The Campi Flegrei Deep Drilling Project 'CFDDP': Understanding the Magma-Water Interplay at Large Calderas.

*Giuseppe De Natale[1], Giovanni Perillo[2], Claudia Troise[1] and Paolo Gasparini[3]
[1]INGV – Osservatorio Vesuviano, Naples (I), [2]Università Parthenope, Naples (I),
[3]AMRA-Campania, Naples (I)
*Corresponding author(s): Giuseppe.denatale@ov.ingv.it, giovanni.perillo@uniparthenope.it

Abstract: Campi Flegrei caldera, including part of the densely urbanised city of Naples represents, like several similar volcanic areas (Yellowstone and Long Valley, USA; Santorini, Greece; Iwo Jima, Japan, etc.), the most explosive volcanism on the Earth: that associated to collapse calderas. Understanding the mechanisms of activity of such areas is fundamental for volcanological research and also for correct evaluations of eruption hazard. Such areas, for instance are often subject to very peculiar unrest episodes, involving very large (up to several meters) uplift and subsidence episodes, generally without interbedded eruptions. Understanding the mechanisms of these unrests, and their possible links to impending eruptions, is fundamental for a correct assessment of eruption hazard and forecast. Campi Flegrei Deep Drilling Project (CFDDP) is a large International, multidisciplinary project, aimed to understand the mechanisms of caldera volcanism by studying directly, by crustal drilling, the deep structure of the Campi Flegrei caldera. One of the main aims of the project is to discriminate the mechanism for caldera unrest episodes. In this paper, we present simulations for the most likely of such mechanism, obtained by the use of COMSOL multiphysics. Results indicate that the most critical parameter to measure during the drilling, in order to discriminate the unrest mechanism, is permeability.

Keywords: Insert two to five keywords that are descriptive of the work presented in the paper. Separate keywords by commas.

1. Introduction

Campi Flegrei caldera (fig.1) is a typical example of the most explosive volcanoes on the Earth: the large collapse calderas. These areas include famous volcanoes like Yellowstone (USA), Santorini (H), Long Valley (USA), Rabaul (PNG), Galapagos (EC). Large collapse calderas are all formed by the so-called 'ignimbritic eruptions', at the higher side of the eruption power spectrum, which represent global catastrophes, so being one of the most serious threats to mankinds, fortunately very rare (1). Besides the extreme 'ignimbritic eruptions', calderas can give rise to the whole eruptive spectrum, from quiet lava effusion to Strombolian, Vulcanian and Plinian explosive eruptions, which represent all the gradation in explosive power (1,2). However, the most typical eruptive style of almost all the calderas is the so-called 'hydromagmatic' one, in which rising magma from deep reservoirs intercept large shallow aquifer systems generating an explosive mixture able to finely fragment magma leaving the typical deposits known as 'tuff' (3). The erupted mix of fragmented magma and water impacts the ground in the form of 'pyroclastic flows and surges', the most dangerous products of explosive eruptions, with velocities on the order of hundreds km/h, able to completely destroy any form of life where they pass, due to the dynamic overpressure and high temperature (300°C-600°C) (e.g. 1). Collapse calderas are also affected by large ground deformations, both as uplift and subsidence. At Campi Flegrei, the level of secular deformation in the last 2000 years spanned a range of more than 20 m (4). Secular ground deformation is typically subsidence, at a rate of 1.5-2.0 cm/year, except for some fast uplift periods lasting some decades. A fast uplift period lasted about 40-50 years preceeded for sure the only historical eruption of Mt. Nuovo in 1538, which was a minor one (about 0.02 cubic km of erupted material). At least another uplift period in historical past has been recently hypothesized (5) on the basis of radio-carbon dating of the time of death of some marine molluscs present on the marble columns of Serapis Temple ruins of the Roman 'Macellum' (market), which indicated a period of emersion of molluscs well above the sea level (ground uplift). The last uplift period started in 1969, and, except for the period 1985-2004 of relative subsidence, seems to be still in progress, with

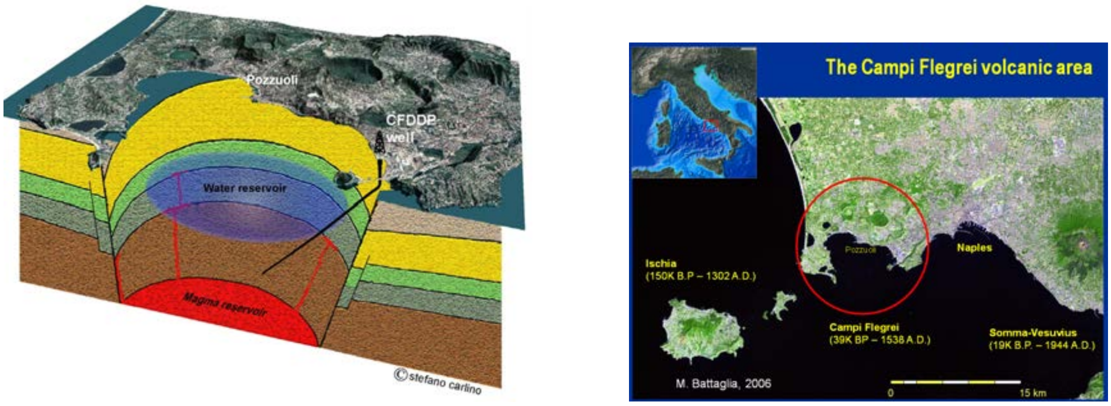

Figure 1. Campi Flegrei Deep Drilling Project. The figure shows the Campi Flegrei caldera (right) and the 3D representation of the deep hole on a idealized sketch of the substructure (left). The Campi Flegrei topography image is courtesy of G. Vilardo.

variable rates (from 1 m/year in 1984 to about 1-2 cm/year today). Since '90s, volcanological research has pointed out that a key role in the up and down ground motion should be played by the complex interaction between magmatic heat and shallow geothermal systems (4, 6). What has been observed and inferred at Campi Flegrei seems to be common to all collapse calderas, so that the complex interaction between magma and aquifers is likely to be the key mechanism affecting both the peculiar eruptive style and the large deformations occurring during unrests. The main problems still opened for understanding the volcanic mechanisms at calderas can be synthesized in the following questions:

1) What is the depth of the magma reservoirs and what the rheological state of residual magma from the caldera formation (i.e., liquid, solid or 'mushy')?
2) What are the mechanisms of complex magma-water-gas interaction leading to ground movements, seismicity and eruptions?
3) What are the typical precursory patterns before eruptions and how could we recognise them?
4) How could we recognise, among the precursory patterns, the ones preceding ignimbritic eruptions, which are a real threat to mankind, and how could we defend from them?

2. The role of deep drilling at calderas: the CFDDP

The modern volcanological research, conducted with classical geophysical methods of 'indirect' inference, i.e. seismic, gravimetric, geodetic, etc., has reached its limits in the understanding of mechanisms of eruptions and unrests at calderas. Although such methods, particularly for Campi Flegrei, shed light on several aspects of this important and intriguing kind of volcanic activity, they were not able to give convincing answers to the still open questions mentioned in the previous paragraph. A decisive step forward is then only possible by direct observation of the volcanic sub-structure and of magma-water interaction mechanisms. Direct observation can only be made by deep drilling. However, given the present technological limits for crustal drilling, related mainly to the maximum depth and the thermal state, deep drilling at calderas is not an easy task, considering that the most interesting depths to study should be those at which temperature reaches 500°C-600°C, so encompassing the limit of critical water temperature, of brittle-ductile transition, and likely penetrating the ductile carapace which should be located some kilometres above the magma chamber and contains the magmatic gases exsolved by it (7). In view of the correlated technological problems given by depth and temperature, the ideal case would be to drill into a very active caldera, with the most interesting volcanic structure and high temperature located at relatively shallow levels. This is exactly what Campi Flegrei represents, comparing for instance the very hot temperatures found by the previous drillings of AGIP-ENEL (8) with the rather low temperatures found at Long Valley caldera (USA) (9) during similar experiments. Critical water temperature has been found here in the range 2.5-3.0 km, brittle-ductile transition should be slightly deeper, and magmatic gases likely responsible of the recent spectacular unrests should be located between 3 and 5 km (4). In addition, understanding in detail the volcanic hazard of Campi Flegrei caldera has enormous positive implications for society, because the area is one of the most densely populated in the Western Countries, making volcanic risk here by far the highest one in the World. These considerations pushed the volcanological community to identify Campi Flegrei as the ideal site for one of the most important and technologically demanding scientific experiments in geophysics and volcanology.

The CFDDP main goal is a deep drilling reaching about 4 km of depth. The schematic picture of the deep well is also reported in fig.1. The well will sample, in vertical, the shallowest part (500-700 m) of the structure located at the caldera borders (i.e. where the shallow structure has not been substantially alterated by the collapse and subsequent filling with recent eruptive products). Below such depths, the well will be deviated, with an angle of 25°, pointing towards the center of Gulf of Pozzuoli, which is also the center of caldera. Along its way, the well will sample the most seismically active layers (1-3 km) and the geothermal system for its whole depth; it will cross the limit of critical temperature (2.5-3.0 km) and will approach and cross the brittle-ductile transition, ending, at about 4 km, to sample the layers, likely saturated of magmatic gases exsholved by an underneath magma chamber, embedded in the ductile layer. At the maximum depths, the drilling should encounter temperatures exceeding 500°C, and would shed light on three key questions linked to the volcanological interpretation of Campi Flegrei and similar calderas. Firstly, it should penetrate the layer which is considered, by almost all the authors (i.e. 4, 10, 11, 12) responsible for the uplift and unrests of the last 40 years. Furthermore, direct drilling could solve the important question, posed by recent active seismic soundings in the area, about the nature of the sharp increase in P and S wave velocity in the depth range 3.5-4.0 km. Judenherc and Zollo (13) ascribed such high velocities to the top of limestone layer, although Vinciguerra et al. (14) argued such high velocities are more consistent with solidified magma (mush), which could explain where are the large volumes of magmas (some hundreds km^3 at least) which should be remained in the shallow magma chamber after the last ignimbritic eruptions (39,000 and 15,000 years ago). But, more importantly, the deepest part of drilling, between 3 and 4 km of depth, will be crucial to measure the thermal gradient below the geothermal system, i.e. at depths in which there is no convecting liquid water which can alter the typical, mostly linear thermal gradient expected for pure conductive heat propagation. Measuring such thermal gradient, it will be possible to linearly extrapolate it to give a precise and almost direct estimate of the depth at which rocks reach the typical magmatic temperature (about 950°C for these magmas), representing the top of the shallow magma chamber at Campi Flegrei.

3. Modeling unrests: surface deformation induced by deep fluid injection

One of the main goal of the CFDDP is to answer the crucial question of how large unrest episodes involving ground deformation of several meters relate with eruptive episodes. Such an answer is intimately related to understand if a mechanism for such up and down deformation can be generated by increase of pressure and temperature into shallow aquifers as due to deep hot fluid migration. In order to build a numerical model for such a mechanism, we used a two-steps scheme as follows:

Step 1 – Thermofluid-dynamical simulation of pressure and temperature changes induced in the shallow aquifers by time-dependent injection of hot fluids;

Step 2 – Elastic modeling of ground displacements generated, at the free surface, by the pressure and temperature changes computed from the step 1.

Actually, computations for the step 1 have been made using the THOUGH2 algorithm (15), whereas computations for the step 2 have been obtained using COMSOL. Applying such a two steps procedure we implicitly neglect possible changes to the thermofluid-dynamical properties of the medium induced by ground deformations. Modelling such changes, which are presumably very small and hence negligible if limited within the elastic limits (i.e. not involving extensive rock fracturing) would require the use of much cumbersome thermo-poro-elastic methods, which would however fail out of the elastic limit. Details of the procedure used to simulate the changes in pressure and temperature as due to deep fluid injection can be found in (16). Here, we want to show how the use of COMSOL, coupled with the THOUGH2 algorithm, made possible to simulate ground deformations due to such mechanism.

For such a computation, the caldera volume is subdivided into a dense mesh of volume elements, with denser sampling in the central part (see fig. 2)

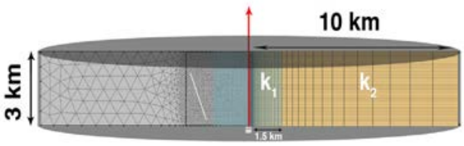

Figure 2. Axial symmetric model domains. Right side: finite-difference computational domain for thermofluid-dynamical modeling. The inner part of the mesh (r<1.5 km) is characterized by a permeability K1 , while the external part has a permeability K2. On the top of the model, Temperature and Pressure are fixed at atmospheric values, while on the bottom just the Temperature is fixed at a 300°C value. Left side: finite element mesh for computation of the ground deformation from the changes of pressure/temperature. The mesh is variable in size, with denser elements close to the center (in the first 3 km). A white line shows the position of the ring fault system added to the model (17).

In each element we consider the pressure and temperature changes as computed by the fluid-dynamical model. The surface displacement at any point is hence computed as the sum of individual contributions of each volume element of the mesh. The gravity term does not appear in the deformation equations, because the deformation and stresses are referenced to an initial state that is in static equilibrium. Since the deformed state is also at static equilibrium, the gravity term drops out when then equation is formulated in terms of the change from the initial static state. In addition, the computational mesh itself does not deform. As boundary conditions, the surface of the cylinder enclosing the axial-symmetric model is rigid, such as the bottom of model. The upper surface boundary conditions of zero stress simulate the conditions of the free surface of the Earth. The application of COMSOL multiphysics with the set of pressure and temperature changes produced by fluid injection at each time interval generates, at each time, a field of displacements in the volume. Fig. 3 shows the field of ground deformations computed by COMSOL in the axial-symmetric volume during one of the simulations; the surface profile shows, at an enhanced arbitrary scale, the shape of surface deformation, which can be compared with geodetic data. The main result of the computed simulations is shown by fig. 4, which reports the time evolution of maximum surface deformation (computed at the center of the mesh). It is apparent, from the figure, that the permeability of the host rock is the most critical parameter to give a good fit to the observed data. In order to give a good fit to the observed data of ground deformation as a function of time, permeability value in the inner part of the caldera must be on the order $K1=10^{-15}$ m^2. The best fitting curve, indicated with the red line in fig. 4, also corresponds to an outer caldera permeability $K2=10^{-16}$ m^2. The gray area, in the figure, indicates the time interval the input flow of water from below is maintained at the maximum rate of 8 kt/day; such interval, in our model, is 3 years, after that the input flow is decreased to 1.15 kt/day. It is worthy to note that resulting time dependent deformation is very sensitive to permeability values. Increasing the permeability, the overpressure induced by fluid injection decreases, so that higher mass flow is required to match the deformation amount. Furthermore, the subsidence resulting by a sharp decrease of the mass flow is very rapid for high permeability and very slow for low permeability. There is only a narrow permeability range which produces a time evolution of surface deformation matching the observed behavior.

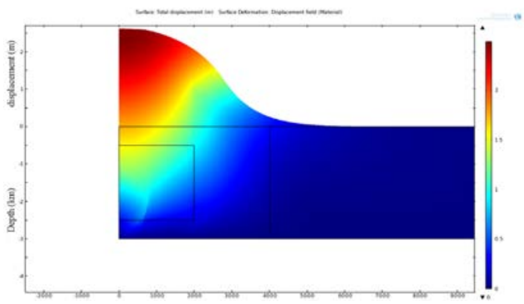

Figure 3. Example of vertical ground displacements computed, using COMSOL, in the caldera volume and at surface (enhanced profile in m.), with the best fitting parameters.

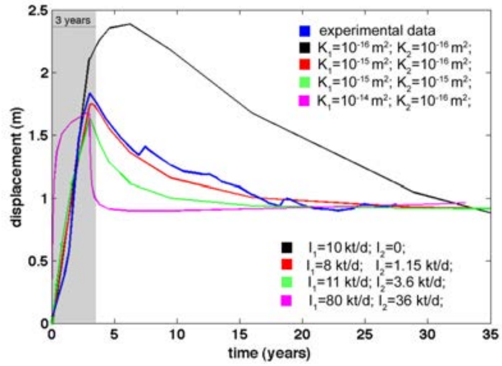

Figure 4. Time-dependent vertical displacements due to fluid injection at the bottom of the mesh, for the best fitting parameters. Blue line represents the values of the vertical displacements observed at the Campi Flegrei area in the period 1982-2009. Red line is related to a continuous injection of pure water, lasting three years, at an injection rate, I_1, followed by a phase of injection at a reduced rate I_2. Green line is related to injection of a water and CO2 mixture. Related injection rates are shown in figure. The H_2O/CO_2 ratio is 10/1.

4. Conclusions

The Campi Flegrei Deep Drilling project is structured as a large multidisciplinary project, whose main focus will consist of a deep crustal drilling in the crust of Campi Flegrei caldera, to overcome the whole aquifer system. The deep drilling will reach a depth of 3.5 km at least, with an expected temperature up to 500°C. The project will shed light on the mechanisms of volcanic activity at large collapse calderas, which represent the most explosive and potentially catastrophic volcanism all over the World. Besides the high volcanological impact, the project will likely have a large impact in the fields of borehole monitoring technologies and, particularly, in the field of geothermal technologies and exploitation. Campi Flegrei, in fact, represents one of the hottest volcanic areas, with extremely high shallow geothermal gradients, up to 200°C in the first 200-400 m of depth.

One of the main scientific goals of the project will be the understanding of the unrest mechanisms at collapse calderas, which often involves several meters of ground deformations, with alternate uplift and subsidence, not necessarily intercalated or followed by eruptions. Understanding the mechanism of such unrests, and their relation with magmatic and/or geothermal processes, is of fundamental importance, mainly for eruption hazard assessment. Actually, two basic mechanisms are proposed in literature to explain such unrests: a purely magmatic one, implying the highest related eruption hazard and a geothermal one, implying more moderate eruption hazard. Accurate in-situ measurements of rock parameters like rigidity, porosity, permeability, etc. represents one of the main goals of the deep drilling experiment, aimed to discriminate the nature of unrest mechanisms. In this paper, we have presented detailed simulations of a model involving injection in the shallow geothermal system of deep hot fluids of magmatic origin. The simulations put in evidence that, in order to reproduce the observations, this kind of model requires permeability values of about 10-16 m2. Actually, permeability at depth is almost impossible to measure in indirect way, and even from previous drillings rock cores. This is because intact samples are not representative of the real situation at depth, in which permeability may increase of several orders of magnitude due to faults and fracturing. Measurement of in-situ permeability during the deep drilling is then the only method which can give a complete answer to this fundamental question, based on the simulations presented here.

5. References

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