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The role of thermo-rheological properties of the crust beneath Ischia Island (Southern Italy) in the modulation of the ground deformation pattern

R. Castaldo [a], G. Gola [b], A. Santilano [b], V. De Novellis [a], S. Pepe [a], M. Manzo [a], A. Manzella [b], P. Tizzani [a,*]

[a] Istituto per il Rilevamento Elettromagnetico dell'Ambiente - Consiglio Nazionale delle Ricerche (IREA-CNR), via Diocleziano 328, 80124 Napoli, Italy
[b] Istituto di Geoscienze e Georisorse - Consiglio Nazionale delle Ricerche (IGG-CNR), via Moruzzi 1, 56126 Pisa, Italy

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A B S T R A C T

In this paper we develop a model of the ground deformation behaviour occurred at Ischia Island (Southern Italy) in the 1992–2010 time period. The model is employed to investigate the forces and physical parameters of the crust controlling the subsidence of the Island. To this aim, we integrate and homogenize in a Finite Element (FE) environment a large amount of data derived from several and different observation techniques (i.e., geological, geophysical and remote sensing). In detail, the main steps of the multiphysics model are: (i) the generation of a 3D geological model of the crust beneath the Island by merging the available geological and geophysical information; (ii) the optimization of a 3D thermal model by exploiting the thermal measurements available in literature; (iii) the definition of the 3D Brittle/Ductile transition by using the temperature distribution of the crust and the physical information of the rocks; (iv) the optimization of the ground deformation velocity model (that takes into account the rheological stratification) by considering the spatial and temporal information detected via satellite multi-orbit C-Band SAR (Synthetic Aperture Radar) measurements acquired during the 1992–2010 time period. The achieved results allow investigating the physical process responsible for the observed ground deformation pattern. In particular, they reveal how the rheology modulates the spatial and temporal evolution of the long-term subsidence phenomenon, highlighting a coupling effect of the viscosities of the rocks and the gravitational loading of the volcano edifice. Moreover, the achieved results provide a very detailed and realistic velocity field image of the subsurface crust of the Ischia Island Volcano.

1. Introduction

The advanced knowledge of the thermo-rheological properties of rocks is a crucial point to clarify several aspects related to the mechanical behaviour and geological evolution of the crust in tectonically active areas (Ord and Hobbs, 1989), as the case of volcanic environments. These latter are natural systems energetically favourable to the onset of mass migration processes and emplacement of partially melted rocks in the upper crust. In the last decades several studies (Burov et al., 2003; Zhong and Watts, 2013; Scott et al., 2015) have shown that these systems are characterized by a ductile rheology, and the driving forces that control the deformation processes are ruled by creeping flow behaviour. In this context, the spatial-temporal evolution of sub volcanic bodies (i.e., dike and sill systems) is strongly conditioned by the active role played by the type and location of the Brittle/Ductile (B/D) transition. Being the crust condition the result of the interaction of several physical parameters, such as the temperature distribution, the density of the rocks and the strain rate of the considered processes, it follows that the definition of a unitary model, which seeks to explain how the volcano works, requires to consider the mutual interaction between the thermic and kinematic physical scenarios. Despite a large amount of studies on the impact of rheology, aimed at understanding the multiscale structural evolution of the rocks as well as defining the cut-off of the natural seismicity in the field of seismology (Ito, 1993) has been proposed, the investigation of the impact of the B/D transition on the long-term ground deformation in volcanic or geothermal areas has not been carried out, yet. In this context, we propose an approach that, developed and implemented in a Finite Element (FE) environment, allows the integration of the available geological and geophysical information in a unitary computational numerical environment to evaluate in a quantitative way the contribution of different physical processes to the spatial and temporal modulation of the observed ground deformation. More specifically, the proposed approach is organized as a Chain Rule Optimization Procedure (CROP), where the output of each optimization step represents the input of the subsequent step.

* Corresponding author.
E-mail address: tizzani.p@irea.cnr.it (P. Tizzani).

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Following this procedure, the achieved best-fit model represents a calibrate solution that takes into account the impact of the most relevant physical parameters involved in the deformation processes.

To demonstrate the effectiveness of our methodological approach, we select as case of study Ischia Island (Southern Italy), a volcanic area characterized by very high values of heat flow, a high temperature geothermal system and active ground deformation processes. We consider a multiphysics model that tries to simultaneously model: (i) the onset of a shallow hydrothermal/geothermal system, (ii) the cut-off of the natural seismicity, and (iii) the observed long-term ground deformation pattern.

As first step of the CROP approach, we build a geological and petrophysical model of the crust beneath the Ischia volcano by integrating geological and geophysical information (e.g., Vezzoli, 1988; Di Napoli et al., 2011; Carlino et al., 2012; Finetti and Morelli, 1974; Bruno et al., 2002, 2003; Nunziata and Rapolla, 1987; Paoletti et al., 2009, 2013). This model represents the computational domain for the development of the 3D thermal model, achieved via the optimization of the available temperature measurements (i.e., shallow and deep borehole thermal measurements). At this stage, we evaluate the amount of the conductive and/or convective thermal regime, in order to simulate the status of the hydrothermal system of the Ischia Island. The optimized thermal field results allow imaging the 3D B/D transition for a defined time window. Finally, we perform a 3D deformation velocity numerical model in viscous flow approximation in order to highlight how the viscosity contrast between the rocks of the ductile and brittle region modulates the Island long-term subsidence, this latter detected via satellite multi-orbit C-Band SAR (Synthetic Aperture Radar) measurements acquired in the 1992–2010 time interval.

2. Rationale of CROP approach

In order to simultaneously consider a large amount of data derived from several and different observation techniques (i.e., geological, geophysical and remote sensing), we propose an integrated approach called CROP (Fig. 1). It represents a tool developed in a numerical environment that tries to simulate the natural phenomena in a multiphysics context. The development of physically-based model is made possible because each step of the chain represents the input of the subsequent step (Fig. 1a). In particular, the multiphysics system evolves towards the subsequent stage via an optimization procedure (Fig. 1b). The thermal and deformation velocity models, performed during the second and fourth step, respectively, have been implemented by exploiting the Comsol Multiphysics software (Comsol Multiphysics Inc., vers. 5.2).

For the specific case study, in order to achieve a unitary physically-based model of the long-term ground deformation process, we applied the proposed methodology as follows: (i) in the first phase, we considered the available geological and geophysical measurements to compute a 3D geological model of the crust beneath the Island; (ii) during the second phase we implemented a 3D thermal model via the optimization of the available thermal measurements; (iii) in the third phase, we merged the temperature distribution of the crust with the physical information of the rocks in order to reconstruct the 3D B/D transition; (iv) in the fourth and last phase, by taking into account the computed rheological stratification of the crust, we performed a fluid-dynamic model through the optimization of the 3D deformation velocity model (under the Newtonian approximation) to investigate the forces and physical parameters of the crust controlling the ground subsidence of the Island.

3. Geological model

3.1. Background information

The Ischia Island is the emergent part of a volcanic edifice located in the Gulf of Naples (Southern Italy), within the Phlegrean Volcanic

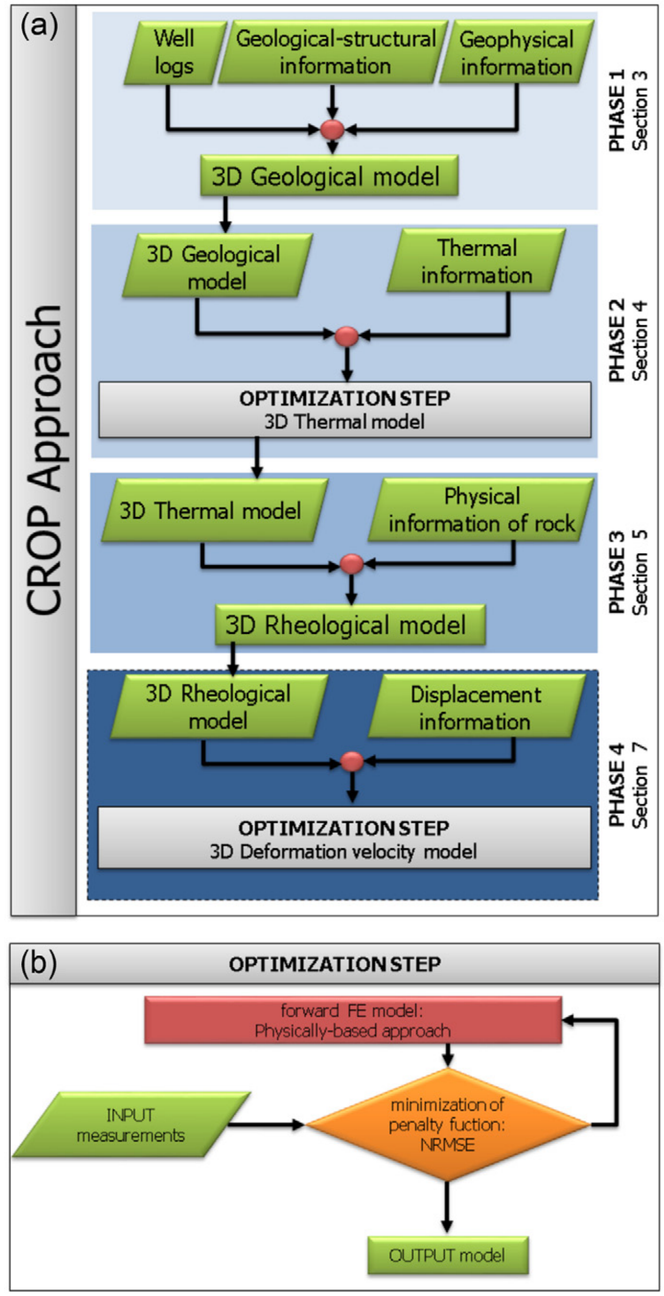

Fig. 1. CROP: Chain Role Optimization Procedure. (a) Flow-chart of the proposed approach and (b) the associated optimization step. The phases of the study are also introduced. In detail, the thermal model (Phase 2) and deformation velocity one (Phase 4) are performed by exploiting the Comsol Multiphysics software [Comsol Multiphysics Inc., vers. 5.2].

District (Orsi et al., 1999) and represents the westernmost active volcanic field of the Campanian Plain. The volcanism in the area is strictly connected to the Plio-Quaternary tectonic evolution of the peri-Tyrrhenian margin of the Apennines, affected by crustal thinning and asthenosphere upwelling (Beccaluva et al., 1991; Serri, 1997; Della Vedova et al., 2001). The extensional tectonics of this area of Mediterranean Sea is supposed to be related to the opening of back-arc basins caused by an East-retreating subduction of the Apulo-Adriatic lithosphere (Doglioni, 1991; Doglioni et al., 1996). The Island is composed of volcanic effusive and explosive rocks (mostly trachytes and phonolites), epiclastic deposits and subordinate terrigenous sediments (de Vita et al., 2006). Volcanism on the Island began before 150 kyr and