GROUND DEFORMATION STUDIES IN CEPHALLONIA ISLAND (WESTERN GREECE) BASED ON DGPS & PS INTERFEROMETRY

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ABSTRACT

Ground deformation studies based on Differential GPS (DGPS) measurements and Permanent Scatterers (PS) Interferometric analysis have been conducted in the seismically active area of the Cephallonia and Ithaca islands. DGPS measurements for the period 2001 to 2010 revealed horizontal component of deformation generally ranging from 3-8 mm/yr with the largest values at the western and southern parts of the island. Considering the vertical deformation, two periods are distinguished on the basis of DGPS and PS Interferometry: The first one (1992 to 2003) is consistent with anticipated motions associated with the main geological and tectonic features of the island. The second one (2003 to 2010) has been tentatively attributed to dilatancy in which relatively small uplift (2-4 mm/yr) occurred along the southern and southeastern parts of the island, while larger magnitudes (>4 mm/yr) took place at the western part of Cephallonia. These large magnitudes of uplift over an extended area (>50 km) are consistent with the hypothesis of dilatancy. On the basis of the analysis of 53 differential ASAR interferograms and the PS product, it has been derived that dilatancy effect should have commenced some time in mid-2005. If this interpretation is correct, it may foreshadow the occurrence of very strong earthquake(s) sometime in the near future.

Index Terms **—** Differential GPS Measurements, Permanent Scatterers Interferometry, Cephallonia, Dilatancy.

1. INTRODUCTION

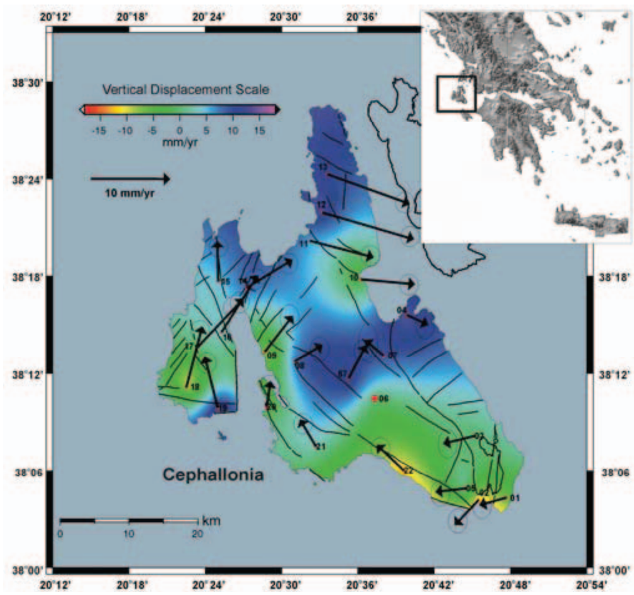
Western Greece lies within a seismo-tectonically complex area that is undergoing rapid and intense ground deformation [1], [2], [3]. The area plays an important role in the kinematic processes of the Eastern Mediterranean. In particular, the Eastern Mediterranean lithosphere is being subducted beneath 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, where the occurrence of earthquakes exceeding magnitude seven.

Ground deformation studies based on Differential GPS (DGPS) and Permanent Scatterers (PS) Interferometry analyses have been conducted in the seismically active area of Cephallonia- Ithaca. A local GPS network was installed in Cephallonia in 2001 and re-measured almost annually up to 2010. In Ithaca, another four stations were installed in 2004; however these stations were remeasured only once, in 2010. The PS Interferometry technique was also applied using two sets of radar images covering the period 1992 – 2000 with ERS1 & ERS2 SAR scenes, and the period 2003 – 2008 with ENVISAT ASAR images. The analysis of both techniques has yielded important aspects relating to the local deformation of the area.

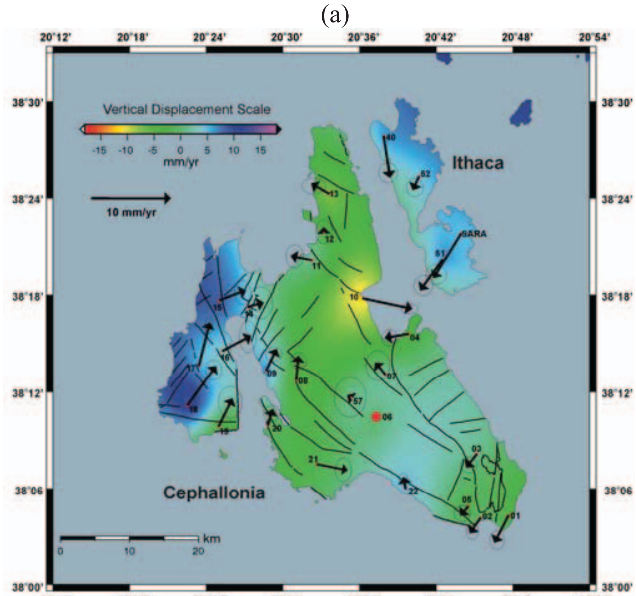
2. DIFFERENTIAL GPS MEASUREMENTS

A GPS network consisting of 23 stations (Fig. 1) was installed in Cephallonia in 2001 [4]. The network was remeasured in January 2003 and in September 2003 following the Lefkas Earthquake (M_w=6.3) in August 2003. It was partly remeasured in February and July 2006 and in September of 2007, and finally it was fully remeasured in March of 2010. The data were analyzed with the Bernese v.5 GPS software [5]. A station (named No 06) on the center of the massive limestone Aenos Mt. was chosen as local reference station, because of its location and its anticipated better geological and tectonic stability compared to other parts of the island. The station was operating continuously during all campaigns and tied up to the ITRF2000. It is noted that the horizontal trajectories of this station relative to Eurasia show a consistent pattern with the overall motion of the western end of the Hellenic Arc as described by previous studies [3], [6], while its vertical component appears to be rather stable.

The DGPS results for the whole observational period have shown horizontal trajectories varying between 3-8 mm/yr. These trajectories show a clock-wise rotation of Cephallonia with respect to the station at Aenos Mt., calculated to be 12.7±5.5 deg/Myr. This value is consistent with recent GPS regional work [2], [6], palaeomagnetic studies [7], [8] and anticipated regional tectonic movements of the area [9] [10]. The occurrence of the Lefkas strong seismic event (August 2003, M_w=6.3) and its associated post-seismic sequence [11], especially its southern cluster, had affected the northern part of Cephallonia where the largest horizontal displacements were detected after the earthquake by the DGPS analysis (Fig. 1a).



(a)



(b)

Fig.1. Ground deformation of Cephallonia-Ithaca islands deduced by DGPS measurements for the period: (a) 2001 to 2003, and (b) 2003 to 2010.

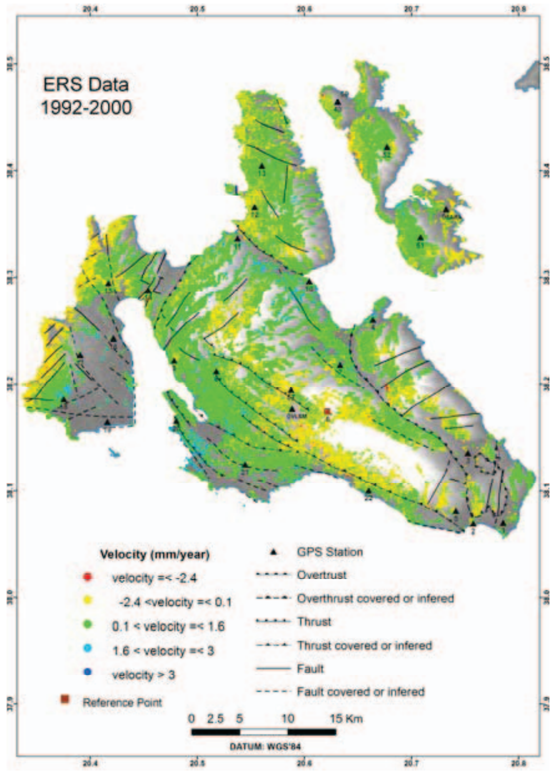
Regarding the vertical deformation, two periods are distinguished. The first one (2001 to 2003) is consistent with a slight subsidence ranging from -2 to -9 mm/yr. This is an anticipated motion associated with the main geological and neotectonic features of the island [4]. The second period starts sometime after 2003 when the sign of motion in the southwestern part of the island subsequently reversed to uplift (about +5mm/yr) and continued up to July 2006. Similar behavior was also observed in the western part where the uplift was much higher (+8 to +12mm/yr). Since there was an overall gradual increase in the magnitude of uplift from East to West, it is probable that this progression of uplift may be extended rather offshore on the West to SW of Cephallonia.

The horizontal ground deformation in Ithaca Island indicates a convergence towards Cephallonia with a rate of 4-6 mm/yr for the period 2004-2010, indicating also a differentiation between the northern and the southern parts of the island that should be controlled by the major local faults. Considering its vertical deformation, an overall uplift of 5-6 mm/yr was generally observed.

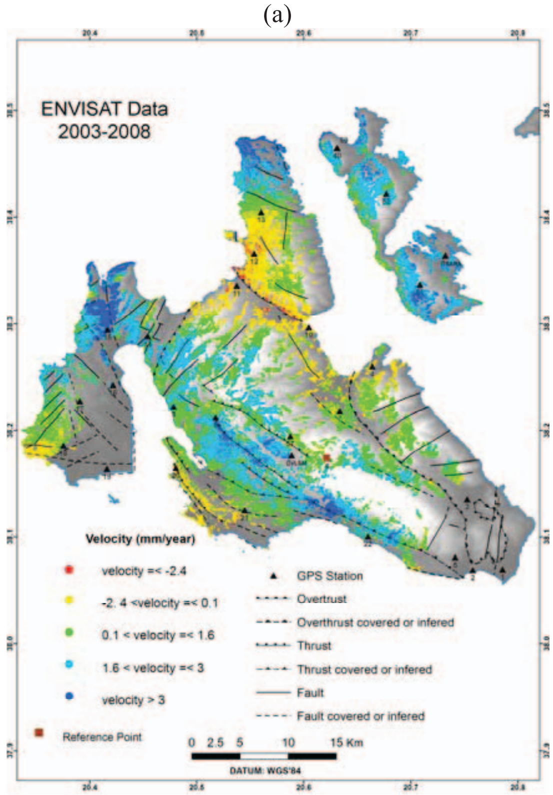
3. PS INTERFEROMETRY

Two sets of Descending Radar images of Cephallonia Island were processed by Tele-Rilevamento Europa (TRE) within the framework of TERRAFIRMA Stage-3 project in order to produce vertical component deformation maps of the island (Fig. 2). The first set of 39 ERS1 & ERS2 radar scenes were used covering the period April 1992 to December 2000. The second set of 21 ENVISAT ASAR images covered the period June 2003 to May 2008. The analysis of both imaging sets identified more than 600,000 and 400,000 Permanent Scatterers (PS) for the ERS and ENVISAT data sets, respectively, with a good coherence (>0.6) that were finally selected. Most of the PS are located in the urban centers of the island, in areas of low vegetation and limestone exposure. The reference point of the PS interferometric analysis was selected to be the same as No 06 of the GPS reference station. Thus both PS Interferometric and DGPS results have a common reference point for a direct comparison of the results.

The ERS PS image (Fig. 2a) showed a moderate subsidence of about 1 mm/year mainly at the northern and at the western most part of the island. Additionally, moderate values of subsidence appeared along the southwestern slopes of Aenos Mt. The rest of the island showed very small values of uplift (<1mm/year). It therefore appears that the period 1992-2000 may generally be considered as a relatively stable period for that area. The overall ERS PS image is consistent with the anticipating motion of the main neotectonic features in the island.



(a)



(b)

Fig. 2. PS Interferometry Map of Cephallonia-Ithaca islands using: (a) ERS (1992-2000) and (b) ENVISAT (2003-2008) Radar Imaging.

However, the ENVISAT PS image for the period 2003-2008 looks quite different (Fig. 2b). In fact, the sign of the vertical motion has changed at most parts of the island showing relatively strong uplift (> 3mm/yr), where stability or even subsidence was indicated by the ERS data in the previous period (1992-2000). The discrepancy between ERS and ENVISAT data is more evident in the northern, northwestern, central and southern parts of Cephallonia. These changes in the sign of the vertical motion were first recognized by the DGPS observations and were confirmed by the subsequent network remeasurements [4].

Regarding the deformation in Ithaca Island, uplift is generally observed in both ERS and ENVISAT PS products. The uplift rate is relatively small (about 1 mm/yr) in the ERS PS imaging, while is substantially increasing (>3 mm/yr) for the period 2003-2008 that the ENVISAT data cover.

4. DISCUSSION

DGPS and PS Interferometry results from the Cephallonia Island illustrate a continuous and consistent pattern of deformation from 1992 to 2003, while for the period after 2003, a very similar vertical pattern is presented, but of opposite sign. It may be stated that the pattern of the vertical motion has changed along a wide zone that extends mainly along the southern parts the island from NW to SE, marking a dramatic change to the tectonic behavior of the Cephallonia Island. Prior to 2003, the ground deformation is consistent with the known and expected neotectonic movements of the area. After 2003, the high magnitudes of uplift may be indicative of a major regional crustal deformation process of a bulging character that could be taking place in the broader region. Presence of evaporites or salt layers could lead to some uplift of these areas. However, extensive presence of evaporites or salt formations is not consistent with the local geology, as has been outlined by seismic reflection studies [12].

At an attempt to interpret that change of the ground deformation pattern, the concept of dilatancy was envisaged for this phenomenon when it was first recognized [4] based only on the limited GPS stations. The PS ENVISAT product however provides now an additional support indicating a deformation area of a much larger areal extent compared to the limited point coverage of the DGPS study.

Regarding the time though when dilatancy may have started, that was difficult to be identified in our earlier study [4]; it should have started sometime after September 2003 and before February 2006. However, this crucial aspect seems to have now being resolved: Detailed consideration of 53 composed ENVISAT differential interferograms covering the period 2003 to June 2010, applying for their analysis the ROI_PAC software, show that the extensive bulging of the area started taking place at about mid-2005. The same outcome is also evident, and in some places very profound, when inspecting the time-series at PS points along the southern and western part of the island where the most prominent uplift was observed.

If dilatancy is occurring in the area that appears to have started in mid-2005, considering (i) the large horizontal extent (>50 km) of the bulged area, (ii) the high seismicity taking place in the area [11], [15], and (iii) the considerable amplitude of the observed uplift (>30 mm), all the above aspects may foreshadow the occurrence of a future large magnitude (M>7) event in the vicinity (rather offshore) of Cephallonia. Some precursory parameters may thus be calculated: Based on the empirical formula $M=1.96\log(D/2)+4.45$ [13], a magnitude of $M\approx7.2$ results for a mean diameter (D) of crustal deformation of D=50 km. The preparatory period (τ) for a magnitude M=7 event is estimated to be at least $\tau=5.3$ yrs, based on the formula $\log\tau=0.0(\pm0.47)+0.47(\pm0.07)M$, as being deduced by geodetic studies [14].

If the magnitude event (M) is higher than M=7, the preparatory period is normally anticipated to be greater than the above calculated value of 5.3 years, which in any case should be considered after mid-2005. Nevertheless, it should be noted that these estimated values of the preparatory period should only be considered as indicative [14], since there have not been many available earthquakes of magnitude around seven (7) to be taken into consideration in the above formula, and therefore larger error estimates are inevitably inherent.

5. ACKNOWLEDGEMENTS

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