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GEODETIC EVIDENCE OF THE CONTROL OF A MAJOR INACTIVE TECTONIC BOUNDARY ON THE CONTEMPORARY DEFORMATION FIELD OF ATHENS (GREECE)

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Abstract (Geodetic evidence for control of a major inactive tectonic boundary on contemporary deformation field of Athens (Greece)): *A GPS-derived velocity field from a dense geodetic network established in the broader area of Athens is presented, whereas local variations of strain rates across a major inactive tectonic boundary separating metamorphic and non-metamorphic geotectonic units are also highlighted. An apparent differentiation of the eastern part of Athens plain with negligible deformation rates, from the western part where relatively higher strain rates are observed, indicate its control of the above mentioned boundary on the contemporary deformation field of the region. These findings are in agreement with previous geological observations, however, due to the dense local GPS network it was fatherly possible to localize and quantify the effect of such a major inherited tectonic feature on the deformation pattern of the area.*

Key words*: GPS velocities, strain rates, tectonics, Athens Basin*

INTRODUCTION

Detailed instrumental observations of the tectonic movements in Athens Basin by geodetic or other methods are absent. The contribution of previous geodetic GPS studies to examine the kinematic field of Attica are limited to observations from regional networks, designed to monitor large-scale rather than local tectonic movements (Clarke et al., 1998; Veis et al., 2003). With a limited number of stations within the region, a general picture of the motion is gained, while changes within are hardly addressed.

In the present study a comprehensive GPS-derived velocity field for the broader area of Athens is presented. Variations of strain rates across a major tectonic boundary occurring in the region are highlighted and implication on the contemporary kinematics and dynamics of the region are discussed.

GEOLOGICAL SETTING

The Athens basement belongs to alpine formations outcropping in the mountains and the hills of the area. Recent post-alpine sediments (syn-rift deposits) often cover the slopes of the mountains as well as areas of low altitude.

The area presents a complex alpine structure comprising mainly by Mesozoic metamorphic rocks of Attica geotectonic unit, occurring at Pendeli and Hymmetus mountains and Mesozoic non-metamorphic rocks of the Eastern Greece geotectonic unit, occurring at Parnitha, Poikilo and Aegaleo mountains. The boundary between the metamorphic and non-metamorphic geotectonic units, although generally accepted to be of tectonic origin, its exact geometric and kinematic characteristics are yet to be determined, since no direct geological mapping could be undertaken. The entire tectonic structure within the area is covered by an allochtonous system, called "Athens schists", tectonically overlaid on the two previously mentioned units, as well as Neogene and Quaternary deposits. It is traced northwards from the Aegean coast of Southern Evia, through Aliveri to Kalamos in northeast Attica and continues to the southwest into the plain of Athens. Within the area of interest its locations coincide approximately with the riverbed of Kifissos R. (Papanikolaou et al., 1999; Mariolakos & Fountoulis, 2000; Xypolias et al., 2003) (Fig. 1), also confirmed by geophysical investigations at the northern part of the basin (Papadopoulos et al., 2007). Results of seismic tomography indicate the presence of abnormally high seismic velocities in the central part of the basin, most likely related to this major boundary, extending towards the southeast at Saronikos Gulf (Drakatos et al. 2005).

According to Papanikolaou & Royden (2007) this boundary represents a broad extensional detachment with significant portion of dextral shear, whereas opinions of a right-lateral strike slip fault zone have also been reported (Mariolakos & Fountoulis, 2000; Krohe et al. 2009). Considering a depth of about 30 km for the metamorphics (Lozios, 1993), it is clear that this tectonic boundary has accommodated more than 25 km of displacement. It was active throughout Late Miocene times and gradually became inactive during Early Pliocene (Papanikolaou & Royden, 2007). However, it forms a major boundary that separates the E-W trending higher slip-rate active faults in the western part of Attica from the NW-SE trending lower slip-rate faults in the eastern part (Mariolakos & Papanikolaou, 1987; Papanikolaou et al. 2004).

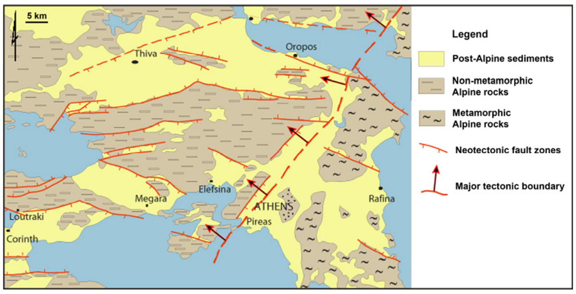

Fig. 1: Simplified neotectonic map of Attica showing the approximate location of the major tectonic boundary separating metamorphic and non-metamorphic alpine rocks (modified from Papanikolaou et al. 1999).

GPS NETWORK ESTABLISHMENT

Given the lack of previous instrumental observations, the design of the geodetic network was primarily focused on the investigation of the local tectonic regime. The minimum number of survey points required is imposed by the tectonic complexity of the region and the degree of fragmentation of the crust.

The established Athens Geodetic Network (AGNET) consisted of a total number of 41 campaign GPS sites (Fig. 2) including already available benchmarks of the Hellenic Military Geographical Service (HMGS), as well as sites previously installed by the Hellenic Mapping and Cadastral Organization (HEMCO) and the National Technical University of Athens (NTUA). Continuous (real-time) GPS station operate in the region by Metrica company (MET0), National Observatory of Athens (NOA1) and National & Kapodistrian University of Athens (UOA1), and despite their relatively limited observations at the time, they where considered in the analysis as well. The network covers essentially both the basins of Athens and Thriassio as well as their bordering mountain ranges, showing a relatively uniform spatial distribution. With an average distance between stations of approximately 5 km, a sufficient sampling of local deformation field is accomplished.

GPS MEASUREMENTS AND ANALYSIS

GPS campaigns were carried out from 2005 to 2008 (3.2 yr) following an annual re-occupation strategy. The benchmarks of the HMGS were first measured during network establishment and together with selected GPS sites once more on 2008. Measurements were conducted using LEICA geodetic GPS receivers equipped with SR299/399, AT202/302 and Ach1202Pro antennas. Carrier phase observations were recorded every 10 seconds from each station for a period of at least four hours. In an effort to achieve optimal results, selected stations were occupied for several days per epoch (independent sessions). To avoid large tropospheric errors an initial elevation cut-off angle of 10° was used.

Collected data were processed using Leica Geo Office v.1.1 and Bernese ver. 4.2 (Beutler et al., 2001). The realization of the reference frame was performed using the coordinates and velocity of Dionysos (DION) continuous GPS station, located on the metamorphic alpine basement. DION was tied to the ITRF2000 at epoch 2005.0 by almost a decade of observations from numerous sites of the EUREF permanent network (Prof. D. Paradissis, personal communication). It can be argued that connecting the local network to the ITRF through DION reference station would be sufficient, taking into account the network extend. Details on data collection and processing could be found in Foumelis (2009).

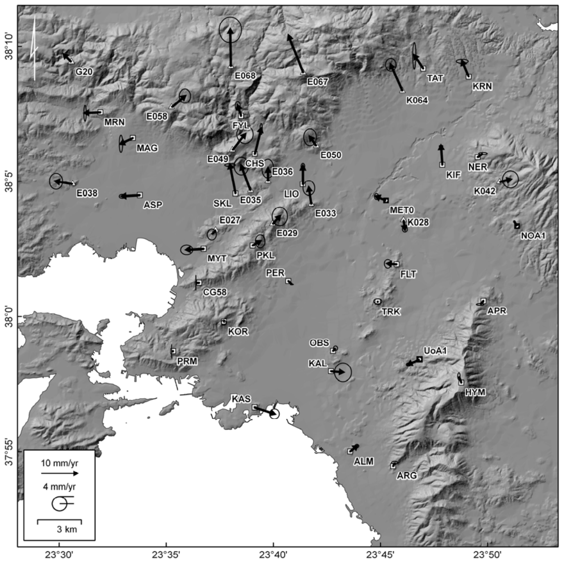

Fig. 2: Annual GPS velocities of broader Athens area, relative to DION, for the period 2005-2008. The error ellipses represent the 1-sigma confidence region. Velocities of E067 and G20 benchmarks from Veis et al. (2003), and NOA1 from the EUREF website, after transformation to the specific ITRF.

Repeated campaign observations allow the determination of the displacement vector as a function of time. The estimation of velocities and the corresponding errors was carried out on a statistical basis, by analysis of time series of each individual component of motion, by least square adjustment. Uncertainties were determined using the average scatter of residuals of the linear regression, providing more realistic error estimates. The estimated GPS velocity field is presented in a local DION-fixed reference frame in order to allow the recognition of local scale displacement patterns (Fig. 2). Site velocities from previous geodetic studies (E067 & G20) as well as EUREF solutions (NOA1) were also considered for the sake of completeness.

STRAIN RATES

In order to provide results independent from the choice of the reference frame, strain analysis was performed by the *grid_strain* Matlab™ software package (Teza et al., 2008). It allows the definition of the deformation pattern by providing the intensity and direction of principal components of strain tensor together with corresponding errors, by means of a modified linear least-squares (LS) inversion, under the hypothesis of uniform strain field condition. Inputs for calculating strain were horizontal GPS annual velocities and their corresponding errors. In this sense results express the linear strain rates in the region.

For the purpose of the analysis, GPS sites located on the mountains bordering the Athens Basin, specifically on the metamorphic basement of Pendeli and Hymettus mountains to the East (APR, ARG, HYM, NER and TAT) and on the non-metamorphic formations of eastern Parnitha Mt. and Aegaleo Mt. (E067, CHS, KOR, PKL and PRM) were selected. The analysis involved initially the calculation of a single strain tensor based on all selected stations and then, by gradual segmentation of the area for a more detailed investigation of spatial variations of the deformation regime. All calculations are referred to the center of mass of each set of sites considered.

From single strain tensor calculations, an extension of 0.27 ±0.06 μstrain/yr along a NNW–SSE direction (N 347°) is shown, with a negative eigenvalue (compression) for the minimum principal axes (Fig. 3). It is nevertheless evident that a single strain tensor is insufficient to express adequately the apparent heterogeneity of the local displacement field. Further examination of the strain field (Fig. 4) indicate negligible compressional rates at the southern part of the basin compared to the dominant extensional regime of relatively higher strain rates (0.91 ±0.09 μstrain/yr) at the northern part between Pendeli and Parnitha ranges.

A more detailed consideration of the strain field between the two geotectonic units was performed by triangulation of the selected GPS sites (Fig. 5). Herein, it is interesting to note the major differentiation between the western and the eastern parts of Athens Basin with significantly lower strain rates in the latter. Moreover, the gradual increase of the extension rates at the western part of Athens plain moving to the North is clearly depicted, while a counterclockwise rotation of the maximum principle axis of the strain tensor is also observed. The compressional regime at the southeastern part of the basin should be underlined.

DISCUSSIONS

The stress field in the region is characterized by extension in a NNE–SSW direction, also confirmed by regional geodetic measurements (Veis et al., 2003). However, the 5-km spacing of the geodetic network allowed investigating local variations of the strain rates.

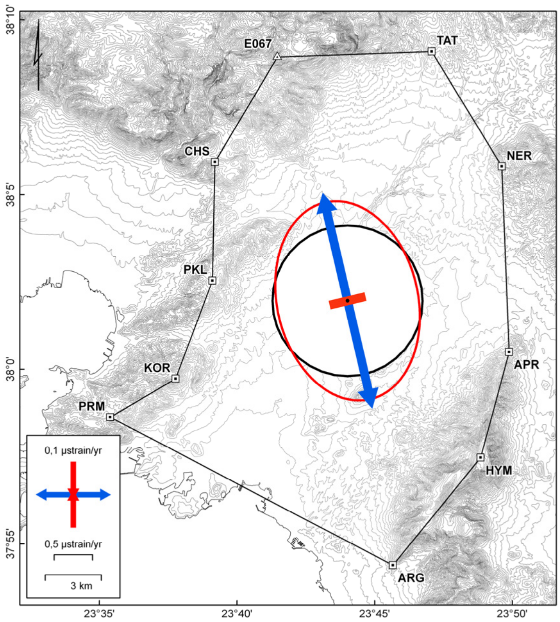

Fig. 3: Principle axes of the strain rate tensor for the area of interest, calculated from velocities of selected GPS sites, in background contour lines of 20m interval.

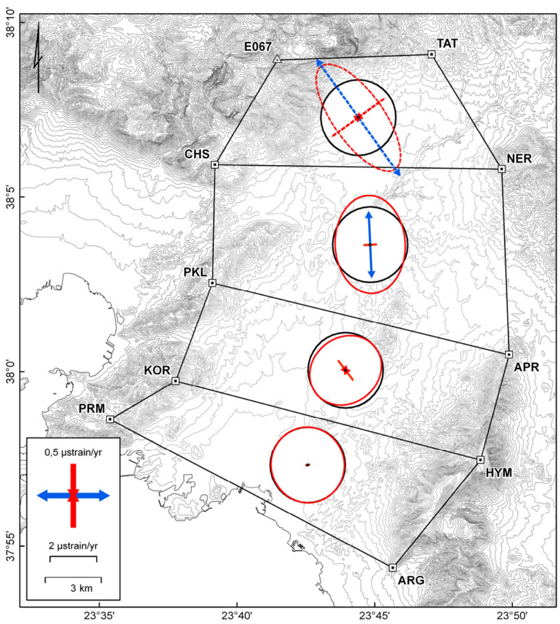

Fig. 4: Principle axes of the strain rate tensors within Athens Basin. Dashed lines indicate local estimates around which GPS data are poorly distributed from a geometrical point of view.

A differentiation of strain rates across the inactive tectonic boundary is evident with significantly higher rates at the western part of Athens Basin. Given its inactive characteristics, a passive control should be considered. Such behavior has also been mentioned during the Athens 1999 earthquake from SAR interferometric observations of the spatial expansion of the co- and post-seismic displacement field (Foumelis et al., 2009).

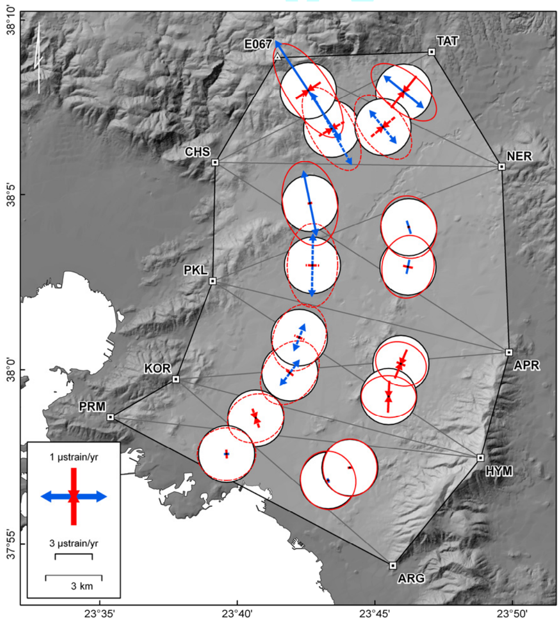

Fig. 5: Detailed strain analysis by different triangulations of selected GPS sites. Principle axes of the strain rate tensors are calculated at the center of mass of each triangle.

The broader area is essentially a transitional zone between the Corinth Gulf and Beotia to the west, characterized by E-W trending active faults with significant seismic activity and those of southern Attica and Cyclades islands to the east, showing low deformation rates (Mariolakos & Papanikolaou, 1987; Papanicolaou & Lozios, 1990). Thus, the observed high strain rates at the northern part of the basin should be attributed to the high crustal velocities observed within Parnitha Mt. an area controlled mainly by E-W trending active fault zones (Ganas et al. 2005; Papanikolaou & Papanikolaou, 2007) although the role of NE-SW trending faults should be important as well (Mariolakos & Fountoulis, 2000).

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