontopoulos, 1996). These fan deltas were sourced by rivers that managed to maintain their original northward flow across later tectonic topography (Seger & Alexander, 1993; Zelilidis, 2000). The same rivers still provide sediment, forming fan deltas along the coastal zone.

The present Gulf of Corinth, trending WNW–ESE, forms elongated asymmetric structures with changing polarity (Stefatos et al., 2002) with a total length of about 115 km and 15 to 30 km width, reaching a depth of 900 m (Fig. 1). This characteristic is thus similar
to other known rift zones, such as the Woodlark basin (Taylor et al., 2009), the East African rift (Hayward & Ebinger, 1996) and the Baikal rift (Mats, 1993). It is bounded by WNW-ESE striking faults, situated both on- and offshore (Brooks & Ferentinos, 1984; Armijo et al., 1996; Sakellariou et al., 2001, 2007; Stefatos et al., 2002; Lykousis et al., 2007, Bell et al., 2009), while the basin fill consists of a succession of turbidite debris flow deposits intercalated with hemi-pelagic sediments (Heezen et al., 1966; Brooks & Ferentinos, 1984; Higgs, 1988).

At the eastern part of the rift, the Gulf of Corinth bifurcates into the Alkyonides Gulf to the north and the Lechaion Gulf to the south (Fig. 1). The two gulfs are separated by the fault bounded Perachora horst. The Alkyonides Gulf is an asymmetrical basin, developed in the Pleistocene (Sakellariou et al, 2007; Leeder et al, 2008), on the hanging wall of the north-dipping Strava, West & East Alkyonides and Psatha faults (Papatheodorou & Ferentinos, 1993; Sakellariou et al., 1998; Leeder et al., 2008).

The Lechaion Gulf is the present day, active part of the wider Corinth – Nemea basin, which occupies the southeastern part of the Corinth rift (Sakellariou et al., 2004). The Corinth – Nemea basin bounding faults are present along the north and the south margins of the basin, while their activity status is debated (Roberts and Jackson, 1991; Goldsworthy and Jackson, 2001; Sakellariou et al., 2004; Leeder et al., 2005).

3. Methodology

This study is based mainly on single channel seismic reflection profiling data collected across the southeastern part of the Gulf of Corinth and the Lechaion Gulf (Fig. 2). Data collected by the Laboratory of Marine Geology & Physical Oceanography (Patras University) during the 2004 survey consist of 3.5 kHz pinger and sparker profiles. The average penetration was achieved ranges from less than 50 to 200 ms two-way travel time (TWTT).
for the Sparker profiles and between 10 and 80 ms TWTT for the 3.5 KHz pinger profiles. The lowest penetration achieved over the slope, due to the steep gradient. Datasets acquired by the Hellenic Center for Marine Research (HCMR) include air-gun profiles, acquired during the 1995 (10 in³ air-gun) and 2004 (5 in³ air-gun) surveys and boomer profiles, acquired during the recent 2010 survey. Penetration for the air-gun profiles reached 600 ms TWTT, while for the boomer profiles it was up to 100 ms TWTT. Profiles from the RSS Shackleton 1982 dataset were included in the study as well. In addition, multichannel seismic reflection data of the Gulf of Corinth, from the R/V Maurice Ewing 2001 survey, already published (Taylor et al., 2011) were used in order to investigate the deeper structure of the area.

The total length of acquired profiles during the various surveys is 750 km of air-gun, 160 km of sparker and 200 km of 3.5 KHz pinger, while the general coverage of the study area is very good, as can be seen in figure 2. Moreover, the wide range of resolution and penetration depths, because of the use of various sources, allowed for a more detailed and in depth analysis of the area.

Swath bathymetric data, collected by the Hellenic Center for Marine Research between 2001 and 2004 were compiled with seismic reflection data for a better understanding of the seafloor morphology. The bathymetric data were gridded with a cell size of 0.0005° (~55 m), also including points digitized from nautical charts, in order to fill data gaps in shallow parts of the Gulf.

In order to quantify fault activity, measurements were depth converted from seismic data using the average velocities as proposed by Bell et al. (2009). Sediments with a two-way travel time (TWTT) of between 0-0.5 s have velocities ranging from 1.5 to 2.0 km/s, while sediments deeper than 0.5 s below the seafloor, have average velocities of 2.0 to 2.5 km/s.

4. Physiography (bathymetry)
The Lechaion Gulf trends in a NW-SE direction (Fig. 3). It is separated from the main
gulf by an ENE-WSW trending ridge, the Heraion ridge, which is the offshore prolongation of
the western most part of the Perachora Horst (Fig. 3).

The Lechaion Gulf is about 14 km long and 9 km wide, with an aerial extent of
approximately 120 km². It is symmetric in cross section at the southeastern end and changes
to asymmetric at the northwestern end. The Lechaion Gulf deepens towards the northwest,
reaching up to 350 m. The shelf to the south extends up to the 150 m isobath. It is 5 km wide,
between Kiato and Corinthos and the seafloor deepens gently northeasterwards at a gradient of
about 1.5º. The shelf to the north is about 2.5 km wide and very steep with a gradient of
about 22º (Fig. 3). The above seafloor morphology indicates that the Lechaion Gulf is a
mirror image of the Alkyonides Gulf (Sakellariou et al., 2007), with the Perachora Horst
acting as the axis of symmetry.

North of the Heraion ridge along the southeastern margin of the Gulf of Corinth from
Xylokastro to the Perachora Peninsula, two regions can be distinguished. The western one,
along the Peloponnesus coast, is characterized by three morphological zones: the shelf, the
slope and the basin floor (Fig. 3). The shelf extends up to a water depth of 100 m. Its width
varies from 15 m just off Xylokastro town to 2.5 km off Kiato town, to the east. The slope
extends from a water depth of 100 to 800 m, with an average NNE dip. The slope gradient
ranges between 17º and 22º in the upper slope, whilst in the lower slope the gradient is much
steeper, exceeding 30º. The basin floor is flat; reaching a depth of 830 m (Fig. 3).

On the other hand, along the northwest coast of the Perachora peninsula, only two
morphological units can be clearly distinguished, the slope and the basin (Fig. 3). The shelf is
either very narrow or non-existent. In most cases the slope starts only a few meters from the
coastline, extends for about 2.2 km and reaches the basin floor at a depth of 800 m. The dip of
the slope is towards the northwest, with an average value of \(20^\circ\), which can be greater locally (Fig. 3).

5. Data presentation

The study of the aforementioned offshore data provide the opportunity for a complete and detailed structural mapping of the area in the south-eastern part of the Gulf of Corinth, from offshore Xylokastro up to the Lechaion Gulf and the Perachora Peninsula (Fig. 3). Recognition of faults was hindered by the lack of marker horizons, the local occurrence of steep primary dips and the presence of channel like erosional surfaces.

5.1. Fault architecture

Deformation in the area of the eastern Gulf of Corinth is accommodated mainly by two sets of faults. The first has an ENE orientation, while the second is oriented WNW (Fig. 3). The Lechaion Gulf is bounded by a set of offshore fault segments (Fig. 3). A series of four (4) south dipping offshore faults mark the northern margin of the gulf, which is characterized by a very narrow shelf. In the western most part the Heraion (HER) fault is formed, which has an ENE-WSW orientation and a length of about 4 km, with a mean dip of about \(64^\circ\). The fault displaces the bedrock for about 1500 m (Fig. 4 and Taylor et al., 2011; their figure 8, line L06). On the hanging wall of the HER fault successive sedimentary packages are highly inclined testifying to the activity of the fault (Fig. 5). Further to the east, there are two parallel faults, north Vouliagmeni (VOUn) and south Vouliagmeni (VOUs) faults that run along the rocky Perachora peninsula for 5 km. The eastern most part of the Lechaion Gulf is bounded by the Loutraki (LOU) fault. It extends for more than 3 km in a SE-NW orientation, up to the homonymous coastal town of Loutraki, where it meets the trace of the onshore Loutraki fault (Fig. 3).
The sedimentary structure along the footwall and hanging wall of VOUn and LOU faults are similar. Taking into consideration that the two faults are both oriented SE-NW and their surface traces are horizontally displaced by about 500 m, they are considered as two different faults, probably of a deeper single segment.

The southern margin of the Lechaion Gulf is formed by a well-developed shelf, which dips gently to the north. The abrupt change in the slope’s gradient between the slope and the south shelf of the Lechaion Gulf is marked by another south dipping fault, the Lechaion fault (LEX). It has an almost E-W orientation and extends for more than 12 km, with a mean dip of 61° (Fig. 5).

Further to the south, closer to the coastline, is the Vrachati (VRA) fault, which dips to the north. It extends for almost 11 km in an E-W orientation, with a mean dip of 56°. The two opposite facing faults, LEX & VRA, deform the sedimentary cover of the shelf. The seismic reflectors on the footwall of VRA fault, below the Holocene cover, forms an anticline structure indicating flexure deformation of the shelf possibly associated with buried faults, (Fig. 5c), as has also been observed in other tectonically active basins (eg. Sporadhes basin, Brooks & Ferentinos, 1980). South of VRA fault, the N-dipping Fryne (FRY) fault seems to offset a marker horizon, which is attributed to the 12 ka (see discussion) by 10 m, indicating the tectonically active character of the area (Fig. 10), although sedimentation rates exceed fault motion.

Between VRA and LEX faults, a secondary set of at least three to four minor E-W trending faults deforms the sediments (Fig. 5). These minor faults run parallel to the LEX fault and take up part of the extension, due to the fast subsiding Lechaion Gulf depocenter on the hanging wall of HER fault.
The Gulf of Corinth is separated from the Lechaion Gulf by a horst, which is formed by the Heraion (HER) fault to the southeast and the Perachora (PER) fault to the northwest. This horst constitutes the offshore prolongation of Heraion cape to the west (Fig. 3).

The southeast margin of the Gulf of Corinth is bounded by a series of four WNW-ESE trending, right stepping, basin faults (XYL). These faults define the basin-slope boundary, with their fault planes acting as part of the slope (Fig. 6). This fault geometry imposes a step-like configuration on the slope and basin-edge morphology (Fig. 3). The fault segments have a length ranging from 3 to 6 km and produce an escarpment that exceeds 580 m in height. The uppermost part of the escarpment has retreated due to erosion caused by mass failures (Fig. 6), thus contributing to the sediment influx to the basin. Due to the escarpment erosion it is difficult to verify whether the present seafloor slope is the actual fault plane or is the result of erosion. The average slope of the fault segments near the base (where erosion is least) is above 30°, similar to the value of 48°, which is reported by Taylor et al. (2011), while below the basin floor the fault’s dip drops to 25° giving a listric character to the fault segments (Taylor et al., 2011; their figure 10, line L37d).

Part of these segments has also been identified by previous studies (Likoporia fault in Bell et al., 2009 & Sithas fault in Taylor et al., 2011). This step-like fault morphology was regarded as a single WNW-ESE trending fault with a length of 20 km and more (Armijo et al., 1996, their figure 2). The absence of historical evidence of earthquakes with magnitudes greater than Ml 6.5 in the area (Papadopoulos, 2000), suggests that the presence of smaller segments instead of a single fault, seems more reasonable.

The overall morphology of the observed slope instabilities indicates recent and continuous activity. The extensive upper slope mass failures locally control the shelf width. However, the erosional processes appear to fail to degrade the lower slope, where continuous
displacement along the fault plane offers a counteractive mechanism to the erosion, indicating
the high activity of the fault.

On the footwall of the eastern XYL fault segment, a south dipping normal fault, the
Kiato fault (KIA), is developed. It extends for about 6 km, with an WNW-ESE orientation
(Figs. 3 and 7) and a dip angle that reaches 75° (Fig. 4 and Taylor et al., 2011, their figure 8,
line L37). The sediments that fill the hanging wall to the KIA fault are more than 1 km thick
(Taylor et al., 2011) forming a shelf 2.5 km wide, much wider than the adjacent areas. This
fault is considered as the offshore prolongation of a comparable, seemingly inactive onshore
fault, the Loutro fault of Sakellariou et al. (2004), west of Xylokastro town, bounding the
south side of the Xylokastro horst.

Along the northwestern coast of the Perachora peninsula, parallel to the coast, the
Perachora (PER) fault develops (Fig. 3). It has a SW-NE orientation and a length of
approximately 11 km. The fault plane acts as part of the slope and the escarpment exceeds
540 m in height (Fig. 8). The fault’s cumulative vertical displacement exceeds the seismic
penetration, leading to a minimum offset of more than 1000 m. The fault dip varies from
approximately 20° at the upper part, to almost 50°, below the basin sediments. As the fault
runs to the southwest it splays into two segments, PERs and PERn, of about 3 km each. To
the northeast, the PER fault terminates on the tip of the Strava (STR) fault, while its footwall
is dissected by three northerly dipping faults (MYL, KAL & OLM) with an almost E-W
orientation and lengths that vary from 2.5 to 4.5 km (Fig. 3). These faults appear to be the
offshore continuation of similar onshore faults.

5.2. Basin architecture - Sequence Stratigraphy

The seismic profiles reveal that the Lechaion Gulf displays to the east a more symmetric
character, changing to an extremely asymmetric towards the west, with the maximum
subsidence located close to the HER and the VOU faults (Fig. 5). Starting from the east (Fig.
5e), the sediments covering both the north and the south sides of the basin floor dip evenly
towards the center of the basin. The dip angle of the sediment strata increases with depth. This
pattern suggests an almost uniform subsidence rate for the eastern part of the gulf, which
decreases with time. Further to the west (Fig. 5c), the sedimentary layers are tilted
considerably towards the north. This uniformly northward tilt implies that the north bounding
faults, down-throw the basin floor sediments faster than the southern faults. Subsidence at this
part of the basin is still highly active even up to today. In the central part of the gulf, the north
bounding faults are also more active than the southern ones, but with a less rapid subsidence
rate in comparison to the western ones.

5.2.1. Lechaion basin’s chrono-stratigraphy

According to the seismic imaging of the basin, the fault-controlled depocenter is made
up of at least 400 m of sediments (Fig. 5). The thickness of the sedimentary infill of the basin
is expected to be much higher, since the penetration of the seismic survey used, was limited.
However, multi-channel seismic profiles (Taylor et al., 2011) indicate that the total post-
alpine sediment thickness reaches almost 3 km below the Lechaion Gulf (Fig. 4). The lower
sequence that overly the pre-rift basement is consisting of sedimentary deposits formed during
the early stages of the rift up to ~680 ka BP (Taylor et al., 2011). The other three sequences,
characterized as late-rift by Taylor et al. (2011), have ages the 1st one from ~680 ka to ~335
ka, the 2nd one from ~335 ka to ~130ka and the 3rd one from ~130 to present.

The internal configuration of the sedimentary deposits resembles the seismic structure
of the main basin of the Gulf of Corinth (Lykousis et al., 2007, their figure 8; Bell et al.,
2009) and of the Gulf of Alkyonides basin (Leeder et al., 2005; Sakellariou et al., 2007, their
figure 13), with alternating packages of high-amplitude, low-frequency reflectors with
relatively transparent, reflection free packages. This configuration indicates alternating
deposition of silt to sand turbidites with mud turbidites and/or hemipelagic mud sediments
during successive low and high sea level stages, occurring in Pleistocene.

The relative chronology of seismic reflectors of the late Quaternary based on sea level
changes is a common method, which has been successfully applied many times by various
researchers. In the case of the Gulf of Corinth, such studies (Perissoratis et al., 2000; Lykousis
et al., 2007; Sakellariou et al., 2007; Bell et al., 2008; etc.) have resulted in estimating the
sedimentation rate of the main Gulf of Corinth, as well as that of smaller sub-basins.

The method is based on the recognition of successive packages of strong parallel
reflectors alternating with relatively transparent, reflection free packages. However, there are
opinion differences regarding the interpretation of the above mentioned stratigraphic
structure. Some authors (e.g. Bell et al. 2009; Leeder et al., 2005) suggest that the high-
amplitude, low-frequency reflectors represent highstand (marine) conditions, while the low-
amplitude, higher frequency represent low stand (lacustrine) conditions. Others authors (e.g.
Perissoratis et al., 2000; Lykousis et al., 2007; Sakellariou et al., 2007) propose that strong
reflectors represent coarse-grained sedimentary phases that were deposited during glacial
periods when the sea level was low, while the transparent horizons with the weak reflections
represent more fine-grained turbiditic sediments deposited in interglacial intervals, when the
sea level was high. In this paper, the view of Lykousis et al. (2007) is followed.

The stratigraphy of the Lechaion Gulf reveals a sedimentary fill, the imaged thickness
of which exceeds 350 m, while the age of the older imaged sediments may exceed the 250 ka,
as it can be seen in the profiles across (Fig. 5 & 9) and along the gulf (Fig. 10). Nevertheless,
it should be pointed out that the high tectonic activity leads to different sedimentation
patterns in space and time, making sedimentary package identification and horizon tracing
rather difficult. The maximum estimated sediment thickness during the last 245ka is 240 m,
while their volume is estimated at between 7 and 10 km³ (Fig. 11).
Interpretation of the stratigraphy of the gulf, based on seismic facies recognition, reveals four distinct sedimentary units (I, II, III & IV) (Table 2), which it is proposed that can be related to 100-ka sea level cycles (Fig. 9). The younger unit (I), between the seafloor and horizon (a), consists of low-amplitude, partially continuous reflectors. Horizon (a), can be considered as the limit between lacustrine and marine sediments, which was recognized in various parts of the gulf and has been dated at ca. 12 ka. Therefore unit I was deposited in marine conditions in the last 12 ka, during oxygen isotope stage 1 (Porter, 1989). It has a relative constant thickness of about 19 m that varies close to faults, and drapes preexisting topography (Fig. 5 & 10).

Horizons (b) and (c) can be interpreted accordingly, as transitions between lacustrine and marine conditions. They are characterized by high-amplitude, low frequency reflectors and according to Siddall et al. (2003) sea-level curve, their age may be attributed to approximately 128 and 245 ka, respectively (Fig. 9). Horizon (b) represents the boundary between oxygen isotope stages 5e and 6, while horizon (c) represents the boundary between oxygen isotope stages 7c and 8 (Porter, 1989).

Units II and III are formed by a succession of high frequency, low amplitude reflectors. These seismic facies reflect an alternation in the conditions of sedimentation in the gulf, from marine (higher sea level) to lacustrine (lower sea level). Similar seismic characteristics have also been described by Bell et al. (2008) and Perissoratis et al. (2000) (down to isotopic stage 6), who suggest that during the glacial periods, when the level of the sea was low, the frequency of the turbiditic deposits can increase, due to the more unstable conditions of the emergent margins of the gulf.

Inside units II and III, layers with strong reflectors are distinguishable, which can be correlated to less intense changes in the sea level, marking the transition from lacustrine (glacial) to marine (interglacial) conditions. According to the sea-level curve (Siddall et al.,
2003), in unit II, horizons b1 and b2 could have an age of ca. 71 ka and 24 ka, respectively, representing the boundary between oxygen isotope stages 4 - 5a and 2 – 3, respectively. In unit II, horizon c1 it could be assumed to be the boundary between oxygen isotope stages 6 and 7a, with an age of ca. 186 ka (Fig. 9).

Taking into consideration the ages that have been attributed to the various horizons, the sedimentation rates in the basin of Lechaion were then calculated. Thus, for unit I, which was deposited in Holocene, the sedimentation rate is relatively high, reaching 2.3±0.3 m/ka. For the lower units II and III the rate is smaller, reaching 1.1±0.1 and 0.7±0.1 m/ka, respectively. Similar sedimentation rates for other parts of the Gulf of Corinth were suggested by other researchers (Table 3). Bell et al. (2008), for the total thickness of the deposits, calculated ca. 1 m/ka, in the western part of the gulf (offshore Aigio) and ca. 0.5 m/ka, much smaller than the 1.8 m/ka calculated by Moretti et al. (2004) in the central part (offshore Akrata). For the eastern part of the gulf Lykousis et al. (2007) calculated sedimentation rates for the upper layers that vary from ca. 1.8 m/ka (offshore Xylokastro) to ca. 2.4 m/ka (offshore Kiato). The mean sedimentation rate for the last 128ka, during isotope stages 1 to 5, for the Lechaion Gulf is 1.3±0.2 m/ka, which is in agreement with the rate that was calculated for the Alkyonides Gulf by Sakellariou et al. (2007).

5.2.2. **Margin’s chrono-stratigraphy**

A set of characteristic oblique progradational clinoforms was identified below the seafloor of the shelf of the Lechaion Gulf (Fig. 12). The foresets dip very steeply, while their upper boundary is truncated due to wave erosion activity, indicating a shallow water environment during their progradation. The dipping foresets are transformed downslope to bedding strata, with strong parallel and continuous reflectors which alternate with continuous reflection-free stripes, across the shelf of the Lechaion Gulf.
The oblique prograding clinoforms represent delta front progradation during successive low sea level stands (Lowstand System Tract - LST). They are capped by a few strong semi-parallel and slightly inclined reflectors (high amplitude) indicating that relatively fine-grained (distal) transgressive sediments overlie relatively coarse-grained (proximal) deposits (Transgressive Systems Tract - TST). The LST and the TST underlie a set of low amplitude reflectors that represents the Holocene distal fine-grained prodelta sediments that were deposited during the present high sea level stand (Highstand System Tract - HST).

The relative chronostratigraphic age of the sedimentary sequences may be inferred from the Quaternary glacioeustatic curve (Martinson et al., 1987; Porter, 1989), assuming comparable low sea level stands during their formation (Collier et al., 1991; Collier et al., 2000; Lykousis et al., 2007).

The HST represents Holocene prodelta sediments that were deposited under marine conditions during the last 6 ka (oxygen isotope stage 1). The Holocene transgression sediments are represented by the TST and were deposited from 12 to 6 ka BP, since the late glacial lake of Corinth was flooded by the post-glacial transgression about 12 ka BP (Collier et al., 2000; Perissoratis et al., 2000; Lykousis et al., 2007). The LST is expected to have been deposited during the peak of the last glacial stage about 35 to 12 ka BP (oxygen isotopic stage 2).

Interpretation of seismic profiles along the southern margin of the eastern Gulf of Corinth and Lechaion Gulf has shown the existence of a wave-cut terrace (t) at various depths, around 75 m below sea level (Fig. 12). The exact position of this horizon cannot be accurately traced since a number of smaller faults seem to dislocate it in places. This terrace was recognized on the shelf all over the Gulf of Corinth (e.g. Perissoratis et al., 2000) and it is assumed that it was formed during the post-glacial transgression about 12 ka BP, as the sea level flooded the Rion Strait (Lykousis et al., 2007).
6. Discussion and conclusions

The data presented above together with previously published research papers, shed light on the evolution of the Lechaion Gulf and its relation (i) to the Corinth-Nemea basin, the eastern most part of the Corinth rift and (ii) to the Gulf of Corinth, the Alkyonides Gulf and the Megara basin. Onshore investigations along the western part of the Corinth rift, south of Derveni, have revealed the presence of fluvio-lacustrine sediments of middle to late Pliocene age (ca. 3.6 – 4.0 Ma) lying unconformable over pre-rift formations (Ford et al., 2007; Rohais et al., 2007; Rohais et al., 2008). Similar deposits of the same age occupy the easternmost part of the rift (east of the Corinth Isthmus) (Collier & Dart, 1991; Ford et al., 2007) and the Megara basin (Ford et al., 2007; Leeder et al., 2008). In addition, Collier et al. (1992) and Leeder et al. (2008) suggest that during the same period, extension was focused on the Megara basin, while only little activity was present in the western part of the Corinth rift (Fig. 1). A similar evolution is described by Doutsos & Kokkalas (2001) for a series of WNW-trending asymmetric grabens (i.e. Tithorea, Atalanti and Almyros), north of the Corinth graben, formed in Pliocene. Therefore, it is evident that extension, for the last 4 Ma, is spread over the broader area of central Greece, from the Almyros graben to the Corinth rift and the Megara basin (Fig. 1).

6.1. Lechaion Gulf

In the Lechaion Gulf, multi-channel seismic data (Taylor et al., 2011) illustrates a thick asymmetric sedimentary sequence of almost 3 km, tilting northwards and underlying the present day Gulf. The lower sequence (colored purple in figure 4), with a little less than 2 km thickness, may be considered the offshore equivalent of the early rift, middle to late Pliocene, fluvio-lacustrine sediments observed onshore. This indicates that the Lechaion Gulf was part of the Corinth-Nemea basin and therefore of the whole Corinth rift. The relation of the
Lechaion’s Gulf early-rift sedimentary sequences with the LEX fault indicates that the faulting was initiated during the same period (Fig. 4). This can lead to the conclusion that the margins of the Corinth-Nemea basin, the eastern part of the Corinth rift, at that time were confined to the north by the south dipping faults of onshore Loutraki – Lexaion – Kiato and Loutro faults and to the south by the north dipping Klenia fault (Fig. 13). Therefore, this basin structure that was controlled by the above faults can be considered as the eastern part of the Corinth rift that was formed around the same period with the Megara basin. Seafloor displacement observed in the seismic profiles along LEX and KIA faults (Fig. 5 & 7) suggests that some activity is still present, most probably to accommodate present day deformation.

In the Lechaion Gulf, the middle Pleistocene sequences overlying the early rift sediments may be considered to consist of lacustrine sediments, indicating deposition along the shoreline of a lake bordered environment (Doutsos & Piper, 1990), interchanging with shallow marine sediments. The same tectono-sedimentary evolution has been adopted for the Gulf of Corinth and the Alkyonides basin (Collier et al., 2000; Leeder et al., 2005; Bell et al., 2009).

The evolution and subsidence in the Corinth-Nemea basin seems to have slowed down and tectonic activity from the LEX and KIA faults migrated further to the north and taken up by the LOU, VOU and HER faults. This is inferred by the steeper slope the sedimentary layers exhibit north (~ 10°) of LEX fault than to the south (< 6°), as well as by the thicker early rift sediments accumulated on the hanging wall of LEX fault (Fig. 4). The migration of the tectonic activity took place, in Pleistocene, between 0.7 and 1.7 Ma. This assumption is based on the presence of about 400 m of early rift sediments in the modern Lechaion basin, north of LEX faults on the hanging wall of HER fault (Fig. 4). Moreover, the greater thickness of the early rift sedimentary sequence below the Lechaion Gulf (> 1.4 s TWTT) suggests a longer history of extension in regard to the main Gulf of Corinth (1.2 s TWTT).
This is in accordance with the estimation of Bell et al. (2009) that there is not any sediment older than ca 1 – 2 Ma in the modern Gulf of Corinth. However, the sedimentary sequences below the two gulfs cannot be directly correlated in time without a drill-hole.

In addition, Bell et al. (2009) suggest that the cessation of the extension in the Megara basin and the transfer of the activity further north to the Alkyonides Gulf took place between 0.8 to 2.2 Ma, which is also the initiation time for the modern, deep marine Gulf of Corinth (Leeder et. al, 2008). This is similar to our findings for the northward migration of tectonic activity from the Corinth rift to the present day Lechaion Gulf and Gulf of Corinth around 1 Ma. In that case, HER, LOU & VOU faults are considered synchronous to the Psatha – East Alkyonides fault zone (named after Leeder et al., 2008), resulting in the formation of the two gulfs, Alkyonides and the present Lechaion Gulf, about the same time (Fig. 14).

The structural relief between the bedrock under the Plio-Quaternary sedimentary cover of the Lechaion Gulf and the bordering mountains is more than 4.5 km. Taking into account that this relief developed over the last ~4 Ma, the mean slip rate is in the order of 0.9 m/ka or less. Present day evolution of the Corinth-Nemea basin is still active below the modern Lechaion Gulf, where tectonic subsidence continues at the hanging wall of active LOU, VOU and HER faults. The latter two faults deformed and tilted the basin to the north, constructing the modern asymmetric basin of Lechaion Gulf. The intense tectonic activity of the second stage of the rift, where the early Pleistocene fan deltas uplifted significantly to the west (Doutsos & Piper, 1990; Zelilidis & Kontopoulos, 1996), has not been observed in the eastern Corinth-Nemea basin. It would seem that the tectonic uplift in the east has been outweighed by the southward dipping of present day active faults.

The VRA fault, although it cannot be traced onshore, is of significant length, so can be considered as a crustal scale feature, which can contribute to the extension of the Lechaion Gulf. The onset of the new generation N-dipping faults of VRA and XYL contributed to the
uplift of the older basin and the formation of the Pleistocene terraces. In particular, it is likely that XYL fault is responsible for the uplifting of the western terraces of the Corinth – Nemea basin, while VRA fault, for the uplifting of the terraces south of the Lechaion Gulf. Likewise, HER and LOU faults contributed to the uplifting of the terraces on the Perachora peninsula. This points to the fact that the model responsible for the uplifting and subsidence of the region around the Lechaion Gulf is more complex than it has been described in the past (Armijo et al., 1996; Roberts et al., 2009; Turner et al., 2011). Therefore, for estimating more accurately the slip rates, the uplift rates, the extensional rates and the earthquake recurrence interval, the presently mentioned tectono-sedimentary evolution of the eastern most part of the Gulf of Corinth, must be taken into consideration.

The dominant S-dipping structural faults that prevail in the Lechaion Gulf, suggest that the polarity has not change for at least the last 250ka. This result partially contrasts with the findings from the western part of the gulf (Bell et al., 2009), where there is also one dominant dipping direction during the last 400ka, but with opposite orientation to the north.

Previous studies (Collier et al., 1992; Goldsworthy & Jackson, 2001; Leeder et al., 2008) support the finding that the currently active faults on the Perachora peninsula may be considered as the next generation of the older Klenia and Kenchreai faults. The existence of other N-dipping offshore faults between them (VRA & FRY), shows that the migration did not occur in a single 15 km step, as Bell et al., 2009 suggest, but in a shorter step of 7 km, which is in accordance with the 5 km gradual stepping in the west (Bell at al., 2009). This across rift fault migration mainly concerns hanging wall migration, without any indications of footwall migration, as has been observed by Bell el al. (2009) for the western part of the rift.

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Table 1  
Comparison between active continental rift zones.

<table>
<thead>
<tr>
<th>Rift</th>
<th>Length (km)</th>
<th>Width (km)</th>
<th>Opening rate (m/ka)</th>
<th>Age (Ma)</th>
<th>Publications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corinth</td>
<td>120</td>
<td>40</td>
<td>10 - 15</td>
<td>3.6</td>
<td>Avallone et al., 2004</td>
</tr>
<tr>
<td>Rhine</td>
<td>350</td>
<td>50</td>
<td>0.5 – 1</td>
<td>33</td>
<td>Dezès et al., 2004</td>
</tr>
<tr>
<td>Woodlark</td>
<td>600</td>
<td>100</td>
<td>56 – 72</td>
<td>6</td>
<td>Taylor et al., 2009</td>
</tr>
<tr>
<td>Rio Grande</td>
<td>700</td>
<td>200</td>
<td>&lt; 5</td>
<td>21</td>
<td>Berglund et al., 2012</td>
</tr>
<tr>
<td>Basin and Range province</td>
<td>800</td>
<td>200</td>
<td>3</td>
<td>18</td>
<td>Thacher et al., 1999</td>
</tr>
<tr>
<td>Baikal</td>
<td>1500</td>
<td>100</td>
<td>3.5</td>
<td>30</td>
<td>Petit &amp; Deverchere, 2006</td>
</tr>
<tr>
<td>East African</td>
<td>3000</td>
<td>100</td>
<td>&lt; 3</td>
<td>32</td>
<td>Karp et al., 2012</td>
</tr>
</tbody>
</table>
Table 2
Summary of the seismic stratigraphy interpretation of Lechaion Gulf.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Seismic character</th>
<th>Thickness $m$</th>
<th>Geological significance</th>
<th>Horizon age Ka</th>
<th>Sedimentation rate $m$/Kyr</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>low amplitude, partially continues reflections</td>
<td>$\sim 28$</td>
<td>O$_2$ isotope stage 1 marine, turbiditic and/or hemi-pelagic mud deposits</td>
<td>$\sim 2.3 \pm 0.3$</td>
<td></td>
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<td></td>
<td></td>
<td>a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>II</td>
<td>low amplitude, high frequency, parallel reflections (stronger at the base)</td>
<td>$\sim 130$</td>
<td>O$_2$ isotope stage 2-5e alternation of lacustrine to marine deposits</td>
<td>$\sim 1.1 \pm 0.1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>128</td>
</tr>
<tr>
<td>III</td>
<td>low amplitude, high frequency, semi-parallel reflections (stronger at the base)</td>
<td>$\sim 78$</td>
<td>O$_2$ isotope stage 6-7c alternation of lacustrine to marine deposits</td>
<td>$\sim 0.7 \pm 0.1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>c</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>245</td>
</tr>
<tr>
<td>IV</td>
<td>weak reflections</td>
<td>??</td>
<td>lacustrine deposits ??</td>
<td>??</td>
<td>??</td>
</tr>
</tbody>
</table>
Table 3
Sedimentation rates (m/kyr) in comparison with other studies.

<table>
<thead>
<tr>
<th>Period ka</th>
<th>This study</th>
<th>Lykousis et al. 2007</th>
<th>Bell et al. 2009</th>
<th>Bell et al. 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lechaion</td>
<td>Alkyonides basin</td>
<td>Alkyonides</td>
<td>Eratini subbasin</td>
</tr>
<tr>
<td></td>
<td>Gulf</td>
<td>Eastern GoC&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Central GoC&lt;sup&gt;a&lt;/sup&gt;</td>
<td>basin</td>
</tr>
<tr>
<td>0 - 12</td>
<td>2.3</td>
<td>2.3</td>
<td>1.0-2.4</td>
<td>1.0-1.8</td>
</tr>
<tr>
<td>12 - 128</td>
<td>1.1</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>128 - 245</td>
<td>0.7</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup> GoC – Gulf of Corinth

Fig. 2. Map showing seismic profiles used for this study. Black thick lines refer to profiles shown in figures. The number besides the profiles corresponds to figure number. Multi-channel seismic (MCS) lines L05, L06, L37 and L45 are from Taylor et al. (2011). Air-gun profiles in the Lechaion Gulf are from HCMR 2004 survey, while for the rest of the Gulf of Corinth from HCMR 1995 and RSS Shackleton 1982 surveys. 3.5 kHz pinger data in the eastern end of the Lechaion Gulf are from HCMR 2010 survey. Data (3.5 kHz pinger and sparker) offshore Xylokastro – Kiato area are collected by the Laboratory of Marine Geology & Physical Oceanography (Patras University) in 2004.


Fig. 4. Taylor et al.,’s (2011, Figure 8) interpreted multi-channel seismic profiles of the eastern part of the Gulf of Corinth (see inset map for location of survey lines). Faults’ names,
as well as sedimentary sequence characterization on the footwall of HER fault in L06 have
been modified according to the interpretation of this study. Abbreviations: HER – Heraion
fault, KIA – Kiato fault, LEX – Lechaion fault, PER – Perachora fault, XYL – Xylokastro
fault (uninterrupted multi-channel seismic profiles can be found at Taylor et al. (2011), their
figure 8a).. Chrono-stratigraphic colors: green – 0 to ~130 ka, orange - ~130 to ~ 335 ka, blue
- ~335 ka to ~680 ka, purple – older than 680 ka.

**Fig. 5.** Interpreted (A) and uninterpreted (B) single channel 5 in³ air-gun seismic profiles
across the Lecahion Gulf (see inset map for location of survey lines). Abbreviations: FRY –
Fryne fault, HER – Heraion fault, KIA – Kiato fault, LEX – Lechaion fault, PERn –
Perachora north fault, PERs – Perachora south fault, VOU – Vouliagmeni Fault, VRA –
Vrachati fault, XYL – Xylokastro fault, BF – minor Buried Faults. Chrono-startigraphic
interpretation of colored horizons is shown in figure 9 (rectangle shaded area in profile c). (M
– seafloor multiple, en – electrical noise).

**Fig. 6.** Single channel 3.5 kHz (a, b, c) and Sparker (d) sub-bottom seismic profiles along the
southeastern margin of the Gulf of Corinth (see inset map for location of survey lines).
Abbreviations: XYL – Xylokastro fault, sc – scarp, slp – slide plane, mfd – mass flow
deposits.

**Fig. 7.** Single channel Sparker sub-bottom seismic profile illustrating the Kiato (KIA) fault,
on the footwall of Xylokastro (XYL) fault (see inset map for seismic profile location).

**Fig. 8.** Single channel 10 in³ air-gun seismic profiles across the Perachora Peninsula (see inset
map for location of survey lines). Abbreviations: KAL – Kalosia fault, MYL – Mylokopi
fault, OLM – Olmio fault, PER – Perachora fault, STR – Strava fault.

**Fig. 9.** Detail of the seismic profile in figure 5c. Relative chrono-stratigraphic interpretation
of Lecahion basin sedimentary infill, based on the eustatic sea-level curve of Siddall et al.
(2003). Oxygen isotope stages (numbers with italics in the diagram) after Porter (1989),

**Fig. 10.** Interpreted (A) and uninterpreted (B) single channel 5 in$^3$ air-gun seismic profile along the Lechaion Gulf (see inset map for seismic profile location). Chrono-startigraphic interpretation of colored horizons is shown in figure 9. (M – seafloor multiple, en – electrical noise).

**Fig. 11.** Sediment isopach map above the 245 ka horizon.

**Fig. 12.** Interpreted (A) and uninterpreted (B) 3.5 kHz pinger seismic profile showing sequence stratigraphic interpretation of prodelta deposits on the south shelf of Lechaion Gulf. Displacement of the 12 ka terrace (t) by Fryne fault (FRY) is also evident. LST – Lowstand System Tract, HST – Highstand System Tract, – TST Transgressive System Tract, M-seafloor multiple, oc - oblique prodelta clinoforms (see inset map for seismic profile location).

**Fig. 13.** (A) Simplified fault map showing the location of the cross sections and age estimation of the faults’ initiation. (B) & (C) Cross sections across the Lechaion Gulf. Colored horizons in section AA’ are depicted from figure 5d (BB’ modified after Goldsworthy et al., 2001). Abbreviations: AG – Alkyonides Gulf, GoC, Gulf of Corinth, CNB – Corinth-Nemea Basin, LG – Lechaion Gulf, MB – Megara Basin, SG – Saronic Gulf.

**Fig. 14.** Schematic map modified after Leeder et al., 2012 showing the Corinth rift evolution since the onset of the distributed extension in middle Pliocene, as well as the northward migration of faulting during Pleistocene. (Inside the box after this study, outside the box after Leeder at al., 2012).