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Pattern of Active Deformation in the Area of Thermaikos Gulf and Pieria (Northern Greece), Based on Morphotectonics and Satellite Geodesy

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The present-day tectonic stress pattern in Northern Greece has been active since Pleistocene, showing a slightly radial crustal extension with variable trend (N-S to NNW-SSW) in central Macedonia. The fault pattern is almost perpendicular to the stress field, crosscutting the older NW-SE alpine deformation structures (Sboras *et al.*, 2017). The current active stress field in the broader area of Thessaloniki has its extensional axis directed N-S, while the corresponding active faults are generally E-W trending. In the past couple of decades, GNSS measurements are widely used as a well-established tool in earth crustal deformation studies. The synergy between geodesy and geophysics can provide some very promising discussions about the Earth's upper crustal processes (Lazos et al., 2018). In this paper the extension of Anthemous fault zone at the broader Thessaloniki area is examined, using an integrated geodetic and geomorphologic approach.

The largest part of the study area is covered by Quaternary deposits, which were developed at the northern side of Anthemous river basin and the basins of Gallikos, Axios, Loudias and Aliakmon rivers (Thessaloniki plain). The deposits are mainly fluvial - torrential sediments containing marsh – marine or fluvial – deltaic layers. The Neogene Sandstone – Marl formation Series underlies the Quaternary sediments. This series consists of layers of very dense sand and sandstone, alternating with clay and silt of light brown to light green color. This formation covers a large part of the broader area. In the study area, this series is extended along the main fault zone from Galarinos to the East, up to the west shoreline of Thermaikos Gulf at the area of Aiginio and Melini. This series is in tectonic contact with the Quaternary deposits of Anthemous basin and the Thessaloniki plain sediments. The oldest Neogene Red Clay Series outcrops at the eastern part of the fault zone. This series consists of alternations of red color very stiff clays, sand and gravel layers and lenses.

The largest active fault zone in the immediate vicinity of Thessaloniki metropolitan area, is the Anthemous normal fault zone, which is located *ca.* 15 km to the south (F-An). The general strike of the zone is E-W, dipping to the north, while its total mapped length is *ca.* 32 km. It can be divided into three discrete segments, namely the Galarinos - Neo Risio, the Aggelochori area (Zervopoulou, 2010) and a possible third one, which is considered to be an extension to Thermaikos Gulf, detected from geophysical (seismic) investigations (Chronis, 1986). In this paper, the existence of a probable fourth segment in Aiginio area is also discussed. The activity of this fault zone is inferred by several indications. It defines the contact between the Neogene series at the south and the Holocene sediments at the central and north part of the basin. The application of quantitative geomorphic indices shows that the relief is responding to a relatively recent activity, as documented by various factors. The dissimilar development of the tributary network between the north and the south banks of Anthemous River, shows a tilting to the south along the surface fault trace. In addition, the asymmetry index of the basin, as well as the poor water channel development at the south part of the basin, indicate that the area has been subjected to rather recent deformation. Mountain front sinuosity is low, also suggesting a relatively high uplift rate of the footwall. The Aggelochori area segment shows indications of higher activity, as is suggested by steep slopes (cliffs). Some other indirect signs of neotectonic activity are the existence of hot springs in the Souroti area, with travertine deposits aligned along the fault line (Zervopoulou & Pavlides, 2005). This fault is also probably associated to the M 6.2 earthquake of Vasilika, as well as with aseismic creep along the fault line at Peraia area. The aseismic cracks follow the fault trace, however they have been attributed to overpumping.

The western extension of Anthemous fault zone towards Aiginio area is a research objective that has not yet been confidently resolved. To this end, a geodetic approach has been applied by extrapolating the active geodynamic state of the area by using primary geodetic data. They have been recorded for seven years (2008-2014) by 18 permanent GPS/GNSS stations in the broader area. Data were recorded daily in 30-second increments. The reference frame of these data is ETRF2000, which assumes that Eurasia is stable. The data processing involved GPS triangulation of three different GPS/GNSS stations, based on the vector analysis of East and North velocity components and their uncertainties. Any given three stations form a triangle, while each of them is located on a triangle vertex., The triangle centroid is determined by taking into consideration the intersection of the triangle medians and the inner circle of the triangle is inscribed. Then, the triangle vertices (GPS/GNSS stations) are relocated, based on their recorded velocity vectors, leading to the deformation of the inner circle into an ellipse. The combination of the major and minor axes of the inner circle and the ellipse, respectively, using specific equations, results in the calculation of certain parameters related to the active deformation of the area (e.g. Lazos et al., 2018). The combination of these 18 GPS/GNSS stations of the broader area led to the construction of 348 different triangles (http://www.unavco.org/).

The maximum horizontal extension is one of the parameters that is directly associated with the determination of the tectonic regime of a study area (extensional or compressional). The calculated maximum horizontal extension values, as well as their geostatistical process (interpolation), confirm that the probable western Anthemous fault zone prolongation is characterized by the highest values of the study area (approximately 200-230 nano-strain), Figure 1. In addition, high values are observed at the eastern part of Thessaloniki city, where numerous faults have been mapped. These high maximum horizontal extension values however, cannot be attributed to a specific fault, as they are concentrated within a limited area.

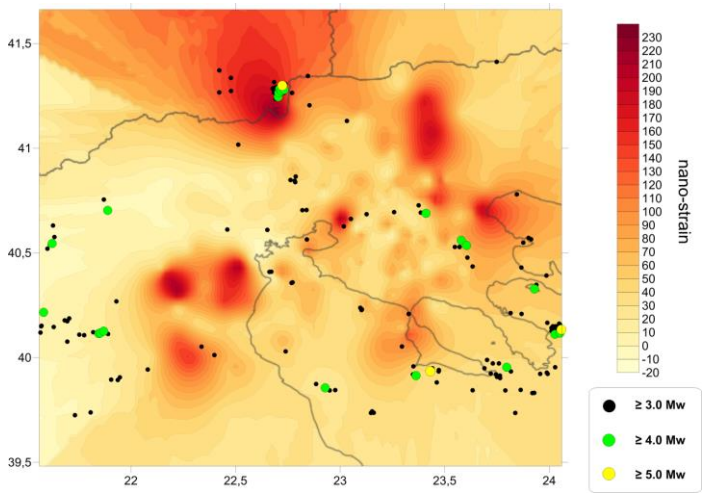

Figure 1. Maximum horizontal extension and recent seismic events of the study area.

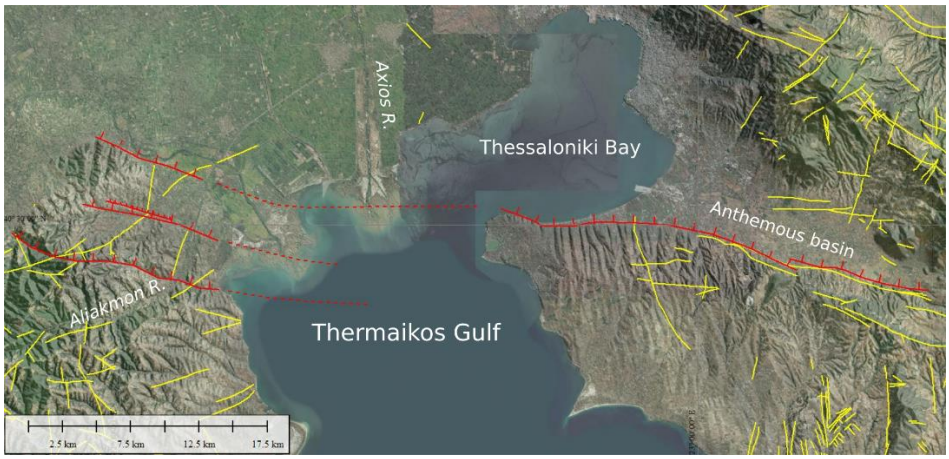

Figure 2. Summary map of faulting in the area of Thermaikos Gulf. Yellow lines show the mapped faults from published IGME geological maps, while red solid and dashed lines show the faults, lineaments and probable faults discussed in this paper.

While geodetic analysis shows that there is a considerable active deformation at the westward probable extension of Anthemous fault zone towards Aiginio area, the continuation cannot be verified due to the lack of precise offshore information. Nevertheless, a geomorphological assessment of Aiginio area shows that there are ESE-WNW to E-W trending linear features that are in good agreement with the expected fault pattern (Fig. 2). They form a low relief with no significant linear scarps, indicating thus that this probable segment is of lower activity level. Further research is needed in the area in order to establish a reliable correlation between the different fault strands.

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