Renewed ground uplift at Campi Flegrei caldera (Italy): New insight on magmatic processes and forecast

C. Troise,[1] G. De Natale,[1] F. Pingue,[1] F. Obrizzo,[1] P. De Martino,[1] U. Tammaro,[1] and E. Boschi[1]

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[1] Campi Flegrei caldera, including the extremely urbanised city of Naples, is the most risky volcanic area in the World. The last eruption in the area (1538) occurred at the end of some decades of ground uplift, superimposed to secular subsidence. During the last four decades, it experienced a huge uplift phase, reaching about 3.5 m in 1985, when a subsidence phase started. Recent geodetic data demonstrate that such a subsidence phase has terminated, and a new uplift episode started in November 2004, with a low but increasing rate leading to about 0.04 m of uplift till the end of October 2006. A new indicator, based on the monitoring of maximum horizontal to vertical displacement ratio with continuous GPS, indicates that this uplift is likely to be associated with input of magmatic fluids from a shallow magma chamber. The method is promising to monitor magma intrusion processes, at this and other volcanoes. **Citation:** Troise, C., G. De Natale, F. Pingue, F. Obrizzo, P. De Martino, U. Tammaro, and E. Boschi (2007), Renewed ground uplift at Campi Flegrei caldera (Italy): New insight on magmatic processes and forecast, *Geophys. Res. Lett.*, *34*, L03301, doi:10.1029/2006GL028545.

1. Introduction

[2] Campi Flegrei is the area with the longest historically documented ground deformation, and one of the most densely populated, making crucial eruption forecast [*De Natale et al.*, 2006; *Dvorak and Mastrolorenzo*, 1991].

[3] The recently active part of the caldera was formed about 15000 years ago, by the 'Neapolitan Yellow Tuff' eruption. A larger caldera, with a radius of about 6 km, can be identified by geological limits, but has not a deep geophysical signature. Some literature ascribes this larger caldera to an ignimbritic eruption occurred about 39000 years BP, producing the Campanian grey tuff deposits [*Rosi and Sbrana*, 1987; *Orsi et al.*, 1996], but there is no global consensus on such a model [*Rolandi et al.*, 2003]. The volcanic edifices in Campi Flegrei caldera are mainly monogenetic tuff cones and tuff rings, produced by hydromagmatic eruptions with alkali-trachitic magma [*Rosi et al.*, 1983].

[4] After the pioneering work of *Parascandola* [1947], the most comprehensive reconstruction of secular ground movements at Campi Flegrei was presented by *Dvorak and Mastrolorenzo* [1991]. Their work has been recently integrated by *Morhange et al.* [1999, 2006], on the basis of new observations on the populations of marine bivalves and corals, producing marine borings on Roman and Middle-age ruins. Figure 1a reports the most recent reconstruction of secular displacements at the center of Pozzuoli, based

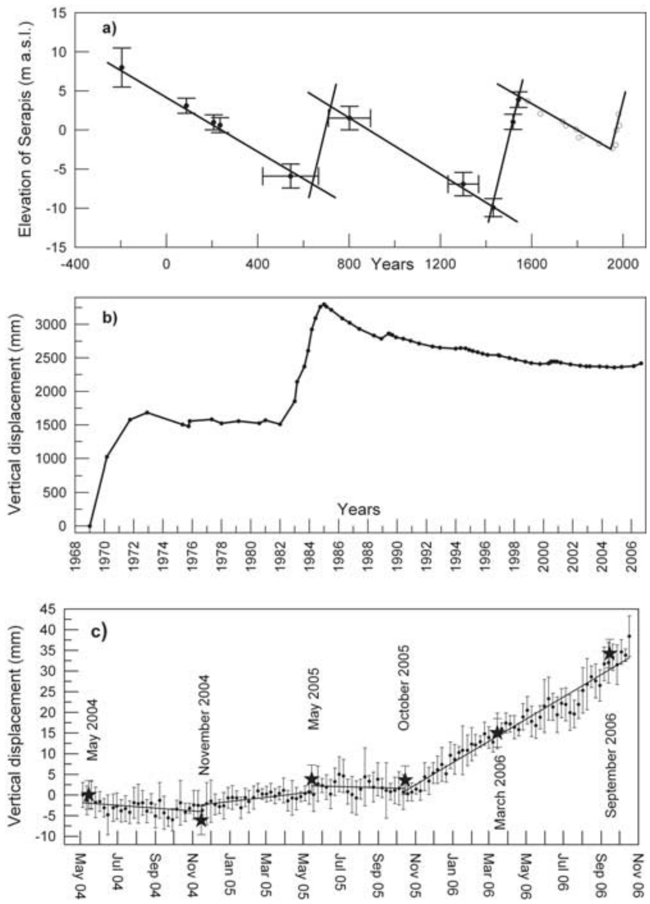

Figure 1. Ground deformation at Campi Flegrei. (a) Schematic vertical movements history at Macellum in Pozzuoli, known as Serapis Temple. Black circles represent the constraints found from radiocarbon and archaeological measurements by *Morhange et al.* [2006]; white circles (post-1538) represent inference from *Dvorak and Mastrolorenzo* [1991] (data from *Bellucci et al.* [2006]). (b) Vertical ground displacements as recorded at Pozzuoli Harbour by levelling data in the period 1969–2006 [*Macedonio and Tammaro*, 2005; *Del Gaudio et al.*, 2005; *Pingue et al.*, 2006]. (c) Detail of vertical displacement from May 2004 to October 2006 as recorded from: CGPS (dots); precision levelling at bench mark in Pozzuoli harbour (stars). Errors on CGPS and levelling data (1σ) are also shown.

[1]Istituto Nazionale di Geofisica e Vulcanologia–Osservatorio Vesuviano, Naples, Italy.

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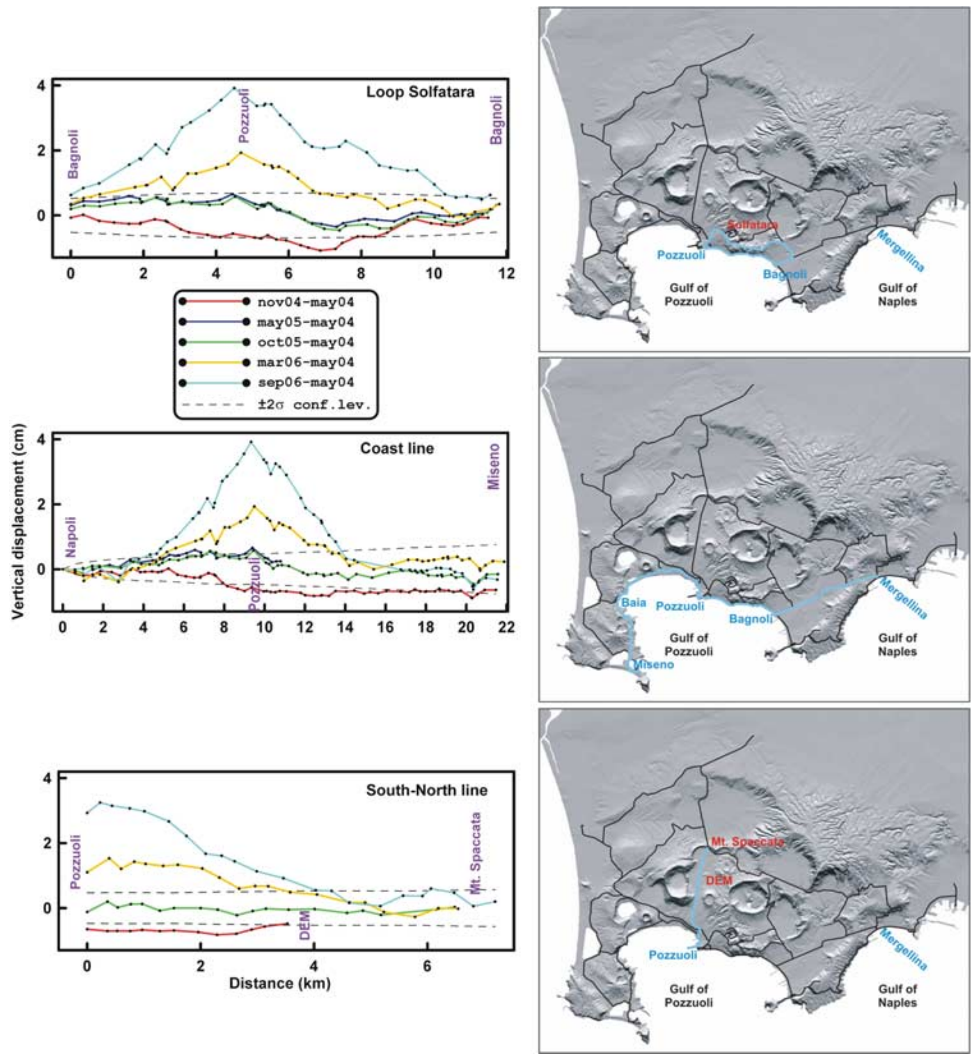

Figure 2. Recent vertical displacements from precision levelling. Vertical displacements measured along three levelling lines during different periods, since May 2004 to September 2006, as indicated in figure. Displacements are all referred to the benchmark of Mergellina. 2σ confidence levels are indicated. Ground uplift starts in November 2004, reaching up to 4 cm in September, when last levelling measures were made.

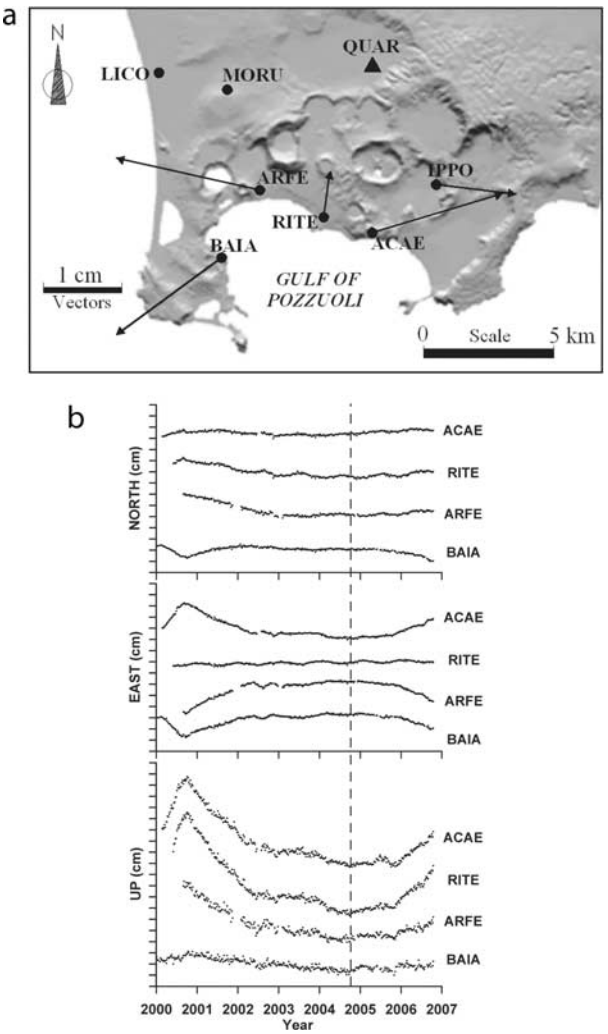

Figure 3. CGPS data. (a) Sketch of Campi Flegrei caldera with CGPS points and inferred horizontal displacement vectors in the period May 2004 – October 2006. (b) Time series of weekly coordinate changes, from January 2000 to October 2006, (along North, East and Up directions) for the Campi Flegrei CGPS stations showing significant displacement. Tick spacing is 1 cm. The vertical dashed line indicate the approximate starting of the last uplift phase.

on quoted papers [*Dvorak and Mastrolorenzo*, 1991; *Morhange et al.*, 1999, 2006]. The background long-term deformation in the area is subsidence, occurring at a rate of 1.5–1.7 cm/year, with two episodes of intense uplift (up to 15 m in 100 years), one starting in the VII century, the last in the XV one. The last one culminated with the 1538 Mt. Nuovo eruption, the only historic one. The last period of uplift started in 1969, with two main episodes occurring at peak rate of 1 m/year, respectively in 1969–1972 and 1982–1984 [*Barberi et al.*, 1984] They were both accompanied by microseismicity, much more intense in 1982–1984, microgravity changes, and several geochemical gas changes [*De Natale and Zollo*, 1986; *De Natale et al.*, 1991, 1995; *Berrino*, 1994; *Troise et al.*, 1997, 2003; *Gottsmann et al.*, 2006; *Battaglia et al.*, 2006]. As a consequence, the town of Pozzuoli, where uplift was maximum, was evacuated two times, in 1970 and 1984. In 1985, a subsidence phase started, with some episodic small and fast uplifts superimposed [*Gaeta et al.*, 2003].

2. Recent Geodetic Data and Interpretation

[5] The recent vertical ground deformation at Campi Flegrei, measured by precision leveling since 1969 and, in addition, by GPS since 2000, is shown in Figures 1b and 1c. The ground-based geodetic measurements we use in this paper to analyze the on-going deformation are of two kinds: precision leveling and continuous GPS data (CGPS), taken from the monitoring networks of INGV in the area (Figures 2 and 3). The recent data clearly indicate that, since November 2004, the subsidence lasting since 1985 is definitely stopped and a new uplift phase has started. The maximum uplift, measured at the Pozzuoli harbour, is about 4 cm till the end of October (see Figure 1c). While leveling data give a complete picture of the spatial pattern of vertical displacement (Figure 2), CGPS signals allow to carefully reconstruct the time evolution of both vertical and horizontal displacements at selected points, since 2000 (Figure 3).

[6] In this paper we use these data to constrain the kind of source producing the recent unrests at Campi Flegrei. As noted in several papers [*De Natale and Pingue*, 1993; *De Natale et al.*, 1997] the shape of vertical ground deformation pattern at Campi Flegrei is remarkably constant, independently from the total amount of displacement, both during uplift and subsidence episodes, which show the same deformation shape apart from the sign. *De Natale et al.* [1997] interpret this in terms of the strong influence of induced slip on caldera ring faults, which represent displacement discontinuities at the caldera borders, rather than a constant source depth and geometry. Recently, *Battaglia et al.* [2006], noted a marked difference in the ratio between horizontal and vertical displacements associated, respectively, to the first phase of large uplift (1982–1983) and to the subsequent subsidence episode (1985–1995), thus demonstrating that uplift and subsidence involve different source depth and geometry. In order to understand the nature of the present uplift episode, it is then crucial to compare it to previous episodes. The most important elements for such a comparison, on the basis of former analyses and results, are (1) the shape of vertical displacement pattern, which is well constrained by the precision leveling; and (2) the ratio between horizontal and vertical displacements, which can be obtained from CGPS measurements and compared with previous uplift and subsidence episodes.

[7] The shape of vertical displacement pattern can be computed by normalizing the leveling data with respect to the maximum, and comparing different episodes among them (Figure 4a). As it is clear, within the errors the shapes of vertical displacements are remarkably similar among different uplift episodes. Unfortunately, no measures are available along the Baia-Miseno line for 1999–2000 uplift, which at the other benchmarks seem very consistent with the 1982–1985 period. The strong similitude of vertical displacement pattern alone, however, it is not sufficient to demonstrate the similitude of source mechanisms, because the effect of caldera borders also contributes the same way [*De Natale et al.*, 1997]. More discriminating about the source mechanism is the ratio between maximum horizontal and maximum vertical displacements [*De Natale et al.*, 2006] (H/V), which

crucially depends on the shape of the pressure source generating ground deformation (see Figure 4c).

[8] Since CGPS observations began in January 2000, we can compare, in a homogeneous way, actual data only with the 2000 uplift. Figure 4b shows the average H/V ratios computed in periods with almost constant positive or negative vertical displacement rate, as recorded at the two stations, RITE and ACAE, where vertical and horizontal displacements are, respectively, maximum. It is noteworthy that, within the errors, the average H/V ratio is very similar in the whole period, ranging between 0.29 and 0.37, except in the period October 2004–November 2005, when the negligible amount of displacement makes the error so large that the inferred ratios are meaningless.

3. Discussion and Conclusion

[9] The similarity of the common low values of vertical deformation shapes and of H/V ratios suggests that the new uplift started at Campi Flegrei caldera shares a similar source geometry and mechanism of any recently observed episodes, including the larger ones. In particular, the strict similitude with previous small uplift episodes is strongly constrained by the comparison of H/V ratios between 2000 uplift and the present one. The only difference with previous small uplift episodes [*Gaeta et al.*, 2003; *Lanari et al.*, 2004] is just the slower deformation rate (average of 0.3 cm/month) and the longer duration. *Battaglia et al.* [2006] showed that the horizontal to vertical displacement ratios were significantly smaller (about one half) during the large 1982–1983 uplift with respect to the 1990–1995 subsidence. Such data are interpreted with two different source geometries and depths of the large uplift with respect to subsidence episodes. The first part of uplift is interpreted as due to overpressure within a penny-shaped crack, located below 3 km of depth [*De Natale et al.*, 2006] which contains magma or fluids of magmatic origin; such overpressure subsequently involves the shallower aquifers (for instance after fracturing of the rock volume between the magmatic fluids and the aquifer). The subsidence is hence interpreted as the water deflation from a prolate ellipsoidal aquifer, located at depths between 1.5–2.5 km, towards the external rocks. The observed H/V ratio for the 2000 and the 2004–2006 uplifts, generally less than 0.37, is indicative of an oblate source (Figure 4c). These observations allow to formulate a model for the occurrence of small uplift episodes, and more generally for the fast ground deformation episodes at Campi Flegrei and similar areas. In fact, in the light of the previously mentioned models, the rather small ratio between horizontal and vertical displacements observed during the small uplift episodes is indicative of overpressure, in the deeper source evidenced by *Battaglia et al.* [2006], of fluids of magmatic origin. A large uplift episode could then occur when the initial pulse of overpressure, after significantly fracturing the upper rocks, is migrated into the shallower

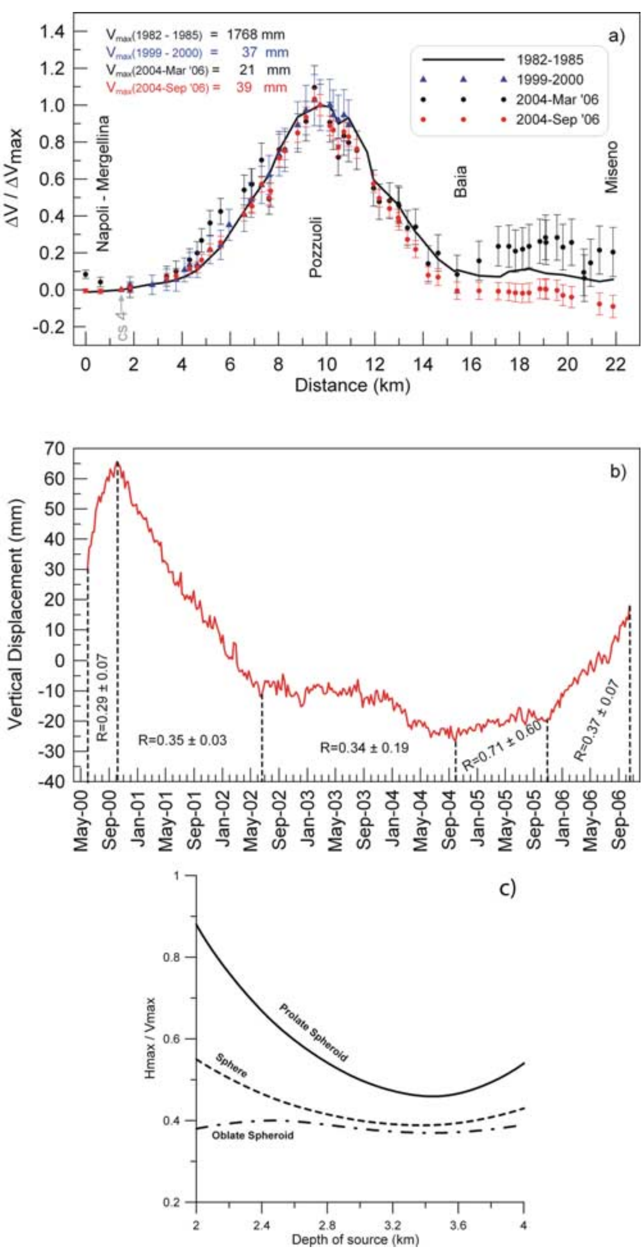

Figure 4. Comparing ground uplift patterns at various periods. (a) Normalized vertical displacements along the Naples-Pozzuoli-Baia-Miseno levelling line (see Figure 3) in four different periods: 1982–1985, 1999–2000, 2004-March 2006 and 2004-September 2006. Displacement errors (1σ) are also shown where significant. Normalization factors, indicated in figure, represent the vertical displacements recorded at the bench-mark in Pozzuoli harbour in the respective periods. (b) Sketch of R (= H/V) values in periods of approximately constant uplift or subsidence rate, as indicated. (c) Theoretical curves of maximum horizontal/vertical ratios vs. depth source in the case of three ellipsoidal sources with different aspect ratio r: prolate ellipsoid, r = 0.5; sphere, r = 1.0; oblate ellipsoid, r = 2.0 embedded in an elastic half-space with ring faults simulating the geometry of Campi Flegrei caldera borders. Curves are obtained by an axial-symmetric boundary element method, in which ring faults are described as conical surfaces on which shear stress is null [*Troise et al.*, 2003]. The geometry and depth of ring faults is taken by *Beauducel et al.* [2004], the radius is 2.7 km. From the figure, it is apparent that ratios larger than about 0.55 are only attained with prolate and very shallow sources. Values of 0.30–0.35 as evidenced in this study are compatible with oblate sources, whose dependence on the depth is negligible.

aquifers. Such interpretation is consistent with the observations of *Chiodini et al.* [2003] that similar peaks of CO_2 follow both large and small uplift episodes, with a time lag of several months, thus indicating that uplift episodes are all associated to a significant input of CO_2 from below, that is essentially independent from the amount of uplift. A further sharp increase of CO_2 flux started some months ago and is still on-going (G. Chiodini, personal communication, 2006). This is in agreement with a model in which all the uplift episodes start with overpressure in a deeper source filled with magma or fluids of magmatic origin, rich in CO_2, which is injected in shallower layers. The longer duration of the present episode with respect to previous small uplifts should mean a longer lasting overpressure pulse at the source. Such a model has anyway important implications for eruption hazard because, if the deeper source is filled with magma or reflects new magma arrival, each overpressure pulse brings the system closer to the critical point for rock failure and eruption [*De Natale et al.*, 2001, 2006]. Thus, the about 2.5 meters of residual uplift cumulated since 1969 could be reasonably interpreted as due to the sum of all the positive overpressure pulses, associated both to large and small unrests, in the deep system, which has then been loaded by a considerable additional stress. As a further conclusion, we suggest that the systematic monitoring of the maximum horizontal to vertical displacement ratio using CGPS data is a useful tool for eruption forecasting, because of the strong sensitivity of this ratio to changes in source depth.

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E. Boschi, P. De Martino, G. De Natale, F. Obrizzo, F. Pingue, U. Tammaro, and C. Troise, Istituto Nazionale di Geofisica e Vulcanologia–Osservatorio Vesuviano, V. Diocleziano 328, I-80124, Naples, Italy. (troise@ov.ingv.it)