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INTEGRATED MODELLING OF GEOPHYSICAL OBSERVATIONS AT ETNA VOLCANO

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Abstract

Geodetic, gravity and magnetic field changes caused by overpressure sources in volcanic areas were computed by an integrated elastic 3-D model based on Finite Element Method (FEM). The numerical computations are focused on the modeling of a complex description of Etna volcano in order to evaluate the effect of topography and medium heterogeneities. Ground deformation, gravity and magnetic changes are investigated by solving a coupled numerical problem. Different multi-layered crustal structures constrained by seismic tomography and geological evidences were considered to evaluate the effects of topography and medium heterogeneities. Comparisons are made between analytical and numerical solutions to estimate the differences caused by these features. Our findings highlight that heterogeneity and topography engender deviations from analytical results in the geophysical changes produced by pressurized sources under elastic conditions. Hence, neglecting the complexities associated with morphology and medium properties of Etna volcano in standard analytical studies, we could obtain an inaccurate estimate of source parameters from geophysical observations. The FEM approach presented here allows for considering a picture of a fully 3D model of Etna volcano, which could advance the reliability of model-based assessments of ground deformations, gravity and magnetic observations.

Key words
Numerical solutions, magnetic anomalies, volcano monitoring.

1 Introduction

Complex systems so as the volcanoes should be studied using an integrated modeling of different geophysical measurements. The integrated approach is probably the only procedure capable of giving a global response to the volcanological problem and to minimize interpretative ambiguities The modifications in the stress field or the thermodynamic state within the volcanic edifice induce a wide variety of geophysical signals, which can be observed before and during eruptive processes. The different geophysical measurements, recorded by the monitoring networks installed in the volcanic areas, are generally interpreted separately from each other and the consistency of interpretations coming from different methods is qualitatively checked only a posteriori. Over the last decade at Etna volcano, where volcanological tradition is consolidated, and scientific and technological standards are highly advanced, geodetic, gravity and magnetic investigations have been playing an increasingly important role in studying the eruptive processes [Napoli et al., 2008; Bonforte et al., 2008; Carbone et al 2007]. A series of analytical solutions, based on a homogeneous elastic half-space model, have been devised and widely used in literature [Sasai, 1991; Utsugi, 2000; Okubo, 1992] for modeling ground deformations, gravity and magnetic variations due to volcanic sources. It is worth noting that Etna volcano is elastically inhomogeneous, as indicated by geological evidences and seismic tomography [Chiarabba et al., 2000; Tibaldi and Groppelli 2002], and that rigidity layering and heterogeneities are likely to affect the magnitude and pattern of observed signals. To overcome these intrinsic limitations and provide more realistic models, which allows considering topographic effects as well as complicated distribution of medium properties we use the finite-element method (FEM). Comparisons are made between analytical and numerical solutions to estimate the differences that could be caused by medium heterogeneities and topography.

2 Numerical model

The gravity anomaly g can be calculated by solving the following boundary value problem for the gravitational potential Φ_g:

$$\begin{array}{l} \nabla^2\Phi_g = -4\pi G\Delta\rho(x,y,z) \\ \Delta g(x,y,z) = -\frac{\partial\Phi_g}{\partial z} \end{array} \qquad (1)$$

Where G is the gravitational constant and $\rho(x,y,z)$ is the density distribution given by:

$$\Delta\rho = \delta\rho_1 - \rho_0 divu - u\cdot\nabla\rho_0 \qquad (2)$$

The first term $\delta\rho_1$, on the right side of Eq. 2, is the density change related to the introduction of the new mass, the second term ρ_0 is the material density before deformation and is related to the contribution due to the volume change arising from compressibility of the material, the third term u is the displacement field and is originated from the displacement of density boundaries in heterogeneous media. As for the magnetic field, the piezomagnetic anomaly can be described by the scalar potential formulation (Sasai, 1991):

$$\begin{array}{l} \nabla^2\Phi_m = -4\pi div\Delta J \\ \Delta J = \beta\mu\left\{-\delta_{ij}divu + \frac{3}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)\right\}J_i \end{array} \qquad (3)$$

where Φ_m is the piezomagnetic scalar potential, ΔJ is the magnetization change, J is the initial magnetization, μ is the shear modulus and β is the stress sensitivity. The Eqs. 1, 2 and 3 show how the deformations of the elastic medium are related to changes in the magnetic and gravity fields. This formulation shows that the deformation field and the potential anomalies produced by volcanic sources need to be modeled simultaneously. Gravity and magnetic anomalies cannot be interpreted only in term of additional mass input disregarding the deformations of the surrounding rocks. Starting from the numerical solution of elastic deformation and its derivatives, the gravity and piezomagnetic anomalies can be computed using the Eqs. 1 and 3 by FEM technique. FEM solutions strongly depend on numerical parameters. In general optimal size of the domain, meshing, and additional conditions to be imposed over the boundary are not known a priori, so it is necessary to calibrate the model. Preliminarily, some benchmark tests were carried out on the well-known solution of Mogi model to compare the analytical results with numerical ones assuming an homogeneous half-space medium. Once the accuracy of FEM solutions has been verified, we incorporate some realistic features in order to evaluate their effects. An effective contribute could be given by topography, since Mt. Etna is rather asymmetric with a prominent mass deficit in the eastern sector with respect to the western sector, in correspondence of Valle del Bove. Moreover, the recent seismic tomography studies showed the presence of a high rigidity body centered below the SE sector. To this regard we choose to include in the FEM model the real topography of Mount Etna extending on an area of 100 x 100 x 100 km and the magnetic and density heterogeneities of the medium and the elastic properties distribution as derived from tomographic investigation.

3 Discussion and Conclusion

The effects of topography and medium heterogeneities were considered separately in order to appreciate each single contribute. So theoretical geophysical signals, computed by the finite element method, have been compared to analytical results computed for a homogeneous half-space medium (Fig.1).

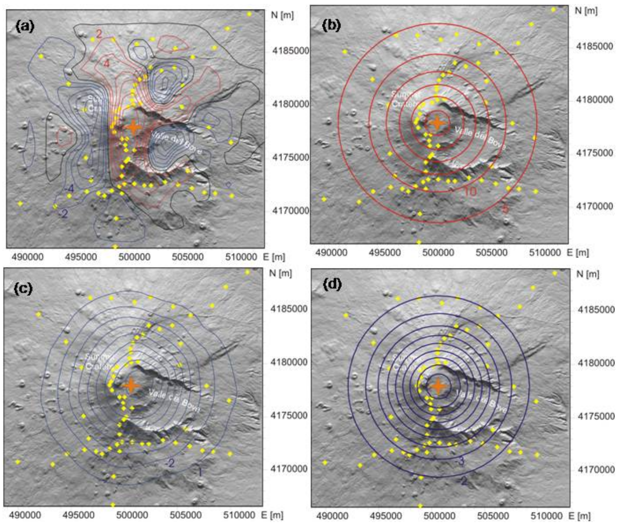

Figure 1. Contour map of the δg_2 and δg_3 gravity contributions at Etna volcano due to the an ellipsoid source located at 4.5 km b.s.l. (star). The δg_3 term computed by the numerical model (a) is compared with the analytical solution (b). The δg_2 term from the numerical model (c) is quite similar to the analytical model (d). The gravity stations (yellow diamond) are also shown.

The comparisons show that geophysical patterns exhibit fluctuations inversely correlated to topography. Indeed the amplitude of the signals at the point of lower topography is enhanced and vice versa. As for elastic heterogeneity, it slightly affects the shape while it amplifies the signals. Combining both topography and tomographic images, it is possible to appreciate a more realistic description. The results highlight that these features engender perturbations to the geophysical fields produced by a pressurized source under elastic conditions. Such perturbations, however, are more evident in presence of accentuated topography, i.e. in the summit area, and in presence of severe heterogeneity (Fig 2), while further away from the summit they are more similar to the simplest cases.

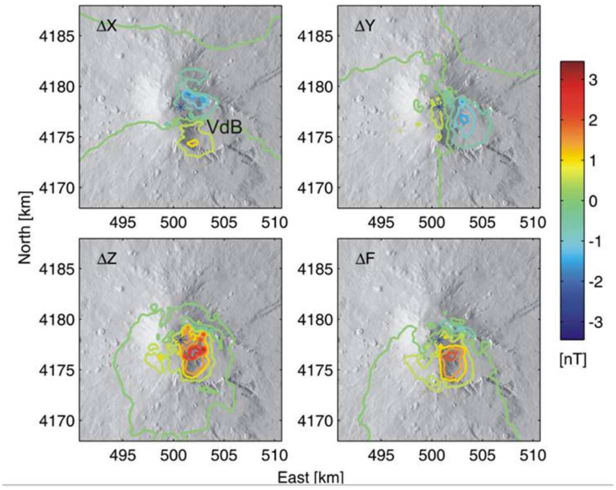

Figure 2. The magnetic field changes for a homogeneous magneto-elastic medium with the real topography of Mt Etna. Contour lines are at 0.5 nT. The star represents the pressure source location.

Standard analytical models, that neglect the complexities associated with morphology and medium properties of volcanic edifice, could provide an inaccurate estimate of the expected geophysical anomalies and, hence, lead to a misinterpretation of source parameters in inverse problems. The application of FEMs, instead, allows for more accurate interpretations and inferences in modeling-based assessments of ground deformations, gravity and magnetic changes associated with volcanic activity providing more reliable insights into volcanic source definition.

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