Seismic Hazard, Critical Facilities and Slow Active Faults

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Identification of buried active structures with preliminary geophysical and morphotectonic analysis, at eastern Thessaly basin, Greece

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Abstract: *Extensive ground fissures frequently occur within the eastern Thessaly basin, in central Greece and have been since 1989. This paper aims to give a preliminary explanation for their generation reasons by interpreting the results of a dense geophysical survey along the basin. This is combined with drilling data, as well as field work tectonic measurements, morphotectonic analysis and remote sensing data interpretation throughout the marginal areas of the basin. The gathering, homogenisation and organisation of different types of geo-data by using various GIS software packages led to the discovery of the alpine basement surface, which is covered by recent sediments, and possible structures that contributed to the development of the basin. The methodology of producing a 3D basement surface model and various lithology profiles across the basin, along with sediment isopach maps by combining surface with subsurface data, is described in this paper.*

Key words*: Vertical Electric Sounding, subsurface structure, basin tectonic control, sub-surface basement map*

INTRODUCTION

The disastrous phenomenon of aseismic ground fissure appearance is causing differential subsidence along the development axis of the eastern Thessaly basin and has been for many decades. The occurrence of several historical and contemporary earthquake events with epicentres in the broader area (Caputo, 1995) makes this area quite interesting to apply both classic and innovative research techniques.

The general orientation of the fissures (WNW-ESE) and their distribution along the basin axis (NW-SE), as well as the absence of surface structures because of the large thickness of recent sediments, led to a combined methodology including geophysical measurements and morphotectonic analysis. The results remain to be validated with gravity measurements, which are planned to be acquired during the next few months.

Vertical Electrical Soundings (VES) have been applied successfully to investigate geological-tectonic structures in other areas (Alexopoulos & Dilalos, 2010; Alexopoulos et al., 2001; Asfahani & Radwan, 2007; Caputo et al., 2003; Papadopoulos et al, 2007), and have also been combined with morphotectonic analysis (Asfahani et al., 2009). The latter is mainly used for analysing geomorphological structures by using elevation data but in any case when underground data; however, the same general techniques can be applied to underground data when subsurfaces can be identified (Vassilakis, 2006).

STUDY AREA CHARACTERISTICS

The study area lies within the central part of mainland Greece. It is an elongated, NW-SE trending, flat basin developed to the west of a range consisting of the mountains Ossa, Mavrovouni and Pilion (from north to south). Further to the east, the North Anatolian Fault is merging with the North Aegean Trough (Papanikolaou et al., 2006), which seems to terminate at the eastern coast of the aforementioned mountain range (Fig.1) as first claimed by Caputo & Pavlides (1993).

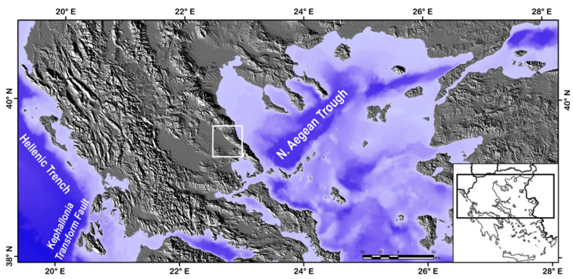

Fig. 1: Morphological relief of the submarine (bluish) and continental (grey) central Greece. White rectangle shows the location of the area studied in this paper (magnified in Fig. 2) and the inset to the right shows the part of Greece, which is magnified in this figure.

The alpine basement rocks, which crop out at the eastern and southeastern margins of the eastern Thessaly basin consist of metamorphic Gneiss, Marbles, Schists, Amphibolites and Ophiolitic bodies (Migiros & Vidakis, 1979). The westernmost marginal area is comprised of Neogene continental sediments, mainly conglomerates, covering alpine flysch and limestones. The tectonic contact between the metamorphic and non-metamorphic rocks lies buried under the Quaternary fluvial and lacustrine sediments of the basin (Fig.2).

For many years up until the 1960's a lake called "Karla" was present at the southeastern margin of the basin. This area has the lowest elevation and therefore all surface water collected there. During 1962 the intentional drainage of the lake was planned and undertaken, mainly because of medical (malaria) and agricultural reasons (Margaris et al., 2006). During 2000's it was decided that a new artificial lake, more or less at the same location as the natural one, be constructed during an environmental enhancement of the area. After several years of construction a new reservoir of about 38.5 km^2 is now created.

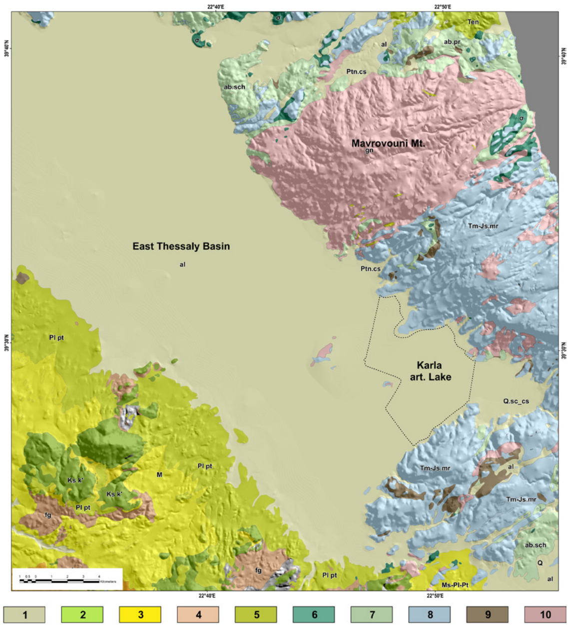

Fig. 2: Simplified geological shaded relief map of the basin and its marginal area. Pale colours refer to Quaternary (1) Pleistocene (2) and Miocene (3) sediments, whilst intense colours refer to the alpine basement rocks, Flysch (4), Limestones (5), Ophiolites (6), Amphibolites (7), Marbles (8), Schistolites (9) and Gneiss (10). The dashed outline shows the borders of the recently filled artificial lake of Karla and west of it several basement rocks are cropping out in the middle of the basin.

METHODOLOGY AND RESULTS

Near surface geophysics

A dense grid of 61 VES measurements (Schlumberger array) was designed and carried out covering the entire basin area. The main objective was to investigate the boundaries between the main sediment lithologies and the upper surface of the alpine basement rocks.

The geoelectrical measurement locations were distributed in the area, taking under consideration the outcrops of the basement rocks located in the marginal areas as well as at few locations inside the basin. The possible existence of a buried marginal, southwest dipping, normal fault zone at the easternmost basin area, covered by Quaternary deposits, was the most realistic case scenario for the geotectonic regime for this basin but the several basement outcrops especially in the southern central part of the basin weaken this theory a lot. Therefore the initial working hypothesis was the existence of a more complicated buried structure, comprised of several faults with various characters and trending orientations; all of them buried and impossible to be distinguished without dense subsurface investigation.

A resistivity survey was also chosen to be applied in the area, in order to investigate the stratigraphic structure of the subsurface geological formations, underlying the study area. The geoelectrical data included five (5) “in-situ” resistivity measurements on surface outcrops of the geological formations and fifty six (56) VES measurements. Additionally, data from thirty six (36) unpublished measurements, which were carried out during early 1970’s were re-interpreted and re-evaluated, increasing the quantity of data for interpretation (Fig.3).

Geophysical-geological calibration

In order to calibrate and better evaluate the geoelectrical results, which were collected from the VES survey, the five (5) “in-situ” resistivity measurements were carried out, on outcrops of basement rocks and more specifically on Gneiss, Marbles, Schists and Amphibolites.

These measurements contributed to a better understanding of the corresponding resistivity limits for each basement rock lithology. The interpretation of these results, revealed for marbles resistivity values of >2.000 Ohm.m and for the Gneiss 300-600 Ohm.m. Moreover, the measured resistivity for the Schists revealed values between 150-250 Ohm.m. A number of drill sections were also used for calibrating the resistivity measurements with depth, especially where the basement rock surface was encountered.

The main target of the geophysical survey was to investigate the stratigraphic structure of the subsurface geological formations, underlying the study area and determine the depth of the alpine formations (where possible). The geophysical data were processed by applying the automatic method of Zohdy (1989), composing a “multilayer” model. Beyond this, the commercial software package IX1D (v.3.5) of Interpex, was used in order to come up with the “layered” model.

In order to investigate the distribution of the geological formations in 2 dimensions, several geophysical geological sections were constructed with SE-NW and NE-SW directions, based on the measurements grid. Furthermore, based on the layered geophysical models and the preliminary geological interpretation, an effort was made to determine the depth of the alpine basement under the Quaternary deposits.

A gravity survey is planned in the near future for validating our results and combining them in an integrated study.

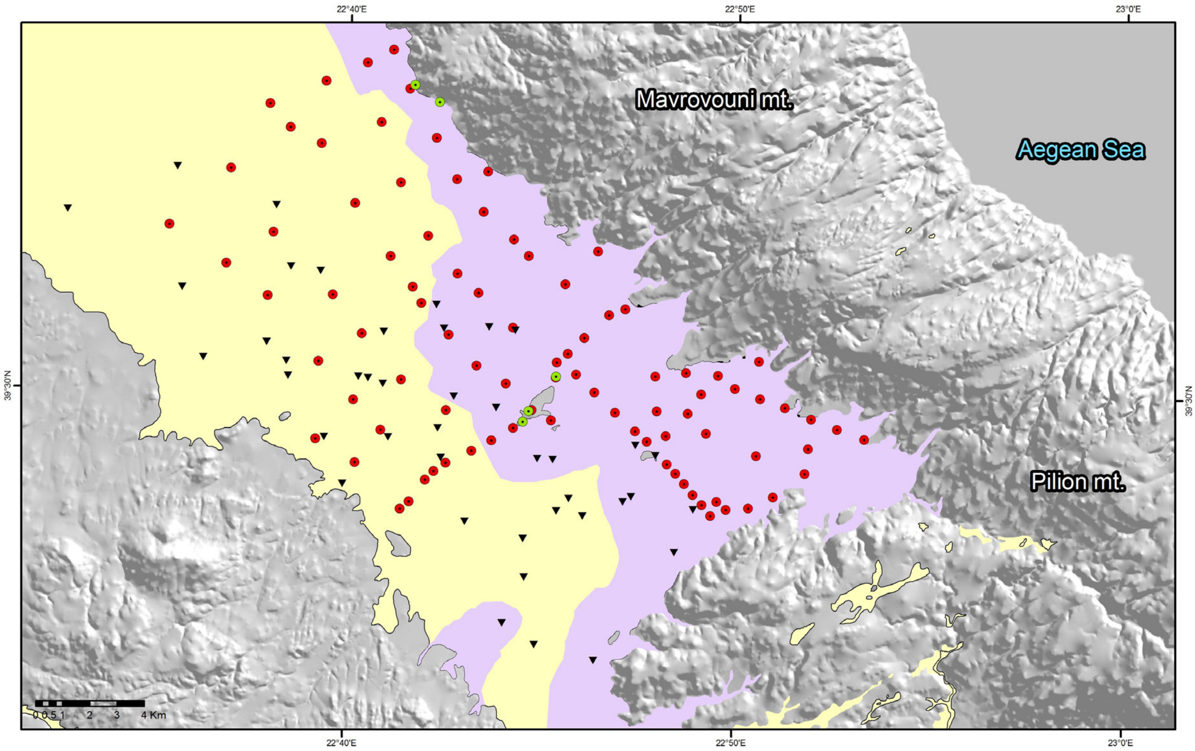

Fig. 3: Location map of the VES measurements (red dots), In-situ resistivity measurements (green dots) and the boreholes (reverse triangles) the drill sections of which were used for the subsurface basement map. Only the Quaternary outcrops are displayed in colour as all the rest have been removed and replaced by a shaded relief. Purple color shows the areas where the alpine basement was found under the sediments at the depth of investigation.

Morphotectonics

The geophysical part of the methodology revealed the basement rock surface covered by the recent basin sediments. The horizontal density and the vertical resolution of the resistivity measurements were essential in creating a lithological model for the entire study area. Additionally, the drill sections were simplified and also taken under consideration for improving the model and to extend it vertically, especially at locations where the VES signal did not penetrate specific horizons. Therefore, a subsurface map of the upper contact of the basement with the lower strata of the post-alpine sediments was created using GIS software packages such as ArcMap v.10 and ArcScene v.10.

Based on these data, a Digital Elevation Model (DEM) was created for the covered basement surface and combined with a DEM that was created from elevation data for the marginal areas, where the alpine rocks are cropping out. The single unified morphological pseudo-surface, which was synthesised, was used for further study by applying tectonic geomorphology indices and algorithms, in order to define potential blind fault zones that are buried beneath the basin material (Fig.4).

It is quite clear that the area where the alpine basement was found in relatively shallow depths (less than 250 meters), represents the gradual subsurface continuation of the eastern marginal outcrops. Two buried steep slopes, which can be attributed to southwest-dipping blind normal faults, could be identified at the shaded paleo-relief map of Fig.4. These seem to belong initially at the same fault zone, which was the main structure for the generation of eastern Thessaly basin. A third NE-SW trending structure has been probably activated at a later period and has laterally displaced the aforementioned marginal faults, separating them with a right slip movement mechanism.

DISCUSION AND CONCLUSIONS

The described methodology gave the opportunity to combine different techniques aiming to explain the appearance of disastrous ground fissures at residential and agricultural areas along the eastern Thessaly basin. The majority of the ground fissures are observed at areas where the thickness of the recent sediments is greater than the investigated depth (as the basement rocks were not found) and consequently this catastrophic phenomenon is highly related to the geotechnical characteristics of these lithological formations and the sudden change of underground water quantities. It would be worth to note that such characteristics as the porosity become cumulative and the greater the formation thickness is the larger amount of underground water can be stored by filling the vacuum. Consequently, over-pumping for agricultural use shrinks the aquifer and increases the vacuum mainly in between the fine grained horizons.

The systematic orientation of the ground fissures, even if the main cause seems to be the over-pumping and subsequently the compaction of several horizons due to the relatively sudden loss of the aquifer water, seems to be related to the large tectonic structures, which are buried under the quaternary formations.

Although no significant seismic activity has been observed in the intra-basin area, there are several clues implying that there are geodynamic procedures still going on. Based on the morphotectonic analysis the activity is concentrated more at the central area and not at its -more or less linear- margins. That is because it seems to be an asymmetric extensional basin, the active margin of which is dipping to the SW and the western margin is back-tilted towards the east along a major tectonic contact which is covered by the recent sediments.

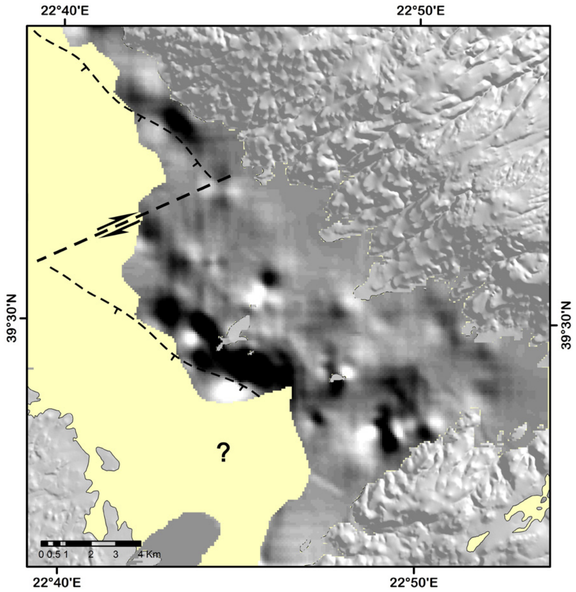

Fig. 4: Pseudo-3D alpine basement map where the ENE-WSW trending dextral strike slip morpho-lineations seem to affect the covered alpine basement as well, by laterally displacing the extensional NW-SE trending normal faults. The question mark symbol shows lack of data at this preliminary phase of research.

Nevertheless, several dextral strike slip tectonic structures trending WSW-ENE, possibly related to the northern branch of the active North Aegean Trough, can be identified across the marginal range by observing the shaded relief maps. This mountain range is the highest morphological relief between the basin and the trough, the tectonic influence of which seems to affect the range and fade away more westerly in the intra-basin area, as the palaeo-relief of the alpine basement extracted by geoelectrical measurements show. The dextral character of these cross cutting structures is clear either by examining the subsurface basement map or by observing the drainage network offset on each side of the morpho-lineaments that can be attributed to strike slip faulting. Nevertheless, almost horizontal striations on vertical fault surfaces were observed at marble outcrops located at the eastern marginal area, accompanied with kinematic indicators compatible with dextral movement.

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