GROUND DEFORMATION OF ZAKYNTHOS ISLAND (WESTERN GREECE) OBSERVED BY PSI AND DGPS

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ABSTRACT

Ground deformation studies based on Differential GPS (DGPS) measurements and Permanent Scatterers InSAR (PSI)* analysis using ERS (1992-2000) and ENVISAT (2003-2010) radar data have been conducted on Zakynthos Island (Western Greece) covering the period 1992 to 2012. These results were compared, validated and integrated with geological, geotectonic and seismological data to evaluate possible pre-earthquake deformation process, and the present tectonic regime. The PSI results indicate that a slight subsidence had occurred during the period 1992-2000, while uplift has mainly observed in 2003-2010. DGPS results for 2005-2006 indicated strong opening of the southern part of the island, while in the period 2006-2012 the amplitude of deformation is relatively smaller. The occurrence of the seismic outbreak that took place offshore to the south of Zakynthos during 2005-2006 may have contributed to the different deformational pattern as revealed by the ERS and ENVISAT PSI products, and also elucidate the DGPS results.

Index Terms— Ground Deformation, Zakynthos Island, DGPS, PSI

1. BRIEF GEOTECTONIC SETTING

The Central Ionian islands in western Greece play an important role in the kinematic processes of the Eastern Mediterranean. They are situated within a very active seismotectonically complex area which is undergoing rapid and intense ground deformation. The highest seismic activity in Europe currently takes place in that region, constituting part of the Eastern Mediterranean Lithosphere that is subducting beneath the Aegean Lithosphere along the Hellenic Arc. The subduction zone terminates against the Cephallonia Transform Fault, a major strike-slip fault that links the subduction boundary to the continental collision between the Apulian microplate and the Hellenic foreland, and plays a key role in the region's geodynamic complexity [1].

Zakynthos Island consists of rocks of two zones, the Pre-Apulian or Paxos Zone and the Ionian Zone (Fig. 1). Both zones lie to the west of the Pindos thrust and the boundary between them is the Ionian thrust which is generally considered to represent the most external Hellenide structure [2]. This thrust is not well exposed in Zakynthos, because the absence of Mesozoic carbonates and the occurrence of a thick Pliocene cover make the boundary between these zones difficult to define. The Pre-Apulian Zone is characterized by Upper Cretaceous to Miocene sediments (limestones, marly limestones etc.), whereas the Ionian zone, which appears in the southeastern part of the island, consists of limestones and evaporitic rocks of Triassic age. The post Alpine deposits are marls of Pliocene age and Quaternary marine and continental formations [2].

2. THE GPS MEASUREMENTS

The GPS network (14 stations) in Zakynthos was first installed in 2005 [3] and re-measured in 2006 and 2012. Overall rms errors of about 1.0-5.3 mm and 2.0-8.1 mm for the horizontal and vertical components of displacement, respectively, were achieved for the majority of the stations (at a 90% confidence level) using the Bernese software

Station No. 73 was chosen as a local reference station; it has a horizontal motion to the SSE direction with respect to ITRF2008 (V_{East}=9.1±1.4 mm/yr and V_{North}=-9.2±1.3 mm/yr), while the vertical component is rather stable (V_{Up}=-1.9±1.8 mm/yr). The overall behaviour of station No. 73 which is consistent with the anticipated regional motion [3] & [4] has to be particularly considered, since it represents the local reference point not only for the DGPS measurements, but also for the interferometric analysis.

Fig. 2a presents the motion vectors with respect to the ITRF2008 for the first re-measurement period 2005-2006. It is evident that a horizontal extension of the southern part of the island had occurred in the area around Laganas Bay

* The PSI work was carried out in the framework of the TERRAFIRMA Stage-3 ESA's Program.

which seems to be "opening". This deformational pattern may be attributed to the increase of the seismicity in the area during that period. 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 4-12, 2006 [5].

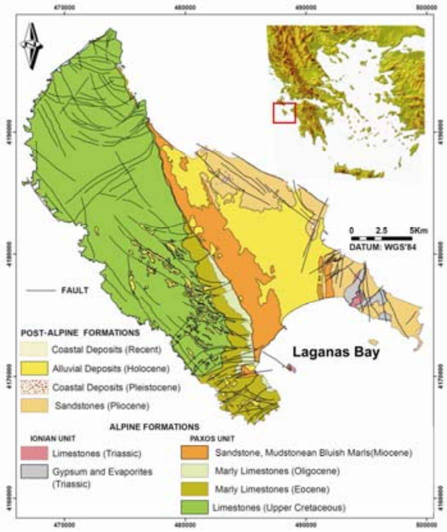

Fig. 1. Detailed Geological Map of Zakynthos Island, showing also the main faulting features (IGME, Geological Map of Greece, 1983)

The central part of the island appears rather stable. The northern part, however, presents an inconsistent pattern with a westward motion that prevailed at most of the stations. The vertical deformation is expressed with uplift mostly in the southern part bounding the area of Laganas Bay, with values up to 60 mm in the western part. The extreme northern part was generally subsided by 12-30 mm.

For the second re-measurement period (2006-2012), the horizontal deformation is consistent with the anticipated southwestern motion of the area with respect to the ITRF (Fig. 2b). However at the northern half of the island, the vectors show a westward motion (about 80 mm), while to the south a southwestern motion of the same amplitude prevails. The vertical deformation shows significant subsidence for the whole of the island, with the higher amplitudes taking place to the south (more than -50mm), in the areas where the strongest uplift took place in the previous period (2005-2006). The later may indicate a rebound of the whole area to the state that existed before the outbreak of the seismic activity during 2006. The strong differentiation in the motion between the northern and the southern parts of the island, observed mainly in the first re-measurement period (2005-2006) but also in the second period (2006-2012), highlights the different kinematic status of the two areas as has been described also in previous works [3], [4].

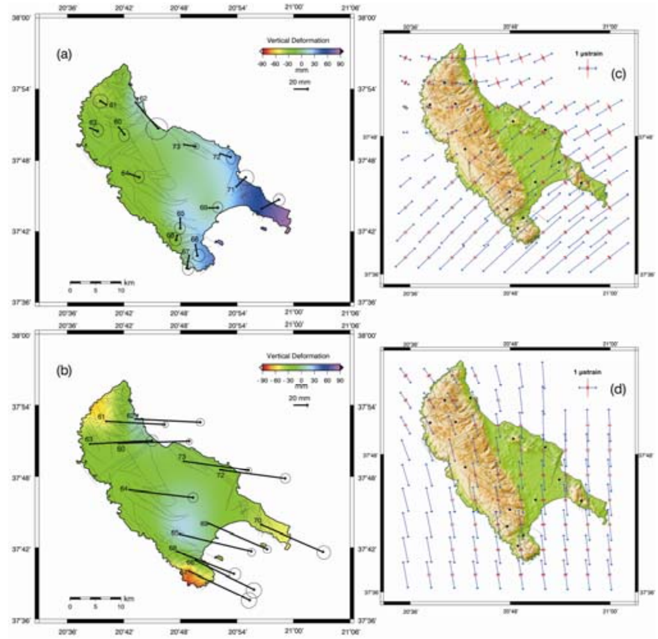

Fig. 2. Horizontal and Vertical displacements (mm) of the Zakynthos GPS network observed for the period **(a)** 2005-2006, and **(b)** 2006-2012 (ITRF2008). Calculated Strain Field for the periods **(c)** 2005-2006, and **(d)** 2006-2012.

The horizontal strain-rate field was calculated based on the horizontal GPS velocities for both periods (Fig. 2c & 2d). The strain-rate results have been produced for a correlation length of 4 km and error estimate (σ) of 2 mm. For the first period, a clear differentiation between the northern and the southern parts of the island is observed. Extension predominantly took place in the south of a NE-SW direction, while slight compression occurred in the north. For the second period (2006-2012), the extension remained, but it changed to an almost N-S direction. Both periods reflect the different tectonic and kinematic characteristics between the two parts of the island (northern and southern). The former may be related to a possible large extensional deformation mechanism that is taking place along N-S direction, almost parallel to the main geological contact of the area (limestones on the west, post-alpine formations on the east, see Fig. 1).

3. THE PSI DESCRIPTION

Differential SAR Interferometry (DInSAR) is based on pixel-by-pixel computation of the so-called interferometric phase using two satellite radar acquisitions, and such determined phase is a measurement of what has changed in the time interval between the two images. Apparent phase variations between two satellite scenes can be caused by actual ground displacement or by atmospheric effects that delay electromagnetic wave propagation. The PSInSAR™ technique ([6]) allows atmospheric effect to be estimated and then removed by combining data from long time series of SAR images. The PSI technique can identify stable ground signals (known as Permanent Scatterers, or PS). Their velocity in the line of sight (LOS) of the satellite can be estimated with greater accuracy (≈1 mm/year). The LOS angle is about 22.5^{o}. Thus, the vertical component of ground deformation is about 93% of LOS, and therefore the PSI is more sensitive to the vertical deformation.

For Zakynthos Island, 39 descending images were used for the ERS PS InSAR product covering an area of about 560 km^2 for the period 1992-2000. The ENVISAT data set consisted of twenty one images covering the period 2003-2010 with more than 52,000 PS points. A point in the vicinity of No. 73 GPS reference station (Fig. 2) was selected as a reference point for the PS product, because of the prevailed vertical stability in this region as already was described above (V_{Up}=-1.9±1.8 mm/yr).

The ERS (1992-2000) and the ENVISAT (2003-2010) descending PSI velocity products are presented in Figs. 3a and 3b, respectively. It is noteworthy that most of the PSI points (more than 80%) are located on the western half of Zakynthos where limestones prevail. Considering the ERS PSI deformational velocity (Fig. 3a), the extreme western part of the island was slightly uplifting (1-1.5 mm/yr), while its southwestern part was moderately subsiding (about -2mm/yr). The largest rates of subsidence (>3mm/yr) occurred at the northern cliffs of the island where landslide phenomena have been recorded. At the southeastern part, a local area of limited extent was slightly uplifting (about 1.5 mm/yr) rather due to local faulting. The ground differential motion along faulting zones is apparent in this image, especially at the multi-fragmented northern and southern parts of the island.

Considering the descending ENVISAT deformational velocity (Fig. 3b), the PSI points are of an order of magnitude lesser as compared to the ERS images. In areas where a slight subsidence was taking place at the western half of the island during the same period as the ERS descending velocity field (Fig. 3a), the motion changed to slight uplift (about 1.5 mm/yr). That change in the ground motion is more evident at the southwestern part of the island. The eastern part, though, maintained the same deformational pattern for both periods of the ERS and ENVISAT descending images. However, a higher rate of uplift occurred at the southern part (Laganas Bay), most probably due to the seismicity outbreak during 2005-2006.

The standard deviation of the velocity field was also computed both for the ERS (Fig. 4a) and ENVISAT (Fig. 4b) data. There are two parameters affecting the calculation of the standard deviation: (i) *The deviation of motion from the linear model.* Since the standard deviation is associated with the average rate of deformation, if a PS point exhibits a strong non-linear motion that would result in a large residual with respect to the linear model, and thus in a high standard deviation value. (ii) *The distance of each PS point from the reference point*. The velocity standard deviation increases moving away from the reference point.

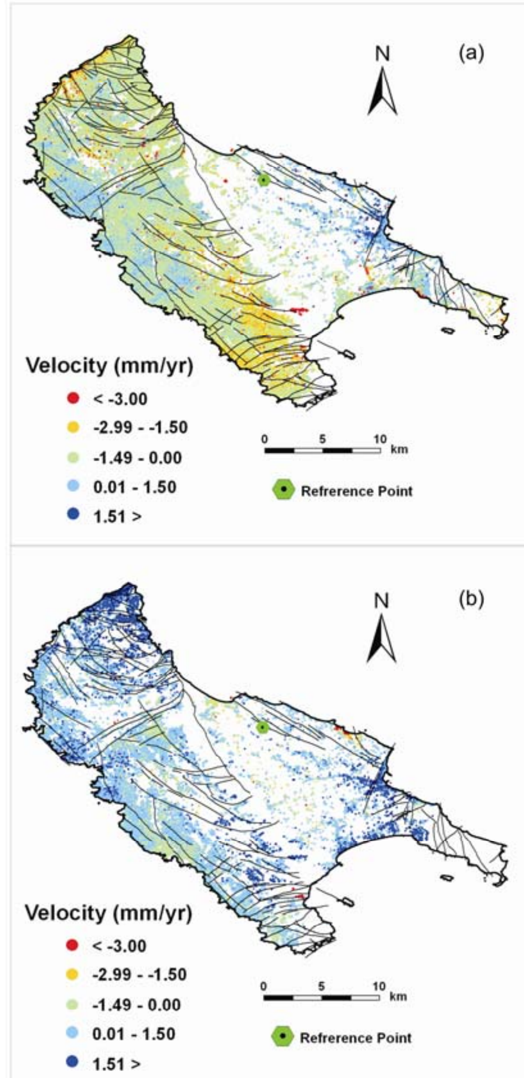

Fig. 3. (a) The ERS (1992-2000), and **(b)** the ENVISAT (2003-2010) PSI deformational velocity maps of Zakynthos.

The standard deviation of the ERS velocity field (Fig. 4a) presents a rather uniform pattern all over the island having small values up to 0.8 mm/yr, with the exception of the extreme south-west peninsula of Zakynthos, where slightly higher values were calculated (about 1 mm/yr) that may be attributed to the longest distance from the reference point. The small values of standard deviation encompassing almost all the island represent a ground deformation which is of an almost linear character throughout the ERS time span of 1992 to 2000.

A complete change of the velocity standard deviation of the ENVISAT data (Fig. 4b) compared to the previous ERS data was resulted. A stronger deviation from a linear deformation pattern is observed. The small standard deviation values (<0.8 mm/yr) are limited only in the vicinity of the reference point. The rest of the island exhibits higher standard deviation values (>1.2 mm/yr) showing thus an almost non-linear behavior. Therefore, it is evident that a discrete change in the character of the deformation field was observed, sometime within the ENVISAT period between 2003 and 2010.

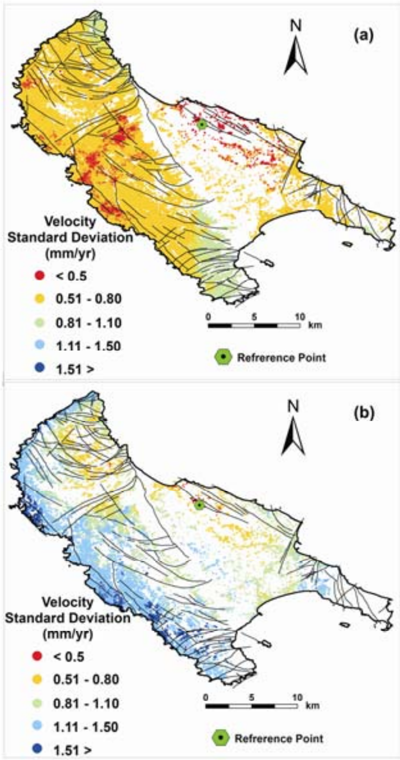

Fig. 4. Standard Deviation of PS velocity deformation map deduced from **(a)** ERS (1992-2000), and **(b)** ENVISAT (2003-2010) radar imaging.

4. DISCUSSION -CONCLUSIONS

During the last decade, a multi-disciplinary study of the broader central Ionian region, and particularly of Zakynthos and Cephalonia islands, was carried out [3],[7], aiming to better understand the tectonic regime of the area, and at an effort to contribute to the earthquake prediction research. The PSI has provided a spatial coverage of the ground deformation of the area compared to the GPS point coverage.

The DGPS results (2005-2012) revealed a different horizontal deformation pattern referring to the northern (eastward motion) and southern part (SSE motion), showing an overall NW-SE extension of the island (Fig. 2); the apparent kinematic boundary seems to be crossing the island in an almost E-W direction, which is not evident in the surface geology. In the northern part that is highly fractured, local faults seem to control both the vertical and horizontal deformation process, while in the southern part, the outbreak of the offshore seismic activity seems to be the main source of the observed ground deformation for the period 2005-2006.

The PSI images of the two distinctive periods (1992-2000 and 2003-2010) revealed a different temporal kinematic process. For the period 1992-2000, overall stability and small-scale subsiding/uplifting phenomena may be attributed to local kinematics across/along local faulting features. During the period 2003-2010, a uniform intense non-linear uplift took place. The observed deformation in the southern part may be attributed to the occurrence of the seismic outbreak offshore, consistent to the DGPS results.

However, the non-linear uplift observed at the northern part may be associated with the regional tectonic process taking place in the broader area, as has already pointed out in the western and southern parts of Cephalonia Island for the same period [7]. This differentiation of the deformation pattern of these two periods may reflect a more regional change of the tectonics in the broader areas interpreted as dilatancy [7]. The two strong seismic events of January (Mw=6.1) and February (Mw=5.9) 2014 that took place in the western part of Cephalonia seem to be consistent with that interpretation invoked earlier [7].

5. REFERENCES

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