

FIELD STUDY OF THE SOUTHERN THESSALY HIGHLY ACTIVE FAULT ZONE

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A B S T R A C T

The strong earthquakes in the area of Southern Thessaly during this century are the result of the reactivation of an E-W trending highly active fault zone, according to our field studies of the pattern, geometry and kinematics of the faults and comparison of the western and eastern parts of the active fault zone. This highly active fault zone consists of many parallel synthetic or antithetic high-angle fault segments bounding the Neogene and Quaternary basins. An old dextral strike-slip motion along the fault zone during the Miocene was followed by two normal reactivations. The first, which affects the Pliocene-Middle Pleistocene sediments, is the result of a NE-SW extension, whereas the second is the recent reactivation of the fault zone due to the N-S extension of the internal Aegean region in Middle-Pleistocene-Recent times. The last movement is also compatible with the focal mechanisms of the earthquakes. The geometry and the dextral strike-slip motion of the fault zone suggest a possible initial connection of the Southern Thessaly fault zone with the western extension of the North Anatolian fault in Miocene times.

ΓΕΩΛΟΓΙΚΗ ΜΕΛΕΤΗ ΤΗΣ ΕΝΤΟΝΑ ΕΝΕΡΓΟΥ ΖΩΝΗΣ ΡΗΓΜΑΤΩΝ ΤΗΣ ΝΟΤΙΑΣ ΘΕΣΣΑΛΙΑΣ

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Π Ε Ρ Ι Λ Η Ψ Η

Οι ισχυροί σεισμοί στη Νότιο Θεσσαλία κατά τη διάρκεια αυτού του αιώνα είναι αποτέλεσμα της επαναδραστηριοποίησης μιας ενεργού ζώνης ρηγμάτων διεύθυνσης Α-Δ όπως συμπεραίνεται από την εργασία μας υπαίθρου που επικεντρώθηκε στη μελέτη των ιδιοτήτων, της γεωμετρίας και της κινηματικής των ρηγμάτων και συγκρίνοντας το δυτικό και ανατολικό τμήμα της ενεργού ζώνης. Η ενεργός ζώνη συνίσταται από πολλά παράλληλα συνθετικά και αντιθετικά τμήματα ρηγμάτων μεγάλης γωνίας κλίσης τα οποία οριοθετούν τις νεογενείς και τεταρτογενείς λεκάνες. Μια παλιά δεξιόστροφη κίνηση οριζόντιας μετατόπισης στη ζώνη ρηγμάτων κατά τη διάρκεια του Μειοκαίνου ακολουθήθηκε από δυο επαναδραστηριοποιήσεις με κανονικές κινήσεις. Η πρώτη που επηρέασε ιζήματα Πλειοκαίνου-

Μέσου Πλειστοκαίνου είναι το αποτέλεσμα του εφελκυσμού διεύθυνσης ΒΑ-ΝΔ, ενώ η δεύτερη είναι πρόσφατη επαναδραστηριοποίηση της ζώνης ρηγμάτων οφειλόμενη στον Β-Ν εφελκυσμό που επικρατεί στον Εσωτερικό Αιγαίικο χώρο από το Μέσο Πλειστόκαινο μέχρι σήμερα. Η τελευταία αυτή κίνηση είναι επίσης συμβατή με τους μηχανισμούς γένεσης των σεισμών. Η γεωμετρία της ζώνης ρηγμάτων και η δεξιόστροφη κίνηση σ' αυτήν, οδηγούν στην παραδοχή μιας αρχικής σύνδεσης της ζώνης ρηγμάτων της Νότιας Θεσσαλίας με την δυτική επέκταση του ρήγματος της Βόρειας Ανατολίας στην περίοδο του Μειοκαίνου.

INTRODUCTION

Several strong earthquakes (i.e. Sophades, Ms=7.0, 1954; Velestino, Ms=6.8, 1957; N. Anghialos, Ms=6.5, 1980) have occurred during this century along a highly active seismic zone trending E-W in the area of Southern Thessaly (Central Greece).

The Southern Thessaly area theoretically represents a back-arc domain to the Hellenic arc (fig. 1) and according to seismological data (Papazachos et al 1983, 1992) it presents earthquakes of extensional mode. However, the fact that the fault zone is at the western end of the North Aegean Trough, where the recorded earthquakes are bimodal extensional and strike-slip ones (Papazachos et al. 1991) ascribed to the continuation of the dextral strike-slip North Anatolian fault, also confirmed by geological data (Pavlidis et al 1990), indicates that its role in the general geotectonic frame dominating the inner Aegean region is crucial.



Fig.1. The framework of the tectonic regime of Greece, including the Southern Thessaly highly active zone (shading box). Diverging black arrows show active extension of the inner Aegean Region.

The purpose of this study was to examine in the field the nature and significance of the seismically active Southern Thessaly area from the broader Ekkara-Domokos region to Nea Anghialos-Volos region (fig.2. see also fig.4 in Pavlides, 1993).

The following questions were addressed during the field work: (1) Can the recent earthquakes in the area be related to certain faults and what is the relationship between these faults?, (2) What is the dominant fault geometry, kinematics and dynamic in the area?, (3) Can the existence of this highly active seismic zone suggested by the seismological data also be confirmed by geological information alone? and if so what are the geometry and tectonic features of this highly active fault zone?, (4) Does the high current seismicity belong only to the late Quaternary tectonic deformation, or does it represent the last stage of a continuous deformation since Miocene times?

Thus, the fieldwork concentrated on the following:

(1) Detection of the general fault pattern and especially of the major faults which control the topography and bound Neogene and Quaternary basins using aerial photographs of scale 1:40.000 and an analysis of digital satellite data to produce enhanced images of the faults.

(2) Mapping (scale 1:50.000) of the faults in the basement and the Neogene-Quaternary basins.

(3) Geological survey and measurements of structural data mainly along the defined active fault segments.

(4) Study of the geomorphological features related to the faults, such as fault scarps, stream offsets, and reverse morphological phenomena.

(5) Information, collected by inhabitants and local authorities, on surface ruptures and other phenomena, caused by the strong earthquakes in the area.

(6) Quantitative structural analysis, including kinematic and dynamic analysis of the faults.

STRUCTURAL GEOLOGY OF SOUTHERN THESSALY

After the geological survey carried out in Southern Thessaly by IGME (sheets of Volos, Velesino, Farsala, Anavra, Domokos and Leontari in scale 1:50.000) and other published geological information (Aubouin 1959, Ferriere, 1982) Southern Thessaly consists of Pelagonian, pre-alpine gneisses, amphibolites and mica schists overlain by recrystallized limestones of Triassic-Jurassic age. Ophiolites associated with deep-sea sediments thrust over the Jurassic limestones and both are transgressively covered by the Upper Cretaceous carbonate rocks and Tertiary flysch. All these alpine and pre-alpine rocks form a well defined "basement" on which the post-alpine sediments lie unconformably and fill up the Neogene and Quaternary basins of the region including the following deposits (IGME 1969, 1983, 1986):

a) mollasse sediments of Miocene age, consisting of consolidated conglomerates, sandstones and siltstones b) Pliocene-Lower Pleistocene fluvio-lacustrine deposits characterized by poorly consolidated conglomerates, sands, silts and whitish marls. The whitish marls dominate mainly in the central part of the basins.

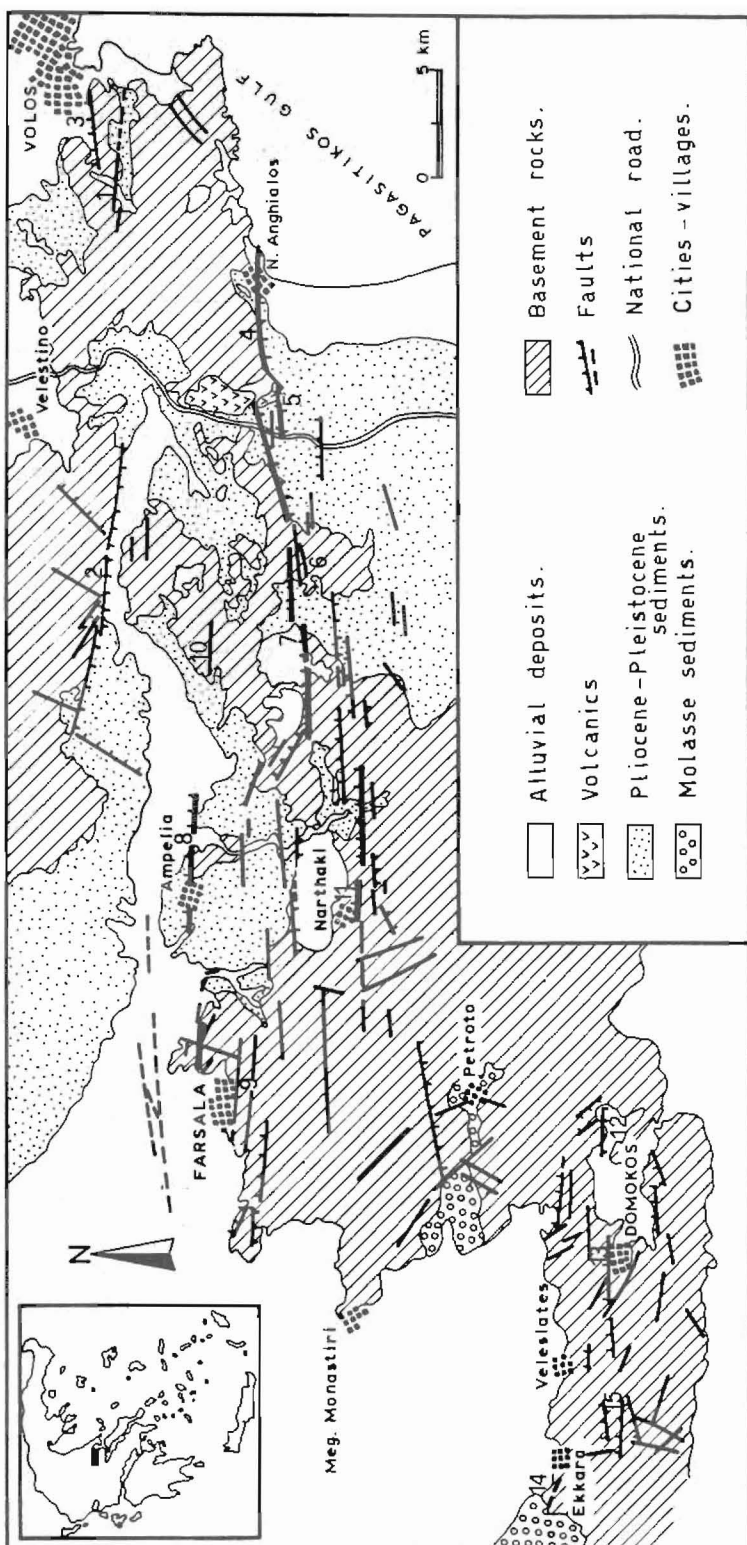


Fig.2. Simplified Geological map of the Southern Thessaly showing the segments of the highly active fault zone. 1. N. Pagasai fault., 2. Riglio f., 3. Dimini f., 4. N. Anchiailos f., 5. Microthivae f., 6. Porta f., 7. Perdika f., 8. Enipeas f., 9. Farsala f., 10. Eretria f., 11. Narthaki f., 12. Vouzi f., 13. Domokos f., 14. Ekkara f., 15. Agoriani f.

At the base of these fluvio-lacustrine sediments, red beds of ?Pontian s.l. age are locally exposed c) Pleistocene red beds including reddish muds, sands and gravels d) Quaternary debris deposits and Holocene alluvial deposits.

A small volcanic outcrop composed of basaltic lavas intrudes the basement and the Neogene sediments in the area of Microtheval west of the village of N. Anghialos. Radiometric dating showed a Quaternary age (1.5 ± 0.5 Ma) of these volcanic rocks (Innocenti et al 1979).

STRUCTURAL DATA AND TECTONICS ALONG THE ACTIVE FAULT ZONE

The fact that the Sophades (1954) and N.Anghialos (1980) strong earthquakes occurred respectively in the western and eastern part of this highly active seismic zone, associated with ground ruptures along well known neotectonic faults, leads us to divide the zone into two parts: the eastern and the western.

a. Eastern part of the active fault zone (N.Anghialos-Volos area)

The eastern part of the zone is dominated by the main N. Anghialos normal high-angle fault trending E-W (fig. 2). This fault bounds mostly the northern margin of the similarly trending Almiros basin, which is filled with Neogene-Quaternary sediments. The strong earthquake which occurred in the area of N. Anghialos in 1980 and caused many ground ruptures (Papazachos et al. 1983) is clearly related to this fault. The fault is easily detected as a long lineament in satellite images and aerial photographs as well as in the field, since it presents highly-angle abrupt scarps, particularly along the segment cutting the Triassic-Jurassic crystalline limestones.

Nevertheless, in this eastern part of the active fault zone similar large scale mainly E-W mainly trending highly-angle faults dipping mostly to the South, such as the N. Pagasai and Rigio faults (fig. 2), have also been found. These faults, as well as others dipping to the North, for example the Dimini and Perdika faults, are kilometric in length E-W trending faults, presented in parallel synthetic or antithetic arrays, which constitute an autonomous E-W trending fault zone. Well observed kinematic indicators, typical of brittle deformation, along their slickensides exposed in the basement show that these faults exhibit an older but dominant striation related to a dextral strike-slip motion, superimposed by two oblique to dip-slip striations, which are related to two younger normal reactivations.

Similar observations of the kinematics of the E-W trending faults within the Pliocene-Lower Pleistocene sediments show that they reveal mostly two oblique to dip-slip striations related to two normal motions, similar to the aforementioned normal reactivations in the basement. However, it is important to mention that a questionable strike-slip striation observed along a very few faults with E-W and NE-SW strike affecting the red beds, at the base of the Pliocene-Lower Pleistocene sediments, is possibly related to the dominant strike slip motion observed along the E-W faults of the basement. Consequently the question of the date of the strike-slip motion remains and further investigation is

needed in order to define the relationship between the two.

Finally, along the E-W faults affecting the Middle Pleistocene and younger sediments the dip-slip striation is the only one observed and is related to an extensive normal motion.

Within this principal E-W trending fault zone some other faults with NE-SW strike have been observed. They are smaller than those trending E-W, but they are dominant in the area of Mt Pelion (eastern edge). Tectonic striations and other kinematic indicators, typical of brittle conditions, along the slickensides of these faults exposed in the basement, show that they have undergone at least two distinct slip events; the first associated with a significant dextral strike-slip motion and the later one with oblique to pure normal motion.

Additionally, a few faults trending N-S are recognized only by remote sensing.

b. Western part of the active fault zone (Ekkara-Domokos area)

The western part of the studied area is also dominated by E-W trending faults several kilometres in length, dipping mostly to the North, although some of them show a dip in the opposite direction (fig. 2). These faults are presented in parallel synthetic or antithetic arrays, bound Neogene and Quaternary basins and are associated with many ground ruptures which occurred during the strong earthquakes in the area (Sophades, 1954; Papastamatiou and Mouyiaris, 1986; Pavlides, 1993). These ground ruptures have been detected by field observations following information from the inhabitants near the villages of Ano Agoriani, Ekkara, Gavrakia, Velesiotes, Farsala and Ampelia (fig. 2).

The Enipeas, Domokos, Vouzi, Farsala and Narthaki faults constitute a principal E-W trending fault zone with similar characteristics and kinematics to those of the eastern part. More precisely, a dominant strike-slip striation corresponding to a dextral strike slip motion has been recognized along the fault slickensides to be superimposed by two oblique to dip-slip striations corresponding, respectively, to two normal reactivations. On the other hand, within the fault-bounded Neogene and Quaternary basins new E-W trending faults have been found to form mesoscopic conjugate synthetic or antithetic arrays, but show mainly two normal striations related respectively to two normal slip events where they affect the Pliocene-Lower Pleistocene sediments and only one where they affect the post-Lower Pleistocene ones. In some cases, along these marginal faults travertine deposits and stream offsets occur. In addition, it is important to mention the detection of some long lineaments on the aerial photos, which follow this general E-W trend and are localized, in the field, by the elongated scarps or terraces mainly along the Enipeas river. Within the E-W trending fault zone, subordinate and small faults with NNW-SSE to N-S strike have been found. They are high-angle to vertical faults which commonly cause noticeable left-lateral offset to the E-W structures. On their slickensides, exposed in the basement, horizontal tectonic striations associated with a general left-lateral movement have also been found.

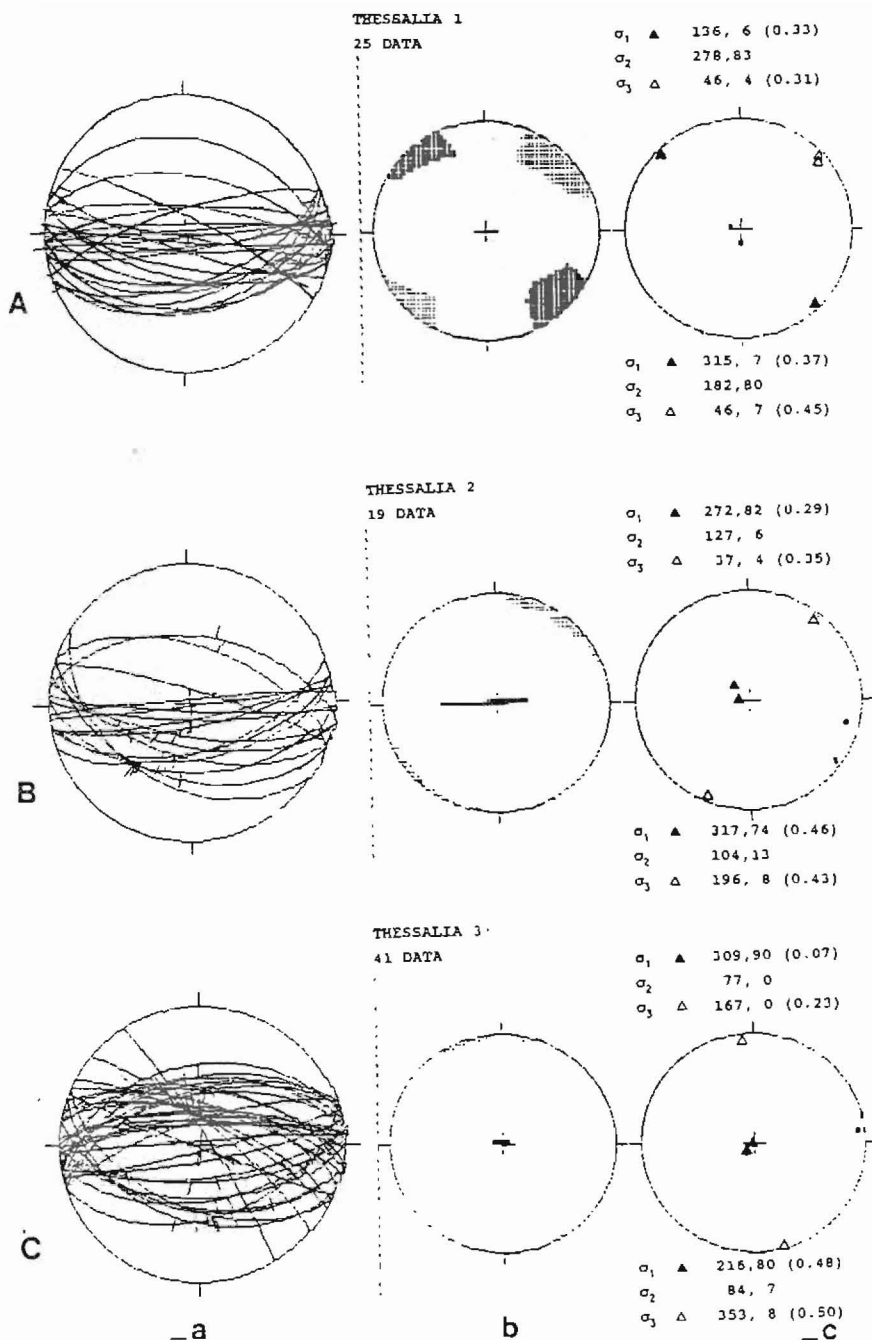


Fig.3. Quantitative stress analysis of the fault kinematics a) Stereographic projection of the faults (as curves) and striation (as arrows); b) The application of the right-dihedron method, c) the results of the "main stress tensor" ($\sigma_1 > \sigma_2 > \sigma_3$) methods.

A. Strike-slip movements (St), B. First extensional phase (T1); C. Second (active) extensional phase.

Additionally, faults with NW-SE strike, coinciding to the general alpine direction, are observed. They are normal faults clearly affecting the alpine structures and produced some important morphological features in the area. In most cases, they are affected by the E-W trending normal faults as indicated by both geomorphological and tectonic structures observed mainly in the marginal parts of the fault-bounded sedimentary basins. On their slickensides, dip-slip striations and corrugations are the only observed dominant features.

PALAEO-STRESS ANALYSIS

To determine the neotectonic - active stress pattern of the area, known quantitative methods (Angelier 1979) were used. The reconstruction of the principal stress axes is based on the slickenslides (striae) and other geological kinematic indicators. The Caputo & Caputo (1988) methodology and the "fault" computer program applied to the above mentioned methods were also used. For each site a separate computation was made for the different categories of structures (normal and strike-slip faults).

Analysis of the collected data (fig. 3,4) allows us to distinguish the following tectonic phases which affected the Southern Thessaly fault zone in neotectonic times and confirms the field observations on the superimposed microstructures suggesting the following deformations.

Thus, the first, a strike-slip deformation (St), shows that tensional axes σ_3 trending NE-SW (45°) and compressional axes σ_1 trending NW-SE (135°) were almost horizontal during this phase, while the intermediate axes (σ_2) were generally sub-vertical. The second tectonic phase (T_1) caused normal reactivation of the E-W trending fault planes as an extensional regime. The maximum (σ_1) axes remained constantly sub-vertical during this phase. For the normal faults the σ_3 were sub-horizontal trending NE-SW (37°) and the σ_2 trended NW-SE (125°), dipping towards NW or SE. For the strike-slip faults, sinistral and dextral, of the same extensional phase the σ_3 remained sub-horizontal trending NE-SW, and the σ_2 became vertical.

The orientation of the main axes of the strain ellipsoid changed later, in Middle Pleistocene-recent times, during a successive extensional phase (T_2) in the N-S direction. The σ_3 were almost horizontal in the N-S general direction, ranging from 350° to 10° . Normal faults show that the σ_2 trended E-W and the σ_1 were sub-vertical while for the strike-slip faults the σ_1 trended E-W and the σ_2 were sub-vertical.

DISCUSSION

This first approach to the structural evolution and present geotectonic situation of Southern Thessaly, particularly based on the field work, which focused on the pattern, geometry and kinematics of the faults and compared the western and eastern parts of the active fault zone, can be summarized as follows:

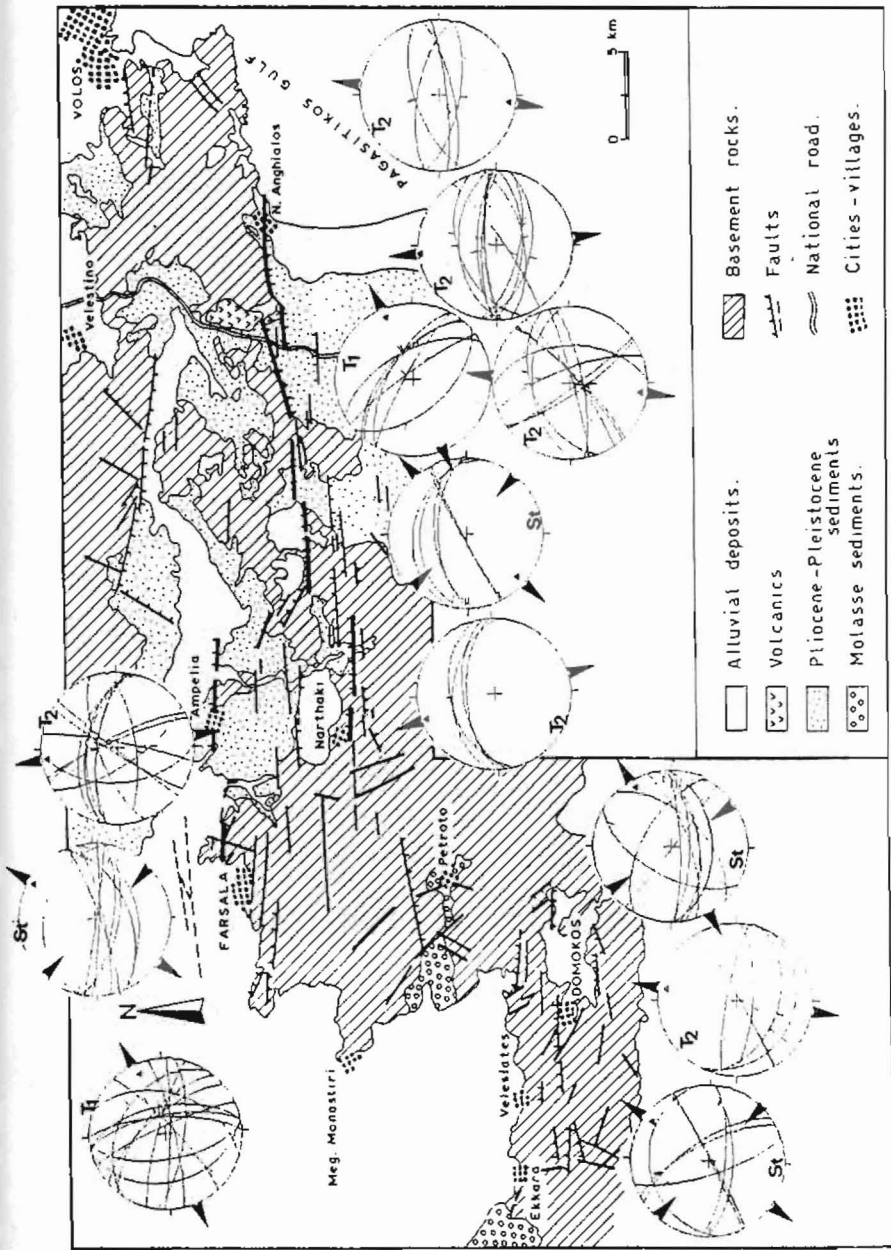


Fig. 4. Simplified Geological map of Southern Thessaly with the palaeostress analysis diagrams (stereographic projections, lower hemisphere) of the fault zone (Further explanation in the text).

A principal E-W trending fault zone, well established in the basement, formed in Miocene times, since it clearly affects the structures and the mollase sediments of Miocene age. However, there is not yet clear evidence that it affects the ?Late Miocene and Pliocene sediments. This fault zone, consisting of linked or unlinked, parallel, high-angle faults, is characterized by a dominant dextral strike-slip motion and could be interpreted as a principal dextral wrench fault zone which was formed in Miocene times.

This fault zone could represent either the western continuation of the North Anatolian dextral strike-slip fault or an isolated fault branch independent of and previous to the North Anatolian fault.

Within this E-W dextral wrench fault zone, the NE-SW trending faults fit well in the same stress field, as they show a similar strike-slip motion compatible with that of the E-W faults.

The NW-SE trending faults, showing a significant dip-slip motion, affect the basement, the mollase sediments and the unconformably overlain ?Late Miocene-Pliocene sediments. Thus, the normal motion of these faults postdates the initial strike-slip motion of the E-W trending faults during Miocene times and could be attributed to the T_1 , NE-SW, extensional phase (fig. 3,4) which has been shown to dominate the Inner Aegean region during Late Miocene-Pliocene (Mercier et al 1989). Additionally, fault segments of the original E-W dextral wrench fault zone have been reactivated as oblique normal faults during this T_1 , extensional tectonic phase of Late Miocene-Pliocene times. This E-W wrench fault zone shows in Quaternary-recent times an intense normal reactivation representing a highly active fault zone in the basement and the Neogene-Quaternary sediments. In fact, the E-W normal faults affect the NW-SE faults and generally the structures caused by the T_1 extensional phase, but even more cut the Holocene deposits. This new reactivation of the fault zone represents the more recent T_2 extensional phase (fig. 3,4) which is well known in the broader area of Thessaly (Caputo 1990, Caputo & Pavlides 1993). The main seismic events which took place during the present century in Southern Thessaly present clear evidence for the recent normal reactivation of certain fault segments of the initial E-W wrench fault zone. A possible explanation for the polarity shown in the dip-direction of the fault segments activated during the Sophades (1954) Velestino (1957) and N. Anghialos (1980) earthquakes could be the pre-existing geometry of the initial wrench fault zone (fig. 5).

From the above mentioned data we can suppose that there has been a general change in the kinematics of the initial E-W dextral wrench fault zone since ?Late Miocene with the reactivation of many fault segments, behaving as marginal faults for the Neogene and Quaternary basins of the area. This reactivation is believed to have been the result of the well known neotectonic extensional regimes in the Inner Aegean area with NE-SW and N-S tensional directions respectively, (Mercier et al 1989, Papazachos et al 1991), the former from Late Miocene to Pliocene and the later since Middle Pleistocene.

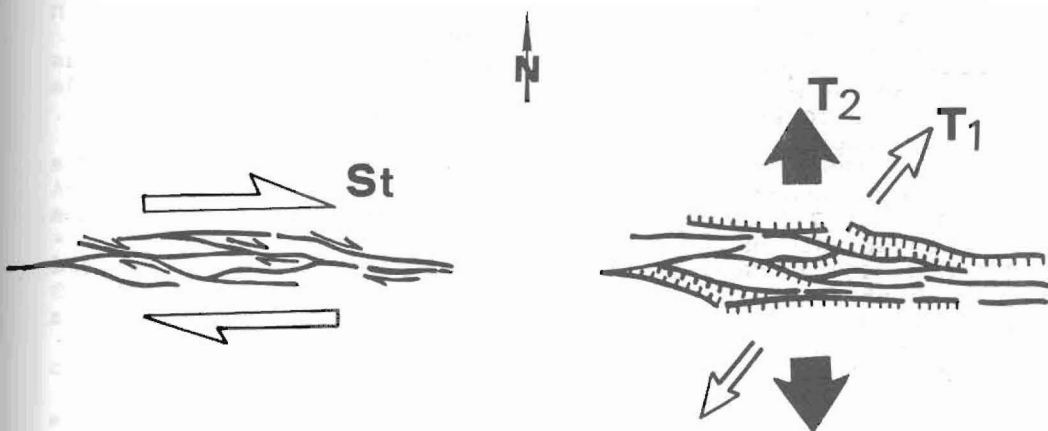


Fig.5. Sketch showing a possible model for the evolution of the deformational phases along the Southern Thessaly fault zone. A. Strike-slip deformation (St). B. Extensional deformation (T_1 older and T_2 younger)

The present tectonic situation of the initial E-W wrench fault zone is one of high seismic activity with strong earthquakes, having focal mechanisms of normal faulting, (Papazachos et al., 1992) distributed mainly along active fault segments trending E-W, so that it may reasonably be considered as one E-W highly active fault zone.

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