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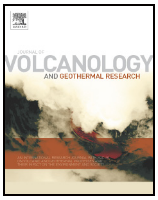

The thermal regime of the Campi Flegrei magmatic system reconstructed through 3D numerical simulations

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ABSTRACT

We illustrate a quantitative conductive/convective thermal model incorporating a wide range of geophysical, petrological, geological, geochemical and isotopical observations that constrain the thermal evolution and present state of the Campi Flegrei caldera (CFc) magmatic system. The proposed model has been computed on the basis of the current knowledge of: (1) the volcanic and magmatic history of the volcano over the last 44 ka, (2) its underlying crustal structure, and (3) the physical properties of the erupted magmas. 3D numerical simulations of heat conduction and convection within heterogeneous rock/magma materials with evolving heat sources and boundary conditions that simulate magma rise from a deep (≥8 km depth) to shallow (2–6 km) reservoirs, magma chamber formation, magma extrusion, caldera collapse, and intra-caldera hydrothermal convection, have been carried out. The evolution of the CFc magmatic system through time has been simulated through different steps related to its changes in terms of depth, location and size of magma reservoirs and their replenishment. The thermal modeling results show that both heat conduction and convection have played an important role in the CFc thermal evolution, although with different timing. The simulated present heat distribution is in agreement with the measured geothermal profiles (Agip, 1987), reproduces the thermal gradient peaks at the CFc margins in correspondence to the anomalies in surface gradients (Corrado et al., 1998), and suggests temperatures of 700 °C at depth of 4 km in the central portion of the caldera, in agreement with the estimated temperature for the brittle-ductile transition (Hill, 1992).

1. Introduction

Thermal modeling of magmatic intrusions and heat transfer in geologic materials is a largely studied and reviewed scientific topic (e.g. Furlong et al., 1991; Annen and Sparks, 2002 and references therein). The conductive cooling history and associated thermal effects on the country rocks for variably shaped intrusive magma bodies were studied by Jaeger (1964), following studies by Lovering (1935, 1955) and Carslaw and Jaeger (1959) that used analytic solutions of the heat conduction equation. Those analytical solutions provide an efficient mean to describe the heat budget of the system and to evaluate the thermal regime. However, in the last decades numerical techniques to solve the heat conduction equation have been developed in order to consider complex spatially and temporally dependent boundary conditions and to include the effects of heterogeneities within both intrusion and host rocks, as well as latent heat contribution (de Lorenzo et al., 2006 and references therein). Convection dominates heat transfer for fluid phases in porous media, that are relatively permeable, as in the case of the emplacement of an intrusion. The set of coupled partial differential equations describing heat convection can be solved for appropriate boundary conditions and simplifying assumptions. Analytical solutions can be achieved only assuming simple geometries and approximations of fluid properties (e.g. Turcotte and Schubert, 1987), so convective heat transfer has been computed mostly by using numerical methods (e.g. Shao, 1997; Bank et al., 1998; Frolkovic and De Schepper, 2001).

Heat transfer in terms of conduction/convection is not easy to compute in volcanic areas, where the thermal regime is strongly dependent upon the architecture of the magmatic plumbing system and its evolution through time (e.g. Wohletz et al., 1999; de Lorenzo et al., 2006). Accurate thermal models of magmatic intrusions require a detailed 3D definition of their geometries, which arises from thorough geological and geophysical studies. This is the case for Campi Flegrei caldera (CFc), an active volcanic system located in a densely inhabited area (Napoli, Southern Italy), for which a large amount of geological, geophysical, petrological and geochemical data has been collected in the past decades (Fig. 1, Agip, 1987; Orsi et al., 1992, 1996; Civetta et al., 1997; D'Antonio et al., 1999, 2007; Wohletz et al., 1999;

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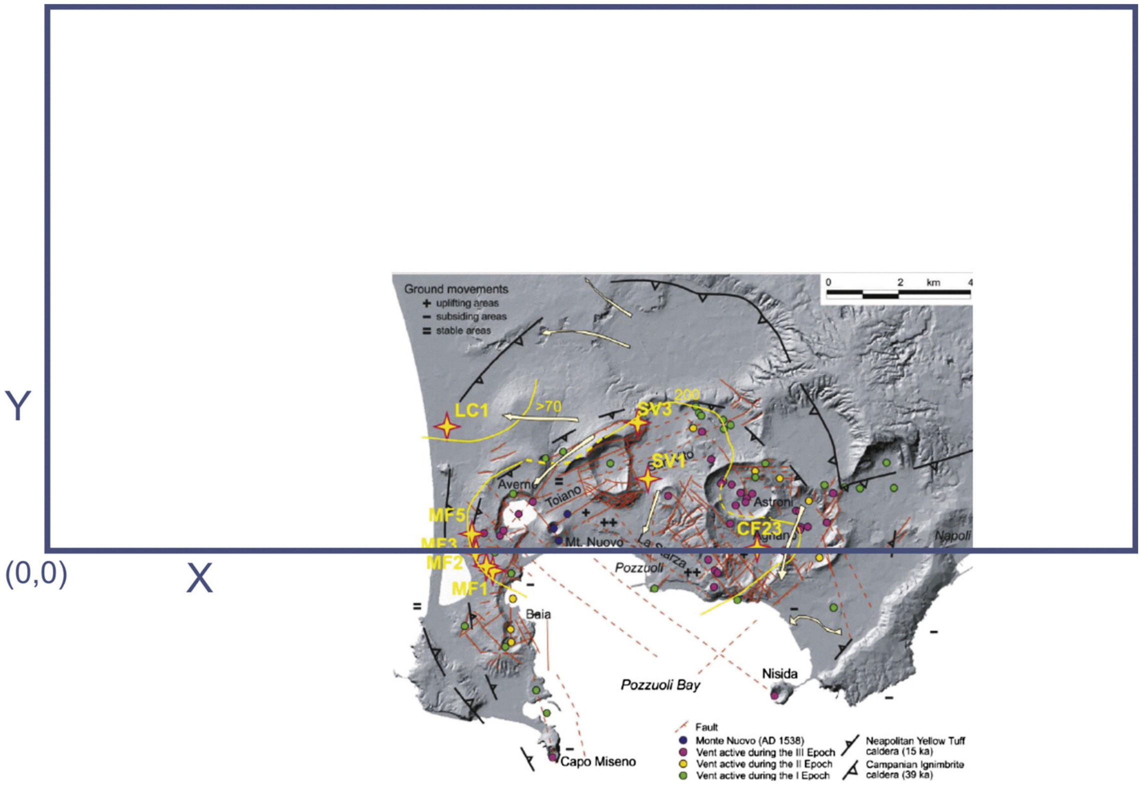

Fig. 1. Campi Flegrei structural sketch map (modified from Piochi et al., 2014). Solid dots are the volcanic vents of the first (green), second (brown), and third (magenta) epoch of volcanic activity. Stars indicate location of drillings Licola 1 (LC1), San Vito 1 (SV1), San Vito 3 (SV3), Mofete 1 (MF1), Mofete 2 (MF2), Mofete 5 (MF5), Campi Flegrei 23 (CF23). Thermal profiles for LC1, SV1, SV2, MF1, MF2, MF5 are reported in Agip (1987). The surface trace of the computational domain is given by the rectangular blue box. The blue dotted line represents the trace of vertical profiles described in Figs. 4 and 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Chiodini et al., 2001, 2010, 2011, 2012; de Lorenzo et al., 2001a, 2001b; Pappalardo et al., 2002a, 2002b; Zollo et al., 2008; Zollo et al., 2003; Judenherc and Zollo, 2004; Vanorio et al., 2005; Battaglia et al., 2006; Marianelli et al., 2006; Caliro et al., 2007; Mangiacapra et al., 2008; Pabst et al., 2008; Arienzo et al., 2009, 2010; Tonarini et al., 2004; D'Auria et al., 2008, 2011, 2012; Del Gaudio et al., 2010; De Siena et al., 2010; Di Renzo et al., 2011; Trasatti et al., 2011; Capuano et al., 2013; Amoruso et al., 2014). Such a large amount of data has been collected at CFc because the volcanic hazard is extremely high, also due to its explosive character (Orsi et al., 2004, 2009; Costa et al., 2009; Selva et al., 2012). The CFc is in unrest since decades, with numerous uplift episodes, seismicity and strong degassing from a volatile rich source (Del Gaudio et al., 2010; D'Auria et al., 2011; Mormone et al., 2011; Chiodini et al., 2012).

The current scientific knowledge of the CFc gives a unique opportunity to perform a 3D conductive/convective modeling of the thermal evolution and present state of its magmatic system. The results of such a modeling are of great importance in order to understand the present structural setting and state of the caldera and interpret its ongoing dynamics. In this paper we present the simulations of the CFc magmatic plumbing system thermal regime over the last 44 ka performed by a 3D updated version of the Heat code (Wohletz, 1999; Appendix 1), whose results are in agreement with the known geothermal profiles and geophysical data (Agip, 1987; Corrado et al., 1998).

1.1. Previous work and the necessity of a 3D thermal model

The CFc has shown signs of unrest in the last 50 years and the volcanic risk of the area is very high (Orsi et al., 2004). The main recent uplift episodes that occurred in 1970–1972 and 1982–1984 caused a cumulative vertical displacement of about 3.5 m at the town of Pozzuoli (Orsi et al., 1999a, 1999b and references therein). A long lasting debate followed regarding the relative role of newly emplaced magma and/or hydrothermal system instabilities in triggering the unrest. Gravity changes, occurred during the 1982–1984 unrest, have been interpreted as caused by a shallow (about 3 km deep) penny-shaped magma intrusion fed by a deeper magma chamber (Amoruso et al., 2008), or are found to be compatible with the intrusion at 5.5 km depth of ~60–70 · 10^6 m^3 of volatile rich magma with density ~2400 kg/m^3 (Trasatti et al., 2011), whereas Gottsmann et al. (2006) ascribed to a hybrid magmatic and hydrothermal source the uplift episode at CF.

In both interpretations, magma uprising contributed to the unrest at CFc. For this reason the knowledge of the present state of CF magmatic system is important to forecast the future activity of the volcano and the elaboration of a conductive/convective model describing the thermal regime of CF plumbing system is useful also in terms of hazard evaluation and risk mitigation.

A 2D thermal evolution of the CF magmatic system since 60 ka BP, has been proposed by Wohletz et al. (1999) in order to predict the measured thermal gradients in the Phlegraean area (Agip, 1987), using a previous version of 2-D finite difference Heat code. The initial and boundary conditions of computed models consisted of a general crustal structure determined by geology and geophysics and major eruptive events: 1) the 39 ka Campanian Ignimbrite (CI); 2) smaller volume 39–16 ka eruptions; 3) the 15 ka Neapolitan Yellow Tuff (NYT); 4) recent magmatism (e.g., Minopoli at 10 ka and Monte Nuovo in 1538 CE). In these simulations, the authors assumed a persistent shallow magma chamber at ~4 km depth, constrained by P-SV velocity conversion (Ferrucci et al., 1992). The assumed volume of this chamber was based on the findings of Smith and Shaw (1975, 1979) and Smith et al. (1978) such that it was approximately an order of magnitude larger than the dense-rock equivalent volumes of the extruded products of both CI and NYT caldera-forming eruptions. The authors discussed the results of 12 individual models to demonstrate the controls, being the

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