Available online at www.sciencedirect.com
ScienceDirect
Tectonophysics 444 (2007) 119 – 145
TECTONOPHYSICS
www.elsevier.com/locate/tecto

Crustal deformation in the Central Ionian Islands (Greece): Results from DGPS and DInSAR analyses (1995–2006)

E. Lagios [a,*], V. Sakkas [a], P. Papadimitriou [a], I. Parcharidis [b], B.N. Damiata [c], K. Chousianitis [a], S. Vassilopoulou [a]

[a] *Space Applications Research Unit in Geosciences, Department of Geophysics & Geothermics, University of Athens, Panepistimiopolis, Ilissia, Athens 157 84, Greece*
[b] *Department of Geography, Harokopio University, Athens, Greece*
[c] *Cotsen Institute of Archaeology, University of California, Los Angeles, CA USA and Earth Tech, Inc., Colton, CA, USA*

Received 2 November 2006; received in revised form 1 August 2007; accepted 21 August 2007
Available online 4 September 2007

Abstract

Ground deformation studies based on Differential GPS (DGPS) and Differential Interferometric SAR (DInSAR) analyses have been conducted in the seismically active area of the Central Ionian Islands. Local GPS networks were installed in Cephallonia (2001) and Zakynthos (2005). The Cephallonian network has been remeasured five times and Zakynthos' once as of July 2006. The studies have yielded detailed information regarding both local and regional deformations that are occurring in the area.

For Lefkas Island, DInSAR analysis (March to September 2003) revealed 56 mm of uplift in the central and western parts and is attributed to the August 2003 earthquake ($M_w = 6.3$) that occurred offshore to the west. Synthetic DInSAR modelling of the magnitude and extent of deformation is consistent with the seismologically deduced parameters for the ruptured segment along the Lefkas Transform Fault. Subsidence (<28 mm) along the northern part of the island is attributed to local conditions unrelated to the earthquake. For Zakynthos Island, large-magnitude earthquakes that occurred offshore to the south in October 2005 and April 2006 most likely contributed to the observed deformation as deduced from DGPS measurements for an encompassing period (August 2005 to July 2006). The largest amount of horizontal deformation occurred in the south, where its western part moved in a W–NW direction, while the eastern part moved towards the NE, with magnitudes ranging from 15 to 26 mm. The southern part of the island uplifted a maximum of 65 mm whereas the north subsided from 12 to 28 mm.

For Cephallonia Island, DInSAR analysis (1995 to 1998) indicated ground deformation up to 28 mm located in small sections of the island. Further interferometric analysis for the period 2003 to 2004, encompassing the occurrence of the Lefkas earthquake in August 2003, indicated 28 mm of uplift in the northern part, while during the next two years (2004 to 2005), further uplift of at least 56 mm had taken place at the western and northern part of the island.

DGPS measurements for the period 2001 to 2006 revealed a clockwise rotation of the island with respect to a centrally located station on Aenos Mt. The horizontal component of deformation generally ranged from 6 to 34 mm, with the largest values at the western and northern parts of the island. Considering the vertical deformation, two periods are distinguished. The first one (2001 to 2003) is consistent with anticipated motions associated with the main geological and tectonic features of the island. The second one (2003 to 2006) has been tentatively attributed to dilatancy in which relatively small uplift (20–40 mm) occurred along the southern and southeastern parts of the island, while larger magnitudes (>50 mm) happened at the western part (Paliki Peninsula). These large magnitudes of uplift over an extended area (>50 km), in conjunction with an accelerated Benioff strain determined from the

* Corresponding author.
E-mail address: lagios@geol.uoa.gr (E. Lagios).

doi:10.1016/j.tecto.2007.08.018

analysis of the seismicity in the broader region, are consistent with dilatancy. This effect commenced some time after 2003 and is probably centered in the area between Zakynthos and Cephallonia. If this interpretation is correct, it may foreshadow the occurrence of a very strong earthquake(s) sometime during 2007 to 2008 in the above designated region.

Keywords: Ground deformation; GPS measurements; SAR interferometry; Ionian Islands; Cephallonia; Dilatancy

1. Introduction

Western Greece lies within a seismotectonically complex area that is undergoing rapid and intense ground deformation. The area plays an important role in the kinematic processes of the eastern Mediterranean. In particular, the Eastern Mediterranean lithosphere is being subducted beneath the Aegean lithosphere along the Hellenic Arc. The highest seismic activity in Europe currently occurs in the region of the western part of the subduction zone that includes the central Ionian islands of Lefkas, Ithaca, Cephallonia and Zakynthos.

The regional crustal deformation along the entire Ionian Sea and western Greece has been studied through repeat Differential Global Positioning System (DGPS) measurements (Kahle et al., 1995; Peter et al., 1998; Cocard et al., 1999; Hollenstein et al., 2006). However, the additional monitoring of dense GPS networks in such an active area may yield useful information regarding local ground deformation and kinematics, and possibly contribute to large-magnitude earthquake prediction. This paper reports on the GPS networks that have been installed in the islands of Cephallonia (2001) and Zakynthos (2005) in the central Ionian Sea (Fig. 1). Ground deformation studies based on repeat DGPS measurements from Cephallonia and Zakynthos, in combination with Differential Interferometric SAR (DInSAR) analyses of the broader areas of Lefkas and Cephallonia, are presented.

We note that for these studies, we have incorporated a large amount of data (topographic, geodetic, geological, tectonic, seismological and satellite images) of different formats (vector, raster, ASCII, HDF, *etc.*), map projections (Greek HATT, UTM) and Datums (European 1950 and WGS'84) with different ellipsoids (Bessel and WGS'84).

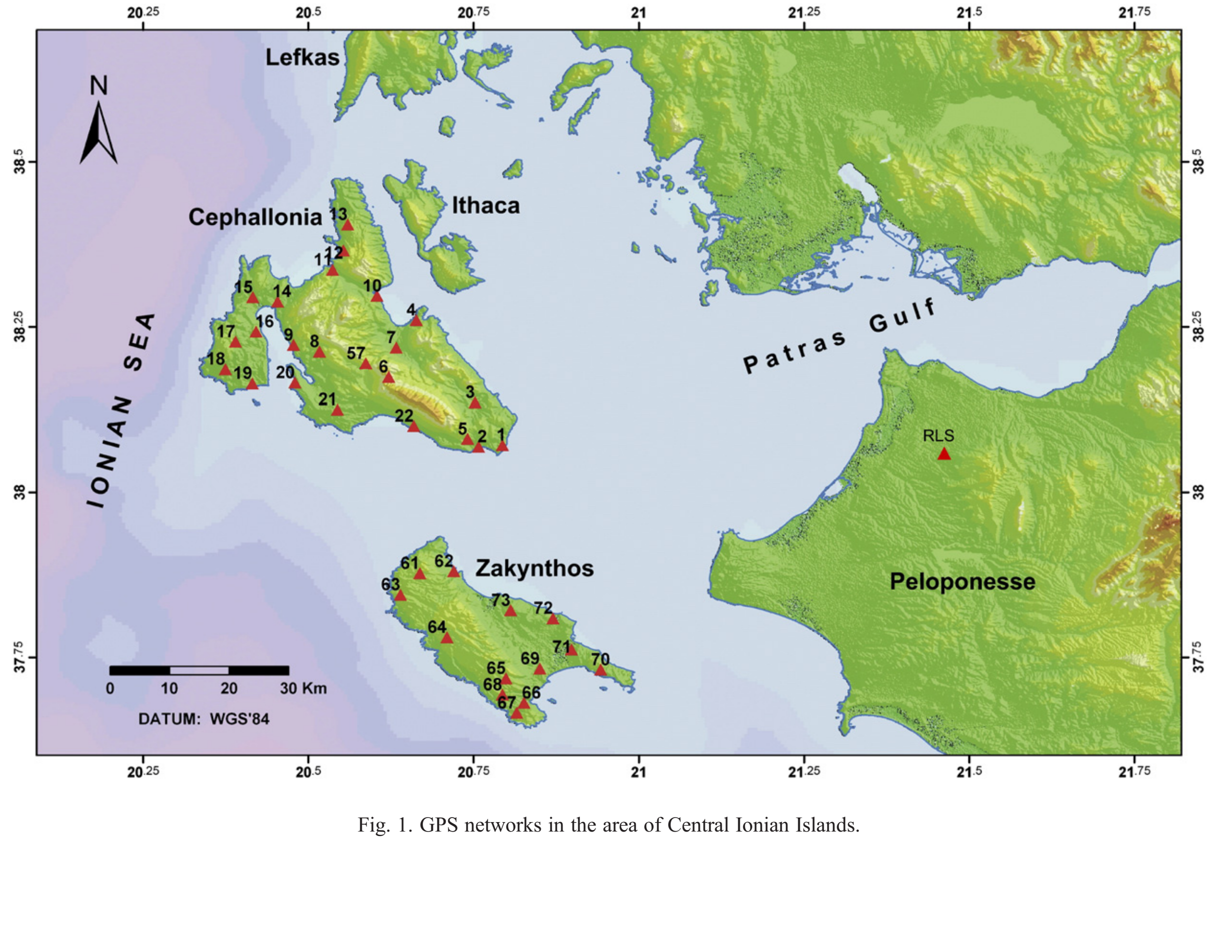

Fig. 1. GPS networks in the area of Central Ionian Islands.

These data were processed to produce synthetic layers and maps in a common projection system–the Hellenic Geodetic Reference System 1987 (HGRS'87)–by using ArcGIS software (ESRI, 2002) for database management. The Digital Elevation Models (DEM) of the islands of Lefkas, Cephallonia and Zakynthos (WGS'84 datum with 90-meter pixel size) were acquired from the USGS's SRTM Elevation Dataset, while the DEM used for DInSAR analysis of Cephallonia (HGRS'87 datum with 20-meter pixel size) was created according to Vassilopoulou (1999, 2001) based on 1:50,000-scale topographic maps.

2. Geological and tectonic setting

The area of western Greece is a case study of interaction between the African and the Eurasian tectonic plates in which the Eastern Mediterranean lithosphere is being subducted beneath the Aegean lithosphere along the Hellenic Arc–Trench System (Le Pichon et al., 1995; Papazachos and Kiratzi, 1996). The subduction zone terminates against the Cephallonia Transform Fault (CTF)—a major strike–slip fault that links the subduction boundary to the continental collision between the Apulian microplate and the Hellenic foreland (Sachpazi et al., 2000), and plays a key role in the region's geodynamic complexity (Sorel, 1976; Le Pichon and Angelier, 1979; Le Pichon et al., 1995; Louvari et al., 1999).

The CTF lies offshore to the west of Cephallonia (Fig. 2) in an area with a deep bathymetric trough (water depths in excess of 3000 m) that strikes N20E. Its slip-rate varies from 7 to 30 mm/yr based on DGPS measurements (Anzidei et al., 1996; Hollenstein et al., 2006) which is consistent with seismological data (Papazachos and Kiratzi, 1996). The phenomena of active subduction and continental collision are responsible for earthquakes

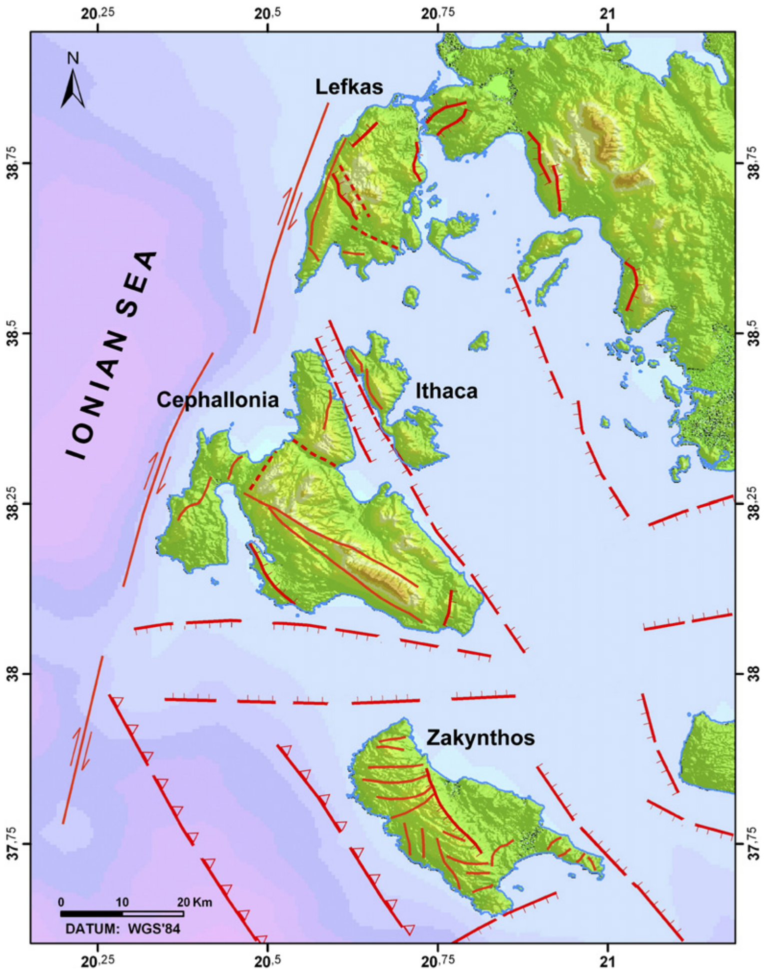

Fig. 2. Main Fault Systems in the broader area of Cephallonia, Ithaca, Lefkas and Zakynthos islands (taken from the Seismotectonic Map of Greece (IGME) and Lekkas et al., 2001). The CTF lies to the west of the islands. Representation of fault systems is the same as in Fig. 3.

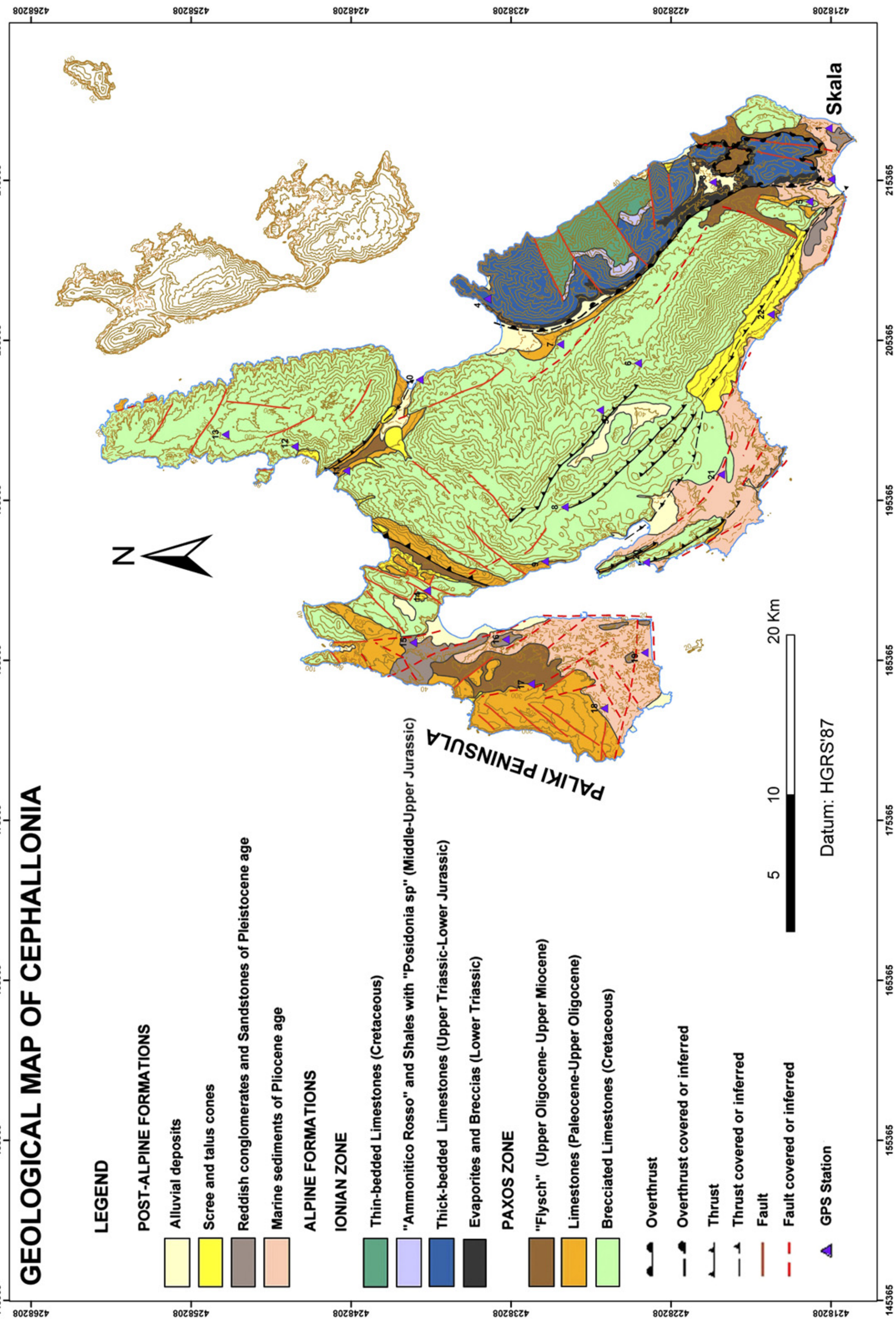

Fig. 3. Sketch Geological Map of Cephallonia Island.

produced by compressional stress along the western coasts of Greece and Albania, as well as the convex side of the Hellenic arc. Subduction results in high shallow seismicity along low-angle thrust faults of the Hellenic arc and in intermediate-depth seismicity along a well-defined Benioff zone in the southern Aegean (Papazachos, 1990; Papazachos et al., 2004).

The western part of the Hellenic convergence zone, extending from Cephallonia to the south of Zakynthos, is also characterized by a positional change of the frontal thrust in this domain. The evolution here could be described as a continuation of the Alpine orogeny with a foreland-propagating fold and thrust belt of the Hellenides, the front of which jumped during the middle Miocene from its position at the Pindos thrust (east of Ionian zone) to the west of this zone at the Ionian thrust which is now clearly expressed to the east of Cephallonia and Zakynthos (Underhill, 1989; Hatzfeld et al., 1990). The present convergence is taking place further to the west and offshore of Zakynthos where the pre-Apulian domain is thrusting over the marine basin of the Ionian Sea.

Cephallonia comprises the western part of the fold-belt of the External Hellenides. The island was formed during Tertiary times as a result of the convergence between the African and the Eurasian plates that initiated at the end of the Cretaceous (Kamberis et al., 1996). It mainly consists of Alpine Mesozoic and Cenozoic sedimentary rocks belonging to the External Hellenides, the Paxos or Pre-Apulian zone and the overthrusted Ionian zone (Fig. 3; Aubouin and Dercourt, 1962; Lekkas et al., 2001).

The Pre-Apulian zone forms the major part of Cephallonia. The zone has experienced significant late Neogene and Quaternary shortening (Underhill, 1989). The corresponding stratigraphy contains a thick series of Mesozoic to Palaeogene carbonates that are overlain by a series of folded Oligocene to earliest Tortonian deep-marine marls and interbedded turbiditic calcareous sandstones (Mercier et al., 1972). Uncomformably overlying these, mainly in the SSW part of the island, are younger Plio-Quaternary sediments. Along the southern coast of the island, a series of Messinian clays alternating with mass-transported conglomerate and sand beds emerges beneath a thick series of Messinian evaporites and Lower Pliocene Turbi facies sediments and marls. A series of gently dipping Upper Pliocene silts, sands and calcarenites are also developed in the area (Underhill, 1989).

The region around Aenos Mt. (see Fig. 1, No. 06) is dominated by a major asymmetric NW–SE to N–S trending anticline. At the northern tip of this anticline, a NE dipping Cretaceous to Miocene succession emerges, which was overthrusted by cleaved Cretaceous carbonates of Aenos Mt. (Mercier et al., 1972). Further to the east, a zone of intense brecciation occurs bounding these carbonates. Shortening is evident in the western areas of Cephallonia where a series of approximately N–S trending folds and at least one major thrust fault can be traced (Underhill, 1989).

The Ionian zone is dominated by compressional tectonics. The boundary of the zone is defined by the Ionian thrust, which is generally considered to represent the most external structure of the Hellenides. The thrust is well exposed in Cephallonia where a distinct scarp has formed with Mesozoic carbonates of the hanging wall lying next to eroded Miocene marls. In southern Cephallonia, a sub-horizontal thrust brings Mesozoic carbonates and sheared evaporites onto Miocene marls (Underhill, 1989).

The high seismicity in the central Ionian Sea is the result of intense crustal deformation associated with right-lateral strike–slip faulting along the CTF which supports earthquake magnitudes up to $M=7.4$ (Louvari et al., 1999). Several strong earthquakes ($M>6.0$) have occurred in the vicinity. Some of the most recent large-magnitude events include: (1) January 17, 1983 ($M_w=6.7$) in Cephallonia, (2) August 14, 2003 ($M_w=6.3$) to the west of Lefkas (Papadopoulos et al., 2003; Pavlides et al., 2004; Papadimitriou et al., 2006), and (3) a sequence of earthquakes in October 2005 ($M_w=5.6$) and April 2006 ($M_w=5.5$–5.7) to the south of Zakynthos. Since then, no other events of comparable magnitudes have occurred although a great number of smaller events ($4.0<M_w<5.0$)

Table 1
Component displacement of stations No. 06 and RLS with respect to ITRF2000 for all Measuring Periods

GPS station	Period	N–S (mm)	RMS_{N-S} (mm)	E–W (mm)	RMS_{E-W} (mm)	Up (mm)	RMS_{Up} (mm)
06	SEP 2001–JAN 2003	12.20	4.2	23.50	4.0	−3.90	8.1
	–SEP 2003	6.40	3.6	30.10	3.6	−17.70	8.3
	–FEB 2006	17.70	3.2	77.10	2.8	−11.90	7.1
	–JUL 2006	11.50	3.9	79.80	3.0	−15.60	7.0
RLS	JAN 2005–AUG 2005	−15.20	2.7	1.70	2.4	−2.30	4.8
	–FEB 2006	−17.30	3.0	9.70	2.7	−6.20	5.5
	–JUL 2006	−30.00	3.7	20.90	3.0	−7.70	5.7

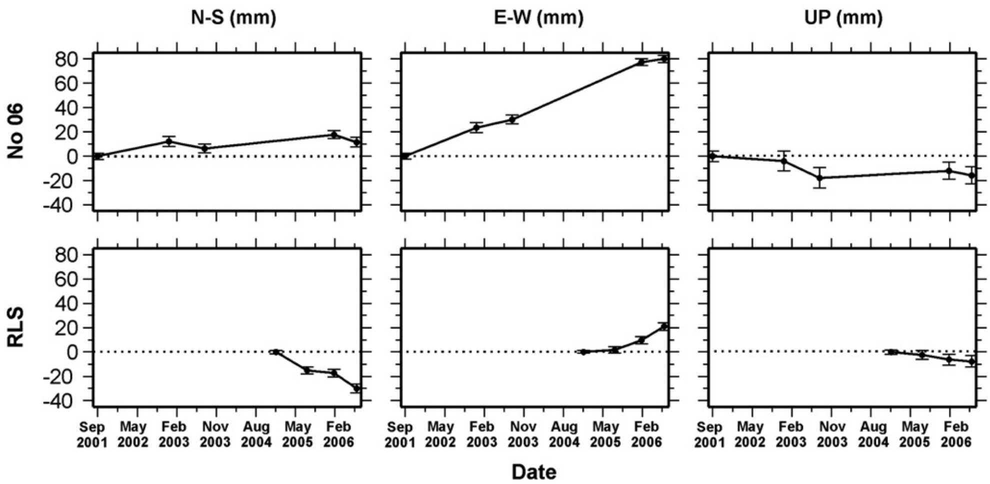

Fig. 4. Displacements of N–S, E–W and Up components with respect to ITRF2000 (with rms error) for the local reference stations of the Cephallonian (No. 06) and Zakynthos (RLS) networks.

have been recorded and at least one event of $M_w \approx 5.0$ is expected in the broader region every year.

3. DGPS measurements

3.1. GPS networks

Several dense GPS networks were installed in the central Ionian islands to study local ground deformation and, when combined together, regional deformation of the broader region that covers the western end of the Hellenic Trench and the CTF. The Cephallonian network consists of 23 stations that were installed in 2001. The Zakynthos network was established during the summer of 2005 and consists of 14 stations. All stations were located based on the main tectonic blocks and fault zones that could be recognized in the islands, and they were distributed accordingly for the study of the tectonic deformation triggered either by motions along major faults or anticipated pre- and post-seismic activity. Generally, the stations were located at about the center of the main tectonic blocks and separated by 10 km or less. This spacing is deemed sufficient for detailed monitoring of local and regional tectonic movements.

Several reoccupation campaigns have been conducted since the installations of the local GPS networks. The Cephallonian network was completely remeasured in January 2003 and in September 2003 following the Lefkas earthquake of August 2003 (M_w=6.3). It was partly remeasured in February and July 2006. The Zakynthos network was also remeasured in July 2006 after the seismic activity that occurred offshore to the south of the island in April 2006.

3.2. GPS data analysis

Eight dual-frequency geodetic receivers (WILD type: SR299, SR399 and AX1200Pro) were used in our GPS campaigns. The data were analyzed with the Bernese GPS software V4.2 (2001). Final IGS satellite orbits and clocks were used.

Table 2
Stations occupied during GPS campaigns in Cephallonia

GPS station no.	September 2001	January 2003	September 2003	February 2006	July 2006
01	√	√	√	√	√
02	√	√	√	–	√
03	√	√	√	√	√
04	√	√	√	√	√
05	√	√	√	√	√
06	√	√	√	√	√
07	√	√	√	–	–
08	√	√	√	–	√
09	√	√	√	√	√
10	√	√	√	√	√
11	√	√	√	√	√
12	√	√	√	–	–
13	√	√	√	√	√
14	√	√	√	–	–
15	√	√	√	√	√
16	√	√	√	–	√
17	√	√	√	√	√
18	√	√	√	√	√
19	√	√	√	–	√
20	√	√	√	√	√
21	√	√	√	√	√
22	√	√	√	√	√
57	√	√	√	–	–

Table 3
Component displacements of GPS stations referred to station No. 6 (Aenos Mt.) of the Cephallonian network for all measuring periods

GPS station no.	Period	N–S (mm)	RMS_{N-S} (mm)	E–W (mm)	RMS_{E-W} (mm)	Up (mm)	RMS_{Up} (mm)
01	SEP 2001–JAN 2003	−3.2	3.2	−11.8	3.6	−5.6	9.0
	–SEP 2003	−1.4	3.0	−4.9	3.2	−13.9	7.4
	–FEB 2006	−10.1	3.0	−9.2	3.2	−32.6	7.8
	–JUL 2006	−5.9	2.8	−8.0	2.6	13.4	9.6
02	SEP 2001–JAN 2003	−6.0	3.6	−2.3	3.8	−12.7	8.2
	–SEP 2003	−5.8	3.0	−6.3	3.2	−23.9	7.8
	–JUL 2006	−2.1	3.0	3.4	3.6	4.5	10.2
03	SEP 2001–JAN 2003	−2.8	4.2	−13.0	3.4	10.4	7.4
	–SEP 2003	−1.6	3.0	−6.0	3.2	−2.9	7.6
	–FEB 2006	−1.2	3.0	−0.1	3.2	20.3	10.2
	–JUL 2006	−2.3	2.6	−13.2	2.8	19.2	9.4
04	SEP 2001–JAN 2003	−0.8	3.2	−2.0	3.6	21.8	10.2
	–SEP 2003	−2.8	3.0	6.8	3.2	9.4	8.4
	–FEB 2006	−12.0	3.0	1.7	3.2	4.5	12.2
	–JUL 2006	−15.2	3.0	5.5	3.2	2.0	10.6
05	SEP 2001–JAN 2003	1.6	3.6	−9.9	4.0	−0.3	8.0
	–SEP 2003	−1.4	3.0	−6.5	3.2	0.7	10.4
	–FEB 2006	−12.9	3.0	−3.9	3.2	21.9	10.2
	–JUL 2006	−2.3	2.6	−9.3	3.2	−5.1	9.8
07	SEP 2001–JAN 2003	3.1	3.2	−6.6	3.6	29.2	6.8
	–SEP 2003	3.8	4.2	−3.8	3.2	40.0	6.0
08	SEP 2001–JAN 2003	6.7	3.6	−2.1	3.8	20.8	8.4
	–SEP 2003	3.1	3.0	8.6	3.2	12.3	8.8
	–JUL 2006	12.4	3.0	11.1	3.6	18.3	10.2
09	SEP 2001–JAN 2003	6.8	3.2	−2.0	3.4	−13.2	6.8
	–SEP 2003	8.8	4.0	8.6	3.2	−14.1	9.4
	–FEB 2006	4.0	3.0	3.7	3.2	−31.0	8.4
	–JUL 2006	13.7	2.2	18.0	2.0	11.0	9.6
10	SEP 2001–JAN 2003	−1.0	3.2	−0.8	3.4	−16.2	6.8
	–SEP 2003	−1.2	3.0	16.0	3.2	−1.6	10.2
	–FEB 2006	−14.1	4.4	15.3	3.2	−26.6	8.4
	–JUL 2006	−21.1	3.0	15.9	2.6	−31.6	10.2
11	SEP 2001–JAN 2003	0.3	3.2	2.9	3.6	15.0	7.0
	–SEP 2003	−4.9	3.0	17.9	3.2	9.7	12.6
	–FEB 2006	−15.1	3.0	16.8	3.2	28.2	7.6
	–JUL 2006	−0.8	2.2	15.2	2.2	38.6	9.6
12	SEP 2001–JAN 2003	−1.9	3.6	−2.2	3.8	29.7	8.4
	–SEP 2003	−7.4	3.0	27.5	3.2	36.6	9.0
13	SEP 2001–JAN 2003	0.6	3.2	7.0	3.6	13.1	7.2
	–SEP 2003	−8.8	3.0	22.4	3.2	20.8	8.4
	–FEB 2006	−21.9	3.0	25.8	3.2	13.6	8.2
	–JUL 2006	−23.8	3.6	26.9	3.6	11.6	10.4
14	SEP 2001–JAN 2003	5.6	3.2	9.7	3.6	6.4	6.8
	–SEP 2003	6.8	3.0	11.0	3.2	16.4	10.2
15	SEP 2001–JAN 2003	2.0	3.6	−7.0	3.8	6.2	8.0
	–SEP 2003	11.3	4.2	1.5	3.6	15.0	8.4
	–FEB 2006	11.0	3.0	−4.8	3.2	30.4	12.2
	–JUL 2006	17.2	3.0	11.4	3.4	82.6	10.0
16	SEP 2001–JAN 2003	7.2	3.2	3.9	3.6	9.5	7.0
	–SEP 2003	14.8	3.0	9.6	3.2	19.6	8.4
	–JUL 2006	25.3	3.6	22.7	3.8	72.0	10.4
17	SEP 2001–JAN 2003	3.2	3.2	2.5	3.8	0.1	7.0
	–SEP 2003	13.2	3.0	12.6	3.2	1.1	12.2
	–FEB 2006	14.3	3.0	7.7	3.2	30.9	9.6
	–JUL 2006	29.3	2.6	19.2	3.0	40.9	9.6

(continued on next page)

Table 3 (*continued*)

GPS station no.	Period	N–S (mm)	RMS_{N-S} (mm)	E–W (mm)	RMS_{E-W} (mm)	Up (mm)	RMS_{Up} (mm)
18	SEP 2001–JAN 2003	7.1	3.2	2.2	3.8	−4.3	7.0
	–SEP 2003	16.0	3.0	4.1	3.2	−20.8	10.8
	–FEB 2006	23.7	3.0	10.9	3.2	42.8	12.4
	–JUL 2006	33.4	3.2	11.3	3.8	59.4	12.4
19	SEP 2001–JAN 2003	−5.4	3.6	−2.0	3.8	38.2	10.4
	–SEP 2003	16.4	3.0	−3.3	3.2	32.9	11.0
	–JUL 2006	16.8	3.8	3.4	4.2	81.3	15.4
20	SEP 2001–JAN 2003	4.4	3.2	−0.6	3.6	3.5	6.8
	–SEP 2003	6.4	3.0	1.3	3.2	−6.2	9.6
	–FEB 2006	6.2	3.0	5.1	3.2	13.5	10.8
	–JUL 2006	14.4	2.8	10.1	2.8	40.5	9.8
21	SEP 2001–JAN 2003	4.3	3.2	−1.3	3.6	−2.7	6.8
	–SEP 2003	6.8	3.0	−4.3	3.2	7.6	9.6
	–FEB 2006	2.9	3.0	−6.4	3.2	24.1	10.2
	–JUL 2006	7.9	4.4	4.0	6.6	58.1	11.0
22	SEP 2001–JAN 2003	1.7	3.2	−6.3	3.4	−17.4	8.4
	–SEP 2003	7.0	3.0	−6.3	3.2	−22.5	8.8
	–FEB 2006	7.1	3.0	1.9	3.2	17.3	9.4
	–JUL 2006	15.8	1.8	−4.7	1.8	37.3	8.2
57	SEP 2001–JAN 2003	5.6	3.2	0.0	3.6	20.5	6.8
	–SEP 2003	8.3	3.0	5.1	3.2	23.1	10.0

In the Cephallonia network, station No. 06 was chosen as local reference station, because of its location on the center of limestone massive Aenos Mt. and its anticipated better geological and tectonic stability compared to other parts of the island (see Fig. 3). The station was operating continuously during all campaigns and tied to the ITRF2000 by means of four IGS stations, namely MATE (Italy), WTZR (Germany), GRAZ (Austria) and SOFI (Bulgaria), and one site DION (Dionysos) in Greece, by introducing the coordinates and velocities with respect to ITRF2000. For the DION site, the components for the east (υ_e), north (υ_n) and up (υ_u) velocities were 8.5 mm/yr, −12.3 mm/yr and 0.2 mm/yr, respectively, with respect to ITRF2000 (http://itrf.ensg.ign.fr/ITRF_solutions/2000/sol.php; D. Paradissis, personal communication).

In the Zakynthos network, station RLS (Riolos) at the northwestern part of Peloponnese established on massive limestone bedrock was chosen as local reference station, based on neotectonic considerations, since it was difficult to find a relatively stable reference point on the island due to the complicated multi-directional faulting features. A similar procedure as in the Cephallonia network was applied to obtain absolute ITRF2000 coordinates of RLS. The variation of the absolute coordinates (ITRF2000) for both local reference stations is summarized in Table 1 and depicted graphically in Fig. 4.

Each campaign was treated separately. For each daily session, one station was selected as a "connecting station" in the center of the "roving" receiver stations and was tied to the first-order stations of No. 06 and RLS. Each roving station was occupied at least twice with a recording time ranging from 4 from 8 h and a sampling rate of 15 s. For each station, solutions for every daily session were computed and compared to its 'final' solution in order to evaluate the scatter of the coordinates deduced from each session. The final station coordinates for each campaign were obtained by combining the solutions of all daily sessions. Overall rms errors of about 2–4.4 mm and 6–12 mm for the horizontal and vertical components of displacement, respectively, were achieved for the majority of the stations (at a 95% confidence level). In the following analyses, we present results in terms of total displacement of a station for a given observational period instead of average rate of displacement, because the interpreted mechanism causing movement can vary at a station for different periods (*e.g.*, earthquakes, dilatancy, local effects, *etc.*). In addition, presentation in terms of displacement helps to facilitate comparison of DGPS results with DInSAR analysis.

3.3. Cephallonian network

To study the local ground deformation in Cephallonia, all vectors of crustal displacement were calculated relative to the station No. 06 at Aenos Mt. that was referred to ITRF2000, as previously mentioned (see Table 1 and Fig. 4). Therefore, all deformations mentioned in the following figures and tables are referred to station No. 06 site. Table 2 shows the occupational history of the GPS sites for all measuring periods, while Table 3 exhibits the component displacements referred to station No. 06 which are plotted in Fig. 5. We tend to present results of displacements instead of velocities because the time span of the GPS measurement period of about one and five years for the Zakynthos and Cephallonia network, respectively, is considered as rather not very long.

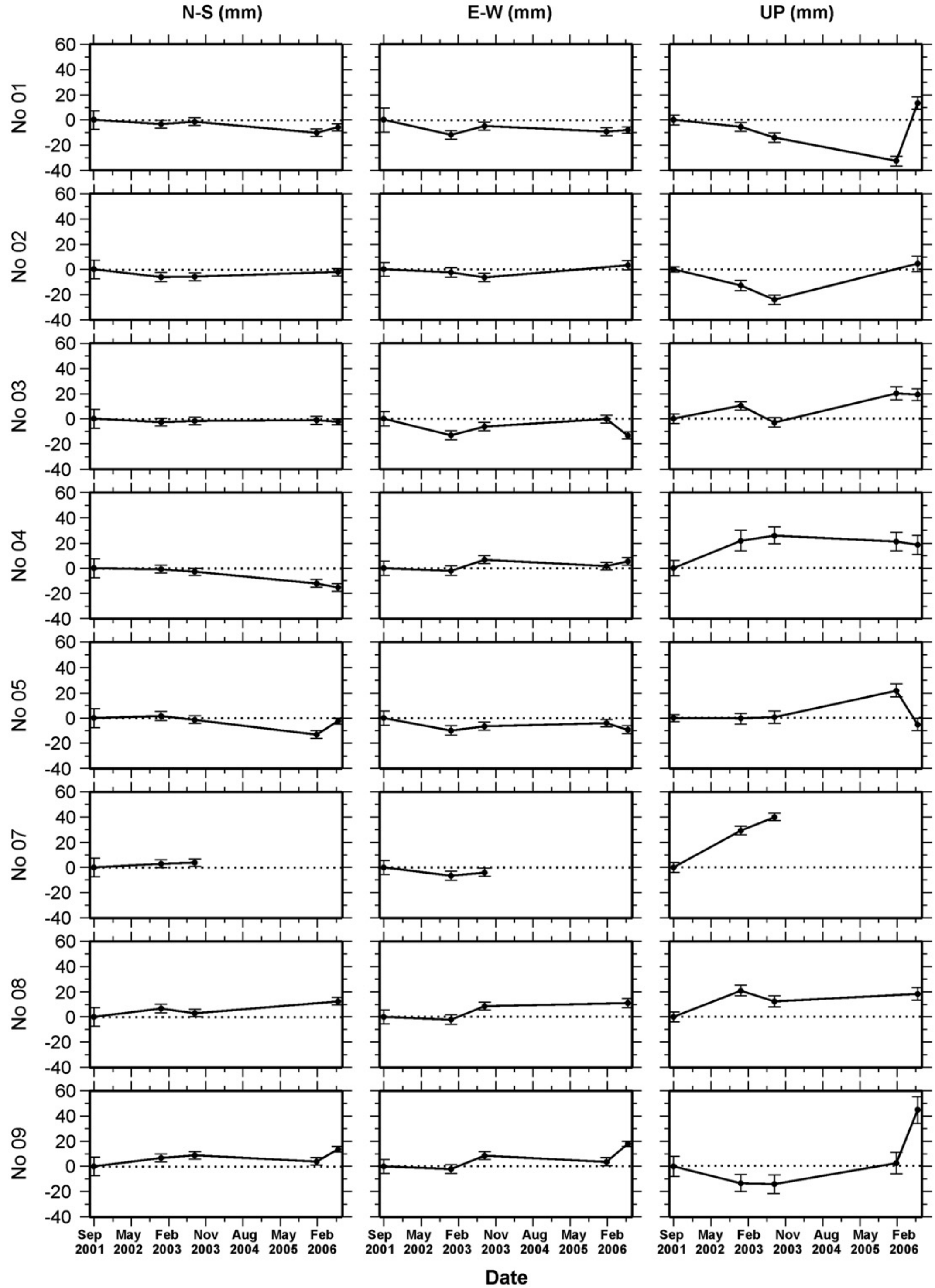

Fig. 5. Displacements of N–S, E–W and Up components for all sites of the Cephallonian network referred to station No. 06 (Aenos Mt.).

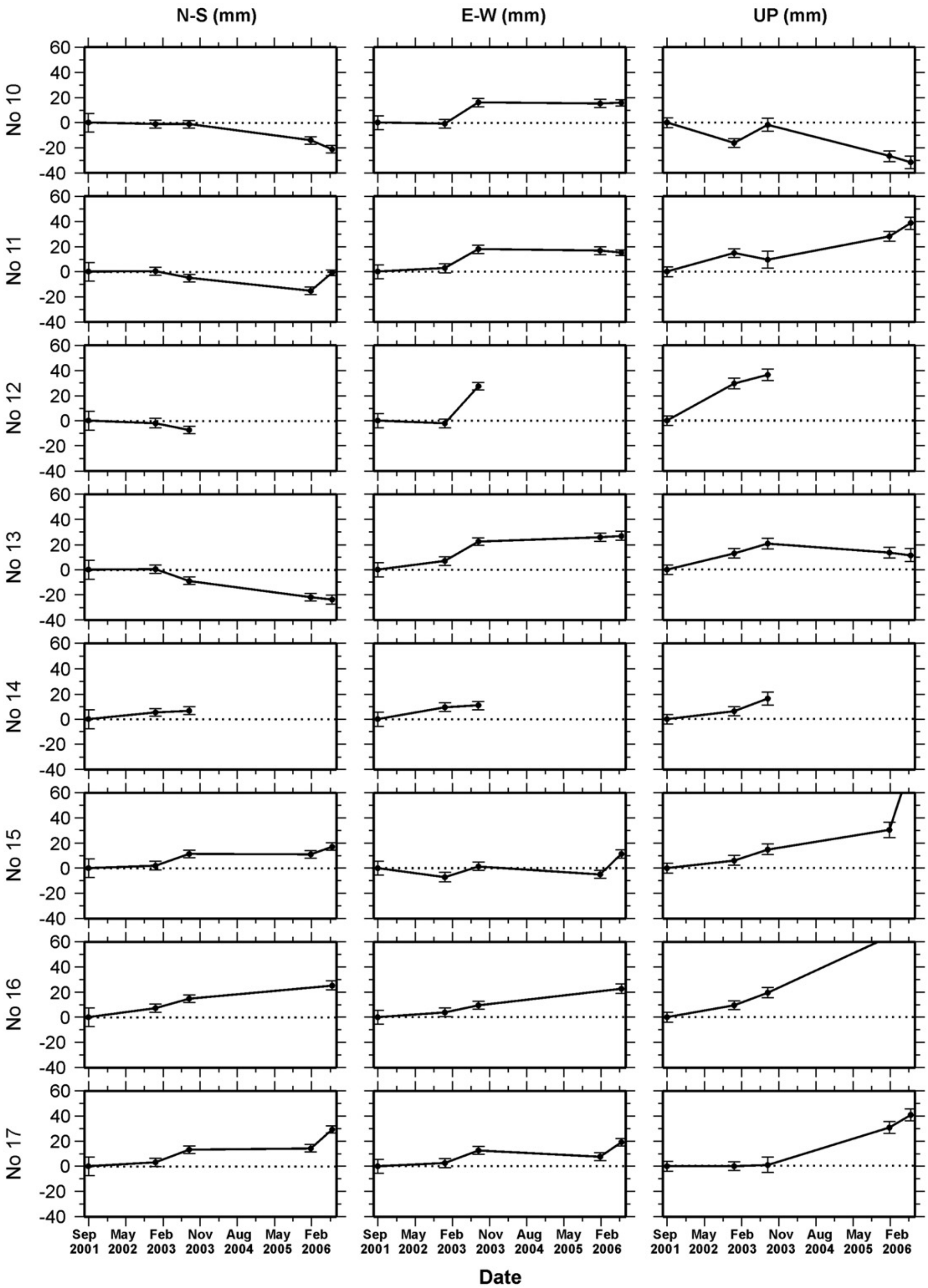

Fig. 5 (*continued*).

It is noted that station No. 06 has a horizontal motion towards the E–NE direction with respect to ITRF2000, while the Up component shows subsidence. The least-squares calculated velocities of the three components along E–W, N–S and Up during the time span of the measuring periods are $\upsilon_e = 16.9 \pm 0.7$ mm/yr, $\upsilon_n = 2.5 \pm$

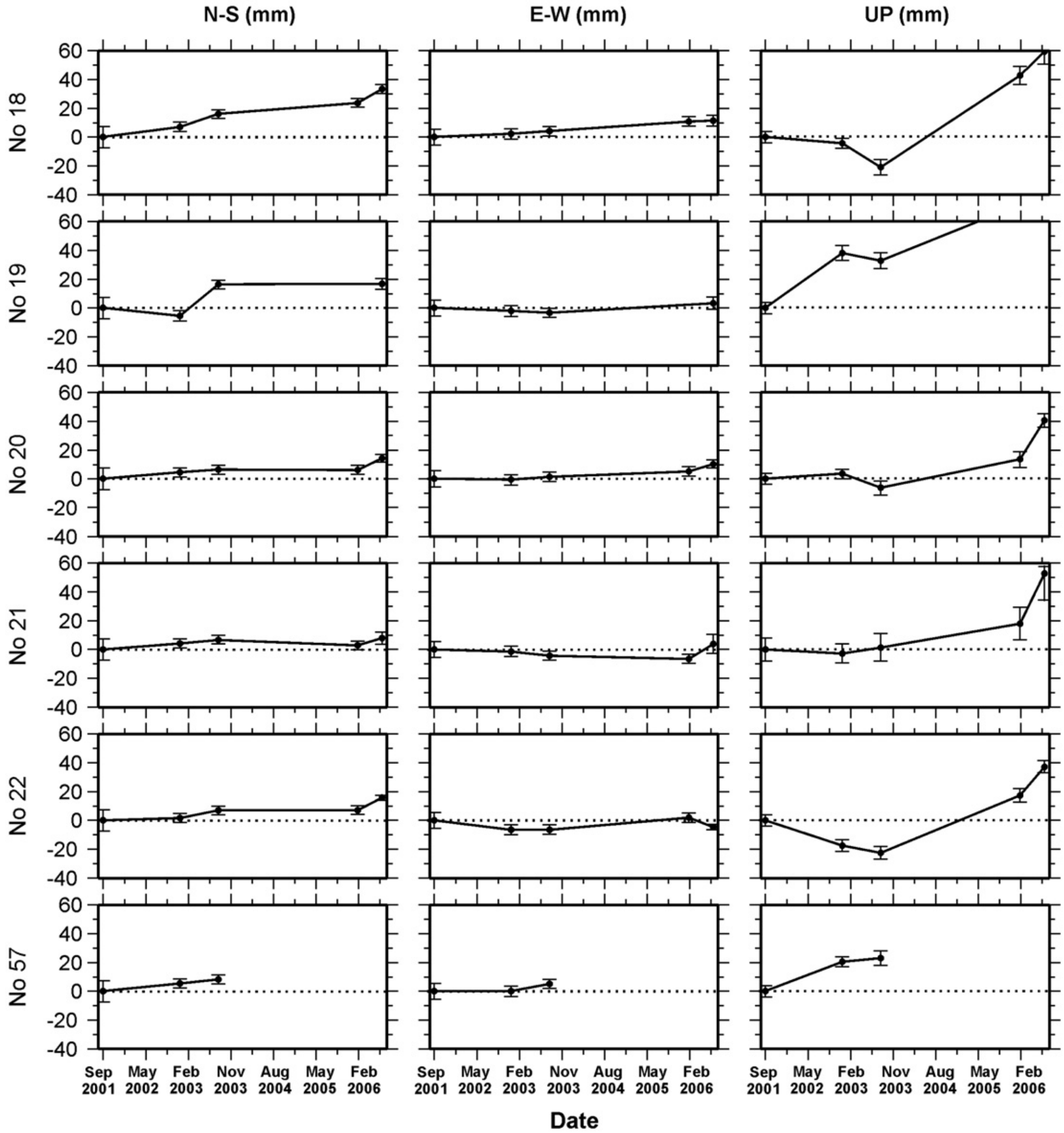

Fig. 5 (*continued*).

1.6 mm/yr and $\upsilon_u = -2.6 \pm 1.8$ mm/yr, respectively. Transforming these values (Soler and Marshall, 2003a,b) to the Eurasian reference system, the horizontal velocity components are $\upsilon_e = -6.6 \pm 0.7$ mm/yr and $\upsilon_n = -9.3 \pm 1.6$ mm/yr. The above values are consistent with the velocity components determined by Hollenstein et al. (2006) for two stations in the western (GERO) and northern (FISK) parts of the island for an earlier period (1995 to 2001). Analytically, comparing the velocities of those two stations with our station No. 06, they have the same directions and very similar magnitudes for the υ_e component; while our υ_n is slightly higher but of the same order of magnitude. The latter may be attributed to the local differential motions of the various neotectonic blocks of the island (see the clockwise rotation of the island presented further down). Referring to the υ_u component, our results are compatible with that (about −4 mm/yr) determined by Hollenstein et al. (2006).

3.3.1. September 2001 to January 2003 period

For the first observational period–September 2001 to January 2003–small horizontal displacements had occurred (Fig. 6a). The magnitudes were generally less than 10 mm, and only those stations located at the southern part of the island had values reaching 10–12 mm.

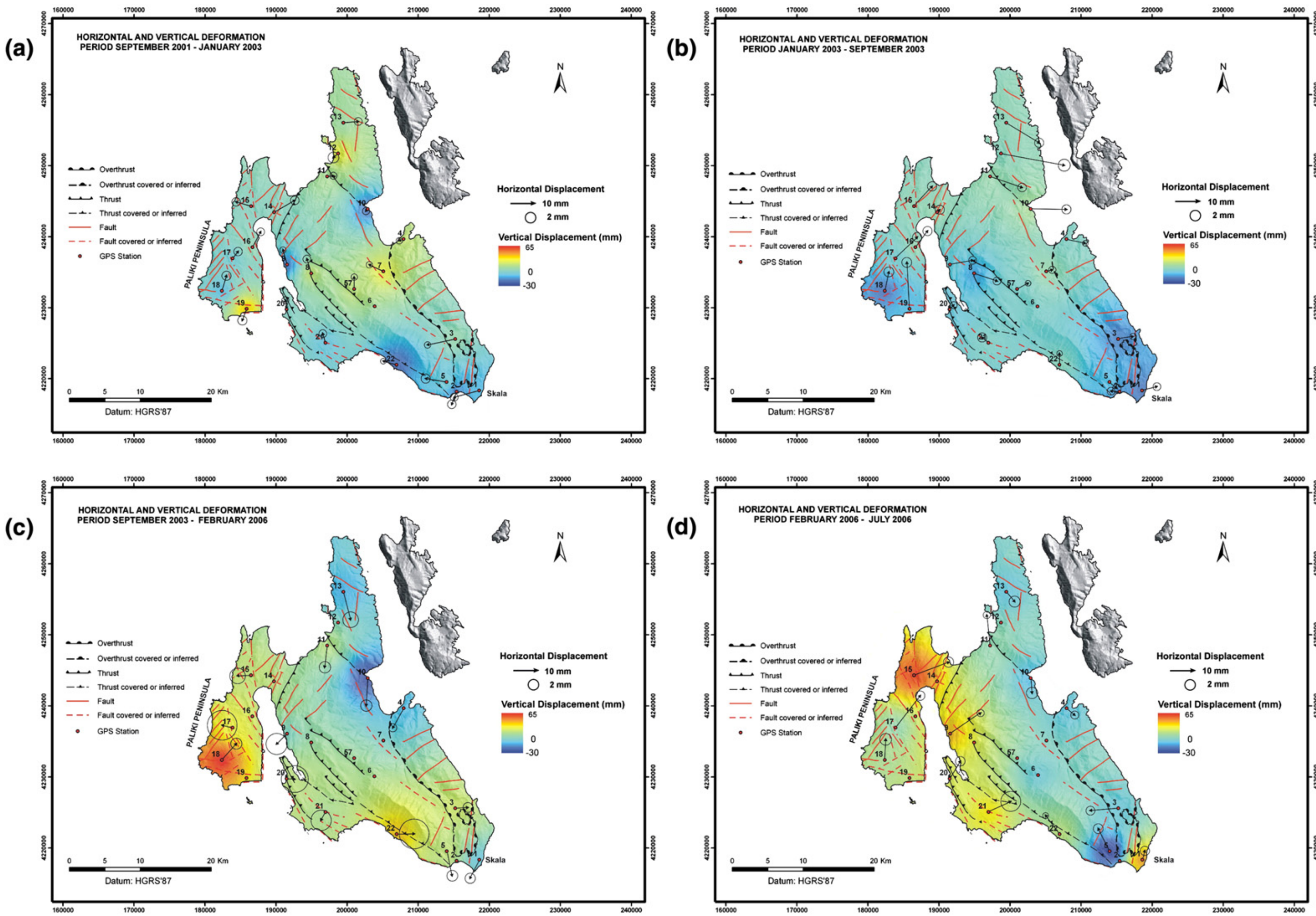

Fig. 6. DGPS results from the Cephallonian network relative to station No. 06 (Aenos Mt.) for various observational periods, (a) Sept. 2001 to Jan. 2003; (b) Jan. 2003 to Sept. 2003; (c) Sept. 2003 to Feb. 2006; and (d) Feb. 2006 to July 2006.

A clockwise rotation relative to station No. 06 had occurred. More specifically, the horizontal vector indicates a westward displacement between 5 and 10 mm for stations in the southern part of the island, but changing to a northward direction with smaller values (5–8 mm) in the central part. For stations located on the Paliki Peninsula in the western part, 4–11 mm occurred. The displacement in the northern part is within the error limits, except for the extreme northern station No. 13 which had an eastward direction of 7 mm and is consistent with the overall clockwise rotation. Anomalies at a few stations are interpreted as local phenomena due to the complex and extensive nature of faulting in the near vicinity. This is the case for some stations in the northern part where there has been stress accumulation along local fault systems.

The vertical component of displacement exhibited behavior that is consistent with the expected tectonic motions of the island. Subsidence of 5–17 mm occurred along the southern part. This is a well-known region where systematic neotectonic subsidence is anticipated due to the type of deposits in the area and the associated step-like fault system along the southern part of the Aenos Mt. Long-term continual subsidence, especially around the area where station No. 22 has been installed, necessitates ongoing building repairs.

Small magnitudes of uplift of about 5–15 mm occurred at the northern and western parts of the island. More intense uplift (>15 mm) that exceeded the average value of 10 mm for the whole island happened in the eastern part, which is characterized by the contact between the Ionian and Paxi tectonic zones. In addition, the presence of evaporites and potentially associated bulging phenomena that may take place there could explain the uplift.

3.3.2. January 2003 to September 2003 period

For the second observational period–January 2003 to September 2003–the horizontal vectors maintained the clockwise rotation around station No. 06 as with the previous period (Fig. 6b). In addition, the northern part of the island appears to have been significantly affected by the major earthquake that occurred west of Lefkas in August 2003 and will be addressed later. Note that the horizontal vectors have magnitudes that are significantly larger than those of the previous period of longer duration, ranging from 15 to 25 mm and with direction ESE–SE. Vectors with magnitudes of 9–14 mm and with NE–NNE direction characterize the western part of the island along the Paliki Peninsula. The rest of the island (central and southern parts) yielded horizontal displacements of 5–7 mm, which are slightly higher than the error estimates, but consistent with the directional pattern of the previous period.

In general, the vertical component of displacement was a continuation of the pattern observed in the previous observational period. Although this period was shorter in duration, there was a similar value of overall uplift of about 10 mm. Deviations occurred at some stations located in the central–western part of the island; however, their magnitudes were close to the error estimates. Subsidence in the SE part was maintained, especially around the area of Skala which dropped by 10 mm.

The total deformation (both vertical and horizontal) from September 2001 to September 2003 (*i.e.*, combines the first and second observational periods) is presented in Fig. 7a. The clockwise horizontal displacement is very pronounced with magnitudes varying from 5 to 17 mm. The largest magnitudes (18–28 mm) occurred in the northern part of the island. Most of the island had uplifted by 12–25 mm, although subsidence (3–20 mm) took place in the southern and SE parts (*e.g.*, Skala area).

3.3.3. September 2003 to February 2006 period

During the procedure of establishing the Zakynthos network and its local reference station RLS in August 2005, station No. 22 in the Cephallonian network was measured, too, and all tied to station DION. An unexpected vertical displacement was noted at station No. 22. Subsidence had been expected considering its tectonic setting, and was indeed systematically observed until September 2003. However, the motion reversed to uplift almost two years afterwards. New measurements during January 2006 confirmed the uplift.

To further substantiate this change in behavior, a new campaign was conducted in February 2006. For the third observational period–September 2003 to February 2006–it is noted that the horizontal clockwise rotation of the previous period was not maintained (Fig. 6c). The magnitudes of horizontal displacement varied from 5 to 14 mm; the vertical component though showed some unanticipated changes.

Stations located in the western and southern parts of the island (*i.e.*, Nos. 15, 17, 18, 20, 21 and 22) revealed significant uplift with magnitudes ranging from 16 to 63 mm. The maximum uplift was observed at the westernmost stations Nos. 17 and 18 with values of 30 mm and 63 mm, respectively. Station No. 22 in the south uplifted by 39 mm. However, the extreme SE part (Skala area) continued to systematically subside, reaching a total of 32 mm.

3.3.4. February 2006 to July 2006 period

The main purpose of this campaign was to further investigate the observed uplift in the southern and western parts of Cephallonia. The vertical component of

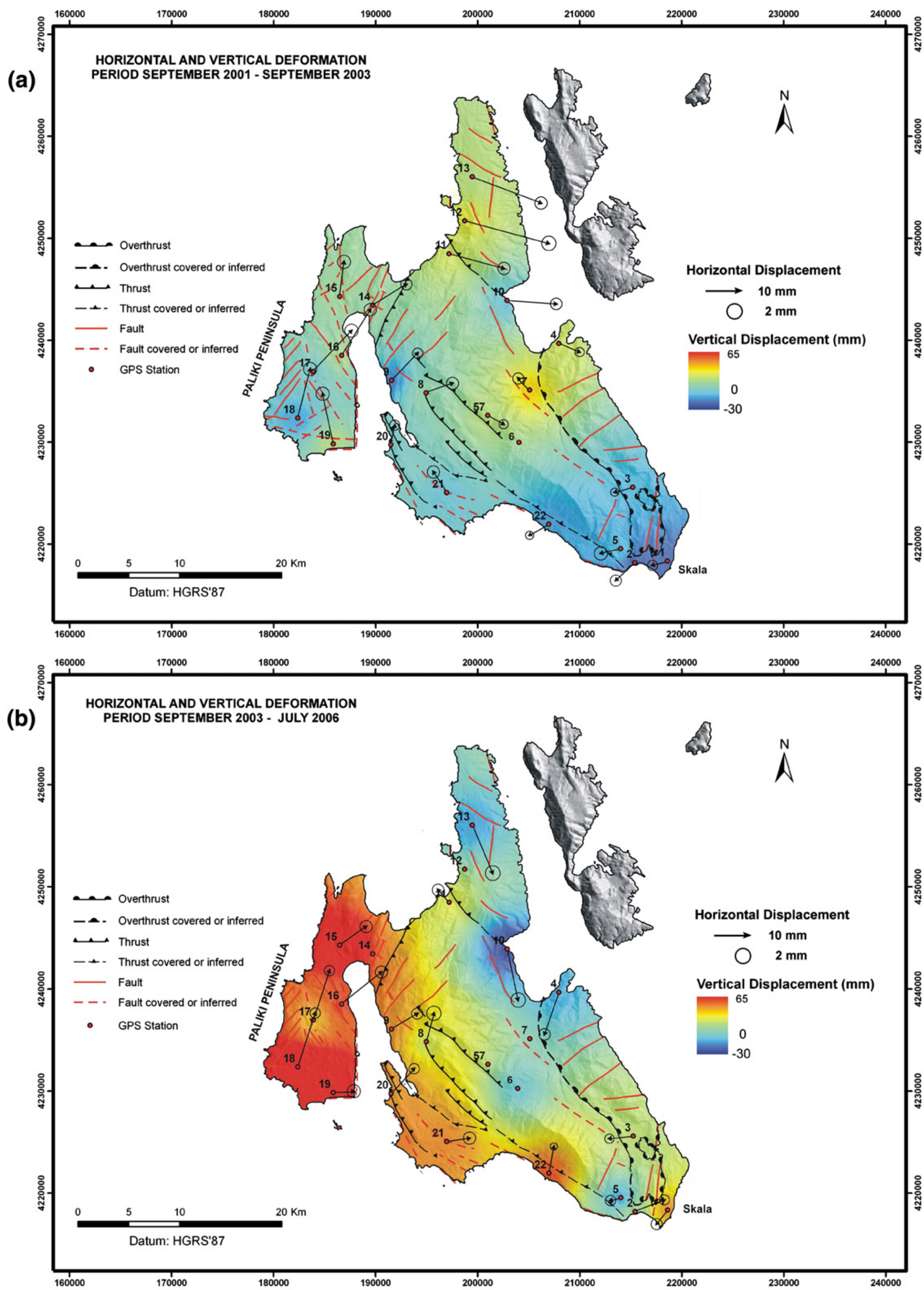

Fig. 7. DGPS results from the Cephallonian network for the combined periods: (a) Sept. 2001 to Sept. 2003; (b) Sept. 2003 to July 2006.

displacement showed continued uplift in the western and southern parts (Fig. 6d). Magnitudes in the west ranged from 10 to 17 mm in Paliki Peninsula. Larger magnitudes (reaching 34 mm) were measured at all stations along the southern part of the island. Even the stations around Skala that were previously systematically subsiding changed their sign of motion. The horizontal displacements ranged between 4 and 17 mm, but did not show any systematic movement.

Fig. 7b depicts the overall change between September 2003 and July 2006 (*i.e.*, combines the third and fourth observational periods). The horizontal component of displacement at the western and northern parts of the island is similar to the first combined period (Sept. 2001 to Sept. 2003; see Fig. 7a) in terms of magnitude and orientation. It is in the SE part of the island that small changes of similar magnitude occur at some stations located within multi-fragmented micro-tectonic blocks. Concerning the vertical component of displacement, the western and southern parts have been strongly uplifted, while the rest of the island maintained a similar behavior as the first combined period (2001 to 2003) without any distinct changes.

The overall vertical behavior of stations Nos. 03, 04, 05, 08, 10, 11 and 13 was consistent for all the observational periods (Table 3; Fig. 5). Station No. 06 at Aenos Mt. which was the local reference station experienced an insignificant vertical motion since its installment in September 2001, having a slight tendency to subside by a total of 15.6 mm relative to ITRF2000. In summary, the northern, central and eastern parts of Cephallonia exhibited consistent vertical displacement, while the western and southern parts experienced an unanticipated extensive uplift.

3.4. Zakynthos network

The local GPS network in Zakynthos was remeasured at the end of July 2006, almost one year after its establishment in August 2005. In the mean time, an earthquake $M_w = 5.6$ occurred offshore to the south of the island on October 18, 2005. Thereafter, a significant sequence of at least four earthquakes ($M_w = 5.5$ to 5.7) occurred in the same region between April 4 and 12, 2006 (NOA earthquake catalogue). This seismic activity most likely contributed to the deformation presented in Fig. 8, where the results are referred to the station RLS in the Peloponnese that was tied to ITRF2000.

Two additional measuring periods (January 2005 and January 2006) were included in the analysis of station RLS for a better estimation of its coordinates with respect to ITRF2000 (see Table 1 and Fig. 4). For such a relatively short period (about 1.5 years), the station had moved to the SE with velocity components of $\upsilon_e = 14.2 \pm 4.5$ mm/yr and $\upsilon_n = -18.5 \pm 3.9$ mm/yr, along with subsidence of $\upsilon_u = -5.4 \pm 6.0$ mm/yr. With respect to the Eurasian reference frame, the velocity components are $\upsilon_e = -9.5 \pm 4.5$ mm/yr and $\upsilon_n = -30.4 \pm 3.9$ mm/yr. These values are consistent with the results from the nearest stations of regional networks, namely CHLE (Kahle et al., 1995), No. 61 (Clarke et al., 1998) and ZAHA (Cocard et al., 1999), even considering the short time period of our measurements.

3.4.1. August 2005 to July 2006 period

It is evident that a horizontal extension of the southern part of the island had occurred in the area around Laganas Bay (Table 4; Fig. 8) which seems to be "opening". Its western part showed generally a westerly motion with magnitude ranging from 15 to 20 mm, while its eastern part had magnitude of 26 mm but towards the NNE. The central part of the island appears stable. The northern part, however, presents an inconsistent pattern with two stations (Nos. 60 and 62) having directions to the SW, while the most northerly ones, Nos. 61 and 63, had movement to the NW and N with magnitudes of 24 mm and 5 mm, respectively.

The vertical deformation is expressed with uplift mostly in the southern part bounding the area of Laganas Bay, with values of 40 mm and 60 mm in the western and eastern parts, respectively. More than 60 mm occurred at station No. 70. The extreme northern part (Nos. 61 and 63) had subsided by 12–30 mm, while the section to its SE (Nos. 60 and 62) was unchanged.

4. DInSAR analysis

DInSAR analysis was performed to study the regional deformation of Cephallonia for the period 1995 through 2005 (Table 5). One interferogram covers the period prior to the installation of the GPS network in the broader area (1995–1998), and three of them (mid-2003 to end-2005) correspond to the second half of our GPS measuring period (Sept. 2003 to July 2006). The ground deformation associated with the Lefkas earthquake was considered also, and a synthetic model was produced using ASAR images and constrained by available seismological information. Note that because of technical problems with some of the images, together with satellite (ERS-2) orbital problems that were announced by the European Space Agency since February 2001, it was not possible to form interferograms corresponding to the first observational period of the GPS analysis, which could have provided control on the constructed interferograms.

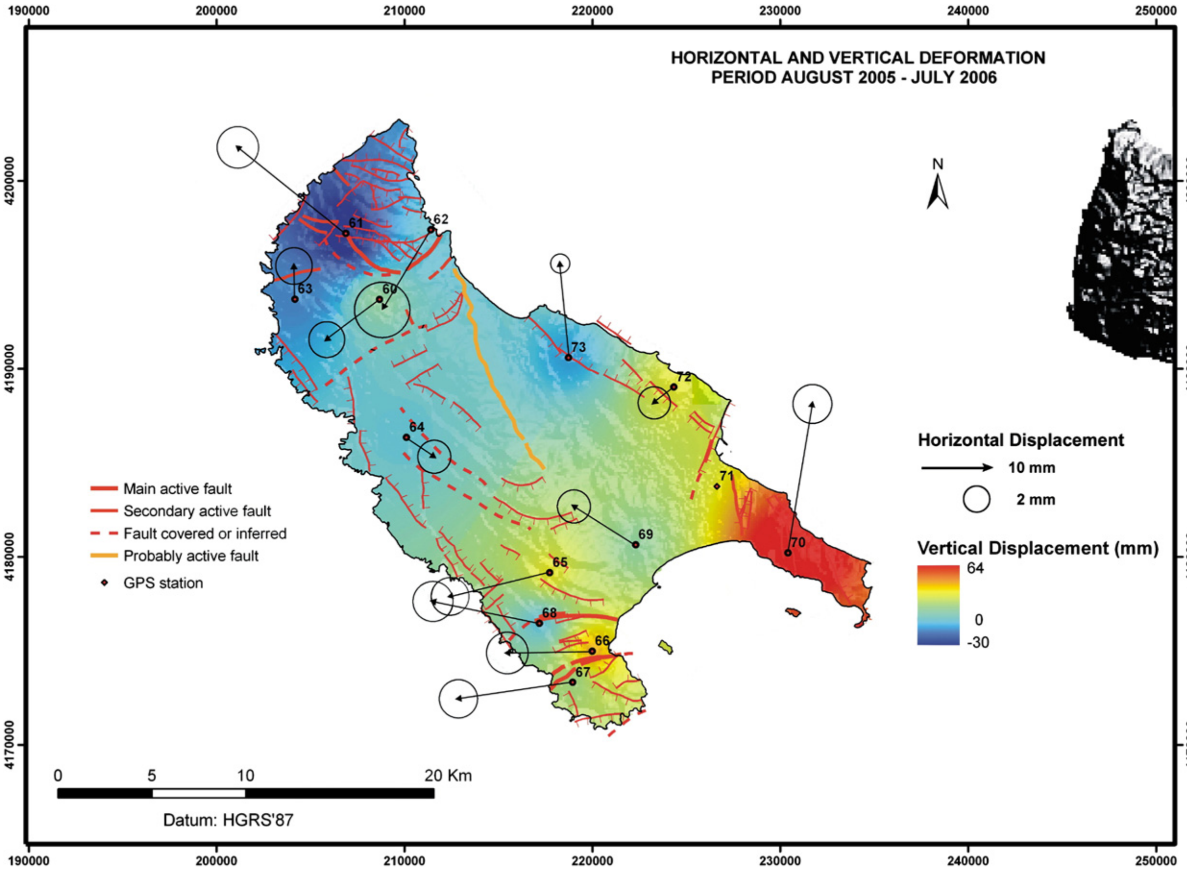

Fig. 8. DGPS results from the Zakynthos network referred to RLS station (see Fig. 1) for the observational period Aug. 2005 to July 2006.

Suitable interferometric pairs of SAR and ASAR images of the ERS and ENVISAT satellites, respectively, were selected to produce the DInSAR images. The "two-pass differential interferometric method" or "DEM-elimination method" was chosen in which two images are used to produce a single interferogram. A second interferogram had to be created or synthesized to perform the differential analysis. For both Cephallonia and Lefkas, the synthesized interferograms were generated from a DEM with pixel size of 20 m that was subsequently subtracted from the original interferogram. After removing all fringes related to ground elevation only those

Table 4
Component displacements of GPS stations referred to station RLS (Riolos) of the Zakynthos network for the measuring period August 2005 to July 2006

GPS station no.	N–S (mm)	RMS_{N-S} (mm)	E–W (mm)	RMS_{E-W} (mm)	Up (mm)	RMS_{Up} (mm)
60	−7.10	2.8	−9.40	3.2	11.60	6.7
61	15.30	4.8	−19.20	5.6	−38.51	7.4
62	−13.80	12.6	−8.40	8.6	−0.70	8.5
63	5.90	2.8	−0.20	3.4	−12.48	7.1
64	−3.40	2.6	4.90	3.2	−0.79	6.7
65	−4.20	2.8	−17.70	3.0	30.70	7.2
66	−0.30	3.2	−15.10	3.2	43.10	8.2
67	−2.90	3.0	−20.30	3.6	16.91	7.8
68	3.90	3.0	−18.90	3.2	−1.59	7.8
69	6.80	2.6	−11.00	2.8	12.00	6.2
70	26.40	3.0	4.30	3.0	63.41	7.6
72	−2.80	2.4	−3.50	3.2	29.90	7.1
73	16.70	2.4	−1.50	2.6	−8.10	5.8

Table 5
SAR (ERS-1) and ASAR (ENVISAT) pairs for Cephallonia and Lefkas Islands

Area	Date	Orbit	Frame	Pass	Interval (days)	Satellite	Bp (m)
Cephallonia	28 September 1995	21989	765	Ascending	1051	ERS-1	19
	14 August 1998	17346					
	↕ 58 months gap						
Cephallonia	25 June 2003	6889	2835	Descending	379	ENVISAT	136
	14 July 2004	17346					
	↕ 6 months overlapping						
Cephallonia	21 January 2004	9895	2835	Descending	207	ENVISAT	−3
	18 August 2004	12901					
	↕ 2 months gap						
Cephallonia	27 October 2004	13903	2835	Descending	379	ENVISAT	−69
	16 November 2005	19414					
Lefkas	21 March 2003	5522	765	Ascending	173	ENVISAT	53
	12 September 2003	8027					

fringes representing surface displacements remained. Orbital and topographic phase residuals were removed from the raw differential interferogram by adjusting the perpendicular baseline line component and yaw angle. The phase differences, which then appear as fringes in the final interferogram, are the result of displacements of the ground surface from one interferogram to the other or, in some cases, are the result of atmospheric path effects.

Every circle (360°) of fringe represents a specified height difference for all the fringes in the interferogram. The height difference is known as altitude of ambiguity (Δz) and can be calculated as a function of the wavelength of the radar signal, the altitude of the satellite orbit, the angle of the signal and the perpendicular (baseline) distance (Bp) between the two orbits. Each fringe of deformation is directly related to the radar's wavelength, which is 56 mm for the ERS and ENVISAT satellites, and represents displacement along the slant range (*i.e.*, line of sight) of only half the above wavelength (*i.e.* 28 mm).

4.1. Cephallonia analysis

A pair of SAR images was selected with a small Bp and long temporal separation to produce a differential interferogram for Cephallonia for the period September 28, 1995 to August 14, 1998 (Fig. 9a). Since there were no major earthquakes close to Cephallonia during that period, the long time separation between images may be considered a sufficient condition for the detection of any possible ground deformation.

The quality of the interferogram is determined by considering the coherence image of the selected SAR pair. Good coherence is limited to the NE and the SE parts of the island. The long-time separation and the dense vegetation that covers most of the island may be the main reasons for the poor coherence that is observed for the rest of the island. The vegetation is not dense at the western part (Paliki Peninsula); however, poor coherence there is probably due to the poorly consolidated sediments combined with strong soil-erosional phenomena that mostly prevail in the southern part. Regardless of the relatively low coherence observed for most of the island, at least three fringes are identifiable.

The area with the most significant deformation is the SE part where at least one fringe had formed (see inset on Fig. 9a for location). The deformation (at least 28 mm) is confined between two fault zones that extend in the E–W and NE–SW directions. The area consists of Alpine formations of the Ionian Zone and, more specific, thin plate Cretaceous carbonate formations, Middle to Upper Jurassic schists, and Lower Triassic evaporites and breccias. A small circular fringe (28 mm) is noted around station No. 10, and is located near to a NNW–SSE trending fault. An explanation for this fringe is not readily apparent, mainly due to its limited extent. Ground subsidence, though, may be attributed to local phenomena and is consistent with DGPS analysis for subsequent observational periods. A third fringe (28 mm) is noted, but associated with steep topography in the northern part of the island. This fringe is considered artificial given that the height difference (500 m) over its areal extent is almost equal to the calculated altitude of ambiguity (Δz=495 m) for the SAR pair that was used to produce this interferogram.

The interferometric pair covering the period June 2003 to July 2004 is characterized by the absence of clear interferometric fringes (Fig. 9b). However, an almost complete fringe is identified at the extreme northern part of the island, and is most probably associated with the cluster of epicenters in this area from the post-seismic sequence of

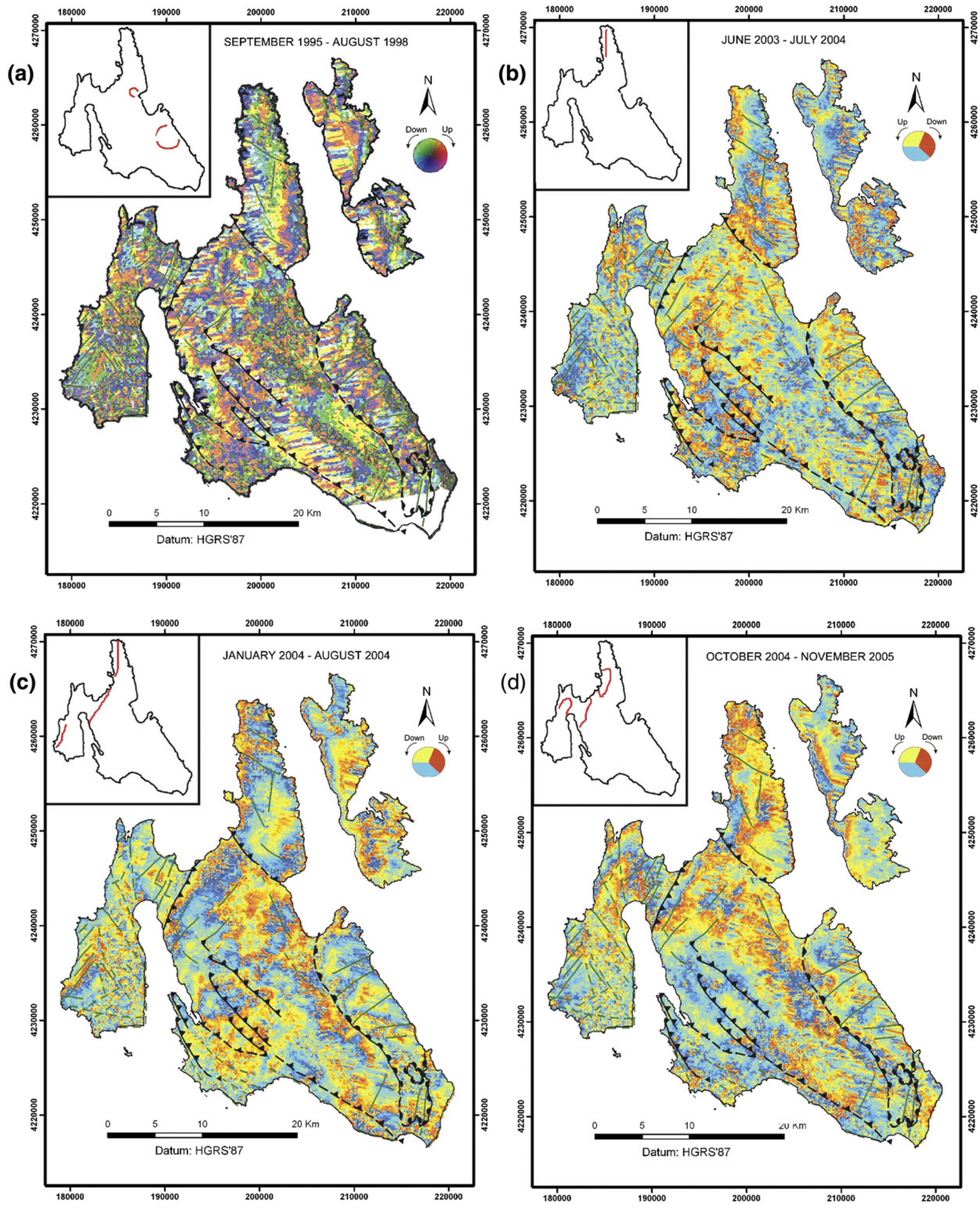

Fig. 9. DInSAR images of Cephallonia Island for the periods: (a) Sept. 1995 to Aug. 1998; (b) June 2003 to July 2004; (c) Jan. 2004 to Aug. 2004; (d) Oct. 2004 to Nov. 2005. Insets indicate position of fringes.

the Lefkas earthquake (Fig. 10). This conclusion is supported by the noted increased deformation in this part of the island as deduced through DGPS observations (see Fig. 6b).

The interferometric pairs covering the periods January 2004 to August 2004 and October 2004 to October 2005, reveal fringes along the western and extreme northern parts of the island (Fig. 9c–d). In the first pair, a discontinuous fringe (28 mm) is observed along the western part of Paliki Peninsula. It extends further to the north along a major thrust fault, and subsequently prolongs near and along the western coast of the extreme northern peninsula. In the second pair, a similar fringe (of another 28 mm) is observed at almost the same locations as in the previous pair. The existence of two fringes in total indicates a total deformation of about 56 mm for the two-year period covered by both pairs. Taking into consideration the sign of the phase-change in both images, uplift is inferred. Uplift is compatible with the observed DGPS measurements that encompass the period (see Fig. 6c).

4.2. Lefkas earthquake analysis

On August 14, 2003, a large magnitude earthquake (M_w=6.3) occurred to the west of Lefkas. Body wave modelling revealed a fault plane solution characterized by dextral strike–slip motion (φ=15°, δ=80° and λ=170°). Furthermore, the focal depth was about 9–10 km, the duration of the source time function was 8 s, and the seismic moment was $2.9 \cdot 10^{25}$ dyn cm with directivity towards the south (Papadopoulos et al., 2003; Karakostas et al., 2004; Benetatos et al., 2005; Papadimitriou et al., 2006).

Seismological analysis revealed that the aftershock sequence consisted of two distinct clusters (Fig. 10). The first one was located close to the epicenter of the main

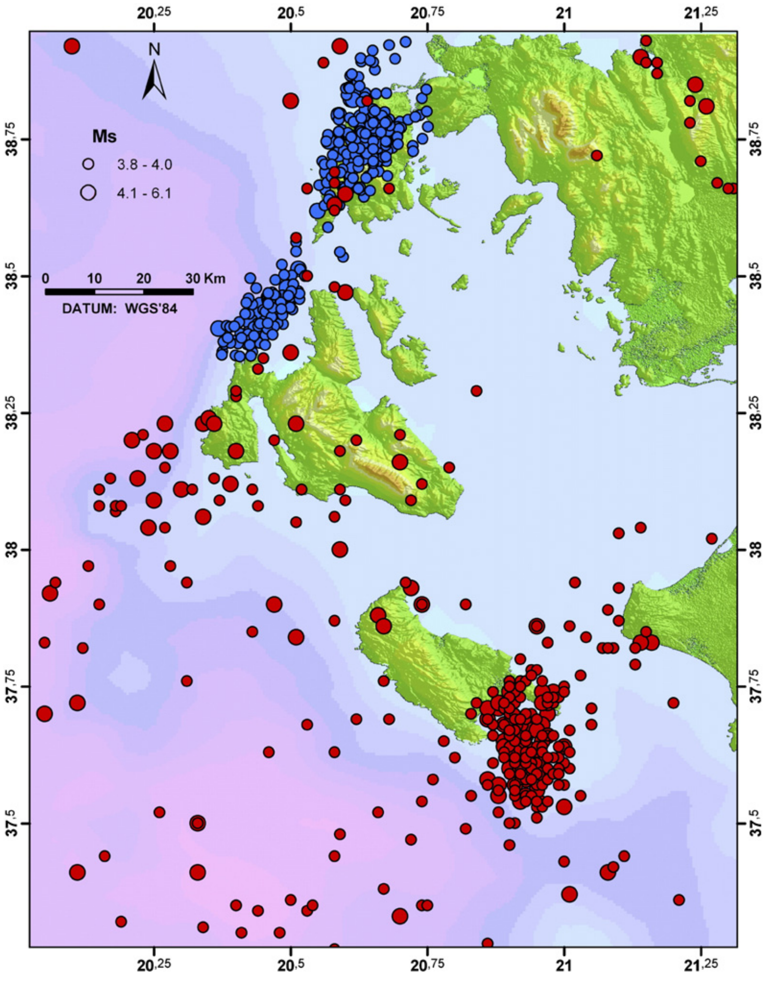

Fig. 10. The post-seismic sequence (August to September 2003) of the Lefkas earthquake formed in two clusters, represented as blue circles, superimposed on the seismicity of the broader area (January 1, 2004 to October 10, 2006) denoted by red circles.

shock. The second was further to the south near the NW coast of Cephallonia. Between these two clusters was a seismic gap. Thus, the overall length of the activated zone was approximately 60 km and is considered large for the given magnitude. In an attempt to explain the observed seismicity, the first cluster has been attributed to the aftershock sequence of the main event, while the second one to stress transfer (Papadimitriou et al., 2006). The occurrence of the $M=5.1$ aftershock on November 16, 2003, near the southern edge of the southern cluster, provides evidence of the static stress increase in this area (Karakostas et al., 2004).

An ASAR pair covering the period March 23, 2003 to September 12, 2003 was selected to form a differential interferogram that would include any probable ground deformation associated with the Lefkas earthquake (see Table 5). The resultant interferogram indicates that the main areas of deformation were located at the western and the northern parts of the island (Fig. 11). Ground deformation may have occurred also at other places, but is not detectable by DInSAR analysis due to low coherence over much of the island.

A well-formed fringe that extends from the western coast to the center of the island is clearly noticed. A second fringe also appears in the same area but is not fully formed. The presence of the sea partially obscures this fringe. However, it is likely that such a large-magnitude event should have created at least one more fringe of deformation, something that is supported by our modelling attempts as described below. Therefore, a total ground deformation reaching 56 mm probably occurred in this area.

Another fringe is observed at the northern part of the island in the vicinity of the City of Lefkas. Note that this fringe has a colour sequence (GRB) that differs from the fringes in the western part (BGR). This difference in sequence may be explained by different sources of ground deformation. In the west, the deformation is attributed to the main shock event exhibiting a predominant strike–slip component, and the ensuing post seismic activity that followed in the broader area. In the north, though, the deformation is caused by side effects of the observed seismicity as discussed below.

4.3. Modelling results

Forward modelling was performed to determine the likely causes for the observed deformation. The model assumes offshore fault activation along the Lefkas Transform Fault (LTF) which lies to the west of the island. Displacements were quantified using the single fault plane algorithm of Feigl and Dupre (1999), which is based on the formulation of fault-dislocation developed by Okada (1985). Modelling parameters referring to likely minimum and maximum values of depth and length extent of the LTF were assumed (Table 6). The seismological parameters for the focal mechanism of the earthquake (Papadimitriou et al., 2006) were used as an *a priori* model. The sign of the slip-component vector (U_1, U_2, U_3) that describes the fault motion was set to express a right-lateral slip motion and a thrust fault mechanism ($U_1<0$, $U_2>0$). Based on seismological analysis, the major component of the vector motion was lateral slip (U_1), while the tensile component (U_3) was insignificant.

A synthetic interferogram was created based on ascending-pass geometry (Fig. 12). The location of the adopted fault model is in agreement with the seismotectonically expected one; *i.e.*, about 5 km offshore on the west. The strike angle was determined at $15\pm3°$ (East of North) and the dip angle to $80\pm5°$. The width of the fault describes a feature not reaching the sea bottom. However, the length of the modelled fault (12 km) is smaller than that inferred by the seismological analysis (25 km). The slip-motion vectors U_1 and U_2 are in good agreement with the seismological parameters, where the U_1 component dominates the motion and confirms its lateral slip character, and is compatible with the tectonic regime of the area. Finally, the shape and spatial distribution of the two modelled fringes are in good agreement with the observed ones for the western part of the island (compare Figs. 11 and 12).

The modelled fault activation does not fully account for all of the observed ground deformation. Efforts to model the fringe that appears at the northern part of Lefkas were unsuccessful. The fault characteristics that are needed to fit the observed fringe in that area adversely affects the shape and the areal extent of the other main fringe and cannot be supported by the adjacent tectonics. Consequently, this fringe is attributed to locally induced side effects of the recorded seismicity of the broader area, and mainly to the strongest aftershock (August 14 (16^h 18’), M=5.4) that occurred at the northern end of the rupture close to the City of Lefkas, where it was more strongly felt as compared to the rest of the island (Karakostas et al., 2004). These side effects are associated with subsidence and liquefaction phenomena even inside the City of Lefkas, together with probable small-scale displacements along local faults that bound the area (ITSAK, 2004; Papathanassiou et al., 2005; Benetatos et al., 2005).

5. Seismicity pattern

Seismological studies before the occurrence of an earthquake indicate that the spatial and temporal distribution of the seismic events changes. As such, a specific analysis approach to this distribution could provide

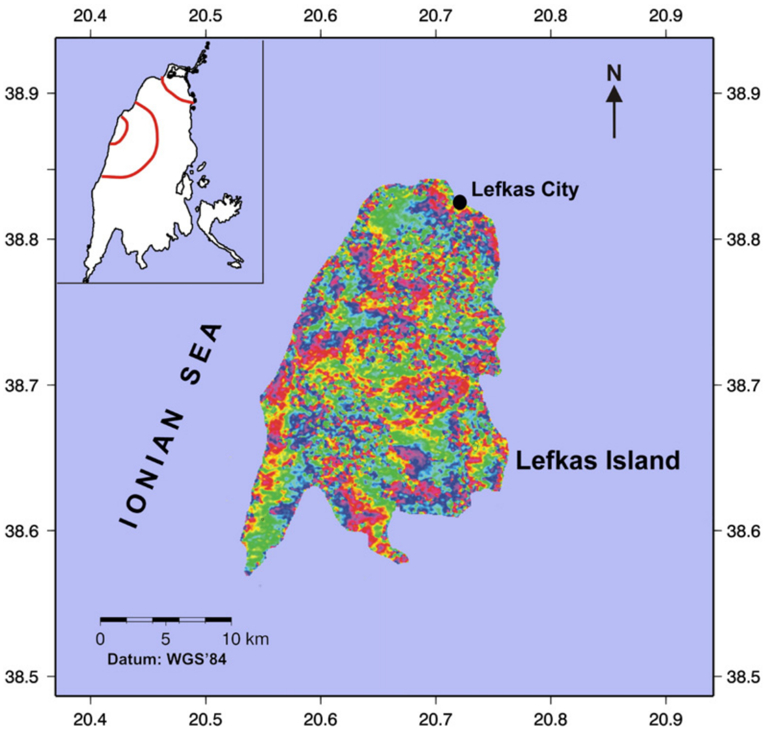

Fig. 11. Differential ASAR interferometric image of Lefkas Island for the period March to September 2003. Inset indicates position of fringes.

important information about the occurrence of a future earthquake in a study area. One approach is to model this process as a critical phenomenon that culminates in a large event (Sornette and Sornette, 1990). The clustering of small-to-intermediate events before a large-magnitude shock produces an increase of seismicity. Bufe and Varnes (1993) proposed that in the broader area where a large-magnitude earthquake may occur the seismic energy release increases and the acceleration procedure, known as cumulative Benioff strain, can be modelled by a power law time-to-failure relation. This methodology has been applied to several regions with encouraging results (Bowman et al., 1998; Jaume and Sykes, 1999; Zoller and Hainzl, 2002). Investigation of the evolution of seismicity patterns has been applied also in Greece as part of earthquake prediction research (Tselentis et al., 1999; Papazachos and Papazachos, 2000; Tzanis and Makropoulos, 2000; Papadimitriou, 2002; Papazachos et al., 2004).

In our study area, intense seismicity has occurred since 2004 (see Fig. 10). The clustered events are mainly concentrated to the west of Cephallonia and to the south of Zakynthos islands. The accelerating energy release hypothesis was applied using the earthquake catalogue provided by the Geodynamic Institute at NOA. The data were declustered using the Reasenberg (1985) algorithm. Precursory phenomena were identified based on the degree of acceleration and curvature parameter (as defined by Bowman et al. (1998)) and using the methodology developed by Papadimitriou (2004). According to this approach, a circular area of radius $R = 100$ km centered at about 20 km NW of Zakynthos was defined, and all events within that area having magnitude $M > 4.0$ were selected for the analysis.

The Benioff strain variation prior to and during the beginning of 2004 is approximately linear, corresponding to the null hypothesis that the seismicity rate is constant. Considering the above, only data since the beginning of

Table 6
InSAR modelling parameters for assumed motion along the Lefkas Transform Fault

Fault system	Strike (a) (degrees CW N)	Depth (d) (km)	Dip (δ) (degrees)	Length (km)	Width (km)	U_1^* (mm)	U_2^* (mm)	U_3^* (mm)
Fig. 12	10–17	11 to 16	90–70	10 to 20	9 to 14	−350 to −600	25 to 60	0.0
Best-fit model	15±3	13	80±5	12	11	−450	40	0.0

(*) U_1, U_2, U_3 are the right-lateral, up-dip and tensile components of the slip vector on the fault plane, respectively.

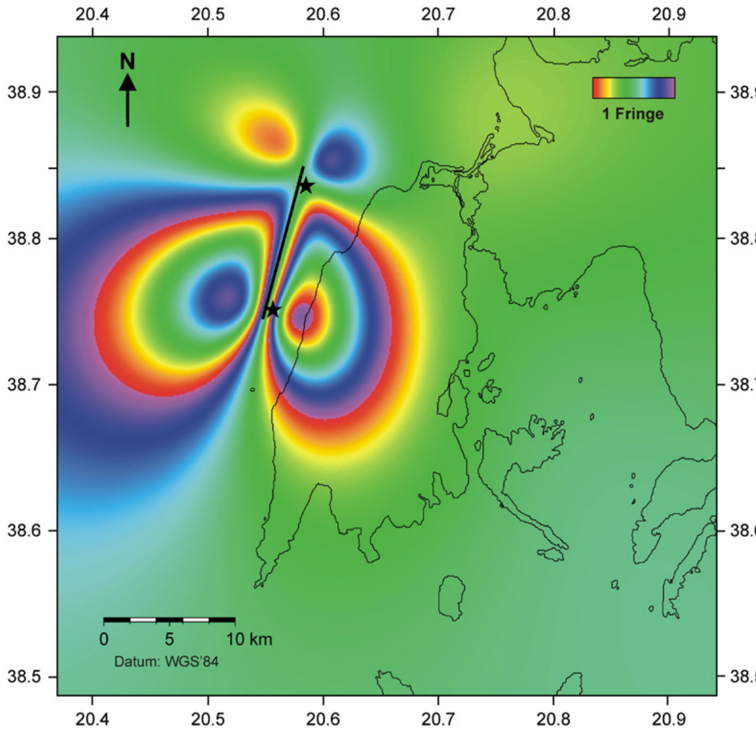

Fig. 12. Synthetic interferometric image of the LTF motion. The two stars indicate the epicenters of the two main sub-events of the Lefkas earthquake.

2004 were used in order to identify possible anomalies. Fig. 13 depicts cumulative Benioff strain *versus* time for the period January 2004 to October 2006. The best-fit result from the inversion of the Benioff strain yields the degree of acceleration, ***m***, with the curvature parameter, ***c***, defined as the root-mean-square error. Having in mind that the cumulative Benioff strain is defined here as the square root of the seismic energy, it was found that $m=0.42$ and $c=0.6$. The resultant values of $m<0.5$ and $c<0.7$ are clear indicators of a non-linear accelerating energy release, since ***m*** and ***c*** must be smaller than unity for such a process to occur. It is evident therefore that an accelerating seismic crustal deformation has been taking place in the area since 2004.

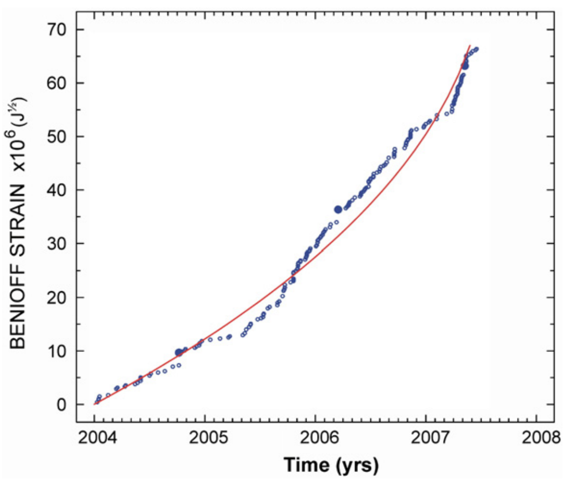

Fig. 13. Observed (blue circles) and calculated (red line) Benioff strain variation in the Central Ionian Islands (Jan. 1, 2004 to Oct. 31, 2006).

6. Discussion and conclusions

In this paper, we have presented results of ground deformation studies based on DGPS and DInSAR analyses for the seismically active area of the Central Ionian Islands. These studies have yielded detailed information regarding both local and regional deformations. The occurrence of recent earthquakes near Zakynthos and Lefkas has contributed significantly to the observed deformations in the region.

6.1. Lefkas Island

The DInSAR modelled parameters for the Lefkas earthquake can fully account for the observed deformation of about 56 mm at the western and central parts of the island, but not for the northern part. Here, the source of the measured deformation of about 28 mm is attributed to local subsidence and liquefaction phenomena observed in and around the City of Lefkas. The modelled fault length (12 km) is smaller than that anticipated for a magnitude $M_w = 6.3$ tremor. However, applying teleseismic waveform analysis, Benetatos et al. (2005) demonstrated that this earthquake was an event of multiple source character consisting of three sub-events along the strike of the LTF. The first two sub-events ($M_w = 5.6$ and $M_w = 6.0$) occurred to the west of Lefkas at a very short time from one to the other (2.5 s) and were separated by a distance similar to the modelled fault length. The third event ($M_w = 5.8$) occurred 14 s later at about 35 km further to the SW, just west of the northern edge of Cephallonia. The three-sub-event concept was also suggested by Zahradnik et al. (2005).

The third sub-event may not have been a main event, but a stress transfer to the SW produced by the first two sub-events (Papadimitriou et al., 2006). In any case, it should have affected the northern part of Cephallonia to a certain extent as indicated by the DGPS measurements. However, the horizontal magnitudes were smaller than the DInSAR threshold of 28 mm. This conclusion is also supported by the fact that the differential interferogram for the Cephallonia area, which was produced from the same ASAR pair used in analysis for Lefkas, did not show any fringe of deformation for any part of Cephallonia. For this reason it is not presented herein.

6.2. Zakynthos Island

Intense ground deformation has also been noticed in Zakynthos for the period 2005 to 2006. A consistent pattern of deformation has been observed in the southern part of the island, showing an opening of about 24 mm along the E–W axis, while uplift had extensively taken place, reaching more than 60 mm in its SE peninsula. This pattern of deformation has been attributed to the seismic sequence that had occurred in the area during the time span of the measurements. The northern part though did not exhibit systematic deformation, as the horizontal trajectories varied from 6 to 26 mm in different directions. However, subsidence was observed in almost all the northern sites, with values reaching more than 35 mm. This different behavior between the southern and northern parts of the island was also noticed by Hollenstein et al. (2006), implying large extensional deformation along the N–S direction.

6.3. Cephallonia Island

The tectonic regime of Cephallonia was studied by considering the seismicity pattern of the broader area, DInSAR analysis for the period 1995 to 2005 and DGPS analysis for the period 2001 to 2006. To better resolve local tectonic motions, a reference station at Aenos Mt. was established that was tied to the ITRF2000 system. The horizontal trajectories of this station relative to Eurasia show a consistent pattern with the overall motion of the west end of the Hellenic West Arc as described from previous studies (Cocard et al., 1999; Kahle et al., 2000; Hollenstein et al., 2006). However, a total subsidence of about 15 mm had occurred. This movement is opposite to the generally expected tectonic behavior, something that was also noticed and discussed by Hollenstein et al. (2006).

The DGPS results for the whole observational period show horizontal trajectories varying between 10 and 35 mm (Fig. 14). These trajectories show a clock-wise rotation of Cephallonia with respect to the station at Aenos Mt., calculated to be 12.7±5.5°/Myr. This value is consistent with recent GPS regional work – about 8°/Myr (Cocard et al., 1999), palaeomagnetic studies – about 5–21°/Myr (Laj et al., 1982; Kissel and Laj, 1988; Duermeijer et al., 1999; Kondopoulou, 2000) and anticipated regional tectonic movements of the area (Le Pichon and Angelier, 1979; Duermeijer et al., 2000; Laigle et al., 2002). The occurrence of the Lefkas strong event and its associated post-seismic sequence, especially its southern cluster, had affected the northern part of Cephallonia where the largest horizontal displacements were detected after the earthquake by DGPS and DInSAR analyses (see Figs. 6b and 9b, respectively).

Regarding the vertical deformation, the western and southern parts of the island have had an unanticipated extensive uplift since September 2003. The GPS stations on the southern (downthrown) side of the Aenos step-like fault system had subsided until 2003 as neotectonically anticipated (Poscolieri et al., 2006). However, the sign of motion subsequently reversed after 2003 and had continued up to July 2006. Similar behavior was also observed in the western part where the uplift was much higher. Since there is a gradual increase in the magnitude of uplift from East to West and from North to South (see Fig. 7b), it is probable that this progression extends offshore to the SW of Paliki Peninsula. The high magnitudes of uplift may be indicative of major regional crustal deformation process of a bulging character that could be taking place in the broader region. At an effort to interpret this phenomenon, we have considered several scenarios.

The widespread presence of evaporites or salt layers that underlie the southern and western parts of Cephallonia and extend offshore to the south could lead to some uplift of these areas if stress relaxation or a regional extensional regime was prevailing. An extensive presence of evaporites

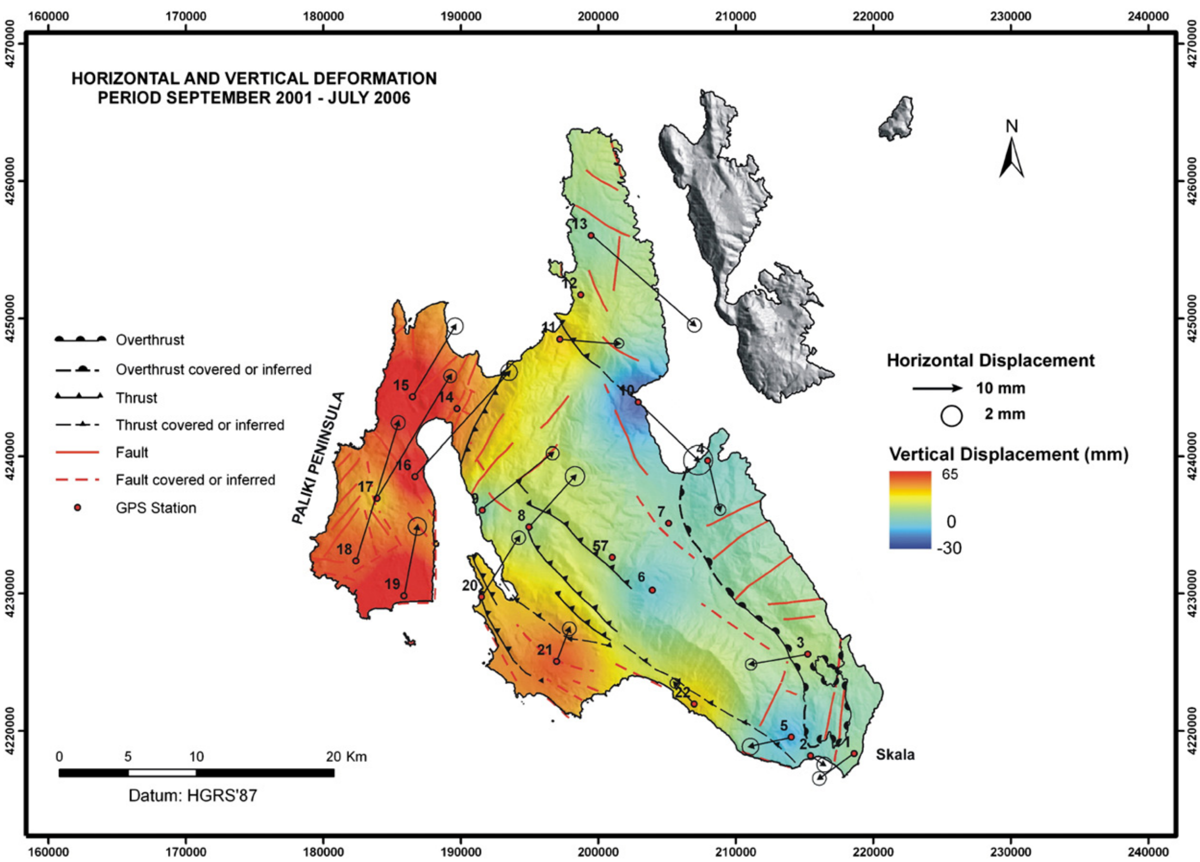

Fig. 14. Vertical and horizontal deformation of Cephallonia deduced from DGPS measurements for the total period 2001 to 2006, relative to station No. 06 (Aenos Mt.).

or salt formations, though, is not consistent with the local geology. Seismic reflection studies that were conducted offshore and along a NE–SW profile between Zakynthos and Cephallonia did not yield any evidence to support the likely existence of such formations (Sachpazi et al., 2000).

The concept of dilatancy which received significant attention in the early seventies (Dambara, 1966; Scholz et al., 1973; Rikitake, 1975) was also considered here, despite the skepticism about its effectiveness for short-term earthquake prediction (Scholz, 1997). It is not an easy task to prove that dilatancy is occurring in the study area. It is a plausible scenario, though, that cannot be excluded considering that the broader region is the most seismically active one in Europe and very strong earthquakes ($M \approx 7$) have occurred over the last 60 years. As such, we have attempted to interpret the uplifted parts of Cephallonia by invoking the dilatancy hypothesis (Lagios et al., 2006). Extensive dilatancy could be occurring along one of the major faults having lengths of several tens of kilometers in the marine area to the S–SW of Cephallonia and/or between Zakynthos and Cephallonia (see Fig. 2). An increased rate of deformation is supported by the seismological analysis of the broader region where an increased accumulated Benioff strain is evident since 2004.

If the adopted dilatancy hypothesis is correct, then various empirical formulas may be used to quantitatively estimate the magnitude and precursory time interval associated with the future occurrence of large-magnitude earthquakes (Dambara, 1966; Scholz et al., 1973; Rikitake, 1975, 1987). Assuming that the dilatant region approximately equals the earthquake zone, as suggested by Rikitake (1975), then for the present case in which the observed area of uplift in the southern and western parts of Cephallonia is more than 50 km, the resultant magnitude for a future earthquake is estimated at $M \geq 7$. For such magnitude, the precursory time to its occurrence is about $T = 4.2$ to 4.6 years starting from 2003.

The regional behavior of station No. 06 (Aenos Mt.) relative to ITRF2000 and the Eurasian reference frame is relatively stable, indicating an interseismic period during which a slight subsidence is taking place due to the subducting process. This condition is maintained until very strong earthquakes occur when the lithosphere under the broader area of Cephallonia rebounds, producing the long-term uplift observed generally in the area in a co-seismic manner (Hollenstein et al., 2006). During that co-seismic process of very strong earthquakes, uplift of the bedrock geological formations of the area (like Aenos Mt.) takes place, while prolonged subsidence occurs locally in areas characterized by loose formations (*e.g.* Skala area), as actually has happened in the 1953 very strong ($M>7$) earthquake (Stiros et al., 1994).

The joint interpretation of the three different applied methodologies shows that after September 2003 a change in the tectonic situation of the area had taken place. It is likely that the Lefkas earthquake (August 2003) may have effectively contributed to the noticed tectonic change in the Cephallonia area. Aenos Mt. retained its subsidal mode in accordance with an interseismic time-period, but in local scale, an extensive uplift has been observed at the western and southern parts of the island, implying a broader bulging of the area. The locally observed strong uplift associated with possible dilatancy effects may possibly indicate the end of the interseismic period and the approaching time of a very strong seismic event in the near vicinity.

Acknowledgements

This work was funded by the Earthquake Protection and Planning Organization (EPPO), the General Secretariat of Research and Technology (GSRT), Athens, Greece (analytically by (i) the European Union (75%), (ii) the GSRT of the Ministry of Development of the Hellenic Republic (25%), and (iii) the private company *Terra-Mentor EOOS*, within the framework of action 8.3 of the EU "Competitiveness" — 3rd Community Support Program), and *KAPODISTRIAS* of the Special Account for Research Grants of the University of Athens. GMT software (Wessel and Smith, 1995) was used to generate some of the figures. Sincere thanks are extended to the Hellenic Forestry Commission (Athens, Greece) and the Higher Geodesy Laboratory (Prof. D. Paradíssis and Mr. J. Galanis, National Technical University, Athens) for their help and support.

References

Anzidei, M., Baldi, P., Casula, G., Crespi, M., Riguzzi, F., 1996. Repeated GPS surveys across the Ionian Sea: evidence of crustal deformations. Geophys. J. Int. 127, 257–267.

Aubouin, J., Dercourt, J., 1962. Zone Preapoulien, Zone Ionienne et Zone de Gravrovo en Pelloponnese occidentale. Bull. Soc. Geol. Fr. 4, 785–794.

Benetatos, C., Kiratzi, A., Roumelioti, Z., Stavrakakis, G., Drakatos, G., Latoussakis, I., 2005. The 14 August 2003 Lefkada Island (Greece) earthquake: focal mechanisms of the mainshock and of the aftershock sequence. J. Seismol. 9, 171–190.

BERNESE GPS Software, 2001. In: Hugentobler, U., Schaer, S., Fridez, P. (Eds.), Version 4.2, Astronomical Institute, University of Bern. 515 pp.

Bowman, D.D., Ouillon, G., Sammis, C.G., Sornette, A., Sornette, D., 1998. An observational test of the critical earthquake concept. J. Geophys. Res. 103, 24359–24372.

Bufe, C.G., Varnes, D.J., 1993. Predictive modelling of the seismic cycle of the Great San Francisco Bay Region. J. Geophys. Res. 98, 9871–9883.

Clarke, P.J., Davies, R.R., England, P.C., Parsons, B., Billiris, H., Paradissis, D., Veis, G., Cross, P.A., Denys, P.H., Ashkenazy, V., Bingley, R., Kahle, H.-G., Muller, M.-V., Briole, P., 1998. Crustal strain in central Greece from Repeated GPS measurements in the interval 1989–1997. Geophys. J. Int. 135, 195–214.

Cocard, M., Kahle, H.-G., Peter, Y., Geiger, A., Veis, G., Felekis, S., Paradissis, D., Billiris, H., 1999. New constraints on the rapid crustal motion of the Aegean region: recent results inferred from GPS measurements (1993–1998) across the West Hellenic Arc, Greece. Earth and Planet. Sci. Lett. 172, 39–47.

Dambara, T., 1966. Vertical movements of the Earth's crust in relation to the Matsushiro earthquake. J. Geod. Soc. Japan 12, 18–45 (in Japanese).

Duermeijer, C.E., Krijgsman, W., Langereis, C.G., Meulenkamp, J.E., Triantaphyllou, M.V., Zachariasse, W.J., 1999. A late Pleistocene clockwise rotation of Zakynthos (Greece) and implications for the evolution of the Western Aegean Arc. Earth Planet. Sci. Lett. 173, 315–331.

Duermeijer, C.E., Nyst, M., Meijer, P.Th., Langereis, C.G., Spakman, W., 2000. Neogene evolution of the Aegean arc: palaeomagnetic and geodetic evidence for a rapid and young rotation phase. Earth Planet. Sci. Lett. 176, 509–525.

ESRI, 2002. ArcDoc for ArcGIS, version 8. Help on CDROM.

Feigl, K., Dupre, E., 1999. RNGCHN: a program to calculate displacement components from dislocations in elastic half-space with applications for modelling geodetic measurements of crustal deformation. Comput. Geosci. 25 (6), 695–704.

Hatzfeld, D., Pedotti, G., Hatzidimitrioiu, P., Makropoulos, K., 1990. The strain pattern in the western Hellenic arc deduced from a micro-earthquakes survey. Geophys. J. Int. 101, 181–202.

Hollenstein, Ch., Geiger, A., Kahle, H.-G., Veis, G., 2006. CGPS time-series and trajectories of crustal motion along the West Hellenic Arc. Geophys. J. Int. 164, 182–191.

ITSAK Report, 2004. The Earthquake of Lefkada 14.08.2003 and its Effects on the Built and Natural Environment. Open File Report, p. 61 (in Greek).

Jaume, S.C., Sykes, L.R., 1999. Evolving toward a critical point: a review of accelerating seismic moment/energy release prior to large and great earthquakes. Pure Appl. Geophys. 155, 279–306.

Kahle, H.-G., Muller, M.-V., Geiger, A., Danuser, G., Mueller, S., Veis, G., Billiris, H., Partadissis, D., 1995. The strain field in Northwestern Greece and the Ionian Islands: results inferred from GPS measurements. Tectonophysics 249, 41–52.

Kahle, H-G., Cocard, M., Peter, Y., Geiger, A., Reilinger, R., Barka, A., Veis, G., 2000. GPS-derived strain field within the boundary zones of the Eurasian, African, and Arabian Plates. J. Geophys. Res. 105 (B10), 23353–23370.

Kamberis, E., Marnelis, F., Loucoyannakis, M., Maltezou, F., Hirn, A., Streamers Group, 1996. Structure and deformation of the External

Hellenides based on seismic data from offshore Western Greece. In: Wessely, G., Liebl, W. (Eds.), Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. EAGE Special Publication, vol. 5, pp. 207–214.
Karakostas, V.G., Papadimitriou, E.E., Papazachos, C.B., 2004. Properties of the 2003 Lefkada, Ionian Islands, Greece, earthquake seismic sequence and seismicity triggering. Bull. Seismol. Soc. Am. 94, 1976–1981.
Kissel, C., Laj, C., 1988. The Tertiary geodynamical evolution of the Aegean arc: a palaeomagnetic reconstruction. Tectonophysics 146, 183–201.
Kondopoulou, D., 2000. Palaeomagnetism in Greece: Cenozoic and Mesozoic components and their geodynamic implications. Tectonophysics 326, 131–151.
Lagios, E., Sakkas, V., Chousianitis, K., Poscolieri, M., Paparo, G., Gregori, G., 2006. Evidence of dilatancy in the broader area of Cephallonia Island may foreshadow large magnitude earthquakes. 11th Intern. Symposium on Natural and Human Induced Hazards, pp. 61–62. Abstract Vol.
Laigle, M., Hirn, A., Sachpazi, M., Clement, C., 2002. Seismic coupling and structure of the Hellenic subduction zone in the Ionian Islands region. Earth Planet. Sci. Lett. 200, 243–253.
Laj, C., Jamet, M., Sorel, D., Valente, J.P., 1982. First palaeomagnetic results from Mio-Pliocene series of the Hellenic Sedimentary Arc. Tectonophysics 86, 45–67.
Le Pichon, X., Angelier, J., 1979. The Hellenic Arc and Trench System: a key to the neotectonic evolution of the Eastern Mediterranean area. Tectonophysics 60, 1–42.
Le Pichon, X., Chamot-Rooke, N., Lallemant, S., Noomen, R., Veis, G., 1995. Geodetic determination of the kinematics of Central Greece with respect to Europe: implications for Eastern Mediterranean tectonics. J. Geophys. Res. 100, 12675–12690.
Lekkas, E., Danamos, G., Maurikas, G., 2001. Geological structure and evolution of Cefallonia and Ithaki Islands. Bull. Geol. Soc. Greece XXXIV/1, 11–17.
Louvari, E., Kiratzi, A., Papazachos, B.C., 1999. The Cephalonia Transform fault and its extension to western Lefkada Island (Greece). Tectonophysics 308, 223–236.
Mercier, J., Bousquet, B., Delibasis, N., Drakopoulos, J., 1972. Deformations en compression dans le Quaternaire des rivages Ioniens.(Cephalonie, Greece). «Ácademie des Science» ceance du 30 Octobre, Paris.
Okada, Y., 1985. Surface deformation due to shear and tensile faults in a half-space. Bull. Seismol. Soc. Am. 75 (4), 1135–1154.
Papadimitriou, P., 2002. Evidence of accelerating/decelerating seismic energy release in Aegean area. 2nd Symposium in Geophysics and Seismology, Athens, Greece.
Papadimitriou, P., 2004. Accelerating seismic strain rate prior to large earthquakes. XXIX ESC General Assembly, Potsdam, Germany, p. 136. Abstract.
Papadimitriou, P., Kaviris, G., Makropoulos, K., 2006. The Mw=6.3 2003 Lefkada Earthquake (Greece) and induced stress transfer changes. Tectonophysics 423, 73–82.
Papadopoulos, G.A., Karastathis, V., Ganas, A., Pavlides, S., Fokaefs, A., Orfanogianaki, K., 2003. The Lefkada, Ionian Sea (Greece), shock (Mw=6.2) of 14 August 2003: evidence for the characteristic earthquake from seismicity and ground failures. Earth Phys. Lett. 22, 1737–1740.
Papathanassiou, G., Pavlides, S., Ganas, A., 2005. The 2003 Lefkada earthquake: field observations and preliminary microzonation map based on liquefaction potential index for the town of Lefkada. Eng. Geol. 82, 12–31.
Papazachos, B.C., 1990. Seismicity of the Aegean and surrounding area. Tectonophysics 178, 287–308.
Papazachos, C., Kiratzi, A., 1996. A detailed study of the active crustal deformation in the Aegean and surrounding area. Tectonophysics 253, 129–153.
Papazachos, B., Papazachos, C., 2000. Accelerated preshock deformation of broad regions in the Aegean area. Pure Appl. Geophys. 157, 1663–1681.
Papazachos, C.B., Karakaisis, G.F., Scordilis, E.M., Papazachos, B.C., 2004. Probabilities of activation of seismic faults in critical regions of the Aegean area. Geophys. J. Int. 159, 679–687.
Pavlides, S., Papadopoulos, G.A., Ganas, A., Papathanasiou, G., Karastathis, V., Keramydas, D., Fokaefs, A., 2004. The 14 August 2003 Lefkada (Ionian Sea) earthquake. Proceedings of the 5th Int. Symp. on Eastern Med. Geology, vol. 2, pp. 942–946. Thessaloniki 14–20 April, Greece.
Peter, Y., Kahle, H.G., Cocard, M., Veis, G., Felekis, S., Paradissis, D., 1998. Establishment of a continuous GPS network across the Kephalonia Fault Zone, Ionian islands, Greece. Tectonophysics 294, 253–260.
Poscolieri, M., Lagios, E., Gregori, G., Paparo, G., Sakkas, V., Parcharidis, I., Marson, I., Soukis, K., Vassilakis, E., Angelucci, F., Vassilopoulou, S., 2006. Crustal stress and seismic activity in the Ionian Archipelago as inferred by combined satellite- and ground-based observations, Cephallonia, Greece. In: Cello, G., Malamud, B.D. (Eds.), Fractal Analysis for Natural Hazards. Geological Society, London, Special Publications, 261, pp. 63–78.
Reasenberg, P., 1985. Second-order moment of central California seismicity, 1969–1982. J. Geophys. Res. 90, 5479–5495.
Rikitake, T., 1975. Dilatancy model and empirical formulas for an earthquake area. Pure Appl. Geophys. 113, 141–147.
Rikitake, T., 1987. Earthquake precursors in Japan: precursor time and detectability. Tectonophysics 136, 265–282.
Sachpazi, M., Hirn, A., Clement, C., Haslinger, F., Laigle, M., Kissling, E., Charvis, P., Hello, Y., Lepine, J.-C., Sapin, M., Ansorge, J., 2000. Western Hellenic subduction and Cephalonia Transform: local earthquakes and plate transport and strain. Tectonophysics 319, 301–319.
Scholz, C., 1997. What ever happened to earthquake prediction? Geotimes 17.
Scholz, C.H., Sykes, L.R., Aggarwal, Y.P., 1973. Earthquake prediction: a physical basis. Science 181, 803–810.
Soler, T., Marshall, J., 2003a. A note on frame transformations with applications to geodetic datums. GPS Solutions 7 (1), 23–32.
Soler, T., Marshall, J., 2003b. Erratum: 'A note on frame transformations with applications to geodetic datums'. GPS Solutions 7 (2), 148–149.
Sorel, D., 1976. Etude neotectonique dans l' Arc Egeen externe occidentale. Les iles ioniennes de Kephallinia et Zakinthos et l' Elide occidentale. These 3e cycle, Univ. de Paris-Sud. 205 pp.
Sornette, A., Sornette, D., 1990. Earthquake rupture as a critical point: consequences for telluric precursors. Tectonophysics 179, 327–334.
Stiros, S.C., Pirazzoli, P.A., Laborel, J., F., 1994. The 1953 earthquake in Cephallonia (Western Hellenic Arc): costal uplift and halotectonic faulting. Geophys. J. Int. 117 (3), 834–849.
Tselentis, G.-A., Mori, N., Ramon, P., 1999. Fractal properties of earthquake electromagnetic precursors. Earthqu. Predict. Res. 7, 121–142.
Tzanis, A., Makropoulos, K., 2000. The 7/9/1999 M5.9 Athens earthquake may have come with a warning. Ann. Geol. Pays Hell. 197–216.
Underhill, J.R., 1989. Late Cenozoic deformation of the Hellenic foreland, Western Greece. Bull. Geol. Soc. Am. 101, 613–634.

Vassilopoulou, S., 1999. Geodynamics of the Argolis Peninsula with GIS development and the use of Remote Sensing Data. Doctorate Thesis, University of Athens, Faculty of Geology, 194 p.

Vassilopoulou, S., 2001. "PROANA" A useful software for terrain analysis and geo-environmental applications—a study case on the geodynamic evolution of Argolis Peninsula, Greece. Proc. 20th International Cartographic Conference, Beijing, China. Chinese Society of Geodesy, Photogrammetry and Cartography, pp. 3432–3440.

Wessel, P., Smith, W.H.F., 1995. New version of the Generic Mapping Tools released. Eos, Trans. - Am. Geophys. Union 76, 329.

Zahradnik, J., Serpetsidaki, A., Sokos, E., Tselentis, A., 2005. Iterative Deconvolution of Regional Waveforms and a Double-Event Interpretation of the 2003 Lefkada Earthquake, Greece. Bull. Seismol. Soc. Am. 95, 159–172.

Zoller, G., Hainzl, S., 2002. A systematic spatiotemporal test of the critical point hypothesis for large earthquakes. Geophys. Res. Lett. 29, 53–57.