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# A QUANTITATIVE MORPHOTECTONIC APPROACH TO THE STUDY OF ACTIVE FAULTS; MYGDONIA BASIN, NORTHERN GREECE

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## ABSTRACT

Scarps of seismically active faults in the Mygdonia basin (Thessaloniki-Northern Greece seismogenic area) are divided into three groups based on the relationship between the measured scarp height and the scarp angle: a) steep bedrock scarps along active faults, b) less steep scarps affecting Neogene sediments and c) steep ones in the Neogene-Quaternary deposits. Their slope angle is proportional to the logarithm of the scarp height, while the slope angle decreases with the age. Geomorphic features, scarp height, active fault lengths and fault displacement related to earthquake magnitudes show the close relationship between quantitative geomorphology and active tectonics in the area.

**KEY WORDS**: Fault scarps; Diffusion equation; Morphotectonics; Active tectonics; Degradation processes; Mygdonia basin; northern Greece.

## ΣΥΝΟΨΗ

Τα τεκτονικά πρανή των σεισικά ενεργών ρηγμάτων στη Μυγδονία λεκάνη (σεισμογενετική περιοχή Θεσσαλονίκης, Β. Ελλάδα) έχουν διακριθεί ποσοτικά σε τρεις ομάδες με βάση τη σχέση ύψους και γωνίας κλίσης των πρανών. Οι τρεις κατηγορίες ρηγμάτων είναι: α) απότομα πρανή κατά μήκος ενεργών ρηγμάτων που επηρεάζουν τα πετρώματα του υποβάθρου ($\theta = 17.7 - 2.22\log H$), β) μικρότερης γωνίας κλίσης πρανή στα Νεογενή ιζήματα και γ) απότομα πρανή στις Νεογενείς - Τεταρτογενείς αποθέσεις ($\theta = 11.7 + 4.54\log H$). Η γωνία κλίσης τους είναι ανάλογη με το λογάριθμο του ύψους του πρανούς, ενώ η γωνία της κλίσης μειώνεται συστηματικά με την ηλικία. Τα γεωμορφολογικά χαρακτηριστικά, όπως το ύψος των τεκτονικών πρανών, το μήκος των ενεργών ρηγμάτων και τα άλματα των ρηγμάτων σχετίζονται με τα μεγέθη των σεισμών και δείχνεται η άμεση σχέση ποσοτικής γεωμορφολογίας και ενεργού τεκτονικής για την περιοχή.

**ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ:** ρηξιγενή πρανή, εξίσωση διάχυσης, Μορφοτεκτονική, ενεργός τεκτονική, διαδικασίες διάβρωσης, λεκάνη Μυγδονίας, βόρεια Ελλάδα.

## 1. INTRODUCTION

### a) Fault Scarp morphology

There is a great uncertainty in the estimation of earthquake risk using recorded events or historical data, even for areas where historical information is available for a great period of time. Various geological approaches have been made towards the understanding of the past behavior, mainly during the late Quaternary, of an earthquake-producing fault.The most reliable methods for this purpose are the

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paleoseismological ones, where the prehistoric reactivations of the faults can be detected by means of stratigraphy, dating of the deposed material, etc. They help significantly in extending the earthquake record back in time and, consequently, in increasing the precision of risk assessment.

Another type of dating the age of formation of a fault and hence the paleoseismicity, is the so called morphologic dating of the fault scarps (*Nash 1980*). This can be done by using quantitative morphologic techniques which are based mainly to the diffusion model that has been proposed by *Culling (1960)*. Culling applied the diffusion equation generally to slopes, but later researchers used this model for studying fault scarps. The main point of *Wallace's (1977)* model was that for "similar" scarps, some geometric differences could mean a measure of relative ages. *Bucknam and Anderson (1979)* showed that there is a logarithmic relation between scarp height and maximum scarp slope. Based on that, they developed a method for comparing scarps of different ages. *Nash (1980, 1981, 1984)* applied a similar procedure for determining absolute ages of scarps by using a finite element solution to the diffusion equation. *Andrews and Hanks (1985*) developed a method of inverting an observed profile to find the "diffusion age" which is defined as the product of diffusivity times chronological age. A non-linear slope dependence that fits much of the data of previous studies has been proposed by *Andrews and Bucknam (1987)*. However, there are several uncertainties in such models as is discussed by *Mayer (1984) Pierce and Coleman (1986)* and *Nash (1987)*. Those uncertainties are mainly referred to the change of the degradation coefficient with the variation of lithology, cohesion, aspect, or even height of the scarp, and of course to the total dependence of the coefficient from the microclimate of the area *(Pierce and Colman, 1986)*.

The purpose of this paper is to apply the scarp height - slope angle technique on the faults of an active area of continental Greece, which, together with other neotectonic and paleoseismological techniques, makes this area a pilot one for paleoseismological research *(Pavlides & Soulakellis, 1991; Pavlides, 1993)*.

**b) Study Area**

Mygdonia basin (fig.1) is located NE of Thessaloniki. Geologically it belongs to the Serbomacedonian geological zone, an old massif, which consists mainly of metamorphosed crystalline rocks (gneisses, amphibolites, mica schists and marbles) and post-orogenic magmatic intrusions of Mesozoic to Oligocene age.

The neotectonic evolution of the basin started during the Early-Middle Miocene, when the Pre-Mygdonian subsidence was formed *(Psilovikos, 1977; Koufos et al., 1993)*. This "graben" was due to an extensional stress field oriented mainly NE-SW *(Mercier, 1977; Mountrakis et al., 1992, Dinter and Royden 1993)*. From that period up to Lower Pleistocene (Villafranchian), the lake that filled the graben (Pre-Mygdonian lake) along with the rapid erosion of the surrounding mountains caused a high sedimentation rate. Those sediments (sands, conglomerates, silts, clays, marls and red beds) formed the Pre-Mygdonian sequence which is the first sedimentary system of the basin. Recent fault scarps that affect pre-Mygdonian (late Miocene - Villafranchian) deposits are believed to be of middle to late Pleistocene and especially Holocene age, directly associated with the active tectonic pattern and the instrumentaly, historicaly and paleoseismologicaly recorderd earthquakes of the area. During the middle Pleistocene a new extensional tectonic phase started that formed the main Mygdonian basin. Sediments that characterise this stage belong to the Mygdonian sequence which consists of gravels, coarse sands, clays, pebbles and travertines.

The active faults that bound the basin have mainly strike of either NW - SE, E - W and ENE - WSW direction. There are indications that the NW - SE faults have a sinistral component of movement, while the ENE - WSW faults a dextral one (oblique-slip faults). The E - W trending faults are mainly dip-slip ones. These observations and especially the cross-fault structure *(Pavlides, 1993)* suggest that the tectonics of the area are probably more complicated than previously thought, especially if one takes into consideration the proximity of the area to the North Aegean Trough which is considered to be the continuation of the dextral North Anatolian fault into the North Aegean Sea *(Carver and Bolinger, 1981; Pavlides et al., 1990)*. The complexity of the area has been also shown from geodetic studies that have been made in the graben *(Vlachos, 1980; Dermanis et al., 1982; Stiros, 1986)*.

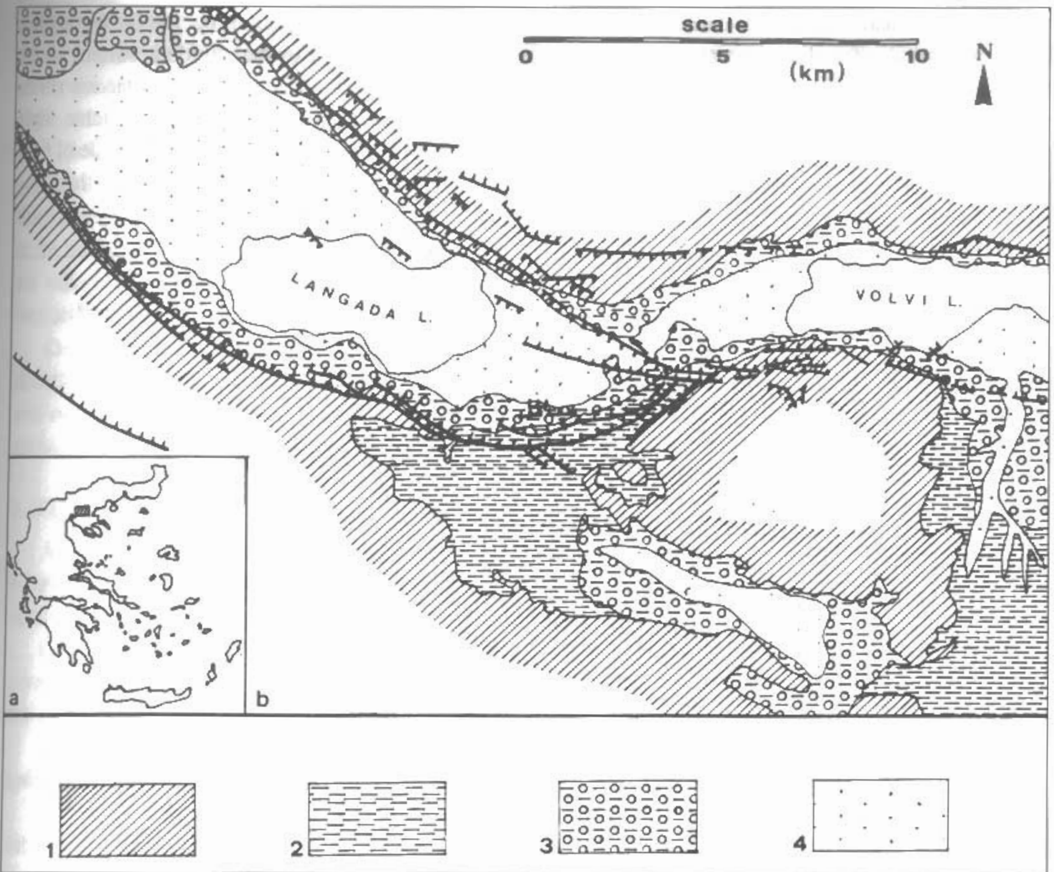


**Fig. 1: a.** Location map of the basin. **b.** Simplified geological map of Mygdonia basin. Heavy lines represent the active faults of the area, with teeth indicating the downthrow block. **1.** Pre-Neogene basement. **2.** Pre-Mygdonian sequence. **3.** Mygdonian sequence. **4.** Holocene sediments.

There has been an effort for distinguishing independent segments along some "linear" faults of the basin according to known criteria *(Wheeler, 1987)*. But in the Aegean region, the moderate to large magnitude earthquakes (M > 6.0) commonly involve the failure of a number of multiple fault structures. This has as result that various segments belonging to the same fault zone (antithetical, cross-faults etc.) are in motion simultaneously during an earthquake event. As fault zones we mean belts of multiple - multi mode intersecting faults that give rise to an often diverse pattern of fault movement. So, one can conclude that the general picture of the tectonic pattern in such seismogenic areas, and especially the Mygdonia-Thessaloniki one, is of multi-fractured type *(Pavlides, 1993, Pavlides et al. 1997)*.

Mygdonia basin belongs to the well-known Serbomacedonian seismic zone. There have been two periods of strong earthquake activity in this zone during the present century, including some shocks that had their epicenters in the region of Mygdonia *(Papazachos et al., 1979; Carver and Bolinger, 1981)*. The greatest instrumental recorded shocks of the basin were the M = 6.6 Assiros earthquake of 1902 and the 1978 M = 6.5 Stivos earthquake. There have been also many shocks with magnitude greater than 5. This earthquake was studied very well from a seismological as well as from a geological point of view *(i.e. Papazachos et al., 1979; Mercier et al. 1979, 1983; Mercier & Carey-Gailhardis 1989; Voidomatis et al. 1990; Mountrakis et al. 1990; Pavlides & Soulakellis 1990; Fang et al 1994; Pavlides et al 1997)*.

From the six known historical earthquakes of the area (620 to 1759 AC) the observed seismic intensity (MM) was VII to IX corresponding to magnitudes of M = 6.5 - 6.6, while the same results arise from the instrumental seismicity as has been discussed before *(Papazachos & Papazachos, 1989)*. We applied different formulas for the estimation of the maximum expected earthquake magnitude according to the fault rupture length, which, for the 1978 shock, was 32 km. For these data, the formula of *Matsuda* (1975) gives a magnitude of 7.34, the one of *Kiratzi et al.* (1985) a magnitude of 6.65, which is acceptable, while that of *Papazachos* (1989) gives the best correlation for the specific earthquake with a magnitude of 6.58. Generally, it seems that the maximum earthquake magnitudes of the basin should be no more than 6.6 - 6.7.

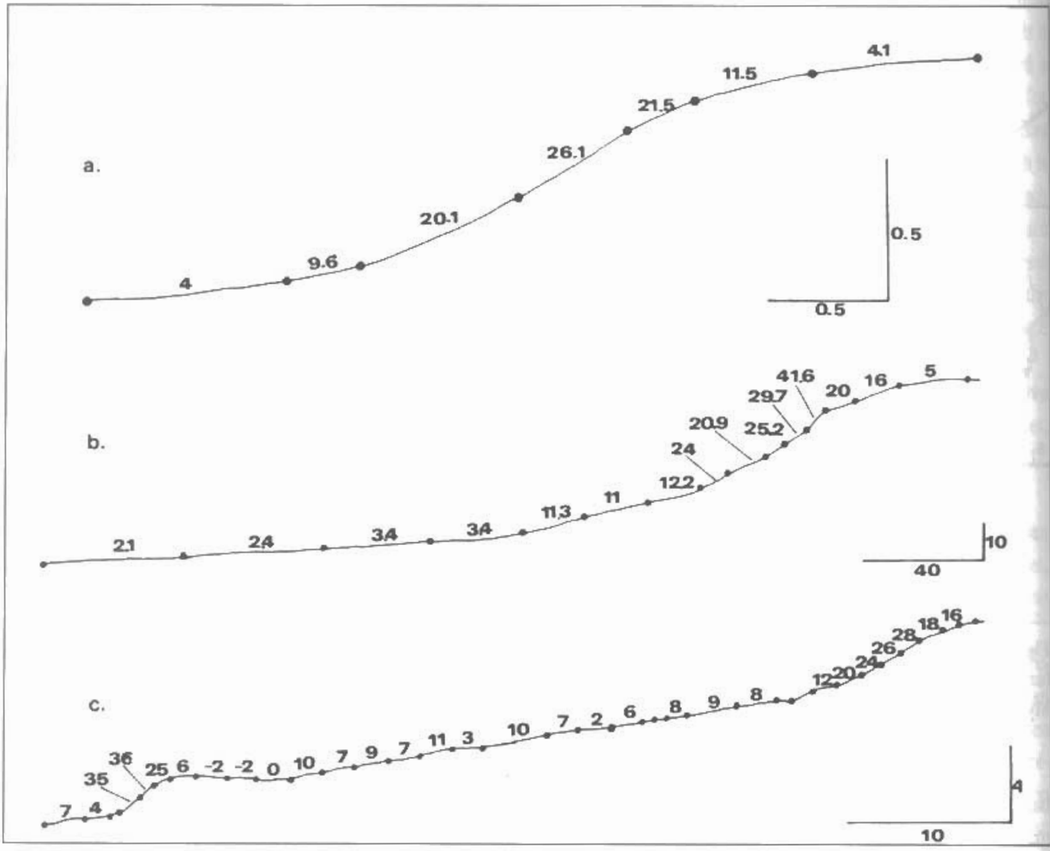


**Fig. 2:** Examples from fault scarp profiles of the area. The slope angles for each measured segment are shown. **a.** Simple fault scarp. **b.** Composite fault scarp. **c.** Multiple fault scarp.

## 2. FIELD OBSERVATIONS

The study of the fault scarps was done by using detailed morphological cross-sections constructed by near-field topographic methods (theodolite measurements) as well as 1:5.000 scale topographic maps (Greek Military Geographical Service). The method applied each time depended mainly on the scarp height. So the higher scarps were measured directly from the maps, while the smaller ones from near-field data.

The main faults of the basin along much of their length define the contact between different materials. This has in result that the scarps have different behavior concerning the relationship between their height and the corresponding slope angle.

A classification of the scarps was made, with the main criterion being the type of the scarp according to its formation procedure (fig. 2). The scarps were divided into three groups:

a) Simple fault scarps: they were formed during one seismic event. Their slope angle is more or less the same all over their surface (fig. 2a).

b) Composite fault scarps: scarps that were created during more than one earthquake. The main characteristic of the scarps of this type is that the more recent displacement is expressed as a greater slope angle at the scarp profile (fig. 2b).

c) Multiple fault scarps: scarps of this type consist of a sequence of smaller scarps that are roughly parallel to each other (fig. 2c). This is a common phenomenon to active areas such as Mygdonia basin. The frontal scarps, that is the scarps that lie closer to the basin, are steeper than the ones behind them. This could be explained in two ways: either they belong to different fault strands of different activity, or they are superficial expressions of the same fault and the difference in the slope angle reflects a progressive formation of them in time. The second explanation seems to be the most logical one.

*One problem in this case is that the Mygdonia basin is a heavily cultivated area, and many scarps were disturbed by farmer activity or other anthropogenic causes. Those scarps were excluded from the study, and only the unaltered fault scarps were taken into account. In total, 111 fault scarp profiles were measured, from which the 79 were further analysed in this paper.*

## 3. DATA ANALYSIS

As has been mentioned above, the scarp degradation procedure can be modeled using the diffusion equation of *Culling (1960)*.The main assumptions of the dating models based on the diffusion equation applied to fault scarps are:

i. The slopes have to be transport-limited. That means that the transported mass of material should be conserved in the cross-strike direction. The processes that control the evolution of such a scarp are mainly the creep of the soil and slope wash.

ii. The diffusivity is considered to be constant during the period since the last fault reactivation and independent from the geometrical characteristics of the scarp. This of course is not always true.

iii. The elevation of a point at the surface of a scarp depends only on time. That means that the scarp is subjected only to the usual degradation processes without any external interference (natural or man-controlled).

iv. The density of the superficial material remains constant during the degradation procedure. If this was not true, many complications would have been created, and a lot of uncertainties would have been inserted..

The rate of downslope transport $S$ is expressed as:

$$S=Kx^{m}\frac{\partial^{n}y}{\partial x^{n}} \tag{1}$$

where $K$ is a constant (transport coefficient), $x$ is the horizontal distance and $y$ is the elevation. For the transport-limited processes and the assumptions that have been described above, it is generally considered that $m = 0$ and $n = 1$. There are of course scarps controlled by other types of processes, where $m$ and $n$ are different from the ones proposed above, but in the present analysis we will only consider scarps of the first kind.

The continuity equation that expresses conservation of the mass during degradation (assumption **i**) is the following:

$$\frac{\partial y}{\partial t}=\frac{1}{\varrho}\frac{\partial S}{\partial x} \tag{2}$$

where $\varrho$ is the density of the superficial material. This equation states that the change in elevation of a point at a scarp profile equals the difference between the amount of material transported to this point and the material removed away from it. If we assume that density is constant (assumption **iv**)and if we follow assumption **ii,** then the combination of (1) and (2) gives:

$$\frac{\partial y}{\partial t}=k\frac{\partial^2 y}{\partial x^2} \tag{3}$$

where $k$ is the diffusivity. Diffusivity in this case is expressed in units of dimensions (length)$^2$/ (time). The diffusion equation has been widely used to describe many processes in chemistry and physics. In the study of scarp evolution it implies that with time the scarp becomes rounded and the slope angle is decreasing.

The main problem in this method is, as has been mentioned, the estimation of the diffusivity of the scarp. It only can be estimated from a scarp of known age. By using an analytical solution for (5) *(Colman and Watson, 1983, Pierce and Coleman 1986)*, $k$ can be calculated from the equation

$$k=\left(\frac{H}{4t\tan a\, erf^{-1}\left(\frac{\tan\theta}{\tan a}\right)}\right)^2 \tag{4}$$

where $H$ = scarp height, $\alpha$ = starting angle, $t$ = time in years, $\theta$ = maximum slope angle and $erf^{-1}$ = inverse error function.

An other non numerical way for finding the value of $k$ in a specific area is by generating many synthetic scarp profiles for different values of $k$, using equation (6). *Nash (1980, 1981)* developed a similar technique by using a single $k$ value to generate synthetic scarp angles for different scarp heights.

As has been shown by *Bucknam and Anderson (1979)* there is a constant relationship between $H$ and $\theta$ which is a logarithmic one. This regression equation has the following form:

$$\theta=a\log H+b \tag{5}$$

where $a$ and $b$ are constants. For scarps that are either younger or formed in a more cohesive material, constant $a$, which expresses the slope of the plot, is greater than the corresponding $a$ for older scarps or scarps that are formed in a relatively incohesive material. Graphically this can be represented in a logH versus $\theta$ plot; the data of the first type will have steeper regression lines than those of the second.

## 4. RESULTS AND CONCLUSION

The corresponding plots of the data of the Mygdonia basin are shown in fig. 3. The grouping of the points show the three types of scarps according to the material that is deformed by the faults *(Chatzipetros & Pavlides, 1993, Chatzipetros, 1998)*:

a) Group A: scarps that were formed in the bedrock. They are steep scarps with a relatively big amount of displacement. These are considered to be the older generation of faults that formed the Pre-Mygdonian basin. Despite being older, their slope angle is greater than the scarps of the other groups. This of course is a result of the different physical properties of the cohesive bedrock material, in contrast to the incohesive basin sediments.

b) Group B: scarps that affect the Neogene deposits. Those scarps have a big displacement and consist the faults of the post-middle Pleistocene tectonism. The scarps of this group are generally the less steep of all. This happens because of the age of their formation, and the material that they deform.

c) Group C: scarps that affect Neogene-Quaternary deposits. Those scarps are small and much steeper than the ones of Group B, although the material they are located into has more or less the same properties. The explanation in this case is that they are the youngest due to the active stress field, representing Holocene, if not historical, tectonic events. Their height suggests that they were probably created during recent earthquake events, probably no more than three or four.

The equations that describe the relationship between the maximum scarp height and the scarp angle arrising from this study are:

$\vartheta=-2.22\log H+17.7$ for the scarps in the bedrock (group A), (6)

and $\vartheta=4.54\log H+11.7$ for the scarps in the basin sediments (groups B and C). (7)

As it can be clearly seen from the regression equations, the scarps of group A have generally a much greater slope angle than the scarps of the other groups, as has already been described above. Apart from the rock properties that have as a result this phenomenon, there is also the problem of age control. The scarps of group A represent the faults of the first generation. That means that the origin of these faults is quite old, but there is evidence, mainly from the 1978 earthquake faulting, that they are still active. Because of that, one would expect that the profiles of those scarps would be similar to those of a composite scarp. Instead, they look much more like a simple fault scarp. This assumption of course is wrong, because there is no way that scarps tens of meters high could have been formed during a few earthquake events only. So for the scarps of this type the degradation procedures are slow, and therefore the recent reactivations do not reflect a significant visible change in the scarp profiles.

In contrary, the morphology of the scarps of groups B and C that are formed in similar loose materials, depends greatly on the age of their latest reactivation. This is shown clearly on their profiles, where many morphologic phenomena that can be interpreted as earthquake-induced can be found. Such are abrupt changes in the slope angle of composite scarps, different slope angles of the strands of multiple scarps, etc. The scarps of group B show in places a much steeper angle at about the middle of their height. This angle is similar to the observable angle of scarps of group C with the same height, thus indicating a chronological identification of the corresponding activity of these different faults. So apart from the well-documented two major tectonic phases, a subsequent extension that could be connected with the present stress field created small-scale faults and minor reactivations of the older ones. Unfortunately this later event cannot be dated exactly by using only morphological dating techniques, due to the lack of adequate information concerning past earthquakes. The only available data concern the 1978 shock sequence. A maximum throw of 35 cm of the northern part in respect to the southern was observed, but the usual value was about 10 cm. If we assume that displacements of this order are the typical ones, then the latest reactivations of the faults, in order to create fault scarps as high as those of group C, had to produce a number of great earthquakes of magnitude of greater than 6.

The effect of the active faulting on the ground surface can be also seen in the longitudinal profiles of selected streams in fig. 4. The erosion rate in the area is great, because of the active faulting, and it has as a result the formation of very steep and deep valleys. Nevertheless, the streams are influenced by the fault activity, which is reflected as a change in their slope angle. This change is very apparent to the faults of group A, mainly due to the change of lithology, but knick points can also be seen in other mapped faults. Since streams are a very changeable form of geomorphic structures, that means that the erosion rate is not as great as the faulting rate of some faults. This also means that there is a great amount of aseismic creep in the basin, since there were no major shocks with surface expression during the past 15 years.

As has been discussed, the active erosion, and consequently the fault activity, is great. The recurrence interval for earthquakes of $M > 6.5$ has been determined from seismological data at 35-40 years for the whole Serbomacedonian seismic zone.

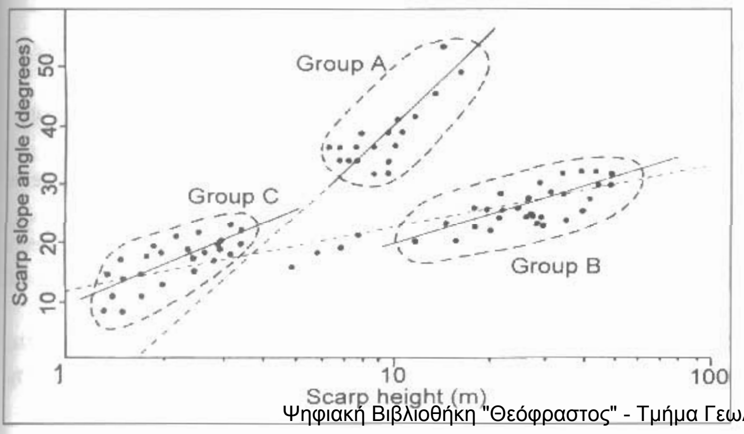


**Fig. 3:** Fault scarp height-angle relationship for the scarps of Mygdonia basin. Group classification is explained in the text.

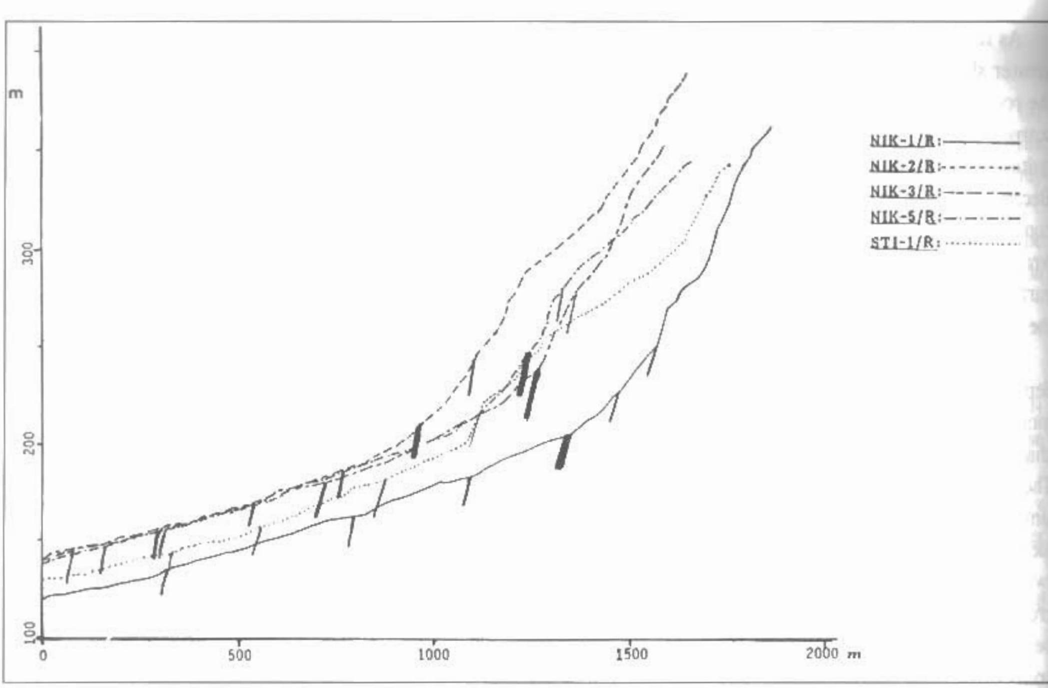


**Fig. 4:** Longitudinal stream profiles of selected streams of Mygdonia basin. The effect of active faulting is shown at the knick points of the stream lines.

In the Mygdonia basin itself, only two great shocks (1902, M = 6.6 and 1978, M = 6.5) took place during the present century, with a time interval of 76 years. In addition, surface faulting has been observed only during those earthquakes. With this assumption, and taking into consideration the fault scarp height, one could suggest, with a great degree of uncertainty, that the latest phase with great earthquakes (M > 6.5) started at c. 2500 yrs BP or even later, if creeping has played an important role in scarp formation. Because not every fault is reactivated during one earthquake though, this age should be earlier than that. It is not possible to be exact on the timing of the forming of the scarps with the presently available geological data. Paleoseismological investigation (Pavlides 1996; Chatzipetros 1998)along certain parts of active faults in Mygdonia basin has shown significant differences in slip rate and recurrence intervals.

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