

Neotectonic folds in the central-western Peloponnese, Greece

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Abstract: The western Peloponnese, being very close to the Hellenic Trench, is one of the most active areas in Greece. The study area is located at the central western part of Peloponnese and it is developed in a NNW–SSE direction along 45 km, parallel to the Ionian Trench, which occurs at a distance of only 30–40 km to the west. Based on the morphotectonic studies of the neotectonic macrostructures of the central-western Peloponnese in many scales, it was concluded that the main neotectonic mega-structure is the “Megalopolis–Lykaeon–Minthi–Tetrazio Composite Morphotectonic Structure” (MELYMITE CMS) (1st order structure). The neotectonic deformation is expressed not only by faults, but also by folds which in some cases are the principal structures of the neotectonic deformation. Neotectonic folds occur in the Alpine formations as well as in the post-Alpine ones in various scales. The folds, and the ductile deformation in general, are not easily observed on the surface because of the intense presence of brittle tectonics. A rotational couple stress-field could satisfactory incorporate and explain the brittle-ductile neotectonic structures of the area.

Kurzfassung: Die westliche Peloponnes, recht nahe dem Hellenischen Graben gelegen, ist eines der tektonisch aktivsten Gebiete Griechenlands. Das Untersuchungsgebiet liegt im zentralen Teil der West-Peloponnes und erstreckt sich über 45 km in NNW–SSE-Richtung parallel dem Ionischen Graben, der in einer Entfernung von 30–40 km westlich davon verläuft. Auf Grund morphotektonischer Untersuchungen der neotektonischen Makrostrukturen der zentralen West-Peloponnes in verschiedenen Maßstäben ergab sich, dass die sog. Megalopolis–Lykaion–Minthi–Tetrazio-„Composite Morphotectonic Structure“ (MELYMITE CMS) die wichtigste neotektonische Megastruktur darstellt. Die neotektonische Verformung wird nicht nur durch Verwerfungen sondern auch durch Faltungen deutlich. Neotektonische Faltungen erscheinen in alpinen und postalpinen Formationen in unterschiedlicher Größenordnung. Faltungen und duktile Veränderungen sind allgemein, wegen der kräftigen bruchtektonischen Einflüsse, nicht leicht von der Oberfläche her nachzuweisen. Ein durch ein Rotationspaar bedingtes Stressfeld kann die neotektonische Bruchfaltenstruktur des Gebietes zufriedenstellend darstellen und erklären.

Keywords: neotectonic, fold, deformation, ductile, brittle, uplift, subsidence, rate, sediments, Greece

Schlüsselwörter: Neotektonik, Faltung, duktile Verformung, Bruchverformung, Hebung, Senkung, Raten, Sedimente, Griechenland

1. Introduction

Central-western Peloponnese covers the main western part in the Aegean Arc system (Hellenic Arc), which lies at the western margin of the Aegean continental block. The Hellenic Arc is a convergent zone associated with northward subduction of the African Plate beneath the Aegean (Fig. 1a). The western part of Peloponnese is located in one of the tectonically and seismically most active areas of the Africa-Eurasia collision zone.

The study area is a complex multi-fractured neotectonic macrostructure, which is characterized by the presence of large grabens and horsts bounded by wide fault zones, trending approximately E–W. Inside these first-order neotectonic

macrostructures a considerable number of small order structures are present (Fig. 2).

Western Peloponnese is dominated by extensional tectonics as expressed by the E–W oriented normal faults on its central-western part (Fig. 2). The deep-seated compressional tectonics is not in contradiction with the extensional features observed on shallow structures on the upper plate. Many geophysical, geological, morphotectonic and paleomagnetic investigations were conducted in western Peloponnese, dealing with the crustal structure and the seismic hazard of this area. Mariolakos & Papanikolaou (1987) claim that the deformation pattern of the area is not only a result of axial extension but also a result of simple shear and torsion.

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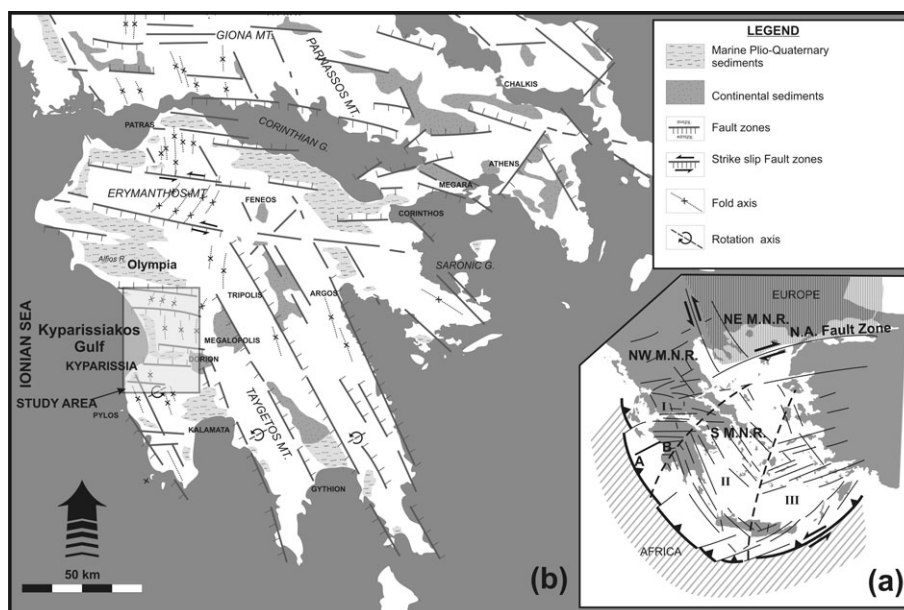


Fig. 1: The three Morpho-Neotectonic Regions (MNR) (a) as well as the three sectors and the main marginal fault zones of the post-Alpine basins in the southern continental Greece (b); modified by Mariolakos & Fountoulis 2004, from Mariolakos & Papanikolaou 1981, 1987.

The general tectonic trend of the western Peloponnese is NNW–SSE, following the geometry of the fold and thrust belt of the External Hellenides (Philippson 1898, Aubouin et al. 1961, Aubouin 1977, Jacobshagen 1979) and of the modern Hellenic Arc and Trench System (McKenzie 1972, LePichon & Angelier 1979). However, the neotectonic structures in the area are not oriented parallel to the arc in the NNW–SSE direction and there are several east–west trending fault zones forming the margins of the post-Alpine basins developed on top of the thrust sheets of the Hellenides, with alternating horst and graben structure (Fig. 1b; Mariolakos & Papanikolaou 1981, 1987, Mariolakos et al. 1985).

Extended outcrops of marine Lower Pleistocene sediments are observed within the grabens along the coastal zone up to 15–20 km distance from the coastline and at altitudes of several hundred metres (Kowalczyk et al. 1975, Kelletat et al. 1978, Kowalczyk & Winter 1979, Fountoulis 1994, Mariolakos et al. 1998). This demonstrates the occurrence of significant vertical tectonic movements during the Quaternary, which permitted the deposition of marine Quaternary sediments in subsided areas and their subsequent uplift and erosion at their present state.

Ductile structures (folds) within the post Alpine deposits of western Peloponnese have not been studied so far, not even found or described. The only folds mentioned so far in sediments younger than Upper Miocene on the Ionian Islands, are related to diapiric phenomena (Underhill 1988, 1989). Mariolakos & Fountoulis (1990), having studied the neotectonic deformation in the broader area of Filiatra in SW Peloponnese, described a neotectonic macrofold within the Early Pleistocene marine deposits. This paper deals with the neotectonic ductile structures that occur in various scales in central-western Peloponnese.

In order to understand the nature of the deformation affecting the central-western Peloponnese, the neotectonic structures (folds and faults), the spatial distribution and the

dip direction of the planation surfaces created on the Early to Middle Pleistocene sediments, were studied.

In areas where only the Alpine basement crops out the only source of data, other than morphological data, is the deformation of the Alpine tectonic features during the neotectonic period that is the period after the end of the thrust tectonics. The general direction of the thrust surfaces and the Alpine fold axes in western Greece is NNW–SSE. Statistically significant deviations of structural elements of the aforementioned Alpine directions should result from neotectonic deformation, such as faulting or block rotation.

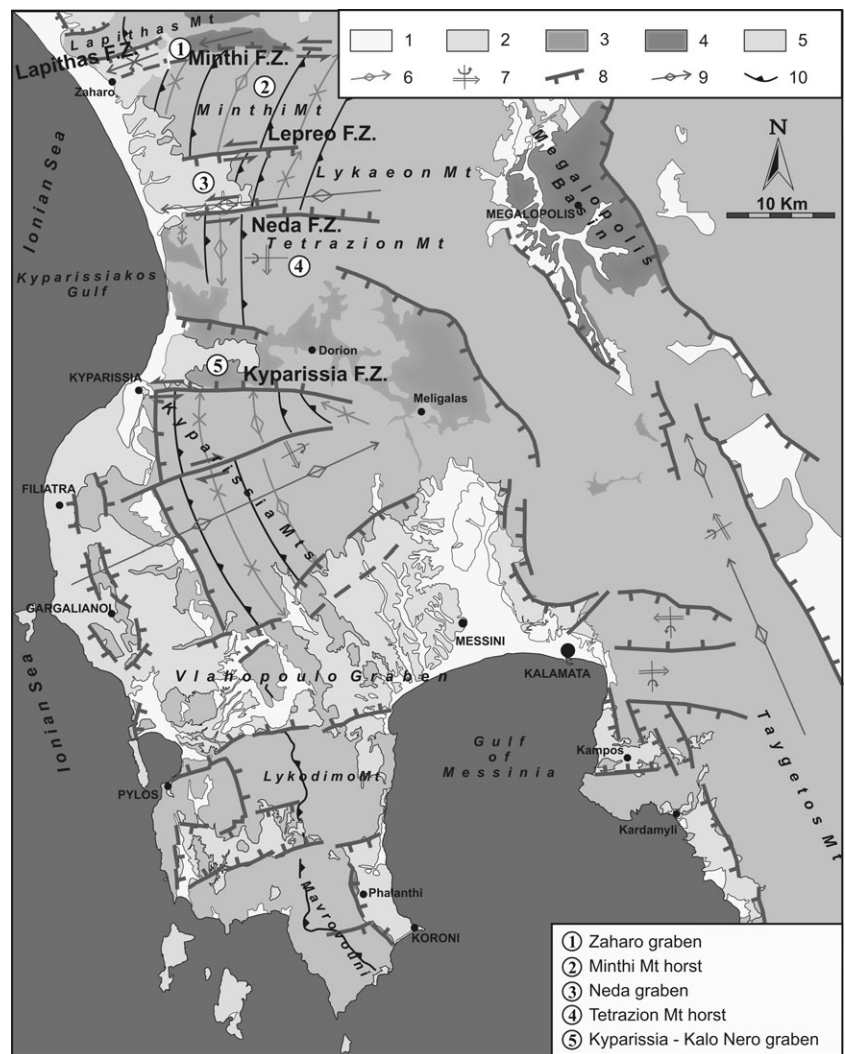
2. Geology – neotectonics

2.1. General

At a regional scale the Hellenic territory can be divided in three morphoneotectonic regions (Mariolakos & Fountoulis 2004; Fig. 1a). More specifically, Mariolakos & Papanikolaou (1981, 1987) and Mariolakos et al. (1985) divided the southern morphoneotectonic region in three sectors (I, II, III) according to the general direction of the morphologic and the neotectonic major fracture zones prevailing in each region (Fig. 1b). These morphoneotectonic structures consist of successive neotectonic multi-fractured more or less parallel horsts and grabens (Fig. 1b).

At a regional scale, several neotectonic first-order structures may be distinguished in central-western Peloponnese (Fig. 2). These are from south to north: (1) the Kyparissia Mts. composite morphotectonic structure, (2) the Megalopolis–Lykaeon–Minthi–Tetrazio Composite Morphotectonic Structure (MELYMITE CMS) and (3) the Lapithas Mt. Horst. Within the major MELYMITE CMS the following second order macrostructures occur: (1) the Zaharo Tectonic Graben, (2) the Minthi Mt. Horst, (3) the Neda Tectonic

Fig. 2: Schematic map showing the neotectonic regime of central-western Peloponnese. 1 = Holocene deposits; 2 = Pleistocene marine deposits; 3 = Plio-Pleistocene continental deposits; 4 = Plio-Pleistocene lacustrine deposits; 5 = Alpine basement; 6 = dominant plunge of Alpine fold axes; 7 = rotational axis; 8 = Neotectonic fault zone; 9 = Neotectonic fold axis; 10 = thrust. After Mariolakas et al. 2001, modified.



Graben, (4) the Tetrazion Mt. Horst, (5) the Kyparissia–Kalo Nero Tectonic Graben, (6) the Lykaeon Mt. Horst and (7) the Megalopolis Tectonic Graben (see also Fig. 2). All the macrostructures located at the western part of the studied area strike E–W, except the Lykaeon Mt. Horst and the Megalopolis Graben that strike NNW–SSE.

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

The Alpine formations mainly belong to the Pindos Nappe, which comprises a Mesozoic pelagic sequence and a Paleogene flysch. Thick molassic conglomerates of Miocene age occur at the front of the Pindos Nappe in the area south of Kyparissia (Fig. 2). The underlying Gavrovo Nappe, com-

prising Mesozoic to Upper Eocene shallow water carbonates and an Upper Eocene–Oligocene flysch occurs at the area of Filiatra in the south whereas a small outcrop of the more external Ionian Nappe occurs at the western part of Lapithas Mt. near the Olympia Basin at the north (Fig. 2; Fountoulis & Lekkas 1991).

Concerning the regional neotectonic characteristics of the study area, it should be mentioned that the marginal fault zones of the neotectonic macrostructures strike mainly E–W in the western part and NNW–SSE in the eastern part (Fountoulis 1994). Their vertical throw is not constant along their whole length, but usually it increases from east to west concerning the E–W fault zones and from south to north concerning the NNW–SSE fault zones. The faults that constitute a fault zone have an en echelon arrangement. They do not have a constant strike along their whole length. The striations observed on fault surfaces in most cases show a horizontal component of either right lateral component of movement or left lateral.

The **Zacharo Basin** lies between the Lapithas and Minthi Mountains (Figs. 2, 3). The **Neda Basin** lies between the Minthi and Tetrazion Mountains in central-western Peloponnese and constitutes the eastern prolongation of the Kypariss-

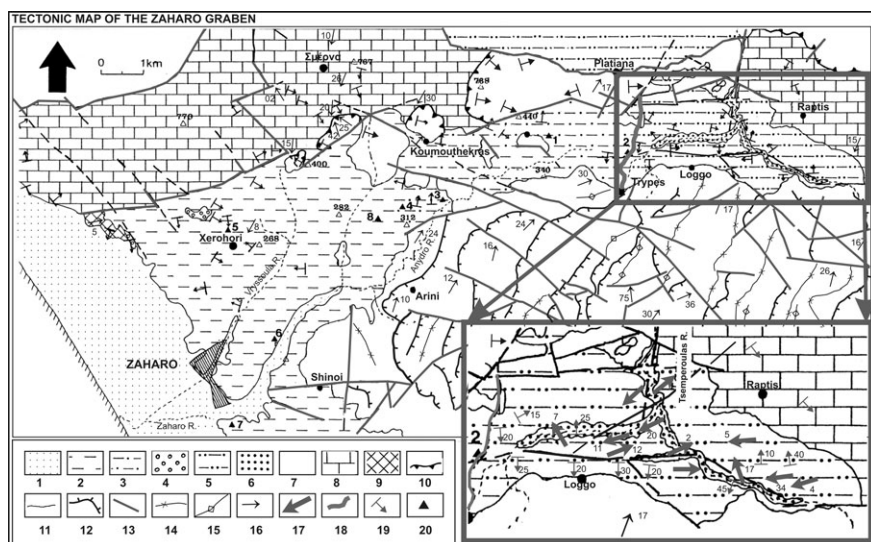


Fig. 3: Schematic geologic-tectonic map of the Zaharo Graben. 1 = Holocene deposits; 2 = Zaharo Formation; 3 = Anydros Formation; 4 = Xirohori Formation; 5 = Loggos Formation; 6 = Tsemberoula Formation; 7 = Pindos Unit; 8 = Gavrovo Tripolis Unit; 9 = Ionian Unit; 10 = thrust; 11 = geological boundary; 12 = overthrust; 13 = fault; 14 = syncline; 15 = anticline; 16 = plunge of fold axis; 17 = neotectonic fold axis; 18 = watershed; 19 = strike and dip of strata; 20 = observation site. After Fountoulis 1994.

sia Gulf during the Plio-Pleistocene (Fig. 2). Both basins constitute small, E–W elongated typical grabens that are bounded by the Arini Fault Zone in the south and the Kaiafa-Koumouthekra Fault Zone in the north and the Neda Fault Zone in the south and the Lepreon Fault Zone in the north correspondingly.

Post-Alpine sediment formations have filled the Zaharo Graben (Hageman 1977, Mitropoulos et al. 1982, Streif 1977, 1978, Kamberis 1987 and Fountoulis 1994). Hageman (1977) considered the sediments in the eastern Zaharo Graben (south of Platiana Village) to represent the basal post-Alpine strata within the Pyrgos-Olympia Basin and correlated the lacustrine deposits with the base of the Makrisio Stage Sequence (Upper Pliocene) in the Megalopolis Basin. Kamberis (1987) considers them to be the corresponding Plio-Pleistocene deposits of Vounargo Formation in the Pyrgos-Olympia Basin. Fountoulis (1994) divided the graben into two subbasins, the eastern and the western one, according to the present-day watershed, which passes through the Trypes and Platiana Villages (Fig. 3). No marine post-Alpine sediments (Upper Pliocene–Early Pleistocene) crop out in the eastern subbasin, while the western one has been filled in with marine and lacustrine post-Alpine sediments (Late Pliocene–Early Pleistocene; Fountoulis 1994).

The **Neda Basin** has been filled with post-Alpine deposits classified into the following formations: (1) The Elaia Formation occurs at the SW part of the basin and consists of Late Pliocene cohesive conglomerates (Fountoulis 1994, Fountoulis & Moraiti 1998), and (2) the Neda Formation is an Early to Middle Pleistocene shallow marine formation that consists of marls, sands, sandy marls and polymict conglomerates alternations. The Neda Formation is divided in 2 parts, the lower consisting mainly of sandstones, marls, sandy marls and polymict conglomerates alternations and the upper part consisting exclusively of polymict conglomerates (Fountoulis, 1994, Fountoulis & Moraiti, 1998).

It is remarkable that folds occur not only in the Alpine formations but also in the post-Alpine ones. These neotectonic folds occur at various scales and types of symmetry and

mainly follow a WSW–ENE trend. Plunge and trend of the neotectonic folds were either measured during fieldwork or later using stereographic projection of bedding planes. Apart from the measurements of bedding surfaces “ss” in specific folds, bedding measurements were made in the post-Alpine deposits of the tectonic grabens, so that the fold axes “ β ss” within the grabens could be determined. The main fold axes trend WSW–ENE to SW–NE. The NW limb of these folds is stronger developed, and the folds appear to be NW-vergent. Despite some upright folds, most folds are reclined.

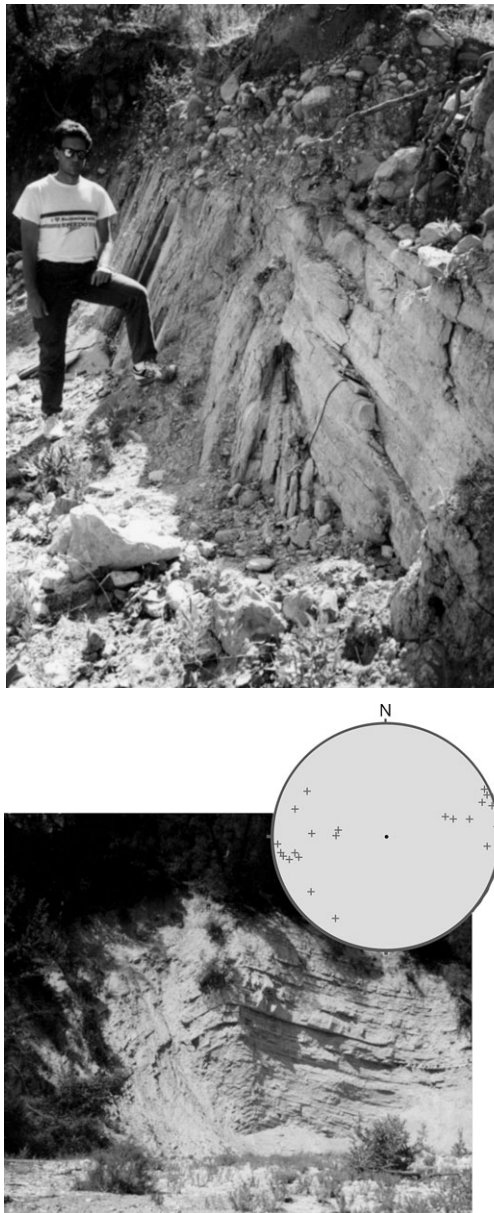
The tectonic maps constructed, show the location of the folds, the fold axes “ β ss” (Fig. 3), determined by the stereographic projections and the location and the fold axes measured within the three grabens.

2.2. Neotectonic folds within the Zaharo Graben

The Zaharo Graben is an advantageous place for the study of the ductile deformation during the neotectonic period, since the most and best-preserved mesoscopic-scale folds are observed within it. Folds were observed in both subbasins of the graben, but the majority was found in the eastern subbasin in which the oldest post-Alpine deposits occur (Figs. 3, 4).

Eastern subbasin

Fourteen mesoscopic-scale folds have been studied along the Monodendri hillslopes, which are eroded by the Tsemberoula River and its tributary. The trend of the folds is mainly WSW–ENE and the axes plunge towards WSW, except for 3 axes plunging towards ENE (Fig. 5). The axial trend coincides with orientation of the ravine that cross-cuts through the Trypes Village. Such folds were observed only within the part of Tsemberoula Formation that consists of thin-bedded intercalations of mudstones, marls and rarely sandstones. The limbs of 11 mesoscopic-scale folds measured in the Tsemberoula riverbed point to WSW–ENE trending fold axes. Their axes trend mainly WSW–ENE whereas their



Figs. 4, 5: Characteristic neotectonic folds within the Tsemberoula Formation in the Zaharo Graben. The stereographic projection in figure 5 (equal area, lower hemisphere) shows all neotectonic fold axes in the Zaharo Graben.

plunge is towards both WSW and ENE, respectively. However, two folds with NW–SE trending axes and NW-ward plunge were also found. Such folds were observed only within the part of Tsemberoula Formation that consists of thin-bedded intercalations of mudstones, marls and rarely sandstones. A characteristic large fold with SW-plunging axis is depicted in figure 5. All the fold axes defined within the eastern subbasin of the Zaharo Graben were plotted (Fig. 5). It is obvious that the trend of the main fold system is WSW–ENE. The WSW–ENE trending fold system dominates in both scales and is a characteristic of the fold pattern of the Tsemberoula Formation.

Western subbasin

Only one mesoscopic-scale fold was observed and two folds of larger scale were deduced by plotting the sedimentary bedding-planes “ss” of the Zacharo Formation. In any case, the axis trend WSW–ENE in the same fashion as the first fold system axis in the eastern subbasin. These three folds are determined as very open with steeply dipping (66° to 82° NNW) axial planes. Two of the three fold axes plunge towards WSW, while the third macrofold axis plunges towards east. In both cases the plunge is less than 10° .

As already mentioned, within the western subbasin only few faults are observed, most of which formed synsedimentary; their throw is always small. Such faults occur mainly at the eastern part of the subbasin. Despite this fact, the post-Alpine sediments dip steeply towards NW. Indeed, they dip towards NW near Minthi, whereas they dip towards SE near Lapithas, giving the impression of a NE-trending syncline coinciding with the valley between Neohori–Xirohori. Diapirism must be very important for this synclinal structure since the Ionian Unit occurs in the Kaiafa area near the studied subbasin (Fig. 3; Fountoulis & Lekkas 1991).

2.3. Neotectonic macrofold within the Neda Graben

The Neda Graben (Fig. 6) is filled in with marine sediments (conglomerates, sandstones, sandy marls) of Lower (at least) to Middle Pleistocene age. The deformation of these sediments is the result of a synsedimentary tectonism, as concluded by the existence of synsedimentary faults, as well as that of a postdepositional deformation during the last 0.27 Ma. The combination of (i) the lithology, (ii) the period of deformation and (iii) the location of the area in the centre of the 1st order mega-structure (MELYMITE CMS) are the reasons why the results of ductile (folding) deformation are not evident in a mesoscopic scale.

In order to elucidate the kinematics and the ductile deformation (folding) of the area in a mega-scale since the Middle Pleistocene, two of the main morphotectonic structures have been used, e.g. the planation surfaces and the drainage network, which have been developed on the Early to Middle Pleistocene sediments.

The detail analysis has shown that, north of the Neda riverbed, the beds as well as the planation surfaces, formed on the characteristic horizon of polymict conglomerates, dip towards NW, while south of Neda riverbed, beds and planation surfaces dip towards SSW (Figs. 6, 7). North of the Neda riverbed the beds of the Neda Formation as well as the planation surfaces dip towards NW, while south of the riverbed the same features (bedding, planation surfaces) dip southwards. This structure gives the impression of a very open anticline. The axis of this anticline should trend parallel to the riverbed, which separates the two “limbs” of the anticline. As a result, in an N–S cross-section, the post Alpine sediments of the Neda Formation present an anticline structure of great curvature, with its axis trending WSW–ESE and dipping to the WSW. It should be mentioned that the defor-

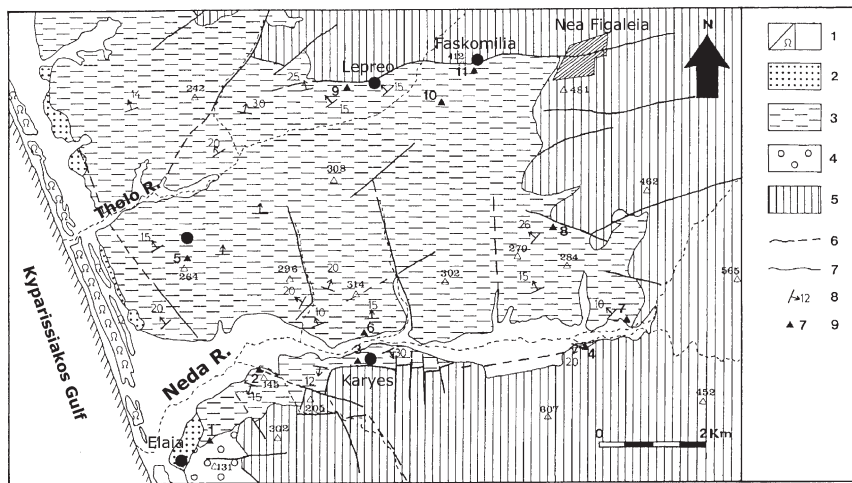


Fig. 6: Simplified geological map of the Neda Graben. 1 = Holocene dunes, scree; 2 = red coloured siliceous clastic formation; 3 = Neda Formation; 4 = Elaia Formation; 5 = Pindos Geotectonic Unit, 6 = geological boundary; 7 = fault; 8 = strike and dip of strata; 9 = site of observation and sampling. After Fountoulis 1994.

mation of the Neda Formation is not only of ductile type, but also of brittle type, since faults that cut through these sediments have been observed trending NNW–SSE and WSW–ESE (Figs. 6, 7). It is notable that the direction of the macrofold axis is the same with the ones observed in the first fold system in the Zaharo Tectonic Graben and the macrofold axis in the Filiatra area (Mariolakos & Fountoulis 1990).

2.4. The deformation of the Alpine tectonic structure during the Neotectonic period

For a study of the neotectonic deformation in areas where only the Alpine basement outcrops, the only source of data (other than morphological one) is the deformation of the Alpine tectonic features during the neotectonic period. As it is known the general direction of thrust surfaces and fold axes

are NNW–SSE in Western Greece. Thus, any statistically significant deviation should be evidence of neotectonic deformation, especially in areas which are tectonically and seismically active and located very close to the Hellenic Trench (Mariolakos & Papanikolaou 1987).

In the schematic map of figure 2, tectonic features of the Alpine basement and the post-Alpine formations are shown. More specifically, thrust surfaces and dominant plunges of Alpine fold axes are shown, together with the neotectonic fault zones and the neotectonic folds. Figure 2 is a simplified sketch-map of the tectonic structure of the study area, which is based on detailed analytical work in scales varying from 1 : 50 000 to 1 : 5.000 (Fountoulis 1994, Mariolakos et al. 1998).

Within the Minthi Mt. (NW corner of Fig. 2) the main strike of the thrusts and fold axes is NE–SW, at the Tetrazio Mt. the main strike of the thrusts and fold axes is N–S,

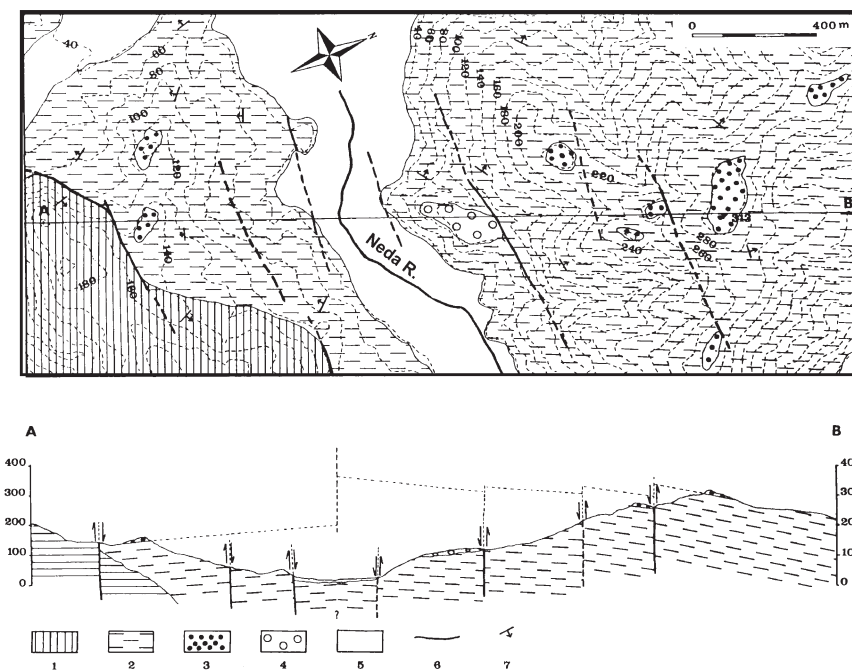


Fig. 7: Detailed geological map of a part of the Neda Graben. 1 = Alpine basement; 2 = Early–Middle Pleistocene marine deposits; 3 = polymictic conglomerates (within 2); 4 = oligomictic conglomerates (river terrace); 5 = Alluvial deposits; 6 = fault; 7 = strike and dip of strata. After Fountoulis (1994).

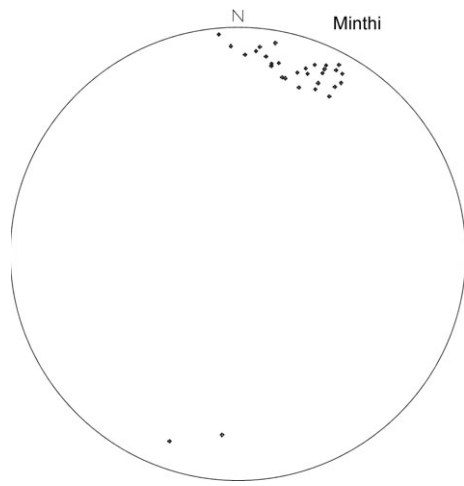


Fig. 8: Stereographic projection (lower hemisphere) of the fold axes within the Pindos Unit in the northern part of the Minthi Mt.

whereas further to the south, within the Kyparissia Mts., the main strike of the thrusts and fold axes is NNW–SSE. Taking into account the mentioned descriptions, the geometry of the thrust and the fold axes creates a curved shape the convex part of which faces the Gulf of Kyparissia.

The plotting of the fold axes plunge created in the Pindos Unit in an N–S cross section within the MELYMITE CMS composite graben forms a mega-anticline with an E–W axis located between Minthi Mt. and Tetrazio Mt. (Fig. 9).

3. Discussion – conclusions

The Neotectonic folds occurring in both the Alpine and the post-Alpine formations are of various scales and can be characterized as open, closed or tight folds. The interlimb angle of younger folds appears to be larger. Furthermore, it must be underlined that all these folds have not been created in conditions of considerable depth (the theoretical area of ductile deformation) but under surface conditions (the theoretical area of brittle deformation) as the deformed sediments are of Plio-Pleistocene age and the environment of their deposition was close to the earth surface (shallow marine or/and lacustrine deposits). The folds cannot be synsedimentary since the trending of the fold axes is consistent and folding affects all bedding planes in a particular formation.

It is evident that in the Minthi Mt. Horst the dominant trend of thrust surfaces and fold axes is NE–SW (Figs. 2, 3, 8), in the Tetrazio Mt. Horst N–S (Fig. 2) and in the Kyparissia Mt. NNW–SSE (Fig. 2). In all these structures the thrust surfaces and the fold axes follow an arc-like form, with the convex part facing to the Kyparissia Gulf.

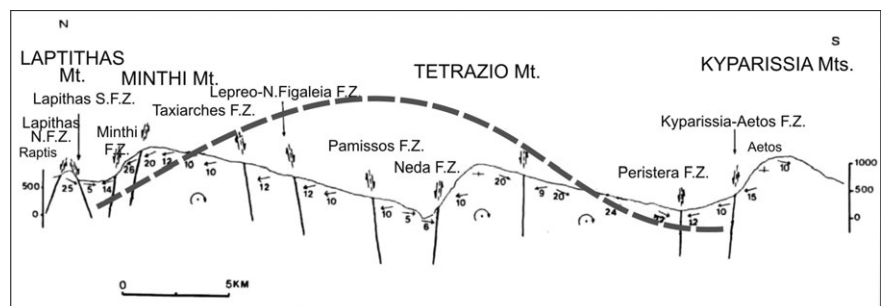
Furthermore, it is evident that the geometry of the thrust surfaces of the Pindos Tectonic Unit has changed considerably from NNW–SSE to NE–SW in the Minthi area (Fountoulis 1994) and is similar to the geometry of thrust surfaces in the Erymanthos Mt. Horst (Fig. 1b; Mariolakos & Papanikolaou 1987). This change in geometry in the Minthi Mt. can be explained according to the model of neotectonic structure of the Hellenic Arc proposed by Mariolakos & Papanikolaou 1987, based on the major marginal fault zones of the main post-Alpine basins. According to this model, the E–W striking Minthi and Neda Fault Zones, which border a tectonic horst, should have a sinistral strike-slip kinematics, thereby leading to dextral rotation of the middle tectonic block (Minthi Mt. Horst).

In a schematic N–S cross-section, extending from Lapithas Mt. to Kyparissia Mt., showing the surface relief, the fault zones, the fold axes plunge (Figs. 9, 10) as well as the dip of post-Alpine strata, the deformation of the complex tectonic graben MELYMITE during the last 0.27 Ma (Late Quaternary) appears to be that of a mega-anticline, with an axis trending E–W developed between Kyparissia Mt. and Lapithas Mt. (Fig. 9). This geometry is not expressed throughout the whole area relief, but only in the Tetrazio Mt., Kyparissia Mt. and the area between Lapithas Mt. and the Minthi watershed.

This geometry is limited to the Tetrazio Mt., and in the area between the Minthi Mt. watershed and the Tetrazio Mt. the morphology dips opposite (south) to the fold axes (north). Accepting the fold axes as a characteristic element of the Alpine structure – instead of the bedding, since all the formations of the Pindos Unit are folded – then in the Minthi Mt. area a structure of conform and antithetic faulting is similar to the one described by Freyberg (1973) for the post-Alpine sediments in the Corinth Isthmus and by Mariolakos (1975) in the Gulf of Corinth.

The high seismic activity of the Kyparissiakos Gulf is well known, and this seismic activity coincides with the major NW–SE oriented offshore fault zone. Seismotectonic data (Hatzfeld et al. 1990, Papoulia & Makris 2004, Roumelioti et al. 2004, Papanikolaou et al. 2007) and in-situ stress

Fig. 9: Schematic N–S cross-section showing the geometry of the fold axes occurring within the Pindos Geotectonic Unit in central-western Peloponnese.



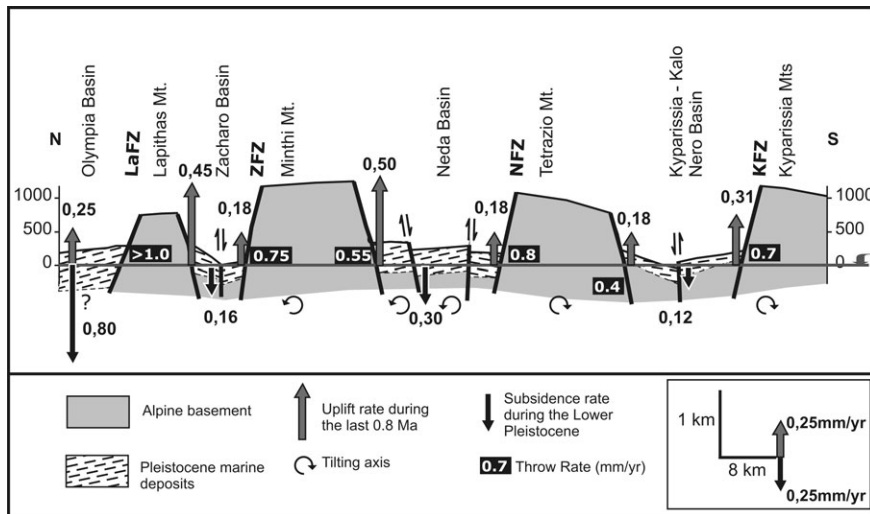


Fig. 10: Uplift and subsidence rates of the Lower-Middle Pleistocene marine deposits in the western part of the neotectonic structures of the study area; based on Fountoulis 1994 and modified after Papanikolaou et al. (2007).

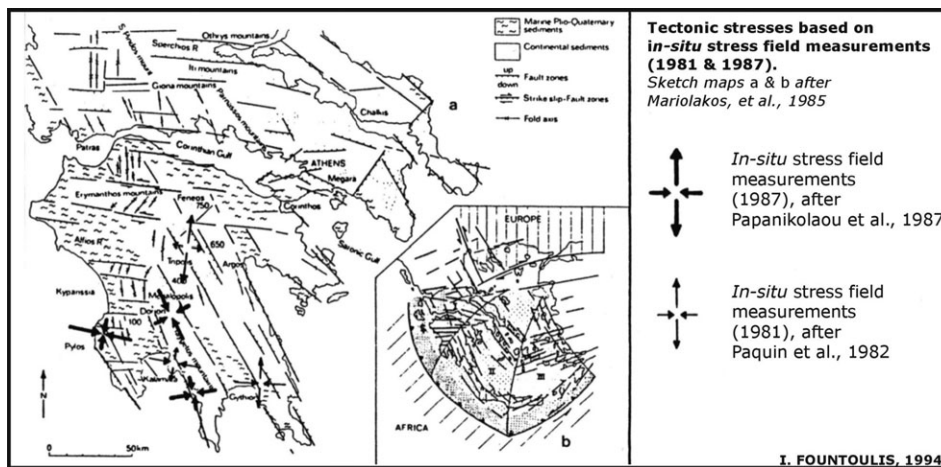


Fig. 11: Sketch-map of the post-Alpine basins in the Peloponnese. The main marginal fault zones and the locations for the in-situ stress field measurements are also shown. After Fountoulis (1994).

field measurements (Fig. 11; Paquin et al. 1982, Papanikolaou et al. 1990) indicate a compressive stress field with slight strike-slip in the external zone of the Hellenic Arc. A more complicated stress field should be the reason, similar to that described by Mariolakos et al. 1991 (Fig. 12), in which transtensional and transpressional stress fields co-exist.

The explanation of the neotectonic deformation in space (3D) and time is very complex. If one takes into account the neotectonic ductile and brittle type deformation structures, then it becomes extremely difficult, if not impossible, to explain their formation by an axial tensional or compressional stress field. In our case a more complicated stress field should be responsible, similar to that described by Mariolakos et al. 1989, 1991 (Fig. 12) in which the deformation structures (normal faulting and folding) are the result of a local transtensional and/or transpressional stress field, which in turn is connected to a regional rotational couple stress field (Fig. 12). By this deformation model the rotational movements of the Minthi Mt. Horst can be explained as well as the folding of the marine sediments of the Neda Formations and their uplift to an altitude of 400 m (Fig. 10). Only a rotational stress field due to coupling could satisfactory incorporate and explain all these elements.

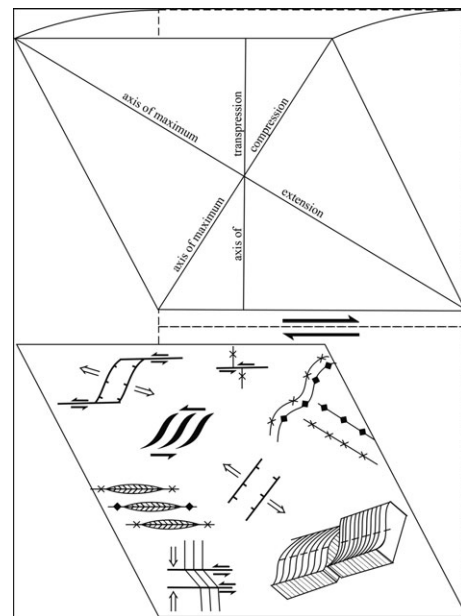


Fig. 12: The tectonic structures produced by a rotational couple stress field; after Mariolakos et al. (1991).

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5. References

- Aubouin, J. (1977): Alpine tectonics and plate tectonics: thoughts about the Eastern Mediterranean. – In: Ager, D.V. & Brooks, M. (eds.): *Europe from crust to core*: 143–158, London (Wiley).
- Aubouin, J., Brunn, J.H., Celet, P., Dercourt, J., Godfiaux, I. & Mercier, J.L. (1961): *Esquisse de la géologie de la Grèce*. – *Mém. Soc. Géol. France*: 583–610, Paris (Soc. Géol. France).
- Dufaure, J.J. (1977): Néotectonique et morphogénèse dans une péninsule méditerranéenne: le Péloponnèse. – *Rev. Géogr. Phys. Géol. Dyn.*, 19 (1): 27–58, Paris (Masson).
- Fountoulis, I. (1994): Neotectonic evolution of the Central-Western Peloponnese. – PhD thesis, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, GAIA 7: 386 p. (in Greek; abridged English version <http://labtect.geol.uoa.gr/pages/fountoulis/1HOME.htm#english>).
- Fountoulis, I. & Lekkas, E. (1991): The occurrence of the Ionian geotectonic unit at the Lapithas Mt. (central-western Peloponnese, Greece). – *Bull. Geol. Soc. Greece*, 27: 47–56, Athens (Geol. Soc. Greece) (in Greek).
- Fountoulis, I. & Moraiti, E. (1994): Paleogeography, sedimentation and neotectonic implication at the Kyparissia–Kalo Nero basin (Western Peloponnese, Greece). – *Bull. Geol. Soc. Greece*, 30 (2): 323–336, Athens (Geol. Soc. Greece) (in Greek).
- Fountoulis, I. & Moraiti, E. (1998): Paleogeography, sedimentation and neotectonic implication at the Neda basin (central-western Peloponnese, Greece). – *Bull. Geol. Soc. Greece*, 32 (1): 251–262, Athens (Geol. Soc. Greece) (in Greek).
- Freyberg, B. von (1973): *Geologie des Isthmus von Korinth*. – *Erlanger Geol. Abh.*, 95: 1–183, Erlangen.
- Hageman, J. (1977): Stratigraphy and sedimentary history of the Upper Cenozoic of the Pyrgos area (W. Peloponnesus, Greece). – *Ann. Géol. Pays Helléniques*, 28: 299–333, Athens (Univ. Athens).
- Hatzfeld, D., Pedotti, G., Hatzidimitriou, P. & Makropoulos, K. (1990): The strain pattern in the western Hellenic Arc deduced from microearthquake survey. – *Geophys. J. Int.*, 101 (1): 181–202, Oxford (Blackwell).
- Jacobshagen, V. (1979): Structure and geotectonic evolution of the Hellenides. – 6th Coll. Geol. Aegean Region, Athens 1977, Proc. 3: 1355–1367, Athens.
- Kamberis, E. (1987): Geology and petroleum geology study of NW Peloponnese, Greece. – PhD thesis National Techn. Univ. Athens, Faculty of Mining Engineering and Metallurgy: 143 p., Athens (in Greek).
- Kelletat, D., Kowalczyk, G., Schroeder, B. & Winter, K.P. (1978): Neotectonics in the Peloponnesian coastal regions. – *Alps, Apennines, Hellenides*, Sci. Rep., 38: 512–518, Stuttgart.
- Kowalczyk, G. & Winter, K.P. (1979): Neotectonic and structural development of the southern Peloponnesus. – 7th Int. Congr. Mediterranean Neogene; *Ann. Géol. Pays Helléniques*, tome hors serie 1979, fasc II: 637–646, Athens (Univ. Athens).
- Kowalczyk, G., Winter, J. & Winter, K.P. (1975): Junge Tektonik im Südwest-Peloponnes. – *Bull. Geol. Soc. Greece*, 12 (1): 40–51, Athens (Geol. Soc. Greece).
- LePichon, X. & Angelier, J. (1979): The Hellenic arc and trench system: a key to the neotectonic evolution of the Eastern Mediterranean area. – *Tectonophysics*, 60: 1–42, Amsterdam (Elsevier).
- Mariolakos, I. (1975): Thoughts and viewpoints on certain problems of the geology and tectonics of Peloponnesus (Greece). – *Ann. Géol. Pays Helléniques*, 27: 215–313, Athens (Univ. Athens).
- Mariolakos, I. & Fountoulis, I. (1990): Neotectonic macrofolds in the Filiatra area (W. Messinia, Peloponnese, Greece). – *Bull. Geol. Soc. Greece*, 25 (3): 19–38, Athens (Geol. Soc. Greece) (in Greek).
- Mariolakos, I. & Fountoulis, I. (2004): The current geodynamic regime in the Hellenic area. – In: Mariolakos, I., Zagorchev, I., Fountoulis, I. & Ivanov, M. (eds.): *Neotectonic transect Moesia Apulia; field trip guide book – B26, 32nd Int. Geol. Congr., pre-congr. field trip B26: 12–16 & B26 Greek route – appendix: 25 p.*
- Mariolakos, I. & Papanikolaou, D. (1981): The neogene basins of the Aegean Arc from the paleogeographic and the geodynamic point of view. – *Proceedings of Int. Symp. Hellenic Arc and Trench (HEAT)*, I: 383–399, Athens.
- Mariolakos, I. & Papanikolaou, D. (1987): Deformation pattern and relation between deformation and seismicity in the Hellenic Arc. – *Bull. Geol. Soc. Greece*, 19: 59–76, Athens (Geol. Soc. Greece) (in Greek).
- Mariolakos, I., Papanikolaou, D. & Lagios, E. (1985): A neotectonic geodynamic model of Peloponnesus based on morphotectonics, repeated gravity measurements and seismicity. – *Geol. Jb.*, 50: 3–17, Stuttgart (Schweizerbart).
- Mariolakos, I., Fountoulis, I., Logos, E. & Lozios, S. (1989): Surface faulting caused by the Kalamata (Greece) earthquakes (13/9/86). – *Tectonophysics*, 163: 197–203, Amsterdam (Elsevier).
- Mariolakos, I., Fountoulis, I., Logos, E. & Lozios, S. (1991): Methods to study the torsional neotectonic deformation: the case of Kalamata area (SW Peloponnesus, Greece). – *Proc. 4th meeting IGCP project No 250, Athens-Kalamata, Sept. 30–Oct. 8, 1989* (ed.: Chen Qingxuan), *Chinese Acad. Geol. Sci. (CAGS)*, 3: 15–21, Beijing (China).
- Mariolakos, I., Sabot, V., Fountoulis, I., Marcopoulou-Diacantoni, A. & Mirkou, R. (1998): Neotectonic map of Greece at scale 1 : 100 000, Filiatra sheet. – *Earthquake Planning & Protection Organization*, Athens.
- Mariolakos, I., Fountoulis, I. & Ladas, I. (2001): Paleogeographic evolution of SW Peloponnese (Greece) during Quaternary. – *Proc. 9th Geol. Congr. Geol. Soc. Greece*. – *Bull. Geol. Soc. Greece*, 34 (1): 37–45, Athens (Geol. Soc. Greece) (in Greek).
- McKenzie, D. (1972): Active tectonics in the Mediterranean region. – *Geophys. J. Royal Astronom. Soc.*, 30: 109–185, Oxford (Blackwell).
- Mitropoulos, D., Perisoratis, K. & Aggelopoulos, I. (1982): Geological map of Greece, scale 1 : 50 000, Kyparissia sheet. – *Institute of Geology and Mineral Exploration*, Athens, Greece.
- Papanikolaou, D., Paquin, C., Bloyet, J., Foudoulis, D. & Moschopoulos, P. (1990): In-situ stress measurements in Messinia after the 1986 Kalamata earthquakes. – *Bull. Geol. Soc. Greece*, 24: 95–101, Athens (Geol. Soc. Greece).
- Papanikolaou, D., Fountoulis, I. & Metaxas, C. (2007): Active faults, deformation rates and Quaternary paleogeography at Kyparissiakos Gulf (SW Greece) deduced from onshore and offshore data. – *Quaternary Int.*, 171–172: 14–30, Amsterdam (Elsevier).

- Papoulia, J. & Makris, J. (2004): Microseismicity and active deformation of Messinia, SW Greece. – *J. Seismology*, 8: 439–451, Dordrecht (Springer NL).
- Paquin, C., Froidevaux, C., Bloyet, J., Ricard, Y. & Angelidis, C. (1982): Tectonic stresses on the mainland of Greece: in-situ measurements by overcoring. – *Tectonophysics*, 86: 17–26, Amsterdam (Elsevier).
- Philippon, A. (1898): La tectonique de l'Egée. – *Ann. Géographie*: 112–141, Paris.
- Roumelioti, Z., Benetatos, C., Kiratzi, A., Stayrakakis, G. & Melis, N. (2004): A study of the 2 December 2002 (M5.5) Vartholomio (western Peloponnese, Greece) earthquake and its largest aftershocks. – *Tectonophysics*, 387: 65–79, Amsterdam (Elsevier).
- Streif, H. (1977): Geological map of Greece, scale 1 : 50 000, Olympia sheet. – Institute of Geology and Mineral Exploration, Athens, Greece.
- Streif, H. (1978): Stratigraphy and tectonics of Late Cenozoic rocks in Western Peloponnesus. – In: *Alps, Apennines, Hellenides*, *Sci. Rep.*, 38: 501–502, Stuttgart.
- Underhill, J.R. (1988): Triassic evaporites and Plio-Quaternary diapirism in Western Greece. – *J. Geol. Soc. London*, 145: 269–282, London (Geol. Soc. London).
- Underhill, J.R. (1989): Late Cenozoic deformation of the Hellenide foreland, western Greece. – *Geol. Soc. America Bull.*, 101: 613–634, Boulder (CO) (Geol. Soc. America).

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