Numerical Evidences of Unrest Related Electromagnetic Effects in the Campi Flegrei Caldera

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Abstract: Increasing the observables that can be monitored will raise a better evaluation of the volcanic risk. Electric, magnetic and electromagnetic methods are widely used to monitor active volcanoes. A numerical study performed using the Comsol Multiphysics® code is presented, carried out to evaluate the effects on the main physically observable fields of an ideal unrest episode of the Campi Flegrei Caldera (Italy). Four distinct unrest phases have been modeled, each one characterized by a fixed injection of a multiphase mixture of water and CO2 in the bottom of the caldera. The thermo dynamical evolution of the hydrothermal system has been evaluated in terms of temperature and pressure changes. In the following, these changes in the caldera state are considered as sources of electric potential and magnetic anomalies generated during the ideal unrest.

Keywords: Electric anomalies. Magnetic anomalies. Volcano monitoring.

1. Introduction

Electric, magnetic and electromagnetic (em) methods are widely used to monitor active volcanoes. A review of such applications is presented in Johnston (1997). Em signals were recorded in correspondence of several volcanic eruptions, for example in the case of the Mt. Unzen in Giapppone (Hashimoto and Tanaka, 1995), of Merapi in Indonesia (Byrdina et al., 2003), Etna in Italy (Del Negro and Ferrucci, 1998) and during rapid deformation in Long Valley in California. Observations of volcanomagnetic effects are reported also for the Mt St. Helens and for Piton de la Fournaise. During volcanic activity, different physical processes give rise to perturbations of electric and magnetic fields as the physical conditions (stress, temperature, flow, etc.) and the geometry of the magmatic bodies change. Large-scale variations in electromagnetic fields were also recorded before the eruptions, resulting related to the mechanical stress accumulation and consistent with the ground deformation. These eruptions related changes, occurring mainly near the active vents, result strong and localized, and related to huge mass displacement, rocks magnetization/demagnetization and stress changes effects. Thermal contributions result instead related to the transport of large and high temperatures fluid volumes. Generally, the experimental observations indicate that both the magma upwelling and the hydrothermal system reactivation phenomena significantly affect the values of the em fields. Several studies have explained this relationship linking it to the effects of circulation of charges induced by the endogenous dynamics of volcanic structures, deducing that the recording of em fields provides information for the determination of eruptive hazard comparable to those contained in the gravimetric and deformation signals, normally monitored. A numerical study performed using the Comsol Multiphysics® code is presented, aimed to evaluate the effects, on the main physically observable fields, of an ideal unrest episode occurring at Campi Flegrei Caldera (Italy), one of the most risky volcanic areas worldwide. Four distinct unrest phases have been modeled, each one characterized by a fixed injection of a multiphase mixture of water and CO2 at the caldera bottom. The thermo dynamical evolution of the whole hydrothermal system has been evaluated in terms of temperature and pressure changes. In the following, these changes in the caldera state are considered as sources of electrical potential and magnetic anomalies, simulated during the ideal unrest using the AC/DC modulus.

2. Method

The simulation approach, applied to study the effects of the hydrothermal system reactivation in the Campi Flegrei Caldera, consists in a two-steps procedure. Initially, the coupled multiphase, multi-component fluid flow and heat transport problem has been solved using the numerical code TOUGH2. This code allows to compute the mass and heat exchange related to multidimensional flows of multiphase (gas and liquid) mixtures of many components within a porous medium of assigned permeability (Pruess, 1991; Pruess et al., 1999) through the solution of the continuity equations for the mass and heat flows, considering a multiphase version of the Darcy law. It assumes local equilibrium between fluid and rock matrix, through the direct discretization of the balance equations for mass and energy describing the thermodynamic conditions of the system in their integral form, in a scheme called integral finite difference method (Edwards, 1972). The solution consists of a set of values assumed by the independent (or primary) thermodynamic variables (pressure and temperature) as function of time, at the nodes of the elementary cells discretizing the physical space. All the geometric information for the flow problem is provided through the specification of the cell volumes, interface areas, nodal distances and components of the gravity acceleration in the direction of the line connecting the nodal points. A review of the solved equations for this problem is presented in Ingebritsen et al. (2010). Once the fluid thermo-dynamical evolution of the system is known in terms of temperature and pressure changes in the whole volume, the induced effects in terms of electric and magnetic field has been estimated in a following steps.

In our framework, the evaluation of these induced effects has to be coupled with the hydraulic flows problem, however a partial decoupling is possible, due to the fact that the field generated by the flow of the pore water does not measurably influences the fluid displacement into the porous medium (Revil et al., 1999a and b; Souied Hamed et al., 2014) and a wide range of simulations adopts a one-way coupling approach in similar simulations (Reid, 2004; Todesco et al., 2004; Hurwitz et al., 2007; Troiano et al., 2011; Troiano et al., 2013). Therefore, separate equations for the electric, magnetic and gravity fields and for the ground deformations with respect to the fluid flows are solved in the present case using Comsol Multiphysics®.

2.1 Electrical anomalies

Electrokinetic effects describe the interaction between electric fields and flow of fluids, in particular, the motion of fluids forced by a pressure gradient through a porous medium can in turn generate voltages, so-called electrokinetic potentials. This effect has long been studied to explain electrical fields near volcanoes and active hydrothermal areas (Zlotnicki and Nishida, 2003). Fields have been observed prior to eruptions at many volcanoes and have been successfully used to delineate active faults.

The electric potential changes induced by fluid injection has been reconstructed resolving the Poisson equation by Comsol Multiphysics®

$$\nabla^2 V = \rho C \nabla^2 P$$

where P represents the fluid pressure, ρ the electrical resistivity, and C represents the coupling term, expressed in [A m^{-1} Pa^{-1}], characterizing the electrical current density produced in response to the unit hydraulic gradient. The coupling coefficient has been assumed as a constant during the simulation. A uniform resistivity half-space of ρ=10 Ωm has been considered.

2.2 Magnetic anomalies

2.2.1: Magnetic changes due to hydraulic flows.
Given the current system that was established in the electrokinetic system, the magnetic field follow the Ampere Law in the quasi-static formulation of the Maxwell equations (e.g. $\nabla\times\mathbf{E}=0$):

$$\nabla\times\rho(\nabla\times\mathbf{H}-\mathbf{J}^e)=0.$$

In fact, several observations of magnetic fields at volcanoes in the past were interpreted as caused by electrokinetic currents (Zlotnicki and Le Mouël 1990, Michel and Zlotnicki 1998).

2.2.2: Piezomagnetic changes
Changes in the Stress distribution produce variations in the magnetization of rocks, resulting in a local magnetic field of about few nT (Nagata, 1970; Pozzi, 1977). Piezomagnetic changes are calculated using the Poisson equation for the magnetic potential (Currenti et al., 2009):

$$\nabla^2 W = \nabla(\Delta\boldsymbol{\Gamma})$$

where W represents the magnetic potential and ΔΓ represents the change in rock magnetization, express as function of the mechanical stress, following the:

$$\Delta\mathbf{\Gamma}=3/2\cdot\beta\mathbf{T}\cdot\mathbf{\Gamma}$$

where β represents the stress sensitivity ($2*10^{-9}$ Pa^{-1}) and **T** is the deviatoric stress tensor. Again an uniform resistivity half-space of ρ=10 Ωm has been considered.

3. Numerical model

The computational model assumed consists of a cylinder with a height of 3 km and a radius of 10 km (Fig. 1). Also the mesh grid considered for TOUGH2 and for Comsol Multiphysics are shown.

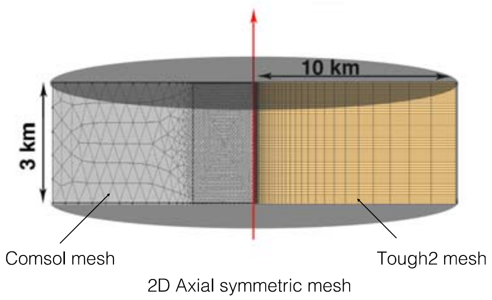

Figure 1. Axial-symmetric model domains used for thermo-fluiddynamical modelling and for electric and magnetic fields computation. Right-hand side: finite-difference computational domain for thermofluid dynamical modelling. Left-hand side: Comsol Multiphysics element mesh for computation of the electric and magnetic from the changes of pressure and temperature.

The cylinder, representing the Campi Flegrei caldera, is characterized by the permeability reported in Fig.2. We assume that the water table coincides with the ground surface and that the topography is flat. In contrast to stratovolcanoes where topography is a major control on hydrodynamics (Hurwitz *et al.* 2007), topographic gradients in calderas, as such of the Campi Flegrei, are in fact relatively small and the water table is usually close to the ground surface.

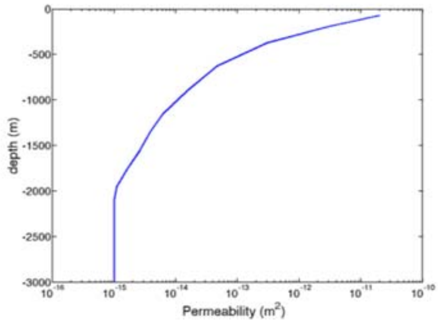

Figure 2. Permeability vs. depth related to the model of Fig.1.

The height of the cylinder, 3 km, represents the maximum depth of the Campi Flegrei aquifers as determined by previous drillings in the area (AGIP 1987). The cylinder has been initially parted in a 3D grid of elementary cells considered during the TOUGH2 simulations. It presents a horizontal spacing ranging from some meters (in the central part) up to 1 km (at the outer edges), while the vertical spacing varies from some meters in the fluid injection area, up to 100 m in the outer slices. A tetrahedral mesh of 45502 volume elements, 3350 surface elements and 448 side elements has been considered for Comsol Multiphysics. Numerical tests were performed on both meshes to check the stability of the solutions obtained by varying the elementary cell dimensions, in order to verify the absence of significant boundary effects. We defined the dimensions of the prism through looking for a good compromise between maximum stability and minimum computational effort. The tests showed that the results are very stable with respect to further mesh enlargements, and are practically indistinguishable from an infinite mesh. Flow systems are initialized by assigning, as initial condition, a complete set of primary thermodynamic variables to all grid blocks, in which the flow domain is discretized. Pressure distribution is initially assumed as basically hydrostatic, starting from an atmospheric value at the model surface and linearly increasing with depth down to the bottom of the model. Temperature distribution is also linear, varying from 10°C on surface up to 300°C on the bottom.

At the top boundary, temperature and pressure are set constant to represent the water table condition. At the bottom of the model, just the temperature is held fixed. Pressure changes are enabled to simulate the effects of large fluid injections in the lower parts of the caldera. Fluid sources are placed at the base of the cylinder, through an area with a radius of 150 m. Pure water or a mixture of water and carbon dioxide are injected at a temperature of 350°C and at a fixed rate of injection. Four distinct unrest phases has been considered, as reported in Table 1.

Apart from such fluid injections, the cylinder is isolated from the outside and is impervious on the external edges and along the lower base.

Values of the parameters characterizing the physical properties of rocks (density, porosity, specific heat and thermal conductivity) are chosen based on literature and data wells (e.g. AGIP 1987; Rosi and Sbrana 1987) and remain constant during simulations.

Electrically, a null flux condition is imposed at the insulating air-ground interface and the potential is considered as null on the external edges.

4. Results

Results are now reported for the four unrest phases modeled. Each phase results characterized by a specific fluid injection rate, as indicated in Table 1.

Changes in SP related to the maximum uplift point are reported as function of time in Fig.3.

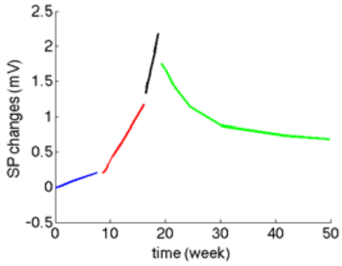

Figure 3. Self Potential anomaly vs. time related to the maximum uplift point. Each unrest phase considered in related to a distinct color.

A few mV electrical anomaly is retrieved as consequence of the simulated unrest. This anomaly results above the detectability threshold (usually considered as 0.1 mV). However the presence of noise both anthropic or related to the natural oscillations of the water table could likely mask the SP signal and so application of statistical techniques to obtain an acceptable s/n ratio are not avoidable.

Changes in the Magnetic Field are reported in Fig.4 where the contribution due to the volcanomagnetic and to the piezomagnetic effects are both considered. A maximum magnetic anomaly of 0.5 nT is retrieved, again slightly above the sensibility threshold (usually considered as 0.1 nT).

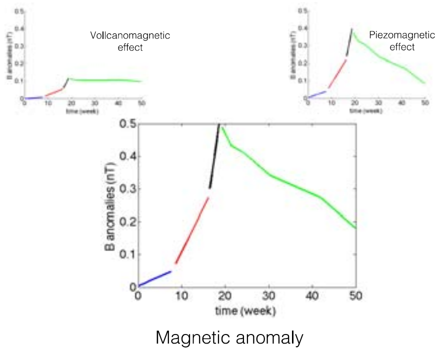

Figure 4. Magnetic anomaly vs. time related to the maximum uplift point. Each unrest phase considered in related to a distinct color. Single

volcanomagnetic and piezomagnetic component are reported, as well as the total anomaly.

5. Conclusion

Electric and magnetic (both volcanomagnetic and piezomagnetic) fields produced by hypothetical unrest scenarios for the Campi Flegrei Caldera were evaluated by Comsol Multiphisics®. For both components detectable, also if weak, anomalies has been retrieved. As the ground displacement and gravity changes, that represent the geophysical observable parameters usually monitored, the analysed fields show an analogous temporal evolution (Todesco and Berrino, 2005; Rinaldi et al., 2011; Troiano et al., 2011). Increasing the number of observables that can be simulated and compared with available observations will result in a better evaluation of the eruption hazard at volcanoes.

9. References

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Table 1: Unrest phases

Unrest phase	Time	H_2O rate	CO_2 rate
Phase I	8 weeks	10 kton/day	4 kton/day
Phase II	8 weeks	25 kton/day	10 kton/day
Phase III	2 weeks	70 kton/day	28 kton/day
Phase IV	32 weeks	5 kton/day	2 kton/day