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Simultaneous inversion of deformation and gravity changes in a horizontally layered half-space: Evidences for magma intrusion during the 1982–1984 unrest at Campi Flegrei caldera (Italy)

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ABSTRACT

A very large uplift (about 1.8 m) occurred in the period 1982–1984 at Campi Flegrei caldera, Italy, without culminating in an eruption. A still-standing controversy accompanies the interpretation of deformation and gravity changes recorded during the unrest, which were interpreted to result from the sub-surface magmatic reservoir by some authors and from the hydrothermal system or hybrid sources by others. Here for the first time we take into account crustal layering while inverting leveling, EDM, and gravity data using uniformly-pressurized sources, namely small vertical spheroids and finite horizontal penny-shaped sources. The weight of EDM data in the misfit function is chosen from a trade-off curve in order to balance the compromise between fitting the leveling and the EDM data well. Models using a homogeneous medium cannot give a good simultaneous fit to leveling and EDM deformation data of the 1982–1984 unrest, whereas incorporating a layered structure (determined from seismically derived estimates of the P wave speed for the crust, and not adjusted to improve the fit in any of the inversions) allows a significantly better fit. Also, layering affects the sub-surface mass redistribution effects on gravity changes, and we show that the retrieved intrusion density is in full agreement with densities for highly evolved magmas expected at the Campi Flegrei caldera for depths of 3 to 4 km, ruling out hydrothermal fluids as the primary cause of the 1982–1984 unrest. The source of the 1982–1984 CF unrest was probably a shallow (about 3-km deep) penny-shaped magma intrusion fed by a deeper magma chamber; source overpressure was few MPa.

1. Introduction

Volcanic risk in the explosive Campi Flegrei (CF) caldera is extremely high, because of its location in a densely populated area about 15 km west of Naples inside the Campanian Plain. The caldera was created by subsidence of the CF area generally ascribed to several collapses during the last 40,000 yr. Its background long-term deformation is spectacularly recorded by the peculiar geographic setting and the presence of Roman ruins: the caldera is partially submerged, so sea level provides a natural reference level for relative ground movements, and marine deposits on Roman ruins and historical documents have been studied to reveal large, secular subsidence, on which are superposed very fast uplifts, giving rise to only one eruption since Roman times (Dvorak and Mastrolorenzo, 1991). This last eruption occurred in 1538 at western periphery of CF and created a spatter cone (Monte Nuovo, about 130 m, at the periphery of the inner caldera). Since the last eruption, CF, like many calderas, suffered notable unrest episodes, including large ground deformations (Newhall and Dzurisin, 1988), seismic swarms and increases in the degassing activity (Barberi et al., 1984). The caldera has been generally subsiding (at about 1.5 cm/yr) from 1538 till 1969. A substantial ground uplift, more than 1.5 m, occurred in the period 1969–1972 and, after a small subsidence of about 30 cm after 1972, a very large uplift occurred in the period 1982–1984 (about 1.8 m), with subsequent partial recovery (about 60 cm in 2 yr). Superposed on the still continuing subsidence are some short uplift phases (mini-uplifts with a few cm amplitude during 1989, 1994, 2000, 2004–2006); ground level still remains about 2.5 m above pre-1970 levels at the town of Pozzuoli.

While post-1985 deflation is usually ascribed to changes in the sub-surface hydrothermal system, a long-standing controversy accompanies the interpretation of geodetic data recorded during the 1982–1984 rapid uplift episode. Deformation and gravity changes were interpreted to result from the sub-surface magmatic reservoir by some authors and from the hydrothermal system or hybrid sources by others (e.g. Battaglia et al., 2006; Gottsmann et al., 2006a, and references therein). The controversy is of major importance for assessing the Campi Flegrei volcanic hazard, because distinguishing

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Table 1
Campi Flegrei multilayered elastic models used in this work

Model A			Model B			Model C		
Depth (km)	Vp (km/s)	Density (kg/m^3	Depth (km)	Vp (km/s)	Density (kg/m^3	Depth (km)	Vp (km/s)	Density (kg/m^3)
0.00	1.60	1800	0.00	1.47	2000	0.00	2.30	2000
0.62	2.50	2100	0.62	2.34	2000	1.00	3.80	2200
1.40	3.20	2270	1.40	3.08	2200	2.50	4.20	2400
1.55	3.90	2380	1.55	3.76	2200	3.20	5.00	2600
2.73	3.95	2400	2.73	4.02	2400	≥4.00	5.92	2700
3.92	5.20	2580	3.92	5.63	2600			
≥4.03	5.92	2700	≥4.03	5.92	2700			

between magmatic and hydrothermal sources of volcanic unrest is the first node of any volcanic hazard tree.

Different source shapes (spherical, prolate, penny-shaped finite sources as well as ellipsoidal point sources) have been tested in the past, but even the most recent works share the homogeneous half-space assumption when inverting deformation and gravity data (e.g. Gottsmann et al., 2006b; Battaglia et al., 2006). Battaglia et al. (2006) demonstrated that a finite horizontal penny-shaped source can fit horizontal and vertical displacements much better than spherical or prolate sources and pointed out the large inferred density difference when assuming different source shapes in the inversion of deformation and gravity data. Since the sub-surface mass redistribution gives a large contribution to gravity changes in case of a horizontal penny-shaped source embedded in a homogeneous half-space, Battaglia et al. (2006) obtained a very low intrusion density (i.e. 600 ± 500 kg/m^3) and excluded the intrusion of magma. For comparison, intrusion density inferred for spherical sources was >3000 kg/m^3 both for the single source model in Battaglia et al. (2006) and the deeper of the two spherical sources in Gottsmann et al. (2006a).

It is known that the presence of heterogeneities affects superficial deformation due to dislocation sources (e.g. Amoruso et al., 2004, and references therein) and expansive sources (e.g. Trasatti et al., 2005, and references therein). Numerical tests in Amoruso et al. (2007) revealed characteristic discrepancies between the synthetic deformation data generated by an expansive source embedded in a layered medium and best-fit models for a homogeneous half-space, mainly related to an underestimation of horizontal displacements. Generally speaking, it is always possible to fit vertical displacement data assuming a homogeneous half-space and using an ad hoc shape and depth of the source. When horizontal and vertical displacement data are fitted jointly, the number of vertical displacement data is usually much larger than the number of horizontal displacement data and consequently predictions of the best-fit model fit verticals much better than horizontals when assuming a homogeneous half-space (see e.g. relevant plots in Battaglia et al., 2006; Gottsmann et al., 2006b). Amoruso et al. (2007) enlightened the presence of this kind of discrepancies when trying to model deformation data of the 2004–2006 CF mini-uplift using a homogeneous half-space. Incorporating a layered structure appropriate for CF (determined a priori from seismically derived estimates of the P wave speed for the crust) allows a significantly better fit, avoiding the above-mentioned characteristic discrepancies. A similar layered structure had been previously used in Crescentini and Amoruso (2007) for performing synthetic numerical tests on the role of layering on the sub-surface mass redistribution effects on gravity changes. They showed that neglecting crustal layering can lead to strong density underestimation if the source is modelled as a horizontal penny-shaped source, either point or finite, and suggested that such underestimation might have affected results in Battaglia et al. (2006).

In this work, we focus on the major question related to the large 1982–1984 CF unrest, that is to distinguish between magmatic and hydrothermal sources for the observed deformation and gravity changes. To invert available deformation (leveling and EDM) and gravity data, we use the layered elastic model proved to be appropriate for the CF area by the results for the 2004–2006 CF mini-uplift in Amoruso et al. (2007). We show that taking into account layering leads to intrusion density values in full agreement with densities for highly evolved magmas expected at CF for depths of 3 to 4 km. Small source overpressure (few MPa) is requested to fit observations. The source of the 1982–1984 CF unrest was probably a shallow (about 3-km deep) penny-shaped magma intrusion fed by a deeper magma chamber.

Topography affects the surface deformation pattern, but needs to be considered only if it is steep and comparable to source depth (e.g. Williams and Wadge, 2000; Trasatti et al., 2003). Here we do not consider the effects of topography because of the smoothness of the CF area.

2. Modelling surface deformation and gravity changes

The layered elastic model (Model A in Table 1) is obtained from a recent 1D Vp model (Judenherc and Zollo, 2004) and the Nafe–Drake curve (Ludwig et al., 1970) taking into account the drained response of the medium by setting the Poisson's ratio to 0.25 at all depths. Even if the Nafe–Drake curve may be inappropriate to an explosive volcanic environment like CF, nevertheless we obtain a density profile very similar to the one inferred by the Italian Oil Agency from gravity anomalies (2000 kg/m^3, above 1-km depth; 2200 kg/m^3, 1 to 2.4 km; 2400 kg/m^3, 2.4 to 3.2 km; 2600 kg/m^3 below 3.2-km depth; AGIP, 1987). Values for intermediate depths are obtained by linear interpolation between adjacent listed depths. No deformation data are used to obtain

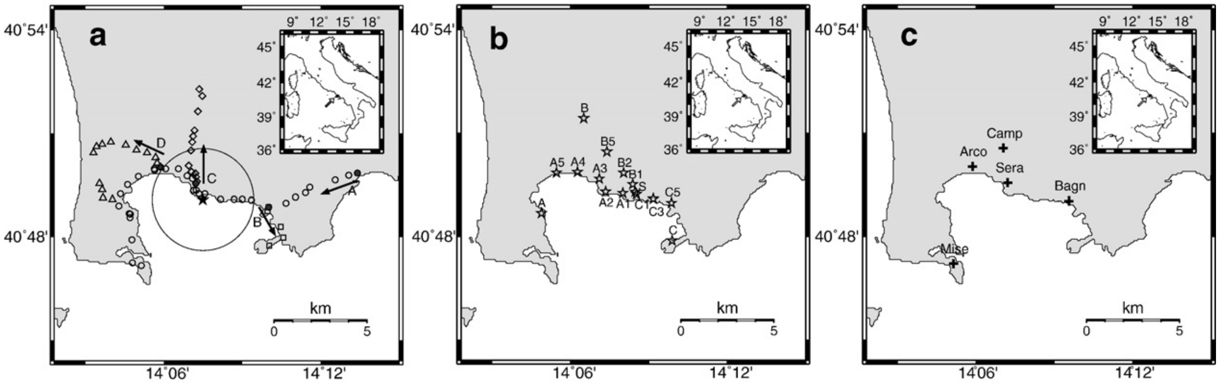

Fig. 1. Maps of the Campi Flegrei area. Left map shows position of bench-marks along the four leveling routes (A, circles; B, squares; C, diamonds; D, triangles; filled symbols indicate point 0 on each route) and horizontal projection of the best-fit source of the 1982–1984 unrest (large open circle; the solid star indicates its center). Center map shows position of EDM bench-marks (open stars). Right map shows position of gravity stations (pluses).