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Geodetic evidence for tectonic activity on the Strymon Fault System, northeast Greece

Vasiliki Mouslopoulou^{a*}, Vasso Saltogianni^b, Michail Gianniou^c, Stathis Stiros^b

^aGFZ German Research Centre for Geosciences, Telegrafenberg, D-14473 Potsdam, Section 3.1,
Germany (vasso@gfz-potsdam.de)

^bDepartment of Civil Engineering, University of Patras, Greece (vsalt@upatras.gr; stiros@upatras.gr)

^cNational Cadastre and Mapping Agency SA, Athens, Greece (mgianniu@ktimatologio.gr)

Abstract

The current kinematic patterns of northeast Greece remain largely unknown. This is mainly because this region is characterised by low seismicity rates and is poorly covered by GPS stations. Here, we analyse new homogeneous GPS data collected over a period of 5.5 years from the first permanent network in northeast Greece (HEPOS) to shed light in the kinematics of this region. We find that the GPS displacement vectors on either side of the natural depression of the Strymon Valley differ significantly in orientation and magnitude. Specifically, we find that across a distance of ca. 30 km the GPS displacement vectors change orientation by $>130^\circ$ (from NNW to SSW), producing a mean horizontal strain rate of 3.3 ± 0.3 mm/yr. We attribute this kinematic translation to result from movement along the Strymon Fault System (SFS), a >200 km-long structure that strikes NW-SE and extends from SW Bulgaria to North Aegean (where possibly abuts against the North Anatolian Fault). Up to date, the SFS was considered to be a major Alpine and Neogene geotectonic boundary of unclear Holocene activity. If the

* Corresponding author: German Research Centre for Geosciences, Telegrafenberg, D-14473 Potsdam, Section 3.1, Germany, Tel.: +49 (0)331/288-1312 Fax: +49 (0)331/288-1370; vasso@gfz-potsdam.de

interseismic strain stored currently across the fault system is released seismically, large earthquakes ($M > 7$) and associated coseismic lateral displacements should be expected in the area. These results call for a better assessment of the earthquake risk in northeast Greece, which is currently evaluated as a low seismic hazard region.

Keywords: Strymon Fault System, GPS, strike-slip fault, displacement, earthquakes, Greece.

1. Introduction

GPS data have quantified the deformation of Greece and provided evidence of significant displacements, both seismic and aseismic (e.g. McClusky et al., 2000; Reilinger et al., 2010; Perouse et al., 2012; Müller et al., 2013). However, these data cover mainly the Hellenic Arc or areas of intense seismicity, such as the Gulf of Corinth (Briole et al., 2000; Avallone et al., 2004; Bernard et al., 2006), while the distribution of survey stations in areas of low historic seismicity is poor. Hence, the details of the kinematic patterns that characterise these areas of sparse seismicity remain largely unknown. This is the case particularly for northeast Greece (Thrace and East Macedonia), where most GPS displacements derive from a limited number of continuous and survey stations and as a consequence, the noise in these measurements (that often cover periods of up to ten years) is of the same order of magnitude with the tectonic dislocations (e.g. Reilinger et al., 2010). Seismically quiet areas may, however, produce catastrophic earthquakes. The non-positive relationship between the lack of modern seismicity and long-term activity on a fault has been emphasized recently in New Zealand by the M7.1 and M6.3 Christchurch earthquakes in 2010 and 2011, respectively, which occurred in a region of low seismic hazard (Allen et al., 2010; Van Dissen et al., 2011). Similarly, this has been illustrated in

Greece by the catastrophic 1995 M6.5 Kozani-Grevena earthquake which occurred in an area assumed to be aseismic (Stiros, 1998; Fig. 1).

Here, we derive new tectonic information for northeast Greece, by analysing for the first time GPS data from a continuously operating network, the *Hellenic Positioning System* (HEPOS). This network was established in Greece in 2007 and consists of 98 real-time permanent GPS stations (Fig. 1). The uniformity, density, resolution and quality of this dataset provide an excellent opportunity to optimize displacement estimates, even for measurements that derive from areas of relatively low tectonic activity (Fig. 1).

Collectively, we have analysed GPS displacements that derive from 20 continuous HEPOS stations in northeast Greece and span a period of 5.5 years (e.g. from January 2008 till June 2013), to assess the activity of the Strymon Fault System (SFS), a major enigmatic structure in northern Greece and Southern Bulgaria (e.g. Zagorcev, 1992a & b; Tranos, 2011). Our data, in combination with regional tectonic data, reveal that the SFS does not simply represent the boundary between two major Alpine basement units in Greece and Bulgaria (e.g. Bornovas and Rondogianni, 1983), but also forms a significant active left-lateral strike-slip fault, which operates in conjunction with the North Aegean Trough, the continuation of the North Anatolian Fault into the Aegean (Taymaz et al., 1991). This result has important implications for the seismic hazard in the region, especially because critical infrastructure (among them the TAP gas pipeline, currently in construction) crosses the Strymon Fault System.

2. Geometry and Kinematics of the Strymon Fault System (SFS)

The ~200 km long and ~40 km wide SFS extends from southwest Bulgaria to the North Aegean Sea (e.g. Strymonikos Gulf) (Fig. 2). The SFS strikes NW-SE, defining a complex system of

topographic lows, within which the Strymon (Struma) River flows (Figs. 1&2). It comprises numerous individual smaller fault systems, each of which being about 80 km long and up to 5 km wide (Zagorcev, 1992). South of the Greek-Bulgarian border, the SFS traverses northern Greece for about 80 km before it extends offshore into the Strymonikos Gulf, where it may connect with the North Aegean Trough, a feature formed in response to the prolongation of the North Anatolian Fault into the north Aegean Sea (Taymaz et al., 1991; Armijo et al., 1999) (Fig. 2). At its northern end, this segment of the SFS abuts against the E-W trending Belasitsa–Kerkini Fault System (BKFS) (Tranos et al., 2008) (Fig. 2).

The SFS has played a key role in the Mesozoic tectonics of northeast Greece as it formed the boundary between two main alpine tectonic units, that of the Serbomacedonian Massif in the west and the Rhodope Massif in the east (Bornovas and Rondogianni, 1983) (Fig. 2). Several field studies have tried to characterize the kinematics of this large structure, without, however, a universal consensus. Lyberis (1984), for example, suggests that the Strymon Valley formed originally as a Paleogene molasses basin which was subsequently reactivated (in Neogene) due to extensional tectonics. Specifically, Lyberis (1984) recorded three main phases of Neogene extension which are (from the oldest to the youngest): 1) post-middle Miocene extension of NW-SE orientation; 2) post-Lower Pliocene to Lower Pleistocene extension of NE-SW orientation during which the main subsidence took place, with the basin accommodating oblique right-lateral strike-slip movement; and 3) post-late Pleistocene to present extension of N-S orientation. The Neogene subsidence is evidenced by >6 km thick sediments (Lyberis, 1984). By contrast, Zagorcev (1992) argues that the SFS corresponds to a major dextral, oblique-slip fault in the late alpine period (till probably early Miocene), while Dinter and Royden (1993) propose that the SFS represents a major southwest dipping low-angle fault that has accommodated ca. 25 km of

extension between middle Miocene and early Pliocene. More recently, Tranos (2011) attributes the formation of the Strymon Valley to movement along a right-lateral strike-slip fault around middle-late Miocene, which was subsequently overprinted by extensional tectonics. Some evidence of strike-slip faulting provides the shape of the Serres Basin (Fig. 2).

Regarding its Quaternary activity, Zagorcev (1992) suggests that the SFS is active and accommodates slip in response to transverse extension (normal faulting with right- and left-lateral strike-slip component). He also utilises offset geomorphic features to provide estimates of long-term (Quaternary) vertical displacement rates for faults that traverse southwest Bulgaria. Throw rates on individual faults are in the order of 0.1-0.2 mm/yr whereas the total throw rate across the system is estimated at ca. 0.4 mm/yr (Zagorcev, 1992).

In contrast, Burchfiel et al. (2000) suggest that during Late Quaternary, the NW-trending low-angle normal faults of the SFS have accommodated about 3.5 km of total displacement in response to NE-SW extension and this activity has been subsequently overprinted by NE trending dextral strike-slip faults (parallel to the strands of the North Anatolian Fault). Further, Meyer et al. (2002) mapped three active normal faults in SW Bulgaria which are elements of the SFS. One of these faults, the Krupnik Fault, has been considered responsible for the 1904 M7.9 Krupnik earthquake (Meyer et al., 2002; Ganas et al., 2005) (Fig. 2). The mean rate of vertical slip on the Krupnik Fault in the last 13 Ma is ca. 0.1 mm/yr (Meyer et al., 2002). In the Greek territory, Tranos (2011) suggests that the present-day faulting in the Strymon Basin is produced in response to N-S extension and is characterised by dip-slip movement on E-W trending normal faults.

Interestingly, and despite the observations recorded in southwest Bulgaria, there is little evidence for strike-slip faulting along the section of the SFS that traverses north Greece. The

only evidence of strike-slip movement within the Strymon Valley is striations on NW-SE trending faults that displace Neogene formations reported by Tranos (2011) – however this is attributed by the author to an earlier deformational phase. The lack of field evidence of strike-slip displacements within the Strymon Valley can be explained by intense erosion/modification of the soft rocks proximal to the Strymon River. Subtle traces of recent tectonic deformation are likely to be removed by the dynamic river flow and/or buried under the thick cover of Holocene alluvial deposits. In addition, the fertile land proximal to the Strymon River has undergone intense cultivation for millennia. Interestingly, the largest instrumentally recorded earthquake in the area, the 1978 M6.5 Thessaloniki earthquake (Fig. 2), did not produce any measurable surface displacement (Soufleris et al., 1982; Papazachos, 1982; Tranos et al., 2003). Instead, this event was constrained by elastic dislocation modeling (using leveling data) which suggests ~15cm of ground subsidence (Stiros and Drakos, 2006). The Quaternary activity of the SFS in northeast Greece is further supported by the occurrence of, possibly, post-Pliocene volcanic deposits proximal to the fault system (see triangle in Fig. 2) and at large distances from the currently and formerly active volcanic centers in south and central Aegean, respectively (Maratos, 1966; Fyticas et al., 1984).

3. Instrumental and Historic Seismicity along the SFS

Historically, there is only one event that may be associated with rupture of the SFS: the 1904 M7.9 Krupnik earthquake that is assigned to the Krupnik Fault, a segment of the SFS in SW Bulgaria (Meyer et al., 2002; Ganas et al., 2005) (Fig. 2). No major historic or instrumental earthquake has been accommodated by the southern section of the SFS (e.g. the section that extends across north Greece). In contrast, according to the catalogue of the National Observatory

of Athens (<http://www.gein.noa.gr/en/>), ~140 earthquakes of $M < 5$ occurred during the last 20 years in depths < 20 km along the Strymon Valley (Fig. 3). Although these earthquake epicentres are not relocated, they clearly appear to straddle the Strymon Valley, extending across a strike-distance of about 20 km (Fig. 3).

Two other major ($M > 6$) 20th century earthquakes have occurred in the vicinity of the southern SFS (both associated with normal faulting): i) the 1932 M7 Hierissos earthquake (Papazachos 1982; Pavlides and Tranos, 1991) and ii) the 1978 M6.5 Thessaloniki earthquake (Soufleris et al., 1982; Papazachos and Papazachou, 1997; Tranos et al., 2003; Stiros and Drakos, 2000). The epicenters of both of these events are shown in Figure 2.

4. GPS Displacement Vectors

The GPS data utilised in this article derive from continuous recordings collected, over a period of sixty-six months, on twenty permanent HEPOS stations located in northeast Greece (Fig. 4). Data correspond to sixty-six monthly solutions that cover the time interval between January 1st, 2008 and June 30th, 2013. Each monthly solution derived from 48 hours of continuous recordings, synchronously with all 98 stations of the HEPOS network. This approach permits the acquisition of uniform and reliable data of similar quality.

The overall network consists of identical instruments (Trimble NetRS receivers with Trimble Zephyr Geodetic antennas with Radome mounted on steel masts of 10 cm in diameter), carefully founded on top of stable, mostly single-floor, bulky buildings in selected positions with minimal multipath and ample sky view.

The coordinates of the stations were computed in the ITRF2008 (IGS08) using adjusted baselines and final precise orbits from the International GNSS Service (IGS). Because of the

focus of this work, the overall network was tied into ITRF2008 using one EPN station (EUREF Permanent Network) at the middle of the study area (AUT1 in Thessaloniki). The quality of the adjustment was tested on the basis of the differences of adjusted coordinates of three other EPN stations in Greece (NOA1, PAT0 and TUC2; for location see Fig 1). The selected adjustment strategy, offering sub-cm differences for the three control EPN stations, was adopted because (1) it is simple and easily tested, (2) it is optimal for the study of tectonic motions in a relatively small area, and (3) with the necessary transformations data can be used for more regional studies.

Another important aspect in the processing was the selection of the baselines. We processed baselines up to 150 km in length, creating a network of 720 baselines between the 98 HEPOS stations. In this way, we could ensure high redundancy and – at the same time – very precise baseline solutions. Very few outliers were detected using standard techniques and were excluded from further processing. The coordinates for each monthly solution have been computed by means of a least squares network adjustment. Processing was based on the Trimble Total Control ver. 2.73 software. The ambiguities of the double-differenced carrier phase observations have been fixed for all baselines. The iono-free linear combination has been used to minimize the ionospheric influence. The a-posteriori 1-sigma error for the East (E) and North (N) components was typically in the sub-millimeter level. From the repeated analysis of the network, 66 epoch coordinates for each of the 20, out of the 98 in total, stations examined were available for further processing.

From these coordinates, and using a least squares-based trendline analysis, annual rates of displacement in the East (E) and North (N) axes, and the associated mean misfit errors, were computed and are summarized in Table 1. Few outliers, detected to strongly deviate from the trendline using standard techniques, were removed from our database. The database practically

consists of 66 points for the vast majority of stations. Three representative examples are shown in Figure 5 and indicate that data are characterized by an unambiguous linear trend. Because of the consistency of the data (Fig. 5), the near uniformity of the processing-derived errors and the high redundancy of the system of equations for each trendline in Figure 5 (66 observations minus two unknown variables), a non-weighted fitting was selected. Computed mean misfit errors, around 0.2 mm/yr for E and 0.3 mm/yr for N (Table 1), typically corresponds to white noise and ignore coloured noise which affects continuous GPS data (Mao et al., 1999; Williams et al., 2004; Santamaría-Gómez et al., 2011). This makes necessary to compute the total noise (error).

For the area of Greece the relationship between white noise and total noise in permanent stations have been studied by Hollenstein (2006) and Muller (2011), who computed a scaling factor which permits to derive total noise in GPS measurements as a function of white noise and of time span. For continuously recording stations covering a period of 5-6 years, this factor is of the order of 5, but it seems to overestimate total errors because it was derived from non-uniform data showing a large scatter (see Fig. 3.13 in Muller 2011).

Based on Williams (2003) time-correlated noise can be described by power-law models, in which the power spectrum P has the form $P=f^a$ (1), where f is frequency and a the spectral index, which corresponds to the slope of the spectrum. When $a=0$ only white noise is present in time series and when $a=-1$ or $a=-2$ the time series is contaminated by time dependent noise (usually flicker or random walk noise; Williams et al., 2004; Santamaría-Gómez et al., 2011).

For this reason we computed the power spectra of observations from which displacement rates were derived, and some representative results are shown in Figure 6. The spectral analysis was made using the least-squares based NormPeriod Code, which permits to analyse without padding short time series (Pytharouli and Stiros 2008). Line fitting to the statistically significant

part of the spectrum (periods 5 years to 3 months) indicates nearly zero inclination for the East component, indicative of nearly white noise, and mild inclination for the North component, indicative of limited time-dependent noise (Fig. 6).

Based on Fig. 4 in Williams (2003) computed inclinations (i.e. the spectral index α) correspond to scaling factors of the order of 3; a result consistent with the results of Feng and Newman (2009) who found that two types of coloured noise (flicker and random walk noise) are roughly up to two times larger than white noise, and hence the ratio of total noise to white noise is less than 3. Hence error estimates in Table 1, up to 0.7mm/yr for displacements along E and up to 1mm/yr along N, seem to represent realistic estimates of the total noise in displacement rates in the 1-sigma level.

Furthermore, and in order to obtain more easy-to-understand results, we adopted a linear transformation, a simple translation of the coordinate system not introducing additional noise. In the new coordinate system, the origin was shifted by a constant value, approximately equal to the displacement rate of station 041A, near the Bulgarian border and close to the west side of Strymon River (Fig 4). Hence, computed annual displacement vectors refer to a local reference system which practically indicates movement of stations relative to point 041A. Computed displacement rates are reliable, in their majority statistically significant (Table 1; Fig 6) and can be used to characterize tectonic movements in NE Greece.

5. Evidence for Tectonic Movements on the SFS

Figure 4 illustrates the magnitude and orientation of the GPS displacement vectors in NE Greece with respect to the reference station 041A. East of the Strymon River, the displacement vectors appear to have a consistent and uniform NNW orientation and amplitude of ca. >2 mm/yr, which

increases eastwards (up to 5 mm/yr) (Fig. 4). By contrast, immediately west of the Strymon River, and across a distance of <30 km, the displacement vectors show a variable character, with an overall prevailing SSW orientation (Fig. 4). An exception to this is the station located north of the epicentral area of the 1932 earthquake (station 075A; Fig. 4), which records NNE movement of ~2.4 mm/yr. This station is likely to reflect a local perturbation in the displacement field as it is located in the immediate proximity of the active normal fault that ruptured during the 1932 M7 Hierissos earthquake (Papazachos and Papazachou 1997; Pavlides and Tranos, 1991). The region west of the Strymon River includes also the epicentral area of the 1978 M6.5 Thessaloniki earthquake (Figs. 2&4), the causative fault of which was deduced from elastic dislocation analysis and elevation changes (Stiros and Drakos, 2000; Müller et al., 2013). The sparse distribution of GPS stations around this fault does not, however, permit a precise quantification of the strain that is currently accumulated on this structure.

In order to further explore the velocity field proximal to the Strymon Fault System, each onshore displacement vector located to the east of the Strymon river (Fig. 4) is analysed in two components, one parallel and one normal to the mean trend of the Strymon River (335°N) and projected along this trend, which coincides with the mean strike of the SFS (see S-S' transect in Fig. 4). The mean value of these components, weighted by their uncertainties is 3.3 ± 0.3 mm/yr (Fig. 7). The along-strike component of displacement shows clear evidence of left-lateral strike-slip movement across the Strymon Basin (Fig. 4). This rate is significantly larger than the Quaternary throw-rate across the SFS (~0.4 mm/yr), as estimated in southwest Bulgaria (Zagorčev, 1992). This is not surprising as large horizontal to vertical slip ratios are typical for strike-slip faults globally (Keller et al., 1982; Mouslopoulou et al., 2007; Carne and Little, 2012).

Further examination of Figure 7 shows that there is an eastward increase (from ~ 2 mm/yr to $> \text{ca. } 5$ mm/yr) in the amplitude of the displacements vectors with increasing distance from the Strymon River. This abrupt increase that occurs across the Nestos River, may be indicative of an additional left-lateral strike-slip fault (Figs 4 & 7). Indeed, the amplitude of the displacement vectors west of the Nestos River is significantly smaller (ca. 2.5 mm/yr) compared to that recorded immediately to the east of the river (ca. 4-5 mm/yr), providing some evidence of additional left-lateral strike-slip faulting. Nevertheless, this observation should be further explored as it cannot be fully supported by our data. Thus, the area east of the Strymon River (east Macedonia and Thrace) is considered to form a quasi-rigid block.

The deformation field south of the SFS is dominated by the prolongation of the fast-moving (e.g. > 20 mm/yr) strike-slip North Anatolian Fault (NAF) into the primarily extensional field of the North Aegean Trough (NAT) (Armijo et al., 1999). This area has accommodated numerous earthquakes (Papazachos and Papazachou, 1997), with the most recent earthquake sequence occurring in May 2014 (these earthquakes, the largest of which was of M6.9, are not recorded in our dataset) (Fig. 2). The interaction of strike-slip and normal faulting produces oblique-normal slip, resulting to the formation of numerous pull-apart basins along the NAT (Taymaz et al., 1991; Armijo et al., 1999). This area is also the locus of numerous historic earthquakes (Papazachos and Papazachou, 1997) (Fig. 2).

There are no data that would allow us to track the offshore continuation of the SFS into the north Aegean. Nevertheless, a bathymetric low immediately north of the NAT strand, and east of the Athos peninsula (see grey shading in Fig. 2), may indicate that the left-lateral SFS extends southward to intersect at high angles the faults in the NAT. Two synchronously active strike-slip faults with opposing sense of slip facilitate the formation of a bathymetric low proximal to their

mutual intersection as the crust in this area is extensively stretched (Fig. 2). Interaction between strands of the SFS and NAT may place a time constrain to the activity of SFS as a left-lateral fault. The SFS prior to 5 Ma was known to accommodate oblique right-lateral slip (Zagorcev, 1992a & b). The formation of the NAT occurred in the last 5 Ma when the right-lateral NAF propagated into the north Aegean (Armijo et al., 1999). It is, thus, likely that the SFS may have switched its sense of slip, from right-lateral to left-lateral, during the last 5 Ma in response to, and concurrently with, the formation of the NAT. Thus, it appears that left-lateral faulting along the SFS may be intimately linked in space and time with oblique right-lateral faulting on the NAT.

A further observation in support of our suggestion that the SFS is an active strike-slip fault derives from the occurrence of important geothermal fields within the Strymon Basin (Maratos, 1966; Fyticas et al., 1984) (Figs. 2&4). It has been established that the occurrence of high heat-flow in northern Aegean and southern Balkan correlates positively with strike-slip faulting (Stiros, 1991). Additional independent evidence in support of active strike-slip faulting along the SFS comes from numerous borehole data that testify shearing deformation along the Strymon Valley (Karystinaios, 1984). Interestingly, analysis of GPS displacements from south Bulgaria do not support left-lateral displacement along the SFS (Pérouse et al., 2012); they instead indicate extension (Kotzev et al., 2001; 2006; Georgiev et al., 2007). However, these data result from a limited number of survey stations with small signal to noise ratio (see also discussion in Section 4). Yet, focal mechanisms of microearthquakes from the same area (south Bulgaria) provide evidence of a complex deformation pattern, not inconsistent with a shear zone (e.g. combination of transpression and transtension) (Kotzev et al., 2006).

6. Seismic Hazard and Call for Future Work

GPS data reveal that the SFS is active, accommodating lateral displacements at rates of ca. 3.3 ± 0.3 mm/yr. Contemporary GPS measurements provide a geologically instantaneous strain record which is likely to include both permanent (seismic or aseismic) and elastic strains (e.g. McCaffrey et al., 2000; McClusky et al., 2000). Hence, one question that arises is whether the strain currently stored across the SFS is converted entirely into permanent tectonic deformation (by fault slip or creep) or whether the GPS data record horizontal displacements that result from a combination of additional processes such as, magmatic intrusions, block rotations around vertical axis and/or microseismicity (Friedrich et al., 2003; Pancha et al., 2006; Nicol and Wallace, 2007; Sue et al., 2007; Calais et al., 2008; Mouslopoulou et al., 2013). Both of the above scenarios, and also their combination, have been encountered in Nature. Indeed, several studies globally have shown that GPS data compare favourably with geological and/or seismic data (e.g. Hindle et al., 2002; McCaffrey, 2005; Nicol and Wallace, 2007). However, there are cases in which GPS and geological rates are dissimilar, as these datasets often sample different timescales and record different processes (e.g. Donnellan et al., 1993; Liu et al., 2000). Although the available data do not allow the discrimination between the above scenarios, the dramatic change in the displacement pattern across the SFS and the little internal deformation of the block east of the Strymon River (Figs. 4 & 7), suggest that the accumulated strain (3.3 ± 0.3 mm/yr) is likely to be released seismically during future rupture of the southern SFS. Thus, in the following discussion we will be conservative and assume that the interseismic strain is converted in its entirety to permanent deformation through large magnitude earthquakes.

It is known that the size of the earthquake events scales with the length of the fault that ruptures (Wells and Coppersmith, 1994). Although the SFS is more than 200 km long, it is

unlikely that it will rupture in its entirety. This is because the SFS is clearly segmented (Zagorcev, 1992). Its southernmost onshore segment traverses northeast Greece, from Strymonikos Gulf to the Greek-Bulgarian border (where it abuts against the BKFS) and is, at least, 80 km long (Fig. 2). Strike-slip faults of such length are capable of producing earthquakes of up to 7.4 in Magnitude (M_w) with associated coseismic displacements that may reach up to 3 m in size (Wells and Coppersmith, 1994). The capacity of the area to produce earthquakes of such magnitude is confirmed by historical data, such as the M7.3 earthquake that occurred near Drama and Xanthi in 1829 (Papazachos and Papazachou, 1997) (Fig. 2).

If the strike-slip rate recorded by the GPS data across the SFS (3.3 ± 0.3 mm/yr) persists over thousand yearlong timescales, the cumulative lateral displacement during Holocene would be 35-40 m while the cumulative vertical displacement would be ~ 3 m (based on the horizontal to vertical ratio; see section 5). Interestingly, and despite these relatively high rates of displacement accumulation, there is no clear evidence of recent faulting along the section of the SFS that traverses northern Greece. This may be due to a number of reasons, including: a) incomplete mapping of the late Quaternary trace of this section of the SFS, as the fault was thought to be inactive and/or mainly dip-slip (normal). Thus, no particular attention has been given to identifying potential left-lateral displacements within the Strymon Valley; b) vertical coseismic displacements of ~ 20 -30 cm are easily modified/eroded, especially because the fault straddles a major active river system that continuously resets the landscape by its large sediment supply (small fault scarps may be fast buried beneath alluvial deposits); c) the agricultural communities that inhabited the riverbeds of Strymon cultivated for millennia the land and almost certainly have contributed to the non-preservation of the small-scale coseismic vertical offsets. The only other known strike-slip fault in continental Greece is located near Patras in

Peloponnesus (south Greece, for location see Fig. 1). Similarly to the SFS, this fault also lacks surficial geomorphic expression and it was only identified in 2008 when it ruptured through a M6.4 earthquake (Feng et al., 2010; Stiros et al., 2013).

In the light of these new data, we urgently need to quantify the late Quaternary activity on the SFS. This may be achieved by identifying and measuring cumulative displacements across offset features (e.g. streams, spurs, river terraces or even manmade constructions). This will provide a geological (thousand year old) fault displacement rate which could be directly compared to the GPS rate (3.3 ± 0.3 mm/yr). The comparison will shed light to whether other processes, in addition to fault slip/creep, operate in this region. Last but not least, potential fault trenching would help constrain the number and, possibly, the slip-size of each paleoearthquake that ruptured the SFS during the recent past (e.g. Holocene). This is particularly important because in this way the slip per event and the average earthquake recurrence interval will be measured directly on the fault (e.g. Pantosti et al., 1996; Rockwell et al., 2000; Dawson et al., 2003; Nicol et al., 2010; Mouslopoulou et al., 2012).

Estimating the average earthquake recurrence interval on the SFS is a pressing need not only because there are large cities proximal to the SFS (e.g. Serres, Kilkis, etc.) where more than 200 thousand people reside, but also because the important civil infrastructure that is accommodated in the area (bridges, dams, gas pipelines, etc.) is designed for low seismic hazard. Among them, the Trans Adriatic Pipeline (TAP), which is soon expected to transfer natural gas from the Caspian Sea to Italy, is designed to traverse the SFS at high angles (Fig. 4). Possible episodic deformation on the SFS will therefore affect the TAP. In a similar setting, the Trans-Alaska Pipeline System, that crosses the surface trace of the large strike-slip Denali Fault, was severely affected when the fault ruptured through a M7.9 earthquake in 2002. Despite the

severity of this earthquake, which resulted in the lateral and vertical movement of the pipeline by 2.5m and 0.75m, respectively, the pipeline suffered significant but not fatal damage, as it was designed to move laterally along beams to withstand major shaking (Sorensen and Meyer, 2003). Perhaps a similar mechanism, that would allow sufficient lateral and vertical movement, should be considered for the construction of the TAP. Similarly, a dam in the 17 km long and 5 km wide Kerkini Lake, originally built in 1932 and redesigned in 1982, is located in the immediate proximity of the SFS and is likely to be seriously affected by rupture along this fault (Fig. 4).

Hence, much attention should be placed not only to areas with frequent earthquakes such as the Gulf of Corinth in Greece (see Avallone et al., 2004), which are indeed somewhat prepared for strong earthquakes, but also in areas of low historic seismicity, where earthquakes may cause serious problems (cf. Stiros, 1998).

7. Conclusions

The current kinematic patterns of northeast Greece (Thrace and East Macedonia), an area of relatively low rates of deformation, remain largely unknown. In this article we analyse new homogeneous data that derive from the first permanent GPS network in Greece (HEPOS) to shed light in the kinematics of the area. We find that GPS displacement vectors that record deformation across the Strymon Valley for a period of 5.5 years differ significantly in orientation and magnitude. Specifically, the velocity vectors appear to have rotated, from NNW to SSW, across a distance of <30 km, accommodating a mean horizontal displacement rate of 3.3 ± 0.3 mm/yr. We attribute this kinematic translation to result from movement along a left-lateral strike-slip fault of NW-SE orientation. A likely candidate responsible for accommodating this strain is the Strymon Fault System (SFS), a large structure that traverses SW Bulgaria and NE Greece. The southernmost segment of SFS traverses northeast Greece for at least 80 km. A fault

of such length is capable of producing earthquakes of $>M7$ and lateral coseismic displacements of up to 3m. If the interseismic strain currently stored across the SFS is converted into permanent deformation during large-magnitude earthquakes, this may have significant repercussions in the seismic hazard of northeast Greece (and southern Balkans), a densely populated region that accommodates significant infrastructure (e.g. the Trans Adriatic gas Pipeline).

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Figure captions

Figure 1:

Annual displacement vectors from the HEPOS GPS network in Greece for the period October 1st, 2007 to December 31st, 2009. The motion is calculated relative to a station located in north Greece and marked by a grey triangle. Some vectors indicate perturbation of the displacement field by seismic displacements. A star indicates the 1995 Kozani-Grevena earthquake. The study area is indicated by a white dashed rectangle. NAT: North Aegean Trough, NAF: North Anatolian Fault, SR: Strymon River, CG: Corinth Gulf. EUREF Stations mentioned are located in ATH (Athens, NOA1), CHA (Chania, TUC2), PAT (Patras, PAT0) and THE (Thessaloniki, AUT1).

Figure 2: Seismotectonic map of northeast Greece showing the main tectonic structures of the study area (map modified after IGME, 1989). Offshore shaded area indicates a likely pull-apart basin near the intersection of the SFS with the NAT/NAF. Red stars indicate major earthquakes in the vicinity of the Strymon River, including also the recent events of the 2014.05.24 seismic sequence along the NAT (not covered by our study period). Large and small stars indicate 6-7 and 4-5 magnitude earthquakes, respectively. Solid and dashed circles represent epicenters of $M > 6.5$ earthquakes that ruptured the upper 60 km of the crust post and prior to 1900 AD, respectively (extending back to 2500 years BP). Red triangle depicts the Pliocene volcanics (Maratos, 1966). SFS= Strymon Fault System, NAT=North Aegean Trough, NAF=North

Aegean Fault, SG= Strymonikos Gulf, BKFS = Belasitsa Kerkini Fault System, THE=Thessaloniki, KIL: Kilkis, SER=Serres, DRA=Drama, KAV=Kavala, XAN=Xanthi, KRU:Krupnik.

Figure 3: Micro- to moderate earthquake activity ($M < 5$) that ruptured the upper 20 km of the crust within the Strymon Valley during the last 20 years (1993-2013). Data derive from the earthquake catalogue of the National Observatory of Athens, Greece (<http://www.gein.noa.gr/en/>).

Figure 4: Vectors of relative annual displacement rates of the HEPOS stations in northeast Greece (red arrows) for the period 2008.01.01- 2013.06.30 and the corresponding 1- σ error ellipses. Epicentres and inferred faults of the two large ($M > 6$) 20th century earthquakes west of the Strymon River are also shown. The Strymon (Struma), Nestos (Mesta) and Evros (Maritsa) Rivers are also indicated. A yellow star depicts Pliocene volcanics (Maratos, 1966). Offshore tectonic structures simplified after Armijo et al. (1999) and Papanikolaou et al. (2004). The approximate location of the Trans Adriatic Pipeline (TAP) is shown by a black dashed line. S-S' axis corresponds to the mean strike of the SFS (335°N). BKFS = Belasitsa Kerkini Fault System, SG= Strymonikos Gulf, SFS= Strymon Fault System. Data cover a different time span and derive from a different analysis from those of Figure 1.

Figure 5: Time-series showing the East and North component of three representative GPS stations of Table 1 and the corresponding best fitting lines for the period 2008.01.01-2013.06.30, in a total of 66 sets of homogeneous data. See Figure 4 for locality.

Figure 6: Power spectra of the datasets in Figure 5. The area of statistically significant frequencies is highlighted, and the best fitting lines of the spectra and their slope are also shown.

Figure 7: Displacement rates of the onshore GPS stations east of the Strymon River, parallel (black square) and normal (red circles) to the mean strike of the SFS (SS' axis in Fig. 4).

Table 1. Summary of the analysed data for each GPS station: approximate station coordinates, displacement rates and 1- σ errors (misfit errors corresponding to white noise and σ_E to total noise). r^* : absolute displacement rate, r : relative displacement rate. For the locality of each station see Figure 4.