Integrated methodologies for 3D deformation analysis at Ischia Island (Italy): state of the art, prospectives and modelling

Vincenzo SEPE*[a], Guido VENTURA[b], Giuseppe VILARDO[c]
[a]Istituto Nazionale di Geofisica e Vulcanologia, dept. Centro Nazionale Terremoti, Roma (Italy)
[b]Istituto Nazionale di Geofisica e Vulcanologia, dept. Roma 1, Roma (Italy)
[c]Istituto Nazionale di Geofisica e Vulcanologia, dept. Osservatorio Vesuviano, Napoli (Italy)

ABSTRACT

Ischia Island, located SW of Naples (Italy), has been characterized by both explosive and effusive activity with the last eruption occurred in 1302. Subsequent dynamics, characterized by seismic activity with the strongest events occurred in 1881 and 1883 and a diffuse hydrothermal phenomena, shows a significant subsidence in the S and NW sectors. The presence of the active volcanoes in a very densely area needs continuous monitoring of the dynamics related to the pre-eruptive processes. Ground deformation studies are an important precursor because are linked to magma overpressure and migration. In particular, the geodetic monitoring system is mainly based on GPS and Precise levelling techniques. Here, we present a study of the surface deformation occurring in the island based on Differential Synthetic Aperture Radar Interferometry (DInSAR) referred to as Small BAseline Subset (SBAS) technique. Levelling surveys carried out between 1990 and 2003 on the Mt Epomeo resurgent block record negative dislocations on the northern and southern flanks with a maximum subsidence rate of 1.27 cm/yr. This deformation is not associated with cooling, crystallization or lateral drainage of magma and cannot be explained by a pressure point or prorate ellipsoid source. The data show that between 1990 and 2003 Mt Epomeo has been affected by a subsidence with two maxima located on its northern and southern sectors. Then, the 1992–2003 time interval and SAR data acquired by the European Remote Sensing (ERS) satellites from ascending and descending orbits have been used, thus allowing us to discriminate the vertical and east–west components of the displacements. A validation of the DInSAR results has been carried out first by comparing the vertical deformations estimated from the SAR data with those measured from the spirit levelling network that is present in the area. The deformation is due to the closure of cracks associated with ENE–WSW to E–W preexisting faults along which degassing processes occur. We propose that the recorded dislocations reflect a decrease in the fluid pressure within these cracks.

Keywords: Ground deformation, GPS, leveling, PS, Sar Interferometry.

1. INTRODUCTION AND GEOLOGICAL SETTING

The Neapolitan volcanic area, located in the south sector of the Campanian plain, includes three active volcanoes: Somma-Vesuvio, Campi Flegrei Caldera, and Ischia Island.

Ischia is located in the West of the Gulf of Naples and is mainly formed by volcanic rocks, by landslide deposits and subordinately by sea sediments. Also, the structural setting of the island has been determined by deformations induced by both regional tectonics and volcano-tectonics. The regional tectonics is the cause of two main fault systems with NW-SE and NE-SW directions. Actually, the presence of a magmatic still active system and potentially able to give future eruptions is testified, besides by the last eruptive event occurred in 1302 (the Arso eruption), and also by an intense fumaroles activity, by vertical ground displacements and by low seismic activity.

Ischia is the westernmost, active volcanic complex of the Campanian Plain (Italy) (Fig. 1) and volcanic consist of of trachybasalts to phonolites and alkalitrachytes, (Fig. 1). The oldest volcanics (130–150 ka) crop out along the coast.

emplaced at about 55 ka forming a caldera depression, in which the marine Tuffite and Colle Jetto formations emplaced (Fig. 1).

* Corresponding Author: Sepe Vincenzo; sepe@ingv.it; phone 39 6 51860203; fax 39 6 51860203. The Green Tuff ignimbrite

Citara Tuff emplaced between 44 and 33 ka, and, around 33 ka, a 800–1100 m uplift affected the Mt Epomeo resurgent block (Fig. 1).

Successive volcanism concentrated in the last 3 ka, in the eastern part of the island (Orsi et al., 1991). The most recent eruption (Arso lava flow) occurred in 1302 AD. Four main fault systems affect Ischia (Vezzoli, 1988; Molin et al.,

2003): a ENE–WSW to E–W striking system cuts the northern and southern flanks of Mt Epomeo, while NNW–SSE to N–S faults delimit its eastern and western sectors; NE–SW faults affect the eastern sector of Ischia; NW–SE faults outcrop in the south-western corner of the island.

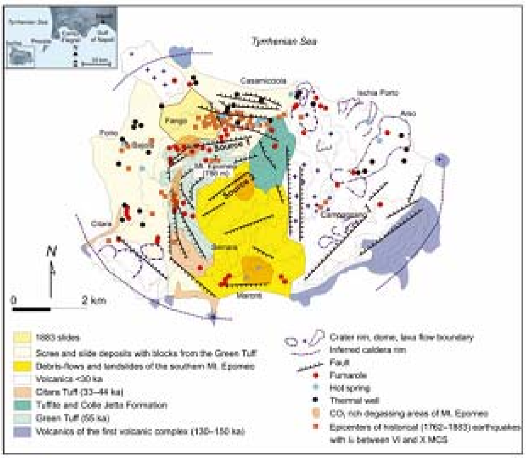


Fig. 1 Location (inset) and geological map of Ischia Island

The southern and north-western flanks of Mt Epomeo are affected by active landslides (Fig. 1). The slide of the north-western sector developed after the 1883 Casamicciola earthquake X MCS (Io = IX); Postpischl, 1985). Historical earthquakes occurred between 1762 and 1883 and were related to the E–W striking faults (Alessio et al., 1996; Fig. 1). However, the shallow source of the 1883 earthquake could also be due to the dynamics of the Ischia hydrothermal system, which consists of two main reservoirs: a shallower reservoir (temperature =250 °C) located at 100–300 m of depth, and a deeper one (temperature =300 °C) at about 900 m of depth. According to Penta and Conforto (1951), the hydrothermal circulation concentrates in the highly fractured lavas underlying the Green Tuff (Fig. 1). The hydrothermal fluids rise to the surface along the main faults and cracks delimiting the northern and western flanks of Mt Epomeo, and along the fault affecting its southern, upper slope (see Fig. 1). Subsidence is testified by Greek and Roman ruins at about 2 m b.s.l.). Precision levelling surveys were done by the Italian Army Geographic Institute from 1913 and by the Italian Geodetic Society in 1967. This latter survey shows that, relatively to 1913, the central and southern sectors of the island subsided with a maximum dislocation of 31 cm, and a little uplift affected the Ischia northern sector. Using spaceborne Synthetic Aperture Radar images collected between 1993 and 2003, [1] Manzo et al. (2006) suggest that the vertical deformation of Ischia is due to the combined effects of active landsliding and fault activity. However, these data cover the zones of the island located along the coastline, where the presence of buildings allows interferometric processing. On the contrary, dense vegetation prevents from obtaining a good result on Mt. Epomeo and other sectors of the island.

2. LEVELLING SURVEYS

The INGV-Osservatorio Vesuviano levelling network of Ischia is shown in Fig. 2. Levelling surveys were carried out in 1990, 1994, 1999, 1997, 2001 and 2003. The reference benchmark (bm 1 in Fig. 2) is located in the north-eastern sector of the island, which is considered a stable area [2] (INGV-Osservatorio Vesuviano, 2001).

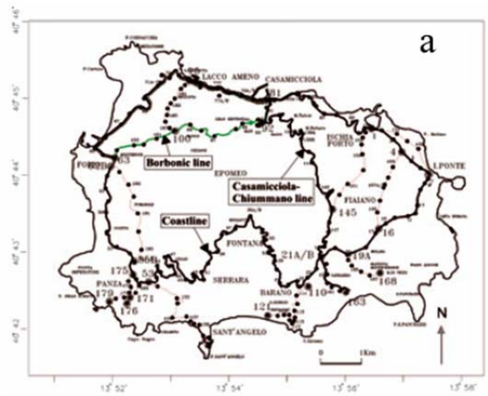


Fig. 2 Leveling network of Ischia Island

The network consists of 230 benchmarks with a mean distance of 300 m on about 100 km of nine circuits besides the coast line. Auto levels equipped with plain-parallel lamina micrometres and couples of rods with invar ribbon have been used in all surveys. Measurements are submitted to least squares adjustment with the method of indirect observations, with a final value of the standard deviation per unit of weight of 0.965 mm. Here, we report results from levelling surveys carried out starting from May 1978 to June 2003 along the Coastline, while from 1987 for Borbonic line and from 1994 for Casamicciola-Chiummano (Campagnano) line (N-S line in the East sector), which bound and cross Mt Epomeo (Fig. 2). The measured error on the single circuit is less than 3.2 mm, a value well below the maximum expected error (11.4 mm). The vertical deformation recorded in the 1990–2003 period is reported in Fig. 3. A maximum value of -16.5 cm occurs in the Fango area of the _Borbonic line_ at bm 100. The maximum subsidence rate is 1.27 cm yr^{-1}. The data along this line show two relatively stable areas located in the westernmost and north-easternmost sectors of Ischia (bm 63–65 and bm 86). The subsidence concentrates between bm 93 and 103. However, this subsidence is not constant and increases between bm 97 and 103, where the levelling survey partly crosses the active landslide associated with the 1883 earthquake. A significant subsidence of -8.6 cm occurs in the Serrara area of the Coastline, along the southern flank of Mt Epomeo. The maximum subsidence rate is 0.65 cm yr-1 at bm 35. The data of the _Coastline_ reveal that the northern sector of Ischia is not affected by significant vertical deformations (bm 1–15 and bm 69–90). Subsidence increases moving from these outer sectors towards the southern flank of Mt Epomeo. An abrupt increase in subsidence occurs between bm 24 and bm 43 (Fig. 3), where the Coastline partly crosses active landslides and the ENE–WSW fault affecting the southern flank of Mt Epomeo (see Fig. 2). The levelling survey carried out between 1994 and 2003 along the _Casamicciola-Chiummano line, which crosses the sector of the island where the more recent volcanic activity concentrated (Fig. 2 and 3), shows a maximum vertical displacement of ~3.6 cm in 9 years, i.e. a subsidence rate of 0.4 cm yr^{-1}. The subsidence rate along the Casamicciola-Chiummano line is roughly constant.

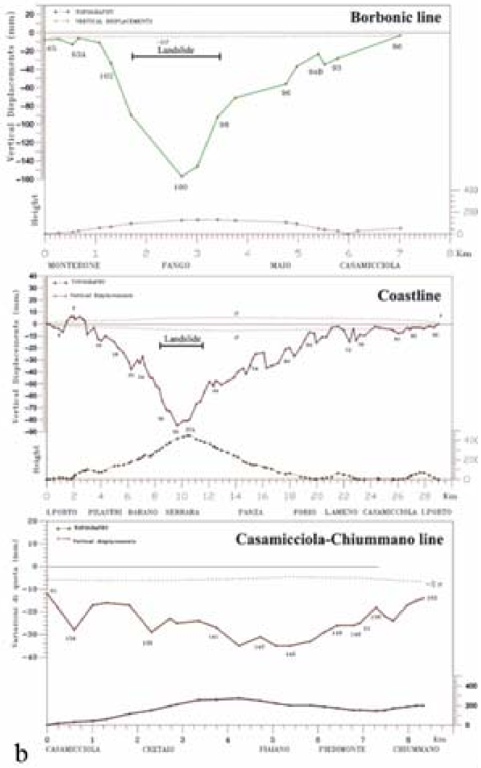


Fig. 3 Results of measurements from levelling lines

The levelling data (Fig. 4) show that the subsidence rate at bm 35 (Coastline) and bm 100 (Borbonic line), which are the benchmarks where the maximum values of subsidence are recorded, is constant with time. The linear interpolations suggest constant subsidence rates (1.27 cm yr)1 at bm 100 and 0.65 at bm 35).

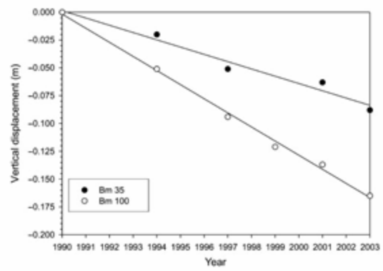


Fig. 4 Time (years) vs. vertical displacement at benchmarks (bm) 35 of Coastline and 100 of _Borbonic_ line.

As concern the top of Mt Epomeo, where levelling lines are lacking, the data collected during 1999, 2001 and 2003 GPS surveys [2] show that this is a stable area, being the recorded displacement within the measurement error.

3. GPS DATA

The GPS network operating on Ischia Island consists of 25 vertices homogeneously distributed on the island. Five different GPS surveys of the whole network were carried out since 1997, in order to investigate the subsidence phenomena better defined by leveling surveys. The comparison among the 1997, 1998, 1999, 2001 and 2003 GPS surveys results show that some GPS points present significant horizontal (plano-altimetric) displacements confirming slow but continuous deformations in the Southern and North West sectors of the island.

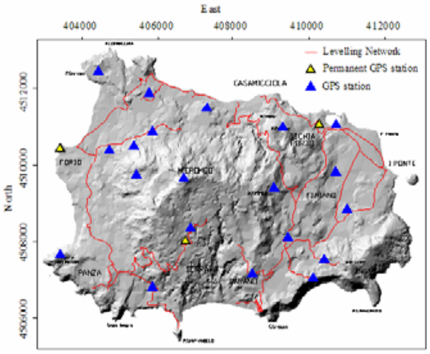


Fig. 5 Location of the GPS stations

We used 4000SSI Trimble dual frequency receivers and Geodetic antennas Trimble Compact L1/L2 with Ground Plane (TRM 22020.00 + GP) and Trimble Microcentered with Ground Plane (TRM 33429.00 + GP); Trimble 4700 dual frequency receivers and Geodetic antenna Trimble Compact L1/L2 with Ground Plane (TRM 22020.00 + GP); LEICA 399 dual frequency receivers with geodetic internal antenna LEI399. The Step sampling GPS observations was at 30 sec. with 24 hours sessions, with an average total observation time of at least 48 hours for station during each survey. Data processing was carried out with the scientific Bernese 5.0 software in automatic mode BPE (Bernese Processing Engine) and here below we report the analytical processing steps.

Observations: Double difference phase;
IGS precise orbits and EOP (Earth Orientation Parameters) set.
Correction on phase center.
Resolution of ambiguities strategy with QIF (Quasi Ionosphere Free).
A priori tropospheric Model DRY-Niell, with estimated hourly tropospheric zenith delays.
The coordinates of all the sites have been placed at 10 m.
The solutions are weakly bound and expressed in an unknown reference system, different every day;
To obtain a reliable combination were included in the analysis, 9 IGS network sites that act as "anchor" that are common to all clusters.;
The daily solutions were not covered under the ITRF2005 reference system, distributed in sinex ITRF2005_IGS-TRF.snx, available at the website http://irfr.ensg.ign.fr by Helmert transformation (translation, rotation, hard change of scale) – Loosely constrain;
Outliers and annual signals and instrumental offsets that affect the permanent stations.
The velocities and connected errors are associated to the whole covariance matrix;
The formal errors were compared to the heating value of the $\chi 2$
The velox obtained was rotated in a reference system associated with the movement of the Euro-plate by means of an Euler pole of rotation ITRF2005.
The Eurasia ITRF2005 pole was estimated considering the velocities and the relative errors of almost 11 vertices contained in ITRF2005_IGS-TRF.snx, placed in the middle portion of northern Eurasia (stable Eurasia)

In Fig. 6 we report the results of velocity field at Ischia Island during the period 1997-2003.

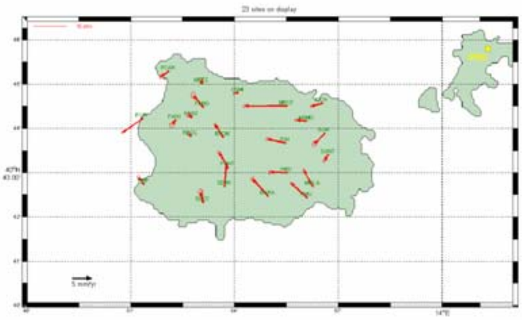


Fig. 6 Velocity field at Ischia Island during the period 1997-2003

4. INSAR

When interpreting the velocity values obtained by interferometric processing it must be kept in mind that InSAR technique provides a measurement of change in distance along the look direction (LOS) of the radar spacecraft, which is on average 23° from the vertical, and a linear rate of movement is assumed. However, the availability of both ascending and descending datasets allows us to separate the vertical and horizontal components of the deformation for the sampled areas that are common to both the acquisition geometries. The ERS (1992-2001) and RadarSat (2003-2007) signals were analyzed. Mean deformation velocity maps have been produced in order to examine the large spatial scale features of the investigated area and, to achieve this task, three processing stages have been applied. These include: a) data selection based on the coherence value; b) computation of mean deformation velocity maps in SAR coordinates; c) separation of east west and vertical deformation components. To minimize the effects due to displacement estimations accuracy, a data selection has been performed on both ascending and descending datasets. A PS selection was done by excluding the reflectors characterized by a lower signal to noise ratio (pixel coherenceb0.85; C85 dataset). By comparing the velocity maps of FULL and C85 datasets for the ascending orbit and for the descending orbit, we could observe that the distribution of positive and negative values confirm the same sub regional patterns showing different amplitude. For the C85 dataset, the mean deformation velocity maps, from both the ascending and descending orbit data sets, were derived by inverse distance interpolation weighted (IDW) method. IDW method is commonly used to interpolate scatter points that not necessarily have relationship or influence over neighbouring data values, and allows us to preserve local data variations yielding suitable results.We used a quadratic weighting power to within a 1 km radius neighbourhood to obtain 100 m regularly spaced grids, referenced to UTM zone 33 and toWGS-84. In the grid, we do not use faults like discontinuities because data on the activity of the faults within the analyzed time period are not available. The estimate of the east–west and vertical deformation components has been performed by properly combining the radar LOS mean displacement velocity maps computed from the ascending and descending orbits on pixels common to both maps [1]. To separate the vertical and horizontal components of the deformation has been assumed that the ascending and descending radar LOS directions belonging to the East-Z plane and the look-angle is the same for both ascending and descending geometries. Based on these assumptions, simple geometric considerations (Fig. 7) allow us to retrieve the vertical and the east–west displacement components as follows:

$$d_{\mathrm{East}} \sim \frac{(d_{\mathrm{LOSDesc}} - d_{\mathrm{LOSAsc}})/2}{\sin(\theta)}$$

$$d_z \sim \frac{(d_{\mathrm{LOSDesc}} + d_{\mathrm{LOSAsc}})/2}{\cos(\theta)}$$

where d is the displacement vector of an investigated PS, θ is the look-angle, dz and dEast are the projections along the Cartesian axes, and dLOS Desc and dLOS Asc are the projections along different LOSs.

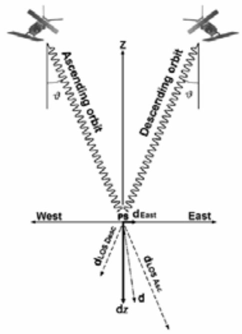


Fig. 7 Geometry of the acquisition system

Ischia Island shows a subsidence centered in the inner sector of the volcanic complex (Fig. 8). The horizontal velocity field suggests a general eastward movements with a component of contraction evidenced by the higher eastward velocity (3 to 25 mm/year) of the western sector of the island with respect to the eastern one, which is characterized by maximum velocities of 3 mm/year. Very localized areas with westward velocity are probably related to gravity phenomena, as well-known for the Fango area, where an active gravity slide occurs [3]. According to results from geological investigations and models from levelling line data [3], the Ischia deformation pattern is related to a combination of endogenous and exogenous processes that include (a) depressurization of the local hydrothermal system and (b) landslides due to gravity instability on steep slopes.

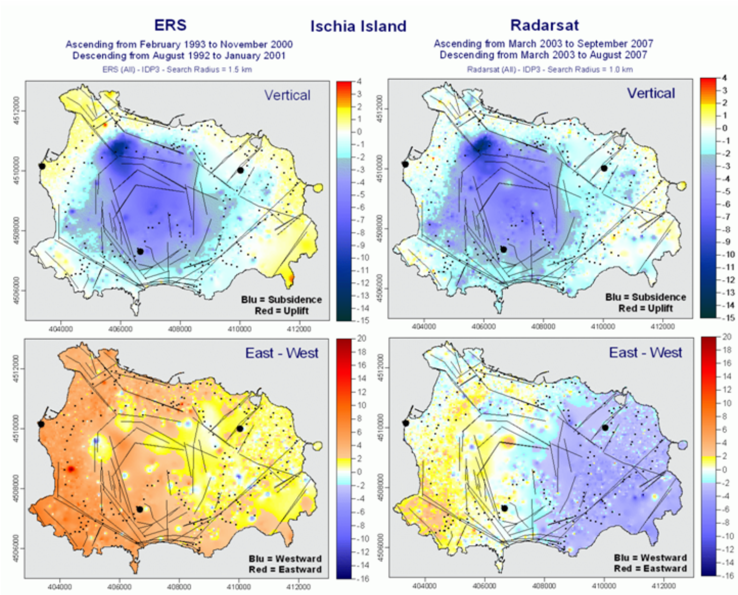
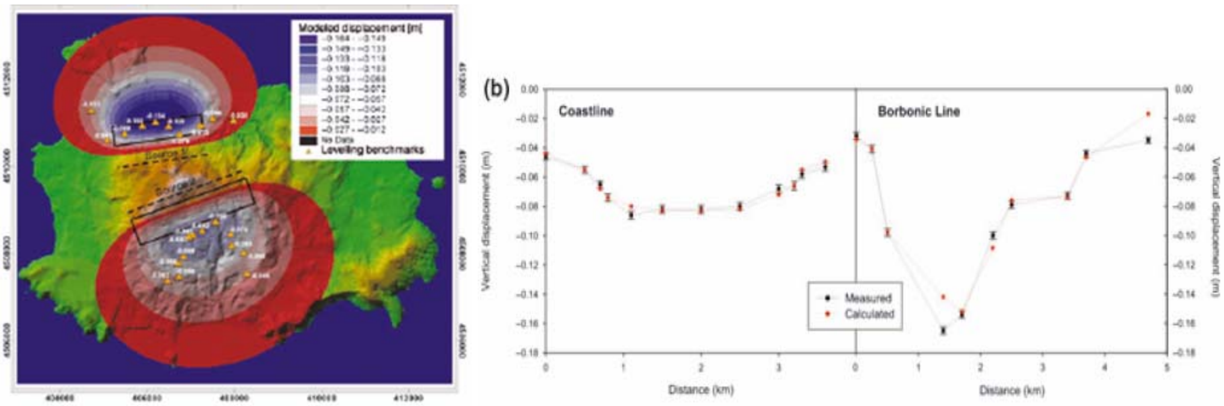


Fig. 8 Summary of ERS and Radarsat data

5. MODELING

The leveling data allowed to propose the model shows in Fig. 9. Boxes represent the plane view of the crack planes, while the dashed lines are the projection of the planes on the surface. Observed displacement for the levelling benchmarks are also shown. (b) Comparison between the calculated (red dots) and measured (black dots) displacement. Error bars of the measured vertical displacements are also reported. Lines between points show the dislocation trends.



	Length (m)	Width (m)	Depth (m)*	Dip (°)	Strike (°E)	East (m)†	North (m)†	Displacement (m)
Source 1	2050	670	600	50	80	406250	4510850	−0.55
Source 2	2800	1800	600	70	60	407050	4508960	−0.30

*Depth of the top edge of the dislocation.
†UTM coordinates, WGS84 system, zone 33.

Fig.9 1990–2003 vertical displacement field modelled according to the source parameters listed in Table.

The data presented here show that Mt Epomeo has been affected by a subsidence with two maxima located on its northern and southern sectors. These displacements are due to the closure of cracks associated with ENE–WSW to E–W preexisting faults along which degassing processes occur. We propose that the recorded dislocations reflect a decrease in the fluid pressure within these cracks. We exclude that the progressive crack closure is due to self-sealing processes because self-sealing induces an increment in the fluid pressure with consequent, possible local uplifts. The decrease in the fluid pressure within the ENE–WSW to E–W striking cracks at Mt Epomeo could reflect a decrease in the fluid pressure within the larger scale, deep hydrothermal system on the basis of radar interferometric data, and by the nearly constant subsidence rate recorded along the Casamicciola-Chiummano line. The results indicate that changes, i.e. uplift or decrease in the subsidence rate, in the dislocation pattern recognized here could reflect changes, i.e. pressurization, in the deep hydrothermal system. As a conclusion, the monitoring of the dislocations and of the CO_2 flux along the cracks could give useful information on the dynamics of the Mt Epomeo hydrothermal system.

6. CONCLUSIONS

The main results about monitoring in the volcanic area of Ischia by using levelling ,GPS and SAR Interferometry surveys have been shown. Such geodetic method aims to refine the knowledge about dynamics inside an area characterized by highest volcanic risk. The study of the deformative sources in the volcanic island and the continuous necessity of a more reliable evaluation of the eruption precursors have carried to the development, optimization and the continuous technological evolution of the geodetic monitoring system.

Although we recorded geodetic, geochemical and seismological data which can provide an overall representation of the phenomena which affected the island, still much to be done because the complexity of this volcanic structure to define its behavior and evolution in the time. All these, inside an already complicated tectonic of Neapolitan volcanic district, could not immediately identify any time to restart the magmatic system and, in a possible state of alert, for beginning procedures of Civil Defense Dept. for Hazard mitigation.

Acknowledgements

This study was supported by Project S1 INGV-DPC funds. We thank Roberto Devoti and UF “Data processing for Geodesy” of INGV-CNT for software and the perceptive comments and suggestions. Original data were acquired by the Department of Geodesy of INGV-Osservatorio Vesuviano from 2001.

REFERENCES

[1] Manzo, M., Ricciardi, G. P., Casu, F., Ventura, G., Zeni, G., Borgstro¨m, S., Berardino, P., Del Gaudio, C. and Lanari, R., 2006. Surface deformation analysis in the Ischia Island (Italy) based on spaceborne radar interferometry. J. Volcanol. Geoth. Res., 151, 399–416,doi:10.1016/j.jvolgeores.2005.09.010.

[2] INGV-Osservatorio Vesuviano, 1999-2003. Rendiconto sull'attivita di sorveglianza.

[3] Sepe V., Atzori S., Ventura G. (2007) Subsidence due to crack closure and depressurization of hydrothermal systems: a case study from Mt. Epomeo (Ischia Island, Italy). Terra Nova, doi: 10.1111/j.1365-3121.2006.00727.x