CRUSTAL DEFORMATION OF THE ALBAN HILLS VOLCANIC COMPLEX (CENTRAL ITALY) BY PERMANENT SCATTERERS ANALYSIS

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1 INTRODUCTION

The Alban Hills volcanic complex, 15 km SE of Rome, Italy, is considered a quiescent volcano, whose last erupted products have been radiometrically dated at 20 ka [1].

The area of most recent activity (maar lakes of Albano and Nemi, last magmatic products younger than 23 ka, Funiciello et al., in press) experienced periodical unrest episodes documented since the Roman age.

They consist of intermittent swarms of moderate intensity earthquakes (Fig. 1; [2]; [3]; [4]), of occasional episodes of magmatic CO_2 release ([5]), of lahar events due to catastrophic lake overspills ([6]), and of considerable surface deformation ([7]; [3]).

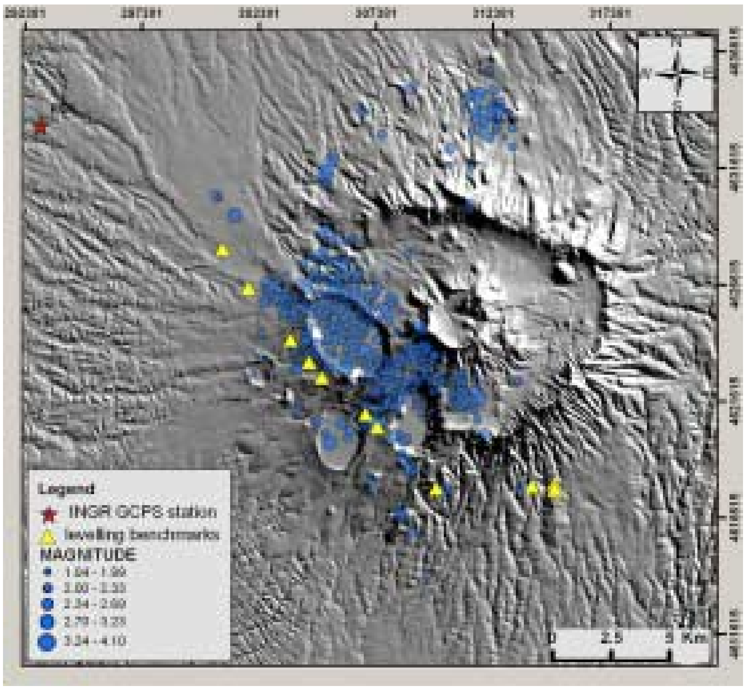

Figure 1 - Shaded relief of the Colli Albani volcano showing earthquake locations for the 1989-1990 seismic unrest period, levelling benchmarks and the location of the INGR CGPS station.

The occurrence of considerable uplift (up to 30 cm) of the Albano and Nemi lakes regions has been inferred from the analysis of two lines crossing the maar lakes area, which have been used to constrain source models ([3]). Unfortunately the number and extension of leveling lines in the Alban Hills is rather limited, and the model reliability is affected by the limited data resolution.

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To retrieve the deformation field at a higher spatial resolution, we applied the Permanent Scatterers analysis on ERS1-2 descending and ascending SAR images. The new data set clearly shows the inflation patterns of the Alban Hills in the period 1993-2000. We use the data to constrain simple analytic models of the source.

2 PERMANENT SCATTERERS FROM ERS-SAR INTERFEROMETRY

Since the advent of satellite SAR interferometry, volcanologists have discovered a new way to measure deformation of volcanic edifices, with unprecedented spatial resolution and sub-centimetric precision. Recent methodological developments have allowed further improvements of the measurement accuracy, providing estimates of displacement velocity of mm/years over stable natural targets (Permanent Scatterers – PS, [8]).

The PS technique is based on the analysis of time series of SAR images. Only the natural targets showing a good stability of the backscattered signal in all the amplitude images (Permanent Scatterers, hereinafter PS) are considered for the calculation of the phase differences between acquisitions.

Note that generally the PS coincide with buildings or anthropic structures, whose density is very high in urban areas.

The analysis technique allows to estimate and remove the tropospheric contribution from the phase signal, restoring the ground displacement trend for each PS, in the line of sight of the SAR antenna (slant range).

The PS technique has been applied to the Alban Hills area using 66 ERS1-2 images relative to descending orbits and 33 images from ascending orbits, acquired in the period 1993-2000.

Over 47,000 PS with a coherence greater than 0.70 were identified on the descending images and over 53,000 PS were detected on the ascending images using a coherence threshold of 0.77. the general pattern of the velocity field is rather clear, and confirms the presence of an N-S uplift zone around the western border of the caldera, in the area of most recent phreatomagmatic activity, allowing to define the deformation patterns with unprecedented resolution (Fig. 2 and Fig. 3).

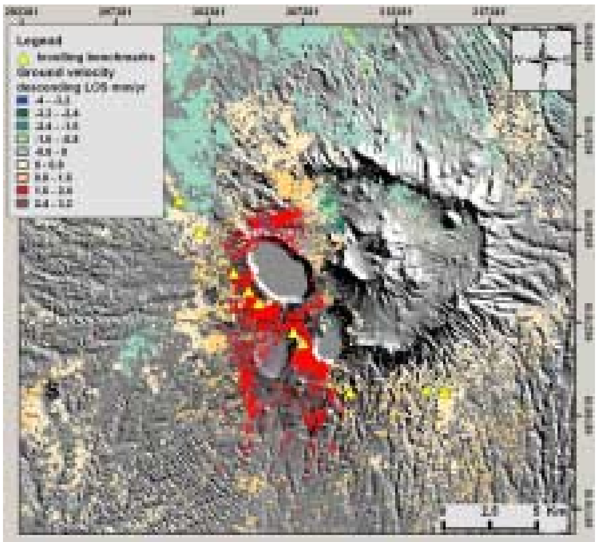

Fig. 2 - Ground velocity in the period 1993-2000, in the Line of Sight of the descending ERS orbit. The site of the Solforata gas vents is indicated (S).

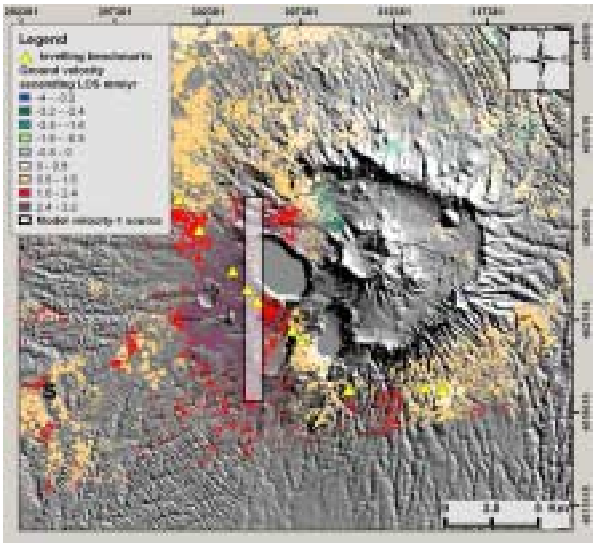

Fig. 3 - Ground velocity in the period 1993-2000, in the ascending ERS orbit. Also shown is the dislocation area for our model 1S. The site of the Solforata gas vents is indicated (S).

3 DATA VALIDATION AND ANALYSIS

Independent ground data have been used for the validation of the remote sensing observations. We first compared the PS slant range ground velocities to the levelling data produced by the Italian Military Geographical Institute – IGMI, using the average vertical velocities (i.e. calculated considering a constant ground displacement rate) resulting from the 1951-1997 height differences. We calculated the average ground velocity for each of the 10 levelling benchmarks (Fig. 1) considering all PS falling in a circular radius of about 200 m.

Observing Fig. 4, we can see a similar trend and a quasi-symmetric shift of the PS-data ascending and descending maxima with respect to the levelling one, and a factor of ~3 difference in the peak velocity values. We can also deduce the presence of a horizontal component of ground displacement, which translates to different slant range displacements. The difference in velocity values was expected and given to the different time span of the levelling and PS data sets (47 vs 8 years) and the low seismicity rate during the time span of the PS data. This confirms that, as already suggested by [3], the uplift rate of the area is positively correlated with the seismicity rate.

We fixed a common reference point for the ascending and descending velocity maps using the Continuous-GPS station (INGR, Fig. 1), active since 2000 with velocity equal to 0 mm/yr, and rescaled the PS velocities accordingly.

The general deformation pattern is rather clear and shows that the highest velocities (up to 2.6 mm/yr) are concentrated in the area of the Albano, Ariccia and Nemi craters, along a general N-S direction. The ground velocities decrease radially from this alignment down to about 0 in ~15 km (for the ascending data) and ~ 8 km (for the descending data); for both data sets the rate of velocity decrease is lower in the southeastern side of the volcanic edifice (Fig. 2, 3 and 7). This general trend shows only two important deviations; the first one lies NE of the Albano lake, where a limited area (1 x 3 km) of strong subsidence is present (Fig. 2 and 3). Given the general similarity of ascending and descending velocities, with values up to –3.5 mm/yr, we estimate the ground displacement here to be mainly vertical. We attribute the subsidence to sediment compaction due to the strong water pumping which has caused in several zones of the Colli Albani a considerable lowering of the water table.

Another area deviating from the general trend is located SW of the main edifice, towards the Tyrrhenian coast. Here both data sets indicate high positive velocities (~1.3 mm/yr) over an area of 8 x 8 km, suggesting the presence of a deep source.

The shift of the ascending and descending maxima visible in Fig. 4 is also evident in the velocity maps (Fig. 2 and 3) and confirms the symmetry of the horizontal deformation with respect to the midpoint between the two zones. Take into consideration that the angular separation between the ascending and descending tracks on the ground is ~24°, and that the slant range direction is inclined ~23° from the vertical, looking East or West during ascending or descending orbits, respectively. So an eastward displacement of a point on the ground is seen as an 'uplift' in the descending Line of Sight, and a 'subsidence' in the ascending LoS, and viceversa.

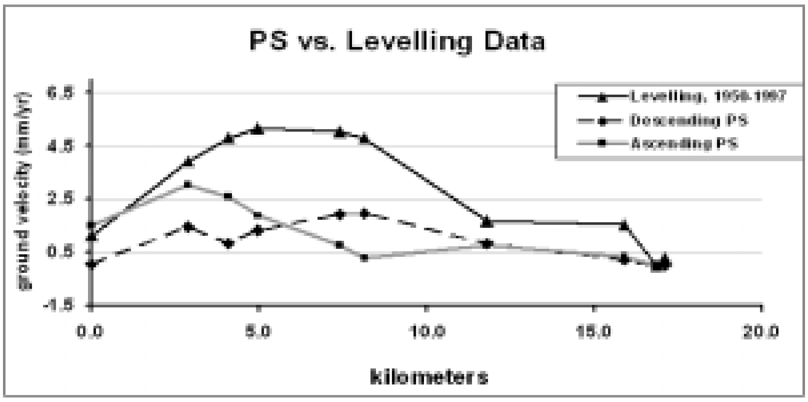

Fig. 4 - Comparison between the ground velocities retrieved by the PS technique in the 1993-2000 period, and the average ground velocity retrieved by levelling in the 1997-1950 period.

4 SOURCE MODELLING

We used the Up and East velocity maps to constrain preliminary source models for the total inflation observed in the 8-year period. At first we smooth the high frequency components using a 500 x 500 m moving window. We also excluded from the model fit calculations the two areas previously described for which we hypothesized a different source (masked areas in Fig. 5 and 6). We employed a forward modeling approach and the Okada, [9], analytical formulations to determine the parameters of a rectangular, purely tensile dislocation in an elastic half space (sill).

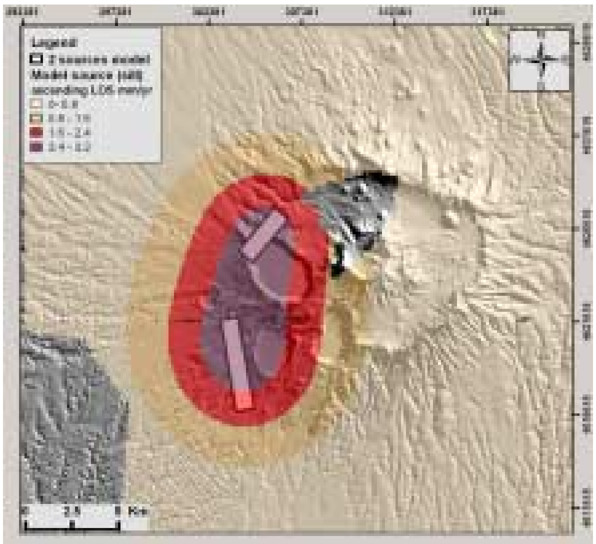

Fig. 5 - Ground velocity for our model 2S in the ascending LoS. Also shown is the dislocation area for our model 2S.

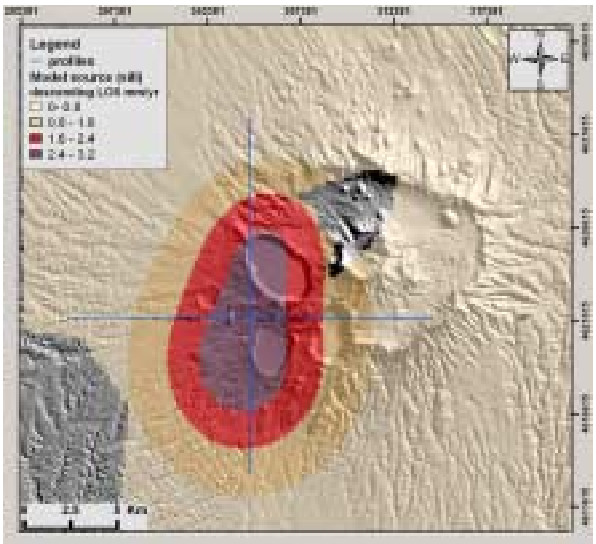

Fig. 6 - Ground velocity for our model 2S in the descending LoS. Also shown are the traces of the profiles reported in fig. 7.

We tested over 30 source models, varying the sill depth, location and dimensions, and the magnitude of the tensile component. We also tested source dips between 0° and 10°. Our best single-source model parameters are reported in Table 1 (Model_1S). We noted the existence of a clear trade-off affecting the model fit to the two data sets: improving the fit to the ascending data degrades the fit to the descending ones (Fig. 7).

In the attempt to improve the fit to the central zone of the deformation pattern, we tried to partition the source in two sub-sources, slightly varying their strike, depth and tensile component. In total we explored more than 50 different models and in our final result (S2 in Table 1) we reduce the residuals RMS to 0.63 and 0.61 (for ascending and descending data). A general improvement of the fitting was obtained in the N-S direction, but the mentioned trade-off remains evident in the E-W residuals profiles (Fig. 7).

Model Type	**Depth (km)**	**Strike (deg)**	**Dip (deg)**	**Lenght (km)**	**Width (km)**	**U3 (mm)**	**Total ΔV 1993-2000 (km^3)**	**RMS of Ascending Residuals (mm/yr)**	**RMS of Descending Residuals (mm/yr)**
1S	7.5	0	0	11	1	50	0.00055	0.59	0.71
2S	6.0	40	0	3	1	55	0.00054	0.63	0.61
	7.5	170	0	5	1	75			

Table 1- Modelling parameters and modeled injection volumes for sources 1S and 2S.

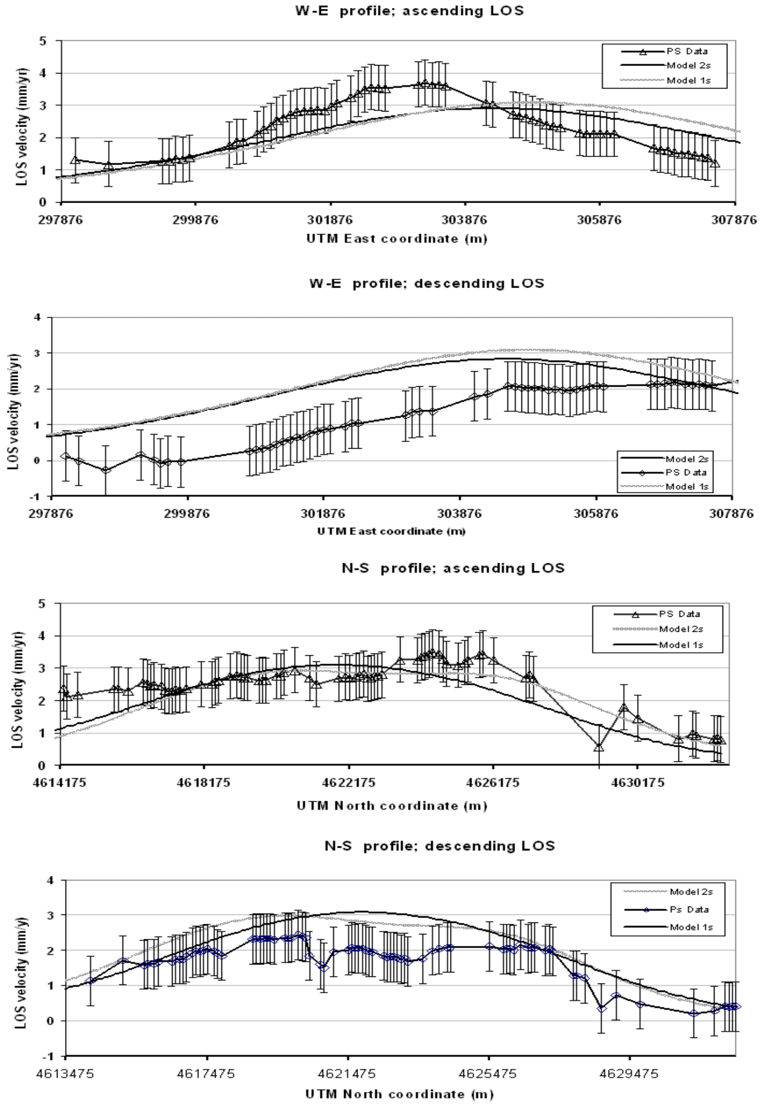

Fig. 7 - Comparison of observations (PS data) and model results (1S and 2S) for the N-S and E-W profiles marked in fig. 5, for the ascending and descending geometries.

5 CONCLUSIONS

The Permanent Scatterer technique allows a very accurate measurement of ground deformation velocities, with an extremely good spatial resolution, especially in highly urbanized areas. The view of the patterns of ground deformation allowed us to correlate the area of the most recent volcanic activity (Final hydromagmatic phase, younger than ~ 20 ka; [10]), corresponding to the Albano, Ariccia, and Nemi craters, to the highest ground velocity area.

Our preliminary work shows that the dense spatial sampling of the deformation field allows to constrain more accurate source models than previously available even if not possible to fit both data sets with simple dislocations and that the volcanic source geometry in likely more complex. Volume changes estimated by our preliminary modelling for the 1993-2000 period (Table 1) are two order of magnitude less than those estimated for the 1950-1994 period by the sole modelling of the levelling heights changes [3], while the PS maximum ground velocity in the crater area is approximately 3 times less than that estimated by levelling [average for the entire 47-yr period). Moreover, our observations show that the present deformation pattern is only partially correlated to the trend and location of the last seismic swarm, opening new questions on the mechanical processes driving the shear stress changes in the area.

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