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NEOTECTONIC STRUCTURE AND EVOLUTION OF THE GULF OF ALKYONIDES, CENTRAL GREECE

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ABSTRACT

Offshore geophysical data from the Eastern Gulf of Corinth correlated with the geology of the adjacent land areas indicate simultaneous opening of the Central Gulf of Corinth and the inner Alkyonides Gulf basins about 1 Ma ago. The maximum values of the subsidence rate of the basin floor and of the sedimentation rate during this interval have been obtained close to the southern margin and exceed 0.9 m/1000a and 0,45m/1000a in the inner Alkyonides basin and 1,5m/1000a and 0,6m/1000a respectively in the Central Gulf of Corinth. Both basins are asymmetric with the southern marginal faults controlling mainly their evolution while the northern ones are antithetic to them. The southern bounding faults run offshore and form a zig-zag N-dipping tectonic feature, which continues eastward to the Psatha-fault, with a total vertical throw between 600-1200 m. The shape of the inner Alkyonides basin indicates a possible superposition on the paleomorphology of the previous Upper Miocene-Pliocene Megara basin.

KEY WORDS: Alkyonides basin; Gulf of Corinth; active faults; turbidites; Megara basin; Late Pleistocene; subsidence; sedimentation rate; depocenter.

1. INTRODUCTION

The eastern part of the Gulf of Corinth is divided to two embayments separated from each other by the Perachora Peninsula: the "Gulf of Lechaion" to the south and the "Gulf of Alkyonides" to the north. The later has been widely known as the epicentral area of the 1981 catastrophic earthquakes, during which several people lost their lives and extensive damages occured in a wide area including Athens.

Extended geological-neotectonic and seismotectonic research carried out after the 1981 earthquakes brought to light a high amount of information on the neotectonic structure of the onshore areas surrounding the Gulf of Alkyonides. Numerous active faults, some of which were reactivated during the 1981 earthquakes (Mariolakos et al, 1981; Jackson et al, 1982), control clearly the geomorphology and the morphotectonic structure of the area and makes it one of the most active areas in Greece.

Geodetic measurements (Billiris et al, 1991; Rigo et al 1992) and modeling of long term deformation of geological datums (Armijo et al, 1996) indicate a consistent N-S extension rate across the adjacent central part of the Gulf of Corinth of 0,7-1,6 cm/yr. According to Roberts & Jackson (1991) the entire, 150 km wide, area between N. Peloponnese and N. Evia has undergone a minimum overall extension of 20-30 km during the last 5 Ma in NNE-SSW direction, with present day motion of 10-20 mm/a. Detailed microtectonic investigation of the 1981 reactivated fault segments revealed normal movement along their surface with 30% dextral component (Mariolakos et al, 1981).

Three main, N-dipping, active fault segments, the Pisia, the Skinos and the Psatha faults, border Alkyonides basin soythwards to Gerania mountain range and the inactive Neogene Megara basin (Mariolakos et al, 1981; Jackson et al, 1982; IGME, 1984). According to Leeder et al (1991) these faults were possibly initiated before 1 Ma, at about the same time when the S-SW dipping Pateras fault, the main

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marginal fault of the Megara half-graben, became inactive. Paleoseismological investigation on the Skinos fault (Pantosti et al, 1996) revealed a periodicity of 700 yr for 1981-type earthquakes and a mean Holocene vertical slip rate for this fault segment of 1mm/yr, which corresponds to a similar N-S extension. But since this extension rate is too small in respect to the one derived by geodetic methods, the same authors assume indirectly *"the existence of several unknown structures paralleling the Skinos fault"*.

Nevertheless our knowledge on the neotectonic structure of the Gulf of Alkyonides is based on data and geological information resulted from various research projects carried out almost exclusively onshore and may thus not fully reconstruct the complete structure of the area.

The present paper deals with the interpretation of geophysical data obtained during an offshore survey with R/V "AEGAEO" of N.C.M.R. in the Gulf of Alkyonides in November 1995 aiming to the elaboration of the submarine neotectonic map at scale 1:100.000, similar to that of the adjacent Saronikos Gulf (Papanikolaou et al, 1989). More than 350 km of single channel seismic profiling were obtained using a 10 in^3 air gun source. The evaluation and interpretation of the seismic profiles will enable us to improve our knowledge on the neotectonic structure of the area combining the offshore data with the geology of the adjacent land areas.

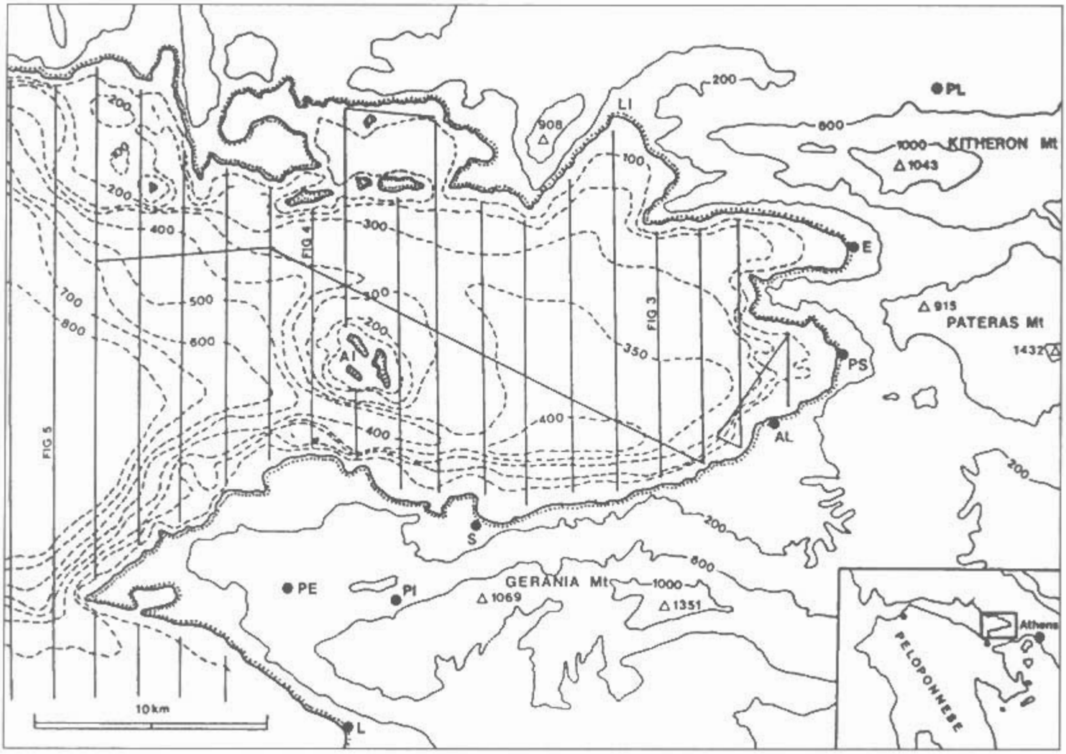


Fig. 1: Morphological and bathymetric map of the Alkyonides Gulf and the adjacent area. N-S solid lines in the Gulf indicate the Air Gun 10 in^3 seismic profiles obtained during the present survey. Dashed lines represent water depth contours, solid lines indicate topography contours. Open triangles mark the location and altitude of the main mountain peaks. AI: Alkyonides Islands, AL: Alepochori, E: Egosthena, L: Loutraki, LI: Livadhostra, PE: Perachora, PI: Pisia, PL: Platees, PS: Psatha, S: Skinos

2. MORPHOLOGY

The Alkyonides Gulf itself is a 30 km. long and 10 km wide, E-W trending longitudinal depression, bordered by the Gerania mountain ranges southwards (1351m.), the Pateras Mt. eastwards (1400m.), the Kitheron Mt. northeastwards (1043m.) and the Korombili Mt. - SE Parnassos Mt. range (908m.)

northwards. Morphologicaly it can be divided to the inner basin east of the Alkyonides islands and to the outer basin west of the Alkyonides islands (Fig. 1).

The inner basin is characterized by a gently S-wards dipping, 300-400 m. deep plateau surrounded by impressively steep slopes (20-25%). The depth of the basin exceeds 400 m. along a narrow zone trending parallel and close to the southern slope, as well as between the northern coast of Perachora Peninsula and the Alkyonides islands. The upper edge of the steep escarpments is usually located a few hundreds of meters offshore the present coastline, restricting thus dramatically the development of the shelf. A very narrow shelf is preserved only along the southern coast of the Gulf, between Strava and Alepochori, and within the small gulfs of Psatha, Germenos and Livadhostra.

The outer Gulf of Alkyonides, westward of the Alkyonides islands, marks actually the transition from the "marginal basin"-type inner part to the 900 m deep main basin of the Gulf of Corinth. The depth of the western part increases constantly westwards toward the deep plateau of the Central Gulf of Corinth.

3. INNER ALKYONIDES BASIN

The subbotom structure of the Inner Alkyonides Basin is marked by the presence of predominantly E-W trending active faults, which control clearly the mophology of the seabed and the structure of the sedimentary basin (Fig. 2).

Two 10 km. long, N-dipping fault segments form the active southern margin of the inner part of the basin between Strava and Alepochori. The western one trends E-W, while the eastern segment prevails WSW-ENE mean direction. The minimum total vertical throw of the southern marginal fault zone of the Gulf exceeds 600 m. and decreases gradually toward east.

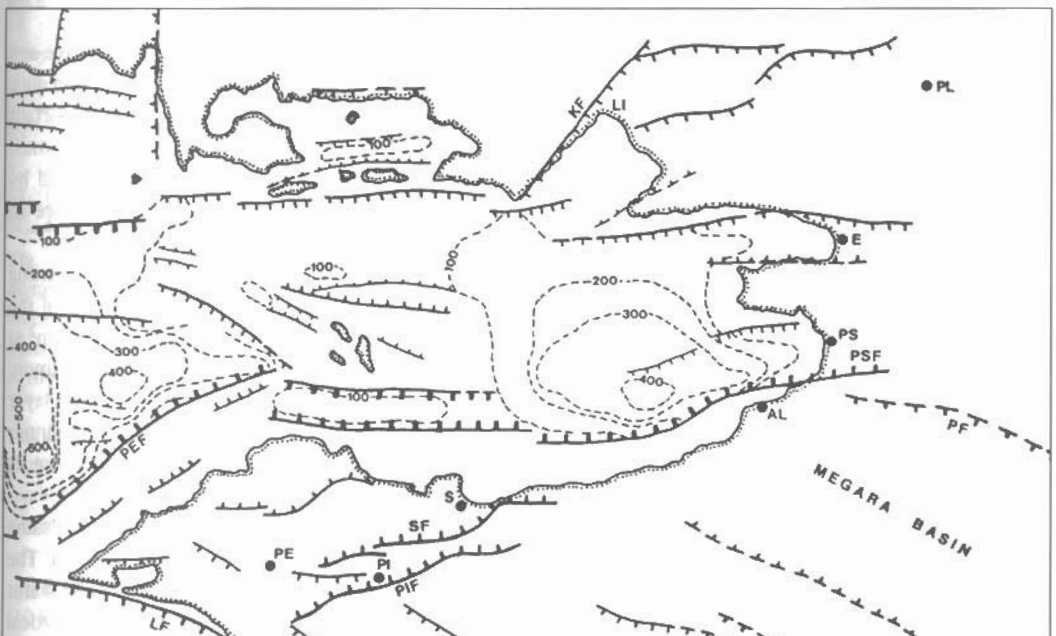


Fig. 2: Faulting and Late Pleistocene sediment thickness in the Alkyonides Gulf and main faults of the adjacent land areas. Dashed lines indicate sediment thickness contours in meters. Faults are divided in three categories according to their cumulative vertical throw: Heavy lines = over 400 m (major faults), intermediate lines = 200-400 m, thin lines = less than 200 m. Teeth indicate the downthrown side of the faults. KF: Korombili fault, KSF: Kakia Skala fault, LF: Loutraki fault, PF: Pateras fault, PEF: Perachora fault, PIF: Pisia fault, PSF: Psatha fault, SF: Skinos fault.

The control of the southern fault zone on the sedimentary evolution as well as on the morphology of the Gulf is clear. The active depocenter of the basin, as revealed by the 400 m. sediment thickness contour (Fig. 2), as well as the deepest parts of the Gulf surrounded by the 400 m. depth contour (Fig. 1), are located very close to the southern fault, giving thus an asymmetric character to the basin. The eastward prolongation of the southern marginal fault of the Inner Alkyonides Basin on land is to be found in the Psatha-fault. On the contrary there is no evidence that this fault continues to the Skinos fault southwestwards as assumed by Jackson et al. (1982).

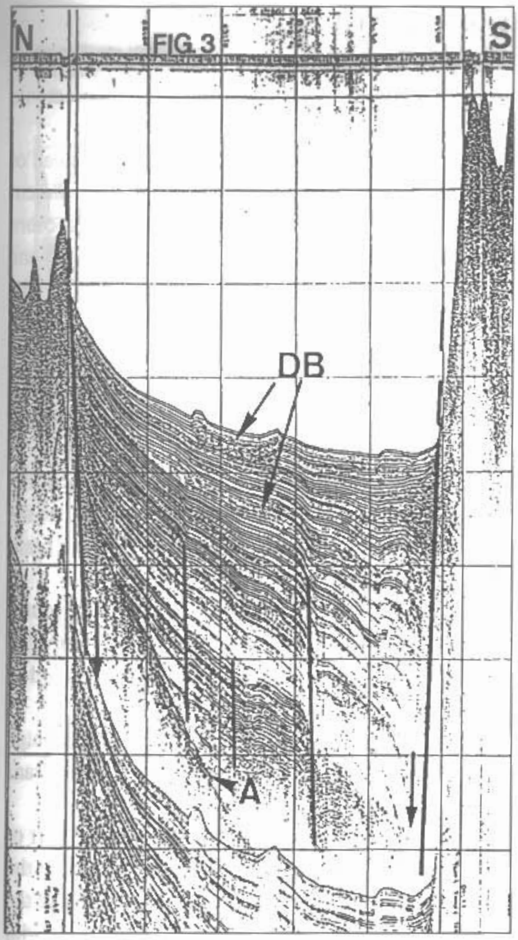
The northern marginal fault zone consists by several S-dipping fault segments, which run E-W, parallel and in small distance offshore the rocky northern coast of the Gulf. The length of each one of the segments is less than 8 km. and their vertical throw exceeds locally 300 m. Both the length of the segments and the vertical throw increase rapidly toward the Central Gulf of Corinth. The westward prolongation of the northern marginal fault zone is to be found to the Aigosthena fault, which borders to the south the Kitheron mountain range. It is worth noting that the SW-NE trending Korombili fault, which forms a significant, about 1000 m. high, morphological discontinuity along the western margin of the Livadhostra gulf, stops at the intersection with the trace of the northern marginal fault and does not continue southwards, in the sedimentary basin of the inner Gulf (Fig. 2).

The sedimentary basin itself exhibits an asymmetric character, similar to the submarine morphology (Fig. 3). Based on the reflection character of the seismic sequence between the sea floor and the basement, a continuous deep water tourbiditic sedimentation prevails throughout the basin since its formation (Fig. 3). The sediment thickness in the basin increases southwards and exceeds 450m. WNW-ward from the village of Alepochori and very close to the southern marginal fault. The sediment layers are dipping constantly southwards toward the southern margin of the sedimentary basin, while the dip value increases toward the lower strata. Additionally the southern margin is much steeper than the northern one.

The sedimentary - seismic sequence is characterized by several alternations of stronger reflective and weaker reflective packets of seismic layers with a general tendency for reflection strength to reduce upwards, which may be interpreted as alternations of coarser and finer turbidites. No important unconformity has interrupted the continuous tourbitidic sequence. Various gravity phenomena as mass flows, debris flows and slumping occur at various stratigraphic levels have been described as well by Perissoratis et al. (1984) and can be recognized by their hummocky top surface and the absence of persistent internal reflectors or the presence of intensively deformed and disturbed internal reflectors.
The turbidites of the lower part of the deep water sedimentary sequence are clearly onlapping a strong reflective seismic layer (Reflector A, Fig. 3) resting on top of the southward dipping basement of the northern margin of the basin. This layer is observed throughout an extensive area of at least 15-20 km^2 at the central part of the basin and continues very probably southwards, in the area of the maximum sediment thickness. The thickness of this layer exceeds 15-20 m. and its acoustic character of the layer reveals coarse grained (possibly conglomerate-type?) sediments which predate the initiation of the inner Alkyonides Gulf deep water basin and should represent the last sediment deposited in the area before its subsidence.

The eastern termination of the inner Alkyonides Gulf is marked by two 2nd order grabens, the Psatha and the Germeno embayments, divided from each other by the tectonic horst of Mytikas Peninsula. The faults which have been mapped onshore (IGME 1984) continue westwards within the Gulf. The water depth at the entrance of both embayments exceeds 250 m. while the sediment thickness and the vertical throws of the bounding faults are clearly greater in the Psatha embayment. It is not unrelated that the active depocenter of the inner Alkyonides Gulf is located a small distance westward of the entrance of the Psatha embayment.

The transition from the inner to the outer Alkyonides Gulf is marked by the presence of the tectonic horst of the Alkyonides island. It is bounded southwards and northwards by two S- and N- dipping faults respectively, which in combination with the southern and the northern marginal fault zones of the Gulf form two E-W trending elongate sub-basins lying between the islands and the southern and northern margins of the Gulf.



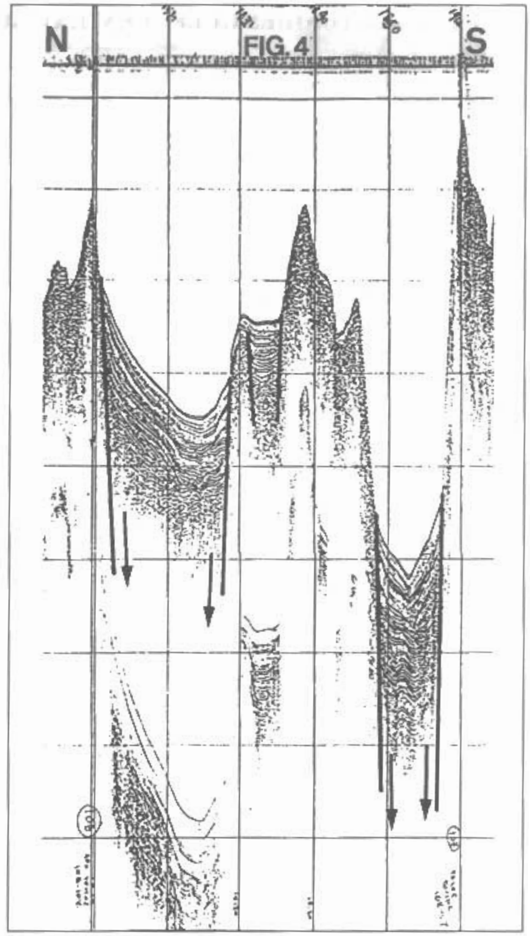


Fig. 3: Air Gun 10 in^3 seismic profile from the inner Alkyonides basin (for location see Fig. 1) illustrating clearly the asymmetric character of the basin. The 450 m. thick turbidite sequence onlaps the strong reflector A, which rests on the basement rock of the northern margin. Reflector A corresponds probably to the Middle Pleistocene conglomerates occurring in the Megara basin. DB: debris flow deposits. Scale: each cell is 75 m. high and 0,5 mile (926 m.) wide. Arrows indicate sense of movement.

Fig. 4: Air Gun 10 in^3 seismic profile from the outer Alkyonides Gulf (for location see Fig. 1) showing the tectonic horst of the Alkyonides island and the two sub-basins north- and southwards. Note the difference between them in water depth, width, sediment thickness and slope inclination. Scale: each cell is 75 m. high and 0,5 mile (926 m.) wide. Arrows indicate sense of movement.

The southern graben ("Strava graben" in Papatheodorou & Ferentinos 1993) is narrower and deeper (10 km. length, 3 km. width, 440 m. maximum depth) than the northern one and reveals greater sediment thickness (150m. maximum) (Fig. 4). The vertical throw of both marginal faults of this trench-like sub-basin are very similar giving thus a more or less symmetric character to it. The morphological and structural characteristics of the southern trench as well as the 150 m. maximum thickness of the gravity flow and turbidite deposits are indicative of its high deformation rate in relation to the sub-basin lying to the north of the Alkyonides islands. The later is shallower and wider and is characterized by a constant S-ward dipping of the sediment layers, the total thickness of which varies between 30-70m. and only locally, close to the southern b[illegible] thus a clear asymmetry in its structure.

4. OUTER ALKYONIDES GULF - CENTRAL GULF OF CORINTH

The area between the Alkyonides islands and the deep plateau of the Central Gulf of Corinth, called here Outer Alkyonides Gulf, is the link between the Inner Alkyonides Basin and the main neotectonic graben of the Gulf of Corinth.

The outer Alkyonides Gulf is marked by the wedge-shaped eastern termination of the deep plateau of the Central Gulf of Corinth as displayed by the traces of the main faults, the depth contours and the sediment thickness contours. The most impressive feature of the area is the SW-NE trending, NW-dipping Perachora fault offshore the northwestern coast of Perachora Peninsula. It bounds eastward the morphological and sedimentary basin of the Central Gulf of Corinth forming an 800 m. high submarine escarpment (Fig. 5). The cumulative vertical throw of the 12 km. long fault exceeds 1200 m. at its southwestern tip offshore Cape Iraion and decreases gradually to about 700 m. toward the Alkyonides islands. Together with the southern marginal fault of the basin, of which only the easternmost part is seen on the map (Fig. 2) westward of cape Iraion they form the southern active tectonic boundary of the Central Gulf of Corinth. The traces of both faults stop at the area of their junction and do not continue further.

At the same area stops as well the trace of the S-dipping Loutraki fault, which bounds southwards the Perachora peninsula with a maximum vertical throw exceeding 600 m. (Fig. 5). It is noteworthy that the Iraion horst separates two basins, the Central Gulf of Corinth northward and the Lechaion basin southward, with opposite tectonic assymetry, clearly illustrated on the seismic profile of Fig. 5.

The northern marginal fault zone of the Central Gulf of Corinth basin continues through the outer Alkyonides Gulf to the northern marginal fault zone of the inner Alkyonides basin forming a continuous but segmented rupture more than 40 km. long. The vertical throw of the fault zone increases westward to more than 700 m. in the Central Gulf of Corinth basin.

A WNW-ESE trending fault marks the active tectonic boundary of the basin to the morphological high of the Alkyonides island (Fig. 2). With a cumulative vertical throw of 300 m. forms a significant morphotectonic discontinuity.

The sedimentary basin of the outer Alkyonides Gulf represents the easternmost wedge-shaped part of the Central Corinthian Gulf basin. The northern margin of the basin deepens gradually in contrast to the southern one which is much steeper. The sedimentary layers are dipping gently southwards throughout the basin, while the dip value increases toward the lower strata (Fig. 5). The active depocenter of the basin with maximum sediment thickness above 600m. is located very close to the southern marginal fault (Fig. 2).

Based on the seismic character of the basin infill, the sedimentary sequence can be divided into a lower and an upper part (Fig. 5). The lower seismic packet (X in Fig. 5) is present only at the northern half of the basin and is recognized by weak reflective and mostly not persistent internal reflectors which lie on top of the basement of the northern margin and follow its dip. The thickness of the lower packet reaches 70-100 m. and remains constant with the depth. Due to the limited penetration of the acoustic source used during the survey we are not able to follow this packet further southward, beneath the area of maximum sediment thickness and to find out its relation to the basement of the southern margin.

The lower seismic horizons of the upper sedimentary sequence lie mostly parallel to the reflectors of the lower part and only rear and locally an onlap relation can be recognized. The acoustic character of the reflectors of the upper seismic sequence is quite different from the lower packet and reveals a prevalently deep water tourbiditic sedimentation with coarse grained tourbidites (strong and persistent reflectors) which alternate with more transparent seismic packets representing probably finer grained sediments. Several debris flow deposits and slumping occur at various stratigraphic levels within the tourbiditic sequence and are recognized by the "cobblestone-type" character of their top surface, the disturbance of the internal reflectors and/or the presence of chaotic hyperbolic reflections within the distinct packets. It is note worthy that debris flow and slumping deposits are almost exclusively located at the foot of the northern margin and are dying out southwards suggesting a northern origin of the clastic material. In contrast to the lower seismic packet the reflectors of the upper seismic sequence diverge southwards parallel to the increase of the thickness toward the southern margin of the basin.

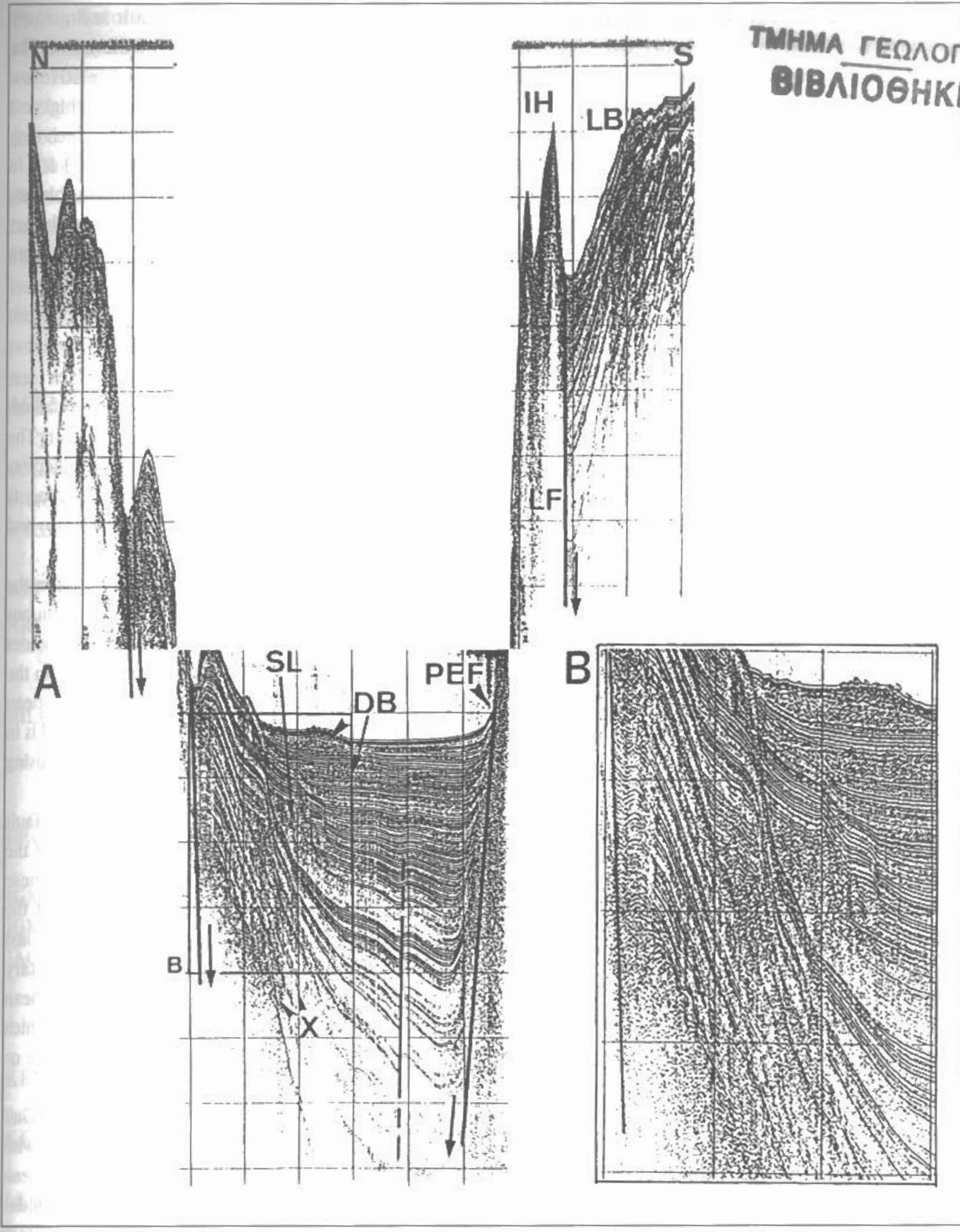


Fig. 5a: Air Gun 10 in^3 seismic profile from the Central Gulf of Corinth (for location see Fig. 1) illustrating clearly the structure of the basin. Note the opposite asymmetry of the Gulf of Lechaion (LB), which is separated from the Central Gulf through the tectonic horst of Cape Iraion (IH). The more than 600 m. thick basin infill is divided to the lower seismic packet X, which rests on the basement rock of the northern margin (compare reflector X, Fig.3 & 4 in Brooks & Ferentinos 1984) and the upper turbidite sequence. DB: debris flow deposits, LF: Loutraki fault, PEF: Perachora fault, SL: slumping deposits. Scale: each cell is 75 m. high and 0,5 mile (926 m.) wide. Arrows indicate sense of movement.

Fig. 5b: Detail of Fig. 5a.

The differences between the lower and the upper part of the Central Gulf of Corinth sedimentary sequence represent very probably two different stages of the geodynamic evolution of the basin. The subsibence of the basin floor and further more the tectonic activity of the area must have been relative low during the deposition of the lower sub-sequence as can be concluded by its more or less constant thickness and the acoustic character of the internal reflectors. The later indicates fine grained sediments which may have been deposited in a lacustrine or shallow water environment (compare also reflector X, fig. 3 & 4 in Brooks & Ferentinos 1984). The onset of the upper part of the sedimentary sequence, with turbidites, debris flows and slumping, represents a dramatic increase of the tectonic activity in the area with higher subsidence rate of the basin and uplift of the margins, or in other words mirrors the initiation of the main marginal faults of the basin.

5. CONCLUSIONS - DISCUSSION

The main sedimentary infill of the inner Alkyonides basin consists of turbidites which rest unconformably on a strong reflective sedimentary layer (Reflector A in Fig. 3), which, as discussed previously, represents the last sediment deposited before the tectonic subsidence of the basin floor. The last (youngest) sediments of the inactive Megara basin are terrigenuous conglomerates and anglomerates of Middle Pleistocene age (IGME 1984) which cover the Pliocene-Early Pleistocene lacustrine sediments of the basin. Similar formations outcrop in the areas of Psatha bay, Egosthena bay (Porto Germeno) and Livadhostra bay resting on alpine basement rocks.

Having that in mind we suggest that the sedimentary layer (Reflector A in Fig. 3), which predates the turbidites of the Inner Alkyonides basin corresponds to the Middle Pleistocene terrigenuous conglomerates and anglomerates. In that case the 450m. thick turbidite sequence of the inner Alkyonides basin must have accumulated during the last 1 Ma since Middle Pleistocene which is in agreement with the age of the major faults bounding southwards the basin as proposed by Leeder et al. (1991). The mean maximum sedimentation rate of the turbidite sequence during this interval is then 0,4-0,5m/1000a and is in good agreement with the sedimentation rates given by Perissoratis et al. (1993) for the Holocene using radiocarbon dating in gravity cores.

Similar age (1Ma) has been proposed by Armijo et al (1996) for the initiation of the main fault bounding southwards the Central Gulf of Corinth basin, and consequently for the main subsidence of the basin floor. This age is in agreement with the post-Calabrian age of the terraces of N. Peloponnese (Kelletat et al. 1976, Schroeder & Kellet 1976, Keraudren & Sorel 1987). Thus the main uplift of the southern margin of the Gulf and the subsidence of the basin floor must have taken place within the last 1Ma (Late Pleistocene and Holocene). Based on that, the turbidite deposits of the upper sedimentary sequence of the basin (Fig. 5) have been accumulated during Late Pleistocene - Holocene with a mean maximum sedimentation rate exceeding 0,5-0,6m/1000a. The lower part (seismic packet X, Fig. 5) which rests directly on the basement may be equivalent to the Late Pliocene - Early Pleistocene lacustrine or shallow water deposits.

Thus the opening of the present basins of Central Gulf of Corinth and of the inner Alkyonides Gulf must have started contemporaneously about 1 Ma ago in Middle Pleistocene but has proceeded with different rates. Taking in account the water depth and the maximum sediment thickness the mean maximum subsidence rate of the basin floor during this interval is 0,9 m/1000a for the inner Alkyonides basin and over 1,5m/1000a for the Central Gulf of Corinth, while the mean maximum sedimentation rate is 0,45m/1000a and over 0,6m/1000a respectively.

Although both basins are bounded north- and southwards by important active faults, the southern marginal faults seem to control predominantly their evolution while the northern ones are antithetic to them. The northern fault zone is segmented but its trace can be followed persistently from the Central Gulf of Corinth to the Alkyonides basin and further eastward, on the land, forming the southern boundary of Kitheron mountain. The southern bounding fault of the Central Gulf basin is connected with the southern fault of the inner Alkyonides basin through the SW-NE trending Perachora fault, forming thus a zic-zac N-dipping tectonic feature, which continues eastward to the Psatha-fault. In the inner Alkyonides basin particularly two more E-W trending important faults, the Skinos and the Pisia faults, contribute to the at least 2000m high vertical differential movement between the basin floor and the Perachora peninsula. The S-verging tectonic asymmetry of both basins is displayed clearly by the bathymetry and the location of the depocenters close to the southern margins.

The tectonic asymmetry of the Inner Alkyonides basin is quite opposite to the one of the Megara basin (Mariolakos & Papanikolaou, 1981) indicating a change of the tectonic polarity during Middle Pleistocene. Furthermore it is note worthy that the active depocenter of the inner Alkyonides Gulf as well as the NW-SE elongated shape of the sediment thickness contours are located in the NW-ward prolongation of the inactive Megara basin. Since there are no evidence for the continuation of the Pateras fault in the basin, this could indicate a superposition of the initiation and evolution of the inner Alkyonides basin on a previously existed morphology belonging to the Pliocene - Early Pleistocene Megara basin.

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