Current geodetic deformation of the Colli Albani volcano: a review

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Abstract

The quiescent Colli Albano volcano is presently characterised by moderate intensity earthquakes, seismic swarms, gas emissions and ongoing uplift that reflects the current evidences of its residual activity. An uplift of ~30 cm over the last 43 years was recently detected by levelling surveys performed in the time span 1950-1993 along a levelling line that crosses the highest elevation area of the western flank of the volcano. Space based GPS and Synthetic Aperture Radar Interferometry geodetic observations confirm that this uplift is distributed in a wide area around the craters of Albano and Nemi, where the most recent volcanic activity occurred. GPS data from continuous monitoring stations indicate that both horizontal and vertical deformations do occur and that can be addressed to a shallow magmatic source. All the geodetic observations are in agreement and highlight that the Colli Albani is still a potentially active volcano. Being located in a densely populated area close to Rome, the volcano should deserve the same monitoring and hazard assessment effort of any active volcano within urbanized areas. Here we review the geodetic results obtained during the last decades for the Colli Albani volcano.

Introduction

Surface deformation detection of volcanoes is traditionally performed through repeated geodetic surveys over control networks. Geodetic data from these networks play an important role to determine the occurrence of magma injection and to forecast volcanic eruptions. Triangulation, levelling and tilt measurements were the first techniques used over tailor made networks established on several active volcanoes of the world since the end of the 19th century. They provided the former valuable data for the detection of long and short term surface deformations of volcanoes (e.g. Dvorak 1995; Dvorak & Dzurisin 1997; Bonaccorso *et al.* 1995; Fernandez *et al.* 1999; Battaglia *et al.* 2003a,b). Since the end of 1980s, the satellites of the Global Positioning System (GPS) become the primary tool for a space based geodetic monitoring of volcanoes, so that measurement campaigns are now carried out at different epochs, or alternatively are operated using a network of permanent stations (Anzidei *et al.* 1998; Battaglia *et al.* 2003a,b; Puglisi & Bonforte 2004; Janssen 2007; Troise *et al.* 2007). This technique has nearly completely substituted the conventional terrestrial optical and tilt measurements, due to the low costs, independence from weather and time (i.e. measures can be done with any atmospheric condition and during day and night), user friendly receivers, data reduction software availability and for the high accuracy (at mm level) with which it is possible to estimate the 3-D positions of geodetic benchmarks. After statistical and strain analysis, the geodetic results can be correlated or combined with volcanological and geophysical data thus providing a crucial contribution to mitigate the volcanic risk in dangerous areas, such as the case of cities on volcanoes (Anzidei *et al.* 1995). Recently, the combination of punctual and spatial measurements from GPS and Synthetic Aperture Radar (SAR) satellite sensors, respectively, even if taken at different times (continuous or discrete GPS measurements and 35 days repeat cycle of the ERS satellites) have become a powerful tool to obtain spatial deformation rates and trends of volcanoes. The SAR signal processing technique, referred to as SAR Interferometry (InSAR), is now widely used in Earth's sciences demonstrating to have unique capabilities for mapping the topography and the deformation of the Earth surface. The InSAR approach is based on extracting the phase component of SAR data to compute the pixel-by-pixel difference of SAR signal relative to a specific area and acquired from nearby geometric conditions. The interferogram, i.e. the result of the interferometric processing, contains the measurement of the sensor to target distance and of any possible changed distance.

Since early 1990s the capabilities of InSAR technique have been exploited to study the surface displacements as effects of volcanic and seismic activities (Massonnet *et al.* 1995; Amelung *et al.* 2000; Salvi *et al.* 2004). More generally InSAR demonstrated its capability to provide an accurate measure of surface deformations from space, being operative with every atmospheric condition, during day and night. Furthermore, the wide coverage of each image, the global coverage, the repetitiveness of the observations allow considering InSAR a valuable tool for the monitoring of volcanic areas during pre-crisis and syn-eruptive phases.

During the last decades, systematically repeated surveys of terrestrial GPS networks and SAR observations have been carried out in most of the Italian active volcanoes, such as Etna (Bonforte *et al.* 2009), Phlaegrean Fields (Dvorak 1991), and in the volcanic arc of the Aeolian islands (Bonaccorso *et al.* 2002; Esposito *et al.* 2007; Bonforte & Guglielmino 2008; Esposito *et al.* 2009). Recently, also the Colli Albani volcano has been studied using seismological, geodetic, and geochemical data (Amato & Chiarabba 1995; Chiarabba *et al.* 1997; Chiodini & Frondini 2001; Beaubien *et al.* 2003; Carapezza *et al.* 2003; Carapezza *et al.* 2005a; Carapezza & Tarchini 2007; Chiarabba *et al.* 2010, this volume; Carapezza *et al.* 2010, this volume; Riguzzi *et al.* 2009). Results are in agreement to indicate that this volcano, which is currently affected by an ongoing uplift, by periodic seismic swarms and by a huge release of gas of magmatic origin, is a potentially active volcano. Here we review and discuss the recent geodetic results obtained in the Colli Albani volcano, located in a densely populated area close to Rome.

Levelling surveys

The levelling route no. 24 was set up in 1950 by the Italian Istituto Geografico Militare (IGM) (Fig.1) along the S.S. Appia (Appian Way). It crosses the whole Colli Albano volcano from North West near Rome to South East toward Cisterna di Latina. Both ends of the levelling route are located outside the volcanic edifice. The first survey was carried out in 1950/51 by the IGM and repeated in 1997 and 1999. The present configuration of the levelling line consists of 120 benchmarks with a linear span of about 80 km, running along a SE-NW profile (Cisterna di Latina-Roma) and including two circuits bordering the Albano and Nemi lakes (Fig.1). The most recent survey was performed during October 2006 by optical auto-levelling and one electronic level equipped with micrometers and invar rod stadia, following the classical measurements procedures. As usual, the observations (heights differences between benchmarks) were adjusted to obtain height and errors, keeping fixed the height of a reference benchmark. The reference benchmark was chosen on the basis of the deformation history of the line looking for a site far from the zone with the highest deformations common to the four main surveys of 1950-1951, 1997-1999, 2002 and 2006. The benchmark is IGM 24/141C (Cisterna di Latina) and its elevation (65.4836 m a.s.l.) was selected as the reference elevation. The comparison between the 1950-1999 surveys has evidenced a remarkable uplift, whereas the subsequent surveys (1997-1999 and 2002) have not shown significant uplift at a confidence level of 95% (Fig.2a). In the last period, from 2002 to 2006, a small uplift is detected along the line and the Albano lake circuit, even if within the confidence interval (Fig.2b). The circuit around the Nemi lake was set up and surveyed only once in 2006 (Fig.1).

In conclusion, the results obtained by the levelling surveys seems to indicate a pulsating inflation behaviour, so a longer and more continuous dataset, along with comparison with data from other measurement techniques are needed to reliably infer the deformation pattern and to model the source.

GPS data

To extend the monitoring of the Colli Albani, in 1995 a discrete GPS network consisting of 10 benchmarks was set up and repeatedly surveyed (Fig.1). The first results from this network were not highly significant, and only some minor horizontal deformations were detected (Anzidei *et al.* 1998). Since such network was not properly designed to detect vertical motion, due to the reduced accuracy of the GPS technique along this component, in 2006 three continuous GPS stations were installed as test sites to improve the detection of the vertical motion (Riguzzi *et al.* 2009) (Fig.1). Compared to non-permanent networks, a continuous monitoring highly improves the accuracy of site velocity estimations by the analysis of long time series of GPS observations (Betti *et al.* 1999; Devoti *et al.* 2008). Moreover, the recent development of the RING GPS permanent networks in Italy (Selvaggi 2006) provides the necessary constraints to anchor the velocity field of this local network to the ITRF2005 reference system (Altamimi *et al.* 2007), to refer local motions in a regional tectonic frame.

The three permanent GPS stations of the Colli Albani network are located at Astronomical Observatory of Monteporzio Catone (RMPO); at the INGV Observatory of Rocca di Papa (RDPI), and at the Padri Verbiti monastery of Nemi (NEMI). The first one (RMPO) is located on the external edge of the Colli Albani caldera, RDPI on the smaller caldera at the top of the Faete intracaldera stratovolcano, and NEMI on the edge of the recent Nemi maar (Fig.1).

The monument of RMPO is a reinforced concrete pillar equipped with a stainless steel rod on which the GPS antenna is screwed on. RDPI and NEMI are placed on reinforced concrete buildings and the antenna mount consists in a short steel pillar (0.65 m height) screwed on a stainless steel benchmark permanently and deeply fixed to the top of the building. The antenna is screwed on the top of the steel pillar in horizontal position through 2 spherical spirit bubbles and 3 horizontal screws. Such monument preserves the horizontal and vertical datum if the antenna has to be changed for maintenance. RMPO and RDPI are equipped with LEICA GRX1200PRO receivers and LEIAT504 choke-ring antennas (RMPO with radome LEIS). NEMI is equipped with a TRIMBLE 5700 receiver and a Zephyr Geodetic antenna TRM41249.00. The data analysis of the GPS observations are performed in the framework of the processing of all the Italian CGPS stations (Riguzzi *et al.* 2009), focusing on those stations located in the near field of the Colli Albano volcano (INGR, ROMA and MOSE). As NEMI, RDPI and RMPO started to work in the middle of 2006, data processing covers a time span of ~2.5 years.

The data analysis was performed by the *Bernese Processing Engine* (BPE) of the Bernese 5.0 software (Beutler *et al.* 2007), using the phase double differences as observables. The IGS precise orbits and Earth's orientation parameters were kept fixed and the absolute elevation-dependent phase center corrections, provided by IGS, were applied. Each daily solution was estimated in a *loosely constrained* reference frame, close to the rank deficiency condition. Each *loosely constrained* solution was realized in an intrinsic reference frame, defined by the observations itself, differing from day to day only for rigid network translations, keeping the site inter-distances always well determined. The constraints for the realization of the chosen reference frame were imposed only *a posteriori*. The daily *loosely constrained* cluster solutions were then merged into global daily *loosely constrained* solutions of the whole network applying a classical least squares approach (Bianco *et al.* 2003).

The velocity field was estimated by fitting the *loosely constrained* time series of daily coordinates with the complete covariance matrix, obtaining a *loosely constrained* velocity solution. Site velocities, together with annual signals and sporadic offsets at epochs of instrumental changes, were simultaneously estimated. The Eurasian fixed representation highlights a different trend between the horizontal velocities of the Colli Albani sites (NE trending) with respect to those located in Rome (NW tending), about 20 km away. The three sites INGR, M0SE and ROMA have a coherent motion with the GPS velocities of sites located along the Tyrrhenian belt (Devoti *et al.* 2008). The different behaviour of the Colli Albani with respect to the Tyrrhenian sites is better evidenced showing their residual velocities with respect to the NGR, M0SE and ROMA sites (Fig. 3). The continuous GPS observations have allowed to estimate, for the first time with this technique, the possible source of deformations. To model the source, the velocities of the Colli Albani sites were referred to the nearest sites external to the volcano edifice (INGR, M0SE and ROMA), to remove any regional pattern from the data. The simplest model able to fit the low number of available observations (14 measurements from 6 GPS stations, 4 rejected due to local effects) is a point-pressure source (Mogi 1958). The source parameters were retrieved by a non-linear inversion based on the Levenberg–Marquardt (LM) least squares approach. This LM algorithm is one of the most efficient and widely used optimization algorithm consisting in a combination of a gradient descent and Gauss-Newton iteration (Levenberg, 1944; Marquardt, 1963). The non-linear inversion sets the point-source at a depth of about 4.7 km, on the western flank of the Colli Albani complex (Fig. 3). Such results are in a good agreement with those from Salvi *et al.* (2004), where a prolate ellipsoid double source is used to model DInSAR data. In terms of volume, the best-fit solution corresponds to an increase of

$1.14 \times 10^6\ m^3$/year. The observed and modelled GPS rates are reported in Table 1, while in Table 2 the comparison between modelling parameters of Mogi source is shown.

Till now, GPS data confirm the uplift trend evidenced by leveling survey and PS-InSar. Plotting the uplift rate of each GPS site against the distance between the site itself and the center of the estimated Mogi source shown in Fig. 3, a significant clear decrease is evidenced. The modeled and the GPS uplift trends well agree within the errors, even if the predicted rates appear underestimated with respect to those obtained from GPS surveys (Fig. 4).

PSInSAR observation and data analysis

Recent remote sensing observation of the current deformation of the Colli Albani volcano were performed through the Permanent Scatterers (PS) InSAR technique. The PSInSAR technique is a methodological development of the classical Differential SAR Interferometry, which allows retrieving ground displacement velocity map (of the order of mm per year) thanks to its capability to improve the SAR measurement accuracy (Ferretti *et al.* 2001). PSInSAR focuses on natural targets which have a good stability in term of backscattered signal in all the images of the dataset (the so called Permanent Scatterers, hereinafter PS) and these are considered for the calculation of the phase differences between acquisitions. The tropospheric bias to the phase signal cannot be neglected, hence it has to be estimated and removed. For this purpose a specific algorithm is applied.

The most recent SAR dataset used to study the Colli Albani area is composed by ERS1 and ERS2 images, for a total of 66 SAR descending acquisitions available from June 1992 to December 2000, whilst 34 images from April 1993 until November 2000 concern the ascending dataset (Salvi *et al.* 2004). More than 240000 and 280000 PS with a coherence greater than 0.7 were identified on the descending and ascending subsets respectively. PS velocities estimated along the line of sight (LOS) for both subsets, are shown in Fig. 5. In general, the pattern of the velocity field is rather clear but for a better understanding of the deformation activity, the ascending and descending velocity maps are combined in order to extract the vertical and the horizontal components of the deformation field. In Fig. 6 are reported the resulting maps. It is worth noting that these maps show a less dense PS distribution because only the common PS within ascending and descending velocity maps can be combined. Moreover, the reported maps are re-sampled to a spatial grid of 200 m x 200 m per pixel.

An uplift zone, mainly located on the west part of the Colli Albani caldera complex is clearly evident. A maximum of about 2.5 mm/yr is measured by the PS close to the villages of Ariccia and Albano (Salvi *et al.* 2004).

The validation of the PS velocity map has been carried out through independent ground data. GPS measurements and optical levelling have been considered for this purpose (Fig. 1), consequently the ten GPS benchmarks of the Colli Albani network (Anzidei *et al.* 1998) surveyed in the time span 1995-1998 were used (Salvi *et al.* 2004). Unfortunately, the only three monuments which show significant velocity estimates fall in areas with no PS. The other sites do not show significant deformation with the exception for the period 1995-96, when 2 cm subsidence had been measured at INGR, CVA and VVR (probably due to shallow earthquakes in 1995). Moreover, continuous GPS data from 2000 to 2003 at the INGR station show the absence of local horizontal velocity components and a negative vertical velocity of about 1 mm/y. The ING site, located about 20 km from the uplift centre, has been selected as reference point, and the PS velocities are rescaled with respect to it.

The vertical PS ground velocities were compared with the average vertical velocities derived from the levelling technique along the IGM line (Fig. 1). The ground velocity is extracted considering a constant ground displacement rate resulting from the 1951–1997 IGM height differences. Ten levelling benchmarks have been considered and the PS ground velocity was averaged within a circular radius of 200 m from each benchmark. Fig. 7 reports the 10 selected benchmarks and in Fig. 8 the ground velocity related to levelling and InSAR processing are reported in the upper and lower panels, respectively. Despite some differences in the absolute values, the general trend of both curves is in agreement and the maximum uplift is detected close to Albano and Ariccia villages. The PS ascending and descending velocities, and hence the vertical velocity, represent the average displacement in the time interval between 1992 and 2000. Taking into account such consideration, the different amount of average displacements between InSAR and levelling, could be interpreted as due to a slowing phase of the deformation phenomenon.

Conclusions

Geodetic data from levelling surveys, GPS stations and InSAR observations have been analyzed during the last decades to measure the current deformation of the Colli Albani volcanic area. The analysis of about 2.5 years of GPS observations has evidenced a peculiar velocity pattern of the Colli Albani stations with respect to those located nearby, but outside the volcano edifice. With respect to Eurasia, the horizontal velocities are NE directed with magnitudes of 2.2±1.4mm/year (RDPI), 3.0±0.8mm/year (RMPO) and 3.3±1.2mm/year (NEMI). The uplift rates are determined with minor accuracy and range from 3.3 and 6.0 mm/year. All data sets are in agreement and indicate that this volcano shows active deformations with uplift rates within 6 mm/year. These are mainly located in a well defined area that includes the surroundings of the Albano and Nemi lakes and the main villages of Marino, Albano and Ariccia, the area of the most recent volcanic activity

(Funiciello *et al.* 2003; Giordano *et al.* 2006; Freda *et al.* 2006; De Benedetti *et al.* 2008). Although this point is a still debated matter, there exist some evidences that last eruptions may have occurred during historical times in this area (Andretta & Voltaggio 1988). Moreover gas emissions sources affects this part of the volcano (Funiciello *et al.* 2002; Carapezza *et al*, 2010a; Carapezza *et al.* 2010b) and recent studies suggest that the Albano lake has undergone significant Holocene level changes and overflows, possibly related to lake rollovers triggered by injections of hot and CO_2 rich fluids at the base of the lake (Funiciello *et al.* 2003; Anzidei *et al.* 2008).

The source of deformation based on GPS data was estimated as point-pressure source (Mogi 1958). Modelling results set the point-source at a depth of about 4.6 km beneath the western flank of the volcano, leading to a volume variation of $3.6 \times 10^{-4} m^3$/year. These data are in agreement with PS-InSAR data but rather different from levelling surveys.

Several decades of geodetic observations suggests that the Colli Albani volcano deserves the same monitoring and hazard assessment effort of any active volcano, especially when its location is within an urbanized area. Due to its potential hazard, this area should be systematically studied in order to timely recognize significant surface deformations related with the structure of the volcano or possibly to a non-linear trend of the shallow hydrothermal system.

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Figures

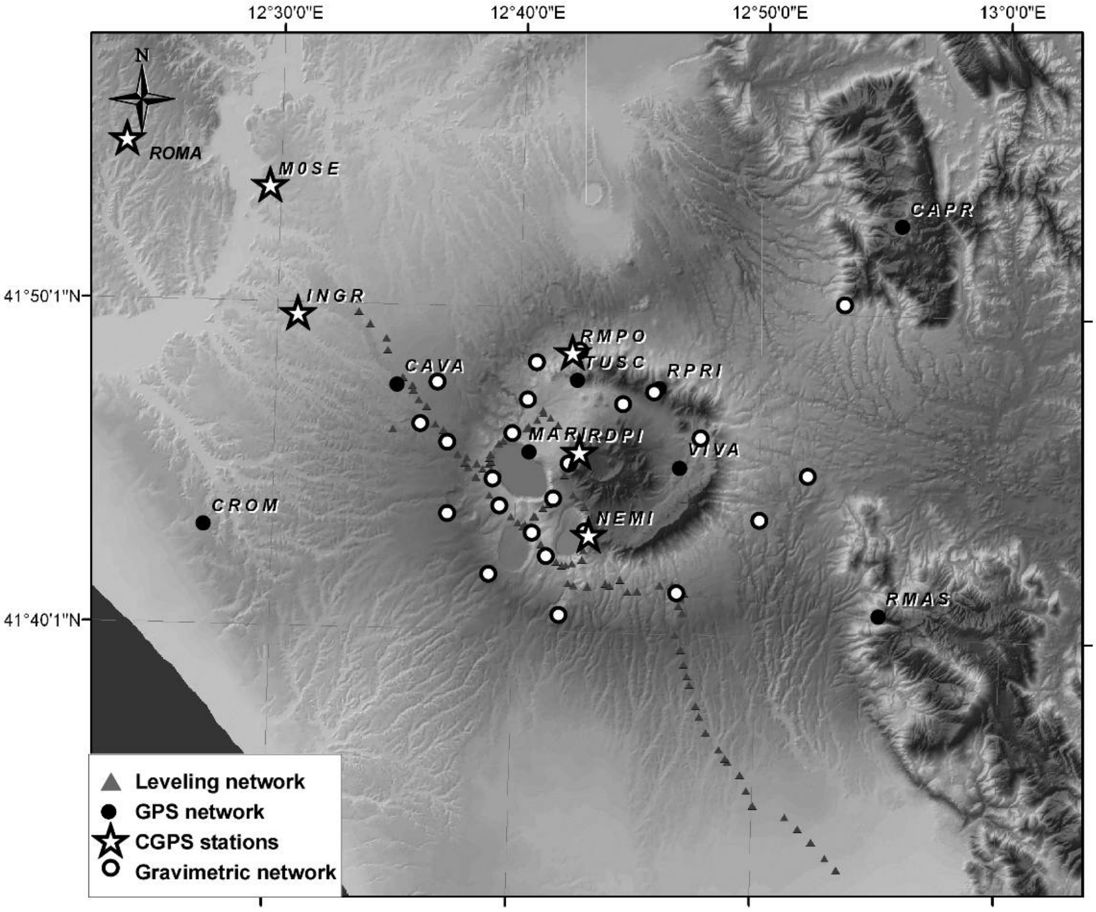
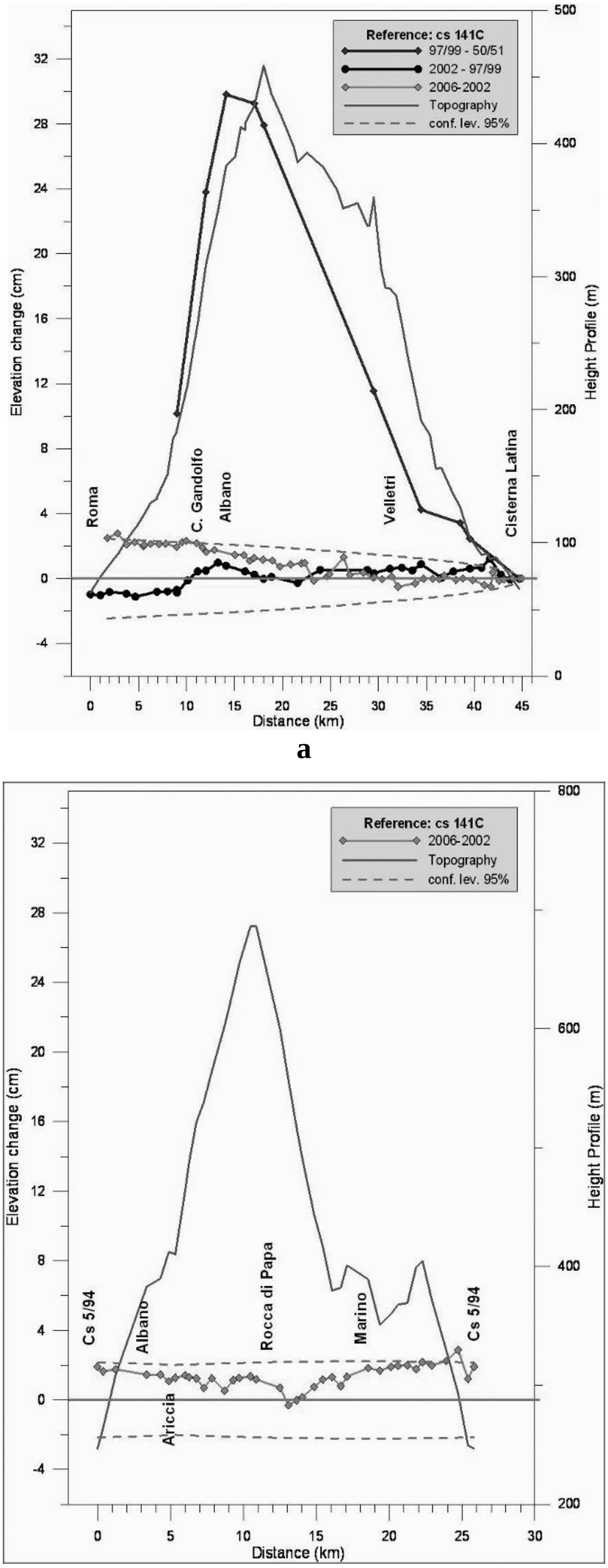


Fig.1 The geodetic networks of the Albano volcano. Gravimetric stations (white circles) are include in the map (after Riguzzi *et al*., 2009, modified).



a

b

Fig.2 Height variations from levelling surveys: a) along Line 24 and b) along Albano circuit.

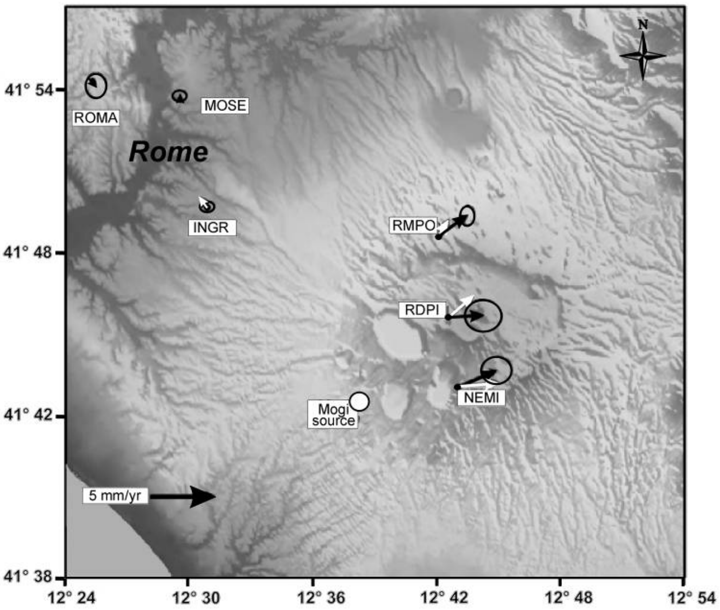


Fig.3 Residual (black arrows) and modelled (white arrows) GPS velocities of RMPO, NEMI and RDPI with respect to INGR, M0SE and ROMA. The white dot shows the location of the Mogi source (after Riguzzi *et al.* 2009, modified).

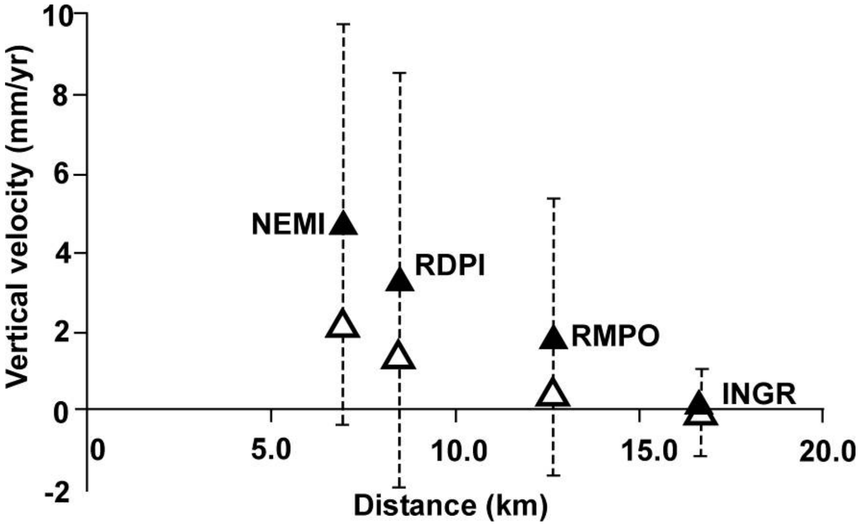


Fig.4 Observed (black triangles) and predicted (open triangles) vertical velocities vs distance of each site from the center of the Mogi source. A linear decrease of rates is shown with increasing distances (after Riguzzi *et al.* 2009, modified).

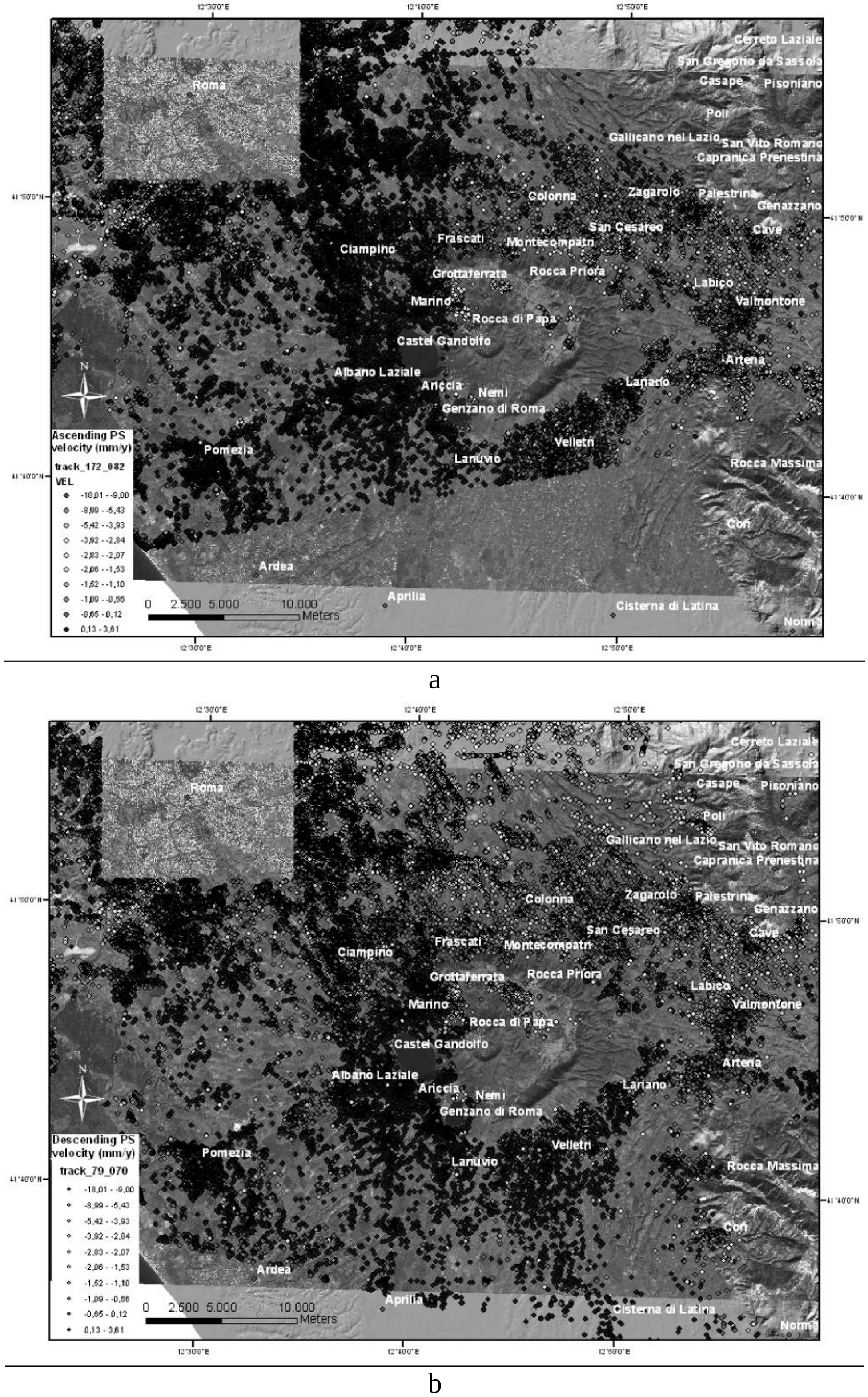
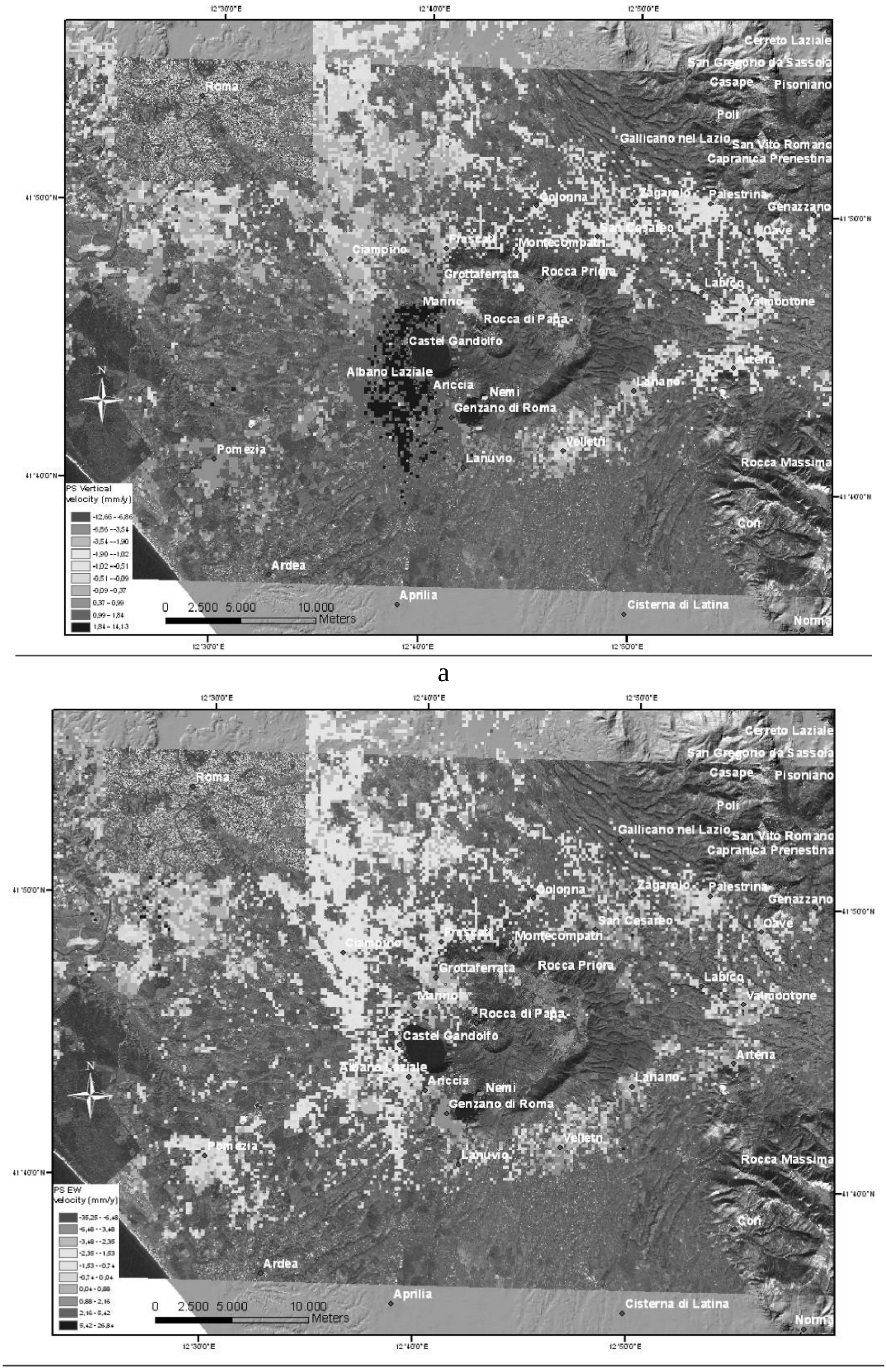


Fig. 5 Deformation patterns of the a) ascending and b) descending PS analysis.



a

b

Fig. 6 Vertical (a) and East-West (b) components of the surface deformation field.

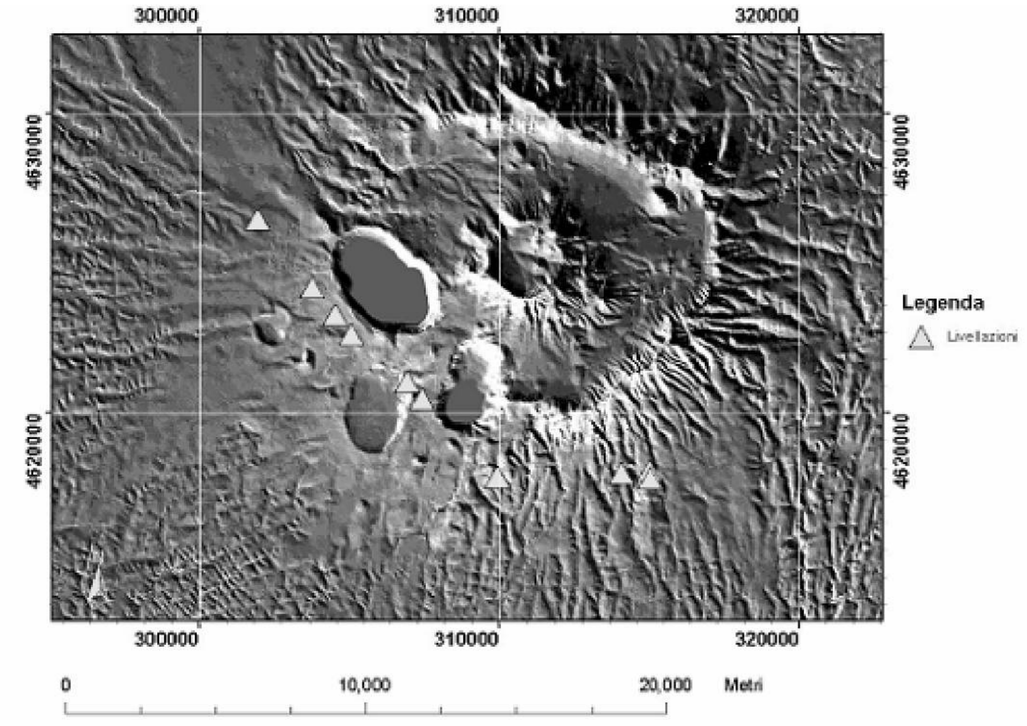
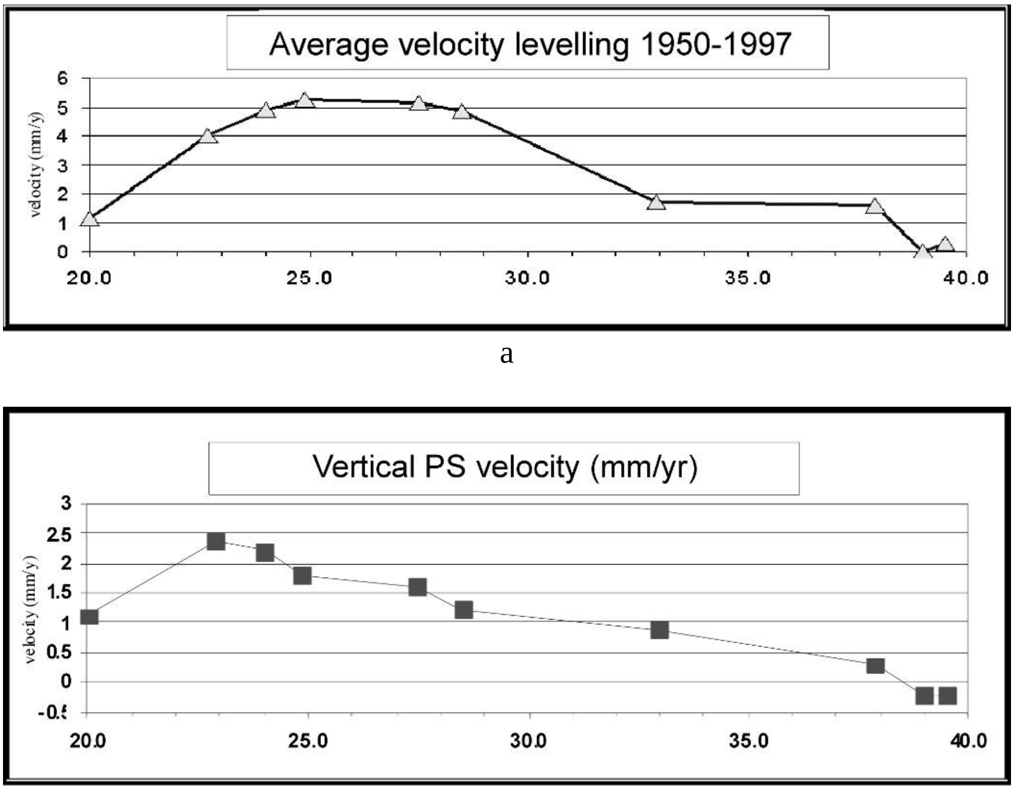


Fig. 7 The selected levelling benchmarks (light grey triangles) used for PS validation.



a

b

Fig. 8 Levelling and PS results comparison: a) average velocity extracted by 1950-1997 levelling campaigns; b) vertical velocity by PSInSAR analysis.

Tables

Site		GPS rate components and errors					modeled rates		
	V_E	V_N	Up	$\pm V_E$	$\pm V_N$	±Up	V_E	V_N	Up
	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr
INGR	0.0	0.0	0.0	0.8	0.6	1.5	-0.51	0.72	0.24
M0SE	0.0	0.4	-1.6	0.8	0.6	1.7	-0.22	-	-
ROMA	0.3	-0.3	-3.5	1.0	1.1	4.0	-0.20	-	-
NEMI	3.2	1.4	4.7	1.4	1.2	5.0	3.26	0.37	2.17
RDPI	2.7	0.2	3.3	1.5	1.3	5.2	1.94	1.69	1.39
RMPO	2.2	1.5	1.9	0.6	0.8	3.5	0.66	1.24	0.51

Table 1 Observed and modeled rates of deformation from GPS data. Dash indicates data excluded from the non-linear inversion (Riguzzi *et al.* 2009).

Model	observation time span (yr)	Lon (°E)	Lat (°N)	Depth (km)	ΔV (km^3/yr)	RMS
PS-InSAR M2 North (Salvi *et al.* 2004)	8	12.665	41.751	4.6	$2.0 \cdot 10^{-4}$	0.57
PS-InSAR M2 South (Salvi *et al.* 2004)	8	12.654	41.666	7.2	$4.4 \cdot 10^{-4}$	0.57
levelling S1 (Feuillet *et al.* 2004)	43	12.687	41.745	4.9	$21.9 \cdot 10^{-4}$	2.00
GPS (Riguzzi *et al.* 2009)	2	12.635	41.709	4.6	$3.6 \cdot 10^{-4}$	0.12

Table 2 Comparison between modelling parameters of Mogi sources(Riguzzi *et al.* 2009).