ANNALI DI GEOFISICA, VOL. XXXIX, N. 3, May 1996

The active Nea Anchialos Fault System (Central Greece): comparison of geological, morphotectonic, archaeological and seismological data

Riccardo Caputo (*)
Dipartimento di Scienze, Università G. D'Annunzio, Chieti Scalo, Italy

Abstract
The Nea Anchialos Fault System has been studied integrating geological, morphological, structural, archaeological and seismic data. This fault system forms the northern boundary of the Almyros Basin which is one of the Neogene-Quaternary tectonic basins of Thessaly. Specific structural and geomorphological mapping were carried out and fault-slip data analysis allowed the Late Quaternary palaeo-stress field to be estimated. The resulting N-S trending purely extensional regime is consistent with the direction of the T-axes computed from the focal mechanisms of the summer 1980, Volos seismic sequence and the April 30, 1985 Almyros earthquake. A minor set of structural data indicates a WNW-ESE extension which has been interpreted as due to a local and second order stress field occurring during the N-S regional extension. Furthermore, new archaeological data, discovered by the author, have improved morphology and tectonics of the area also allowing a tentative estimate of the historic (III-IV century A.D. to Present) fault slip rate. Several topographic profiles across the major E-W topographic escarpment as well as along the streams, have emphasised scarps and knick-points, further supporting the occurrence of very recent morphogenic activity. In the last section, the structural, morphological and archaeological data are compared with the already existing seismological data and their integrated analysis indicates that the Nea Anchialos Fault System has been active since Lower(?)-Middle Pleistocene.

Key words *structural geology – morphotectonics – archaeology – seismicity – Central Greece*

1. Introduction

During past years, the Southern Thessaly region has been recognised as a very active area, crossed by a large E-W trending seismogenic zone where several earthquakes occurred in historical times and others are expected to occur in the future (Papadopoulos, 1992). This study concentrates on the Nea Anchialos Fault System (NAFS), which corresponds to the eastern part of this seismogenic belt (fig. 1). In 1980 a magnitude 6.5 seismic event shocked this area generating major damage and numerous ground ruptures (Papazachos *et al.*, 1983).

Geological and structural studies have shown that the NAFS was generated by a regional tectonic activity affecting Thessaly at least from Middle Pleistocene to the Present (Caputo, 1990). Some of the faults affecting the northern sector of Thessaly have been documented to be active during Late Pleistocene-Holocene times (Caputo, 1990, 1993a; 1995a,b; Caputo *et al.*, 1994). Although

(*) *Mailing address*: Via A. Lollio 7, 44100 Ferrara; e-mail: caputo @ gotham.sci.unich.it

a large seismic gap has been inferred to occur in this northern area (Caputo, 1995b), earthquakes are mainly expected in the southern sector (B.C. Papazachos, personal communication), where a very high seismic potential and consequent seismic hazard have been inferred (Papazachos *et al.*, 1993).

The present research integrates geological, geomorphological, structural, archaeological and seismic data in order to: a) identify the Quaternary trajectories of the stress field generating the NAFS; b) compare the principal stress orientations with those obtained from the focal mechanisms of earthquakes occurred along the fault (*i.e.* present-day stress field); c) estimate the amount of total displacement generated during Late Quaternary times along the whole fault system and d) measure the long-term slip rate of the fault.

2. Geometry of NAFS and local stratigraphy

The NAFS is the superficial expression of a 50 km long east-west trending south-dipping crustal-scale normal fault (fig. 1). This structure bounds to the north the Almyros Basin, which is the southernmost Quaternary tectonic basin of Thessaly (Caputo, 1990). Only the western segments of this fault zone, for about 15-17 km, can be completely mapped, because east of the town of Nea Anchialos the fault enters the Pagasitikos Gulf and its superficial expression is thus mainly submerged (fig. 1). As a consequence, geological, geomorphological, structural and archaeological observations have been limited to the western sector (fig. 2). Nevertheless, in the sea floor of the Pagasitikos Gulf, a major fault has been detected by using geophysical means and traced eastwards from

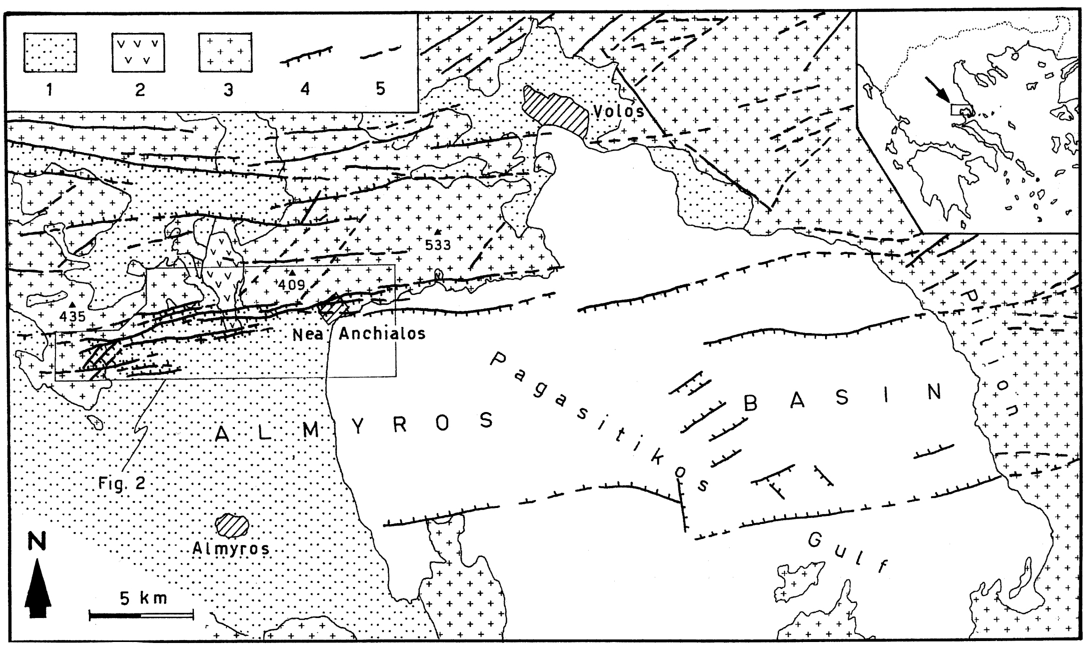


Fig. 1. Geological and structural map of Almyros Basin, Southern Thessaly, Central Greece, bounded by the Nea Anchialos Fault System to the north. 1 = Late Pliocene-Quaternary deposits; 2 = Thive Quaternary basalts; 3 = undivided Palaeozoic-Mesozoic substratum rocks; 4 = major Middle Pleistocene-Present normal faults (barbs on the downthrown side); 5 = other faults and lineaments from satellite images. Some elevations of the footwall block are also indicated. Top right inset shows location of study area. Modified from Caputo (1990) and Perissoratis *et al.* (1991).

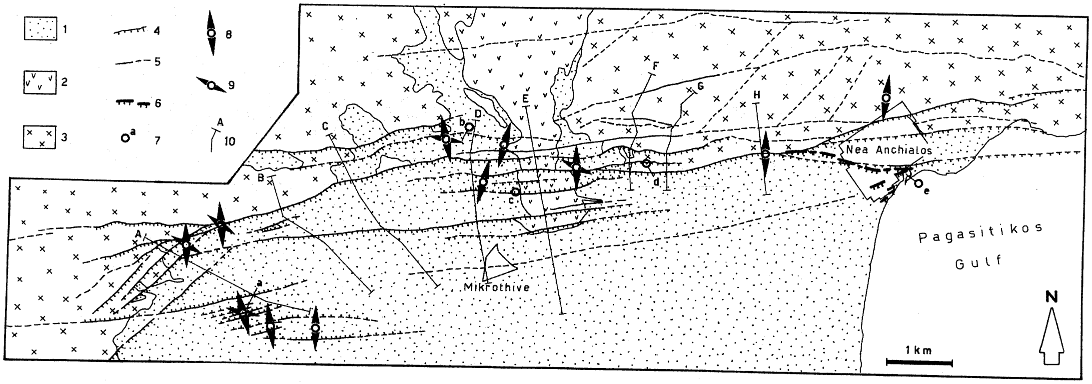


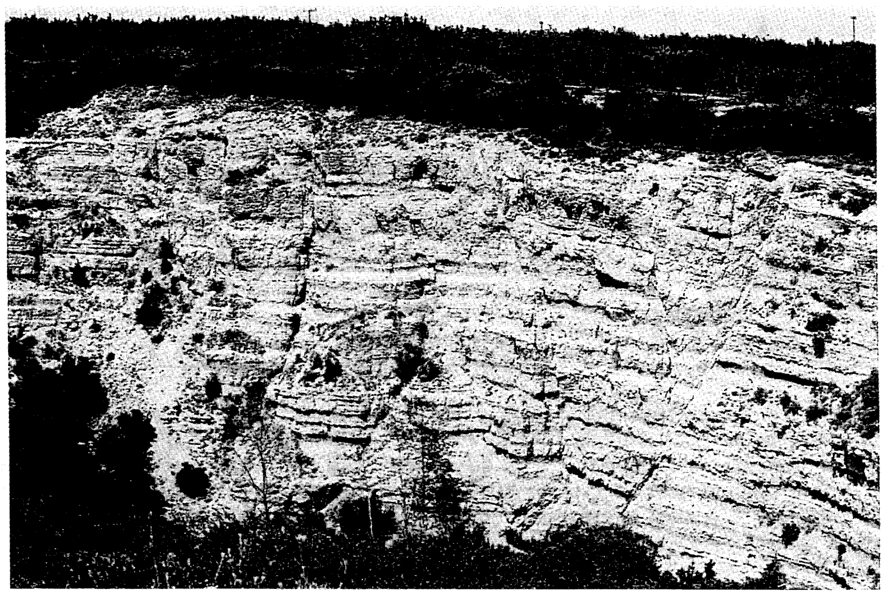
Fig. 2. Simplified morphotectonic and geological map of the western sector of the Nea Anchialos Fault System (original mapping at scale 1:10000). 1 = Late Pliocene-Quaternary deposits; 2 = Thive Quaternary basalts; 3 = Palaeozoic-Mesozoic substratum (barbs on downthrown side); 4 = main recent normal faults; 5 = other faults; 6 = ground ruptures mapped after the 1980 Volos earthquake (Papazachos *et al.*, 1983); 7 = sites referred to in the text; 8 = sites of mesostructural analyses showing regional N-S extension; 9 = sites of mesostructural analyses showing second order NW-SE direction of extension; 10 = traces of the profiles shown in fig. 9.

Nea Anchialos to the Pilion peninsula (Perissoratis *et al.*, 1991) thus indicating the overall dimensions of the fault system (fig. 1).

At the surface, numerous fault branches have been mapped in detail. Bifurcation geometries along the strike are very frequent. Some minor north-dipping faults a few kilometres long have also been recognised. All these synthetic and antithetic branches necessarily merge at depth into a unique major shear zone. The exact depth where the fault splays upwards, thus generating this complex surficial pattern, is unknown. However, according to the general geometry of the segments, to their dip angles at the surface and assuming a crustal-scale listric fault geometry (Papazachos *et al.*, 1983), it is clear that partitioning of brittle deformation into minor fault segments occurs more than 5 km deep (and probably less than 10 km). Moreover, some minor NE-SW trending faults affect the westernmost sector of the NAFS, possibly related to the inherited morphological scarp bounding the Almyros Basin to the west.

The footwall block of the NAFS is characterised by several metamorphic and non-metamorphic formations of Palaeozoic and Mesozoic age belonging to the Alpide substratum. These rocks consist of different kinds of limestones, schists and ophiolites of the Pelagonian Zone (IGME, 1983, 1986). Moreover, in correspondence with the fault zone near the village of Mikrothive, Quaternary basaltic lavas, from a few metres up to 20 m thick (Frankopoulos, 1956), cover an area of about 6 km^2 (fig. 2).

In the hanging-wall block, the Pliocene-Lower Pleistocene fluvio-lacustrine sediments of the Almyros Formation (Caputo, 1990) largely crop out (figs. 2 and 3). The stratigraphic sequence, several tens of metres thick, is characterised by frequent lateral and vertical facies variations, with interfingering of different lithological units. The main lithologies are brownish-reddish breccias and sandstones (probably slope debris deposits), which are mainly distributed in the northern sector (*i.e.* closer to the source area) and in the lowermost stratigraphic levels. Southwards and upwards, these sediments grade into white and yellowish marls locally interbedded with fine-grained clastic layers deposited in a fluvio-lacustrine palaeo-environment. These deposits are generally in tectonic contact with the Alpide sub-



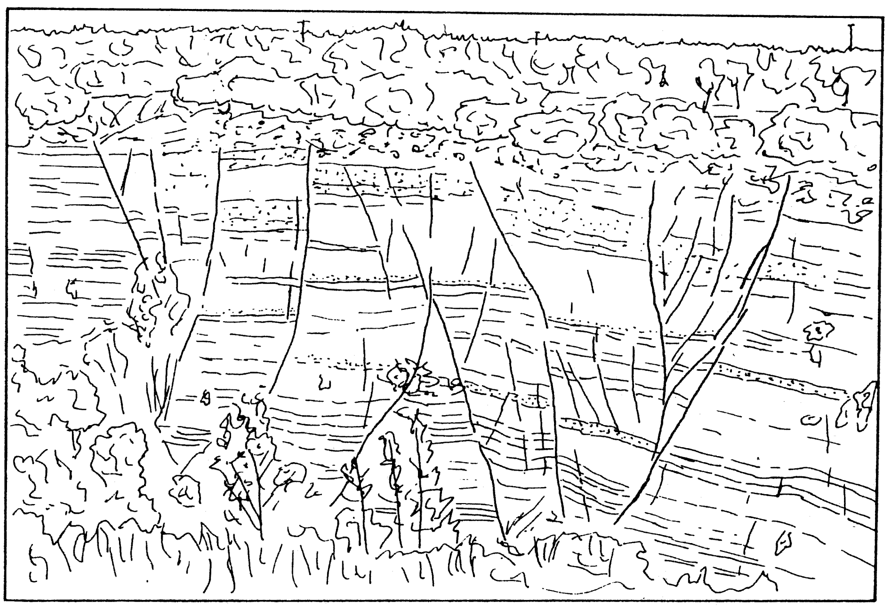


Fig. 3. Normal faults in lacustrine sediments of Almyros Formation (site a in fig. 2). The scarp is about 15 m high. These sediments are cut by prevailing E-W dip-slip normal faults and secondary NE-SW oblique-slip faults with left-lateral components. All faults belonging to the former set have a displacement greater than one meter, whereas the secondary set shows maximum displacements of a few decimetres. See text for further discussion.

stratum and only locally is it possible to map a stratigraphic contact.

The age of the Almyros Formation, for comparison with the close fluvio-lacustrine deposits of the Central Hills of Thessaly, is Pliocene. However, in the uppermost levels of the series, volcano-clastic materials have been found (Caputo, 1990). This volcanic-type source of sediments is very important because the basaltic eruptions of the Thive Volcano have been radiochronologically dated 1.4±0.1 Ma (Innocenti *et al.*, 1979). Except for a very small spot east of Nea Anchialos, which is along the road to Volos, the Thive Volcano is the only effusive point in a distance of many kilometres. Consequently, the uppermost section of the Almyros Formation is necessarily Lower Pleistocene.

Unconformably above the Almyros Formation, Red Beds type deposits rest. These sediments, consisting of poorly cemented clastic deposits with variable grain-size and abundant matrix, have been widely correlated all over Greece and, due to their characteristic colour, a climatic origin has been suggested (*e.g.*, Bousquet, 1976; Dufaure *et al.*, 1979). Although Miocene and Pliocene Red Beds exist at least in Northern Greece (*e.g.*, Psilovikos *et al.*, 1987), the climatic event responsible for the Red Beds of the Almyros Basin probably occurred during the Late Pleistocene because these sediments stratigraphically overlie the Almyros Formation (Pliocene-Early Pleistocene) and all over the Southern Thessaly they unconformably overlie the Pliocene fluvio-lacustrine deposits and therefore they can be correlated to the above mentioned climatic event with reasonable confidence. Both Almyros Formation and the Red Beds are diffusely affected by faulting and are often deeply entrenched by streams crossing the footwall blocks.

Eventually, loose clastic fine-grained sediments are widely distributed in the Almyros plain. These alluvial deposits show a clear onlap contact all along the foothills, south of the fault system as well as along some of the major streams. Due to their stratigraphic position, the latest Pleistocene-Holocene age can be tentatively inferred. No clear morphotectonic scarps have been observed. However, near the southernmost faults, along some of the valleys, these deposits are undoubtedly entrenched thus indicating vertical movements.

The fault-constrained areal distribution of these deposits and the generation of syndepositional growth faults in both Lower and Upper Pleistocene sediments (fig. 4a,b) demonstrate tectonic activity throughout most of the Quaternary period.

3. Archaeological data

During the field work along the NAFS, I found some remnants of an ancient aqueduct (site b in fig. 2) located two kilometres NNW of the village Mikrothive, west of the volcano Thive. It consists of a series of cylinders 80 cm long and 20 cm in diameter (fig. 5). Due to a groove they have on one end, they fit and close in to each other. The pieces are made of red clay and the «cement» all around the connections is a white paste. The pipeline crops out just along two small valleys because of erosion. Both valleys are entrenched in a proximal facies of the Almyros Formation. Elsewhere, it is buried in the ground 0.5 to 1.5 m. At present, no excavations have been carried out by the local Archaeological Authorities, which were advised of the discovery in summer 1987. The type of cement and the shape of the handwork allow the age of the pipe to be constrained between late Roman and palaeochristian times, that is III-IV century (Pavlos Lazarides, 1990 personal communication).

The western valley where the archaeological material was found is V-shaped, about 6 m deep and, in its upper part, 10 to 15 m wide (fig. 6a,b). The pipeline trends obliquely with respect to the axis of the valley and, to cross it, it should have been supported by a bridge 25 m long. But a detailed survey of the area could not find any trace of this bridge or its remnants, that is also unknown in the popular and historical tradition of the area, as instead occurs for similar coeval handworks nearby. As a consequence, the hypothesis of the bridge

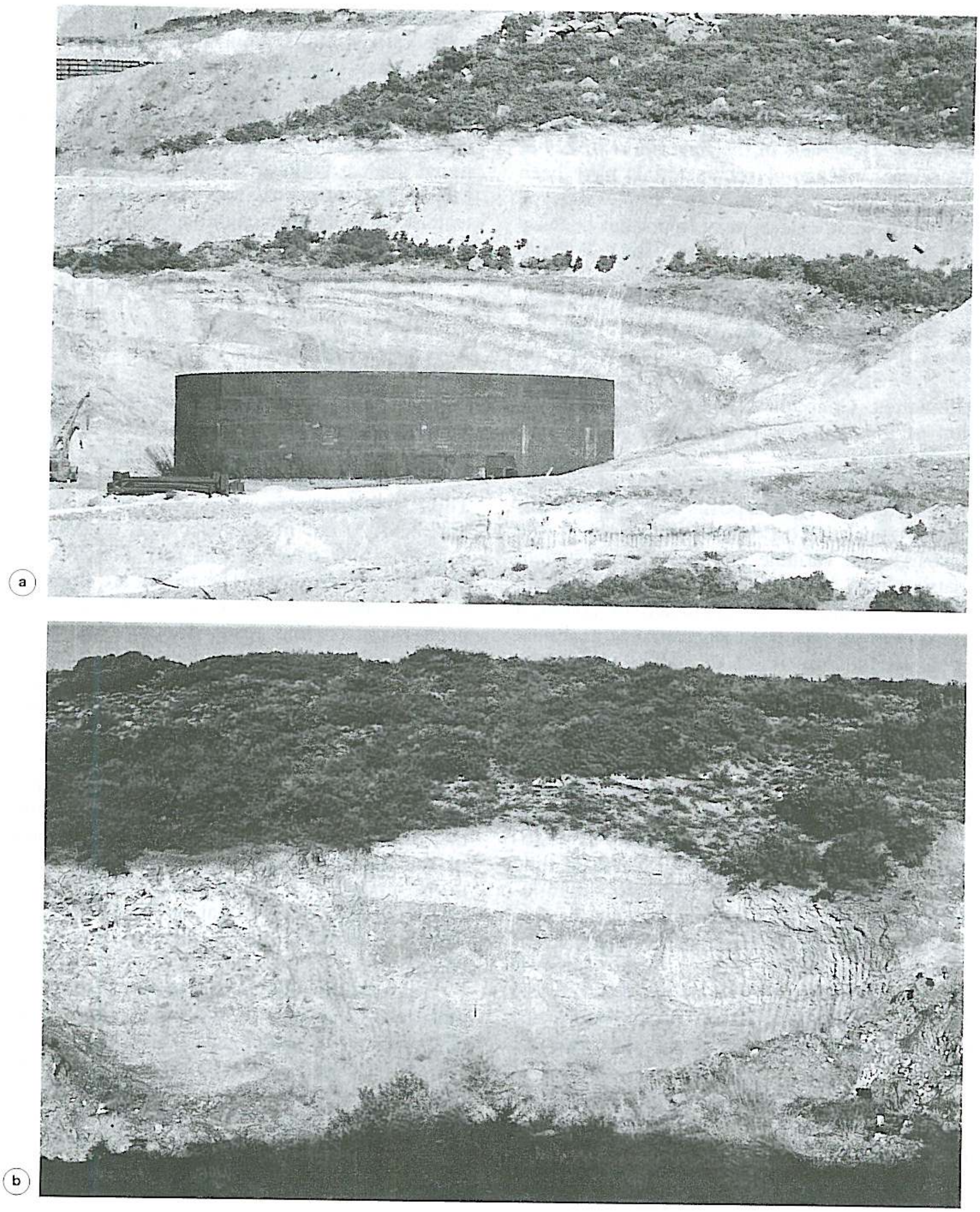


Fig. 4a,b. Examples of growth faults thus indicating synsedimentary faulting during (a) Pliocene-Early Pleistocene and (b) Late Pleistocene times (sites c and d in fig. 2, respectively).

Fig. 5. The palaeochristian aqueduct buried 1 m deep, which crops out along the eastern flank of a N-S trending stream entrenching the foot-wall block of the NAFS (site b in fig. 2). A similar setting has been observed on the other side of the valley.

across the stream is to be rejected and the valley should be younger than the handwork. Moreover, the depth of the valley and the age of the pipe, allow a rate of entrenching along the valley to be estimated at about 3.3 mm/yr.

For a long time (*e.g.*, Gilbert, 1879), the formation of a new V-shaped valley due to water erosion has generally been explained by the lowering of the base level of the equilibrium profile. According to the geological and tectonic environment of the archaeological site we feel confident that the lowering of the base level is due to vertical movements along one or more branches of the NAFS.

On the other hand, in the town of Nea Anchialos (once called Fthiotides Thive) the ancient harbour which is coeval with the pipeline is still at sea level and operating (site e in fig. 2). This implies that no, or very little vertical movement involved the harbour, either tectonic in origin, or eustatic or they eventually compensated each other. It is interesting to note that the harbour is located south of the fault system crossing the Nea Anchialos town. We may also assume the same vertical stability for most of the southern plain of the Almyros Basin because no major faults exist south of the town, in contrast to the above mentioned pipeline which has been found in the footwall block.

4. Morphotectonics

The analysis of the hydrographic network (fig. 7) as well as detailed topographic maps (scale 1:5000) corroborated by extensive field

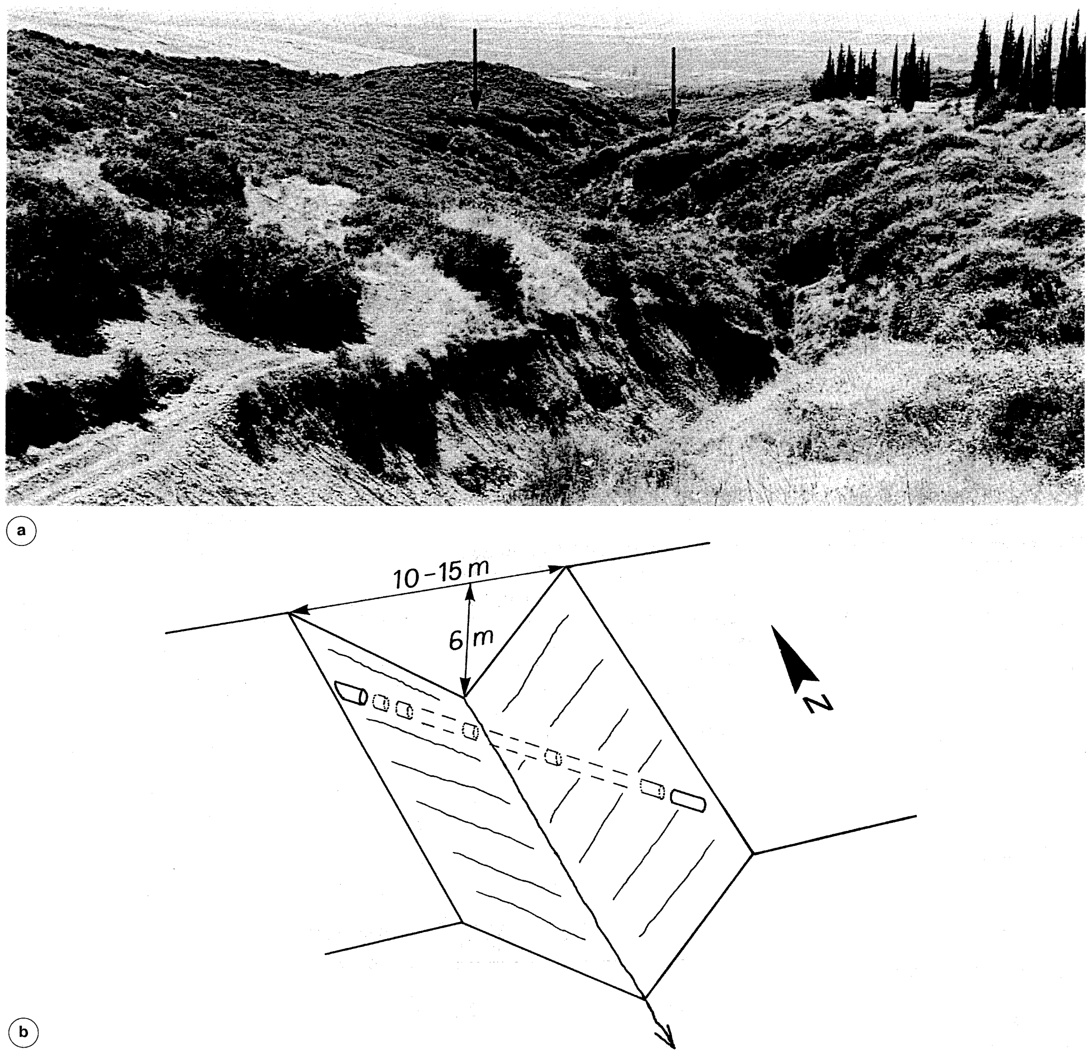


Fig. 6a,b. a) Southward view of the valley. Arrows indicate the locations of the outcropping aqueduct. Almyros plain is in the far field. b) 3D sketch of the V-shaped western valley along which the late Roman palaeochristian aqueduct was found.

observations, clearly show that the morphology of the area is strongly controlled by recent tectonics. In fact, E-W trending morphological scarps and deep stream entrenching are common features all along the northern border of the Almyros Basin. Several new streams debut just along the fault, while clear angular bends connect the V-shaped valleys which developed in the footwall block with streams in the hanging-wall related plain. Topographic profiles have been drawn along the major escarpment, where several small scarps can be recognised along the slope (fig. 8). Other profiles have been also drawn along some of the south-flow-

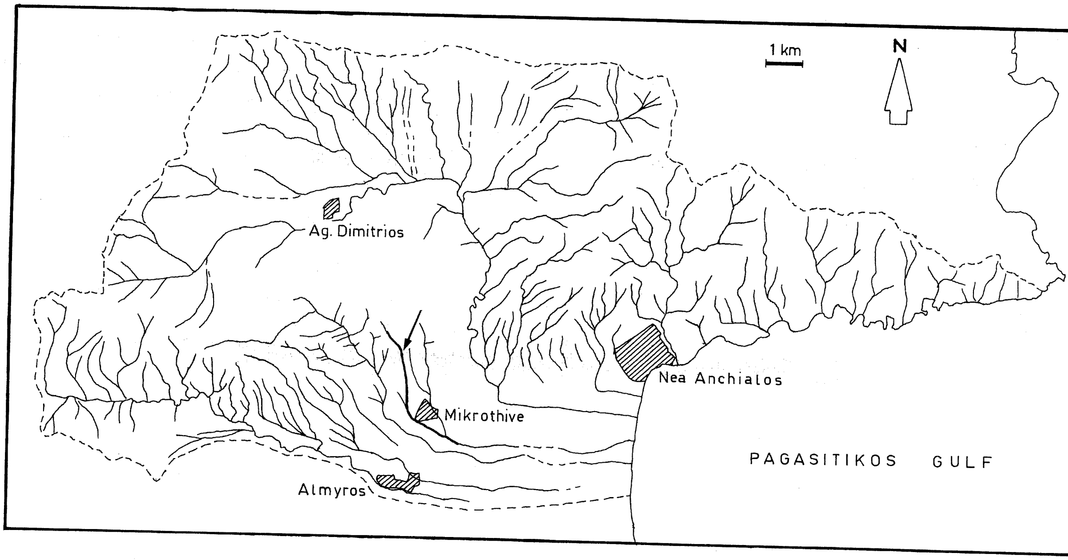


Fig. 7. Hydrographic network of the northern border of the Almyros Basin. The tectonic control, generating deep and diffuse entrenching of the footwall block and abrupt bending of streams is clear. Arrow indicates location of the palaeochristian aqueduct, while the stream, whose profile is represented in fig. 9, has been drawn with a thicker line.

ing streams showing abrupt slope variations marked by knick-points. A straightforward example is the topographic profile drawn along the western valley where the palaeochristian aqueduct crops out (fig. 9). This profile is clearly segmented in several parts, separated by scarps and knick-points. The slope angle progressively decreases downstream from 5.1° to 1.4°. As inferred from the morphology of the fault scarps and according to the length of the faults, the more active segments are the south-dipping planes, and particularly the fault immediately downstream from the aqueduct. Only a recent tectonic activity can explain the partitioning of the profile and the recent entrenching which occurred upstream also causing the disruption of the aqueduct.

The rate of smoothing of a morphotectonic scarp crossed by a stream is a function of several factors such as rainfall, lithology, vegetation and elevation of the drainage basin (*e.g.*, Yoshikawa, 1974). For example, the monitoring of knick-points generated during the 1959 Hebgen, Montana earthquake showed that the 0.6-6.5 m high scarps formed in unconsolidated deposits disappeared in a few months to some years (Morisawa, 1975). Comparable rates of smoothing can be assumed for the study area because, though Pliocene-Pleistocene sediments entrenched along the NAFS are slightly indurated, morphogenic earthquakes, that is seismic events able to generate surficial deformation along the fault they activate (Caputo, 1993b), can only cause small scarps. Indeed, according to the dimensions and the geometry of the faults (fig. 2), any surficial rupturing is mechanically constrained and can be, at most, a few decimetres in throw.

In conclusion, we can assume with some confidence that most linear morphological scarps, along slopes, and knick-points along streams are of tectonic origin and due to a very recent morphogenic activity. If this is the case, the above mentioned entrenching rate should be distributed among the three surficial fault branches crossing the profile. Therefore, at the surface the slip-rates of the single branches, which are morphologically similar to each

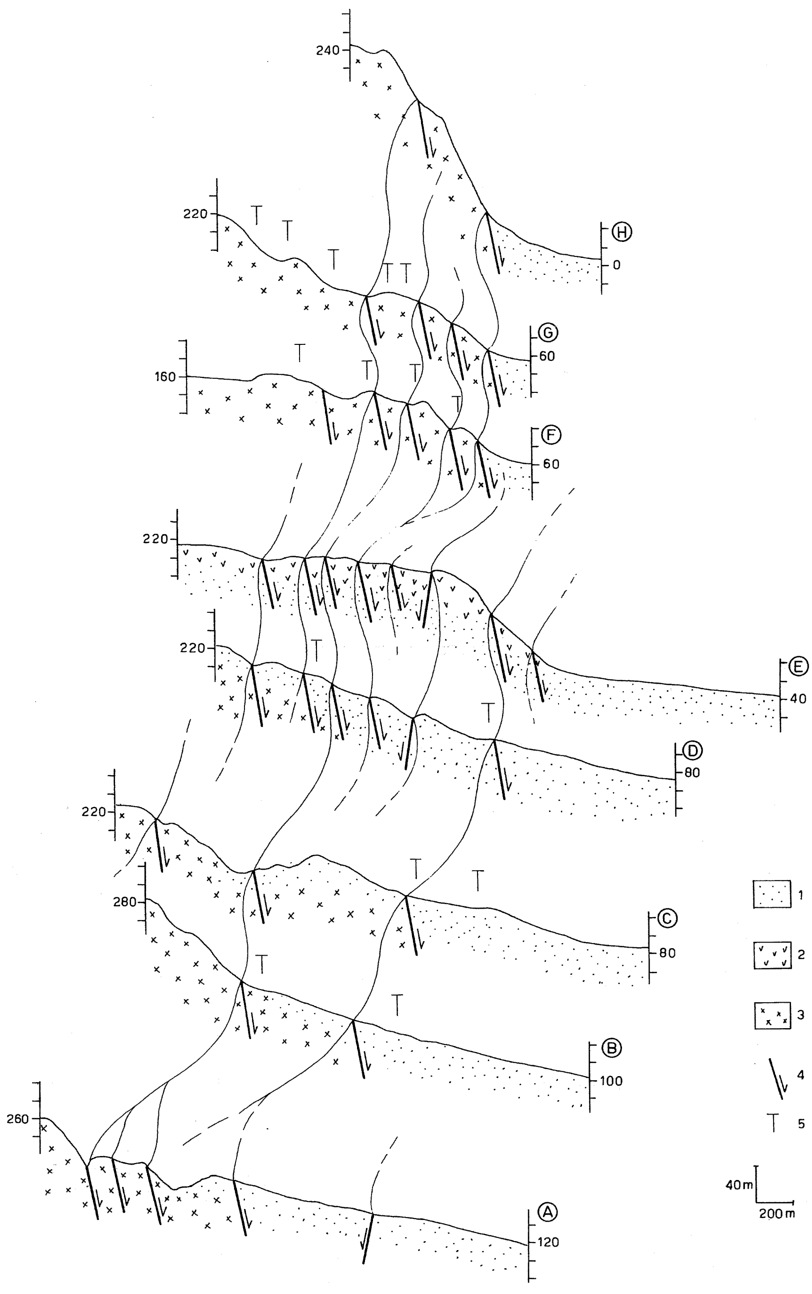


Fig. 8. Topographic profiles across the major morphological escarpment as drawn from 1:5000 scale maps (location in fig. 2). 1 = Late Pliocene-Quaternary deposits; 2 = Thive Quaternary basalts; 3 = undivided Mesozoic-Palaeozoic substratum rocks; 4 = normal faults; 5 = strike variation along profile. Thin lines between profiles connect faults which cross multiple profiles.

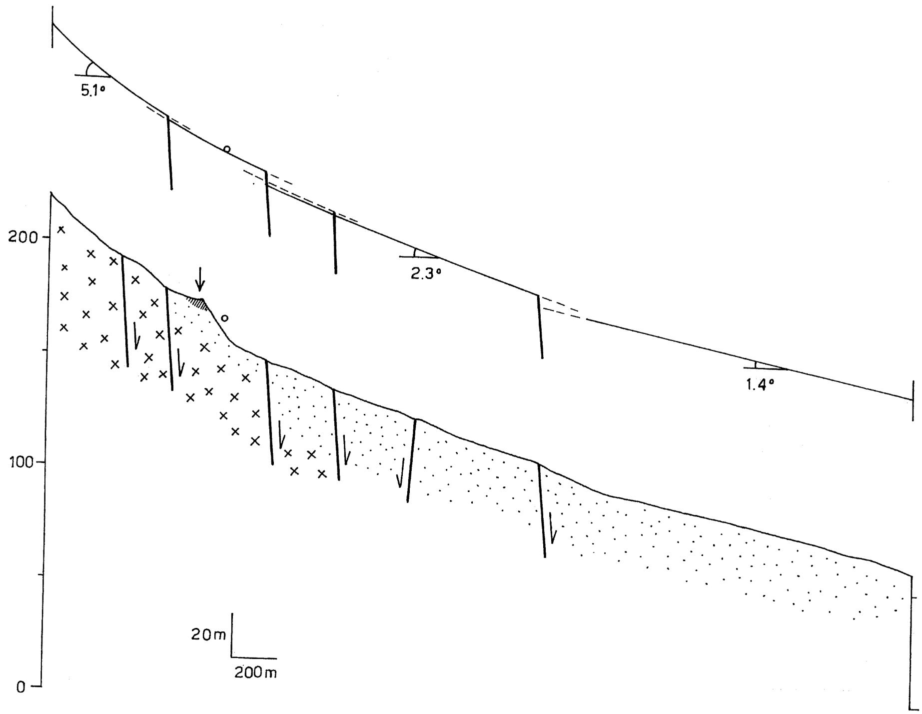


Fig. 9. Topographic profile along the stream where the palaeochristian aqueduct has been discovered (see fig. 2 for location). The small circle indicates the projection, from the valley's flanks, of the handicraft. Symbols as in fig. 8. The arrow shows where the national road crosses the stream; the artificially modified profile is shaded. Above, a tentative reconstruction of the equilibrium profile of the stream is provided which results clearly dissected by recent faulting.

other, are probably about 1 mm/yr. Although the shear rate at depth is certainly higher than this value, a certain amount of slip could also be adsorbed by more plastic (*i.e.* aseismic) deformation. The assumed surficial values are perfectly comparable in magnitude with those obtained for other faults of the Thessaly region (Caputo, 1995b).

5. Seismicity along the NAFS

A seismic sequence occurred in the Magnesia Prefecture during 1980 (fig. 10). The number of events per day and their magnitudes increased during the summer until the main shock on July 9, which had a magnitude M_s = 6.5. The strongest fore- and after-shocks had magnitudes ranging between 5.6 and 6.0, respectively (Papazachos *et al.*, 1983). The epicentres of all shocks distributed parallel to the fault system and clustered in the northern sectors of the Almyros plain, to the west, and of the Pagasitikos Gulf, to the east. Some aftershocks also occurred in the Pilion peninsula, and the whole seismogenic zone showed a total length of about 40 km (fig. 10).

The focal mechanisms obtained for the main-shock and the strongest fore- and after-shocks give E-W (to ENE-WSW) trending planes with almost pure dip-slip movement (fig. 10). In a N-S cross-section, the distribution of all earthquakes and the fault dip at the surface and at depth indicate a 10 to 15 km deep, spoon-shaped, E-W trending south-

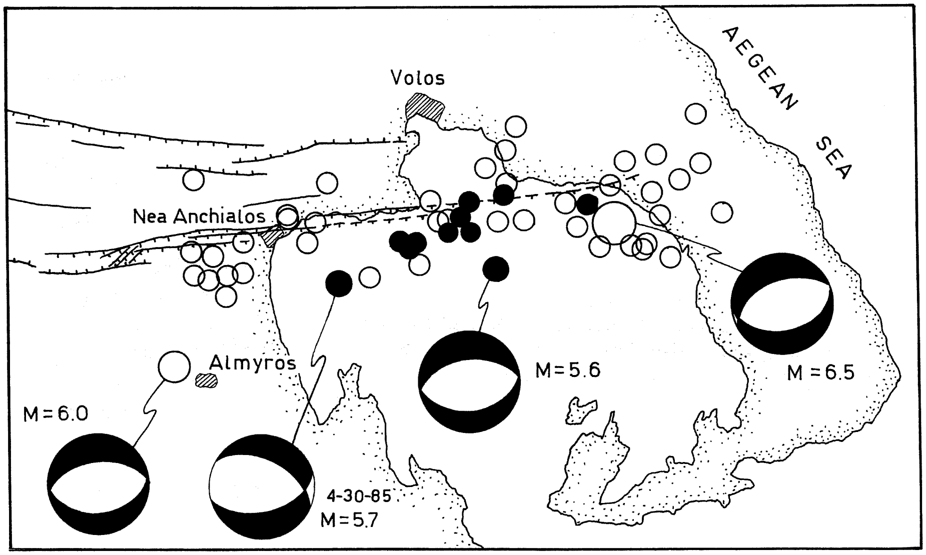


Fig. 10. Distribution of epicentres of shocks with $M_s \geq 4.2$ of the 1980, Magnesia seismic sequence (modified from Papazachos *et al.*, 1983). Full circles: fore-shocks; open circles: after-shocks. Focal mechanisms of main shock ($M = 6.5$), of the strongest fore- ($M = 5.6$) and after-shocks ($M = 6.0$) are shown. The focal mechanism of the 1985, Almyros earthquake ($M = 5.7$) is also given.

dipping fault plane (Papazachos *et al.*, 1983) thus confirming the crustal dimension of the NAFS.

Associated to this seismic event, several ground ruptures affected the town of Nea Anchialos and its surroundings (fig. 2). The trend of these ruptures was mainly E-W, showing a prevailing N-S lengthening and a downthrown southern block. However, south of Nea Anchialos, some of the cracks propagated along a NE-SW direction and showed some oblique-slip displacement associated with left-lateral motion. The peculiarity and the importance of this observation will be discussed in the next section.

Furthermore, on April 30, 1985, an earthquake of magnitude 5.7 again shocked the Almyros Basin. Also in this case, the focal mechanism shows an E-W trending fault plane with dip-slip motion, which is perfectly coherent with the earthquakes occurred during the 1980 seismic sequence (fig. 10). No ground ruptures were reported associated to the April 30, 1985 event. The average direction of the T-axes computed from the focal mechanisms trends N9°E, dipping 2°N (fig. 12).

6. Structural analysis along the NAFS

Following a detailed structural mapping of the area, numerous brittle mesoscale faults were measured at several sites (fig. 2). All the data were collected in the Almyros Formation, except one site (E of the Mikrothive volcanics) which is in the Late Pleistocene Red Beds.

Data collection was restricted to mesoscale fault planes where it was possible to obtain full geometric and kinematic information, that is attitude of the plane, direction and sense of motion along the fault. An example site is presented in fig. 11.

Fault slip data have been elaborated using three different methodologies. Firstly, the graphic method of Right Dihedrons (Pegoraro, 1972; Angelier and Mechler, 1977) has been ap-

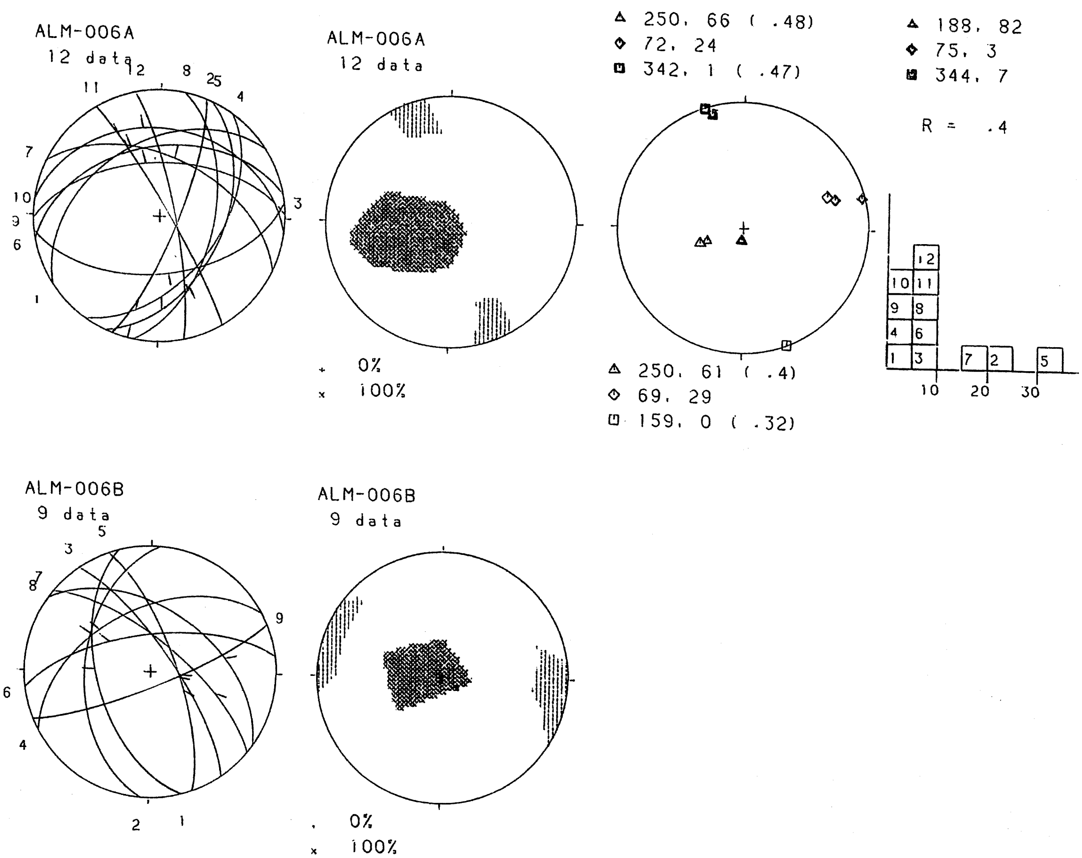


Fig. 11. Example of mesostructural analysis from a site with the two sets of faults associated to regional (a) and second order (b) stress fields. Left stereonets: fault traces with shown pitch and sense of movement. Central stereonets: areas with maximum probability to contain the direction of maximum shortening and lengthening obtained with the Right Dihedrons method (Angelier and Mechler, 1977). Right stereonets: results obtained using the Conditioned Square Minima Method (Caputo and Caputo, 1988) and the Mean Stress Tensor method (Carey, 1976). Triangles = σ_1, rhombs = σ_2 and squares = σ_3. Above triplet represents the three principal components of the stress tensor obtained applying the Conditioned Square Minima Method to the P and T axes method, the lower triplet applying the same method to the areas obtained from the Right Dihedrons method; the top right triplet refers to the Mean Stress Tensor method; histograms indicate the angular deviation between the real and the theoretical stria on the fault plane.

plied. An example result is shown in the central stereonets of fig. 11, where the areas with the maximum probability of containing the direction of shortening and that of lengthening are represented in black and grey, respectively. Secondly, numerical analyses to estimate the principal directions of the stress field have been carried out using the Conditioned Square Minima Method (Caputo and Caputo, 1988; Caputo, 1989) applied to the P-T axes and to the areas obtained from the Right Dihedrons method. The results are shown both graphically and numerically in the right stereonets, where the three estimated principal stresses and, between brackets, the least square errors, which are indicative of the reliability of the results

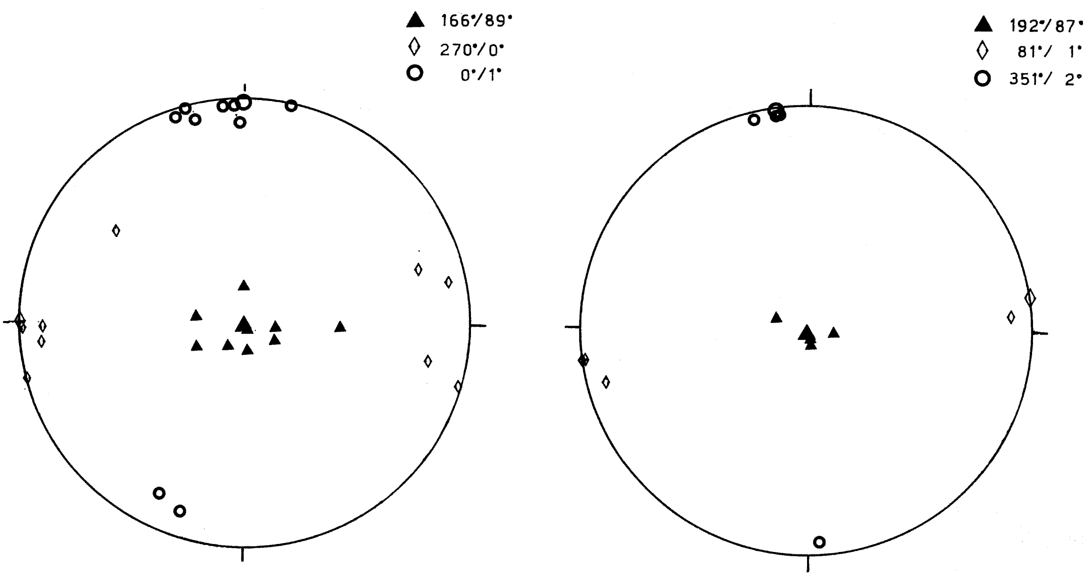


Fig. 12. Stereonets representing results of mesostructural analyses of all sites along the NAFS (left) and P-B-T axes of the 1980-1985 focal mechanisms (right). Triangles = σ_1, rhombs = σ_2 and squares = σ_3. Larger symbols represent the calculated average values.

are given. Thirdly, the same data sets have been elaborated with the inversion technique of the Mean Stress Tensor (Carey and Brunier, 1974; Carey, 1976). The results are shown on the right stereonets (fig. 11) and the relative values at the top right. The angular deviations between the measured and the theoretical striae on the faults are represented in the right histograms. The ratio $R = (\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3)$ representative of the shape of the stress ellipsoid is also shown. The data of this structural analysis have been presented in detail by Caputo (1990) while here the results are simply reconsidered and discussed.

7. Middle Pleistocene-Present regional and local stress fields

In all the studied sites, the results of the structural analysis show a clear N-S direction of extension (fig. 2). However, in some sites also a second direction of extension roughly trending WNW-ESE can be observed. In all these latter sites, the two sets of faults were necessarily separated, and the analysis was made independently following the procedures described in a former section of the paper.

7.1. *Regional N-S extension*

From the different methodologies which have been applied, the extensional stress component (σ_3) of all sites is always subhorizontal with an exactly N-S trending average direction (fig. 12). If we consider the confidence of the diverse methods used for the structural analysis, it is the same average direction of the T-axes as obtained from the focal mechanisms of the 1980 and 1985 earthquakes and roughly the same direction of lengthening along the main E-W ground ruptures, observed immediately after the 1980 earthquake (Papazachos *et al.*, 1983). Also some data sets of extensional joints collected in the bedrock of the footwall block and statistically analysed with a specific computer programme (Caputo and Caputo,

1989) give a similar N-S direction of extension. This is also the mean regional state of stress for the whole eastern part of continental Greece and the Aegean Sea since the Middle Pleistocene (*e.g.*, Mercier *et al.*, 1987; Caputo and Pavlides, 1993).

7.2. *Local WNW-ESE extension*

From a mechanical point of view, the second set of faults is not compatible with the main set (see example in fig. 11). In fact, overlapping the stereonets obtained using the Right Dihedrons method, there is no intersection area with 100% probability of containing the σ_3 axis.

There are several reasons to reject a polyphased tectonics. First of all, in site a (figs. 2 and 11), the second set is superimposed over the main set. The affected sediments being Pliocene-Early Pleistocene in age, it is not realistic to suppose three distinct tectonic «phases» in so short a time span (Middle Pleistocene to Present): a first N-S extension; followed and superimposed by a WNW-ESE extension and eventually followed by the seismically active N-S trending phase.

Secondly, it is important to note that all the faults with more than 1 m of displacement observed in the area always belong to the main set of data (*i.e.* N-S extension). Only minor faults (*i.e.*, from a few cm to some tens of cm of displacement) belong to the second set of data (WNW-ESE extension). A kinematic analysis of all the data together, weighted by their amount of displacement, would yield an almost pure N-S direction of lengthening.

The third and probably most important observation, in all the literature of the Aegean Region is that there is no evidence of a WNW-ESE trending extensional phase throughout the Quaternary.

An alternative answer to this mechanical and tectonic problem is here proposed. As mentioned above, Papazachos *et al.* (1983) describe a second set of NE-SW trending ground ruptures (fig. 2), associated to the 1980 seismic event, with normal and sinistral strike-slip components not mechanically compatible with the N-S direction of extension obtained from the focal mechanisms, while Ambraseys and Jackson (1990) report E-W trending left-lateral superficial faulting. All these secondary structures are very similar to the second set of meso-faults collected in the field.

Moreover, in the northern bound of the study area, the presence of NE-SW trending faults crossing the bedrock is noteworthy (figs. 1 and 2). These faults strike parallel to the second set of meso-structures (fig. 11) and to the secondary set of ground ruptures associated to the Volos 1980 earthquake.

As a consequence of rock unhomogeneities in the uppermost crust, variable stress fields within a seismogenic volume may develop. These minor-scale stress fields are probably due to block-related «accommodation» movements. These local stress fields may activate faults mechanically not compatible with the regional stress regime inferred from the fault plane solutions of the main shocks (*e.g.*, McKenzie, 1978; Papazachos and Comninakis, 1982) and by *in-situ* stress measurements (Paquin *et al.*, 1982).

Indeed, recent studies on seismic sequences of strong motion earthquakes (*e.g.*, Mercier and Carey-Gailhardis, 1989) and of wider areas (*e.g.*, Pedotti, 1988) have clearly shown the coexistence, within the same seismogenic volume, of focal mechanisms not compatible with a unique stress tensor. Unfortunately, no such data are available for the study area and also a recent campaign in Southern Thessaly, with more than 100 portable seismological stations, could not record many earthquakes (Denis Hatzfeld, written communication) and thus test the block-related model.

As a further working hypothesis to explain this phenomenon, we could consider the geometry of the western sector of the NAFS which resembles the horse-tail structure of a transtensional left-lateral fault (figs. 1 and 2). If this is the mechanism, and because no strike-slip movements have been observed in the field (all pitch angles of the second set of faults are more than 40°), we need to assume a sort of partitioning which splits the crustal transtension into two directions of extension (*i.e.*, N-S and WNW-ESE). However, a left-lateral component of motion in Southern Thessaly during the Quaternary seems in contrast with the geodynamic conditions of the Northern Aegean Region. Nevertheless, because in this area several tectonic «paradoxes» have already been outlined (Pavlides and Caputo, 1994), the likelihood of this hypothesis should be fully preserved until a satisfactorily new geodynamic model for the Aegean Region is proposed.

In conclusion, it is not clear, at present, which is the active mechanism generating these secondary structures, but we can reasonably suppose that it could also have occurred throughout the Middle Pleistocene-Present tectonic phase thus creating the second set of meso-faults affecting the Plio-Quaternary sediments.

8. Concluding remarks

This paper presented and compared geological, structural, geomorphological, archaeological and seismic data in order to achieve a better understanding of the NAFS during Pleistocene to Present times. The analysis of the structural data consisting of brittle meso-faults and extensional joints well constrains a Late Quaternary N-S extension which is in good agreement with the regional crustal deformation of the Northern and Central Aegean during the same period.

Moreover, a comparison between (a) the results of the microtectonic analysis, (b) the focal mechanisms of the 1980 and 1985 earthquakes and (c) the ground ruptures which occurred during the Volos earthquake, shows that the tectonic evolution of the area is also characterised by complex local anomalies which seem to repeat the perturbation of the stress field through time.

Furthermore, the rate of relative lowering of the base level of the equilibrium profile of the stream where the palaeo-aqueduct was found has been estimed. This value should thus correspond to the rate of total vertical displacement along the NAFS or, in other terms, to a cumulative slip-rate of some overlapping fault segments. According to the available archaeological data, the relative displacement of the base level was produced by an overall uplift of the footwall block inasmuch as the hanging-wall block has to be considered stable for this period of time (III-IV century A.D. to the Present). As mentioned above, if the total uplift is distributed among more than one branch fault, the vertical slip-rate of each segment is about 1 mm/yr. This estimated magnitude is comparable with that of other active faults of Thessaly (Caputo, 1993a, 1995a,b).

If the cumulative vertical slip-rate (3 mm/yr) is applied to the NAFS as a whole from the Middle Pleistocene to the Present, as the synsedimentary tectonic activity of the area suggests (*e.g.*, Mercier, 1977; Lemeille, 1977; Caputo, 1990), a total displacement of some hundreds of meters can be also estimated. Although the displacement has been partially attenuated by the filling up of the Almyros Basin, in the hanging wall block, and by widespread erosion of the upthrown footwall block, a morphological scarp of this height can be still observed in the area (see indicative altitudes in fig. 1).

Acknowledgements

My first thoughts are dedicated to the memory of Pavlos Lazarides, former director of the Archaeological Museum of Nea Anchialos, for the pleasant conversations and the useful criticisms. Unfortunately, he disappeared prematurely three years ago. Thanks also to Rolando Armijo, Spyros Pavlides and Vladimir Trifonov for discussions in the field. Reviewing by Giuliana D'Addezio and an anonymous referee has been appreciated. Financial support was from the European Union (contract #SC*0056), the CNR, the NATO and the University G. D'Annunzio of Chieti.

REFERENCES

AMBRASEYS, N.N. and J.A. JACKSON (1990): Seismicity and associated strain of Central Greece between 1890 and 1988, *Geophys. J. Int.*, **101**, 663-708.

ANGELIER, J. and P. MECHLER (1977): Sur une méthode graphique de recherche des contraintes principales également utilisable en tectonique et en seismologie, *Bull. Soc. Géol. Fr.*, **19** (6), 1309-1318.

BOUSQUET B. (1976): La Grèce occidentale. Interpretation géomorphologique de l'Epire, de l'Acarnanie et des îles ioniennes, *Thèse d'Etat*, Université Paris-IV, pp. 585.

CAPUTO, M. and R. CAPUTO (1988): Structural analysis: new analytical approach and applications, *Ann. Tectonicae*, **2** (2), 84-89.

CAPUTO, M. and R. CAPUTO (1989): Estimate of the regional stress field using joint systems, *Bull. Geol. Soc. Greece*, **23** (1), 101-118.

CAPUTO, R. (1989): *FAULT, a Programme for Structural Analysis*, diskette and manual, Florence and Ferrara, 1-55.

CAPUTO, R. (1990): *Geological and Structural Study of the Recent and Active Brittle Deformation of the Neogene-Quaternary Basins of Thessaly (Central Greece)*, Ph.D. thesis, University of Florence, *Sci. Ann. Aristotle University Thessaloniki*, **12**, 2 vol., 1-252.

CAPUTO, R. (1993a): Morphotectonics and kinematics along the Tyrnavos Fault, Northern Larissa Plain, mainland Greece, in *Neotectonics and Active Faulting*, edited by I. STEWART, C. VITA-FINZI and L.A. OWEN, *Z. Geomorphol. Suppl.*, **94**, 165-183.

CAPUTO, R. (1993b): Morphogenic earthquakes: a proposal, *Bull. INQUA*, Neotectonics Commission, **16**, 24.

CAPUTO, R. (1995a): The Rodia Fault: an active complex shear zone (Larissa Basin, Central Greece), *Bull. Geol. Soc. Greece*, **28** (1), 447-456.

CAPUTO, R. (1995b): Inference of a seismic gap from geological data: Thessaly (Central Greece) as a case study, *Annali di Geofisica*, **38** (1), 1-19.

CAPUTO, R. and S. PAVLIDES (1993): Late Cainozoic geodynamic evolution of Thessaly and surroundings (Central-Northern Greece), *Tectonophysics*, **223** (3-4), 339-362.

CAPUTO, R., J.-P. BRAVARD and B. HELLY (1994): The Pliocene-Quaternary tecto-sedimentary evolution of the Larissa Plain (Eastern Thessaly, Greece), *Geodinamica Acta*, **7** (2), 57-85.

CAREY, E. (1976): Analyse numérique d'un modèle mécanique élémentaire applique à l'étude d'une population de failles: calcul d'un tensor moyen des contraintes a partir des stries de glissement, *Thèse 3éme Cycle*, Paris-Sud (Orsay).

CAREY, E. and B. BRUNIER (1974): Analyse théorique et numérique d'un modèle mécanique élémentaire appliqué à l'étude d'une population de failles, *C. R. Acad. Sci. Paris*, **279**, 891-894.

DUFAURE, J.J., B. BOUSQUET and P.-Y. PECHOUX (1979): Contributions de la géomorphologie la connaissance du Quaternaire continental grec, en relation avec les études de néotectonique, *Rev. Géol. Dyn. Géogr. Phys.*, **21** (1), 29-40.

FRANKOPOULOS, I.A. (1956): Petrologiki meleti ton lavon tou ifaisteiou ton Thivon en Thessalia, *Ph.D. Thesis*, University of Athens (in Greek), pp. 59.

GILBERT, G.K. (1879): Report on the geology of the Henry Mountains, U.S. Geog. and Geol. Survey of the Rocky Mountains Region, Washington, 1-170.

IGME (Institute of Geological and Mining Research) (1983): *Geological Map of Greece 1:50000, Velestino sheet*, Athens.

IGME (Institute of Geological and Mining Research) (1986): *Geological Map of Greece 1:50000, Volos sheet*. Athens.

INNOCENTI, F., P., MANETTI, A. PECCERILLO and G. POLI (1979): Inner arc volcanism in NW Aegean Arc: geochemical and geochronological data, *N. Jb. Miner. Mh.*, **4**, 145-158.

LEMEILLE, F. (1977): Etudes néotectoniques en Grèce Centrale nord-orientale (Eubee Centrale, Attique, Beotie, Locride) et dans les Sporades du nord (île de Skiros), *Thèse 3éme Cycle*, Paris-sud (Orsay), 1-173.

MCKENZIE, D.P. (1978): Active tectonics of the Alpine-Himalayan belt: the Aegean Sea and surrounding regions, *Geophys. J.R. Astron. Soc.*, **55**, 217-254.

MERCIER, J. (1977): L'Arc Egéen, une bordure déformée de la plaque eurasiatique; reflexions sur un example d'étude néotectonique, *Bull. Soc. Géol. Fr.*, **19** (3), 663-672.

MERCIER, J.L. and E. CAREY-GAILHARDIS (1989): Regional state of stress and characteristic fault kinematics instabilities shown by aftershocks sequences: the aftershock sequences of the 1978 Thessaloniki (Greece) and 1980 Campania-Lucania (Italia) earthquakes as examples, *Earth Planet. Sci. Lett.*, **92**, 247-264.

MERCIER, J.L., D. SOREL and K. SIMEAKIS (1987): Changes in the state of stress in the overriding plate of a subduction zone: the Aegean Arc from the Pliocene to the Present, *Ann. Tectonicae*, **1** (1), 20-39.

MORISAWA, M. (1975): Tectonic and geomorphic models, in: *Theories of Landform Development*, edited by W.N. MELHORN and R.C. FLEMAL, 199-216.

PAPADOPOULOS, G.A. (1992): Rupture zones of strong earthquakes in the Thessalia region, Central Greece, in *Proceedings XXIII General Assembly European Seismological Commission*, Prague, September. 7-12, 1992, **2**, 337-340.

PAPAZACHOS, B.C. and P.E. COMNINAKIS (1982): *A Catalogue of Historical Earthquakes in Greece and Surrounding Area. 479 B.C. - 1900 A.D.*, Publication Geophysical Laboratory of the University of Thessaloniki, **5**, 1-24.

PAPAZACHOS, B.C., D.G. PANAGIOTOPOULOS, T.M. TSAPANOS, D.M. MOUNTRAKIS and G.C. DIMOPOULOS (1983): A study of the 1980 summer seismic sequence in the Magnesia region of Central Greece, *Geophys. J. R. Astron. Soc.*, **75**, 155-168.

PAPAZACHOS, B.C., P.M. HATZIDIMITRIOU, G.F. KARAKAISIS, C.B. PAPAZACHOS and G.N. TSOKAS (1993): Rupture zones and active crustal deformation in Southern Thessalia, Central Greece, *Boll. Geofis. Teor. Appl.*, **35** (139), 363-374.

PAQUIN, C., C. FROIDEVAUX, J. BLOYET, Y. RICARD and C. ANGELIDHIS (1982): Tectonic stresses on the mainland of Greece: *in situ* measurements by overcoring. *Tectonophysics*, **86**, 17-26.

PAVLIDES, S. and R. CAPUTO (1994): The North Aegean Region: a tectonic paradox? *Terra Nova*, **6** (1), 37-44.

PEDOTTI, G. (1988): Etude sismotectonique du Péloponnèse et réponse sismique d'une vallée sedimentaire en Grèce du nord, *Thèse 3éme Cycle*, Université de Grenoble, 1-178.

PEGORARO, O. (1972): Application de la microtectonique à une étude de neotectonique: le Golfe Maliaque

(Grèce centrale), *Thèse 3éme Cycle*, Université de Languedoc (unpublished).

PERISSORATIS. C., I. ANGELOPOULOS, D. MITROPOULOS and S. MICHAILIDIS (1991): *Surficial Sediment Map of the Aegean Sea Floor: Pagasitikos Sheet, Scale 1:200000*, Ed. IGME, Athens.

PSILOVIKOS, A., G. KOUFOS and G. SYRIDES (1987): The problem of Red-Beds in Northern Greece. *Ann. Inst. Geol. Publ. Hung.*, **70**, 509-516.

YOSHIKAWA, T. (1974): Denudation and tectonic movement in contemporary Japan, *Bull. Dept. Geog.*, Univ. Tokyo, **6**, 1-14.