Geodetic Deformation in Central Macedonia, Greece

Stavroula Alatza, Konstantinos Kydonakis, Aggeliki Marinou, Xanthos Papanikolaou, Demitrios Anastasiou, Demitrios Paradissis

Higher Geodesy Laboratory and Dionysos Satellite Observatory, National Technical University of Athens

Abstract: Greece is situated at the convergence limit between the relatively stable Eurasian and the northward subducting African lithospheric plate. As a consequence, is the most seismogenic area in the Mediterranean and one of the most active in the world. Chalkidiki peninsula is part of the region of Central Macedonia in northern Greece. In the present study, we present results from GPS data processing, of a dense geodetic network established in the Chalkidiki peninsula and the adjacent areas. Our results indicate increased velocities (up to 12 mm/y) in the central part of the study area (Chalkidiki peninsula and the area immediately to the north), whereas in the adjacent regions the velocities do not exceed 9 mm/yr. An absolute velocity increase and an abrupt change from SW orientation to SE orientation is evident for the central part of the study area; the transition domain possibly corresponds to the fault zone activated during the 1978 earthquake.

1. Introduction

Satellite geodesy is a powerful tool to quantify present-day deformation, through calculation of the velocity field and the related strain regime. In the Hellenic domain, a velocity field that contains values of up to 30 mm/y, with respect to a fixed Europe, has been established in a number of recent studies (McClusky, 2013). In particular, such velocity values have been calculated for southern Greece, whereas northern Greece is rather attached to Europe; the Aegean Sea stands between the two mentioned extreme parts. In this contribution we present new GPS measurements for a number of stations located in northern Greece. Our results highlight lateral variations in the calculated velocity field and further suggest a correlation between the GPS-derived strain field and the geometry of active fault zones, such as the Thessaloniki-Rentina fault, a highly complex zone in the area. Contrary to the short-term deformation, as seen in the recent and historical seismicity record, the geometry and the assumed established strain regime during formation of the major extensional sedimentary basins in the area do not correlate.

2. GPS Data

2.1. The continuous network

Since the late 90s, several GPS stations were established in Greece, in order to monitor tectonic motion. The stations were installed by various institutes. The first one established in Greece in 1995 by National Technical University of Athens, is DION, situated in Dionysos Satellite Observatory (DSO).

In this study we used eleven continuous GPS stations, distributed around the Chalkidiki peninsula and the adjacent areas [Fig 1], [Table 1]. These are part of a broader network of GPS/GNSS stations, routinely processed by Dionysos Satellite Observatory.

Table 1: *Details of the continuous GPS stations.*

Station	Location/ Institutes	Available time span (years)
AUT1	Thessaloniκi (EUREF)	9.7
DUTH	Drama (EUREF)	6.2
KATE	Katerini (Tree-Company)	2
KOMO	Komotini (Tree-Company)	1.8
KOZA	Kozani (Tree-Company)	2
NVRK	Nevrokopi (NOA)	4.6
PIRG	Pirgos (Tree-Company)	2
PLGR	Polygiros (Tree-Company)	2
SERR	Serres (Tree-Company)	1.3
THES	Thessaloniki (Tree-Company)	2
XANT	Xanthi (Tree-Company)	1.9

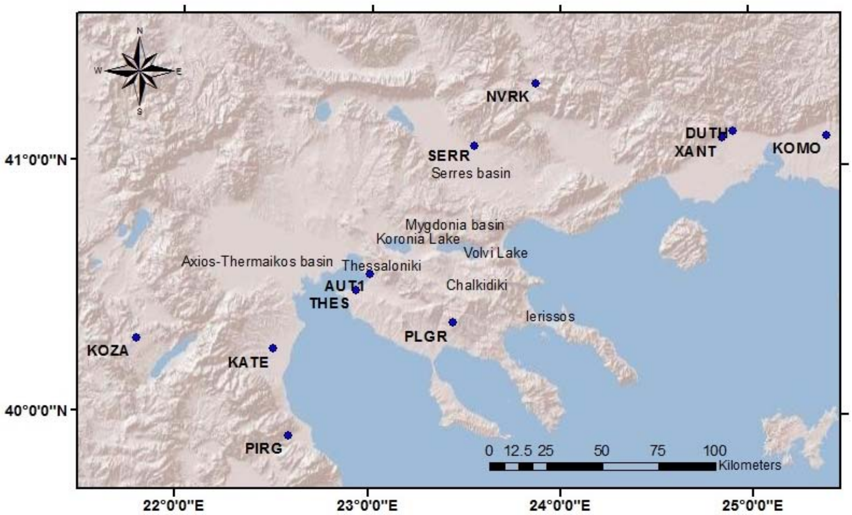

Figure 1: *Continuous GPS stations.*

2.2. Campaign network

The campaign network, consists of thirty-one stations centered around the Chalkidiki peninsula, in an area that stretches from Ptolemaida and Thessalikos basins to the southwest, to Drama basin to the northeast. Three GPS campaigns were carried out, on September 1998, October 1999 and September 2000 under the research program Seismic Hazard in Greece (SING). The number of campaign points measured, as well as the observation periods varies between the three campaigns. The location of the network is shown in Figure 2. Identical instrumentation was used in all three campaigns.

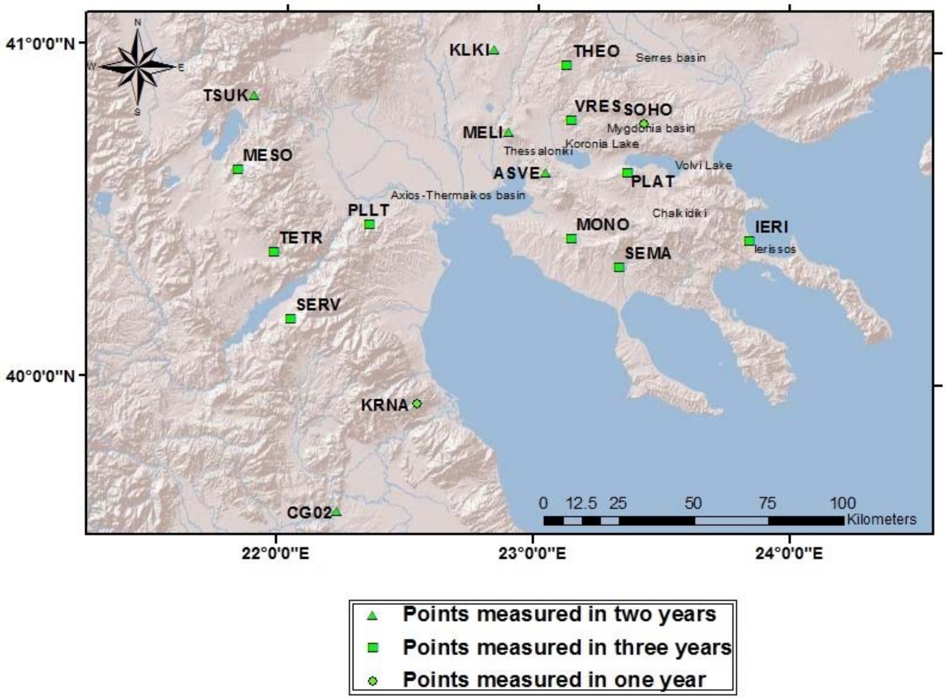

Figure 2: *Distribution of the GPS campaign network sites.*

3. Data Processing

All available data were processed using Bernese GNSS Software v5 (Dach, 2007). The network was aligned to ITRF 2005 (Altamimi, 2007), using eleven European IGS (Dow, 2009) stations [Fig 3] via the minimum constrains approach (Dach, 2007). The network was processed using the double difference approach in baseline mode. When possible, ambiguities were fixed to integers using Quasi-Ionosphere-Free(QIF) method. For a subset of baselines (with limited length), we used the SIGMA method to resolve the ambiguities. Baselines with an ambiguity

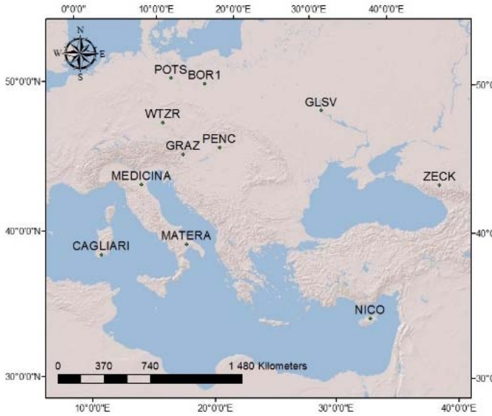

Figure 3: *IGS stations used for the alignment of the network to ITRF2005.*

resolution lower than 70% were not used in further steps. Daily normal equation files were stacked and adjusted per campaign, resulting in three sets of coordinate estimates. These were further used to create time series.

For the time series analysis, we used two different approaches:

(a) For the campaign network a Matlab routine was developed to perform linear regression.

(b) For the continuous stations, tectonic velocities were estimated using several years of analyzed data. For this purpose, Dionysos satellite observatory (DSO) has developed a time-series analysis tool, which can estimate tectonic velocities and velocity changes, as well as possible offsets and annual and semi- annual harmonic coefficients. Time-series analysis information, of the continuous stations is provided in the laboratory's webpage (http://dionysos.survey.ntua.gr/). A raw time-series file is registered and daily updated, for each station, including the newest coordinate estimates.

Through the computation of the time series for each point of the local network, it is possible to draw conclusions on their movement and determine their tectonic velocities. Taking into consideration the correlation coefficient, some stations were excluded from the displacement map. The obtained velocity field for the network, is presented in Figure 4, with respect to a fixed Eurasian plate (V_{north} = 11.4 mm /y and V_{east} = 23.6 mm / y [Yannick, 1998; Yannick, 2000]). In order to estimate land deformation in Chalkidiki area, one main (i.e. using all available points) strain tensor was calculated and is presented in Figure 5. Taking into consideration the orientation of the velocity vectors [Fig 4], we divided the area in three zones and one strain tensor for each sub region was calculated. The deformation parameters are shows in Table 4.

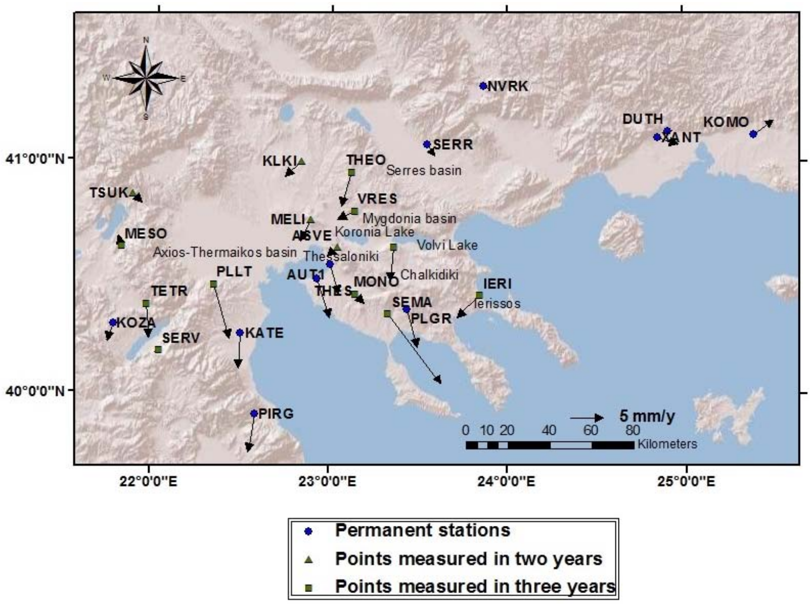

Figure 4: *Tectonic velocities of all stations with respect to a fixed Eurasian plate.*

Table 4: *Deformation parameters of strain tensors.*

		WESTERN TENSOR	CENTRAL TENSOR	EAST TENSOR	MAIN TENSOR
Shift	(Sx)	+23.34 +- 0.70 mm	+24.17 +- 0.79 mm	+25.43 +- 0.57 mm	+23.93 +- 0.52 mm
	(Sy)	+8.55 +- 0.70 mm	+6.64 +- 0.79 mm	+11.25 +- 0.57 mm	+8.36 +- 0.52 mm
Rotation	(Ex)	+0.059 +- 0.038 ppm	+0.043 +- 0.057 ppm	-0.021 +- 0.010 ppm	+0.005 +- 0.008 ppm
	(Ey)	+0.027 +- 0.030 ppm	-0.101 +- 0.038 ppm	-0.034 +- 0.060 ppm	-0.011 +- 0.016 ppm
Total Rot	(E)	+0.043 +- 0.024 ppm	-0.029 +- 0.034 ppm	-0.027 +- 0.030 ppm	-0.003 +- 0.009 ppm
Scale	(Kx)	+0.014 +- 0.038 ppm	-0.001 +- 0.057 ppm	+0.011 +- 0.010 ppm	+0.013 +- 0.008 ppm
	(Ky)	+0.018 +- 0.030 ppm	+0.039 +- 0.038 ppm	+0.047 +- 0.060 ppm	+0.046 +- 0.016 ppm
	(Kmax)	+0.032 +- 0.024 ppm	+0.094 +- 0.033 ppm	+0.048 +- 0.065 ppm	+0.048 +- 0.018 ppm
	(Kmin)	-0.000 +- 0.025 ppm	-0.056 +- 0.040 ppm	+0.009 +- 0.030 ppm	+0.011 +- 0.011 ppm
Mean Scale	(K)	+0.016 +- 0.024 ppm	+0.019 +- 0.034 ppm	+0.029 +- 0.030 ppm	+0.029 +- 0.009 ppm
Azimouth	(Az)	-41.211 +- 42.531 deg	-37.175 +- 13.170 deg	-10.353 +- 44.680 deg	-12.716 +- 14.050 deg
Strain	(γ max)	+0.032 +- 0.035 ppm	+0.150 +- 0.052 ppm	+0.039 +- 0.071 ppm	+0.037 +- 0.021 ppm

4. Velocity and strain field

The velocity pattern, with respect to fixed Eurasian plate in Figure 4, indicates that most of the calculated velocities scatter along a N-S orientation with the exception of some small eastward-trending velocity sites to the east. The absolute values ranges from virtually zero up to 12 mm/yr. In the central part of the study (constrained between the Axios basin to the west and the Serres basin to the east), we can observe an increased velocity magnitude compared to those of the adjacent areas. In detail, velocities in the central part are up to 12 mm/y whereas the maximum velocity for the adjacent areas is 9 and 4 mm/y for the western and eastern parts respectively. A change in the velocity orientation along a virtual N-S traverse passing through the central part of the area can be observed; SW-directed velocities swift to SE-directed velocities from north to south [Fig 4]. The area of transition roughly corresponds to the Mygdonia basin, expressed today as the Koronia and Volvi lakes. As already mentioned, we calculated a single strain tensor for the whole study area [Fig 5]. Although this method might not provide detailed resolution in the smaller scale, it shows quite adequately the regional-scale pattern. The results clearly indicate a NNW-SSE stretching direction. In order to infer more detailed regional kinematic patterns, we applied the same methodology dividing the study area in three sub-domains separated by two major intervening basins (the Axios and the Serres basins to the west and east, respectively). As seen in Figure 6, the strain tensors inferred for the western and central domains are virtually identical and indicate a rather coherent and uniformly deforming region, with NW-trending stretching direction. The western domain, however, displays a somewhat clockwise rotated strain tensor with NNW-trending stretching direction.

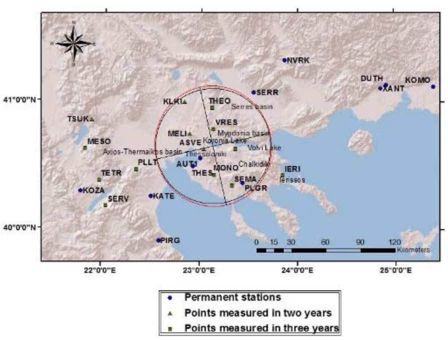

__Figure 5:__ Strain tensor calculated for the broader region of Chalkidiki.

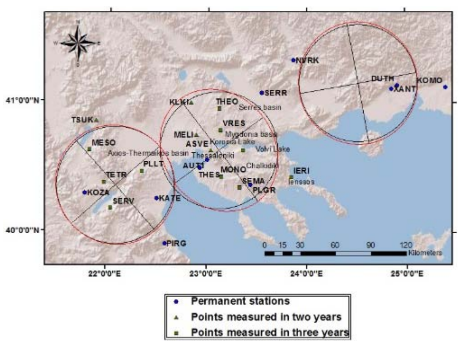

__Figure 6:__ Strain tensors calculated by dividing the area of Chalkidiki in three sub regions.

5. Discussion

GPS velocities: northern Greece vs. mainland Greece and Aegean

Relatively small velocities that range up to 12 mm/y, calculated with respect to a fixed Eurasian plate, are inferred for northernmost Greece [Fig 4]. We concur with the hypothesis that northern Greece is rather attached to the Eurasian plate and we accept that the velocity field shows a change, both in magnitude and orientation, on both sides of the North Aegean Trough [Fig 4]. We see the latter structure as a major feature that separates an area attached to the Eurasian plate, to the north, from a southwestward translating (and expanding) domain, to the south. But even within the region that is attached to the European plate (that is north of the North Aegean Trough) there is a gradient on the velocity field [Fig 4]. Although this can be attributed, in detail, to the combined result of a number of E-trending active normal faults in the area (Tranos, 2011), it clearly shows that the component of southward translation increases southwardly.

We note here, that the rather abrupt differences in the velocity values in the Aegean part of northern Greece (along a virtual N-S transverse), is rather diminished with smooth velocity gradient along the same N-S transverse across northern continental Greece.

Change of the velocity field due to active tectonics

On 20 June, 1978 a shallow destructive earthquake M = 6.5 occurred east-northeast of Thessaloniki in the area between Koronia and Volvi lakes. The main shock activated a steeply-dipping NW-trending sinistral slip fault and was preceded by an intense foreshock activity (largest event with magnitude of 5.8) as well as a series of aftershocks with magnitude of up to 5.3 (Papazachos, 1979; Soufleris, 1982). In fact, this event occurred on a complex and perhaps the most active fault system in the area. It stretches from Thessaloniki, to the west, up to Rentina village, to the east, trends almost E-W it is south of the lakes and exhibits a number of NW-trending branching faults; activity on the latter faults is related to the 1978 earthquake and a number of M > 6 historical events (see Tranos, 2003). As noted on the previous section, we have identified a suspicious variation in the velocity field in the central part of the study area [Fig 4]. This change reflects mainly variations in velocity directions. We suspect that such a change is related to the active Thessaloniki-Rentina fault zone described before. Indeed, exactly north of the mentioned fault zone the geodetic velocities are smaller and trend SW whereas to the south of the zone the velocities are larger and clearly trend SE. In detail, hanging-wall stations [VRES, ASVE; Fig 4] show smaller velocities compared to foot-wall stations [AUT1, PLAT; Fig 4]. Our strain tensor analysis shows a NNW-trending stretching direction that is compatible with sinistral slip on NW-trending faults [Fig 5]. Interestingly, a steeply-dipping, NW-trending sinistral-reverse fault produced the 1978 earthquake according to Papazachos (1979). The variations in the velocity field can be possibly linked to loading and stress build-up or aseismic slip across that particular fault zone.

A similar explanation can be given for the difference in absolute values between the THES and MONO stations due to the existence of the NNE-dipping Vassilika fault (see fig.1 in Tranos, 2011). If this is true, then the THES and MONO stations should lie on the foot-wall and hanging-wall of the fault. However, in the absence of detailed mapping and seismicity record of the fault such convenient explanation cannot be neither confirmed nor excluded.

Ierissos (IERI) station deviates significantly in orientation compared to the adjacent stations immediately to the west [Fig 4]. We note here that on 26 September 1932 another destructive M=7.0 earthquake occurred near Ierissos town which attest for the existence of a highly active E-W-trending fault in the area (Pavlides, 1991). However, in the absence of a denser network near Ierissos we cannot speculate for the velocity change of that station.

Temporal variation in the strain field: from Eocene to the present-day form

An interesting result of our analysis is shown in Figures 5 and 6. Irrespectively of the number of subdomains chosen, both figures show a NNW- to NW- trending stretching direction. This pattern clearly reflects the present-day strain field. On the other hand, the major extensional sedimentary basins in the area trend NW and are bounded by NW-trending, NE/SW-dipping normal faults. These basins are, from west to east, the Thermaikos-Axios basin, the two smaller basins at the edge of the Chalkidiki peninsula, and the Serres basin. Their formation started in Early-Middle Cenozoic and they are rather linked to stretching in the NE-SW direction. Thus, this assumed strain field is almost perpendicular to the inferred present-day field as shown in Figures 5 and 6.

One possibility to explain the difference between the present-day and the assumed past strain fields is to invoke a rotation around a vertical axis during the Cenozoic. However, rather than invoking such a rotation, we want to emphasize that the whole study area rotated around 30-35^o clockwise between ~45 Myr and ~20 Myr based on extensive palaeomagnetic data from sedimentary/volcanic rocks (Kondopoulou, 1986; Kissel,1988; Dimitriadis, 1998; see also Kydonakis, 2015). This analysis shows that the shallow part of the crust rotated and consequently progressively favoured a new geometry on the newly formed basins while rendering the older basins (and their bounding faults) inactive. In other words, it is the rocks that rotate through time rather than the strain field.

6. Acknowledgements

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