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# TECTONIC STRUCTURE OF CENTRAL-WESTERN ATTICA (GREECE) BASED ON GEOPHYSICAL INVESTIGATIONS-PRELIMINARY RESULTS

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## Abstract

*In an effort to investigate the deep geological structure in the broader area of central-western Attica, that suffered severe damage during the destructive Athens earthquake of September 7th, 1999, the Department of Geophysics-Geothermics of the Faculty of Geology and Geoenvironment of Athens University, in collaboration with the Geodynamic Institute of National Observatory of Athens and the Department of Geological Sciences of Durham University, carried out a combined geophysical survey. For the first time in Attica, seismic and gravity geophysical methods were applied along profiles, in such an extensive scale. Within the framework of this investigation the following tasks were accomplished: a) Three (3) seismic lines of about 30 kilometres of total length, two (2) in the area of Thriassion plain and one (1) along the Parnitha-Krioneri-Drosia-Ekali-Dionysos axis (Attica plain) and b) 338 gravity measurements distributed along eight (8) gravity profiles, four (4) of which in Thriassion plain, three (3) in Petroupoli-Aharnes-Thrakomakedones region (Attica plain) and one (1) along Parnitha-Krioneri-Drosia-Ekali-Dionysos axis (Attica plain). Preliminary results of the geophysical investigation combined with existing geological and tectonic data are presented in this paper. Significant variation in the elevation of the alpine basement has been detected, expressed by manifestation of low and high subsurface areas which are well correlated with existing fault zones. In the area of Thriassion plain the thickness of post-alpine sediments is estimated of a few hundred meters (<500 meters) and huge thickness of several hundred meters (~800 meters) of post-alpine sediments were detected in Thrakemakedones and Krioneri areas. The relief of alpine basement is more intense in fault zones areas, such as Thriassion plain (WNW-ESE), Pathitha and Kifissos (NE-SW) as well as along the fault zone outline the Fili and Aharnes graben and is covered by post-alpine formations.*

***Key words:*** *Fault Zone, Seismic Refraction Tomography, Gravity Survey, Thriassion plain, Attica plain.*

## Περίληψη

*Ο Τομέας Γεωφυσικής-Γεωθερμίας του Τμήματος Γεωλογίας και Γεωπεριβάλλοντος του Πανεπιστημίου Αθηνών, με την συνεργασία του Γεωδυναμικού Ινστιτούτου του Αστεροσκοπείου Αθηνών και του Τμήματος Γεωλογικών Επιστημών του Πανεπιστημίου Durham της Αγγλίας, διεξήγαγε μια συνδυασμένη γεωφυσική έρευνα στην ευρύτερη περιοχή της κεντρο-δυτικής Αττικής, σε μια προσπάθεια διερεύνησης της βαθιάς γεωλογικής δομής και της κατανόησης των αιτίων που προκάλεσαν τις σοβαρές ζημιές στην Αττική κατά τον καταστροφικό σεισμό της 9ης Σεπτεμβρίου 1999. Για πρώτη φορά διεξήχθη στην Αττική μια τόσο εκτεταμένη γεωφυσική έρευνα που περιελάμβανε λεπτομερείς βαρυτικές μετρήσεις αφενός και μεγάλου μήκους σεισμικές τομές αφετέρου. Συγκεκριμένα, εκτελέσθηκαν: α) τρεις (3) σεισμικές τομές συνολικού μήκους 30 χιλιομέτρων, δύο (2) στην περιοχή του Θριάσιου Πεδίου και μια (1) κατά μήκος του άξονα Πάρνηθα-Κρυονέρι-Δροσιά-Εκάλη-Διόνυσος (Λεκανοπέδιο Αθηνών) και β) 338 βαρυτικές μετρήσεις κατανεμημένες κατά μήκος οκτώ (8) γραμμών, τέσσερις (4) στο Θριάσιο Πεδίο, τρεις (3) στην περιοχή Πετρούπολη-Αχαρνές-Θρακομακεδόνες (Λεκανοπέδιο Αθηνών) και μια (1) κατά μήκος του άξονα Πάρνηθα-Κρυονέρι-Δροσιά-Εκάλη-Διόνυσος (Λεκανοπέδιο Αθηνών).*

*Στην εργασία αυτή παρουσιάζονται τα προκαταρκτικά αποτελέσματα της γεωφυσικής έρευνας, συνδυασμένα με τα υπάρχοντα γεωλογικά, γεωτρητικά και τεκτονικά δεδομένα. Το αλπικό υπόβαθρο συναντάται σε διαφορετικά υψόμετρα, σκιαγραφώντας βυθίσματα και εξάρσεις του αλπικού υποβάθρου, που συνδέονται με υπάρχουσες ρηξιγενείς ζώνες. Στην περιοχή του Θριάσιου Πεδίου το πάχος των μεταλπικών σχηματισμών εκτιμάται σε λίγες εκατοντάδες μέτρα (<500 μέτρα), ενώ στην περιοχή των Θρακομακεδόνων και του Κρυονερίου σε αρκετές εκατοντάδες μέτρα (~800 μέτρα). Το ανάγλυφο του υποβάθρου είναι περισσότερο έντονο σε περιοχές οι οποίες καλύπτονται από μεταλπικές αποθέσεις και απαντούν ρηξιγενείς ζώνες όπως, του Θριάσιου Πεδίου (ΔΒΔ-ΑΝΑ), της Πάρνηθας και του Κηφισού (ΒΑ-ΝΔ), καθώς και των ρηξιγενών ζωνών που οριοθετούν τα βυθίσματα της Φυλής και των Αχαρνών.*


***Λέξεις κλειδιά:*** *Ρηξιγενής Ζώνη, Τομογραφία Σεισμικής Διάθλασης, Βαρυτική Έρευνα, Θριάσιο Πεδίο, Λεκανοπέδιο Αθηνών.*


# 1. Introduction

Attica was regarded as an area of low seismic risk due to absence of major earthquakes during the instrumental recording period since 1900. This belief changed following the earthquake of 7$^{th}$ September 1999 (Ms=5.9), which occurred in the northwestern suburbs of Athens (Papadimitriou *et al.* 2000, Mariolakos and Fountoulis, 2000, 2002). The earthquake resulted in the loss of 143 lives, 2000 people were injured and 20.000 became homeless.

After Athens 5.9R earthquake occurrence, many controversial debates among geoscientists were raised regarding the source parameters of the event (focal depth, identification of seismogenic fault, etc), the factors controlling the spatial distribution of max intensities or damage in the broader area NW of Athens, as well as which fault zones should be considered active and could potentially produce damage to the city of Athens in the future.

The recent effort made to approach this multi-level problem by carrying out a combined geophysical investigation including deep seismic and gravity methods, is described in this paper. The investigation was focused in the determination of alpine basement morphology and structure,

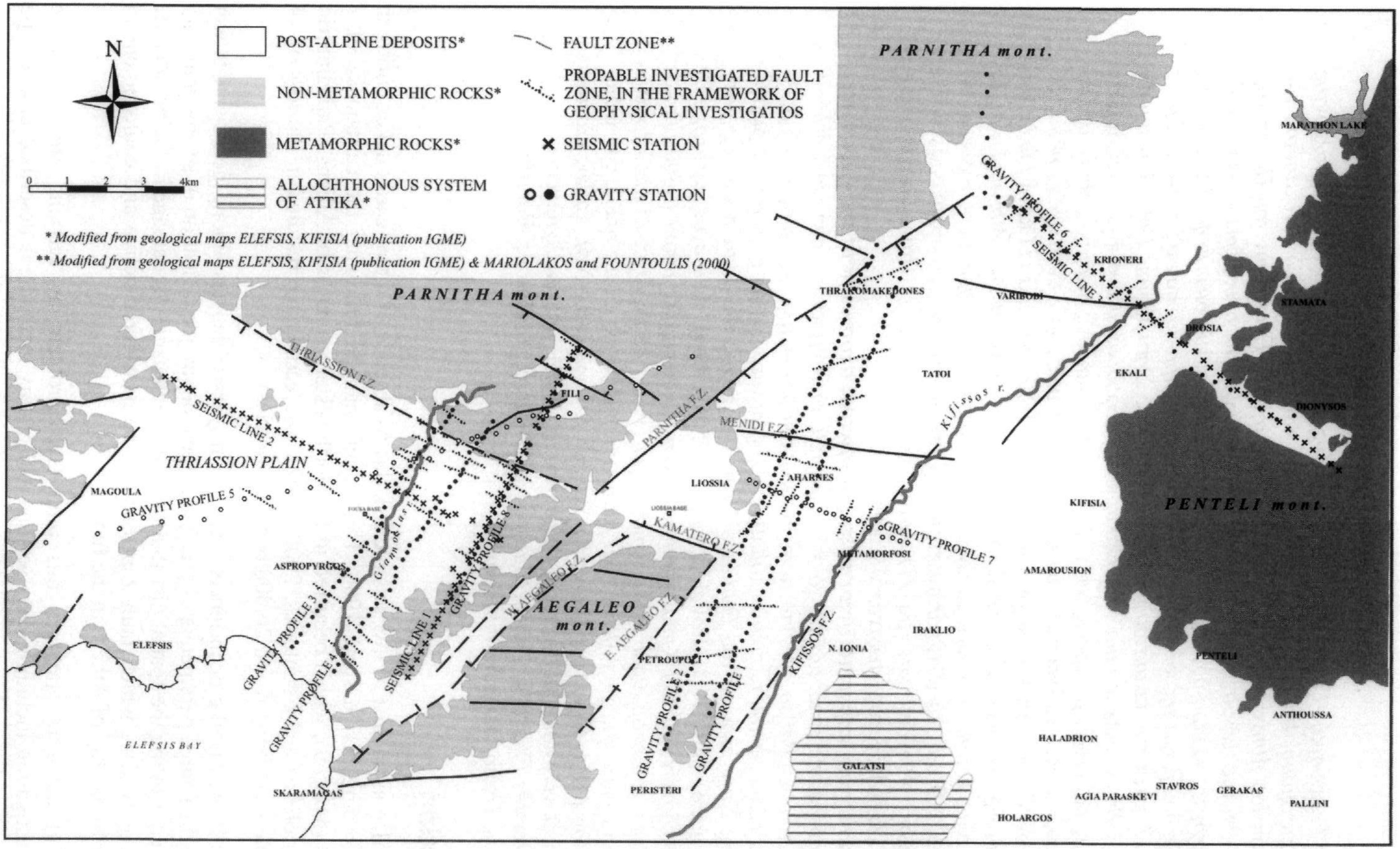


**Figure 1 - Map showing the area under investigation**

as well as the possible related fault zones in the areas of Thriassion plain and along the Petroupolis-Liossia, Aharnes-Thrakomakedones axis (Fig. 1). The investigation was extended along the Parnitha, Krioneri, Drosia and Dionysos axis, in order to determine the relationship between the non-metamorphic rocks of Parnitha and the metamorphic rocks of Pendeli Mountain.

## 2. Geological setting

The area affected by the earthquake is characterised by a complex alpine structure, consisting mainly of two basic rock types, the Mesozoic metamorphics of Attica, occurring mainly at Penteli and Imittos mountains as well as in the broader area of eastern Attica, and the Mesozoic non-metamorphics of the Eastern Greece unit, occurring mainly in the Parnitha and Aegaleo mountains (Fig. 1).

It is important to note that the affected area is located at the boundary between the above-mentioned units and towards Parnitha Mt. Their tectonic relation however, is yet to be determined in this area since detailed geological mapping has not hitherto been carried out (Mariolakos and Fountoulis 2000, 2002). The tectonic contact between the metamorphic and the non-metamorphic rocks is covered tectonically by an allochthonous system known as "Athens schists" (Kober 1929, Petrascheck and Marinos 1953, Katsikatsos 1977, Papanikolaou *et al.* 1999). Furthermore, Neogene and Quaternary deposits have filled in the neotectonic basins (Thriassion and city of Athens) and covered the alpine rocks. The tectonic contact between the metamorphic and non-metamorphic units is probably oriented along a NE-SW direction, while its location possibly coincides with the Kifissos river bed (Fig. 1). The metamorphics consist mainly of marbles, micaschists etc., while the non-metamorphics of carbonates of Triassic and Jurassic age overlying a clastic formation of shales and sandstones, including olistholiths of Permian limestones. Ophiolithic rocks locally overlie the carbonate rocks at the Parnitha Mt. area. These have been tectonically emplaced during the Late Jurassic-Early Cretaceous period. Upper Cretaceous shallow water limestones and Early Tertiary flysch cover the previous formations.

Post-alpine deposits consist mainly of lacustrine lignite bearing sediments (Neogene deposits) and continental (Quaternary) deposits. It must be emphasized that the clastic material comprising the Neogene deposits originates exclusively from the metamorphic rocks, while the clastic material of the Quaternary deposits from the non-metamorphic rocks of Parnitha Mt. (Freyberg 1951, Mariolakos and Fountoulis 2000, 2002).

From a neotectonic point of view the broader Attica area represents a complex post-alpine morphotectonic structure, formed by the following great blocks of first order: the tectonic horsts of Parnitha, Aegaleo, Imittos and Penteli mountains and the tectonic grabens of Thriassion plain and that of the W. Athens basin (Mariolakos and Fountoulis 2000, 2002) (Fig. 1). Within these major first order structures, smaller horsts and grabens can be distinguished (2nd, 3rd order etc.). The geometry of these structures is very complex and their main directions are approximately WNW-ESE and NE-SW. The major fault zones in the meisoseismal area are:

1. The Kifissos fault zone
2. The W. Aegaleo - Parnitha fault zone
3. The Thriassion - Kamatero fault zone

The first two fault zones strike NE-SW while the third strikes WNW-ESE (Fig. 1). In addition, the last two fault zones are typical scissor type fault zones. That is, the Aegaleo segment downthrows west, whereas the Parnitha segment downthrows east and the Thriassion segment downthrows south, whereas the Kamatero segment downthrows north.

No surface expression was reported for the September 7th, earthquake. Several seismic fractures were observed within the SE part of Parnitha Mt. (Mariolakos *et al.* 2000, Mariolakos and Fountoulis 2002). These occurred mainly at the transition zones between the horsts and the grabens along main orientations WNW-ESE and N-S. Body-wave modelling of the main shock and aftershock distribution indicate normal faulting on a fault plane oriented WNW-ESE, dipping to the SSW and that faulting took place over a zone of 15 km wide in a depth range 3-10 km (Papadimitriou *et al.* 2000, Voulgaris *et al.* 2000).

Earthquake damage was mainly located in the area of Liossia, Aharnes, and Thrakomakedones, whereas in the epicentral area of Aspropyrgos, Elefsis, Magoula and Mandra in the Thriassion plain the damage was limited.

## 3. Seismic Survey

Three (3) seismic lines of approximately 10000 meters each were carried out (Fig. 1). The first two were located at Thriassion plain perpendicular to each other, in order to crosscheck their results and investigate possible buried fault zones along two different orientations. The third seismic line was oriented along the Parnitha, Krioneri, Drosia and Dionysos axis (Attica plain).

Thirty (30) Reftek and eleven (11) PDAS seismographs were used equipped mostly with 2Hz vertical component seismometers. Ten (10) broadband seismometers were also used arranged in a regular array along each seismic line in order to study the dispersion of surface waves for deep structure analysis. Seismographs were initially deployed in the field using handheld GPS receivers and their final locations were determined by their internal GPS devices. The elevation of each seismograph was determined from local maps of 1:5000 scale.

Explosive charges of 75–350 kg gelignite-dynamite were detonated inside boreholes at depths of 45 meters.

The endshots and outshots fired in Thriassion plain (Seismic Line 1 & Line 2) were not strong enough to provide clear onsets of first arrivals at long distances. The energy released from the far sources was strongly absorbed mainly due to the karstic nature of limestone where the shots were located. Hence very weak signals were recorded at long distances. In addition, the significant noise level originating from the industrial area of Aspropyrgos, interfered with seismic signals to produce poor quality seismic traces at long distances and hence the results drawn were considered with care. Middle shots gave generally better results because, a) the explosives were usually located inside boreholes of cohesive clay material and b) the recorded distances were shorter (5000 m). The expected investigation depth according to a rule 'of thumb' is of the order of 1000-2000 m. It is obvious that the original design for deeper exploration depths (5000-10000 m) was abandoned because, a) larger amounts of energy are needed for deeper exploration, b) suitable locations for firing shots at long distances are limited (i.e. should be fired at sea) and c) the outcrop of alpine rocks of similar seismic velocities in Parnitha Mt. does not imply a distinct stratigraphic structure that could be identified at depths deeper than 5000 m under the Thriassion plain. Even in this case, a seismic line longer than 40-50 km of length is necessary in order to fulfil the requirements needed to explore such depths.

The Seismic Line 3, along the Parnitha, Krioneri, Drosia and Dionysos axis (Attica plain), presented generally better quality data because all shots were fired in dense and cohesive clay material allowing for less energy loss and better onsets of first arrivals (Fig. 2).

## 4. Seismic Data Processing

According to instrumental specifications the records were initially decoded, corrected for any time shift and subsequently converted and stored in SEGY format. In figure 2 the processed seismic records obtained for Seismic Line 3 are shown.

In the next step, first arrival times were picked, further processed and interpreted by using conventional and inversion methods (seismic refraction tomography). Conventional methods are highly dependent on the picked arrival times while the inversion ones used here depend on the algorithm of wave front construction in regular grid between source and receiver. In this paper, the algorithm of 'Shortest Path Ray-tracing' of Zhang and Toksoz (1998) was used for the wave front construction in regular grid. According to this algorithm the inversion is performed not only through the minimization of differences between the observed and calculated travel times, but also through the minimization of differences between, a) the average slowness and b) the apparent slowness. By applying the 'regularization' algorithm of Tikhonov and Arsenin (1977), the 'poorly determined' matrix is converted into an 'adequately determined' matrix. In figures 3 and 4 the processed and interpreted seismic cross sections, based on the seismic refraction tomography method, are shown.

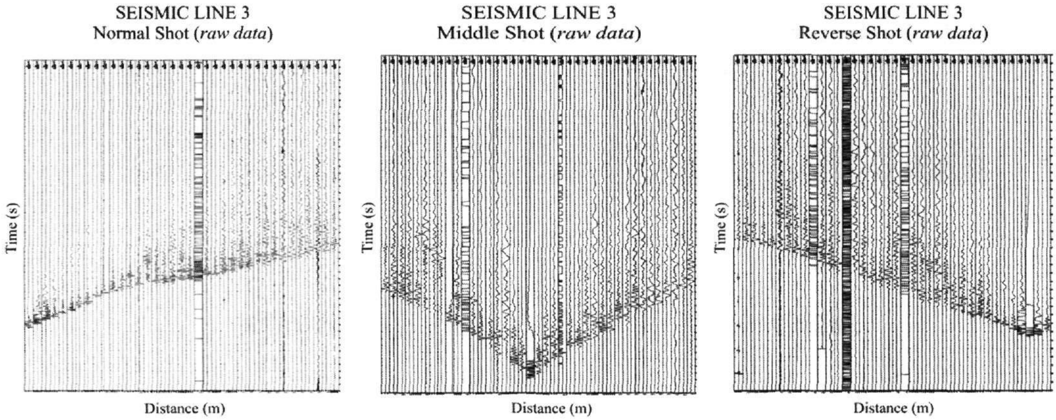


**Figure 2 - Seismic records resulted from the three shots fired along the Seismic Line 3**

Based on travel-time curves plotted from picked arrival times, the layer velocities and depths to interfaces were determined for all seismic lines. According to these results along Seismic Section 3 (Fig. 3) the basement or the deepest layer detected has a velocity of 5500-6000 m/s and lies at several hundred meters depth (~800 m) west of Kifissos river and about a few hundred meters depth (~200 m) east of Kifissos river in Dionysos area. The thick intermediate layer displays a more or less uniform velocity of 3200-4500 m/s. The upper layer could not be accurately determined because of the relatively sparse network of seismographs (average spacing of 250 m apart).

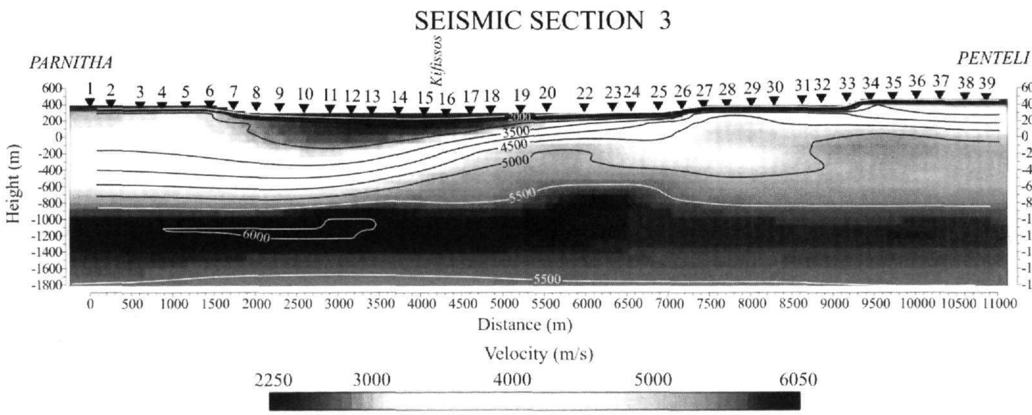


**Figure 3 - Seismic refraction tomography image for seismic section 3 (Attica plain). Contour lines show values of seismic velocities**

The Alpine basement in the Thriassion plain area (along Seismic Section 1 and 2 – Fig. 4) displays lower velocities (<5000 m/s) and lies at shallower depths (<500 meters) than along the Parnitha-Penteli axis. The overburden layer was also not well determined because of its small thickness and the sparse distribution of seismographs.

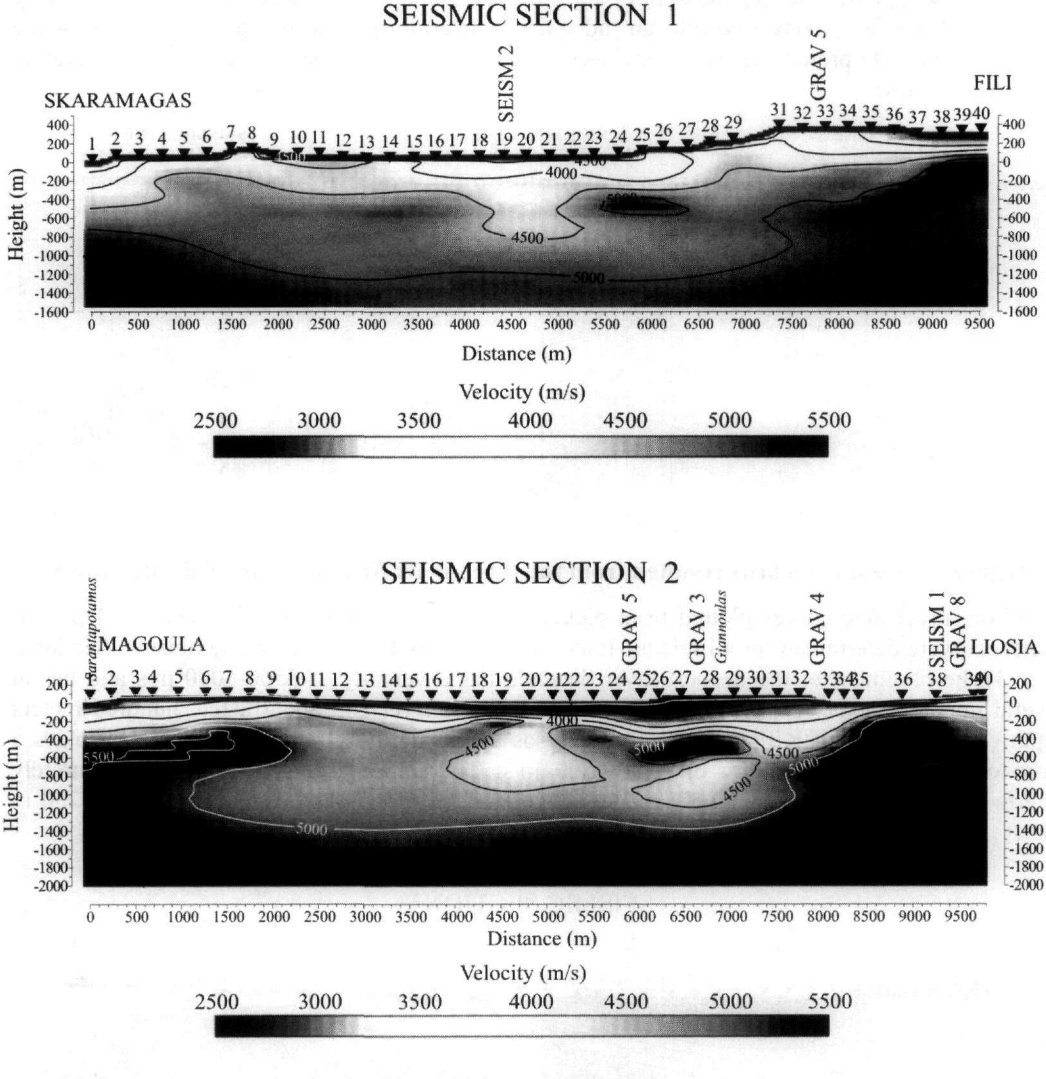


**Figure 4 - Seismic refraction tomography image for seismic sections 1 and 2 (Thriassion plain). Contour lines show values of seismic velocities**

A better insight of the structure is obtained by applying the seismic refraction tomography method, as shown in figures 3 and 4. Lower velocities at depth along seismic sections 1 and 2 may reflect variations in basement structure.

## 5. Gravity survey

Gravity measurements were conducted both in the Thriassion plain and in the area east of Parnitha Mt. that suffered heavy damage following the earthquake of September 7th, 1999. A total number of 338 gravity measurements were carried out along 8 gravity profiles (Fig. 1). A LaCoste &

Romberg gravity meter of type G was used for the gravity measurements. All gravity measurements were referenced to the University of Athens IGSN' 71 station (Hipkin *et al.* 1988). The geodetic coordinates of the gravity stations were measured using two geodetic GPS units (Wild System-200, with Wild sensor 299 antennas) measuring in differential mode. The location error was of the order of a few millimetres and the height of each gravity station was determined with an accuracy of the same order.

Four (4) profiles were located in the Thriassion plain in almost N-S orientation crossing perpendicularly the Thriassion fault zone, for investigating the tectonic structure of the alpine basement and search its relationship to the major fault zones in the area (Figs 1, 5).

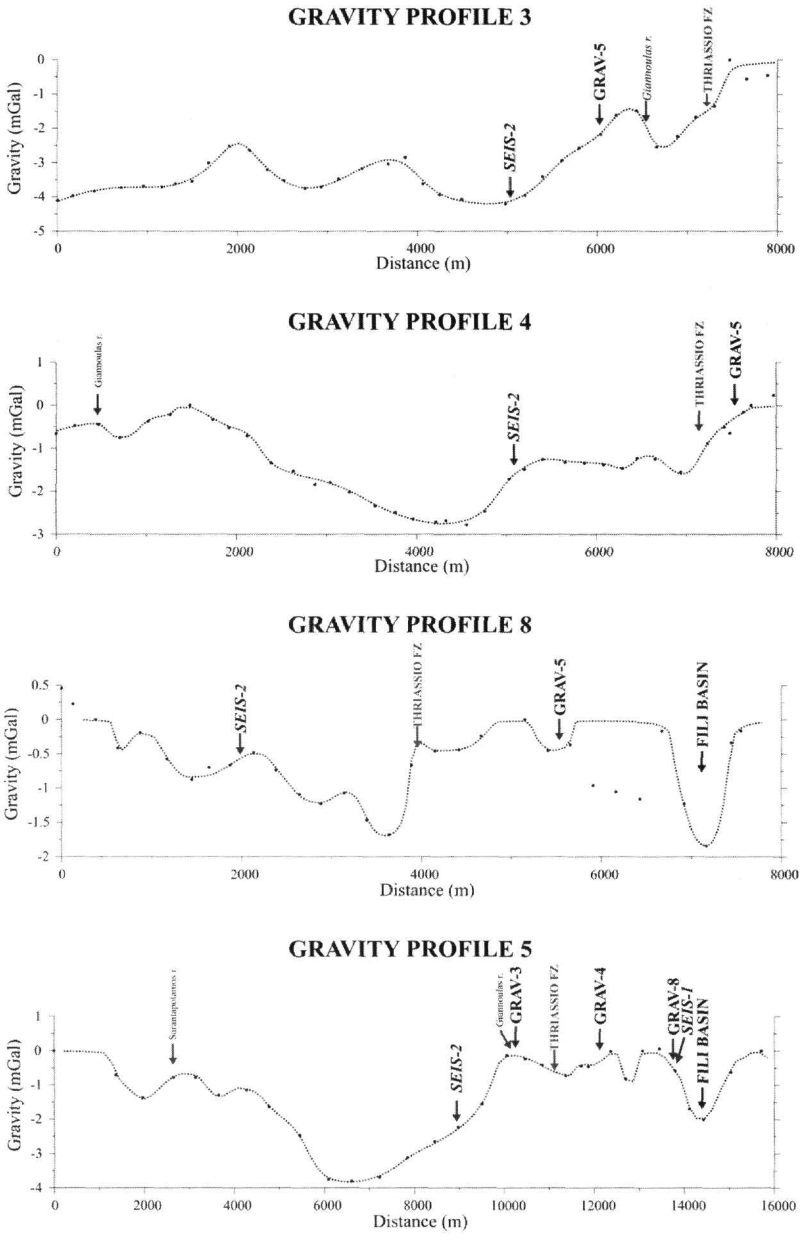


**Figure 5 - Gravity anomaly profiles in Thriassion plain**

Three (3) gravity profiles cross the areas of Petroupolis, Liossia, Aharnes and Thrakomakedones (Fig. 6) in Attica plain. From re-evaluation of existing geological and borehole data for the heavily damaged region eastwards of Parnitha Mt., a "block type" tectonism controlled by the Kamatero, Menidi and Thrakomakedones fault zones has been proposed (Mariolakos and Fountoulis 2000, 2002). Gravity measurements were arranged to study these fault zones.

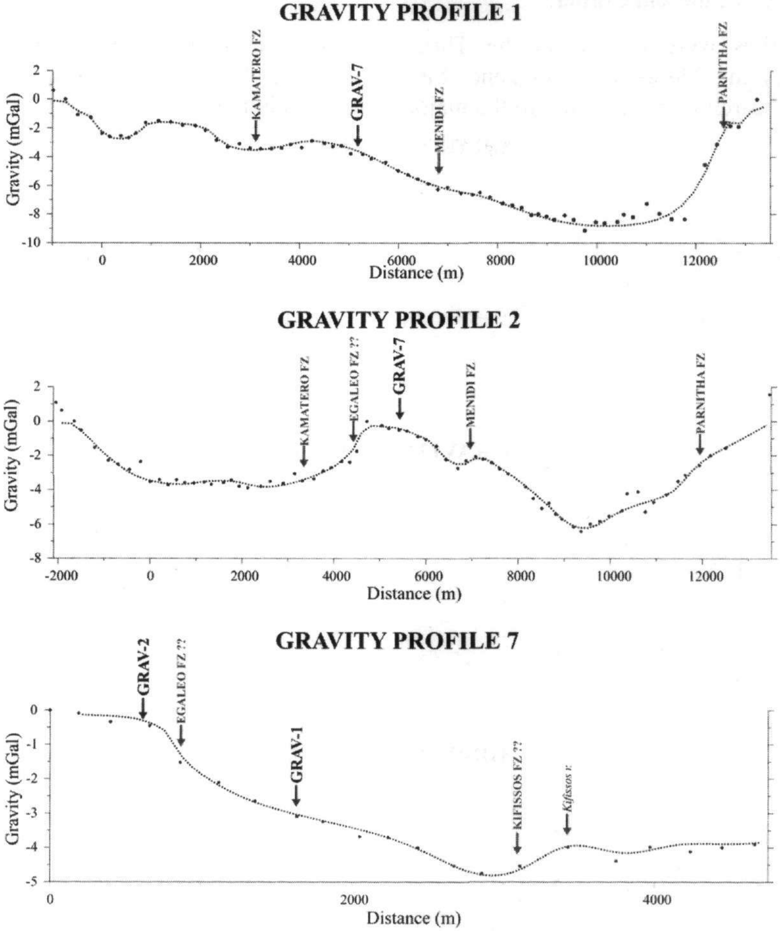


**Figure 6 - Gravity anomaly profiles in Petroupolis, Liossia, Aharnes and Thrakomakedones area (Attica plain)**

Another gravity profile was conducted along the line Parnitha, Krioneri, Drosia and Dionysos area, to assist the investigation of the contact between the non-metamorphic Parnitha rocks and the metamorphic rocks of Pendeli Mountain (Fig. 7).

For gravity reduction a density of 2.67gr/cm$^3$ was used (Bouguer correction, and Terrain correction up to a radius of 22 km). The total estimated error for the calculated gravity anomalies is approximately ±0.3 mGal. The resulting gravity anomaly profiles are shown in figures 5, 6 and 7. A linear trend (which is a dominant feature in some profiles such as in Gravity Profile 3) due to deeper contributing sources, had to be removed in order to enhance and study in detail the effect of shallower structures.

In addition, density measurements were conducted on representative samples of rocks that outcrop in the vicinity of the investigated area. The results are shown in Table 1, revealing a slight differentiation in the density values between the metamorphic (2.75 gr/cm$^3$) and non-metamorphic rocks (2.70 gr/cm$^3$).

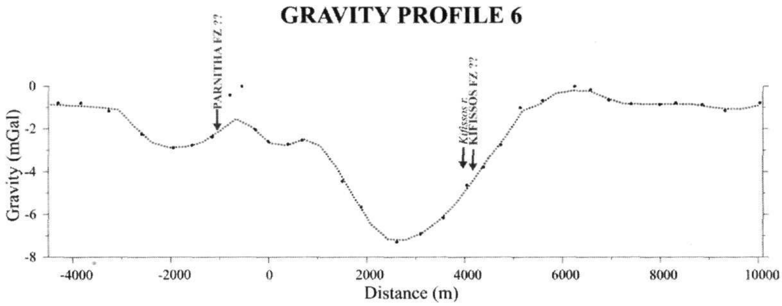


**Figure 7 - Gravity anomaly profile in Parnitha, Krioneri, Drosia and Dionysos area (Attica plain)**

**Table 1 - Density Measurements**

| | **Formations** | **ρ (gr/cm$^3$)** | **Standard Deviation (gr/cm$^3$)** |
|---|---|---|---|
| 1 | Upper Cretaceous limestone | 2.68 | ±0.01 |
| 2 | Triassic limestone | 2.72 | ±0.01 |
| 3 | Dionysos's schist | 2.81 | ±0.05 |
| 4 | Athens's schist | 2.65 | ±0.02 |
| 5 | Penteli's gneiss | 2.62 | ±0.02 |
| 6 | Neogene marls | 2.01 | - |
| 7 | Volcanic rocks | 2.59 | ±0.01 |
| 8 | Penteli's marble | 2.69 | ±0.01 |
| 9 | Permo-Triassic clastic formations | 2.57 | ±0.03 |
| 10 | Conglomerates (Giannoulas r.) | 2.48 | ±0.02 |
| 11 | Conglomerates (Thakomakedones) | 2.42 | - |

Neogene sediments formed mainly by marls, displayed an average density of 2.00 gr/cm$^3$. Quaternary deposits formed from debris and conglomerates, have an average density of 2.42 gr/cm$^3$. These results show that the density contrast between the Mesozoic limestones and Neogene sediments is of the order of 0.70 gr/cm$^3$, while the difference between the Mesozoic limestones and Quaternary sediments is of the order of 0.22 gr/cm$^3$ and between Mesozoic limestones and Pleistocene conglomerates is of the order of 0.28 gr/cm$^3$.

## 6. Preliminary Results – Conclusions

According to the present preliminary results, new evidence for the tectonic structure of CW-Attica has been obtained by conducting deep seismic survey and gravity measurements.

In the area of Thriassion plain the thickness of post-alpine sediments appears to be relatively small (<500 meters) as inferred from the combined initial interpretation of Seismic Sections 1 and 2 (Fig. 4). Indication for the existence of the Thriassion fault trending NW-SE, can be derived from the examination of the four gravity profiles 3, 4, 5 and 8 (Fig. 5). A more complicated structure in the area can be inferred from the detection of smaller faults (gravity anomalies) in the eastern part of Thriassion Plain.

The huge thickness ( of about 800 m) of post-alpine sediments detected NE of Thrakemakedones area, along Seismic Line 3 (Fig. 3) and evidenced by gravity profile 6 (Fig. 7), is of particular importance concerning the understanding of geological and tectonic structure of Kifissos fault zone. Furthermore, qualitative interpretation of gravity anomalies showed the existence of fault zones that appear to be strongly correlated to Kamatero, E. Aegaleo, Menidi and Parnitha fault zones (Fig. 6) as was previously indicated by geological and borehole data. However, additional gravity anomalies observed, could possibly indicate the existence of several faults in this area, organized in a system of grabens and horsts (Fig 1), a hypothesis which remains to be verified by quantitative interpretation.

Further processing and analysis of all data is required in order to obtain a better image delineating fault location and throws as well as the relief of alpine rocks under the investigated areas. This information will be helpful in the evaluation of sub-surface conditions and will be valuable in the elaboration of microzoning studies in these areas.

## 7. Acknowledgements

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