THE MIDDLE-LATE PLEISTOCENE NW-SE EXTENSION IN SOUTHERN PELOPONNESUS AND THE KINEMATICS OF THE SEISMIC FAULT OF THE 1986 KALAMATA EARTHQUAKE (GREECE)

Mercier,J.L. and Lalechos,S.

URA(CNRS 1369), Laboratoire de Geophysique et Geodynamique Interne Universite de Paris-Sud, Bat. 509, 91405 Orsay Cedex, France

ABSTRACT

In southern Peloponnesus, faults which affect marine deposits of Late Pliocene - Early Pleistocene age often show two families of striations. The younger family results from a tress deviator having a NW-SE trending σ_3 (tensional) principal stress direction and is in agreement with the kinematics of the few striated faults we have observed affecting Mid-Late Pleistocene fans and screes. The deviatoric σ_2 stress value of this Recent tectonic regime is also tensional ($\sigma_2 \approx \sigma_3/2$). We show that the motion of the 1986 Kalamata seismic fault as shown by focal mechanisms is satisfactorily explained by this NW-SE (N130 ± 10°) trending extension.

Ο ΜΕΣΟ-ΑΝΩ ΠΛΕΙΣΤΟΚΑΙΝΙΚΟΣ ΕΦΕΛΚΥΣΜΟΣ ΣΤΗ ΝΟΤΙΑ ΠΕΛΟΠΟΝΝΗΣΟ ΚΑΙ Η ΚΙΝΗΜΑΤΙΚΗ ΤΟΥ ΣΕΙΣΜΙΚΟΥ ΡΗΓΜΑΤΟΣ ΤΟΥ ΣΕΙΣΜΟΥ ΤΗΣ ΚΑΛΑΜΑΤΑΣ

Mercier,J.L. and Lalechos,S.

ΠΕΡΙΛΗΨΗ

Στην Νότια Πελοπόννησο ρήγματα τα οποία επηρρεάζουν θαλάσσιες αποθέσεις του Ανωτέρου Πλειόκαινου - Κατώτερου Πλειστόκαινου συχνά δείχνουν δύο οικογένειες τεκτονικών γραμμώσεων. Η νεότερη οικογένεια είναι το αποτέλεσμα τεκτονικών τάσεων με διεύθυνση του σ_3 εφελκυσμού) ΒΔ-ΝΑ, η οποία βρίσκεται σε συμφωνία με την κινηματική μερικών ρηγμάτων που παρατηρήθηκαν στα Μέσο-Ανω-Πλειστοκαινικά ριπίδια και πρόσφατα ιζήματα στις επιφάνειες του ρήγματος. Γενικά, το μέτρο του άξονα τάσης, σ_2 του πρόσφατου τεκτονικού πεδίου είναι επίσης εφελκυστική ($\sigma_2 \approx \sigma_3/2$). Η κίνηση του σεισμικού ρήγματος στη Καλαμάτα 1986 όπως δείχνεται από τους μηχανισμούς γένεσης δεν είναι σε ασυμφωνία με τον ΒΔ-ΝΑ εφελκυσμό.

INTRODUCTION

In northern Peloponnesus, the direction of extension during the Mid-Recent Quaternary and Present-day period is well known from seismic (Mc Kenzie, 1978; Drakopoulos and Delibassis, 1982;

Hatzfeld et al., 1990, Papazachos et al., 1991) and neotectonic data (Sebrier, 1977; Lyberis, 1984; Lallemant, 1984; Mercier et al., 1987); it trends roughly N-S. On the other hand, in southern Peloponnesus the direction of extension is always a subject of discussion: some authors (Sebrier, 1977; Mercier et al., 1979; Angelier, 1979; Lallemant, 1984; Armijo et al., 1992) have suggested that the extension trends roughly E-W and this seems to be supported by the kinematics of the seismic fault of the 1986 Kalamata earthquake as shown by focal mechanisms (Papazachos et al.,'1986; Lyon-Caen et al., 1988; Papadimitriou, 1988). A NW-SE trending direction of extension has been also suggested (Gauthier, 1979; Mercier et al., 1987; Foundoulis and Grivas, 1989). Therefore neotectonic faulting has been studied at numerous sites in southern Peloponnesus (Lalechos, 1992) with emphasis on the kinematics of the faults which affect dated deposits of Late Pliocene to Mid-Late Pleistocene age. Here we present a brief summary of the results which support a NW-SE trending extension. Then we show that the kinematics of the 1986 Kalamata seismic fault (Mariolakos et al., 1986) is satisfactorily explained by this NW-SE trending extension.

KINEMATICS OF THE RECENT FAULTS

Faults affecting formations of Mid-Late Pleistocene age (<0.7Ma). Unfortunately few striated faults are known which affect formations of Mid-Late Pleistocene age. One normal minor fault striking N30° has been observed in the vicinity of the major fault of Sparte (near A.Ioannis, 4km SW of Sparte, site 30, in Lalechos, 1992) affecting a reddish unconsolidated fan attributed to the Late Pleistocene (Dufaure, 1975). Another normal striated fault (site 28, Fig. 1) has been observed in the Magne peninsula (Fytrolakis, 1991; Lalechos, 1992); it affects reddish continental fans and screes attributed to the Mid Pleistocene (Dufaure, 1975). This N-S striking fault is more than 6km long with a 60m-downthrow. The pitch of the striations (n° 1,2,3 on stereonet A3, Fig. 2) has been measured on the major fault plane at the contact with the faulted Mid Pleistocene screes. These data are few but each of them show a dextral strike-slip component which clearly demonstrates that the extensional direction cannot trend E-W because in such a case the motion on the fault plane should have been purely normal. Unfortunately, these data are not sufficient to compute the stress deviator responsible for the fault motion. The computation of the four parameters of the deviator (within a factor k) requires four independant faults of clearly different strikes and dips at least (Carey, 1979). Therefore we have analysed striated faults affecting dated formations of Late Pliocene - Early Pleistocene age. These are numerous and thus may satisfy the necessary condition for the computation (see stereonets B2 and B3, Fig. 2). All the computations have been run with the Carey's inversion program.

Minor faults affecting marine formations of Late Pliocene -Early Pleistocene age near Kardamili village. About 30km southeast of Kalamata near Kardamili village (site 23, Fig. 1), a marine formation of Late Pliocene (Koutsouveli, 1987) - Early Pleistocene (Mariolakos et al., 1992) age lies unconformably on the bed rock. This formation comprising breccia and sandy marls is faulted and some faults show two families of striations (stereonet B2 and B3, Fig. 2). The older family results from a tensional principal stress direction trending NE-SW (stereonet B2, Fig. 2). The younger family results from a tensional principal stress direction trending N125° (stereonet B3, Fig. 2) which is in agreement with the kinematics of the faults we have observed affecting Mid-Pleistocene fans and screes (stereonet A3, Fig. 2).

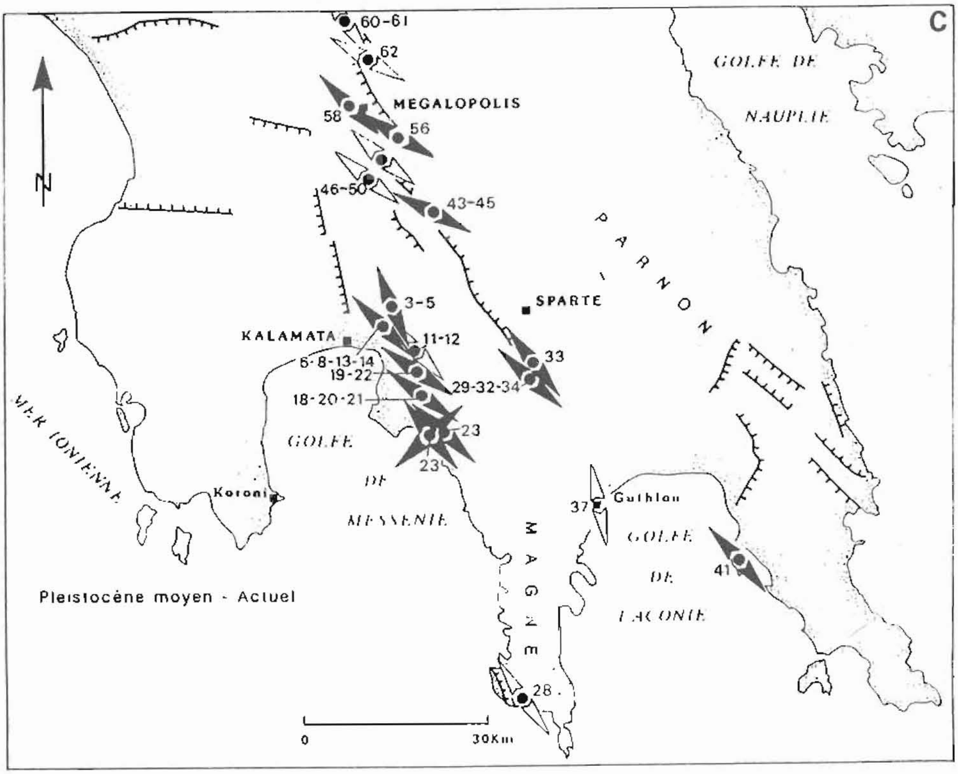

Fig.1. Tensional principal stress (σ_3) directions of Mid-Late Pleistocene age computed (filled arrows) or graphically defined (open arrows) from fault kinematics measured in the field (drawn from Lalechos, 1992). Thick hachured lines are major faults activated during the Pleistocene and Holocene according to Dufaure (1975). Sites are numbered as in Lalechos (1992). About 150 striation data have been used for defining these tensional directions.

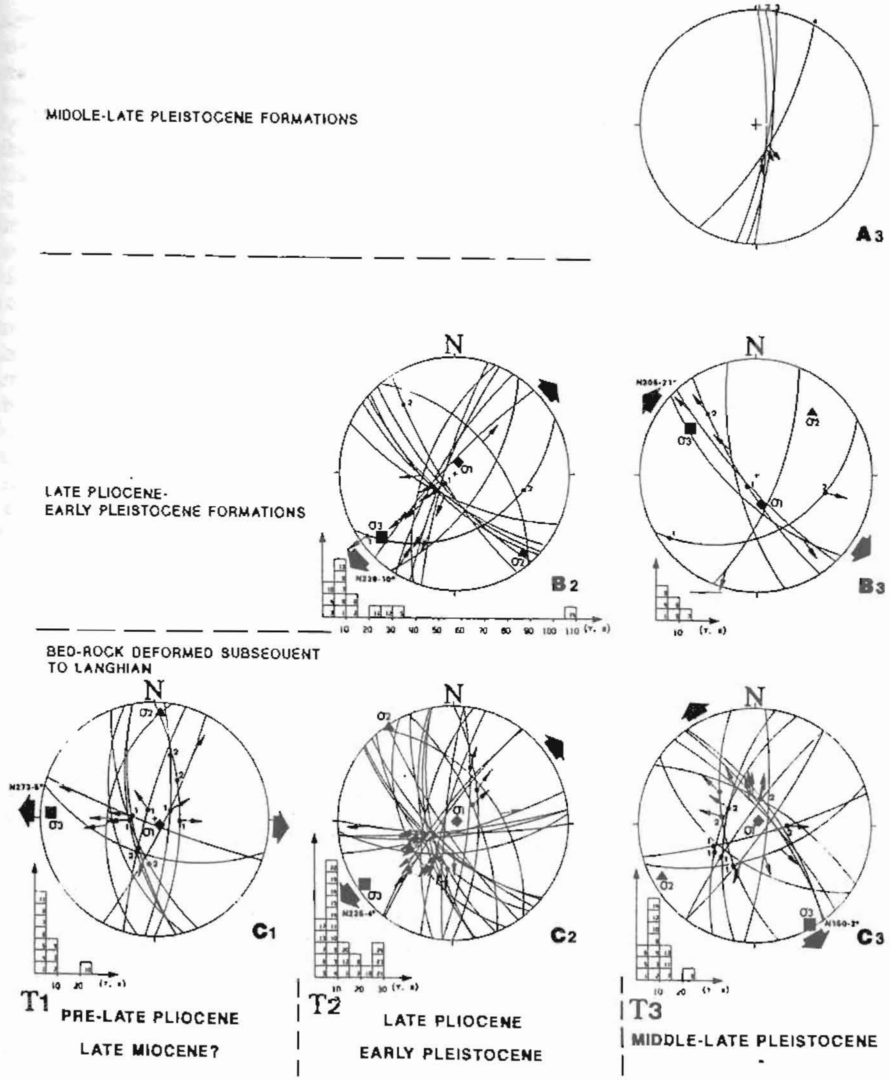

Fig.2. Minor fault data from the Kardamyli region (southern Peloponnesus). Arrows attached to the fault traces correspond to the measured slip-vectors (Wulff stereonet, lower hemisphere). Histograms show the deviations between the measured and the predicted slip-vectors on each fault plane. Divergent black arrows give the azimuths of the computed minimum (σ_3) principal stress directions. Three families T (1, 2, 3) of striations have been separated from faults affecting, (A) Mid-Late Pleistocene formations, (B) Late Pliocene-Early Pleistocene formations and (C) the bed-rock. Numbers attached to the filled circles on the fault planes indicate the relative chronology of superimposed striations when observed (from J.L. Mercier et al., 1993)..

Minor faults affecting the bed-rock near Kardamili village. At the same site (site 23, Fig. 1),the bed-rock which underlies the Late Pliocene - Early Pleistocene marine formations is composed of Mesozoic limestones of the Ionian and Tripolis zones. It is intensively faulted and numerous faults exhibit two, rarely three, families of striations. The third and last family of striations T3 (stereonet C3, Fig. 2) results from a NW-SE trending extension and is in agreement with the second family of striations (stereonet B3, Fig. 2) affecting the marine formation of Late Pliocene - Early Pleistocene age. It also agrees with the kinematics of the faults we have observed affecting continental fans and screes of Mid-Late Pleistocene age (stereonet A3, Fig. 2). Therefore, we consider that the last fault motions which postdate the Late Pliocene-Early Pleistocene are representative of the Mid Pleistocene - Present day tectonic regime. The mean direction of the σ_3 principal stress axes defined at 15 sites (Lalechos, 1992) rends N145° E ± 20° and the computed R ratio $[R = (\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)]$ of the stress deviators generally have a high value (R ≈ 0.7-0.8). This means that the deviatoric value of the intermediate principal stress (σ_2) trending NE-SW is tensional and that $\sigma_2 \approx \sigma_3/2$.

Direction of extension defined by the kinematics of the major faults. Kinematics of major faults, some km to tens of km long, have been measured in the field. These major faults are located on the border of the Megalopolis basin (sites 46-62, Fig. 1), in the region of Kalamata (sites 3-23), along the fault of Sparte (sites 29-45) and in the Magne Peninsula (sites 29-45). The deviator T3 is computed from the faults affecting Mid-Late Pleistocene deposits, Late Pliocene - Early Pleistocene deposits and the bedrock; in the two last cases striation data are those posterior to the striation families T1 and T2 (Fig. 2). The obtained solution demonstrates an extensional tectonic regime with a σ_3 axis trending N120° (Fig. 3T3 in Mercier et al., 1993), i.e. more WNW-ESE than that (N145 ± 20°) computed from minor faults. In conclusion, since probably the Late Miocene period, the tectonic regime in southern Peloponnesus has been extensional (Fig. 2). The extensional direction trended roughly NW-SE and NE-SW during the Mid-Late Pleistocene and the Late Pliocene - Early Pleistocene respectively. The E-W (N85 ± 20°) trending extensional direction deduced from striations observed on major fault planes affecting the bed-rock predates the Late Pliocene.

THE MOTION OF THE SEISMIC FAULT OF THE 1986 KALAMATA EARTHQUAKE

The azimuth of the slip-vector of the seismic fault of the 1986 Kalamata earthquake as shown by focal mechanisms (Papazachos et al., 1986; Lyon-Caen et al., 1988; Papadimitriou, 1988) trends roughly E-W and it has been suggested (Armijo et al., 1992) that the extensional direction in southern Peloponnesus also trends E-W. This does not agree with the Mid-Late Pleistocene kinematics of the faults we have analysed in this region. Yet, it must be recalled that at least four independant striated fault planes are necessary to compute the four parameters of a stress deviator within a factor k (Carey, 1979). The pitch of the slip-vector on a given fault plane depends not only on the orientation of the principal stress axes but also on a ratio R built on the differences of the principal stress values such as for example R= $(\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$. This is clearly shown by a simple numerical experiment (Fig. 3A). Thus, we have used two stress deviators one defined from the kinematics of the minor faults (σ_3 = N150°, R=0.7; stereonet C_3, Fig. 2), the other from the major faults (σ_3= N120°, R=.707; Fig. 3T3 in Mercier et al., 1993), to compute the predicted (τ) slip-vector on the seismic fault. We have compared this one to the seismic slip-vector (s) as shown by the focal solutions. Using the deviator having a N150° trending σ_3 axis, the deviation (τ, s) is high in the order of 30° but remains within the range of the uncertainties (Fig. 3B) on the (s) pitch computed by Lyon-Caen et al. (1986). Using the deviator having a N120° trending σ_3 axis, the deviation (τ, s) is small, less than 10° (Fig. 3C). This shows that the slip-vector on the Kalamata seismic fault may be satisfactorily explained by the deviators responsible for the Mid-Late Pleistocene fault motions. It is better explained by the N120° trending extension than by the N150° trending one.

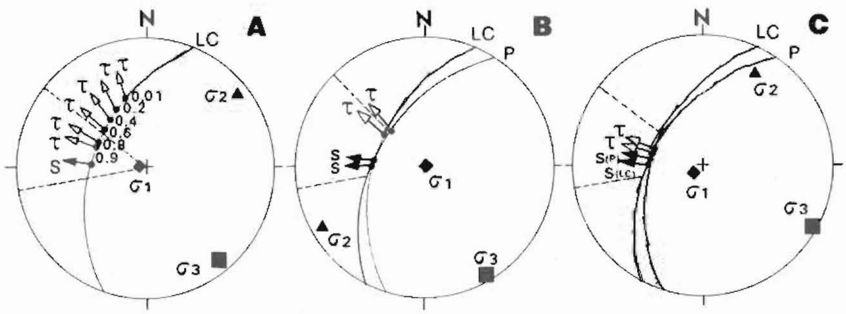

Fig.3. A- Numerical experiment for locating the predicted slip-vectors (τ) on the Kalamata seismic fault plane for different values of the R ratio and a N140° trending σ_3 direction (Wulf stereonet, lower hemisphere). As the R value increases, i.e. σ_2 becomes more extensional, the predicted slip-vector (τ) comes near the seismic slip-vector (s) shown by the focal mechanism. B- Deviations between the slip-vectors (τ) predicted by the deviator (σ_3= N150-1°, R = 0,73) and the seismic slip-vectors (s) of the Lyon-Caen et al's (LC) and the Papadimitriou's (P) fault plane solutions. The deviations (τ,s) are 28°5 and 28°6 respectively. C- Deviations (τ, s) as on Fig. 3B predicted by the deviator (σ_3 = N120-2° , R = 0,70) are 6°8 and 9°1 respectively.Dashed lines indicate the uncertainties on the azimuth of the seismic slip-vector according to Lyon-Caen et al. (1988).

CONCLUSION

In southern Peloponnesus analysis of Mid-Late Pleistocene fault motions at 15 different sites (Lalechos, 1992) has indicated a N145 ± 20° trending σ_3 (tensional) stress axis while the last motions of major faults in this region has indicated a N120° trending σ_3 stress axis. The stress ratio values (R = 0.7 - 0.8) indicate that the deviatoric value of the intermediate stress (σ_2) axis is highly extensional ($\sigma_2 \approx \sigma_3/2$). Using these stress deviators we have computed the predicted slip-vectors on the seismic fault plane of the 1986 Kalamata earthquake and compared them with the seismic slip-vector shown by the focal mechanisms. This shows that the seismic slip-vector is well fitted by the N120° trending extension deduced from the last motions on major faults of southern Peloponnesus (Fig. 3C). Taking into account the results of the numerical experiments (Fig. 3) we conclude that the coseismic fault motion of the 1986 Kalamata earthquake is satisfactorily explained by a state of stress having a NW-SE (preferentially N130 ± 10°) direction of extension and a highly extensional deviatoric σ_2 value (R ≈ 0.7-0.8). There is really no inconsistency between the azimuth of the slip-vector shown by the focal mechanisms and the analysis of the fault motions in terms of stress. Indeed, in an extensional tectonic regime the azimuth of the slip-vector indicates the direction of extension [more precisely the slip-vector is contained in the principal stress plane (σ_1, σ_3)] only if the deviatoric σ_2 stress value is zero (i.e. R = 0.5). It deviates from the extensional direction when the deviatoric σ_2 value is highly extensional as in S. Peloponnesus (Fig. 3B and C) or compressional (see Fig. 3A with R < 0.5).

The E-W extension deduced from striations observed on major fault planes affecting the bedrock predates the Late Pliocene. We have suggested (Mercier et al., 1993) that this presently E-W orientated extension might have trended NNE-SSW to NE-SW during the Late Miocene - Early Pliocene and might have subsequently rotated as a consequence of the clockwise rotation of the western branch of the Aegean Arc since the Late Miocene (Kissel et al., 1985).

This work has been supported by the program DBT-3 'Instabilites' (contribution CNRS-INSU DBT N° 893831/01), Institut National des Sciences de l'Univers, Paris.

REFERENCES

Angelier,J., (1979). Neotectonique de l'Arc Egeen. These d'Etat, Soc. Geol. du Nord n° 3, Lille.

Armijo,R., Lyon-Caen,H. and Papanastassiou,D., (1992). East-West extension and Holocene normal-fault scarps in the Hellenic arc. Geology 20, 491-494.

Carey,E., (1979). Recherche des directions principales de contraintes associees au jeu d'une population de failles. Rev. Geol. Dyn. Geogr. Phys. 21 (1), 57-65.

Drakopoulos,J. and Delibassis,N., (1982). The focal mechanisms of earthquakes in the major areas of Greece for the period 1947-1981. Seismological Laboratory n° 2, Univ. of Athens,

72 pp.
Dufaure,J.J., (1975). Le relief du Peloponnese. These d'Etat, Univ. de Paris-Sorbonne, 1422 pp.
Foundoulis,D. and Grivas,C., (1989). Etude microtectonique des fractures sismiques de Kalamata (periode sismique de Septembre 1986). Proc. 4th Congr. Geol. Soc. Greece, Athens (1988); Bull. Geol. Soc. Greece, 23(3), 259-279 (in greek, french abstract).
Fytrolakis,N., (1991). Contribution in the knowledge of the neotectonic structure of the Gerolimenas-Mezapou peninsula (Mani). Bull. Soc. Geol. Greece, 25(3), 39-56.
Gauthier,A., (1979). Contribution a l'etude neotectonique du domaine egeen : l'ile de Rhodes (Dodecanese, Grece). These 3eme Cycle, Univ. Paris-Sud Orsay, 207pp.
Hatzfeld,D., Pedotti,G., Hatzidimitriou,P. and Makropoulos,K., (1990). The strain pattern in the western Hellenic arc deduced from a microearthquake survey. Geophy. J. Int. 101, 181-202.
Kissel,C., Laj,C. and Muller,C., (1985). Tertiary geodynamical evolution of Northwestern Greece: paleomagnetic results. Earth Planet. Sci. Lett., 72, 190-204.
Koutsouveli,A., (1987). Etude stratigraphique des formations pliocenes et pleistocenes en Messenie occidentale (Peloponnese, Grece). These 3eme Cycle, Univ. Aix-Marseille II, 162pp.
Lalechos,S., (1992). Etudes neotectoniques et sismotectoniques dans le Peloponnese meridional (Grece). Relations avec la geodynamique plio-quaternaire de l'Arc Egeen. These de l'Univ. Paris Sud-Orsay, 230 pp.
Lallemant,S., (1984). La transversale Nord-Maniote; etude geo-logique et aeromagnetique d'une structure transversale a l'arc Egeen externe. These 3eme Cycle, Univ. Paris 6, 175 pp.
Lyberis,N., (1984). Geodynamique du domaine egeen depuis le Miocene superieur. These d'Etat, Univ. Paris 6, 367 pp.
Lyon-Caen,H., Armijo,R., Drakoulos,J., Baskoutas,J., Delibassis,N., Gaulon,R., Kouskouna,V., Latoussakis,J., Makropoulos,K., Papadimitriou,P., Papanastassiou,D. and Pedotti,G., (1988). The 1986 Kalamata (south Peloponnesus) Earthquake :detailed study of a normal fault. Evidences for East-West extension in the Hellenic Arc. J. Geophys. Res. 93, 14,967-15,000.
Mariolakos,I., Foundoulis,I., Logos,E. and Lozios,S., (1986). Surface faulting caused by the Kalamata (Greece) earthquakes (13/9/1986). Tectonophysics, 163, 197-203.
Mariolakos,I., Schneider,H., Foundoulis,I. and Vouloumanos,N., (1992). Paleogeography, sedimentation and neotectonic implications of the Kambos depression and Kitries area (Messinia, Peloponnesus, Greece). 6th Congress of the Geol. Soc. Greece, "Geology of the Aegean", Athens, Abstracts, 68.
McKenzie,D.P., (1978). Active tectonics of the Alpine-Himalayan belt: the Aegean sea and surrounding regions. Geophys. J.R. Astr. Soc. 55, 217-254.
Mercier,J.L., Delibassis,N., Gauthier,A., Jarrige,J.J., Lemeille,F., Philip,H., Sebrier,M. and Sorel,D., (1979). La

neotectonique de l'Arc Egeen. Rev. Geol. Dyn. Geogr. Phys., 21(1), 67-92.
Mercier,J.L., Sorel,D. and Simeakis,K., (1987). Changes in the state of stress in the overriding plate of a subduction zone: the Aegean arc from the Pliocene to the present. Annales Tectonicae 1(1), 20-39.
Mercier,J.L., Sorel,D., Lalechos,S. and Keraudren,B., (1993). The tectonic regimes along the convergent border of the Aegean Arc from the Late Miocene to the Present: Southern Peloponnesus as an example. In "Recent evolution and seismicity of the Mediterranean region", Erice, Sicily, 18-27/9/1992. Kluwer Academic Publishers, Dortrecht, NATO ASI Ser., in press.
Papadimitriou,P., (1988). Etude de la structure du manteau superieur de l'Europe et modelisation des ondes de volume engendrees par les seismes egeens. These Univ. Paris 7, 211 p.e.
Papazachos,B., Kiratzi,A., Karacostas,B., Panagiotopoulos,D., Scordilis,E. and Mountrakis,D.M., (1986). Surface fault traces, fault plane solution and spatial distribution of the aftershocks of the September 13, 1986 earthquake of Kalamata (Southern Greece). Pure Appl. Geophys., 126, 1, 55-68.
Papazachos,B., Kiratzi,A. and Papadimitriou,E., (1991). Regional focal mechanisms for earthquakes in the Aegean Arc. Pure Appl. Geophys., 136, 405-420.
Sebrier,M., (1977). Tectonique recente d'une transversale a l'Arc Egeen: le golfe de Corinthe et ses regions peripheriques. These de 3eme Cycle, Univ. Paris Sud-Orsay, 176 pp.