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Geodetic evidence for passive control of a major Miocene tectonic boundary on the contemporary deformation field of Athens (Greece)

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ABSTRACT

A GPS-derived velocity field is presented from a dense geodetic network (~5km distance between stations) established in the broader area of Athens. It shows significant local variations of strain rates across a major inactive tectonic boundary separating metamorphic and non-metamorphic geotectonic units. The southeastern part of Athens plain displays negligible deformation rates, whereas towards the northwestern part higher strain rates are observed, indicating the control of the inactive tectonic 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.

1. Introduction

Detailed instrumental observations of the tectonic movements in Athens Basin by geodetic or other methods are absent, a fact attributed mainly to the limited interest of the scientific community over areas exhibiting low deformation rates. Indeed, both historical and instrumental data for the broader area of Athens show no large earthquakes since 1700, with an exception of the 1705 event located on the northeastern flanks of Parnitha Mt. [Ambraseys and Jackson 1997, Goldsworthy et al. 2002]. The list of historical earthquakes in the region (480 B.C. - 1900) includes a limited number of reports of earthquakes that caused damage, while there is no evidence of large events at distances smaller than 30 km from Athens [Makropoulos et al. 1989, Papazachos and Papazachou 1997].

It should be noted, however, that historical records are incomplete, particularly in the area of central Greece, while there are sufficient data for the period after 1810 [Ambraseys and Jackson 1990]. Reports on damage and displacement of ancient monuments [Papanastassiou et al. 2000, Ambraseys and Psycharis 2012] suggest in turns that Attica region has experienced several strong earthquakes in the past. It is interesting that despite the unexpected catastrophic seismic event of September 7, 1999, Mw=6.0 [Papadimitriou et al. 2002], no further monitoring of the region was held.

The contribution of previous geodetic GPS studies to examine the kinematic field of Attica are only limited to observations obtained from regional networks, that are designed to monitor large-scale deformation rather than local tectonic movements [Clarke et al. 1998, Veis et al. 2003]. With a limited number of stations within the region, only a gross view of the motion is gained, while changes within are hardly traced.

In this 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 the implications on the contemporary kinematics and dynamics of the region are further discussed.

2. 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 Mesozoic metamorphic rocks occurring

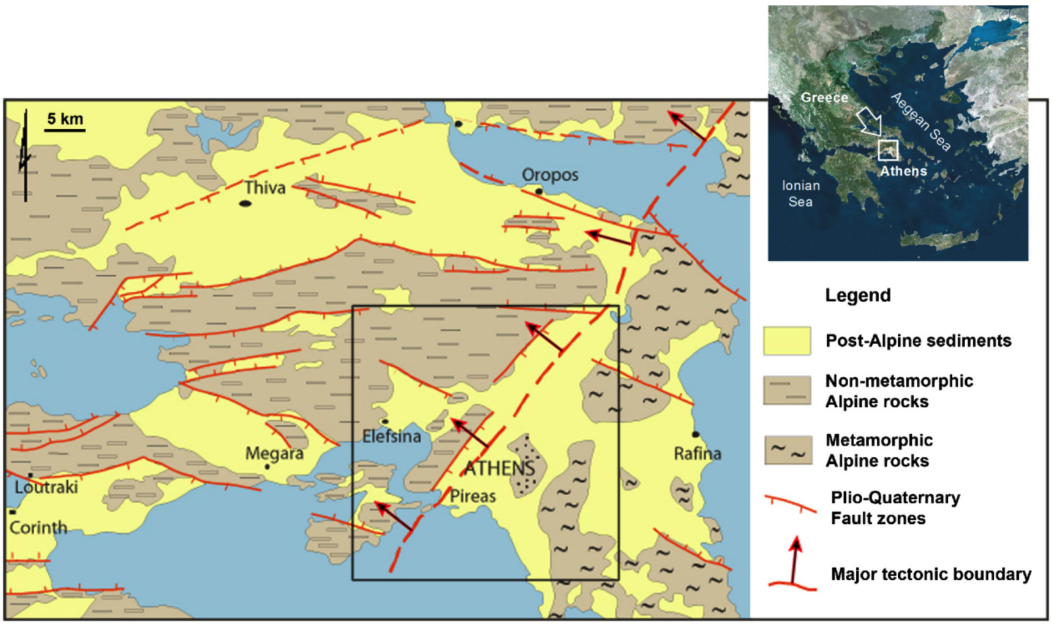

Figure 1. Simplified neotectonic map of Attica showing the approximate location of the major tectonic boundary, separating metamorphic and non-metamorphic alpine rocks (modified from Papanikolaou et al. [1999]).

at Pendeli and Hymmetus mountains and Mesozoic non-metamorphic rocks of the eastern Greece geotectonic unit, occurring at Parnitha, Poikilo and Aegaleo mountains [Katsikatsos et al. 1986, Papanikolaou 1986, Papanikolaou et al. 2004] (Figure 1). 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 because it is covered with Neogene and Quaternary deposits (Figure 2). It is traced northeastwards 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 River [Papanikolaou et al. 1999, Mariolakos and Fountoulis 2000, Xypolias et al. 2003], 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 southwest at the Saronikos Gulf [Drakatos et al. 2005].

According to Papanikolaou and Royden [2007] this boundary represents a broad extensional detachment with a significant portion of dextral shear, whereas opinions of a right-lateral strike slip fault zone have also been reported [Mariolakos and Fountoulis 2000, Krohe et al. 2009]. Considering a depth of about 30 km for the tectono-metamorphic input of the metamorphics in Oligocene times [Lozios 1993], that are now at surface, it is clear that this tectonic boundary has accommodated more than 25 km of vertical displacement. It was active throughout Middle-Late Miocene times and gradually became inactive during Early Pliocene [Papanikolaou and Royden 2007, Royden and Papanikolaou 2011]. 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 and Papanikolaou 1987, Papanikolaou et al. 2004, Papanikolaou and Papanikolaou 2007].

3. GPS network establishment

Local geodetic networks offer a unique opportunity for understanding the fragmentation pattern within a small part of the crust. Most often they are established in relationship to existing geodetic reference frames, as well as independent networks serving highly accurate geodetic control in specific regions. Among the advantages is that these networks are designed with a specific geodynamic regime in mind and that major error sources (e.g. ionospheric) are limited compared to regional networks.

Given the lack of previous instrumental observations, the design of the geodetic network used in this study 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 (Figure 3) including already available benchmarks of the Hellenic Military Geographical Service (HMGS), as

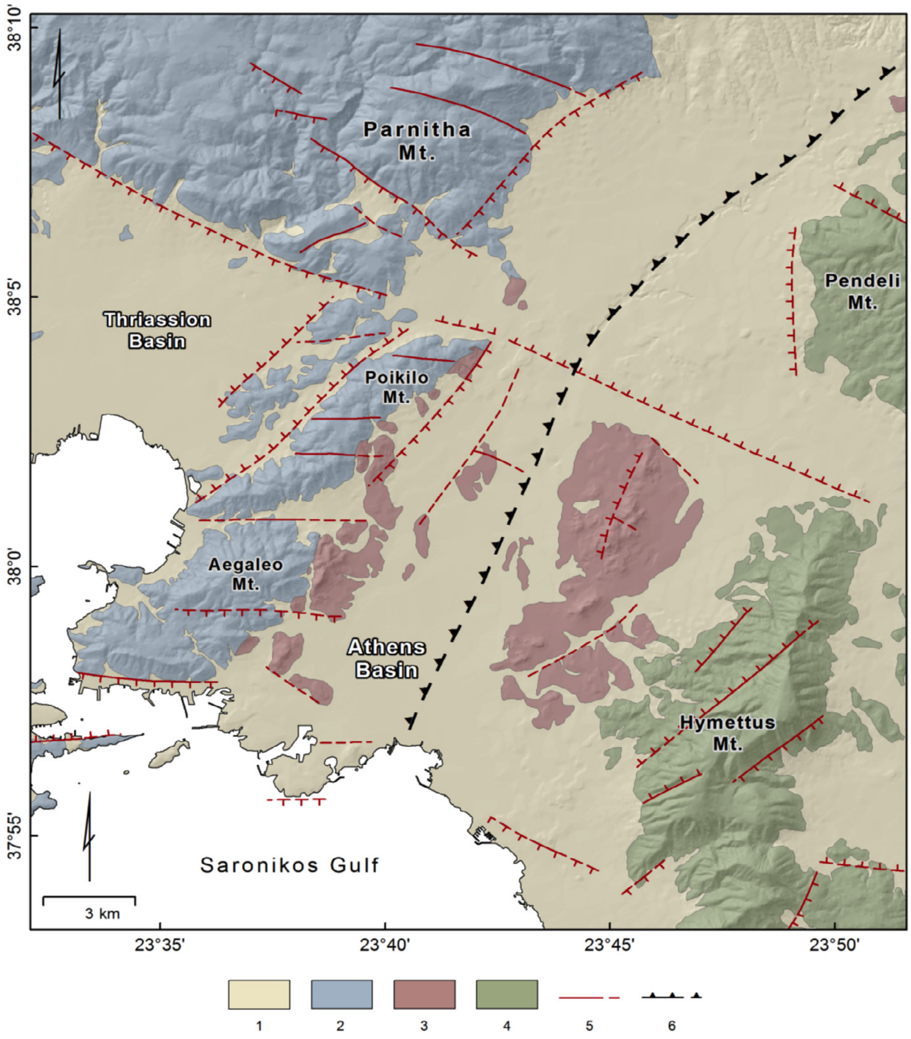

Figure 2. Geological map of the study area, (1) post-Alpine sediments, (2) non- metamorphic rocks (eastern Greece geotectonic unit), (3) allochthonous system (Athens schists), (4) metamorphic rocks (Attica geotectonic unit), (5) fault zone and (6) major tectonic boundary.

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 stations operate in the region by Metrica S.A. (MET0), National Observatory of Athens (NOA1) and National and Kapodistrian University of Athens (UOA1), and despite their relatively limited observations at the time, they were incorporated in the analysis as well. The network covers essentially both the Athens and Thriassio basins as well as their bordering mountain ranges, showing a relatively uniform spatial distribution. With an average distance of approximately 5 km between stations, a sufficient sampling and a high resolution view of the local deformation field is accomplished.

4. GPS measurements and analysis

GPS campaigns were carried out from 2005 to 2008 (3.2 yr) following an annual re-occupation strategy (Table S1, supplementary materials). 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 [Hugentobler 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 and the fact that the goal is to calculate strain rates. Details on data collection and

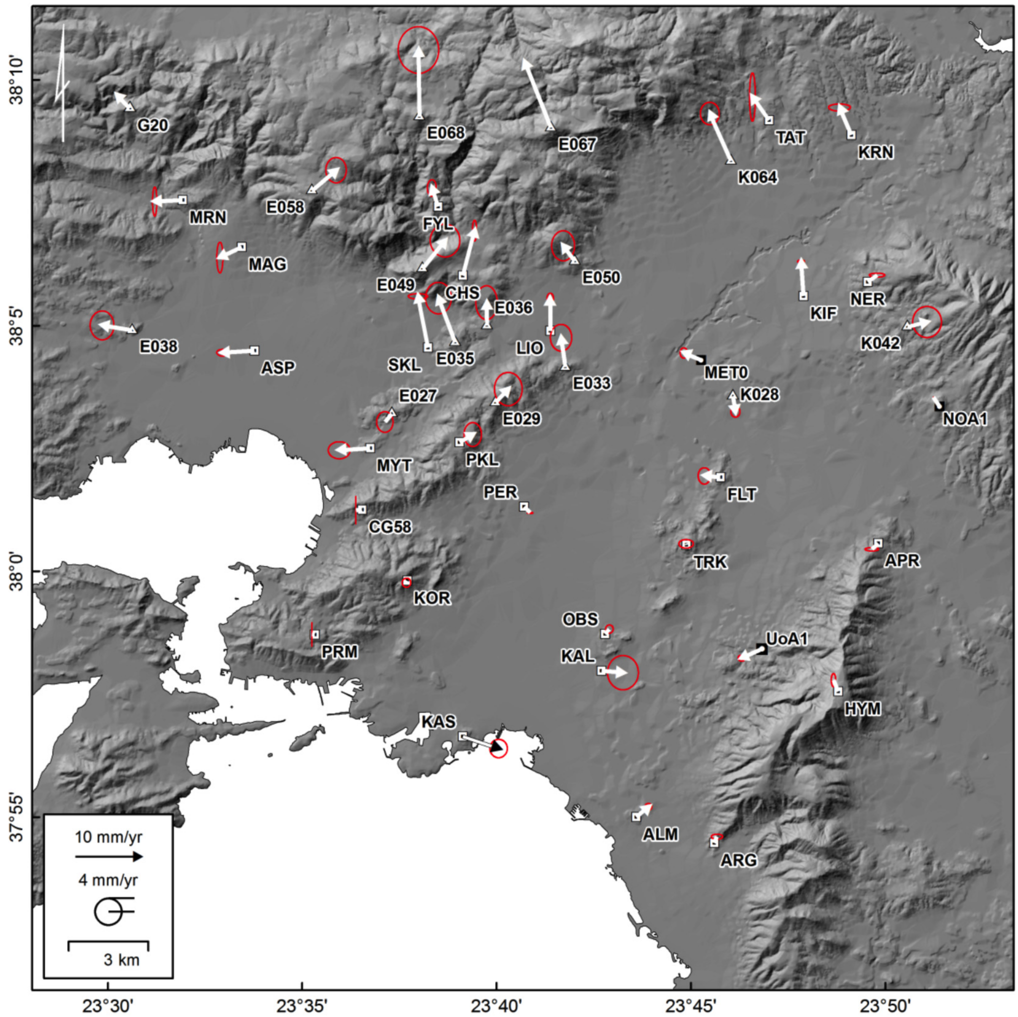

Figure 3. Annual GPS velocities of broader Athens area, relative to DION, for the period 2005-2008. The error ellipses represent the 1-sigma confidence region. Velocities of E067 and G20 benchmarks from Veis et al. [2003], and NOA1 from the EUREF website, after transformation to the ITRF2000.

processing could be found in Foumelis [2009].

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 (Table S2). There was no attempt to evaluate vertical displacements due to the short period of observations. Considering the low motion rates in the area, long-term measurements are necessary to further reduce errors. Nonetheless, the achieved errors, especially over regions of relatively high displacement rates, are significantly smaller than the corresponding velocity estimates.

The obtained GPS velocity field is presented in a local DION-fixed reference frame in order to allow for better recognition of local scale displacement patterns (Figure 3 and Table S3). Site velocities from previous geodetic studies (E067 and G20) as well as EUREF solutions (NOA1), were also considered for completeness purposes.

There are limited sources of quantitative information available for validation purposes. However, negligible differences were found in the calculated velocities at GPS sites occupied during previous geodetic campaigns [Veis et al. 2003]. The compatibility of the obtained motion field with what expected according to geological and tectonic studies provide further evidence for the correctness of the results [Foumelis 2009].

5. 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 [Shen et al. 1996, Shen and Jackson 2000], under the hypothesis of uniform strain

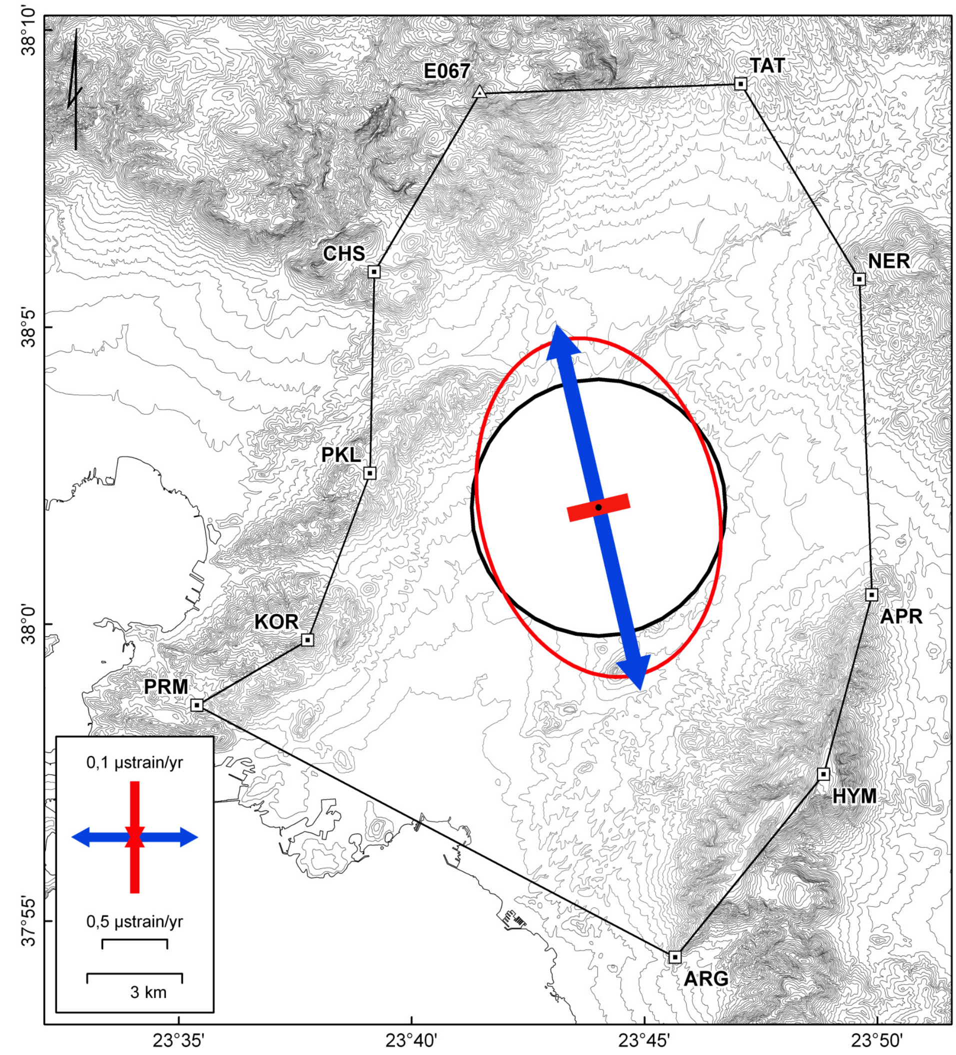

Figure 4. Principle axes of the strain rate tensor for the area of interest, calculated from velocities of selected GPS sites, in background topographic contour lines of 20m interval. An extension rate of 0.27 ±0.06 10^{-6} yr^{-1} along a NNW-SSE direction (N 347°) is calculated.

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 (Table S4).

From single strain tensor calculations, an extension rate of 0.27 ±0.06 10^{-6} yr^{-1} along NNW-SSE direction (N 347°) is shown, with a negative eigenvalue (compression) for the minimum principal axes (Figure 4). It is nevertheless evident that a single strain tensor is insufficient to adequately express the apparent heterogeneity of the local displacement field. Further examination of the strain field (Figure 5) indicates negligible compressional rates at the southern part of the basin compared to the dominant extensional regime of gradually higher strain rates northwards up to 0.91 ±0.09 10^{-6} yr^{-1} towards the northern part between the 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 (Figure 6). 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.

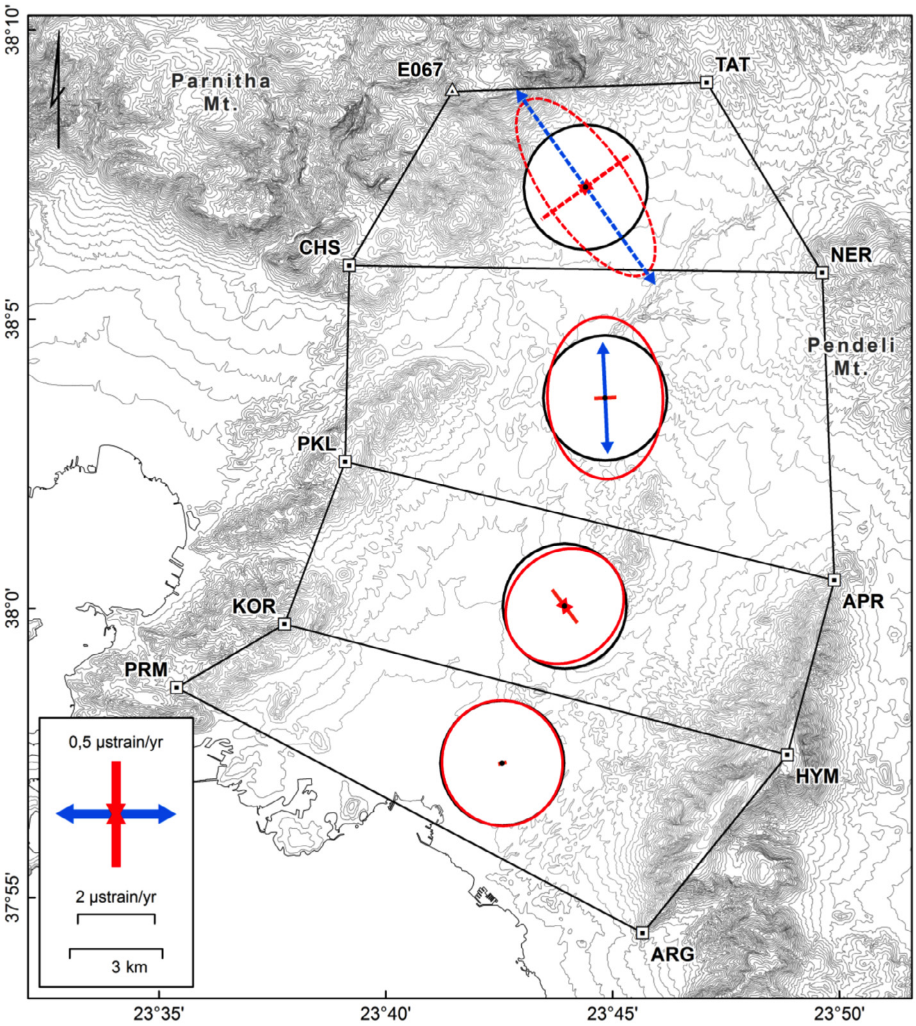

Figure 5. Principle axes of the strain rate tensors within Athens Basin. Dashed lines indicate local estimates around which GPS data are poorly distributed from a geometrical point of view. This figure shows negligible compressional rates at the southern part of the basin compared to the dominant extensional regime of gradually higher strain rates northwards up to 0.91 ±0.09 10^{-6} yr^{-1} towards the northern part of the network between the Pendeli and Parnitha ranges.

6. Discussion and conclusions

The local stress field of the Alpine basement in the broader Athens region is characterized by extension in a NNW-SSE direction. The extension of the crust is been addressed by numerous regional geodetic studies, retaining in the majority of the solutions an N-S direction [Veis et al. 2003, Hollenstein et al. 2008, Rontogianni 2010]. Variations are primarily due to the distribution of GPS sites considered and to a lesser extend to the accuracy of individual solution. This is also confirmed by many geological observations [Ambraseys and Jackson 1990, Papanikolaou and Lozios 1990, Papazachos and Kiratzi 1996], while kinematic characteristics of individual fault structures indicate nearly horizontal tension with azimuth ranging from N 007° to N 025° [Rondoyanni et al. 2000, Ganas et al. 2004].

The availability of dense geodetic measurements (~5 km average distance between stations) presented in this paper, offer a high spatial resolution and therefore permit the investigation of local variations of the strain rates. A change in strain rates across the major inactive tectonic boundary crossing Athens Basin in N-S direction is evident, with significantly higher rates recorded westwards from the boundary (Figure 6). Given its inactive geodynamic characteristics, a passive control on the contemporary stress field should be considered, due to the abrupt change in the nature of the separating geological formations. 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]. The metamorphic basement displays a more compact behavior with a dense fabric with little internal deformation due to their exhumation from a depth of 30 km since Oligocene times. In contrast, the sedimentary Alpine formations display a rather loose behavior, with significant internal brittle deformation distributed in several E-W trending normal faults, exhibiting higher deformation rates. Although a precise mapping of the trace of this tectonic

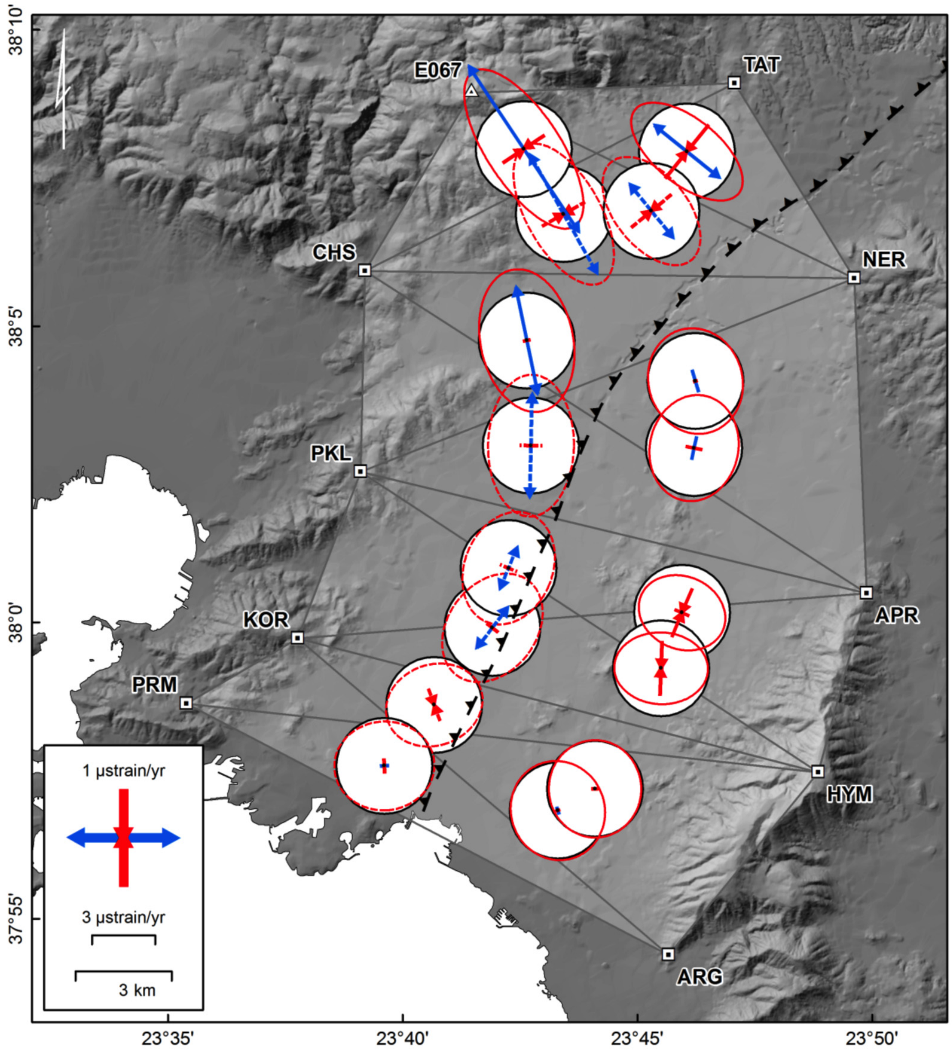

Figure 6. Detailed strain analysis by different triangulations of selected GPS sites. Principle axes of the strain rate tensors are calculated at the center of mass of each triangle. The approximate location of the tectonic boundary separating metamorphic and non-metamorphic alpine rocks in Attica is shown (dashed line). There is a significant strain-rate difference on either side of the boundary.

boundary in the field is not feasible, since it is covered with post-alpine sediments, its indirect effect on the geodynamics of the region can still be recognized. This tectonic boundary also coincides with the boundary that separates the lowest category of seismic risk (zone I), from the intermediate category (zone II) of the national seismic building code [EAK 2003, E.P.P.O.-A.C.E.G. 2001], indicating that it controls also the seismicity pattern [Papanikolaou and Papanikolaou 2007].

Apart from the observed differences across the tectonic boundary there is a clear change as we move from the southern to the northern part of the Athens Basin, both in terms of character and magnitude of the calculated strain. The increased NW-SE extension in the northern part of Athens signifies the larger motion rates over Parnitha mountain range, an area where the Athens 1999 earthquake took place, and seems to accommodate still significant strain compared to the rest of the metamorphic alpine basement. On the other hand, the observed compression in the southern part of the basin, although an order of magnitude smaller than the maximum extension, underlines the geodynamic complexity of region. It is worth noticing that the most-compressive strain rate axis presented herein is consistent with the horizontal compressive stress orientation obtained by Carafa and Barba [2013] during stress axis interpolation over Europe.

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 and Papanikolaou 1987, Papanikolaou and 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. This area is mainly controlled by E-W trending active fault zones [Ganas et al. 2005, Papanikolaou and Papanikolaou 2007] although the role of NE-SW trending faults should be important as well

[Mariolakos and Fountoulis 2000]. The continuation of these active fault zones to the east of the tectonic boundary is a matter of further investigation, but they seem to die out and terminate towards the boundary, whereas the faults on the metamorphic have a different strike. However, the results underline the significant role of such inherited tectonic boundaries in the understanding of contemporary geodynamic settings, a fact that should be taken into account when dealing with seismic hazard assessment.

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