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Geology and Tectonics: Sterea Hellas area

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1. INTRODUCTION TO THE GEOLOGY OF STEREA HELLAS

Greece forms a very characteristic part of the Alpine System, known as the Hellenic Arc. It represents one of the major mountain chains of the Alpine Alpine-Himalayan System, resulted from the convergence/collision between the Eurasian and the African continental plates.

The morphotectonic direction of the Hellenic Arc in Continental Greece is NNW-SSE, (Fig. 1) bending gradually to E-W between Kythera and Crete. Eventually, the direction becomes NE-SW east of Dodekanissa ("twelve islands") island complex up to Turkey.

The Hellenides comprise a large number of geotectonic units, corresponding to individual nappes; the overall kinematics show a movement directed from the core of the arc in the Aegean Sea towards the periphery, in the Ionian and Libyan Seas.

Two main orogenic cycles have been distinguished in the Hellenides, namely: (i) the paleo-Alpine orogeny of Late Jurassic – Early Cretaceous, and (ii) the Alpine orogeny, which started in Late Eocene and culminated during Oligocene and Miocene times. However, plate movements with resulting orogenic processes are still active along the present Hellenic Arc and Trench System.

The geotectonic units of the Hellenides can be separated in two groups, namely the internal and the external ones; the former have undergone deformation in both orogenic cycles, while the latter only in the second.

The main geotectonic units distinguished in Sterea Hellas and more precisely the area of the field trip are the following:

Parnassos: Triassic – L. Cretaceous neritic carbonate sequence (interrupted by 3-4 bauxite horizons) and Paleocene – Eocene flysch.

Western Thessalia Beotia: Continuous sequence from Triassic to Eocene. It is the most internal stratigraphically continuous unit of the Hellenides.

Eastern Greece: It was deformed twice, during the paleo-Alpine and the typical Alpine orogeny. It consists of a neritic Triassic –Jurassic sequence (Subpelagonian unit) overlain by the obducted ophiolites, the transgressive Upper Cretaceous limestones and the Eocene flysch on top.

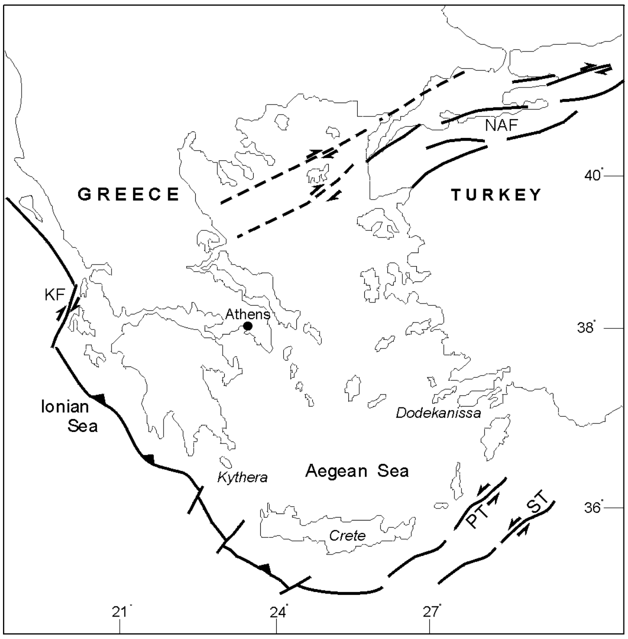

Figure 1 The Hellenic Arc and Trench System. KF: Kefalonia Fault, NAF: North Anatolian Fault, PT: Plini Trench; ST: Strabo Trench.

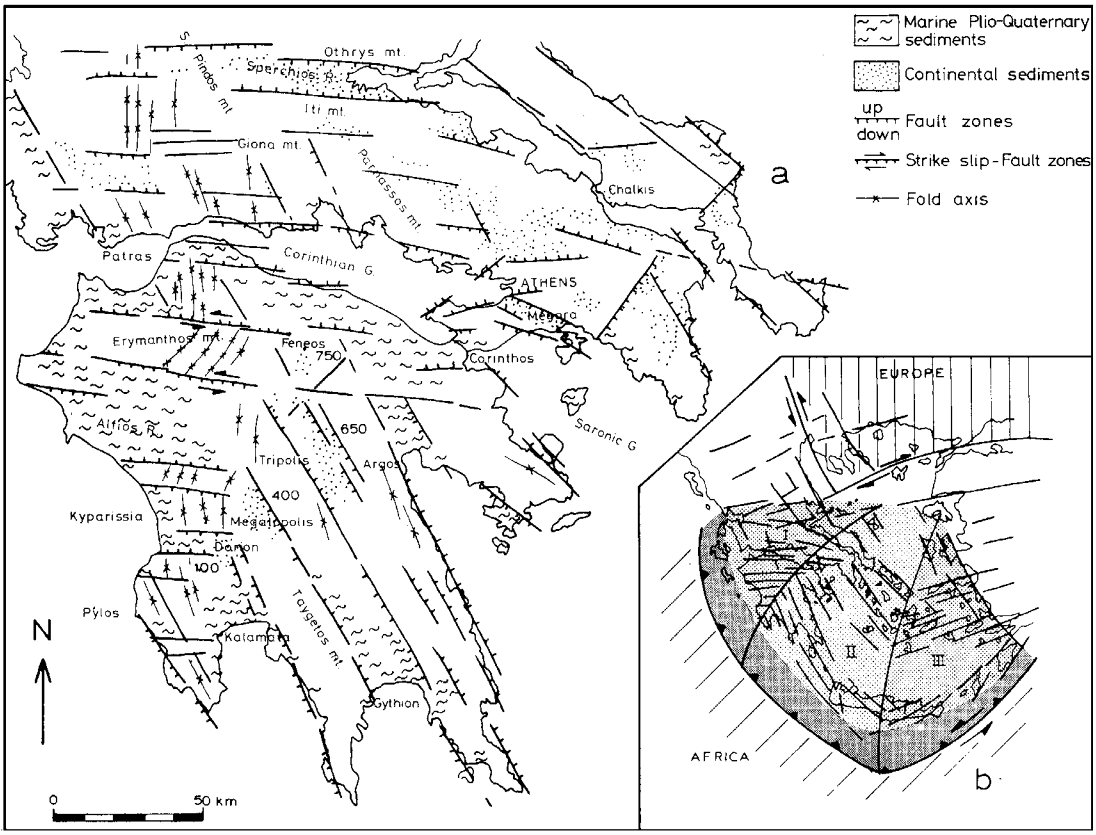

Figure 2 The neotectonic map of the main marginal fault zones of the post-alpine basins in the southern continental Greece (a) and the neotectonic fault pattern of the Hellenic arc (after Mariolakos et al., 1985).

2. HELLENIC TERRITORY: CURRENT GEODYNAMIC REGIME

The present Hellenic Orogenic Arc is restricted at the southern part of the Hellenic territory, in contrast to all the previous ones, which extended throughout the whole length of the Hellenides.

During the Middle Miocene, a part of the Hellenic arc, still active today, was cut off from the Tethyan chain and since then it followed its own evolution. To the north, this part is bounded by the prolongation of the right-lateral Anatolian fault (Fig. 1). In the northern Aegean region, this fault coincides with the northern limit of the active part of the Hellenic arc, bounding an area termed “Aegean microplate” (McKenzie, 1970, 1972, 1978, Galanopoulos, 1972).

The present geometry of the Hellenic Arc has been developing since the Late Miocene. The back-arc basin and the volcanic arc are restricted in the Aegean plate region.

According to Le Pichon et al. (1981), the present geodynamic regime of the Hellenic arc is characterized by asymmetrical movement; along the Ionian trench, the subduction direction is NE-SW and the regime is pure compression, in accordance with the fault plane solutions while, in the Pliny and Strabo trenches, the direction of movement is composite, featuring a substantial sinistral NNE-SSW horizontal component (Fig. 1). In the back-arc area there are extensional structures also with significant horizontal component of movement.

Many geodynamic models have been proposed for the Hellenic arc and especially for Peloponnessos. These models accept that the latter under extensional stress field, accompanied by graben created by normal faulting in the back arc basin (Ritsema, 1974, McKenzie, 1978, Mercier, 1979, Le Pichon & Angelier; 1979, Dewey & Sengör 1979 and others).

Mariolakos & Papanikolaou (1981) suggested that marginal fault zones control the configuration of neogene basins (Fig. 2a). These fault zones create an asymmetry to basin morphology and sedimentation. According to them, the Hellenic arc is separated in three large parts (Fig. 2b). In part I the big fault zones have an E – W direction. In part II the direction is NW - SE and in part III the direction changes to NE - SW. This arrangement shows that only parts

II and III have apparent dynamic relation to the Hellenic arc and trench system, while part I has its own peculiarity.

Data on the current deformation pattern of the Hellenic Arc have been provided by numerous researchers, as: (i) in situ measurements of the stress field in shallow drillings (<10m), (Paquin et al., 1982); (ii) paleomagnetic investigation of the Neogene and Quaternary sediments (Laj et al., 1982); (iii) fault plane solutions (McKenzie 1972, 1978, Ritsema, 1974, Drakopoulos & Delibasis, 1982, Papazachos et al., 1984.

Mariolakos & Papanikolaou (1987) combined the results of various geological, seismological and geophysical studies, and proposed a present (active) deformation model (Fig. 3).

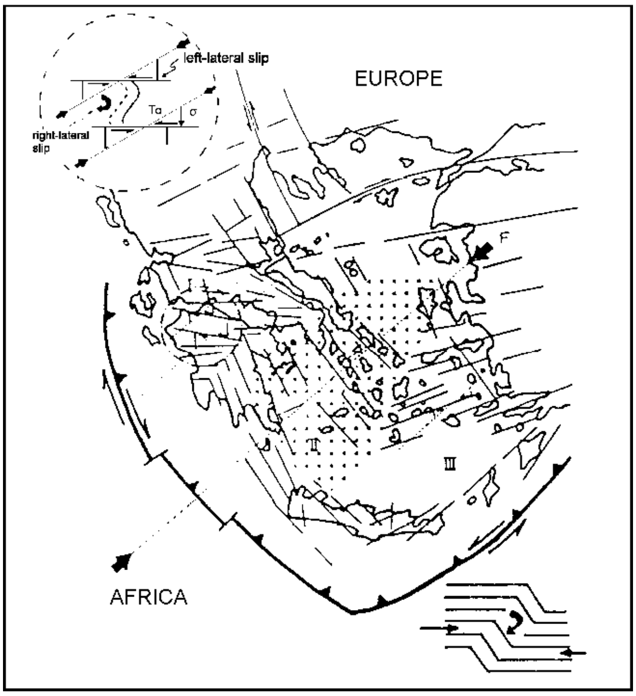

Figure 3 Analysis of the general stress field F on the faults of the three parts (I, II, III) of Fig. 2, into pure (σ) and shearing (Tα) components. In the upper left part of the picture the NW Peloponnessos region is analyzed (under magnification). The faults are developing with a substantial horizontal sinistral component and a dextral rotation of the part in between. The relatively non-seismic Cyclades region is dominated by NW-SE oriented faults. In these faults, the shear component (Tα) of the general stress field is minimum (after Mariolakos & Papanikolaou, 1987).

Further data that assist in the interpretation of the current deformation regime of the Hellenic territory have been supplied by geodetic measurements (Billiris et al., 1989) and the distribution of earthquake foci (Fig. 4).

More recent investigations from SW Peloponnes-

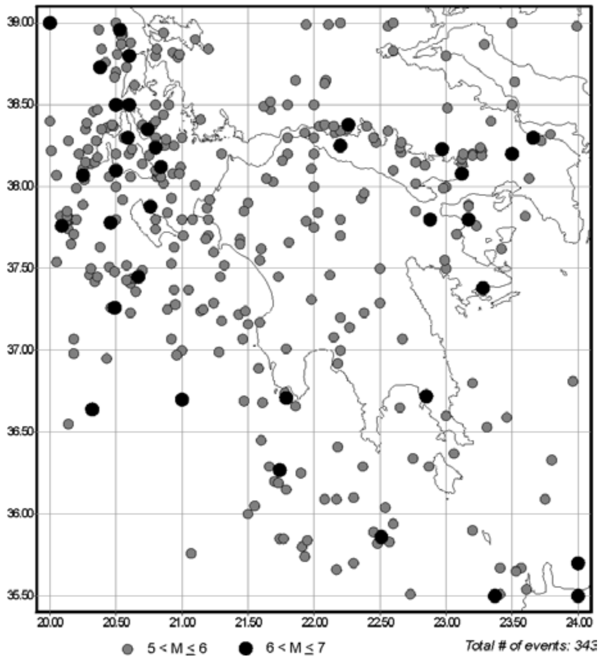

Figure 4 Seismicity map for the years 1900-1997.

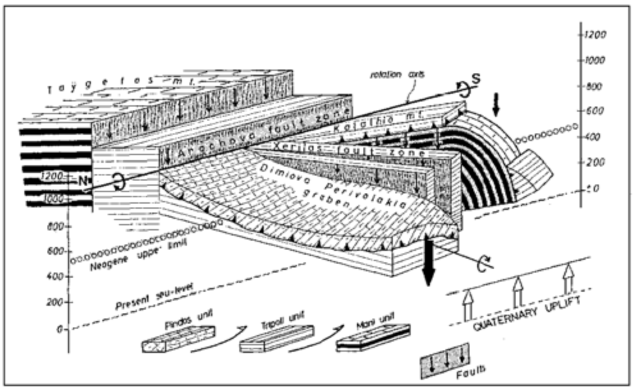

Figure 5 Torsional deformation pattern between Dimiova-Perivolakia graben and Mt. Kalathion Horst (Messinia, SW Greece)(After Mariolakos et al., 1991).

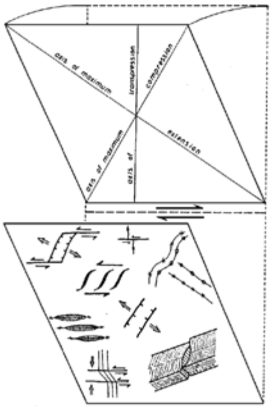

Fig. 6 Torsional deformation and related structures (After Mariolakos et al., 1991).

sos (Messinia) (Mariolakos et al., 1991) showed that the stress field responsible for the neotectonic-active deformation is that of rotational couple (Figs. 5, 6) which caused not only brittle but also ductile deformation structures resulting from local transpression and transtension sectors.

3. SARONIKOS GULF

Saronikos Gulf is located between the peninsulas of Argolis to the west and Attiki to the east. It has a complicated morphology and is divided into a western and an eastern part by a very shallow N-S trending platform, part of which emerges as the islands of Methana, Angistri, Aegina, Salamina (Fig. 7) (Papanikolaou et al., 1988). This N-S zone, separating the Western and Eastern Saronikos gulfs, comprises several outcrops of Plio-Quaternary age, representing the northern edge of the modern volcanic arc. The Western Saronikos Gulf includes two basins, the WNW-ESE trending Epidauros basin to the south (more than 400m deep) and the E-W trending Megara basin to the north, which is relatively shallow (less than 250m). The Megara basin is a tectonic graben bounded by E-W to ENE-WSW marginal faults with a throw of 400-500m. Between the Epidauros basin to the south and Megara basin to the north, an alternation of horsts and graben is observed, bounded by E-W to ENE-WSW trending faults with throws between 200 and 500 m.

The western part of Saronikos Gulf is evidently more active than its eastern one, judging from fault displacement, sediment distribution and the presence of recent volcanoes, which delineates the active western part from the relatively inactive eastern part.

4. NEOTECTONIC EVOLUTION OF THE ISTHMUS OF CORINTHOS

The major area of Corinthos consists of post-alpine formations. It represents a neotectonic graben, bounded by two marginal, E-W striking fault zones, namely the Gerania Mt. fault zone to the North and the of Onia Mt. f.z to the south (Field Trip Map; Fig. 8a).

The Isthmus of Corinthos is a narrow strip of land that connects the Peloponnessos to the Hellenic mainland and marks the easternmost limit of the Corinthiakos Gulf. It is located in the above mentioned graben, and consists of a succession of uplifted, well-exposed Pliocene marls unconformably overlain by several cycles of near-shore Pleistocene conglomerates.

Neogene and Quaternary sediments are cut by numerous, NE-SW and E-W striking normal faults. Some of these can be observed along the 6.3-km-long canal, cut at the end of the nineteenth century along the path of Diolkos, an ancient ramp used as a vessel transportation route connecting the Corinthia-

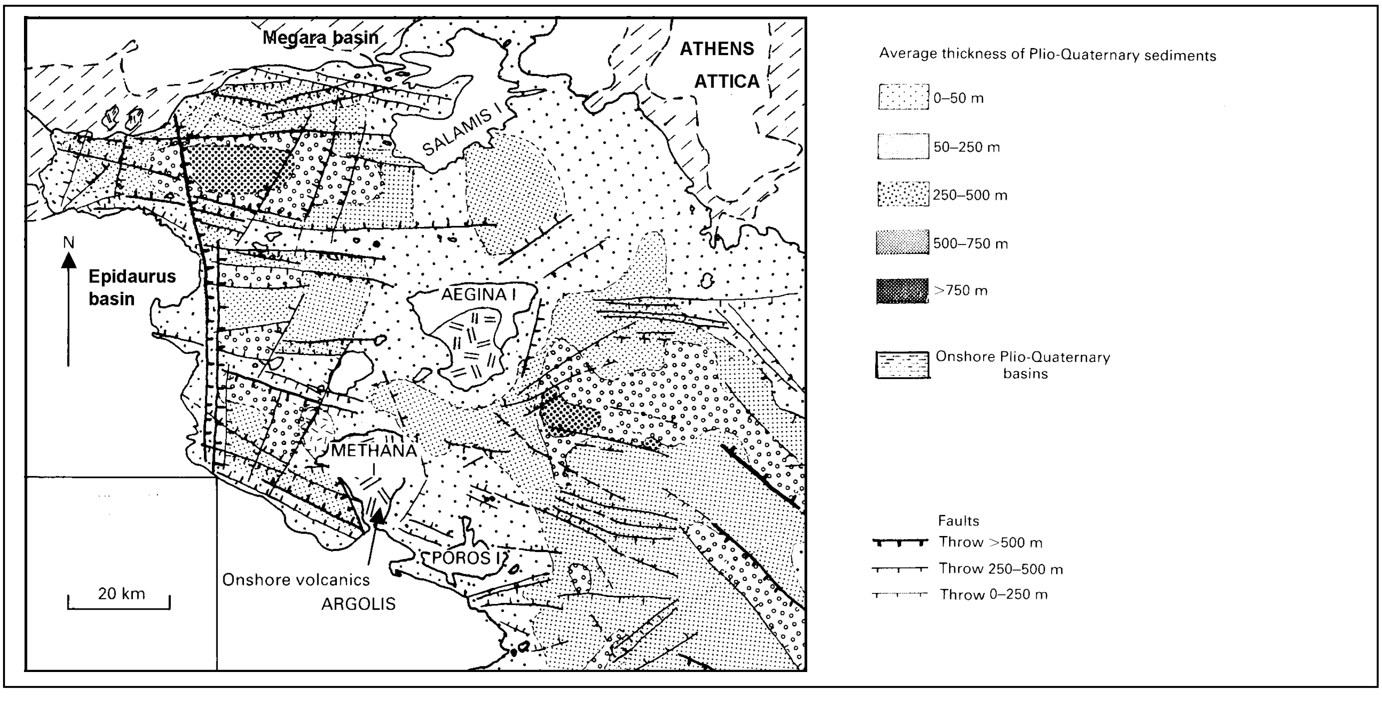

Fig. 7 Neotectonic sketch map of the Saronikos Gulf (after Papanikolaou *et al.*, 1988).

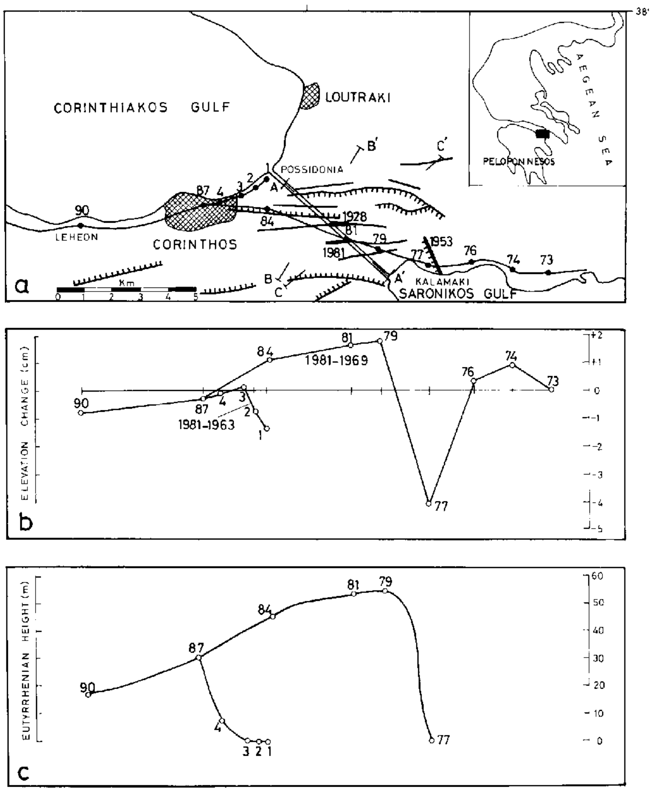

Fig. 8 a: Location map. Main faults, seismic faulting (thick lines), leveling benchmarks common in 1969 and 1981 topographic, and locations of cross sections of Fig. 4.2 are shown (after Mariolakos & Stiros, 1987) (b) Ground-surface displacement for the period 1969-1981: Central part of Isthmus (between benchmarks 79 and 84) appears uplifted relative to near-coastal areas. Subsidence of benchmark 77 is consistent with the motion expected at the hanging wall of the faults that ruptured in 1953 and 1981, as well as with a general subsidence tendency along the Saronikos Gulf. During the intersurvey period, the only important earthquakes that affected the Isthmus were the 1981 events. These earthquakes were associated with normal faulting about 10 km north of the study area. Therefore, any motion observed is likely to be associated with local tectonics (c) Elevation change of the Eutyrrhenian layer along the leveling route. The resemblance of Figure 1b and 1c, presumably showing the present-day and quaternary deformation of the Isthmus, respectively may reveal that the pattern of crustal deformation in this area has not changed since the Early Quaternary.

kos and the Saronikos Gulfs. Because these faults belong to two different sets and dip to the north and south, respectively (section A-A' in Fig. 9), the Isthmus has been interpreted as a horst; i.e., as a simple, extensional feature (Philippson, 1890).

An alternative interpretation based on the mapping of the unconformity between the Pliocene and Pleistocene deposits (Eutyrrhenian) was given by Freyberg (1973). Detailed geologic mapping and borehole and geophysical data were used for the compilation of this surface, shown in Fig. 10. The deformation of this originally horizontal surface to its present-day complex shape is presumed to express the Quaternary deformation pattern in the area. Or, as Freyberg (1973) stated, "*The Isthmus...seems to be formed by anti-tilted fault-blocks. The northern system of the block-faulted area has its greatest height in the East and dips below sea-level towards the West ("Tieflage") while the system in the South acts reversely, and between them, a neutral zone, tilted to a lesser degree, exists*" (see Fig.10). Thus, a NW-SE section shows an apparent horst structure, whereas any section along a southwest-northeast axis would disclose a graben (Fig. 9). The deformation of the Isthmus, the cover of which consists of clay and sand, does not favor brittle fracturing and is accommodated by numerous parallel, homothetic and antithetic normal faults, most of them active, which impart a pseudoplasticity to the crust in this area.

The area of the Isthmus is tectonically active. In the past 60 years, three earthquakes (1928, 1953, and 1981) have been associated with moderate to minor surface faulting (Fig. 8a; Mariolakos & Stiros, 1986).

Lithofaga molluscs and beachrock are exposed at a height of about 1.1 m above the present sea level at the ancient (2000-yr-old) harbor constructions of Leheon; they disclose emerging beaches that can be followed up to Corinthos. Freyberg (1973) reported rounded pottery sherds of undetermined age in this area (Neolithic to Roman) cemented in the conglomerates of former shorelines. The latter are disappearing east of Corinthos, while at Possidonia, beachrock covers some fourth century B.C. constructions of the Diolkos, and an ancient platform next to it is cemented to 0.75 m above sea level. Farther north, at Loutraki, the same, probably beachrock structure is at a height of 1.0 m. At the eastern exit of the canal, submerged ruins of the ancient harbor of Schoenous have been identified at the modern site of Kalamaki. There are also data showing that the westernmost portion of the Saronikos Gulf coast is submerging; the harbor of Kehreai (5 km south of Kalamaki) is the best known example.

The long-term (Quaternary) and short-term (late Holocene to present) data discussed above are summarized in Figure 11.

According to Mariolakos & Stiros (1987), the Corinthiakos Gulf separates a bulging area (anticline?) to the south and a structural depression to the north, the Isthmus marking their easternmost limit

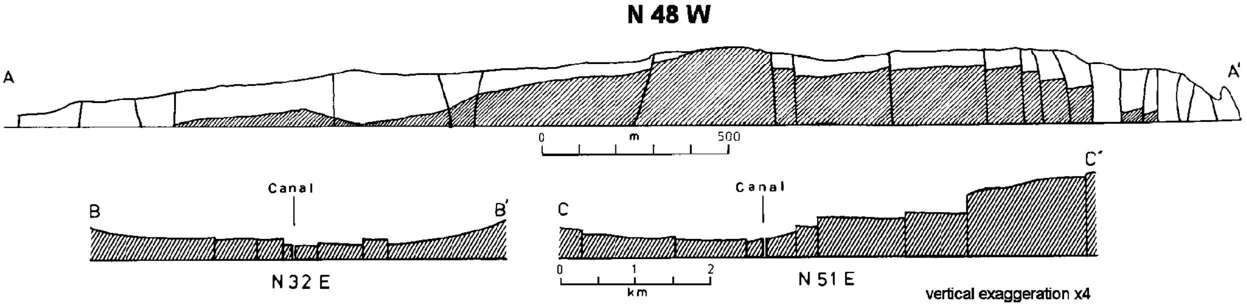

Fig. 9 Schematic cross sections of Isthmus (for locations see Figure 4.1). Neogene deposits are shaded, Quaternary deposits are blank. In sections B-B' and C-C' Quaternary cover is too thin to appear at the scale used. (Based on data by Freyberg, 1973).

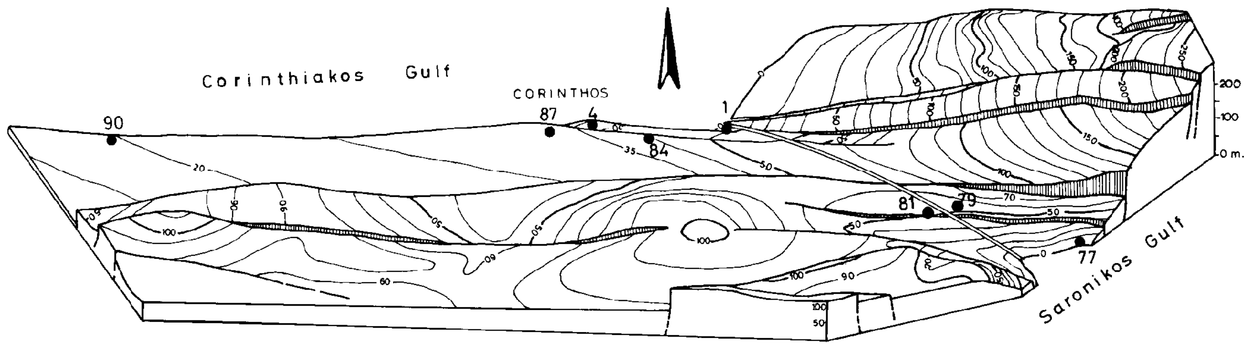

Fig. 10 Perspective view of contour map of Eutyrrhenian layer height, after Freyberg (1973). Canal and leveling benchmark positions (bold numbers) are also shown (After Mariolakos & Stiros, 1987).

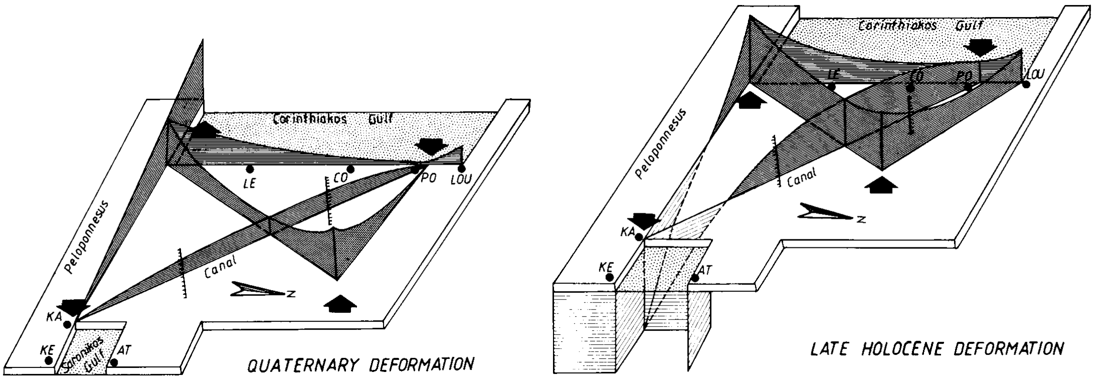

Fig. 11 Quasi-perspective block diagram of Isthmus deformation (not to scale). Arrows indicate torsional deformation. LE=Leheon; CO=Corinthos; PO=Possidonia; LOU=Loutraki; KA=Kalamaki; KE=Kenchreai; AT=Aghioi Theodori.

and an area where the associated deformations are minimum and easily observable. The depression to the north may extend as far as the Ionian Islands, which are characterized by pre-Quaternary reverse faults and a Holocene or even older tilt antithetic to that observed in the northern part of the Isthmus (Fig. 12).

This analysis presumes that back-arc compression is not confined to a narrow zone hardly covering the westernmost end of the Peloponnessos, where minor contraction features have been reported (Mercier et al., 1979), but may extend as far as the isthmus. In the northern Peloponnessos, however, this compression should be mild, thus producing only a very long wavelength bulging. This is contradictory to previous concepts that east-west normal faults and focal mechanism solutions of shallow earthquakes signify that this area is under extension

(Mercier et al., 1979). However, these analyses fail to explain the differential vertical motions along the Corinthiakos Gulf, as well as the antithetic tilting of the Isthmus strata. Furthermore, the fact that the crust in the northern Peloponnessos is up to 2.5 times thicker than in the Aegean, to the east (Makris, 1978), may suggest that the former is an area of crustal shortening.

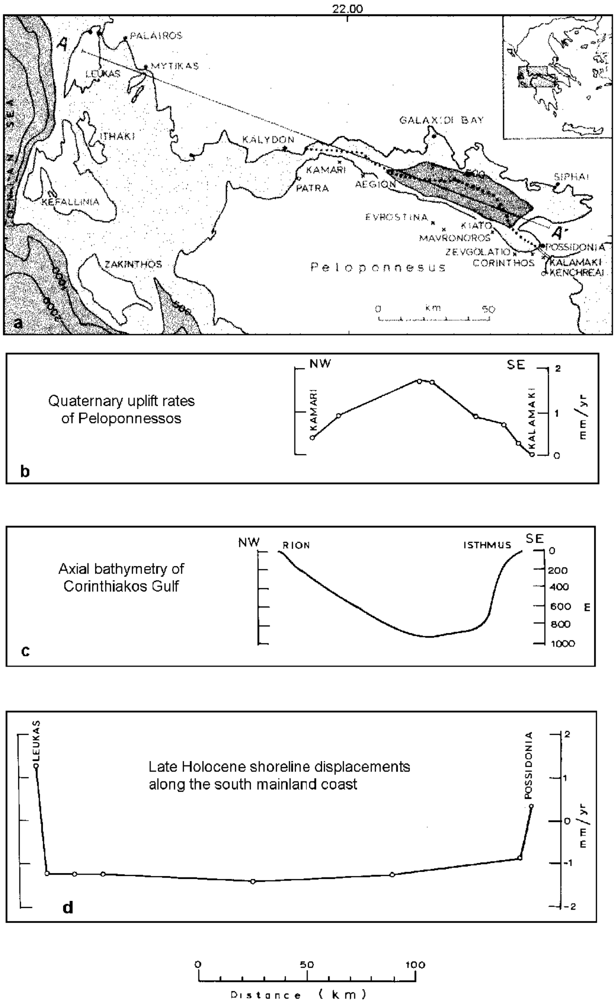

Fig. 12 Differential movements and morphological features in Corinthia-kos Gulf combined with deformation of Isthmus. a: location map, b: Qua-ternary uplift rates from sampling locations (marked with 'x' in (a)); c: axial bathymetry of Gulf; d: Late Ho-locene shoreline displacement (points correspond to solid circles in (a)) (After Mariolakos and Stiros, 1987).

Tselentis & Makropoulos (1986) computed the deformation tensor in the Corinthiakos Gulf by using large (M>5.5) earthquake fault-plane solutions, and showed that north-south extension is not the dominant mode of deformation in this area. Their data seem to corroborate some north-south as well as some east-west extension, but the corresponding values are very small relative to the dominating deformation (uplift and subsidence of the southern and northern coasts, respectively) and may be insignificant, as no standard deviations are computed. However, some north-south extension, as a consequence of the east-west back-arc compression, is likely to exist. East-west-striking normal faults may originate from this second-order extension, especially since older lines of weakness are reactivated (Sebrier, 1977). However, things must be more complicated, because normal faults and focal mechanisms contain some characteristic strike slip.

Hatzfeld et al. (1990) computed 16 focal mechanism solutions of shallow earthquakes that show N-S mostly normal faulting, while few of them are strike-slip. However almost none of the normal mechanisms corresponds to pure dip-slip, but most of them are oblique-slip.

The previous discussion suggests that the well-documented torsional deformation of the Isthmus is taken up by steep, parallel normal faults. Consequently, these normal faults, as well as the normal faults flanking the Corinthiakos Gulf, are not indicative of regional extension, as was previously believed.

5. ANCIENT CORINTHOS AND DIOLKOS

A few kilometres west of the modern town, the Ancient town of Corinthos is founded partially on the Neogene formations and partially on the Quaternary deposits (Tyrrenian). The construction material is mainly pleistocene calcareous oolitic sandstone (known as poros) that outcrops near the city of Corinthos.

Diolkos was a ramp connecting Corinthiakos to Saronikos Gulfs, on which the ancient vessels were pulled from one side to the other in order to avoid the circumnavigation of Peloponnessos. (Fig. 13). It should be noted that although the people who profited from the existing harbors of Lechaion on the Corinthiakos gulf side and Kechreae on the Saronicos Gulf side Diolkos. However, the passage of ships was becoming more and more difficult as commerce was being developed and warfare necessitated the building of larger vessels.

It was Periandros (600 B.C.), the Tyrant of Corinthos, who first conceived the idea to cut the Isthmus by constructing a canal. He soon, however, gave up when he faced the technical problems involved in such a construction. In addition he was afraid of the wrath of Poseidon to whom the Isthmus area was dedicated.

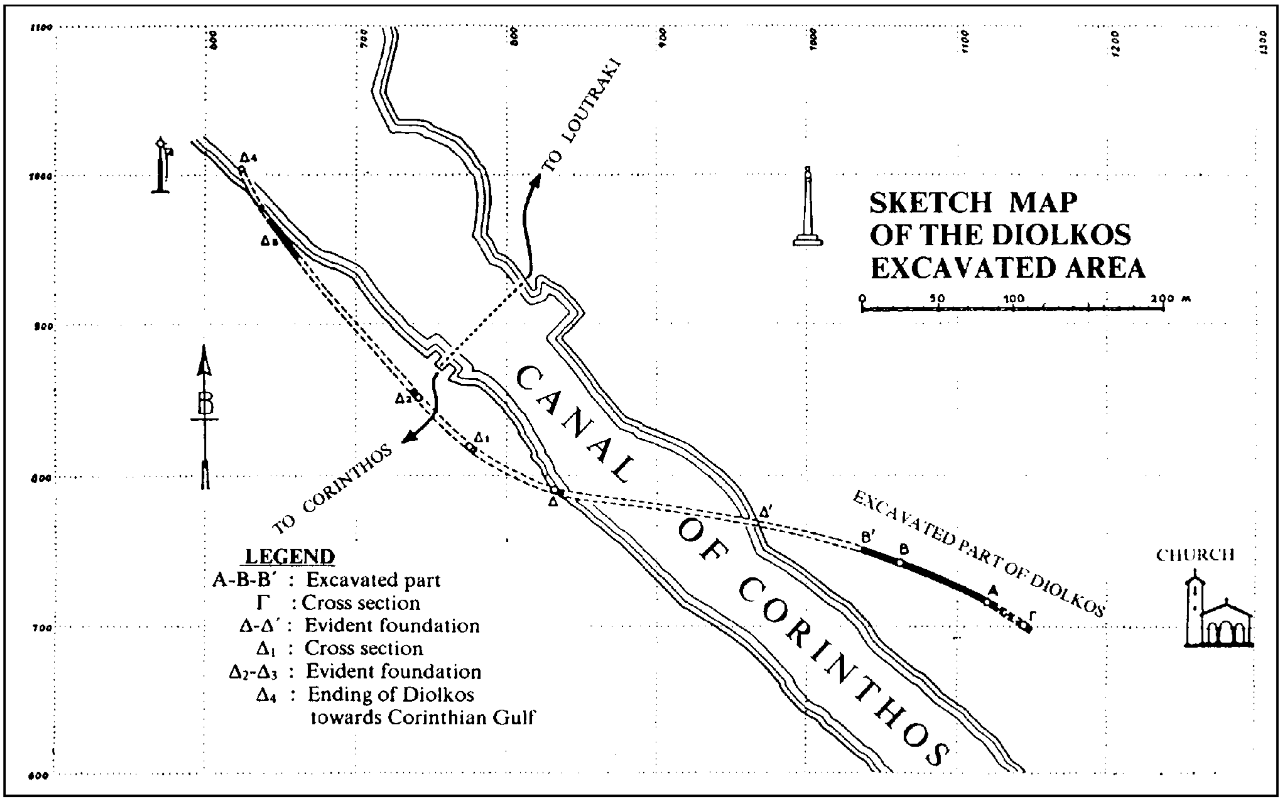

Fig. 13 The Isthmus with Canal and Diolkos.

Three hundred years later, Dimitrios the Besieger planned to construct the canal, but was stopped by his engineers who, (as mentioned by Strabo), asserted that the sea level of the Corinthiakos Gulf was higher than that of the Saronikos Gulf and thus a canal opening could cause the flooding of the coasts of Egina.

Isthmus Canal - Technical data
Total length 6.300 m of which 540 m are the outer port.
Base of slopes is walled by stones for a length of 3.500 m.
Width at the bottom: 21 m.
Width at sea level: 24.6 m.
Depth (uniform): 8 m.
Max. height: 79 m.

Julius Caesar and Calligula considered again the question of opening a canal. About a century later when Nero came to Corinthos to attend the Isthmia festivities, he took the decision to undertake this project. Indeed, the opening started both from the Corinthiakos and the Saronikos Gulf sides. However, after his return to Rome and his death, all work ceased. Herodes Atticus who later attempted to continue the project, was ordered to stop. Several hundreds years later, another attempt by the Venetians was condemned to failure.

Following the liberation of Greece, a new study was made but the estimated cost was more than the newly formed State could afford. Finally, half a century later on March 29th, 1882 the official foundation ceremony took place. The completed canal was inaugurated on July 25th, 1893.

The expert advice of some of the authorities of the time was sought and Ferdinand de Lesseps was consulted. The final design of the cut and the execution of the entire work was undertaken and brought to completion by the Hungarian civil engineer Bela Gerster.

6. NEOTECTONICS OF CORINTHIAKOS GULF

Corinthiakos Gulf is a narrow strip of sea separating Peloponnessos from the rest of continental Greece. According to most researchers it is an asymmetrical tectonic trough, the exact formation time of which is unknown; however it must be between Late Miocene and Early Pliocene. Neotectonic and more specifically the Quaternary deformation studies around the Gulf revealed that the faulting as well as the

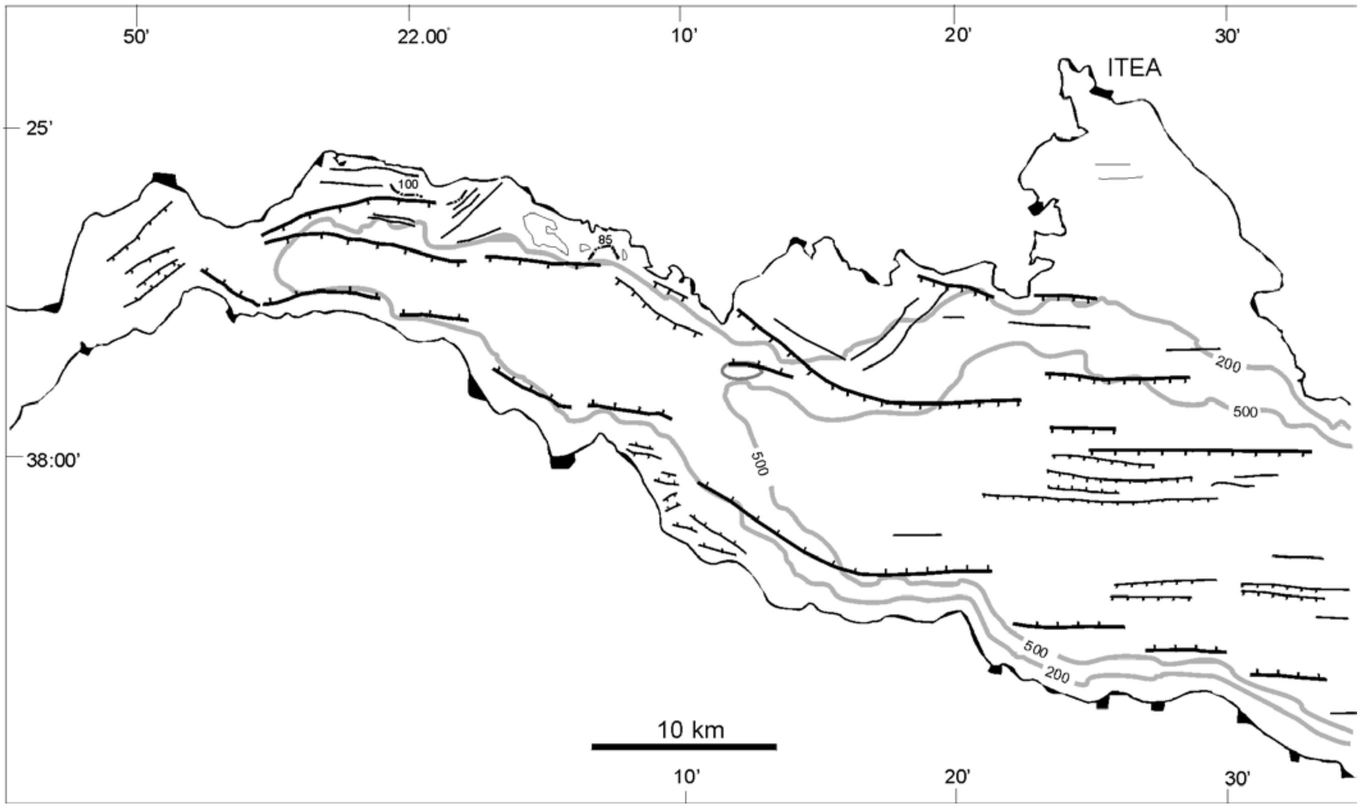

Fig. 14 Simplified tectonic map of western Corinthiakos Gulf showing bathymetry (continuous lines), and main active faults (hachured lines) (After Papanikolaou *et al.*, 1997).

morphology of the coast is the result of rotation phenomena (Freyberg, 1951, 1973, Mariolakos, 1976, Mariolakos et al., 1985). Furthermore, Kelettat & Schröder, (1975), and Mariolakos et al., (1989, 1991, 1994), suggest that certain blocks at the southern Peloponnessos have been subjected to rotation.

The distribution of the pliocene-quaternary deposits along the coast areas of the Corinthiakos Gulf is almost unilateral. North of the Gulf they are nearly absent, with the exception of one occurrence near Itea, the Agia Efthymia lacustrine conglomerates, of about 40-50 m thickness. In contrast, the plio-quaternary sediments are abundant on the southern coast, where they reach a thickness of more than 1200 m. They occur from the sea level up to a height of about 1700 m. The facies of the younger deposits (mainly sandstones and conglomerates) is more or less continental with intercalations of marine beds (Dercourt, 1964; Ori, 1989).

Heezen et al., (1965) conducted an investigation of the sea-floor relief in the Gulf and demonstrated that there are significant differences between the northern and southern parts of it. These differences can be observed on the continental shelf as well as on the continental slope of both margins. The continental shelf of the Gulf along the southern central part is, in general, poorly developed, seldom exceeding 500 m. in width. In contrast, along the northern coast it is consistently wider, (maximum width ~9 km in the bays Antikyra and Krissaion). It is also quite steep on the southern side, as opposed to the northern side where it dips more gently; furthermore, the latter is more intensively dissected and is characterized by a micro-relief. This asymmetry is more pronounced in the central part of the Gulf, where the 'abyssal plain' of the Gulf lies, just opposite to the area where the pliocene-quaternary sediments are most pronouncedly uplifted (i.e. Mts. Ziria.and Helmos, north Peloponnessos) and reach their maximum thickness.

Recent research (Papanikolaou et al., 1997) has shown that the thickness of the sediments in the Gulf increases eastward, and such is the case for the throw of the faults that bound the Gulf.

The following principal features characterize the topography of the northern Peloponnessos (south of the Gulf): (1) high altitudes (Mt. Ziria: 2376 m; Mt. Chelmos: 2341 m; Mt. Panahaikon: 1926 m). All these mountains rise at small distances from the present shoreline, and (2) the step-like relief of the northern part of the Peloponnessos with long and narrow terraces, which is partly due to old abrasion that followed the deposition of recent marine sediments.

The valleys of the northern Peloponnessos are deeply incised and steep gradients are another characteristic of the thalwegs. The geomorphology of the northern margin is completely different and the area occupied by the mountains Parnassos and Giona consists of four erosion surfaces. (Maul, 1921, Philippson, 1930, Sweeting, 1967). The step-like arrangement of the relief, which is so characteristic of the Northern Peloponnessos topography, is absent here. Furthermore, with very few exceptions, the streams of the northern margin are not incised.

The active fault zones of the Gulf comprise en échelon, right-stepping E-W striking faults (Papanikolaou et al., 1997), and the mean direction of the Gulf is the result of this fault pattern (Fig. 14). The southern margin of the Gulf has been uplifting during the Plio-Quaternary, a fact confirmed by the occurrence of the plio-quaternary conglomerate beds at elevations higher than 1600 m (Fig. 15). (Mt. Mavrovouni).

In the vicinity of the Isthmus of Corinthos, Philippson (1892) distinguished two fault systems: the Corinthian fault system at the northern side of the Isthmus and the Crommyonian at the southern side. Although both systems have the same strike the former are homothetic whereas the latter are antithetic. The normal character of the faults in the area of the Isthmus had led to the conclusion that the disruption was caused by tensional stresses. Thus Philippson (1892), who first studied the geologic section of the canal, regarded it as a horst. However, later investigations by Freyberg (1951, 1971) showed that the tectonic movements have a rotational character and therefore the normal faults, regardless of their dip direction relative to that of the faulted strata, have resulted from rotation around an almost horizontal axis.

Based on Freyberg's conclusions that faulting in the area of the Isthmus of Corinthos has resulted from rotation involving tectonic processes, Mariolakos (1977), accepted that the region between Sperchios River basin to the north and Mts. Ziria, Chelmos and Panachaikon south of the Gulf, can be divided into a number of neotectonic multi-blocks. These, on account of their specific tectonic behaviour, were called tectonic dipoles. Thus, the mountains of Lidorikion, Giona and Iti constitute one tectonic dipole, which was referred to as the Giona - Iti tectonic dipole, whereas the northern part of Peloponnessos makes up the Corinthian tectonic dipole (Fig. 16). As Mariolakos (1977) pointed out, the tectonic dipole concept is not identical to that of the tectonic block; in fact a tectonic dipole consists of more than one block and forms a mosaic structure, that is, a tectonic multi - block.

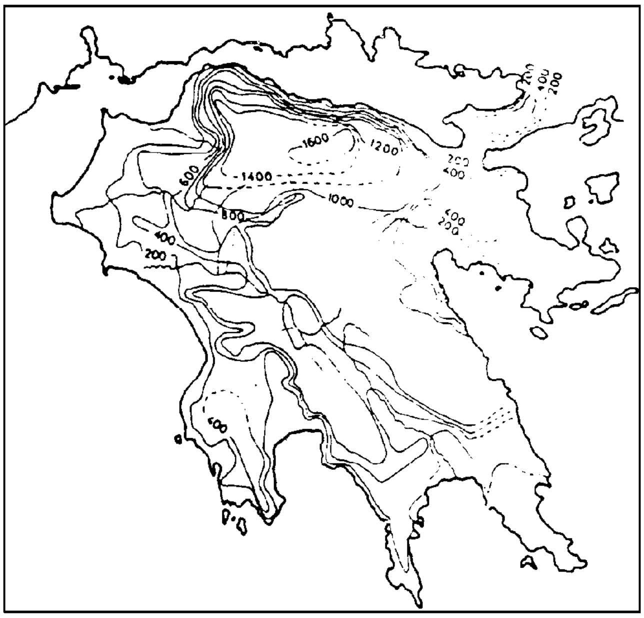

Fig. 15 Elevation of Plio-Quaternary deposits in Peloponnessos.

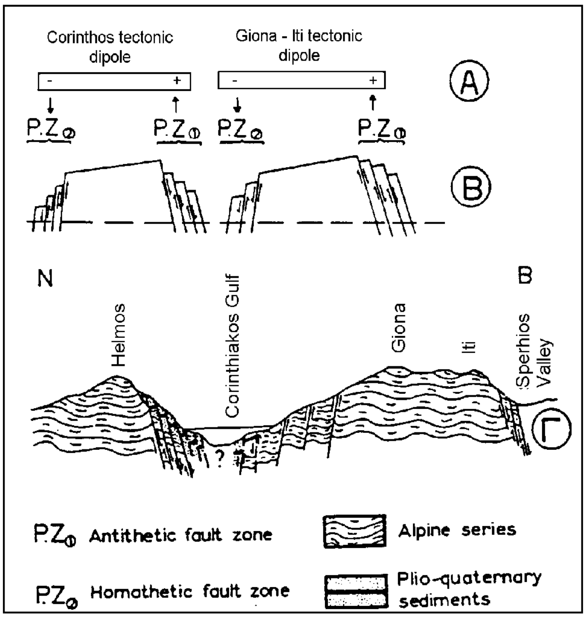

Fig. 16 The proposed tectonic dipoles model (After Mariolakos, 1977).

The characteristic property of the tectonic dipole is that it shows a differential movement, due either to different direction of movement or different velocity. The differential movement is more obvious near the extremities of the dipoles, the poles, one of which appears to rise, relative to the other, which appears to descend. Furthermore, it must be noted that despite the apparent independence of the block-components of the dipole, the final movement, if there is one, resulting from the combination of the partial movements throughout the dipole is such that the two poles attain different movements or velocities relative to each other.

The Giona-Iti tectonic dipole and the Corinthian tectonic dipole, are two independent tectonic units which, nevertheless, behave in a similar manner in as much as there is an upward motion along their northern parts and a downward one along their southern parts.

Despite the fact that the quaternary fault tectonics is represented almost entirely by normal faults, it is debatable whether tensional forces caused it (as proposed, among others, by Leeder & Gawthorpe, 1987, Collier, 1990, Doutsos & Piper, 1990; Leeder et al., 1991) as the rotation effects observed in Isthmus of Corinthos suggest. Undoubtedly, the faults of the northern Peloponnessos, if examined separately, are due to gravity tectonics; the question lies, however, in identifying the primary genetic mechanism and in being able to recognize the tensional or compressive character of the deformation-generating forces.

Thus, if one wishes to explain the neotectonic-quaternary evolution of the Gulf, one should take into account the following:

The uplift of the northern part of Peloponnessos and the region of Iti (southern part of Sperhios basin).

- The varying degree of uplift throughout the Giona – Iti dipole to such a degree, so that erosional surfaces of the same age, i.e. Calyvia surface, show a southern dip.
- The occurrence of Neogene beds in the northern Peloponnessos and their absence from the southern Sterea Hellas.
- The asymmetry observed in the morphology of the sea floor of the Gulf.
- The morphological asymmetry of the northern and southern coast.
- The presence of the normal antithetic faults in the northern part of Peloponnessos
- The mean WNW-ESE direction of the Gulf, which is determined by the en échelon arrangement of the E-W trending “marginal” faults.
- The vertical throw of the faults, as well as the thickness of sediments increases towards the East.

All these, combined with the segmented form of marginal fault zones and depocentres point to the conclusion that the central part of the Gulf is still at an older stage of evolution that the eastern one; the structure and evolution of the Gulf may not be the result of axial extension. The mechanics should involve more complex procedures, including those of a composite stress field (transtension and transpression) and the interaction between brittle and plastic deformation.

7. DELPHI

Greece’s numerous archaeological sites can provide excellent case studies for various subjects related to engineering geology, tectonics and morphotectonics, and historical seismicity, coupled with the intervention of human activity in the course of centuries.

A suitable case study is the ancient town of Delphi, located 250 km west of Athens in the southern slopes of Mt. Parnassos, and overlooking the northern margin of the Gulf of Corinthos. It is one of the most important archaeological sites in Greece, where the most famous oracle of the ancient world was established.

In the geological map of Figure 17 two types of formations, the post-alpine and the alpine, are shown.

The post-alpine formations are mainly represented by scree and talus cones, which cover the major part of the archaeological site. There is a very close relationship between these formations and (i) the very intense morphological slopes and (ii) the successive reactivations of the Arachova – Delfi fault zone in the northern border of the archaeological site (Figs. 17, 18). Four generations of scree can be distinguished (Fig. 18). The first one is mainly represented by compact breccia and conglomerates with calcitic matrix. The second one is represented by breccia and conglomerates cemented by a pelitic material. The third generation consists of polymictic, unconsolidated material, including big blocks or fragments of limestones. The fourth generation is the result of the relative recent rockfalls and is represented by big blocks of limestones (from 0.5 to 10 m^3).

The thickness of the post-alpine formation differs from place to place, depending on the paleomorphology of the basement. So, in the northern part of the archaeological site (Fig. 16), it seems to be small (up to 2 m.), as it is proved by the very frequent basement outcrops. On the contrary, at the southern part it seems to be greater but it does not exceed 15 m.

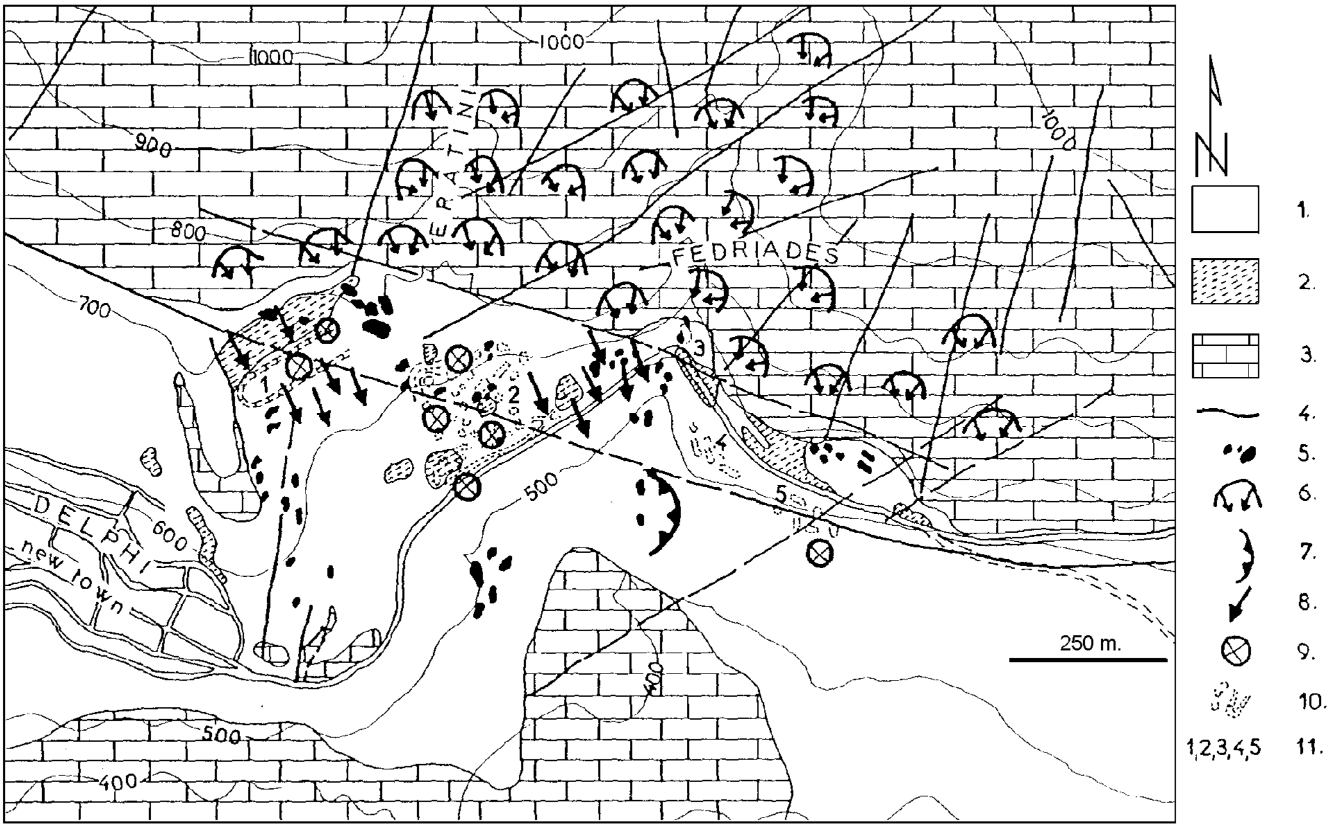

Fig. 17 Geological sketch map of Delhi. 1: Scree; 2: Flysch; 3: Limestones; 4: Fault; 5: Rockfalls; 6: Rockfall-prone site; 7: Landslides; 8:Creep; 9: Subsidence; 10: Ancient remnants; 11: (1) Stadium; (2) Apollo Sanctuary; (3) Kastalia spring; (4) Gymnasium; (5) Tholos (after Mariolakos *et al.,* 1991).

The alpine formations belong to the Parnassos Unit and they are represented (Fig. 16) by the Paleocene flysch (alternations of sandstones, marls and pelites) and neritic Jurassic-Cretaceous limestones.

The alpine tectonics is characterized by a large-scale overturned isoclinal fold (Fig. 19) resulting in the younger flysch underlying the older limestones, at the northern part of the archaeological site. The contact between the limestones and the flysch is mostly regular, while at places the flysch is thrusted over the carbonates. A great number of thrusts and reverse faults can be also observed within the calcareous rockmass.

The neotectonics of the area is characterized by the existence of 1st order macro-blocks (horsts and grabens) separated by fault zones, as the 1st order Arahova – Delphi active one that juxtaposes the Parnassos horst in the north against the Itea graben in the south (Fig. 20).

Numerous second- or third-order faults cut the alpine and post-alpine formations. Some of these faults are active, and seem to be connected to the historical-to-present-day seismic activity of the area. As for the inactive faults, their surfaces are convex or concave, when they are small, and undulated when they are big, while some of them bear striations. On the other hand, the active faults of the area are almost planar and cut the inactive ones. They are usually accompanied by a zone of loose gouge.

The hydrogeological conditions of the area are defined and controlled by the alpine and post-alpine structure and contact or over-flow springs occur along the carbonate-flysch contact. The drainage of the area is accommodated by the Phaidriades and Erateini torrents, in the east and west, respectively. Note that the area is prone to destructive flash floods.

The seismic activity of the major area seems to have been very high since historical times. Ancient of Delphi was razed by the earthquake series of 600 BC. (I_0=VIII-X).

The probability of shallow, $M>6$ earthquake occurring until 2006 is $0.80<p<1.00$ and the expected intensity for a design period of 80 yrs. Is VIII-IX (Papaioannou, 1986). The expected ground acceleration with a 63% probability is 250-275 cm/sec^2 for the next 50 years (Makropoulos, 1986).

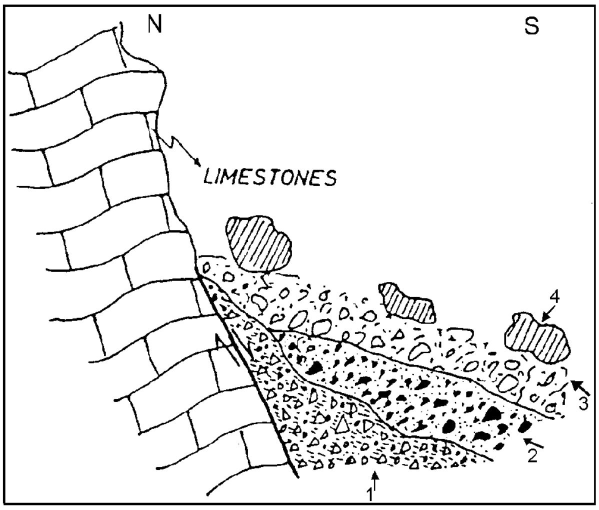

Fig. 18 Four generations of scree in Delphi (after Mariolakos *et al.,* 1991).

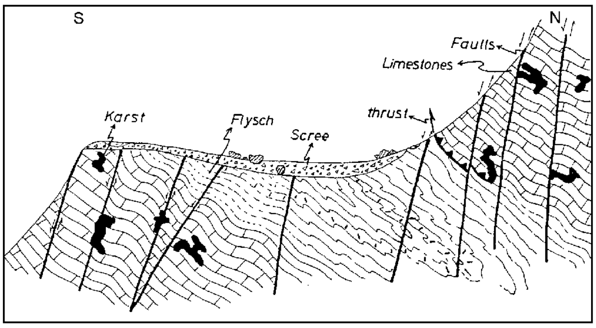

Fig. 19 Schematic geological cross-section (after Mariolakos *et al.,* 1991).

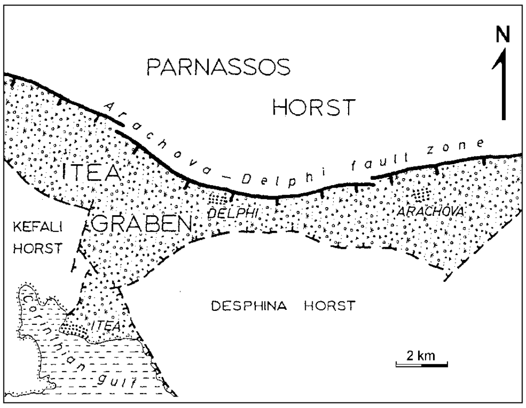

Fig. 20 Local neotectonic setting (after Mariolakos *et al.,* 1991).

8. MINYAN ANCIENT FLOOD PREVENTION WORKS (C. 1600 BC.)

The flood prevention - drainage works in Lake Kopaida are the earliest in Europe, since their construction dates back to 1600 BC. The technique implemented by the ancient people of Minyes is the same as the one currently taught at the Higher Education Institutions all over the world. These works, together with the mines in Lavrio, are the most important archeological sites suitable for the investigation of the technology of the ancient times; however the mining facilities in Lavrio are much younger (c. 800 BC.).

The largest navigable canal of the ancient times (27 km long) was constructed and, according to Knauss, it was used for product transportation (Fig. 21). The water level at some parts of it was 1.5 m. above the adjacent areas that were used for cultivation and the embankment was totally impermeable (Fig. 22). The concept of the construction of that floodway is totally different from the one applied by a British company at the beginning of this century; the latter bore significant drawbacks, and subsequently numerous problems arose.

After the construction of the canal by the Minyes the water level at some parts of it was 1.5 m. above the ground surface (Fig. 22), which was used for crops. The works were totally impermeable, and their stability was excellent. It should be noted that the present national road connecting Kastro and Orhomenos is partially constructed on the embankment.

These works are related to the stage(s) of climatic optimum(s) in the Holocene and any further archaeogeological study should be valuable for the estimation of climatic fluctuations during the last 10 ka. Events as Noah's flood, or the less familiar Deukalion's flood, reflect such climatic conditions, which are, in turn, related to flood-prevention works. Knowledge of such climatic changes is important for the contribution to the prediction of such future changes.

The disappearance of the Minyes and their civilization is connected to the destruction of their works by the thebian Hercules, who sealed the entrance to the sinkhole that funneled the water carried by their canal with a boulder. So the whole area of Kopaida was inundated again, destroying all flood-prevention works, crops, and finally all the towns built on the flanks of the valley. Obviously, the cause of the fall of the boulder was an earthquake. This boulder can nowadays be seen still blocking the entrance to the

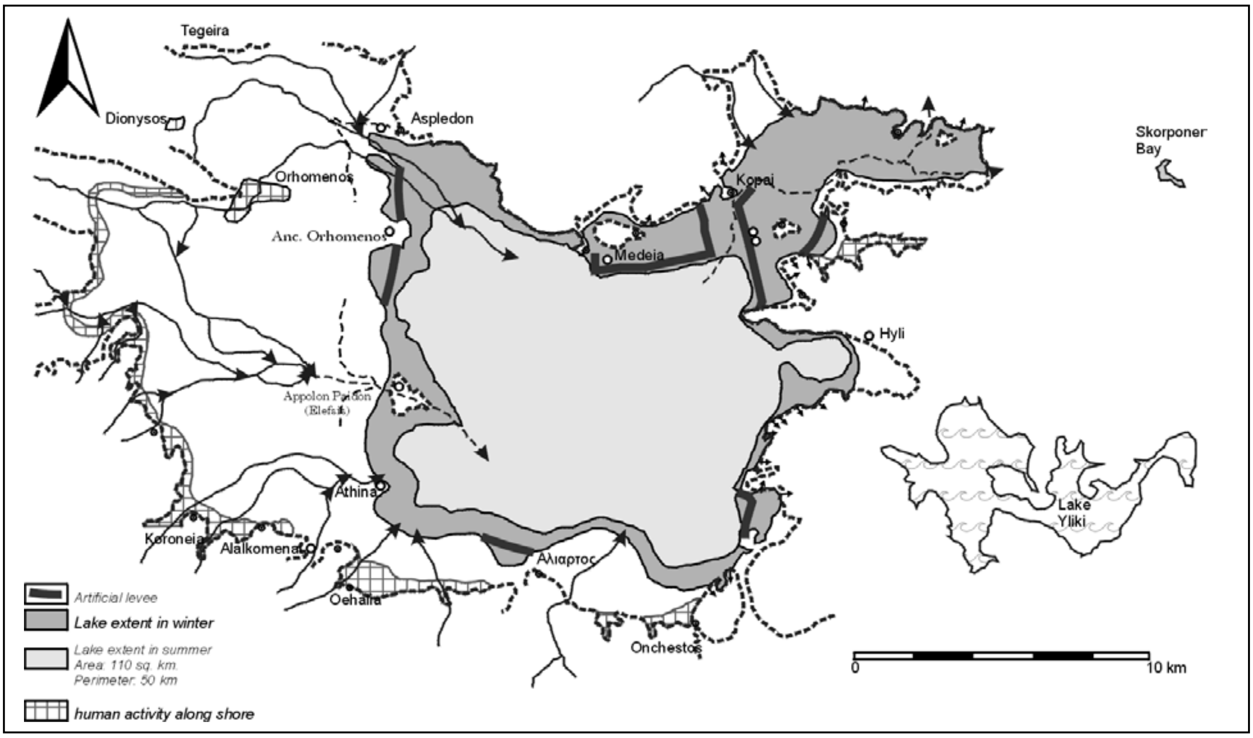

Fig. 21 Kopaida: Hystero-Helladic period reconstruction of lake area (dark-gray fill for winter high-stand, light-gray fill for summer lowstand). Also shown the flood prevention embankments (heavy lines) and location of ancient towns/hamlets (After Knauss, 1984)

sinkhole and the site has been proposed for inclusion in the international Geotope list of UNESCO. We should also say that the whole area between the springs of Orhomenos to the town of Kastro (ancient Kopes) and the sinkhole of Neo Kokkino could be developed into a unique *Earliest European Flood Prevention Technology Park.*

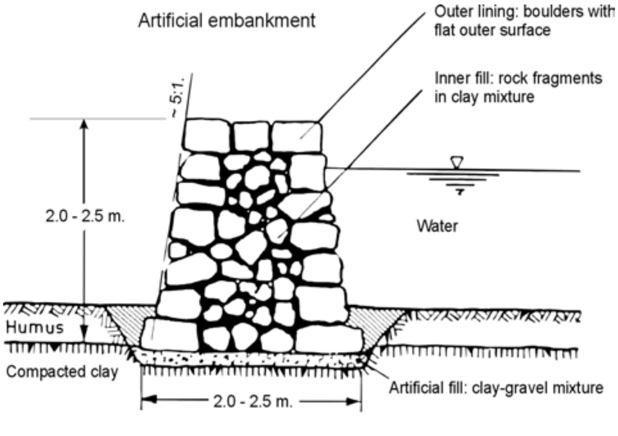

Figure 22 Cross-section of artificial embankment

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