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PHD THESIS

**The last forty years of surface
deformation at Campi Flegrei caldera:
two simple stationary sources are
enough**

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Abstract

The Campi Flegrei (CF) caldera is one of the world's most active caldera; in this area the volcanic risk is extremely high, because of its location in a densely populated area about 15 km west of Naples inside the Campanian Plain. This caldera is renowned for its long historical activity that includes earthquakes, eruption and intense unrest episodes. The source of the observed surface deformation at Campi Flegrei has been and is a matter of debate, particularly in the last two years (2011-2013) because of a considerable uplift (~ 15 cm) that have drawn attention from both the scientists and civil protection.

In such a context, my thesis has been focused to find a simple model source that explains the CF deformation field during the last forty years (1970-2013), analyzing different types of data. The positive bradyseism crisis of 1982-1984 and the negative bradyseism of 1995-2000, in particular, are investigated. Different periods are covered by different types of data, from 1970 to 1994 by leveling data, in 1980 and in 1983 by geodetic precise traversing data, from 1993 to 2010 by Synthetic-Aperture Radar (SAR) data and finally from 2000 to October 2013 by continuous Global Positioning System (cGPS).

The first part of the thesis consists of a description of the deformation history of CF and the state of the art. Different models for earthquake volcano deformation, used to explain the CF phenomenology and two kinds of Monte Carlo inversion methods to determine the model source, are introduced.

In the second part, the results of the analysis and of the inversion are described. Firstly the period 1970-2010 is analyzed, using leveling, geodetic precise traversing and SAR data, and subsequently cGPS data for the 2000-2013 period are used to confirm the found model

We will see that, for the entire investigated period (1970-2013), a single stationary source, at about 4000 m in depth, satisfies overall CF deformation during the whole investigated

period and the residuals (with respect to the above source) deformation is confined to the Solfatara fumarolic field and satisfied by a stationary shallower small source located beneath Solfatara, at about 2000 m in depth; after 2005, also east side of CF seems to uplift abnormally.

In this sense, ground displacement data are analyzed in order to discern similarities or differences between CF inflation and deflation periods and to highlight possible anomalies in particular areas of the CF caldera. The first step was analyzed ground deformation pattern between the major 1982-84 inflation and subsequent deflation, focusing on periods with large signals and constant ratio. To compare the vertical displacements of this periods, each dataset was rescaled to match the 1980-83 one in the area of maximum uplift; the agreement is nearly perfect, apart from benchmarks in the Solfatara area and immediately South of it, where a local deformation source, with a different time history, seems superposed on the large-scale one. Same results are obtained by the comparison of eastward displacements of SAR data (period 1995-2000) and geodetic precise traversing data (period 1980-1983). This suggest the stationarity of the deformation field for these periods, apart for the Solfatara area.

The data of the 1980-1983 uplift are inverted for different models; this period is particularly favorable because of the presence of vertical and horizontal displacements data and because the Solfatara area is not cover by a leveling route in this period, so the inversions are not affected by a possible anomaly in the area.

Since the importance of taking into account the stratification is evidenced by many authors (*Amoruso, Crescentini and Fidani, 2004, Amoruso and Crescentini, 2007, etc*), a layered media is used for the inversion, and a quasi-horizontal elongated crack (oriented NW to SE, at a depth of about 3600 m) satisfies large-scale deformation. All source parameters but potency (volume change) are constant over time. Subtracting the effect of this source from the SAR data for 1995-2000 period, residuals are located in the Solfatara area. The anomaly is much more localized than large-scale deformation and suggests the presence of a local quasi-axis-symmetric shallower source.

From a mathematic point of view the best-fit source is a small (point) pressurized spheroid having vertical symmetry axis at a depth of 2000 m; location, aspect ratio, and volume change were left free in the inversion. The thesis is that this two-source model (a quasi-horizontal elongated crack + pressurized spheroid), can explain all the inflation and deflation phenomena at CF. Indeed, the deformation pattern is stationary during the period of

availability of SAR data, and to prove this, a correlation plot between the vertical displacement, at different points of CF which are representative of the behavior of the region, and the actual vertical displacement in the reference area, is produced. Points out of Solfatara are always very close to the best-fit 1993-1997 regression lines (indicating linear time-invariant correlation), while points related to Solfatara depart largely and non-randomly from the best-fit 1993-1997 regression line. This correlation plot suggests the stationarity of the deformation pattern, except for the Solfatara area, during the availability period of SAR data. This seems to confirm the thesis of two-source model during the whole investigated period (1970 to 2010).

The time histories of the two volume changes are estimated by a multiple linear regression, using the time histories of leveling uplift, and SAR vertical and eastward displacements data. The two sources volume changes histories are somewhat similar but not equal, supporting the existence of a genuine local deformation source at Solfatara against the emergence of a mere distortion of large-scale deformation.

Subsequently the analyzed period is extended, until October 2013, using cGPS data, inverting leveling and precisising traversing data as previously described, but joining displacements cGPS data, for the period 2011-2013 (uplift period), scaled on 1980-83 displacement. The two-source model is confirmed, indeed residuals, with respect to the two-source model, are always almost null. Although reality is probably much more complex, this simple model explains 1970–2013 CF deformation within ground-displacement data errors and is consistent with Solfatara geochemical conceptual models, fumarolic geochemical data, and seismic attenuation imaging of CF. The observation that the CF deformation pattern can be decomposed into two stationary parts is hardly compatible with several recent works which proposed multiple sources with different features acting in different periods, fluid injections implying ample changes of large-scale deformation pattern over time, complex spatio-temporal patterns of distributions of volumetric sources. Our large-scale deformation source is in agreement with the possible presence of a small melt volume – located below the maximum uplift area of the major 1982-1984 unrest between 3000 m and 4000 m in depth – recently evidenced by seismic attenuation imaging (*DeSiena et al., 2010*). The Solfatara deformation source is consistent with the Solfatara geochemical conceptual model (*Chiodini et al. [2010, 2013]*) and related vertical displacements (*Rinaldi et al., 2010*). According to *Chiodini et al., [2010, 2013]*, a plume of vapor-liquid biphasic zones and single vapor zones is fed by a mixture of magmatic and meteoric flu-

ids. The magmatic component enters the base of the system at about 2000 m in depth, where it mixes with and vaporizes the liquid of meteoric origin. Hydrothermal fluids play a role, in the ground deformation, due to thermal expansion and pore pressure acting on rocks. *Rinaldi et al. (2010)* simulated the heat and fluid flow driven by the arrival of magmatic fluids from greater depth and calculate the rock deformation arising from simulated pressure and temperature changes within a shallow hydrothermal system. We employ a mathematical model, based on the linear theory of thermo-poro-elasticity and on a system of distributed equivalent forces. Results show that stronger degassing of a magmatic source may cause several centimeters of uplift (*Rinaldi et al., 2010*). *Fournier and Chardot (2012)* have recently shown that, when ground deformation is related to hydrothermal processes and satisfied by simple point or finite sources, ground deformation is likely to be controlled by the poroelastic response of the substratum to pore-pressure increase near the injection point of hot magmatic fluids into the hydrothermal system. The retrieved source depth points to that of the injection area. As regards geochemical data at Solfatara, the fumarolic CO_2/H_2O ratio shows a mild increasing trend after 2000; this change has been interpreted as the effect of an increased contribution of the magmatic component in the fumarolic fluids (*Chiodini et al., 2012*). A sharp increase of the CO_2/H_2O ratio overlaps the trend during 2007. Also the partial pressure of CO_2 (estimated on the basis of fumarolic compositions and on the assumption of thermodynamic equilibrium within the $H_2O - H_2 - CO_2 - CO$ gas system) starts to increase after 2000 with an evident jump in 2006. The same distinct periods (before 2000, 2000 to 2006, after 2006-2007) are evident in the time history of ΔV_{PS} . Obviously, potency changes of the large-scale deformation source and/or the Solfatara one could be driven by magma and/or magmatic fluids fed by a deeper (≈ 7500 m) magma chamber (*Zollo et al., 2008*). In principle, migration of magma and/or magmatic fluids from the deeper magma chamber should give its own deformation signal.

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