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MONITORING AND DEFORMATION ANALYSIS IN NEAPOLITAN VOLCANIC AREA (SOUTHERN ITALY)

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Abstract

The Neapolitan volcanic area, located in the south sector of the Campanian plain, includes three active volcanoes: Somma-Vesuvio, Campi Flegrei Caldera and Ischia Islands.
Somma-Vesuvio (last eruption occurred in 1944) is characterized by a low level seismic and ground deformation activity; Campi Flegrei Caldera (last eruption occurred in 1538) is characterized by slow deformation and moderate seismicity. During the 1969-72 and 1982-84 events, the Campi Flegrei caldera has been affected by two intense episodes of ground uplift and seismicity, followed by a minor subsidence phase, still active; Ischia, located at W of Naples, has been characterized by both explosive and effusive volcanic activity, with last eruption occurred in 1302. Subsequent dynamics has been characterized by seismic activity (strongest events occurred in 1881 and 1883) and by significant subsidence in the S and NW sectors of the island. 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 is an important precursor, because it is linked to magma overpressure and migration, through the rehological parameters characterising the volcanic rocks.
In particular, the geodetic monitoring system is mainly based on GPS and Precise levelling techniques.
The Group of Geodesy of the Osservatorio Vesuviano–INGV installed and operates several GPS and precise levelling networks in the Neapolitan volcanic area.
GPS non permanent network consists of about 100 3D vertices distributed on Neapolitan volcanic area. Starting from 1999, a GPS permanent network has been installed consisting of 15 stations in continuous recording with a sample rate of 30 seconds. Also, some important results derived from precise levelling surveys in these areas. The levelling network consists of 600 benchmarks, covering an area of about 500 Km^2 . We describe the monitoring network and the main results obtained in the last years.

1. Introduction

The Neapolitan volcanic area geodetic network has been developed in order to monitoring the dynamic of Vesuvius, Campi Flegrei and Ischia Island.
The volcanic country includes:

- the Vesuvius apparatus, to east of Naples, with the last occurred eruption in 1944.: it is in a quiescence phase characterized by a low deformations and seismic activity at present;
- the Campi Flegrei volcanic district, to west of Naples, with the last eruption in 1538 (Mount Nuovo eruption). The area is characterized by slow and continuous vertical movements as well known as Bradyseism. During 1969-72 and 1982-84 this area has been interested by two intense uplift episodes, with a maximum vertical displacement of about 3.5 m. and with more than 15000 earthquakes with magnitudes in the range 0.5-4.0.
  Seismicity is normally absent except in periods of high uplift rate.
- Ischia Island rises at W of the Gulf of Naples with the last eruption in 1302. In 1881 and 1883 was interested from two strong earthquakes (about 3000 victims). At present, the island has characterized by a subsidence phenomena in the South and NW areas and an almost total absence of seismicity.

In this densely populated area (about 1,500,000 people), the presence of several dangerous volcanoes characterized by explosive eruptive mechanisms makes very important the monitoring of eruption precursors for a correct risk evaluation and mitigation. So, the study of the deformation sources in the three volcanic apparatus and the needing for reliable evaluations and forecast of pre-eruptive phenomena, stimulated the development, optimization and the continuous technological evolution of geodetic monitoring systems, both for continuous acquisition and for periodic surveys.
This paper describes the results obtained in the period 1999-2002 by the analyses of GPS and levelling data. During the three years period analysed, two notable volcanic events took place in the Neapolitan volcanic area:

- In October 1999 in the vesuvian area, an increase of seismic activity occurred. This activity culminated with an earthquake occurred at 07.41 GMT of 09 October 1999 (M_d = 3.6; Lat. 40°49.01' Long. 14°25.67', depth ≈ 4.0 Km,) and not accompanied by significant surface deformation.
- In the period March-July 2000 the Campi Flegrei monitoring system shows a small but significant vertical displacements, amounting to about 4 cm. The 22 August 2000 the seismic network records a seismic swarm, composed by 57 events ($M_d \geq 1.4$). The largest event (M_d= 2.2) occurred at 17:58 GMT in the Solfatara area (Lat. 40°49.67' Long. 14°08.69', depth = 2÷3 Km).

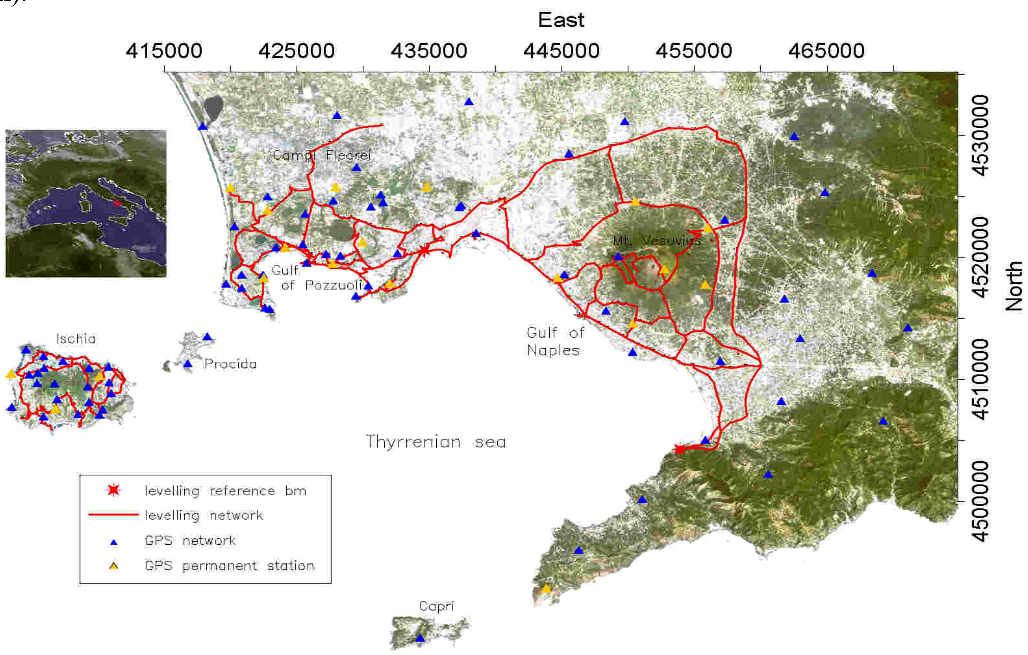

Fig. 1- GPS and levelling networks operating on the Neapolitan Volcanic Area.

In Fig.1 the geodetic monitoring network is shown, consisting of:

- The Vesuvian Levelling Network formed by about 300 benchmarks distributed on a distance of about 225 km, with a mean distance of about 700 m, on sixteen loops;
- The Campi Flegrei Levelling Network formed by about 300 benchmarks distributed on a distance of 120 km, with a mean distance of about 400 m, on eleven loops;
- The Ischia Island Levelling Network formed by 200 benchmarks distributed on a distance of about 90 km, with a mean distance of about 300 m, on seven loops;
- The GPS Network cover the whole neapolitan volcanic area (Vesuvius, Campi Flegrei ed Ischia); its goals are to define the global dynamic of region binding itself to campanian apennine massifs;
- The CGPS network consist of 20 GPS Permanent Stations, covering the three volcanic zone. This network is particularly useful to detect data during phases of rapid deformations.

2. Mount Vesuvius

The Somma-Vesuvius is a layer-volcano composed by an older apparatus, the Mt. Somma caldera, in which the cone of the Vesuvius developed. The tectonic position of Mt. Vesuvius, close two main fault systems, with orientation NE-SW, whose extension crosses the seismogenetic apenninic chain, suggests a possible link between volcanic and seismic phenomena. The last eruption happened in 1944 and subsequent dynamics of the volcano was characterized by fumarolic activity, moderate seismicity (on the order of some hundreds of events/year, maximum magnitude 3.6) and no significant vertical displacements, except in the crater area and around the edifice (Lanari et al., 2002).
The subsidence pattern around the edifice is unusual and hardly interpretable in terms of any meaningful volcanic source; Lanari et al. (2002) put it in relation with relative sliding phenomena occurring at the contact between different rock lithologies.
The Vesuvius is anyway a very dangerous volcano, due to its highly explosive characteristics and the high concentration of people (about 600,000) living in the area.

2.1 2002 Levelling Survey

The last survey was carried out, along the network of Fig. 2, during the period June-July 2002. The benchmark used as reference is Castellammare di Stabia (Bagni di Pozzano), on the mesozoic limestone of the Sorrento Peninsula (Fig. 1). The analysis of the misclosures of the loops checked the coherence of the data; in fact, the absolute values of the misclosures range from 0.1 to 9.8 mm are all below the tolerance calculated from the formula $\pm 2\sqrt{(L_{km})}$ mm, where L is the length (in km) of the circuit. The results of the least squares adjustment of the data gave a maximum residual amounting to 0.8 mm and a standard deviation per unit weight of 1.1 mm., showing the good quality of data.

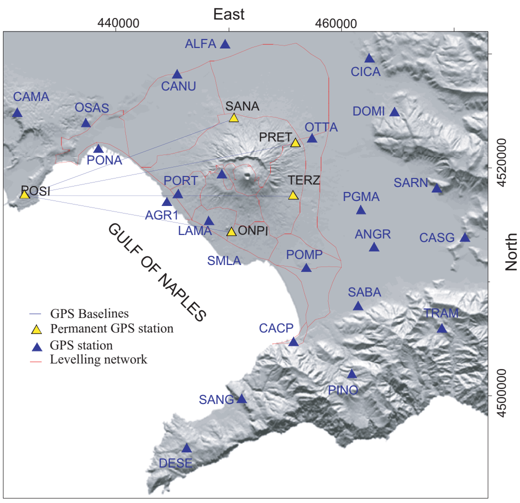

Fig. 2- GPS and levelling networks operating at the Vesuvius area.

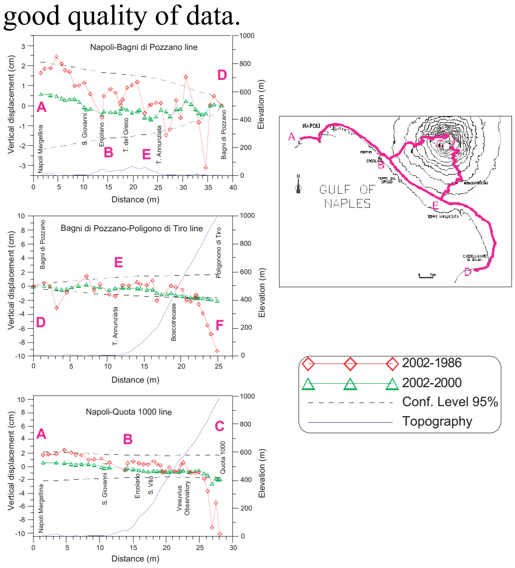

Fig. 3- Vertical displacements calculated on some circuits of the Vesuvius levelling network in the period 1986-2002. The location of lines is also reported.

Fig. 3 shows examples of vertical displacements at the benchmarks belonging to three more significant lines of the Vesuvius network, using data collected in 1986, 2000 and 2002.
These figures show that no statistically significant vertical displacements occurred in the period 2000-2002, except at the crater area, where subsidence occurs at a rate of about 0.7 cm/year.

2.2 Continuous GPS

Presently, Vesuvius CGPS network consists of 4 stations (Fig. 2) connected to reference vertex POSI located in Naples (Fig. 2). The CGPS acquisition system may be considered reliable. In fact, the signal analysis demonstrated a good quality during the whole period examined, considering the amount of data recorded with respect to those expected, the low middle values of the L1 and L2 Multipath residuals and the low number of cycle-slips occurred.
Fig. 4 shows an example of the temporal trend for the POSI-ONPI and POSI-SANA baselines. The general trend doesn't show significant variations related to the volcano dynamics. Some regularities at low frequency are clear, most likely bound up with local factors (as example, thermo-elastic effects) and tropospheric effects.

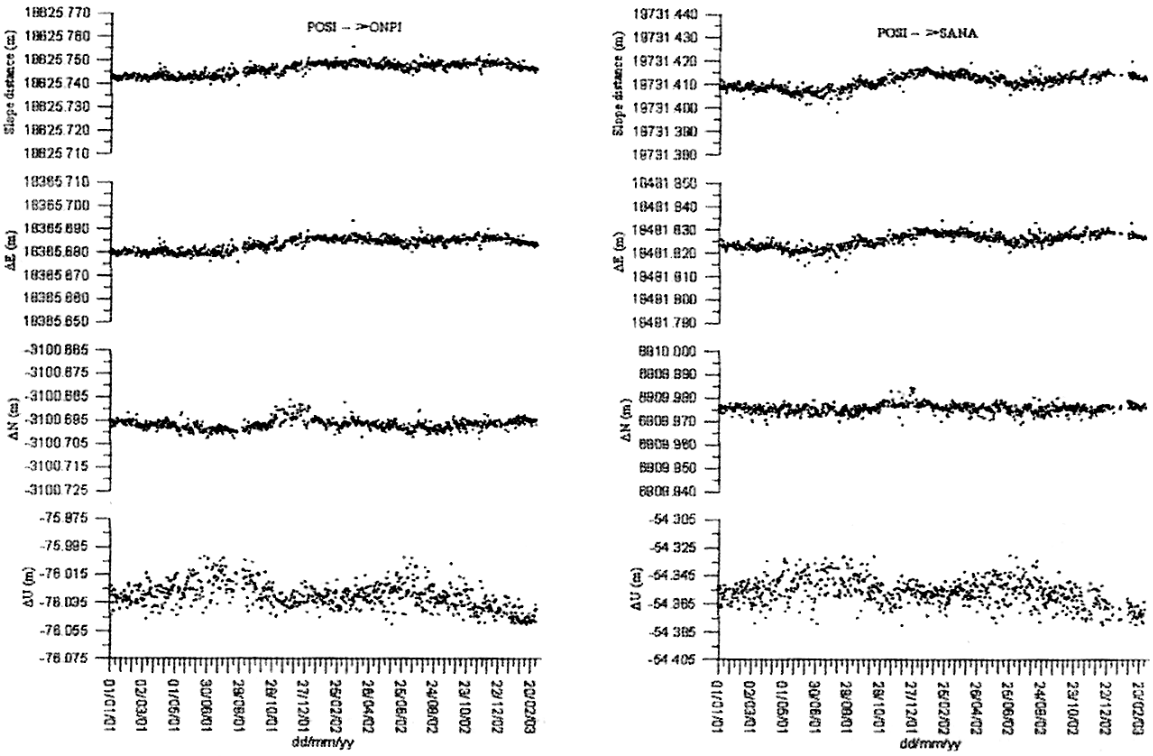

Fig. 4- An example of temporal variations for two baseline located on Mount Vesuvius

2.3 October 1999 event

Starting from October 1999, Vesuvius area was interested by an increase of seismic activity, giving rise to the larger earthquake ever occurred in the last 60 years, on 9 October 1999 (Md=3.6), located at Vesuvius crater area. Therefore, it was decided to monitor the southern flank of the volcano, considered of greater risk. So, a GPS and a levelling surveys were executed and three new permanent GPS stations were installed in addition to the only one operating in the area at that time. The GPS survey was carried out on the 15 GPS vertices, measured also during June 1998, and reported in fig. 2, and 37 independent baselines were calculated with slope distances between 4 and 12 km. A comparison between the length of the same baselines for the 1998 and 1999 surveys represents a simple and effective method in order to verify meant movements in the area. The variations in slope distance of the baselines were lower than one centimetre, in module; only three common baselines to the two surveys showed a decrease of 1 and 2 cm.

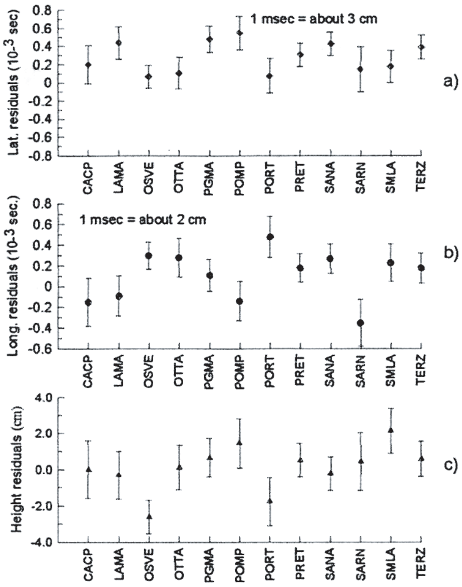

Fig. 5- Results of the GPS survey carried out in October 1999. with respect to the 1998 survey.

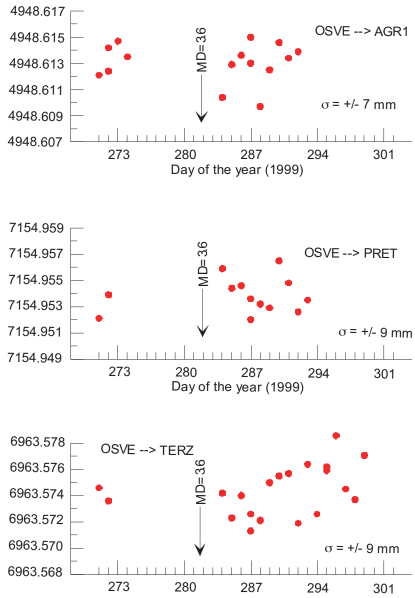

Fig. 6- Variation of the lengths for three baseline measured before and after the earthquake.

The data collected in 1998 and 1999 have been compared, considering as fixed vertices DOMI, CASG and PINO, on the basis of the stability characteristics, relatively vesuvian volcanic area, of the carbonate rocks on which those vertices are materialized.
In fig. 5 the values of residuals in latitude, longitude and height are represented.
The trend confirmed the slow dynamic of the area; infact, the calculated movements are mostly inferior to the centimeter and however with low significance, highlighting that no meaningful modification has happened through that period examined.
Since February 1998 one small net of permanent GPS stations, constituted from four vertices (OSVE, PRET, AGRA and TERZ), were operating in the vesuvian area. From the beginning, remarkable and variable e.m. interferences turned out masking and reducing drastically the quality of records. Such interference on signals increased in the time until, at beginning of the 1999, it was necessary turned off three stations because lack of signal. Just after the earthquake of 9 October 1999, three GPS receivers of new type were installed on OSVE, PRET and AGR1 vertices. These instrumentations were equipped with new technology that guarantees better signal/noise ratio, high resistance to radio interferences and reduces the effects caused by Multipath.
In Fig.6 the time variations of the baselines OSVE-AGR1, OSVE-PRET, OSVE-TERZ are shown, using available data before and after the earthquake of 9 October 1999. Diagrams evidence that no meaningful modification of the lengths of the baselines in observation has happened through the period.
In January 1999, a levelling survey was performed on vesuvian network; the collected data have evidenced no statistically significant movements in 1997-1999 period. Cumulative curves 1986-1999 confirmed the slow subsidence phenomena in the same restricted zones evidenced also in 2002 (fig. 3). The beginning of seismic crisis in October 1999 has pressed to carry out an extraordinary survey on a part of the levelling network, linking the survey to the same reference benchmark (Fig. 1) located in Castellammare di Stabia (Bagni di Pozzano). The lines surveyed are shown in fig. 7; the “Checking loop” has a total length of about 35 km, characterized by an altimetric profile from 30 meters a.s.l. to nearly 1000 meters a.s.l.. The misclosure amounted to -7.64 mm, that is a very satisfactory value for such type of measures.

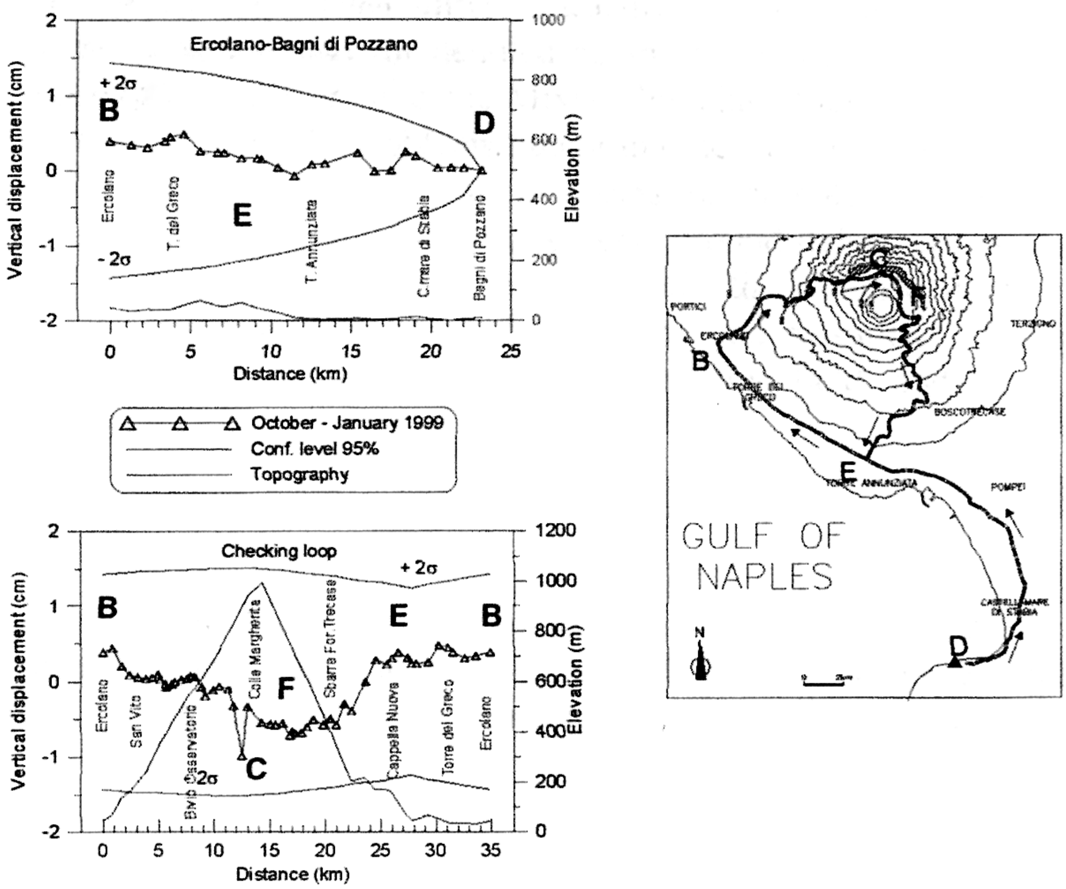

Fig. 7- Vertical displacements calculated on the lines chosen after the October 1999 earthquake, referred to January 1999 data. The location of lines are also reported.

The coast line Ercolano- Bagni di Pozzano extend for a total length of approximately 23 km with a lower gradient of the road. The kilometric r.s.m. has turned out equal to ±0.64 mm/√km., coherent with the instrumentation and the used procedures. The results of the least squares adjustment of the data have yielded a maximum residual amounting to 0.3 mm and a standard deviation per unit of weight is 1.3 mm., showing the good quality of the data. In Fig. 7 the vertical displacements (referred to January 1999) of the benchmarks surveyed after seismic event are shown. It's evident that no statistically meaningful vertical movements occurred, during the 10 months elapsed between the two surveys, confirming the low deformative level already evidenced from previous surveys.

3. Campi Flegrei.

The Campi Flegrei District (Naples - Italy) includes the volcanic areas of the Campi Flegrei and the islands of Ischia and Procida. The Campi Flegrei are characterized from a caldera 35,000 years old (eruption Campanian Ignimbrite) by which numerous volcanic monogenic apparatus developed inside. The last eruption of this caldera rose again in 1538 and carried to the origin of Mount Nuovo. From the geological point of view, the caldera is mainly formed by volcanic rocks and subordinately by clastic sea sediments; from the structural point of view, the configuration of Campi Flegrei is the result of deformations related to the regional and volcano-tectonic events. The regional tectonic is the cause of direct faults with NE-SW and NW-SE direction and subordinately with NS direction. The magmatic chamber is located at low depth (about 4-5 Km). The dynamics of this volcanic field was characterized by slow and continuous vertical movements as well known as *Bradyseism*. During 1969-72 (maximum uplift 170 cm) and 1982-84 (maximum uplift 184 cm) this area has been interested by two intense episodes with strong uplift of the ground and moderate seismic energy activity. Both the episodes were followed from a phase of subsidence interrupted by modest phenomena of uplifts, the last of which pointed out during the period March-September 2000 (maximum uplift about 4 cm). Even though the two main uplift crises are not culminated into an eruption, it is fundamental considering that these events caused significant damages to the buildings and to the economy of the Campi Flegrei, which has 250,000 inhabitants.

Recently, Beauduçel et al. (2002) have carried out a three-dimensional modelling of the ground deformation pattern observed during uplift episodes at Campi Flegrei, using the caldera-bounding discontinuities. The vertical displacement data of the 1982-1984 unrest, measured by levelling have been inverted for location and overpressure of magma chamber, and for detailed geometry of collapse structures (ring fault dip, fault depth and width). For modelling, has been used the Mixed Boundary Elements Method (MBEM) (*Cayol and Cornet*, 1997), which allows to solve 3-D problems taking into account topography, free surface and medium discontinuities (fractures) structures, without the problems of complex meshing of the finite elements methods. In that paper, it is evidenced that, when interpreting ground deformations at calderas, the structural features of the area must be carefully considered. In particular, the collapse structures play a fundamental role during unrest episodes, affecting both static deformation and seismicity. The presence of faults and fractures at volcanoes may strongly affect the ground deformation field, and must be taken into account when modelling unrest episodes.

3.1 2002 Levelling survey

Starting from 1969, Campi Flegrei was interested by two main uplift phases and others minor occurred in 1989, 1994 and, more recently, since March to September 2000 (Fig. 8). At present, the volcanic area records a slow subsidence phase. The last survey was carried out on Campi Flegrei network (Fig. 9) in the period June-July.

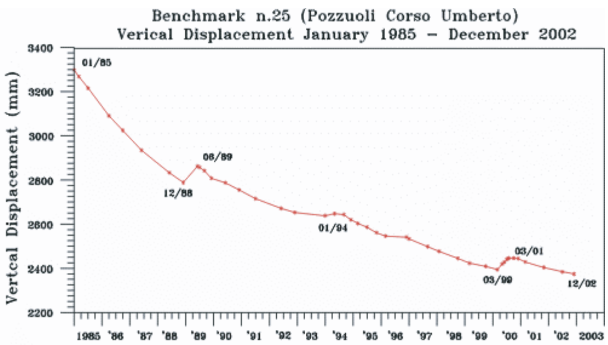

Fig. 8- Vertical displacements vs time at benchmark 25, located near to maximum uplift area, during the period 1985-2002.

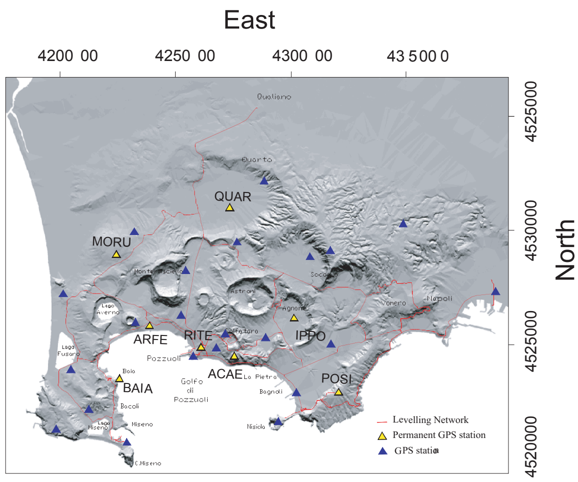

Fig. 9- GPS and levelling networks operating on Campi Flegrei.

The measurements have been submitted to the least squares adjustment, resulting a value of the standard deviation per unit of weight of 0.91 mm. The Fig. 10 shows the deformation trend from March 1999 to July 2002 with the altimetric profiles. The vertical displacements of the benchmarks belonging to the most significant lines E-W and S-W are shown. On the left, vertical displacements (referred to 1999) along the E-W line. On the right, vertical displacements (referred to 1999) along the N-S line; the dotted lines represent the limits of the confidence interval at 95% for the series of compared data.

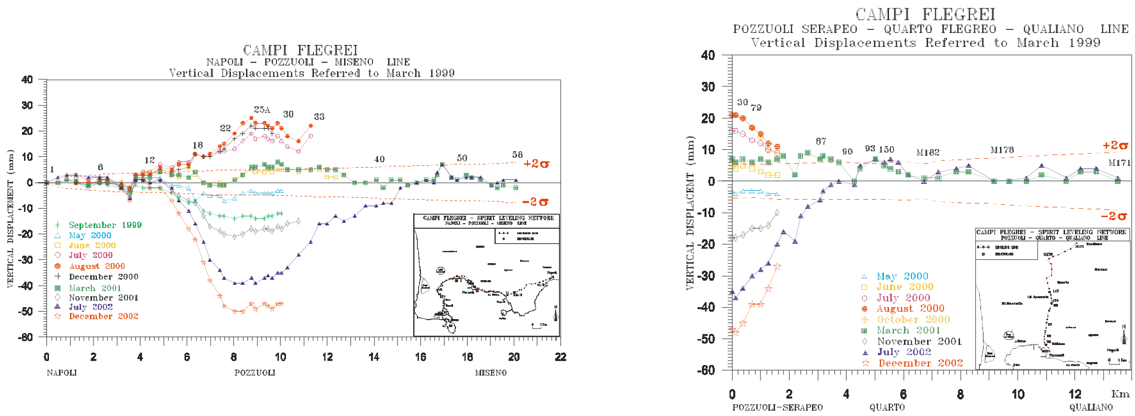

Fig. 10- Vertical displacements at Campi Flegrei, along the E-W line (on the left) and N-S line (on the right) as referred to 1999 survey.

3.2 GPS Surveys and Continuous GPS

The Campi Flegrei GPS network (Fig. 9) was materialized in 1997; it consists of 35 3D vertices, eight of which used as permanent stations.

The geometry of Campi Flegrei network was studied in order to monitor the principal geological structures allowing to estimate with high accuracy the deformation field acting in the area. The vertices configuration of the whole network, planned for the monitoring of relative displacements of the active structures inside the area, defines three main NS lines and two main EW lines.

Three surveys were carried out the period 1998-2000 and the analysis of the collected data have shown no significant variations in the volcano dynamic.

CGPS network (Fig. 9) consists of seven permanent stations connected to POSI vertex, chosen as reference. The fig. 11 shows, as example, the time evolution of the components of the baselines POSI-BAIA; POSI-ACAE; POSI-RITE.

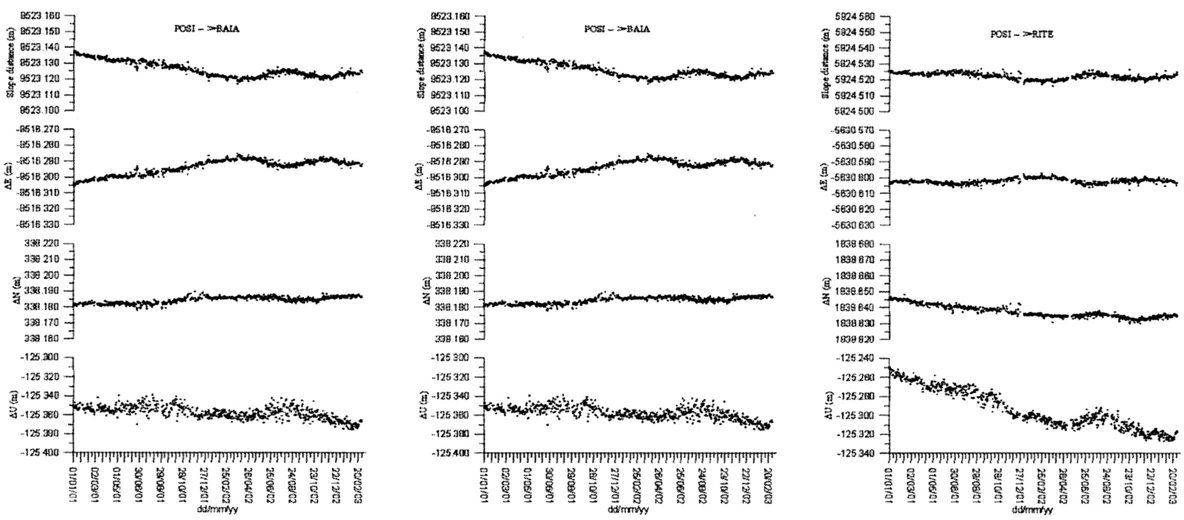

Fig. 11- An example of temporal variations for three baseline located in Campi Flegrei area

3.3 2000 Uplift episode

The potentialities of the geodetic networks operating at present in the Campi Flegrei have been demonstrated during a recent uplift episode, which took place starting from March, 2000.

Levelling data from four different measurements of September 1999, May, June and July 2000, pointed out an uplift phase with maximum vertical displacement amount to 3.5 ±0.5 cm, respect to March 1999.

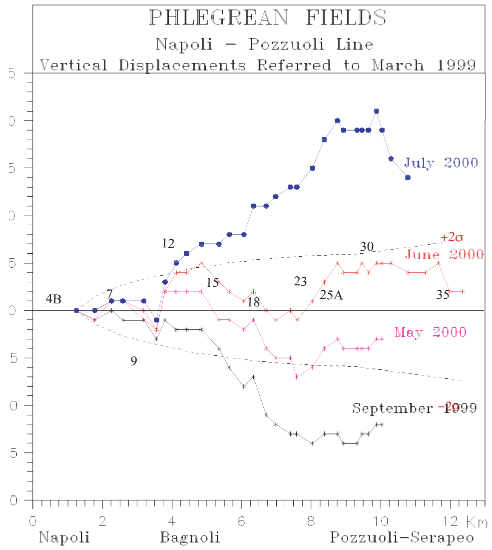

Fig. 12- Vertical displacements calculated during 2000 at Campi Flegrei, along the E-W line, as referred to March 1999 survey.

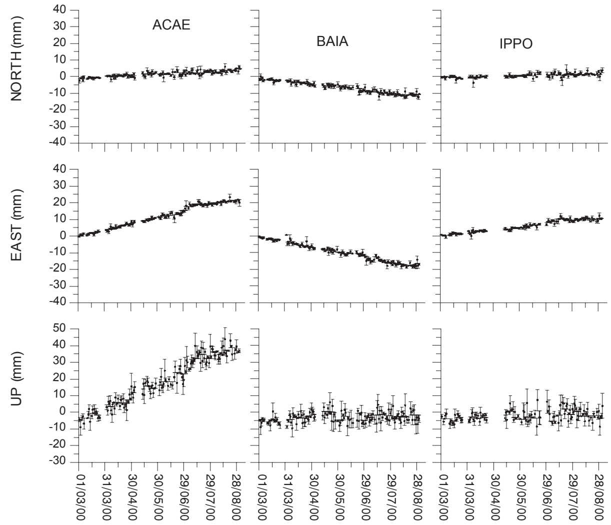

Fig. 13- Time variations of components for three baseline located in Campi Flegrei area, during the 2000 uplift episode

During the second half of July 2000, the results of a further measurement did not point out significant variations if compared to the previous ones.

During the period March-September 2000, the time series of Continuous GPS Stations show significant variations of ACAE, BAIA and IPPO sites referred to QUAR. The error bar indicates the r.m.s. error in daily coordinate solutions. We remark that during the inflation period, the ACAE station, located close the maximum deformation area, had an horizontal displacement of about 2 cm. toward ENE and an uplift of about 4 cm.. Also, BAIA and IPPO show a significant planimetric displacements, respectively of about 2cm. in WSW direction and about 1 cm. in ENE direction.

4. Ischia Island

The island of Ischia is located in the West of the Gulf of Naples and is mainly formed by volcanic rocks, by landslide deposits of different type and subordinately by sea sediments. Also, the structural setting of the island of Ischia has been determined by deformations induced both by the regional tectonics and by the 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 system still active and potentially able to give future eruptions is testified, besides by the last eruptive event occurred in 1302 (the Arso eruption), also by an intense fumaroles activity, by vertical ground displacements and by low seismic activity.

4.1 2001 Levelling survey

Since about 20 years, Osservatorio Vesuviano carried out levelling surveys in Ischia Island. Such measurements have allowed to evaluate the temporal trend of the deformation field acting in the island, which results extremely complex. The last levelling measurements along the whole network (fig. 14) have been carried out in July 2001. The measurements have been submitted to the least squares adjustment, with a final value of the standard deviation per unit of weight of 1.6 mm.

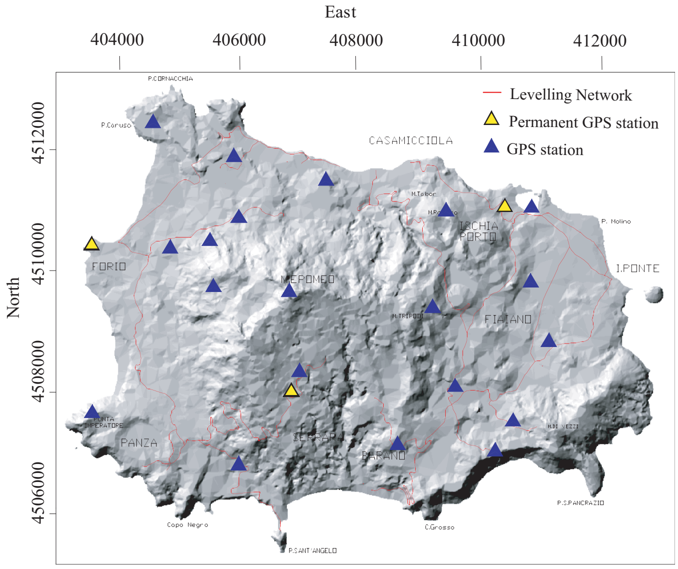

Fig. 14- GPS and levelling networks operating on Ischia Island

The figures 15 show most remarkable results obtained during the 1990-2001 period. Movements interesting the NW and the S sectors of the island are shown in figures. The maximum value of ground subsidence is -13.7 cm (Fango area), with a subsidence rate of about -1.25 cm/year. In NW sector, the subsidence may be due to a gravitational movement of the incoherent layer covering the volcano-tectonic structure of Mt. Epomeo green tuff.

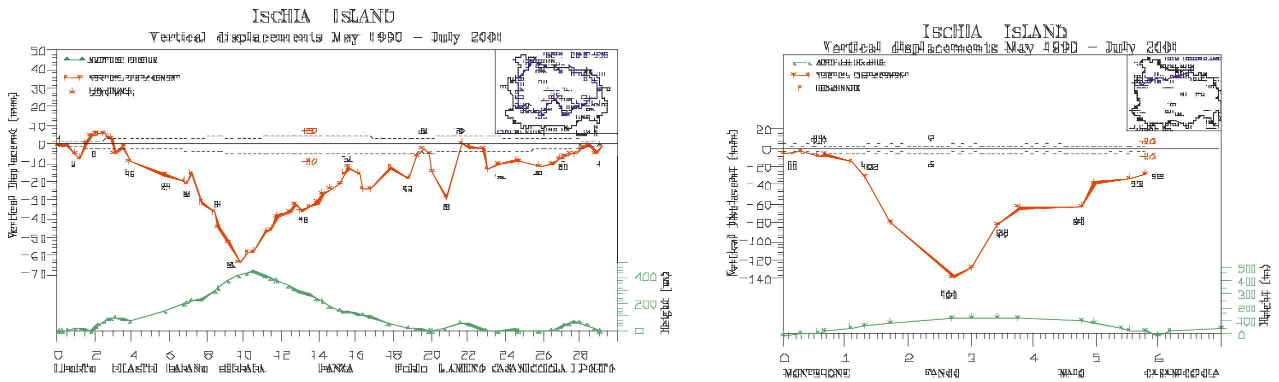

Fig. 15- Vertical displacements measured on Ischia island during the period 1990-2001. The dot lines represents the 95% confidence level.

4.2 *GPS Surveys and Continuous GPS*

The GPS network operating on Ischia Island consists of 25 vertices homogeneously distributed on the island. Three different GPS surveys of the whole network were carried out since 1997. In addition, two new GPS vertices in Forio d'Ischia were installed to define local effects of a probable creep in NW sector. From the comparison between the 1999 and 2001 GPS survey results (Fig. 16) that some GPS points present significant horizontal shifts, confirming slow deformations of Southern and NW sectors of the island.

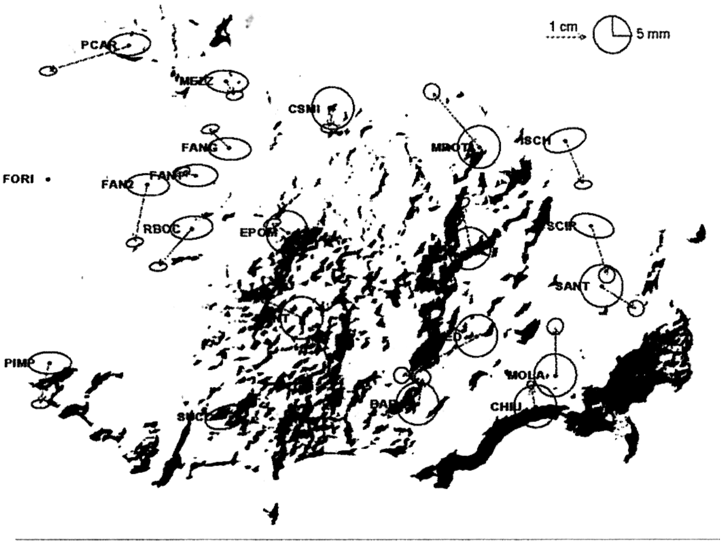

Fig. 16- Horizontal shift calculated for GPS stations in the period 1999-2001.

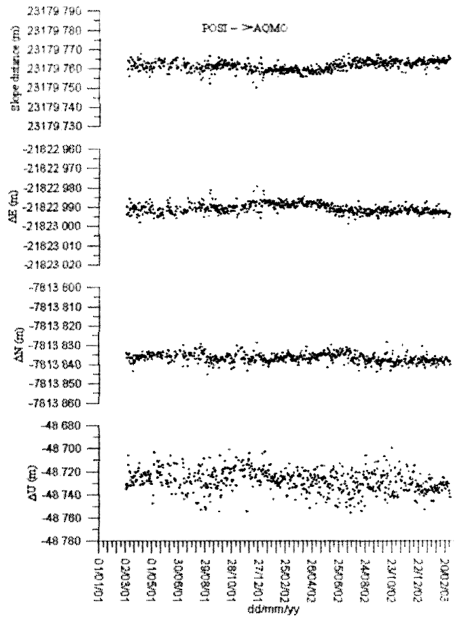

Fig. 17-An example of temporal variations for one baseline located in Ischia island.

CGPS network operating on Ischia island (Fig. 14) consists of three permanent stations connected to POSI vertex, chosen as reference. The time evolution of the components of the baselines POSI-IPPO only is represented (Fig. 16), because the other are similar.

5. Conclusions

The main results about monitoring of neapolitan volcanic area by using levelling and GPS 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 three volcanic structures 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.

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