Surface deformation of Zakynthos Island deduced from DGPS measurements and Differential Sar Interferometry*

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ABSTRACT: A GPS network was established and measured in Zakynthos Island during August 2005, to study the local surface deformation. The network was remeasured in July 2006. Differential Interferometry (DInSAR) was also applied, in conjunction with the DGPS observations, for better spatial coverage of the surface deformation on the island. Suitable interferometric pairs of SAR images were selected after searching the ESA database, covering the period 2004-2006. The DGPS analysis shows an opening of about 24 mm along the E-W axis in southern Zakynthos, while strong uplift has taken place, reaching more than 60 mm, in the SE part of the peninsula. This pattern of deformation can be attributed to the intense seismic sequence that occurred in the area during the time span of the measurements, from April 2006 until May 2006. The northern part though did not exhibit systematic deformation, as the horizontal trajectories varied in magnitude and direction. However, subsidence has been observed in almost all the northern sites, reaching 38 mm. The latter, is confirmed by the DInSAR analysis that exhibits similar deformational behaviour and amplitude with the DGPS measurements. The different deformation pattern between the northern and the southern part can be related to a possible large extensional deformation that is taken place along a N-S striking axis crossing the island.
Key-words: *Satellite geodesy, DGPS, DInSAR, crustal deformation*.

ΠΕΡΙΛΗΨΗ: Στην παρούσα εργασία μελετήθηκε η παραμόρφωση του φλοιού στη νήσο Ζάκυνθο με την συνδυαστική χρήση Διαστημικών Τεχνικών. Η έρευνα επικεντρώθηκε σε Διαφορικές μετρήσεις GPS (DGPS) για σημειακές και μεγάλης ακρίβειας παρατηρήσεις, σε συνδυασμό με Διαφορική Συμβολομετρία Ραντάρ (DInSAR) για χωρική μελέτη της παραμόρφωσης. Το γεωδαιτικό δίκτυο GPS εγκαταστάθηκε στη νήσο και μετρήθηκε για πρώτη φορά τον Αύγουστο 2005, ενώ επαναμετρήθηκε έναν χρόνο αργότερα, τον Ιούλιο 2006. Η ανάλυση των διαφορικών μετρήσεων GPS ανέδειξε διεύρυνση του Κόλπου Λαγανά της τάξεως των 24 mm στην διεύθυνση Α–Δ. Ταυτόχρονα, το τμήμα αυτό της νήσου παρουσιάζει έντονη ανύψωση, το μέγεθος της οποίας ξεπερνά τα 60 mm στην Χερσόνησο Σκοπού, στο ΝΑ άκρο της Ζακύνθου. Η εικόνα αυτή της εδαφικής ανύψωσης δύναται να αποδοθεί στην δράση της σεισμικής ακολουθίας Απριλίου-Μαΐου 2006 η οποία παρατηρήθηκε στον θαλάσσιο χώρο σε μικρή απόσταση από τις νότιες ακτές της Ζακύνθου. Σε αντίθεση με το νότιο τμήμα της Ζακύνθου, το βόρειο δεν εμφάνισε κάποια συστηματικότητα στην οριζόντια εδαφική παραμόρφωση από τις μετρήσεις GPS, αφού τα ανύσματα μετατόπισης εμφανίζουν ποικίλες διευθύνσεις. Παρόλα αυτά, καθίζηση παρατηρήθηκε στο σύνολο των σημείων μέτρησης του βόρειου τμήματος της Ζακύνθου, η οποία ανέρχεται στα 38 mm στο βορειότερο σημείο του δικτύου, κάτι που επιβεβαιώθηκε και από την Διαφορική Συμβολομετρία. Αυτή η διαφορετική συμπεριφορά του νότιου από το βόρειο τμήμα της Ζακύνθου, φανερώνει μια έντονη εφελκυστική παραμόρφωση της νήσου κατά μήκος της διεύθυνσης Β-Ν.
Λέξεις-κλειδιά: *Διαστημική γεωδαισία, DGPS, DInSAR, παραμόρφωση φλοιού*.

INTRODUCTION

Zakynthos Island is located in Western Greece, a seismotectonically complex area of rapid and intense deformation, which is one of the areas that play an important role in the kinematic processes of the Eastern Mediterranean. Particularly, the region of the Central Ionian Islands (Zakynthos, Cephalonia, Lefkas) comprises a multiple junction, where all types of plate boundaries (collision, subduction and transform) connect at a distance of 150 km. This region exhibits some of the largest observed rates of continental crustal deformation accompanied by very high seismic activity. Numerous regional studies have been carried out to assess the geodynamics of this area from neotectonic and seismological points of view (e.g. Brooks *et al*., 1988; Hatzfeld *et al*., 1990; Kokinou *et al*., 2005).

The aim of this work is to provide detailed information concerning regional surface deformation and kinematics of Zakynthos Island throughout repeat Differential Global Positioning System (DGPS) measurements and Differential Interferometric SAR (DInSAR) analysis. Nowadays it is widely accepted that the GPS technique can be successfully used to detect crustal deformation at various scale dimensions (Hollenstein *et al*., 2006; Lagios *et al*., 2007; Chousianitis, 2009), while DInSAR has already proved its capability of providing images of surface deformation (Wright *et al*., 2004).

We present a deformation field using information on the

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motion of a number of points of a dense local GPS network covering entirely Zakynthos Island during the 2005-2006 time interval, with respect to a common reference frame. Moreover, to further constrain the deformation pattern revealed by the DGPS results, we also formed interferograms of surface deformation derived by DInSAR analysis, using radar images of the ENVISAT satellite. A GIS database for Zakynthos Island was organized containing various kinds of data (geological, tectonic, topographical, geomorphological and seismological), which can constantly be updated with new data, depending on the current needs.

GEODYNAMICS

Western Greece is a case study of interaction between the African and the Eurasian lithospheres. Eastern Mediterranean lithosphere, which is the front part of the oceanic-like African lithosphere, is subducted beneath the Aegean continental lithosphere, which is the front part of the Eurasian lithosphere, along the Hellenic Arc – Trench system (Le Pichon & Angelier, 1979). Zakynthos Island is found at the northwestern end of this subduction zone, which terminates against a major strike-slip fault, the Cephalonia Transform Fault (Fig. 1). This fault plays a key role in the above mentioned geodynamic complexity as it joins the subduction boundary with the continental collision between the Apulian microplate and the Hellenic foreland further north (Sachpazi *et al*., 2000). Seismological data for this fault indicate right-lateral strike–slip focal mechanisms (Scordilis *et al*., 1985; Anderson & Jackson, 1987; Papadimitriou, 1988; Kokinou *et al*., 2006), in agreement with geodetic data which clearly show that the slip motion has a NNE–SSW direction (Lagios *et al*., 2007; Chousianitis, 2009). The Hellenic subduction is clearly evidenced by its seismicity which results in high shallow and intermediate-depth seismicity that forms a well defined Benioff zone. Large earthquakes on the Hellenic Arc – Trench system near Zakynthos Island show pure thrust focal mechanisms on a shallow-dipping plane with SW-NE slip vectors. A minor or considerable strike–slip component is present in some of these events, being more clearly from the west to the east (Papazachos *et al*., 1991).

The high level of seismic activity in the central Ionian Sea is the effect of the neotectonic activity and the intense crustal deformation in the broader area, which leads to the occurrence of both strong events and microseismic activity. The first ones help in the understanding of the relative motions of the tectonic plates, while the latter assists in gaining knowledge about their internal deformation. Several strong earthquakes (M>6.0) have occurred in the vicinity. Some of the most recent events include the November 18, 1997 (Mw=6.5) earthquake, SW of Zakynthos Island, which is known as the "*Strofades Earthquake*", the December 2, 2002 (Mw= 5.5), earthquake which struck Zakynthos and Western Peloponnese and is known as the "*Vartholomio earthquake*" (Roumelioti *et al*., 2004), the June 8, 2008 (Mw= 6.4) at SW Achaia (Western Peloponnese) (Ganas *et al*., 2009) and a sequence of earthquakes on October 2005 (Mw=5.6) and April 2006 (Mw=5.5–5.7) south of Zakynthos. The activity of the latter sequence began on April 4, 2006 with a moderate earthquake of magnitude Mw=5.3 that was followed on April 11 and 12 by the strongest events with magnitudes Mw=5.6, Mw=5.6 and Mw=5.7 respectively (Zahradnik *et al*., 2008; Chousianitis, 2009; Serpetsidaki *et al*., 2010). In total at least 10 events occurred in the activated area with moment magnitudes larger than 4.0, followed by an important number of microearthquakes with magnitudes between 1.5<Mw<4.0. The depth distribution of the entire sequence ranges between 10 and 25 km (Chousianitis, 2009; Serpetsidaki *et al*., 2010). Since then, no other events of comparable significance have occurred although a great number of smaller events (4.0<Mw<5.0) have been recorded and at least one event of Mw≈5.0 is expected in the broader region every year.

The evolution of Central Ionian Islands could be described in continuation of the Alpine orogenic evolution as a foreland-propagating fold and thrust belt of the Hellenides (Underhill, 1989; Hatzfeld *et al*., 1990). This evolution has been summarized from numerous investigations in geology (Brooks *et al*., 1988; Underhill, 1989), in paleomagnetism (Laj *et al*., 1982; Horner & Freeman, 1983; Kissel & Laj, 1988), and in seismotectonics (Hatzfeld *et al*., 1990; Maroukian *et al*., 2000). During the Plio-Quaternary, the broader area of Zakynthos underwent a continuous clockwise paleomagnetic rotation of 22° (Kissel & Laj, 1988; Duermeijer *et al*., 1999). This clockwise rotation of Zakynthos can be linked to Late Pleistocene uplift in mainland Greece, related to rebound processes resulting from African slab detachment underneath the Ionian Islands (Duermeijer *et al*., 2000).

GPS NETWORK

A GPS network for monitoring the present-day kinematics of Zakynthos Island was established in 2005 in order to study the tectonic deformation triggered either by motions along major faults or expected pre- and post-seismic activity. The selection of each site location was made after geological investigation and according to the main structural units and active faults that could be recognized on the island (Fig. 2). The geological structure of Zakynthos, which is characterized by complex structural and stratigraphic features, consists of rocks of Pre-Apulian and Ionian Zones, ranging in age from Cretaceous to Pleistocene (Aubouin & Dercourt, 1962; Sorel, 1976; Underhill, 1989). These geotectonic zones are defined on the basis of different sedimentary facies of exposed Mesozoic and Cenozoic rocks and different tectonic styles. Compressive tectonism related to Alpine-age deformation and major recurrent movement of evaporite successions during both Mesozoic and Cenozoic times have produced complicated folding and different styles of faulting (Sorel, 1976; Underhill, 1989). The Pre-Apulian Zone forms the major part of the Island, whereas the Ionian Zone,

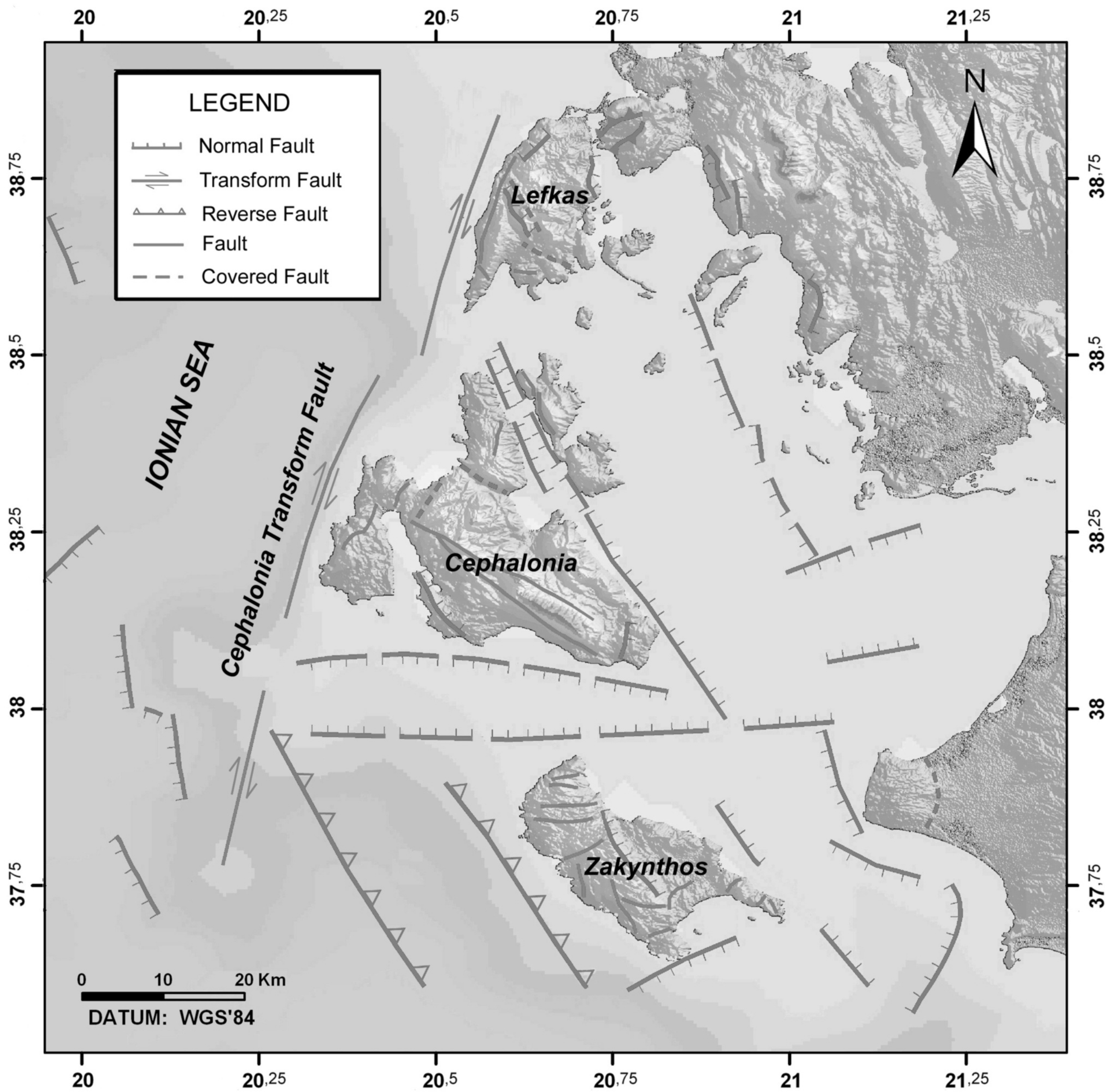

Fig. 1. Tectonic setting of Central Ionian Islands (after IGME 1983 and Lekkas *et al*., 2001).

which is dominated by compressional tectonics, is exposed on a small area of SE Zakynthos. The boundary of these two zones is defined by the Ionian Thrust, which is generally considered to represent the most external structure of the Hellenides. The Ionian Thrust is not well exposed in Zakynthos, because the occurrence of a thick Pliocene cover makes the boundary between these zones difficult to define, but the western limit of evaporite diapirism in SE Zakynthos Island is considered to mark the limit of the Ionian Zone (Underhill, 1988).

Five major tectonic blocks were distinguished with confirmed neotectonic activity based on lithology, on similar structural features and on a common evolution during upper Quaternary (Fig. 3). These blocks are: I. Northern Zakynthos block, II. Central Zakynthos block, III. Keri peninsula block (south-western part of the island), IV. Southern Zakynthos block (south of Keri peninsula block) and V. Skopos peninsula block (south-eastern part of the island). The southern boundary of the Northern Zakynthos block is defined by a zone of semicircular shape consisting of four consecutive active faults with tectonic activity during Holocene (Lekkas, 1996). The major Central Zakynthos block is divided into two subordinate blocks, IIa and IIb, separated by a major probably active thrust fault that runs the Central part of the island from North to South. This division was made because these two subordinate blocks have distinct geological fea-

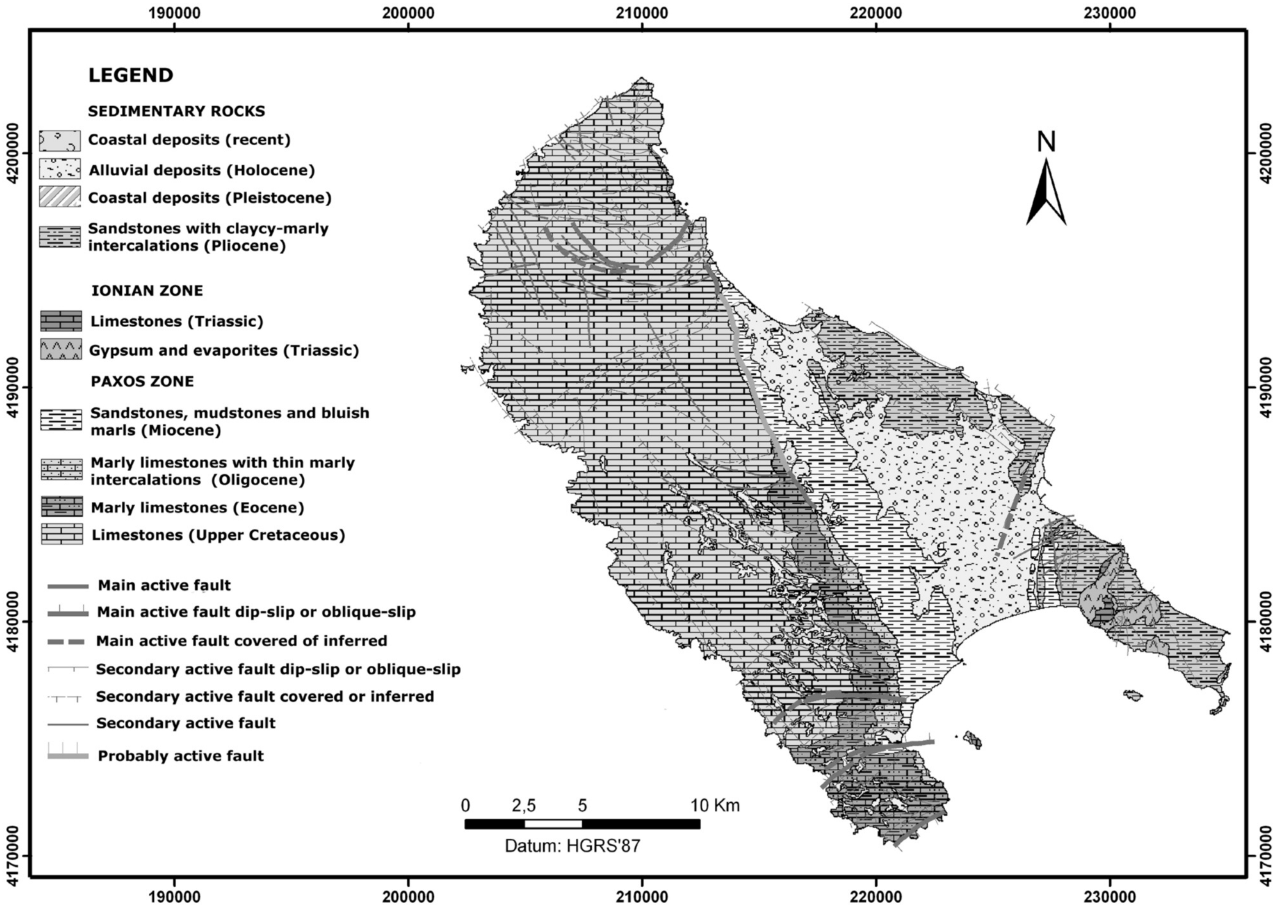

Fig. 2. Geological map of Zakynthos Island (after LEKKAS, 1996).

tures, on account of their difference in geological evolution, since IIa block is mountainous dominated by Alpine formations, contrary to the plain IIb block, which is dominated by Neogene sediments. The southern boundary of the IIa block is a main active fault of E-W direction, which demarcates the northern limit of the Keri peninsula block. The southern boundary of this block is another main active fault with similar direction but with adverse dip, resulting in the characterization of the Keri peninsula block as a tectonic graben (LEKKAS, 1996). On the contrary, the Southern Zakynthos block forms a tectonic horst with southern limit the under tectonic control sheer coast of the island. Finally, the IIb block and the Skopos peninsula block are separated by the Ionian Thrust, which is partially covered by alluvial deposits and not entirely distinguishable. The tectonic evolution of the Skopos peninsula block has been controlled by diapiric processes of the Triassic gypsum and evaporites of the Ionian Zone.

Eventually, a network of 14 sites was established in August 2005 providing spatial coverage throughout the island with baselines between GPS sites from about 2.5 km to 30 km long, a distance which is suitable for detailed monitoring of local tectonic movements. The network was entirely remeasured at the end of July 2006, almost one year after its establishment, with primary objective the calculation of a crustal displacement field of high spatial resolution. During that year, the seismic activity in the broader area was significant, since an earthquake Mw=5.6 occurred offshore a few kilometres south of the island on October 18, 2005 and almost six months later, a significant seismic sequence of at least four earthquakes with magnitudes Mw from 5.5 to 5.7 occurred in the same region during April to May 2006.

GPS DATA ANALYSIS

The stations of Zakynthos GPS network were occupied by eight dual-frequency geodetic receivers (WILD type: SR299, SR399 and AX1200Pro). After a preparation step consisting of reformatting the raw data to RINEX, the processing was performed using the Bernese GPS Software 4.2 of the Astronomical Institute of the University of Berne (BEUTLER *et al*., 2000). The ionosphere free linear combination L3 was used as the basic observable. We followed the recommended Bernese strategies estimating the troposphere delay parameters every 2 h with respect to the Saastamoinen standard model (no meteorological data were used). The ambiguity resolution was performed following the Quasi Ionosphere Free (QIF) strategy. Other characteristic parameters of the analysis include the use of precise IGS ephemeris data, ionosphere models for each day and an elevation cut-off angle of 10º. Satellite clock corrections, antenna height phase centre variations and other general files provided by CODE (Center of Orbit Determination in Europe) of Bern University were included in the computation. The aim of the processing of the GPS data was reliable and consistent site coordinates with accuracies at the sub-centimetre level. In order to obtain this goal, an important feature of the data processing is the reference frame, since site coordinates and velocities as well as satellite orbits used for the processing must be in the same reference frame. For that reason, all the data were referred to ITRF2000, which appears to be the most accurate and extensive ITRF version ever developed (ALTAMINI & BOUCHER, 2001).

Station RLS (Riolos) at the northwestern part of Peloponesse established on a very local visible outcrop of limestone in a broader area of sandstone was used as local reference station (Fig. 4). This selection is based on neotectonic considerations, since it was difficult to find a relatively stable reference site on the island due to the complicated multi-directional faulting and the widespread distribution of neogene sediments, along with consideration of the road network during the campaign planning. This station was operating continuously (time sampling 1 sec) during both campaigns. Two additional measuring periods (January 2005 and January 2006) were included in the analysis of station RLS along with the measuring periods of the entire GPS network of Zakynthos, for a better estimation of its coordinates. The variation of the absolute coordinates (ITRF2000) for the local reference station is given in Table 2. Additionally, to illustrate the behaviour of the station positions, we computed its temporal trend as time-series with the corresponding rms error, decomposed into the north, east and up components (Fig. 5). This figure also shows the weighted best-fit straight line for each component.

For that period of relatively 1.5 years, station RLS had moved to the SE with velocity components of υe=14.2±4.5

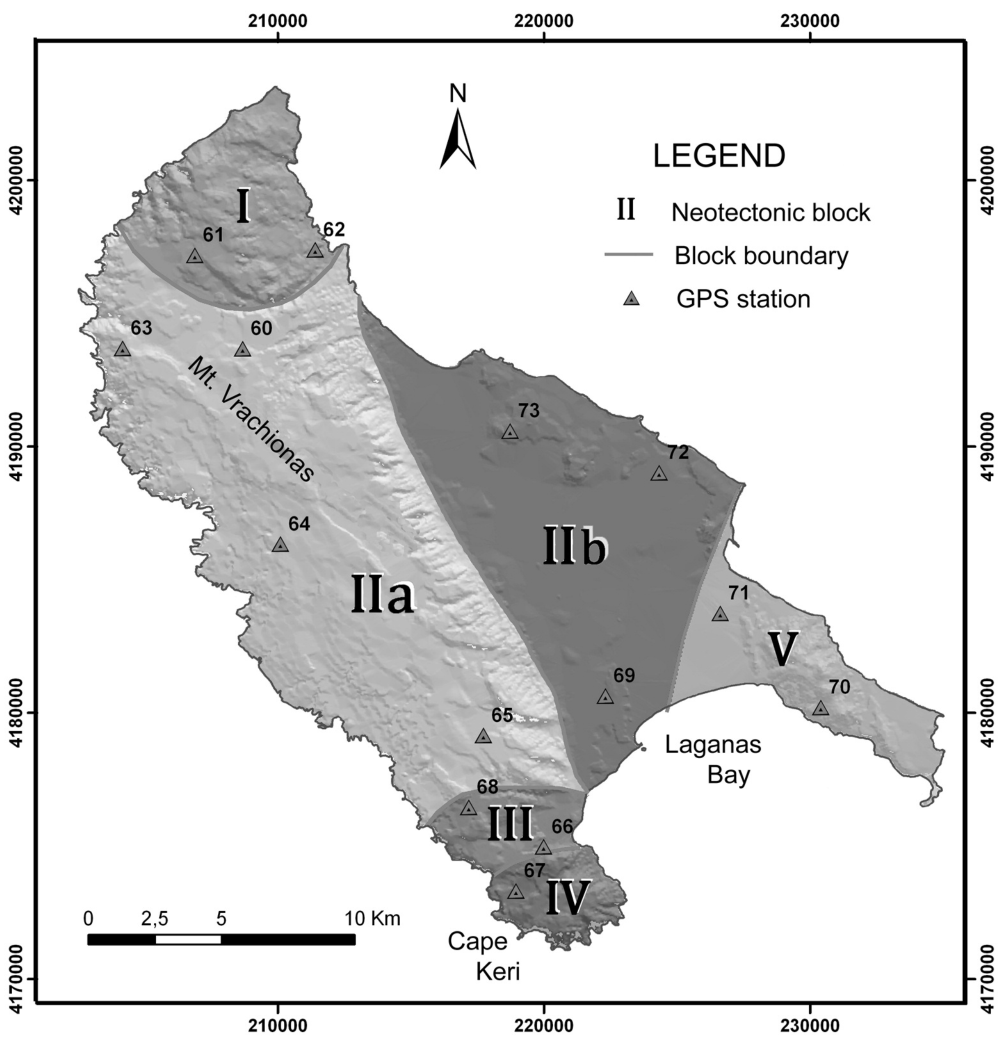

Fig. 3. Neotectonic Blocks along with site locations of Zakynthos network (CHOUSIANITIS, 2009).

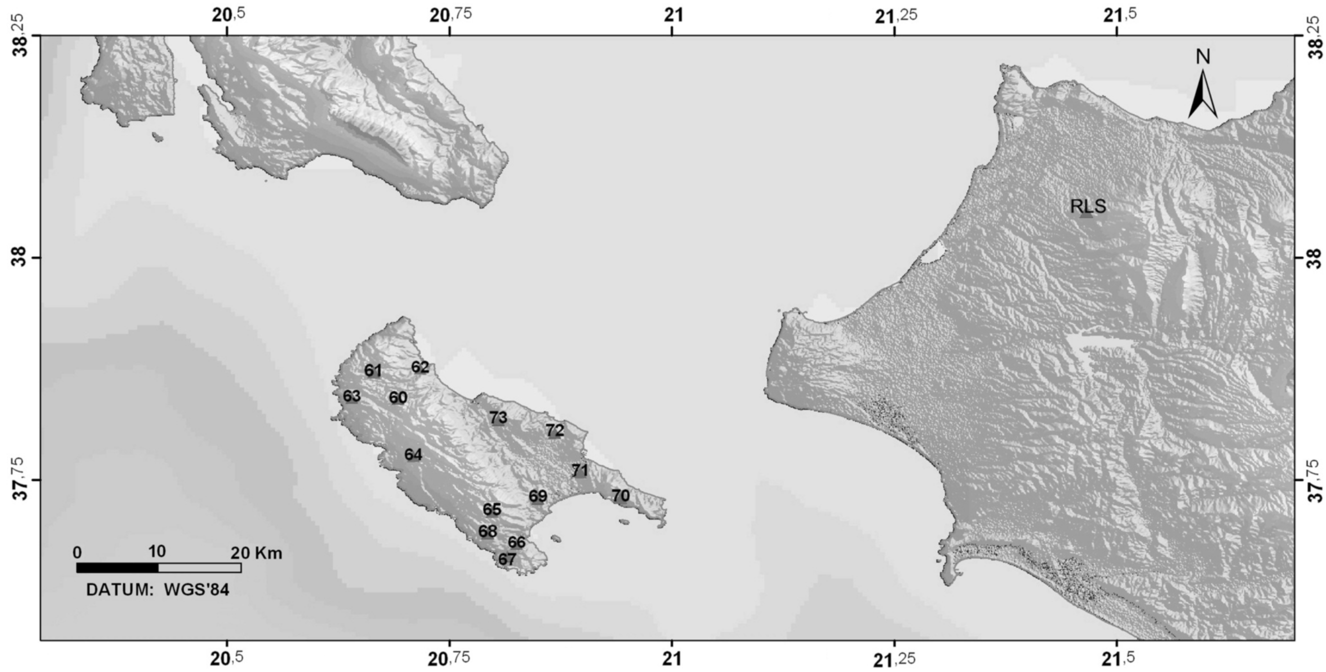

Fig. 4. Local reference station RLS at the northwestern part of Peloponnese.

mm/yr and υn=−18.5±3.9 mm/yr, along with subsidence of υu=−5.4±6.0 mm/yr. The vertical component is almost comparable to the rate of motion showing a general trend for the motion of the reference station, although future remeasurements providing more data, will enhance the picture of the rate of motion. With respect to the Eurasian reference frame, the velocity components are υe=−9.5±4.5 mm/yr and υn=−30.4±3.9 mm/yr. These values are in good agreement with the results which were obtained from repeated GPS measurements for the nearest stations of regional networks, namely No. 61 (Clarke *et al*., 1998) and ZAHA (Cocard *et al*., 1999).

Furthermore, in order to improve the stability of the network, four continuous sites of the IGS network, namely GRAZ (Austria), MATE (Italy), WTZR (Germany) and SOFI (Bulgaria) and one site DION (Dionysos) in Greece, were included in the data processing. This allows connecting and constraining the solution to the ITRF2000 reference frame, since coordinates and velocities of these sites are known with a high accuracy at the mean epoch of each campaign with respect to ITRF2000.

We processed each session independently. For each daily session, one station was selected as a "connecting station" in the centre of the "roving" stations and was tied to the local

TABLE 1
Site distribution of the Zakynthos GPS network with regard to neotectonic blocks and corresponding lithology.

Site	***Block***	***Lithology***	***Geotectonic Zone***	***Foundation***
60	IIa	Limestone	Pre-Apulian	Benchmark
61	I	Limestone	Pre-Apulian	Benchmark
62	I	Marly Limestone	Pre-Apulian	Benchmark
63	IIa	Limestone	Pre-Apulian	Benchmark
64	IIa	Limestone	Pre-Apulian	Benchmark
65	IIa	Limestone	Pre-Apulian	Benchmark
66	III	Marly Limestone	Pre-Apulian	Benchmark
67	IV	Marly Limestone	Pre-Apulian	Benchmark
68	III	Limestone	Pre-Apulian	Benchmark
69	IIb	Marl	Pre-Apulian	Benchmark
70	V	Limestone	Ionian	Benchmark
71	V	Marl	Pre-Apulian	Benchmark
72	IIb	Sandstone	Pliocenic sediments	Benchmark
73	IIb	Sandstone	Pliocenic sediments	Benchmark

TABLE 2
Component displacements of RLS with respect to ITRF2000 for all Measuring Periods.

	North (mm)	*RMS_N (mm)*	*East (mm)*	*RMS_E (mm)*	*Up (mm)*	*RMS_{Up} (mm)*
Mar.2005 - Aug.2005	-15.2	2.7	1.7	2.4	-2.3	4.8
- Feb.2006	-17.3	3.0	9.7	2.7	-6.2	5.5
- July2006	-30.0	3.7	20.9	3.0	-7.7	5.7

TABLE 3
Component displacements of GPS sites of the Zakynthos network referred to RLS (Riolos) for the measuring period August 2005 to July 2006.

Station no.	*N-S (mm)*	*RMS_{N-S} (mm)*	*E-W (mm)*	*RMS_{E-S} (mm)*	*Up (mm)*	*RMS_{Up} (mm)*
60	-7.1	2.8	-9.4	3.2	11.6	6.7
61	15.3	4.8	-19.2	5.6	-38.5	7.4
62	-13.8	12.6	-8.4	8.6	0.7	8.5
63	5.9	2.8	-0.2	3.4	-12.5	7.1
64	-3.4	2.6	4.9	3.2	-0.8	6.7
65	-4.2	2.8	-17.7	3.0	30.7	7.2
66	-0.3	3.2	-15.1	3.2	43.1	8.2
67	-2.9	3.0	20.3	3.6	16.7	7.8
68	3.9	3.0	18.9	3.2	-1.6	7.8
69	6.8	2.6	11.0	2.8	12.0	6.2
70	26.4	3.0	4.3	3.0	63.4	7.6
72	-2.8	2.4	-3.5	3.2	29.9	7.1
73	16.7	2.4	-1.5	2.6	-8.1	5.8

TABLE 4
ENVISAT Imaging pairs used for Interferometric calculations.

Area	*Date*	*Orbit*	*Frame*	*Pass*	*Interval (days)*	*Bp (m)*
Zakynthos	27 Oct. 2004	13903	2835	Descending	385	-69
	16 Nov. 2005	19414				
↕ 6 months overlapping						
Zakynthos	25 May 2005	16909	2835	Descending	385	44
	14 June 2006	22420				

reference station RLS. Each roving station was occupied at least twice with a recording time ranging from 4 to 8 h with a sampling rate of 15 sec. 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. Regarding the accuracy of the final coordinates, RMS errors of about 2–6 mm and 6–9 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 analysis, we present results in terms of displacement of a station instead of average rate of displacement, since the second require additional remeasurements of the GPS network. Only a complete analysis of data from several remeasurements over a longer time period will allow presenting average rates of displacements. Furthermore, the interpreted mechanism causing movement can vary at a station for different periods (e.g., earthquakes, local effects, etc.), while presentation in terms of displacement helps to better compare DGPS results with DInSAR analysis.

In Table 3 the component displacements of the Zakynthos GPS network referred to RLS (Riolos) are listed and illustrated in Fig. 6. Overall, intense ground deformation has been noticed in Zakynthos for this period. A consistent pattern of deformation has been observed in the southern part of the island, where it is evident that horizontal extension had occurred in the area around Laganas Bay. Its western part showed generally a westerly motion with magnitudes ranging from 15 to 20 mm, while its eastern part revealed magnitudes of about 26 mm towards the NNE. The central part of the island appears to be stable, whereas the northern part did not exhibit systematic deformation and the horizontal trajectories varied from 6 to 26 mm in different directions, with two stations (No. 60 and 62) having directions to the SW, while the most northerly ones, No. 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 strong uplift 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. On the contrary, subsidence was observed in the extreme northern part (No. 61 and 63), with values ranging from 12 up to 30 mm, while the section to its SE (No. 60 and 62) was unchanged. 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. Moreover, the occurrence of the seismic sequence of April-May 2006 a few kilometres south of Zakynthos Island (Fig. 7) had affected its southern part where the largest horizontal and vertical displacements were detected by DGPS analysis, as it was demonstrated by Chousianitis (2009). However, only a complete analysis of GPS data over a longer time period with additional remeasurements of the entire network will allow explaining in the future the percentage of deformation caused by tectonic and/or non-tectonic effects.

DInSAR ANALYSIS

Interferometric analysis is an extra satellite-based technique for crustal deformation measurements along with DGPS analysis. The technique of DInSAR is used to form interferograms, which cover the investigated area of Zakynthos using radar images of the ESA satellite ENVISAT. Overall, two pairs of ASAR images were selected, fulfilling the criterion of small baselines (Table 4). Two differential interferograms were produced covering the GPS measuring period August 2005 to July 2006 and May 2005 to June 2006.

For DInSAR analysis the "two-pass differential interferometric method" or "DEM-elimination method" was chosen (Massonnet *et al*., 1993). Coherence characterizes the quality of the interferogram. In the present application, the coherence for the larger part of the island resulted quite low, leaving only selected areas with good coherence. Dense vegetation that covers most of the island and ground morphology are mainly responsible for this effect and particularly, for the plain part of the island the very poor coherence can be addi-

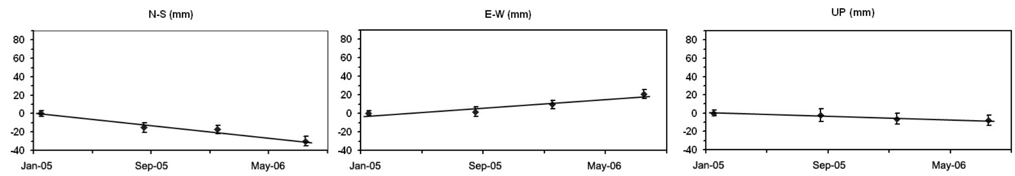

Fig. 5. Time-series of N–S, E–W and Up components with respect to ITRF2000 for the local reference station RLS of the Zakynthos network. Error bars indicate the rms error of each position. The weighted best-fit straight line for each component is also shown.

tionally attributed to a large scale construction taking place to the island and to the geological features of the area, characterized by loose formations and strong erosion. The areas of good coherence therefore are limited to the west, north and NW of the island.

The interferometric pair covering the period October 2004 – November 2005 is characterized by deformation which is limited to the western part of the island consisting of Alpine formations of the Pre-Apulian Zone, where at least two fringes of deformation were noticed (see inset on Fig. 8 for location). For the rest of the island, either clear interferometric fringes can not be distinguished, or noise due to the very poor coherence appears. The latter describes the whole plain part of the island, along with the central and southern Zakynthos. The part of the island where the two fringes are observed is characterized by very good coherence.

The interferometric pair covering the period May 2005 to July 2006, reveals fringes along the western and northern parts of the island (Fig. 9). The first fringe is well formed and is observed almost at the same area as in the previous interferometric pair of the period October 2004 – November 2005. The existence of this fringe indicates a total deformation of about 28 mm for the one year period covered by this pair. Taking into consideration the sign of the phase-change in both images, subsidence is inferred. The second fringe at the northern part of the island is not well formed as previously described above, since the coherence is very poor in the corresponding coherence image. Assuming that the fringe is not noise, then the according to the sign of the phase-change in both images, a subsidence of about 38 mm has taken place. This conclusion is supported by the DGPS results of the period August 2005 – July 2006, according to

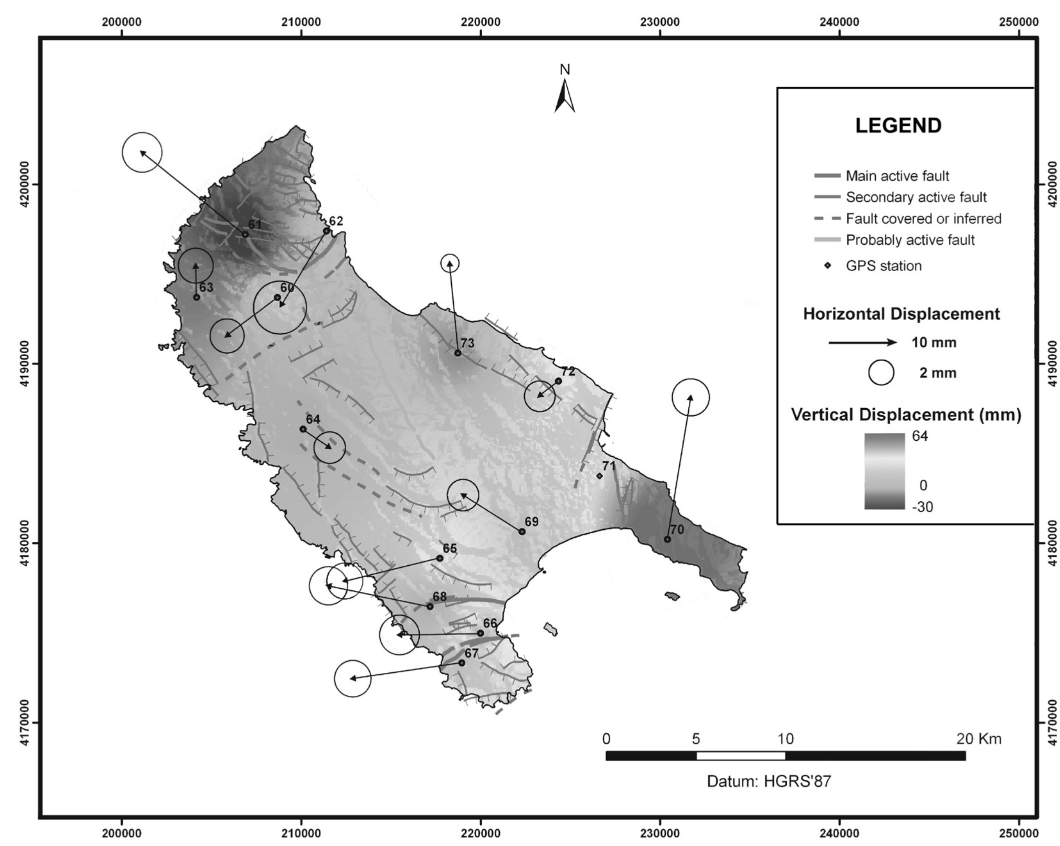

Fig. 6. Map of GPS-derived horizontal and vertical displacements of Zakynthos Island referred to RLS station for the period August 2005 to July 2006. Errors at 95% confidence level (Lagios *et al*., 2007; Chousianitis, 2009).

which the northern part of the island was subducted with a mean value of 40 mm. Although the time separation of the images covers the seismic sequence of April-May 2006, DInSAR analysis did not reveal any significant deformation, mainly due to the poor coherence in the southern part of the island.

DISCUSSION & CONCLUSIONS

The aim of the research is to determine geodynamic movements of Zakynthos Island using DGPS and DInSAR analyses. The methods and procedures applied have proved to be suitable for obtaining high-quality results and have yielded detailed information regarding local deformation. Zakynthos Island can be separated into five blocks and two sub blocks. These blocks comprised the basis of the deployment of the GPS network consisting of 14 points covering entirely the island.

The GPS results revealed intense ground deformation and different patterns of motions for the period 2005 to 2006. Regarding the horizontal displacements, a consistent pattern of deformation has been occurred only in the southern part of the island, in the area around Laganas Bay, showing a distributed horizontal extension of about 24 mm along the E–W axis, as it can be derived from the E – W horizontal component displacements of the corresponding GPS sites. The northern part of the island did not exhibit systematic deformation, as the horizontal trajectories varied from 6 to 26 mm in different directions. Regarding the vertical displacements, intense uplift is manifested 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. Based on the horizontal and vertical displacements of the southern part of Zakynthos Island, a hypothesis about a possible influence between the occurrence of the sequence near Zakynthos during the time span of the measurements and the observed deformation in the region can be made. The central part of the island appears stable, while negative vertical displacements, with values reaching more than 35 mm are predominant in the extreme northern part, a result consistent with the DInSAR analysis. However, an anti-correlation holds for two points of the GPS network (60 and 64) whose GPS data indicate uplift and negligible subsidence respectively, while InSAR data indicate subsidence. This can be attributed to bad data quality for the first case, where also the calculated by the GPS processing uplift is not consistent with the rate of motion of the rest points at the northern part of the network, while in the second case the large rms error comparing to the calculated displacement does not allow the extraction of a secure conclusion. This is why the DInSAR results assist the GPS results in these two cases. The different behaviour between the southern and northern parts of the island, which

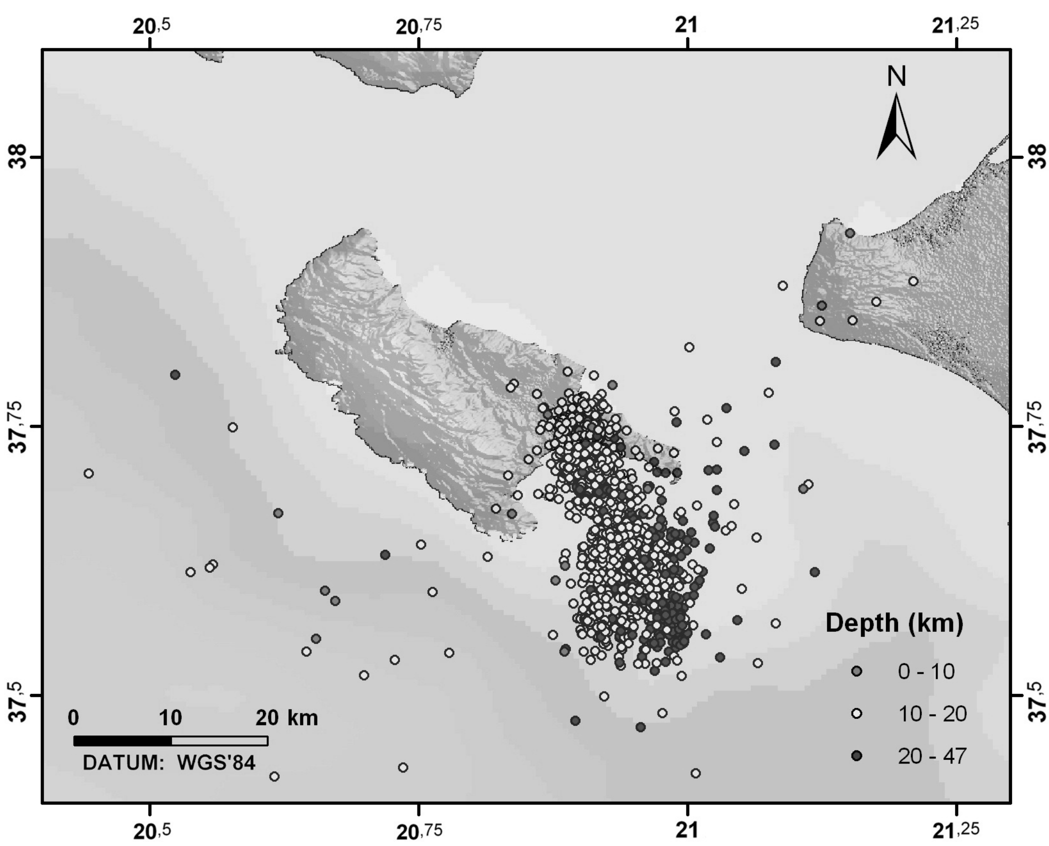

Fig. 7. Epicentral map of the April-May 2006 seismic sequence using data from the national broad-band seismographic network along with a regional network deployed in the broader area by Earthquake Planning & Protection Organization (E.P.P.O.) (Chousianitis, 2009).

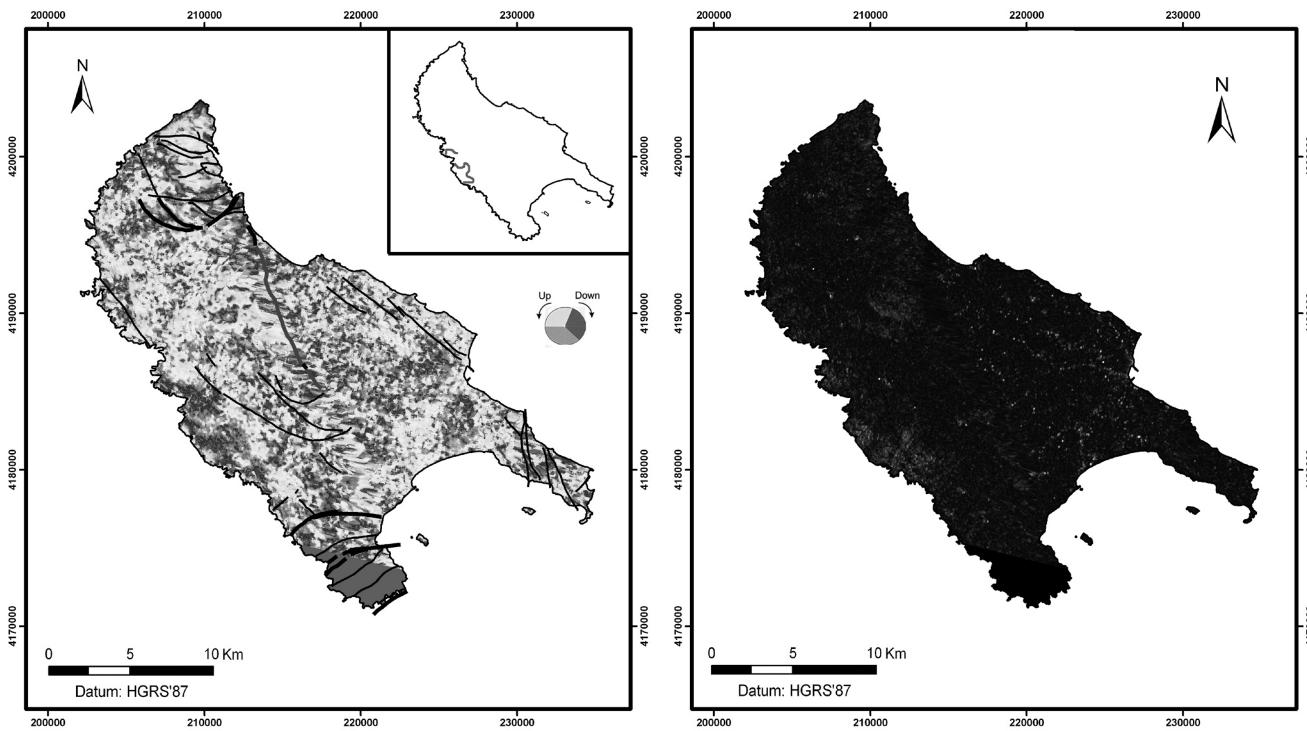

Fig. 8. DInSAR image of Zakynthos Island spanning the period October 2004 to November 2005 and corresponding coherence image. The "high" and "low" coherence values are represented by brighter and darker areas, respectively. Inset indicates location of fringes.

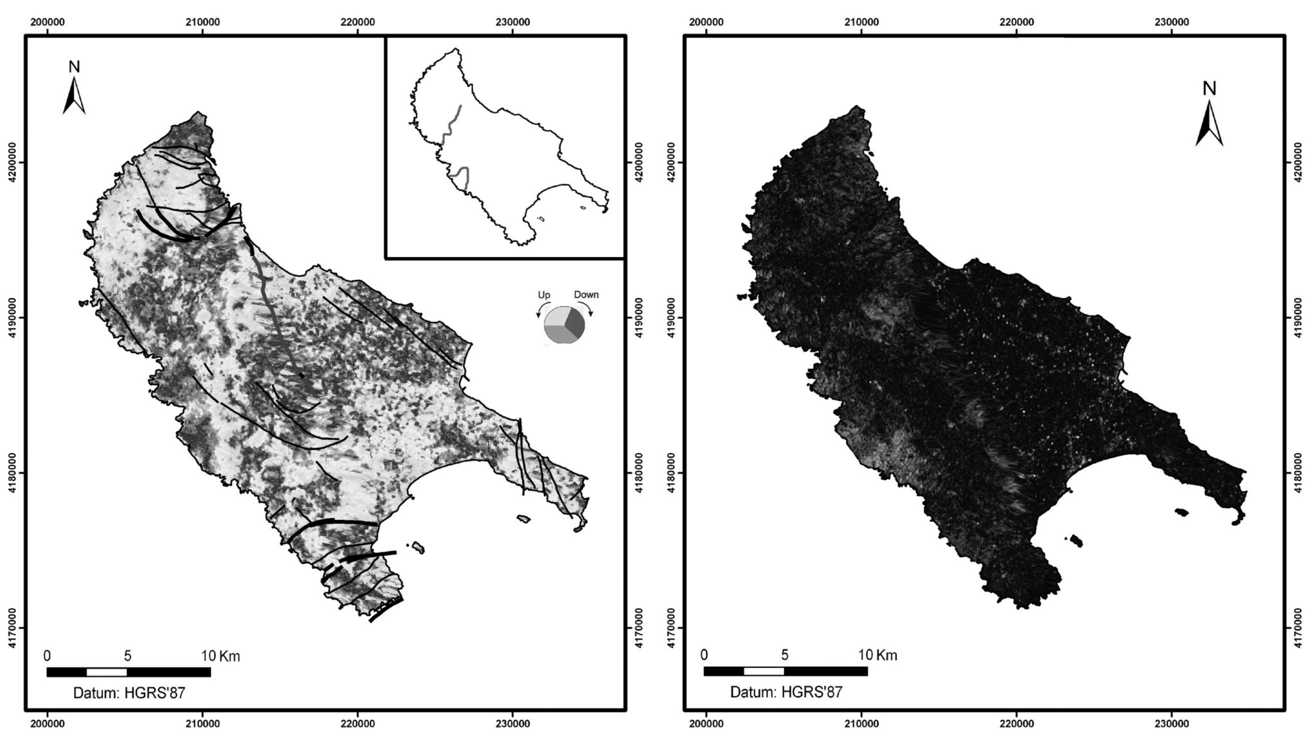

Fig. 9. DInSAR image of Zakynthos Island spanning the period May 2005 to July 2006 and corresponding coherence image. The "high" and "low" coherence values are represented by brighter and darker areas, respectively. Inset indicates location of fringes.

imply large extensional deformation along the N–S direction and is derived from visual inspection of the vectors, was also noticed by other researchers. It appears that the results obtained constrain the complicated tectonic model of Zakynthos Island and reveal a dominant local north-south extensional regime in the island. Taking into consideration the character of the present research work these results must be treated as preliminary, as they provide a basis for further research, and the presented conclusions need verification during subsequent stages of investigations.

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