

# Ground deformation effects from the ~M6 earthquakes (2014–2015) on Cephalonia–Ithaca Islands (Western Greece) deduced by GPS observations

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**Abstract** The implications of the earthquakes that took place in the central Ionian Islands in 2014 (Cephalonia,  $M_w$ 6.1,  $M_w$ 5.9) and 2015 (Lefkas,  $M_w$ 6.4) are described based on repeat measurements of the local GPS networks in Cephalonia and Ithaca, and the available continuous GPS stations in the broader area. The Lefkas earthquake occurred on a branch of the Cephalonia Transform Fault, affecting Cephalonia with SE displacements gradually decreasing from north ( $\sim 100$  mm) to south ( $\sim 10$  mm). This earthquake revealed a near N–S dislocation boundary separating Paliki Peninsula in western Cephalonia from the rest of the island, as well as another NW–SE trending fault that separates kinematically the northern and southern parts of Paliki. Strain field calculations during the interseismic period (2014–2015) indicate compression between Ithaca and Cephalonia, while extension appears during the following co-seismic period (2015–2016) including the 2015 Lefkas earthquake. Additional tectonically active zones with differential kinematic characteristics were also identified locally.

**Keywords** Tectonic motions · Ground deformation · GPS measurements · Cephalonia · Ithaca Islands · Ionian Sea

## Introduction

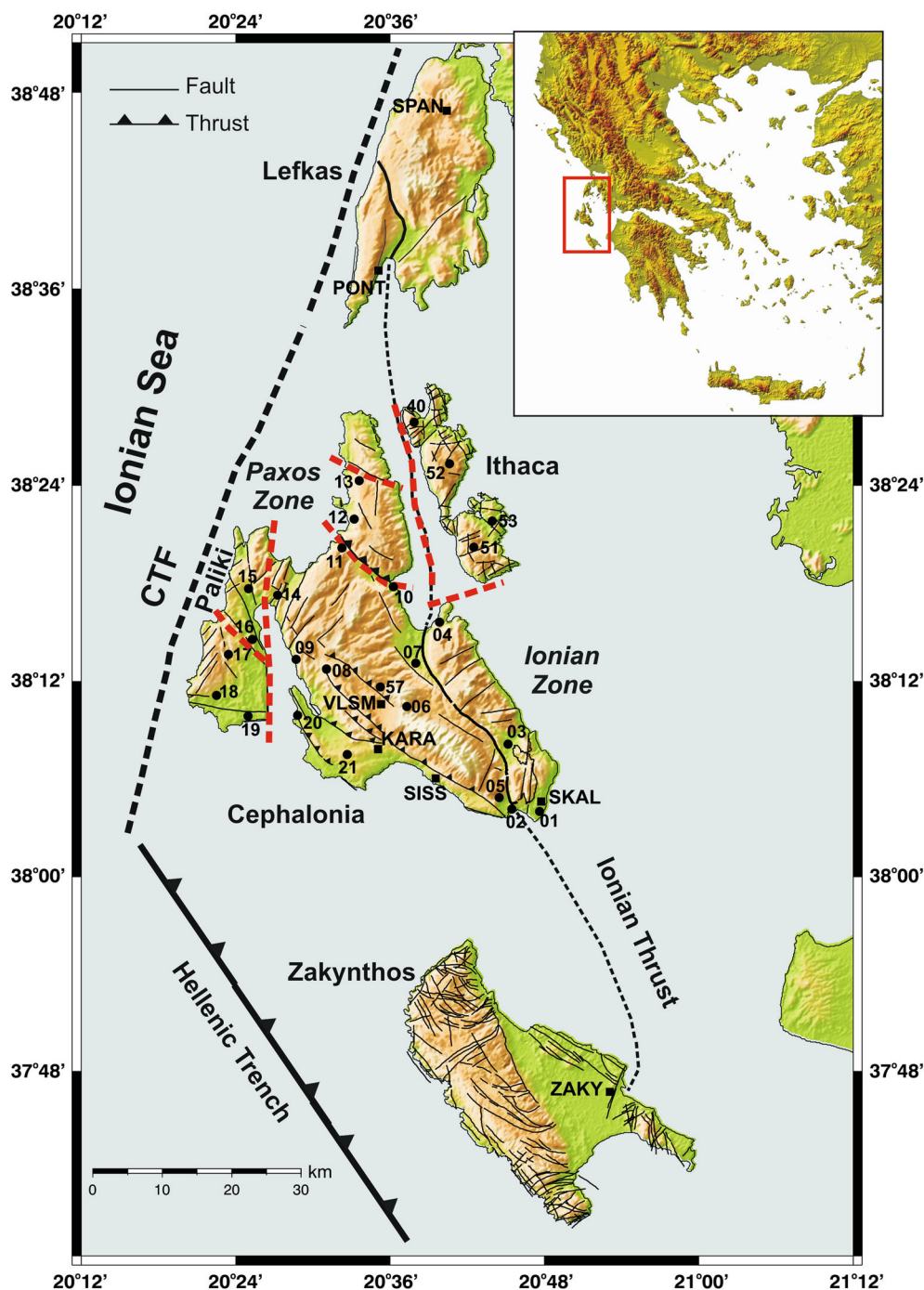
During the last few years, an increased seismic activity has taken place in the central Ionian Islands (Fig. 1), one of the most tectonically active areas of Europe. It is an area with major seismogenic zones that includes the cephalonia transform fault (CTF), the dominant faulting system in the area, as well as several other faulting features which combine to generate the largest seismic energy release in Europe (e.g., Le Pichon et al. 1995).

The broader area exhibits a complex kinematic state that changes from north to south. The collision between Apulian microplate and Eurasia in the north, the right lateral CTF in the central part and the oceanic subduction in the south creates a complicated stress field that affects both regional and local ground deformation, which makes difficult the understanding of the ongoing local tectonic activity in the area (e.g., van Hinsbergen et al. 2006; Vassilakis et al. 2011). Velocities increase systematically from north to south (e.g., Ganas et al. 2013). In addition, a clockwise rotational pattern in the Ionian region complicates the kinematics even more (e.g., Lagios et al. 2007; Chousianitis et al. 2015).

Large-magnitude earthquakes ( $M_w$ 5.9 and  $M_w$ 6.1) occurred in the western part of Cephalonia (Paliki Peninsula) in late January–early February 2014 (e.g., Papadopoulos et al. 2015; Karastathis et al. 2015; Karakostas et al. 2015), causing severe damage in this part of the island (e.g., Lekkas and Mavroulis 2015). After the occurrence of these earthquakes, a long seismic sequence followed (see red and yellow colored epicenters in Fig. 2) that lasted several months in 2014. These epicenters were mainly located along a ruptured NNE–SSW trending faulting zone in Paliki, as modeled from local GPS data (Sakkas and

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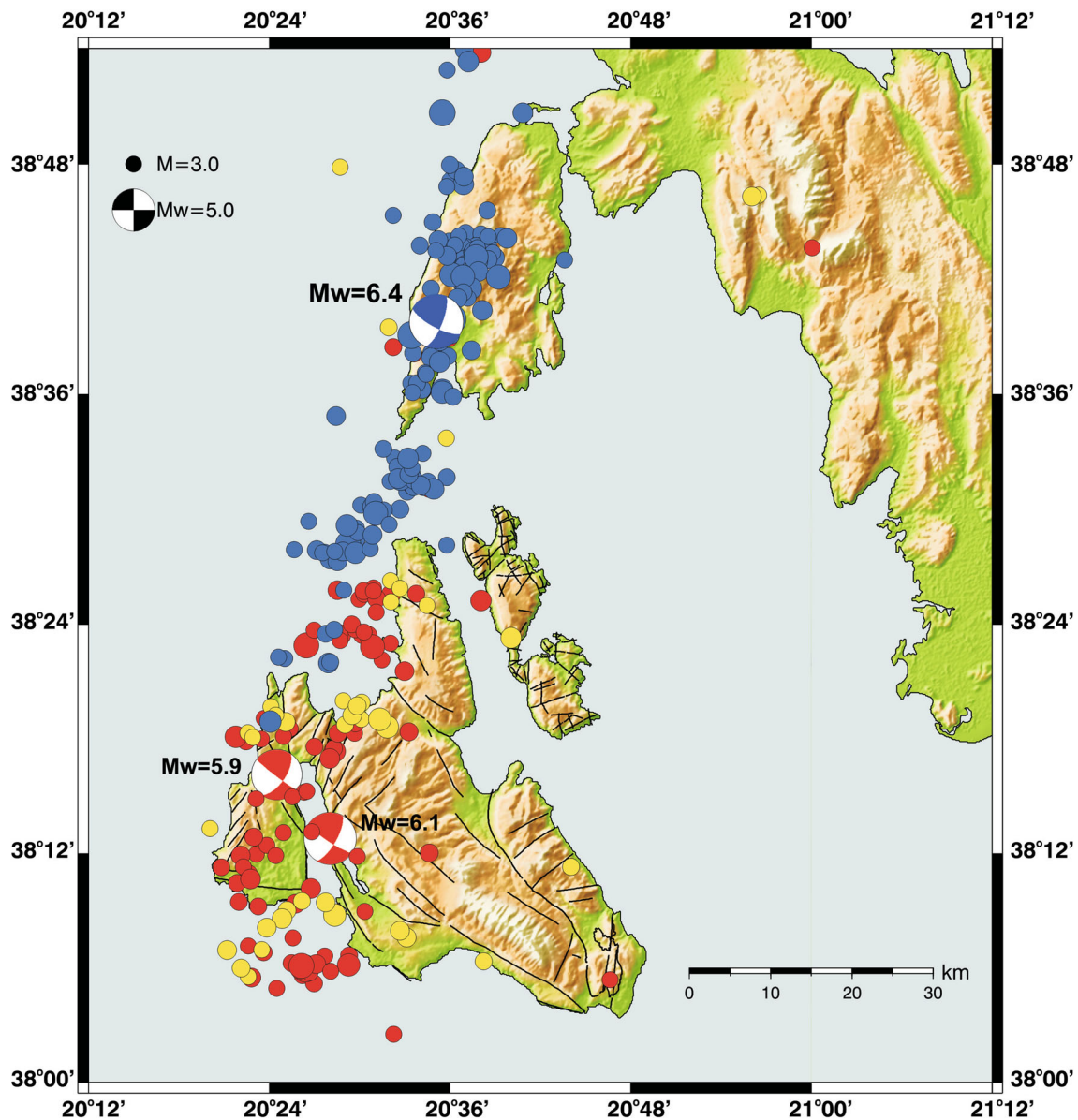
**Fig. 1** Map of the broader area of Central Ionian Islands, showing the main faulting and thrusting zones, together with the distribution of GPS benchmarks (circles) and continuous GPS stations (rectangles). CTF: Cephalonia Transform Fault. Red dashed lines indicate the

approximate locations of inferred major kinematic boundaries deduced from the GPS observations as described in the text. Datum: WGS'84

Lagios 2015) and radar interferometric data (Briole et al. 2015).

An  $M_w$ 6.4 earthquake took place on November 17, 2015 in the southern part of Lefkas Island (Chousianitis et al. 2016; Ganas et al. 2016) just north of Cephalonia (Fig. 2). The earthquake was followed by a significant seismic

activity that also extended southwards into the sea to the west of the northern peninsula of Cephalonia (see blue epicenters in Fig. 2). This southern extension of activity covered the same area in the sea as that after the occurrence of an earlier  $M_w$ 6.3 earthquake in August 2003, which was located further to the north than the 2015 event, and just



**Fig. 2** Distribution of earthquake epicenters ( $M > 3$ ) in Cephalonia, Ithaca and Lefkas islands in the periods April 2014 to March 2015 (red circles), March 2015 to November 16, 2015 (yellow circles), and November 17, 2015 to February 2016 (blue circles) showing also the focal mechanisms of the earthquakes in Cephalonia ( $M_w = 5.9$  and

$M_w = 6.1$ ) in early 2014, and in Lefkas ( $M_w = 6.4$ ) on November 17, 2015. The relocated epicenters are from the NOA (Greece) earthquake catalog, and the focal mechanisms are from the Seismological Laboratory (NKUA)

offshore of the western coast of Lefkas Island (e.g., Karakostas et al. 2004; Papadimitriou et al. 2006; Lagios et al. 2007; Saltogianni and Stiros 2015).

The present paper provides a detailed description of the ground deformation in Cephalonia after the intense seismic activity in 2014, up to early 2016, including also the tectonic implications of the 2015 Lefkas earthquake on the broader area. These accounts are based on the repeat measurement of our Cephalonia–Ithaca GPS benchmarks, and the available continuous GPS stations in the broader area.

## GPS measurements

An extensive GPS network consisting of 27 stations (benchmarks) was installed on Cephalonia in 2001 and expanded to Ithaca in 2004 (Fig. 1). The locations of the stations were selected to better describe and study the kinematics of the recognized fault-blocks of these islands. This network was remeasured several times up to 2010 (Lagios et al. 2007, 2012), as well as in 2014, after the early 2014 earthquake sequence that occurred in

Cephalonia (Sakkas and Lagios 2015). The network was subsequently remeasured in early March 2015, and also in February 2016, after the recent event in the southern part of Lefkas, which occurred just 20 km north of Cephalonia. Data from continuous GPS (cGPS) recording stations located in the broader area were also processed and included in the present analysis.

Time series for the period January 2014 to February 2016 were compiled from four cGPS stations in Cephalonia—(1) Valsamata (VLISM), (2) Karavados (KARA), (3) Sissia (SISS), and (4) Skala (SKAL)—as well as two stations in Lefkas, (1) Spanochori (SPAN) and (2) Ponti (PONT) (Fig. 1). The Cephalonia–Ithaca benchmark network was occupied using Leica receivers of types SR399, SR9500 and GRX1200. For each daily session, the occupied stations were tied to all the Cephalonia-based cGPS stations that served as local reference stations. The motion at VLISM is well known (Table 1), as this station has been operating since 2005. Each roving station was occupied at least twice at a sampling rate of 15 s, and at a nominal duration time of about 48–56 h for each occupational period.

All the available GPS data were homogeneously processed using the Bernese Software version 5.2 (Dach et al. 2015). In addition to the regional cGPS network, data from seventeen IGS, EUREF, and cGPS stations in Greece (<http://www.epncb.oma.be>) were included in the processing. These additional sites were used to define the local reference frame to calculate the coordinates of the stations, and eventually the horizontal and vertical displacements with respect to IGB08 reference frame (<http://igsceb.jpl.nasa.gov/network/refframe.html>).

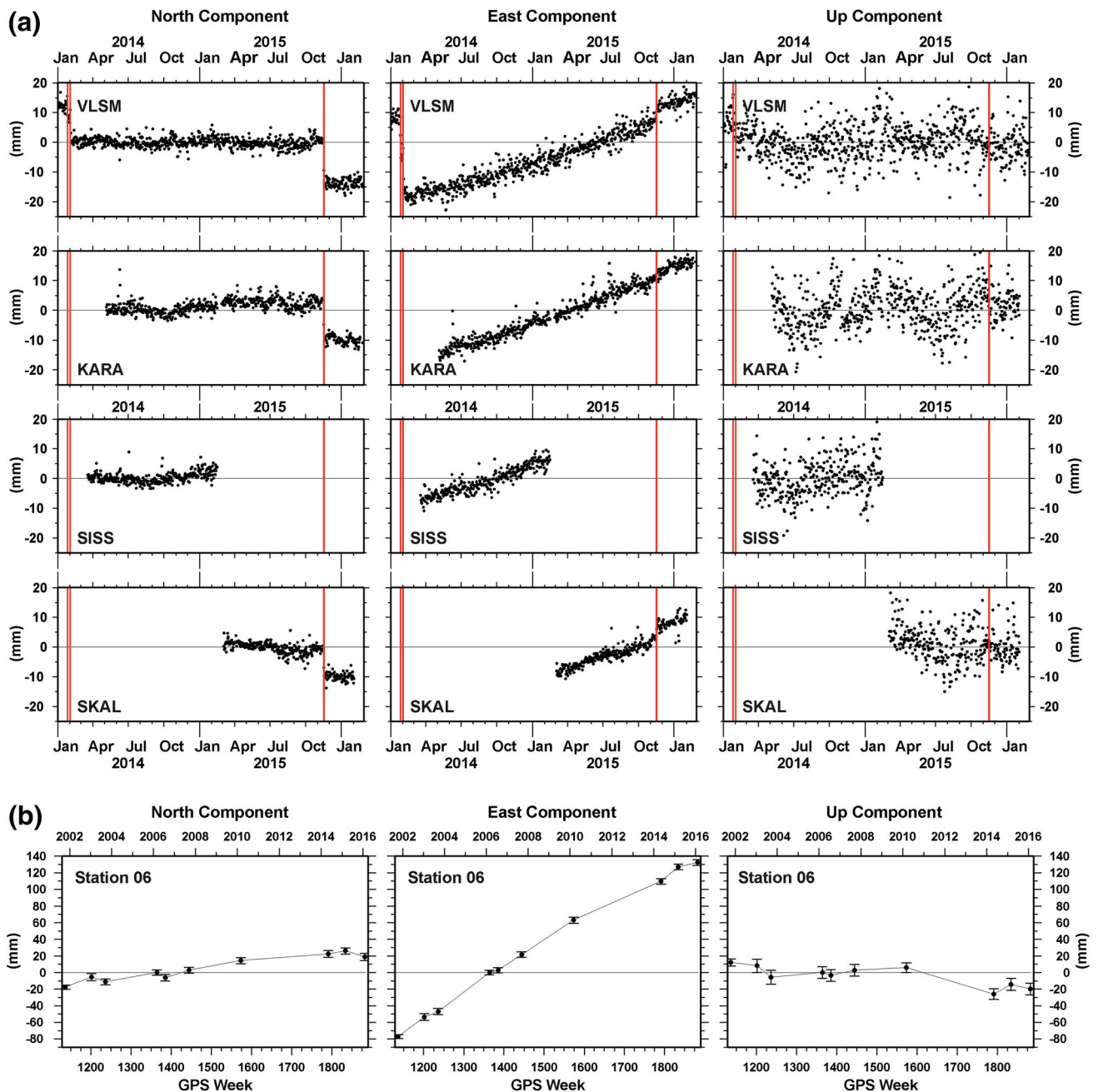
The GPS data were evaluated using a double-difference approach based on daily sessions. The modeled observable was the ionosphere-free linear combination. Ambiguities were solved using the quasi-ionosphere-free (QIF) strategy. For each station, hourly zenith path delays and daily gradient parameters were estimated. The Neill mapping function was used. Ocean tide loading corrections (<http://holt.oso.chalmers.se/loading>) according to model FES2004 and absolute antenna phase center corrections were

applied. Precise orbits, earth orientation parameters (EOP), satellite clock corrections and GPS monthly P1–C1 code bias solutions were obtained from the CODE analysis center (<ftp://unibe.ch/aiub/CODE>), grids of the Vienna Mapping Function (<http://ggosatm.hg.tuwien.ac.at>), and atmospheric coefficients (<http://geophy.uni.lu/>) were used to calculate a set of high-precision coordinates for the stations. The long-time span of the data significantly reduced uncertainties (at a 90% confidence level) for the majority of the stations to overall errors of about 1.4–7.1 and 2.2–8.1 mm for the horizontal and vertical solutions, respectively. Since the observations at each station last for several days, each day was treated as a separate 24 h long session. The errors, expressed as standard deviation, quantify the amount of variation of each daily session coordinate solution from the mean value.

The variation of the coordinates in the IGB08 reference frame for the cGPS stations in the area is shown in Figs. 3 and 4. Until the occurrence of the seismic events in Cephalonia (2014) and Lefkas (2015), these stations exhibited the anticipated regional motion of the area with respect to IGB08 (Ganas et al. 2013), which represents an NNE horizontal motion with small variations from north to south (Table 1). The seismic events in early 2014 caused a WSW horizontal motion accompanied by subsidence only at the station located in Cephalonia, while the 2015 event in Lefkas affected a much broader area extending as far as Zakynthos Island to the south, and AGRI station in the western part of Central Greece (Fig. 4). At the VLISM station in Cephalonia, the overall directional displacement during the early 2014 earthquakes was  $\sim 28$  mm in the WSW horizontal direction, and about  $-11$  mm in the vertical component (Sakkas and Lagios 2015); however, the rest of the central Ionian Islands were not affected. The 2015 Lefkas event caused a relatively large SW horizontal displacement at the cGPS stations in Lefkas ( $\sim 424$  and  $\sim 89$  mm in its southern and northern parts, respectively; Fig. 4a), and southward displacements in Cephalonia and Zakynthos, decreasing from  $\sim 17$  mm in the central part of Cephalonia (VLISM) to  $\sim 10$  mm in its southern part (SKAL), and  $\sim 6$  mm in Zakynthos (ZAKY) (Fig. 4b).

**Table 1** Continuous GPS station velocities with respect to IGB08

Station	Period	$V_{N-S}$ (mm/year)	$V_{E-W}$ (mm/year)	$V_{Up}$ (mm/year)
VLISM	01/2009–12/2013	$4.25 \pm 0.02$	$17.10 \pm 0.02$	$-0.63 \pm 0.05$
	01/2014–11/2015	$1.4 \pm 0.1$	$17.1 \pm 0.2$	$1.6 \pm 0.4$
KARA	05/2014–02/2016	$2.1 \pm 0.2$	$16.8 \pm 0.2$	$2.5 \pm 0.7$
SISS	03/2014–02/2015	$2.2 \pm 0.3$	$15.0 \pm 0.4$	$6.5 \pm 1.2$
SKAL	03/2015–02/2016	$-4.5 \pm 0.5$	$15.4 \pm 0.4$	$-8.5 \pm 2.0$
SPAN	01/2009–11/2015	$3.83 \pm 0.02$	$20.86 \pm 0.02$	$-0.5 \pm 0.1$
PONT	01/2009–11/2015	$6.81 \pm 0.02$	$20.44 \pm 0.03$	$-0.7 \pm 0.1$



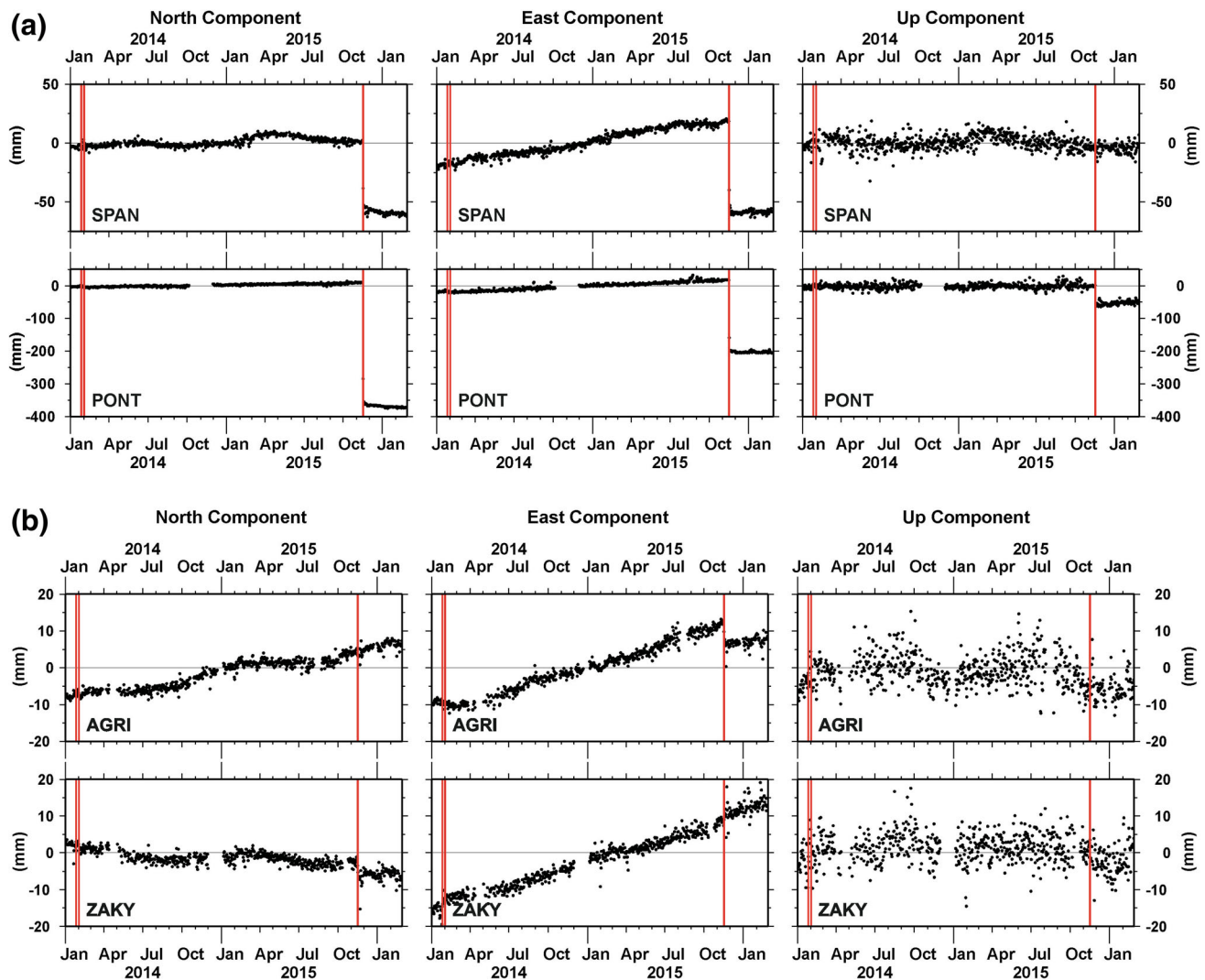
**Fig. 3** Time-series of the displacements observed at the continuous GPS stations in Cephalonia for the period Jan 2014 to Feb 2016 (a), together with the components of GPS station 06 (b), which has been used earlier as a network reference station in Aenos Mt. for the period

2001–2016 (Reference Frame: IGB08). Red vertical lines mark the occurrence of the main seismic events in the broader area (2014–2016)

Displacement of the vertical component during the same event was observed only at station PONT (subsidence  $\sim -56$  mm), which is located very close to the epicentral area, while there were no clear vertical displacements for the rest of the cGPS stations. A nearby benchmark to VLSM, station 06, which served as a local reference station from 2001 to 2010, showed a similar pattern to VLSM for all the observational periods (Fig. 3b).

### Period March 2014–March 2015

Figure 5 represents the displacement vectors for the period interseismic period March 2014 to March 2015 (Table 2). The overall character of the ground deformation was of an ENE displacement with small horizontal amplitudes that describes the anticipated motion of the area with respect to the IGB08 reference frame, as depicted by the cGPS



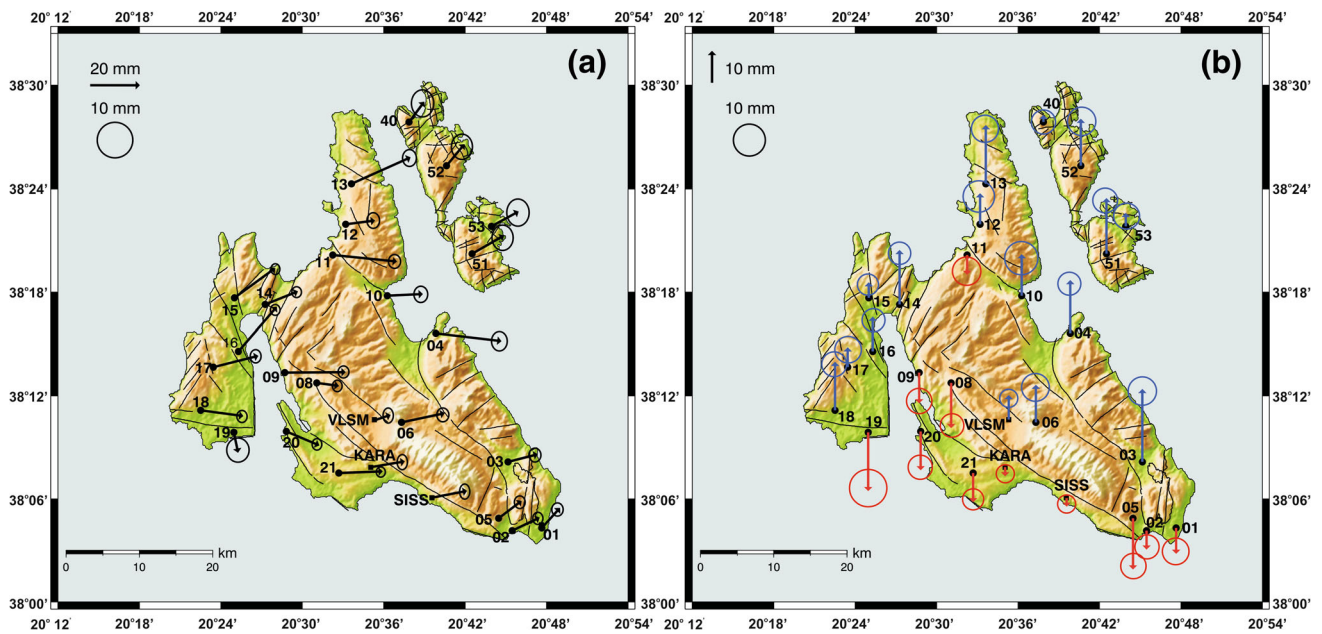
**Fig. 4** Time-series of the components observed at the continuous GPS stations in **a** Lefkas in its northern (SPAN) and southern (PONT) parts, and **b** in central-western Greece (AGRI) and Zakynthos Island

(ZAKY) (Reference Frame: IGB08). *Red vertical lines* mark the occurrence of the main seismic events in the broader area (2014–2016)

stations on the island (Fig. 3). However, there were some discrepancies in the deformational pattern along the island. The southern part of Cephalonia exhibited an almost ENE displacement with small horizontal amplitudes ( $\sim 11$  mm) and almost parallel vectors for all stations located in the area. In the western part of Cephalonia, in Paliki Peninsula, a slight differentiation of the motion along a north–south axis seemed to appear, with stations to the north showing a more northward displacement compared to those to the south. This differentiation took place in the vicinity of station 16, where a boundary of displacement has already been observed and outlined in an earlier analysis (Sakkas and Lagios 2015).

In the northern peninsula of Cephalonia, the amplitude of the horizontal component was slightly increased compared to the rest of the island ( $\sim 25$  mm). However, station

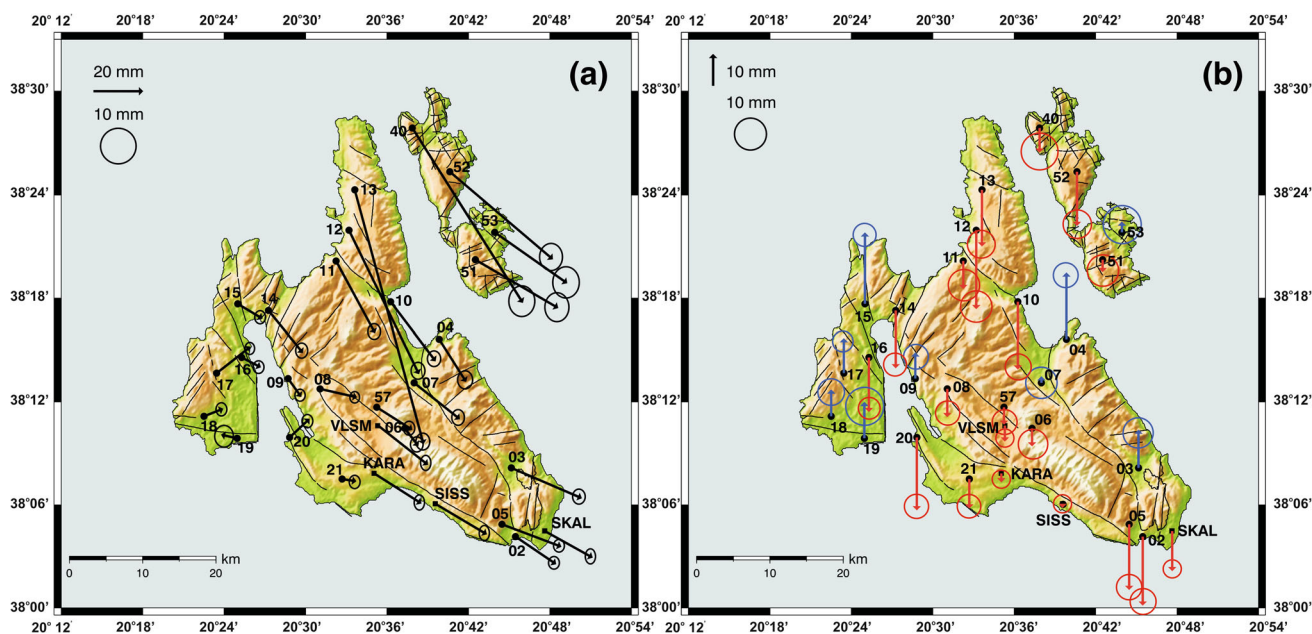
12 shows a smaller amplitude of displacement ( $\sim 12$  mm), a behavior that has also been observed in the past (Lagios et al. 2012). The increased horizontal component observed at these stations may be attributed to the seismic activity that followed the 2014 Cephalonian earthquakes, and was concentrated in the sea just to the west along the northern peninsula, and which was in progress during and after the observational period of March 2014. A similar behavior in this part of the island was also noticed during the post-seismic activity after the 2003 Lefkas earthquake (Lagios et al. 2007). A noticeable element during this period was the discrepancies in amplitude of the horizontal displacement for some neighboring stations, where their proximity did not fully justify the significant differences that were observed. Stations 08 and 09, VLSM and 06, as well as stations 10 and 11 showed displacements of similar



**Fig. 5** **a** Horizontal, and **b** vertical displacements from the Cephalonia–Ithaca GPS network for the period March 2014 to March 2015. *Red* and *blue* arrows indicate subsidence and uplift, respectively (Reference Frame: IGB080)

**Table 2** Component displacements of GPS and cGPS stations referred to IGB08 GPS period 2014–2015

GPS station	N–S (mm)	N–S SD (mm)	E–W (mm)	E–W SD (mm)	Up (mm)	Up SD (mm)
01	8.1	3.7	7.3	3.2	−8.1	8.2
02	5.3	3.4	11.0	2.8	−5.9	7.6
03	3.1	3.9	11.9	3.4	22.8	8.8
04	−3.1	5.4	26.3	4.4	16.6	7.2
05	7.0	3.6	9.2	3.0	−16.0	8.0
06	3.7	3.9	17.3	3.3	11.7	8.6
08	−1.2	3.2	8.9	2.8	−14.1	7.4
09	0.2	3.3	24.4	2.9	−9.6	7.8
10	0.7	4.6	14.2	3.9	13.0	10.4
11	−2.6	3.9	25.7	3.4	−6.2	8.9
12	1.5	4.3	11.7	3.6	9.7	9.7
13	10.7	4.7	23.7	3.9	18.3	8.5
14	5.3	3.1	13.1	2.7	17.0	6.9
15	12.0	3.0	16.4	2.5	4.9	6.6
16	17.9	3.1	15.4	2.7	10.8	7.1
17	4.6	3.7	18.1	3.1	6.2	8.3
18	−2.3	3.4	17.2	2.9	15.1	7.7
19	−8.2	6.7	1.7	6.2	−18.3	11.7
20	−5.6	3.2	13.2	2.7	−12.1	7.5
21	0.7	2.9	17.6	2.6	−9.1	6.6
40	8.2	8.6	6.1	7.3	2.3	7.4
51	7.4	8.1	12.8	6.9	17.4	7.7
52	8.7	8.2	7.2	6.9	14.7	8.8
53	6.0	8.6	10.9	7.2	4.2	8.0
KARA	2.3	3.1	13.4	2.6	−2.9	4.1
SISS	2.80	3.0	14.4	2.9	−2.7	4.5
VLISM	1.9	2.9	5.7	2.4	7.7	3.7



**Fig. 6** **a** Horizontal, and **b** vertical displacements from the Cephalonia–Ithaca GPS Network for the period March 2015 to February 2016. *Red and blue arrows* indicate subsidence and uplift, respectively (Reference Frame: IGB08)

direction, but with high-amplitude deviations. These deviations are attributed to local phenomena possibly associated with the complex and extensive nature of faulting in the near vicinity.

The vertical component (Fig. 5b) revealed a more unified pattern of displacement. Subsidence reaching amplitude of up to  $-15$  mm was observed along the southwestern part, an area characterized by a dominant NW–SE thrusting zone in this part of the island. For the rest of the stations, the vertical component revealed a moderate uplift. Taking into account the larger uncertainties involved in the calculation of the vertical component, it was assumed that the small discrepancies in that pattern (e.g., station 11) and in the amplitude may be attributed to local tectonic phenomena. For instance, the strong uplift ( $\sim 20$  mm) at the eastern stations 03 and 04 could be attributed to the presence of underlying evaporites of the Ionian Zone (Lekkas and Mavroulis 2016).

Finally, a non-consistent pattern of displacement for all measuring periods (2014–2016) both in the vertical and horizontal direction was noticed at station 19, in the southern part of Paliki. This irregularity may be attributed to predominately loose marine sediments in that area, probable fluctuation of the local water table, and lack of good satellite visibility that noticeably decreased the accuracy of the calculated coordinates.

The deformational pattern along Ithaca for this first remeasurement period depicted the previously described differential motion between its northern and southern parts (Lagios et al. 2012; Sakkas and Lagios 2015). The latter

becomes evident by the slightly different directions of the horizontal displacements between these parts. The amplitude of the horizontal displacements was about 11 mm at almost all stations, while the vertical components exhibited larger variations. It may be assumed that stations 52 and 51 better describe the kinematic state of the island, where almost the same amplitude of uplift ( $\sim 15$  mm) was measured.

#### Period March 2015–February 2016

The deformation that took place in the study area during this period was strongly affected by the 2015 Lefkas earthquake and the seismic activity that followed (Fig. 6; Table 3). Intense SSE displacement was observed in the northern, central and southern parts of Cephalonia, as well as in Ithaca. The amplitude of the horizontal displacements gradually decreased from about 100 mm in the northernmost part (station 13) to about 20 mm in the southern part of the island. These amplitudes were almost an order of magnitude higher in the north as compared to the previous period. In the central, western and southern parts, the horizontal displacement was almost two times larger than that in the period 2014–2015.

However, Paliki Peninsula, located in the western part of Cephalonia, revealed a significantly smaller horizontal displacement compared to the rest of the island, inferring a boundary that differentiated the motion in this part of the island from the other areas. Differentiations of the deformation pattern are also observed and along the stations



**Table 3** Component displacements of GPS and cGPS stations referred to IGB08 GPS period 2015–2016

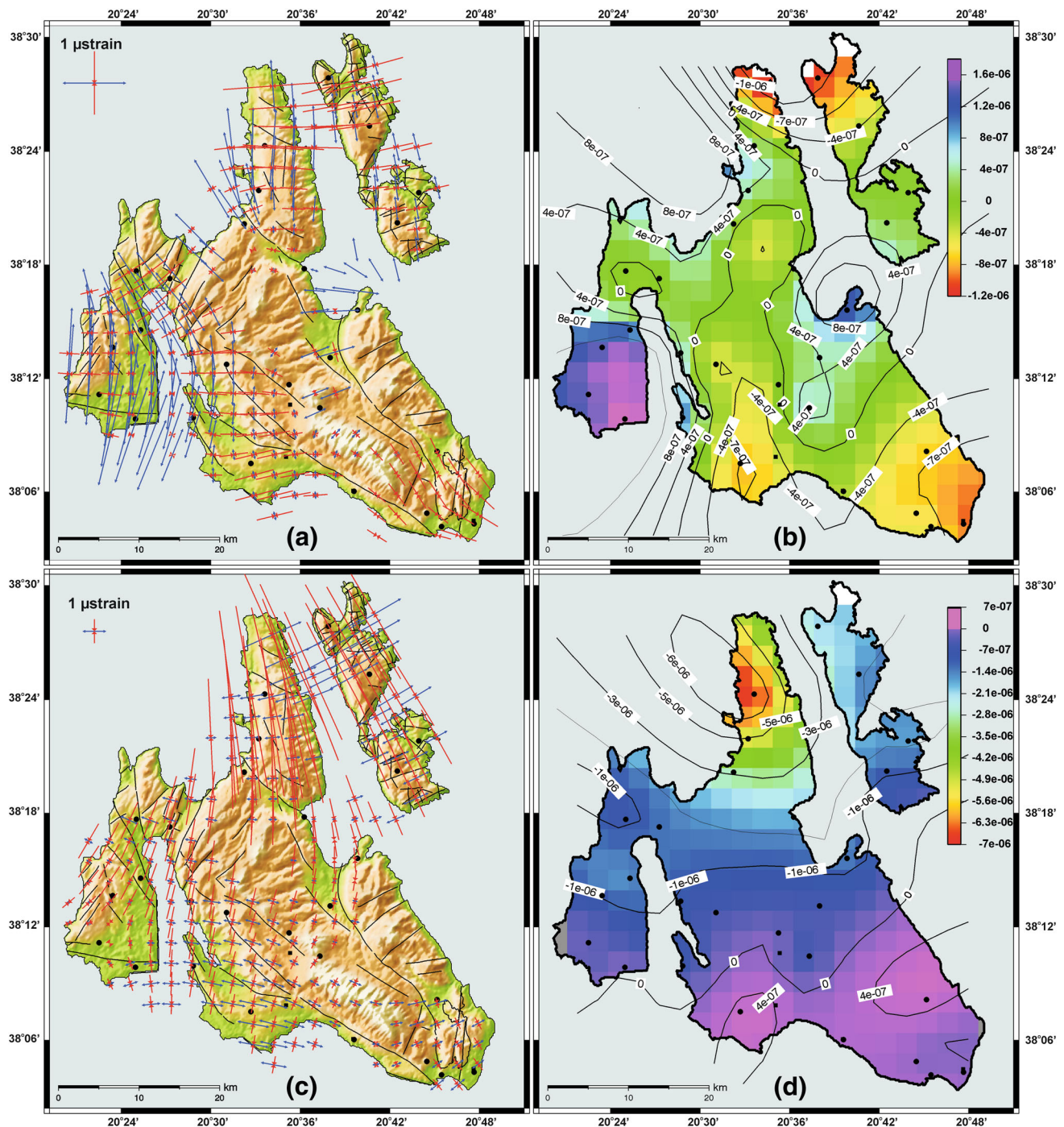
GPS station	N–S (mm)	N–S SD (mm)	E–W (mm)	E–W SD (mm)	Up (mm)	Up SD (mm)
02	–11.1	3.6	16.3	3.0	3.6	8.1
03	–12.2	4.3	28.3	3.6	4.2	9.4
04	–17.1	5.1	10.8	4.2	5.0	7.6
05	–9.1	3.6	23.8	2.9	3.6	7.9
06	–7.1	4.3	5.4	3.6	4.2	9.2
07	–14.6	4.4	18.3	3.6	4.3	9.8
08	–3.4	3.3	14.9	2.7	3.2	7.5
09	–7.4	3.3	5.3	2.9	3.3	7.6
10	–23.8	4.4	18.0	3.7	4.4	8.0
11	–28.9	4.3	15.6	3.6	4.3	9.7
12	–57.7	4.8	28.0	3.9	4.8	9.7
13	–101.9	4.8	27.5	3.9	4.8	8.6
14	–17.0	4.2	13.8	3.4	4.2	7.1
15	–6.0	3.7	10.0	2.9	3.6	7.0
16	–4.0	3.5	7.8	2.9	3.5	6.8
17	10.7	3.3	13.6	2.8	3.3	6.4
18	3.1	3.6	7.8	3.0	3.6	8.2
19	1.5	6.0	–6.5	5.2	6.0	11.8
20	7.5	3.6	8.0	3.0	3.6	7.5
21	–0.9	3.6	5.7	3.1	3.6	7.2
40	–70.2	8.6	44.2	7.2	8.6	10.5
51	–19.4	8.1	33.2	6.8	8.1	9.8
52	–35.2	7.6	41.3	6.4	7.6	8.7
57	–9.1	3.9	14.3	3.2	3.9	7.7
53	–20.5	8.8	29.1	7.4	8.8	10.8
KARA	–12.0	3.5	18.8	2.6	4.2	4.0
SISS	–12.5	4.2	20.7	2.8	4.2	4.5
SKAL	–10.6	3.1	19.0	2.0	4.24	3.6

located in Palliki. Comparing the displacements between the southern and northern parts of Paliki, a kinematic boundary becomes evident just to the south of station 16, as deduced by the observed deformation at the GPS stations. This inferred boundary caused the southern part of Paliki to have an almost NE motion, while the northern part showed an SE motion that should have been affected mainly by the 2015 Lefkadian event. This kinematic discontinuity is also supported by our previous studies (Sakkas and Lagios 2015), where it was mentioned that a boundary should exist in the vicinity of station 16. Moreover, the small horizontal amplitudes at the stations in the northern Paliki area with respect to those at the northernmost part of Cephalonia clearly seem to mark a discontinuity between Paliki and the rest of the island. This argument is supported by the gradual decrease of the horizontal displacements from ~21 mm (station 14) to ~11 mm (station 15), and finally to ~8 mm (station 16).

Similar to the previous period (2014–2015), neighboring stations (08 and 09, VLMS and 06, KARA and 21) also

exhibited non-uniform patterns of deformation regardless of their proximity. This highlights the prevailing intense tectonism in the area, which together with the increased seismicity during the span of this study (2014–2016) seems to govern the local and regional motions.

The pattern of the vertical component (Fig. 6b) confirmed the differentiation between the mainly uplifting Paliki and the subsidence of the remaining portion of Cephalonia, while deviations from this main pattern are attributed to local tectonic and geological features. The pattern of the vertical component showed an intense subsidence in the northern part (–17 mm), close to the Lefkas epicentral area, decreasing gradually towards the central part (about –6 mm), and slightly increasing again in the southern part (about –15 mm), as it was similarly observed during the previous observational period (2014–2015). Stations 03 and 04 in the eastern and southeastern parts revealed uplift almost identical to the previous period, while two other stations in central Cephalonia (07 and 57), which have not been remeasured for several years,



**Fig. 7** **a** Horizontal strain tensor distribution for the period 2014–2015; **b** change field map for the period 2014–2015; **c** horizontal strain tensor distribution for the period 2015–2016; **d** change field

map for the period 2015–2016. *Red and blue arrows* indicate compression and extension, respectively. Note the different strain scales in **a** and **c**

exhibited an overall displacement in accordance with the other stations in the vicinity (06 and 04).

Itthaca was close to the epicentral area of the 2015 Lefkas seismic event and was shifted to the SE, preserving the differential type of displacement between its northern

and southern parts. The horizontal components of the northern stations ( $\sim 80$  mm) were significantly higher than the southern ones ( $\sim 40$  mm), while the northern part seemed to subside compared to the southern part whose vertical motion was found to be within the error limits.

## Strain field

Calculation of the strain tensor based on the horizontal components of displacement in the two observational periods was performed to better define the deformation occurred in the area in the period 2014–2016, during the post-seismic period of the 2014 Cephalonian events and 2015 Lefkadian one, importing time discontinuities (earthquakes) in the calculations. The strain field tensors describe the changes of dimensions or shape along a deformed area and it can be used to better define the tectonic forces in an area of high tectonic activity. The strain field was computed based on the Teza et al. (2008) algorithm on a uniform (2 km × 2 km) grid. The adopted small grid size that is about half the average station spacing (~4 km) may reveal useful information about the deformation occurred in the local tectonic blocks of the area, as well as along the space discontinuities (faults). In each grid node, the eigenvectors were calculated with positive and negative eigenvalues describing extension and compression, respectively. The strain was considered representative of the compressional and/or tensional state of the area only at the nodes whose distance from the data points is smaller or equal to the scale factor used in the calculations (Teza et al. 2008). Based on the computation of the strain tensor, the corresponding trace for each grid point was calculated describing the change in the area (dilatation) that is equal to the sum of the diagonal elements of the tensor. The dilatation corresponds to the relative change of surface area and thus provides the possibility to identify areas of compression or extension, and indicate regions of thrusting or normal faulting (Hackl et al. 2009).

The spatial distribution of the strain during the first remeasurement period 2014–2015 (Fig. 7a) shows a significant attenuation of the extensional deformation from the western part of Paliki toward the eastern part of the island, which is characterized by compression. The area of Paliki with the highest extensional amplitude was obviously affected by the post-seismic visco-elastic relaxation and/or afterslip induced by the 2014 events, as well as by the following seismic sequence. The northern part of Cephalonia and Ithaca exhibited compression with an almost E–W direction of the principal compressive strain, almost perpendicular to the Ionian Thrust Zone (Fig. 1). However, extension occurred in between the southern part of Ithaca and the central-eastern part of Cephalonia. Finally, the southern and southeastern parts of Cephalonia exhibited compression, with its main axis perpendicular to the thrusting lineaments of the area, indicating strain accumulation. The tensors trace (dilatation) which represents areal deformation (Fig. 7b) highlights the

differentiation between the northern and southern part of Paliki, where extension occurred in the southern part. Compression is evident between the northern parts of Cephalonia and Ithaca, as well as in the southern and southeastern part of Cephalonia, differentiating these parts from the rest of the island. The localized dilatation pattern in Paliki may suggest that afterslip, and not a broad-scale visco-elastic relaxation, is the dominant post-seismic mechanism.

The strong Lefkadian event in November 2015 dominated the pattern and the amplitudes of the strain field vectors for the next period, 2015–2016 (Fig. 7c). However, the study of the strain during that period may generally provide insight into the co-seismic deformation, slip location, rupture characteristics, resolving the rupture plain ambiguity of the focal mechanism solution. As expected by the strike slip nature of the Lefkadian event, high compressive strain exhibited in the northern part of Cephalonia, as well as in Ithaca, with the main axis of compression being in an NW–SE direction. A significantly smaller E–W extensional mechanism is observed between northern Cephalonia and Ithaca. This alteration of the deformation mechanism, in our case from extension during interseismic period to compressional on a co-seismic period, satisfies the elastic rebound theory. The amplitude of the compression attenuates towards the southern part of Cephalonia, which has affected less from the Lefkadian event. The dilatation analysis (Fig. 7d) shows that the far field has a very good agreement with the observed focal mechanism of the November 17th, 2015 event (Fig. 2). The southern and southeastern parts of Cephalonia are differentiated from the rest of the island as also noticed in the period 2014–2015.

At an effort to estimate the strain without the co-seismic effect during the period 2015–2016, the fault model produced by Ganas et al. (2016) was used to calculate the co-seismic deformation in Cephalonia–Ithaca islands. The calculated displacement vectors which represent the deformation without the co-seismic effect (which were produced subtracting the model vectors from the observed ones) resulted to a pattern that is not consistent to the previous interseismic periods 2014–2015 and 2001–2010 (Lagios et al. 2007, 2012). It seems that the fault model used to describe the co-seismic displacement in Lefkas resulted in significantly higher displacements in northern Cephalonia and Ithaca compared to the observed ones. Taking into consideration that this event occurred on the Lefkadian part of the CTF, west of the Ionian thrust zone (Fig. 1), it seems that a kinematic boundary should exist in this area (east of CTF) that reduces the co-seismic displacement amplitudes in Cephalonia and Ithaca. This boundary may be related to the Ionian thrust. As a consequence, the strain tensor computed for the period

2015–2016 subtracting the co-seismic effect cannot be used for further analysis.

## Discussion and conclusions

The intense seismic activity caused by three major events of  $\sim M6$  that took place in the broader area of the central Ionian Islands during 2014–2015 is not unusual for such a highly tectonically active area. The ground deformation measured over almost two years (March 2014 to February 2016) from local GPS networks in Cephalonia and Ithaca, including cGPS stations, revealed displacements that describe the kinematic state of significant tectonic features at both local and regional scales. Moreover, these displacements enabled us to better understand the tectonism during the interseismic (2014–2015) and co-seismic (2015–2016) periods.

The broader area of Cephalonia and Lefkas is usually strongly affected by the Cephalonia Transform Fault; nevertheless, the 2014 earthquakes in Cephalonia (Paliki) have shown that there are additional faulting zones with the potential to generate strong events. The 2015 Lefkadian earthquake took place just south of an older event in 2003, and was located along its southern continuation (Ganas et al. 2016; Chousianitis et al. 2016). Both epicentral areas in Cephalonia and Lefkas generated earthquakes with similar focal mechanisms (Fig. 2), showing seismogenic faults of similar geometric characteristics. These two distinct events were followed by seismic activity that extended northward and southward, respectively (Fig. 2). This activity linked the two epicentral areas, thus indicating that the major CTF zone is a system that encompasses several smaller branches capable of generating intense seismicity. The time series of the cGPS stations have shown that the 2014 Paliki events ( $M_w 6.1$  and  $M_w 5.9$ ) caused displacements that were limited mainly to Cephalonia and did not affect Lefkas to the north or Zakynthos to the south (Figs. 3, 4). On the contrary, the occurrence of the Lefkadian event ( $M_w 6.4$ ) affected a much broader area, including Cephalonia and Zakynthos to the south and extending also to the west (Agrinio in western Central Greece, Fig. 4). This supports the observation that the Lefkadian earthquake was generated on the regional CTF system, while the Cephalonian events were generated by the local faulting system in Paliki.

Inspecting the time series of the cGPS stations prior to the Lefkadian event and after the Cephalonian ones, it was found that there was no pre-seismic deformation in the area, regardless of the CTF's major regional characteristics. All stations showed the anticipated regional motion, with the exception of small dislocations that were recorded

during localized smaller earthquakes (e.g., KARA in November 2014, Fig. 3a).

The cGPS time series from the Cephalonian stations (VLSM, KARA, SKAL) showed that the co-seismic deformation due to the Lefkadian earthquake was about 10 mm in the central and southern parts of the island, having an almost linear type of motion in the period before the event. Comparing the amplitude of the deformation vectors for the periods 2015–2016 and 2014–2015, it is evident that the doubling of the deformation amplitude in the period 2015–2016, at least for the central and southern part of the island, was due to the Lefkadian earthquake. The estimated deformation prior to the Lefkadian earthquake may be considered of an almost linear type, at least for the central and southern parts of Cephalonia. For the rest of the island, the large deformation amplitudes observed on the northern peninsula, together with the offshore seismic activity west of the peninsula after the 2014 and 2015 earthquakes, do not provide any indication of the deformation type (linear or non-linear) prior to the Lefkadian event.

A fault zone just to the west of station 14 that extends at an almost N–S orientation along the eastern part of Paliki has already been modeled to explain the co-seismic deformation in the area during the 2014 earthquakes (Sakkas and Lagios 2015). This zone was also active during the two observational periods discussed in this paper (2014–2015 and 2015–2016), both in terms of horizontal and vertical components, although the patterns and amplitudes of displacement are different for each period. A continuation of this faulting zone to the offshore and north of Paliki may be assumed, taking into consideration the extension of the seismic activity to the north that occurred in this area after the 2014 events. This zone may be composed by multiple small fault segments, similar to the modeled faults of the 2014 events. This northward extending fault system may eventually be linked to the major CTF in the offshore, as is indicated by the seismicity in that area (Fig. 2). In addition, another NW–SE trending fault, just to the north of station 13, may also be truncated in the same marine area to the west that marks the northern and southern limits of the seismic activity during the 2014 Cephalonian and 2015 Lefkadian events, respectively (Fig. 2). This fault marks a clear deformation boundary in the northernmost peninsula of Cephalonia, based on earlier PSInSAR analysis (Fig. 6 in Lagios et al. 2012), and may be associated with offshore structures of similar direction as was revealed by seismological analysis in the area (Karakostas et al. 2015).

Another feature of interest is the NW–SE trending fault on Paliki, just to the south of station 16 (Fig. 1), which seems to represent an important boundary between the

southern and northern parts of Paliki. In our efforts to model the early 2014 earthquakes (Sakkas and Lagios 2015), it became necessary to assume the presence of two consecutive faults belonging to the same system, but with a gap between them, which generated the two events in Cephalonia. The lack of GPS observations before the second  $M_w$ 5.9 event, as well as the intense aftershock activity that occurred during the study period, did not confirm convincingly this assumption. However, the observed ground deformation between the southern and northern parts of Paliki identified in this paper provides more evidence for the existence of such a discontinuity. During the first period (Fig. 5), northern Paliki exhibited a displacement to the NE, while the southern part showed an eastward motion. During the second period, 2015–2016 (Fig. 6), southern Paliki showed NE displacement, while its northern half, being affected by the Lefkadian event, was subject of an SE dislocation. These results outline the intense tectonism that is taking place in Paliki, which is an area dominated by the major CTF to the west and an almost parallel faulting zone to the east that has been postulated based on fault plane modeling of the 2014 earthquakes. The different displacements of the northern and southern part of Paliki across the NW–SE fault that lies to the south of station 16 seem to constitute an essential local kinematic boundary, as this was also indicated in the change map of the area (Fig. 7b).

The effect of the NW–SE thrusting zone just north of stations 10 and 11 is clearly evident in the period 2015–2016, when comparing the displacements observed at stations 10 and 11 to those at the northernmost stations 12 and 13. The latter can also be seen in the change map (Fig. 7d). This zone marks the limits of the northern peninsula of Cephalonia that affect the local kinematics. This peninsula moves south-eastward with higher deformational amplitude than the central Cephalonia. As a result, force is exerted towards the southeastern part, in the vicinity of station 10, without any evidence that the coastline marks the end of this zone. This kinematic behavior along this zone may be reflected to the neighboring station 10 that shows smaller dislocation when compared to the surrounding stations throughout the measuring periods (Lagios et al. 2007, 2012; Sakkas and Lagios 2015), both for the vertical and horizontal components.

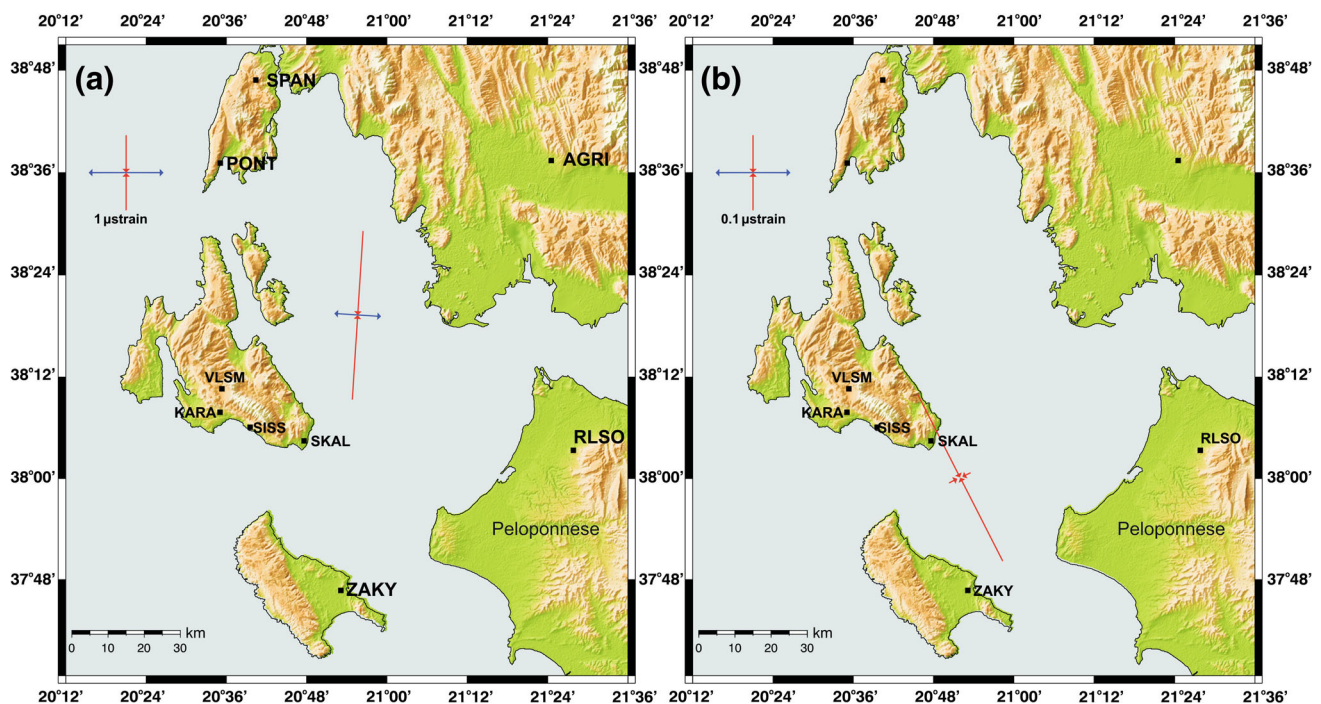
Local tectonic features in the central and southern parts of Cephalonia, which cause differentiated displacements for stations located across/along them, are observed between stations 08 and 09, VLSM and 06. Thrusting lineaments caused the observed compressional forces, as these have been depicted by the change map for the interseismic period (Fig. 7b). The influence of these local tectonic features becomes more evident in some areas after the 2015 Lefkadian event. Stations 20, 21 and KARA,

located close to the NW–SE major thrusting zone, revealed significant variations in both amplitude and direction of the deformational vector for the period 2015–2016 (Fig. 6). In combination with the occurrence of several earthquakes of  $\sim M_w$ 4 during November 2014, this indicates the probable existence of other buried or unknown faults in the vicinity, where their displacement resulted in a non-uniform deformational pattern observed at the surrounding stations. Similar differential displacements along the major thrusting zones running along the southern part of Cephalonia were also observed by radar interferometric analyses (Lagios et al. 2012) during the previous years when the seismic activity was at regular levels.

The displacements that occurred between Cephalonia and Ithaca are another interesting aspect of this study. A thrust system separates northern Cephalonia (belonging to the Paxos zone) from Ithaca of the Ionian zone (Fig. 1). The enhanced eastward displacement during 2014–2015 (Fig. 5) at the northern Cephalonian stations compared to those in Ithaca, in combination with the strain map of the area (Fig. 7a, b), is indicative of the E–W compressional forces between the two islands during that interseismic period. Based on these observations, it can be concluded that the two islands are “approaching” each other. The compressional forces that seem to prevail in the broader area (Ganas et al. 2013; Chousianitis et al. 2015) may explain this kinematic behavior, taking also into account the regional motion in the broader area of western Greece (e.g., Vassilakis et al. 2011). The effect of the Lefkadian event in the co-seismic period 2015–2016 changed the overall strain map of the northern Cephalonia–Ithaca area, as it is expected by the elastic rebound theory (Fig. 7c). The strain tensors have rotated about  $90^\circ$ , with an almost N–S compression and a small E–W co-seismic extension. This extensional component between Ithaca and Cephalonia was also occurred during the 2014 Cephalonian events (Sakkas and Lagios 2015) causing the two islands to “move away” from each other during major seismic events.

In the Paliki Peninsula, a significant extensional component observed along an almost N–S axis during the 2014–2015 measuring period may be attributed to the effect of the seismic sequence of the 2014 Cephalonian events, along the local faulting system that are running along Paliki, suggesting that afterslip is most likely the main post-seismic mechanism in the area.

Another feature of the observed ground deformation in Cephalonia and Ithaca is the differential displacement between southern Ithaca and central-eastern Cephalonia. Although Ithaca and this part of Cephalonia belong to the same geological unit of the Ionian Zone (Fig. 1), the two areas show considerable differences in the displacement vectors (direction and amplitude) for both periods. The



**Fig. 8** Horizontal strain tensor in the broader area of the central Ionian Islands based on the recorded deformation at the cGPS stations during the Lefkas event: **a** all available stations (9 stations) were taken into consideration. **b** Only stations in the southern Ionian Sea (6

stations) were included in the calculations. *Red* and *blue* arrows indicate compression and extension, respectively. Note the different strain scales in **a** and **b**

Ionian Thrust that traverses this area may explain the differences in northern Cephalonia and Ithaca, but cannot account for the difference between southern Ithaca and central-eastern Cephalonia, especially taking into consideration the high dilatation observed in the vicinity of station 04 in the period 2014–2015 (Fig. 7b). The differential displacement between the study areas may be attributed to the presence of an offshore E–W faulting system that crosscuts the Ionian Thrust and is almost parallel to the southern coastline of Ithaca, as well as the coastline to the north of station 04 in Cephalonia. The morphology of these two coastlines is consistent with a possible ENE–WSW fault offshore, especially since many faults in both islands (southern Ithaca and eastern Cephalonia) have a similar strike direction. However, the high dilatation observed locally in the area of station 04 may be caused by a small creeping segment, and may explain also the observed differential motions.

The compression in northern Cephalonia (Fig. 7b) resulting from the strong horizontal displacements due to the  $M_w 6.4$  Lefkadian event implies that the area of the main island is under a significant stress. Cephalonia–Ithaca contains several deformation zones that experience motions related to local and regional tectonic features. The regional features control the observed deformation field, as suggested by the motion of the main tectonic fragments. However, internal localized faults are clearly affecting the

movement of smaller units, which is associated with the locally recorded seismic activity.

Motions along the major CTF structure are the main source of strong seismic activity in the area, as well as regional increase of stress. The localized seismic events of the 2014 and the regional 2015 event on the Lefkadian part of CTF may be linked to stress transfer to nearby fault zones in Cephalonia. Strain calculations based only on cGPS data in the broader area (i.e., two stations in Lefkas, four in Cephalonia, one in Zakynthos, one in NW Peloponnese, and one in west-central Greece) during the Lefkadian event showed the strong compression occurred in the center of the study area (Fig. 8a). Compression is also observed in the sea area between Cephalonia and Zakynthos, when taking into consideration just the southern part of the Ionian Sea (Fig. 8b). According to these observations, and taking into consideration the compression observed in southern Cephalonia during the interseismic periods (Fig. 7a), it may be argued that strain should be accumulating in the southern part of Cephalonia. Previously published work combining GPS and Permanent Scatterer Interferometric data has shown that an intense non-linear uplift took place in Paliki, and another one later along the major NW–SE trending thrusting zone at the southern part of Cephalonia, when compared to the previous decade, which was interpreted as a possible regional dilatancy (Lagios et al. 2012) that could potentially lead to

strong seismic events. Already two major earthquakes have occurred in Paliki in 2014, where the maximum increasing rate of non-linear uplift was observed, compatible with that interpretation. The second, therefore, area, potentially relating to the possible occurrence of future earthquakes, should be taken into consideration.

As a final point, in southern Cephalonia, the seismic activity is relatively low, strain is accumulating, and the deformation showed a pattern similar to the observed one in the already affected area of Paliki. Based on these remarks, it may be assumed that in the future the seismic activity may be shifted toward the southern part of Cephalonia (onshore or even offshore), even though it seems that the seismic events in 2014–2015 have partially released the strain that was locally accumulated in the previous years, and the geodetic data from a number of cGPS stations in the south since 2014 do not currently indicate any change of the deformation pattern. Moreover, a regional offshore source of activity may not be ruled out, especially since the northern part of Zakynthos has also shown a non-linear uplift (Sakkas et al. 2014) and the offshore area southwest of the 2014 Cephalonian events has generated even stronger earthquakes in the past ( $M_s \sim 7.0$  in 1983; Scordilis et al. 1985; Papadimitriou 1993). In addition, the possibility of a new activity in-between Cephalonia and Ithaca is also possible due to the presence of major tectonic features in the area.

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