Journal of Volcanology and Geothermal Research 357 (2018) 276–286

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Invited research article

# Field-scale permeability and temperature of volcanic crust from borehole data: Campi Flegrei, southern Italy

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ARTICLE INFO

*Article history:*
Received 8 January 2018
Received in revised form 2 May 2018
Accepted 8 May 2018
Available online xxxx

*Keywords:*
Campi Flegrei caldera
Drilling
Permeability
Temperature
Borehole
Petrophysics

ABSTRACT

We report combined measurements of petrophysical and geophysical parameters for a 501-m deep borehole located on the eastern side of the active Campi Flegrei caldera (Southern Italy), namely (i) in situ permeability by pumping tests, (ii) laboratory-determined permeability of the drill core, and (iii) thermal gradients by distributed fiber optic and thermocouple sensors. The borehole was drilled during the Campi Flegrei Deep Drilling Project (in the framework of the International Continental Scientific Drilling Program) and gives information on the least explored caldera sector down to pre-caldera deposits. The results allow comparative assessment of permeability obtained from both borehole (at depth between 422 a 501 m) and laboratory tests (on a core sampled at the same depth) for permeability values of ~$10^{-13}$ $m^2$ (borehole test) and ~$10^{-15}$ $m^2$ (laboratory test) confirm the scale-dependency of permeability at this site. Additional geochemical and petrophysical determinations (porosity, density, chemistry, mineralogy and texture), together with gas flow measurements, corroborate the hypothesis that discrepancies in the permeability values are likely related to in-situ fracturing. The continuous distributed temperature profile points to a thermal gradient of about 200 °C $km^{-1}$. Our findings (i) indicate that scale-dependency of permeability has to be carefully considered in modelling of the hydrothermal system at Campi Flegrei, and (ii) improve the understanding of caldera dynamics for monitoring and mitigation of this very high volcanic risk area.



## 1. Introduction

Rock permeability and temperature distribution are essential parameters for studies of fluid circulation and related crustal processes, such as stress field changes (e.g., Gudmundsson, 2011) and heat transport (e.g., Ranalli, 1995). In volcanic areas, these parameters may be used in numerical modelling to assess advection vs. conductive heat transfer, and locate heat sources (Hayba and Ingebritsen, 1997; Ingebritsen et al., 2006; Weis, 2015), with attendant implications for volcano dynamic and hazards.

However, the actual determination of rock permeability is affected by great uncertainty due to scale effects (e.g., Clauser, 1992; Guéguen et al., 1996). Laboratory experiments (small scale, i.e. ≤1 $m^3$) typically underestimate values of permeability with respect to field or in-situ measurements (large scale, i.e. > > 1 $m^3$) (e.g., Batu, 1998; Ingebritsen et al., 2006). Heterogeneity of rocks in terms of lithology, voids interconnectivity and fracturing, as well as the strong dynamic interplay between rock, fluid and thermal processes are among the main causes of uncertainty.

In December 2012, a pilot borehole was drilled on Bagnoli plain, in the eastern part of the Campi Flegrei caldera (Southern Italy; Fig. 1), within the *Campi Flegrei Deep Drill Project* (CFDDP) in the framework of the *International Continental Scientific Drilling Program.* The drilling allowed to (i) measurement of in-situ permeability and (ii) coring for laboratory permeability estimates. A distributed fiber optic sensor installed within the borehole allowed measurement of the thermal gradient continuously from 0 m–475 m depth.

Such measurements are crucial, particularly on active volcanoes affected by voluminous degassing and ground deformation resulting from combined effects of magma injection at shallow depth and disturbance of the surrounding geothermal system (e.g., Bodnar et al., 2007; Troiano et al., 2011; D'Auria et al., 2011, 2015; Chiodini et al., 2001, 2016; Kilburn et al., 2017).

The main aim of this paper is to improve the knowledge of physical properties of rocks hosting the intra-caldera hydrothermal reservoir of

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https://doi.org/10.1016/j.jvolgeores.2018.05.003
0377-0273/

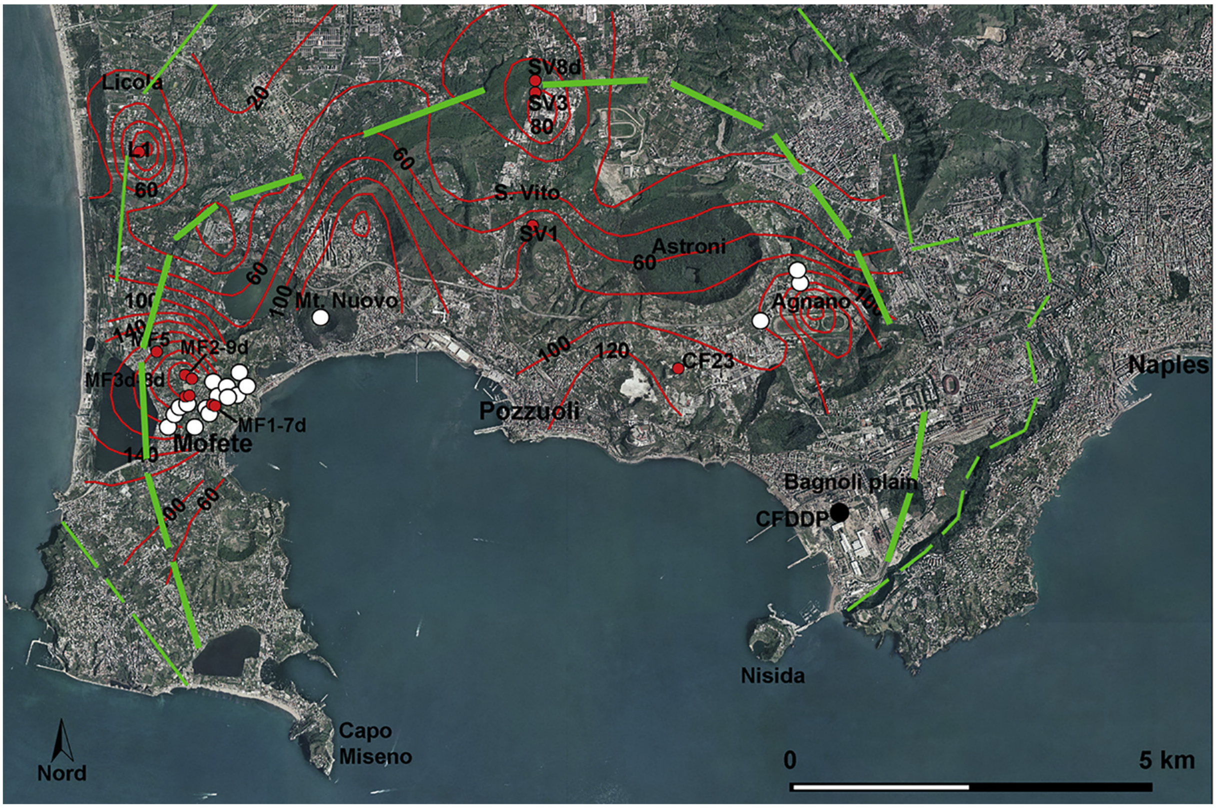


**Fig. 1.** The caldera of Campi Flegrei. Green lines are the caldera boundaries generated during the Campania Ignimbrite (thin green line) and Neapolitan Yellow Tuff eruptions (thick green line) respectively. Red lines are the isolines of heat flow in $mWm^{-2}$ (after Corrado et al., 1998); white and red circles are the shallow (<200 m) and deep (>200 m) bore-holes drilled during geothermal exploration between 1940 and 1982 (after Carlino et al., 2012); black circle is the location of most recent CFDDP well. The highest geothermal gradients are localized in the Mofete and Solfatara-Agnano sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Campi Flegrei and furnish new data that can be used to model caldera dynamics. Further investigations of geochemical and petrophysical parameters of the cored rocks, including X-ray diffraction, gas permeameter measurements, X-ray fluorescence, and electron and optical microscopy, were carried out to extend previous studies on the same samples (Mormone et al., 2015). Integration of the whole dataset - porosity, density, mineralogy, texture, rock geochemistry and temperature provides a background to discuss the origin of the scale dependency.

The new acquired data expand the database of petrophysical information that derives from (i) outcropping welded tuffs and (ii) cores and geophysical logs from previous AGIP drillings in the central and western part of the caldera (AGIP, 1987; Zamora et al., 1994; Vanorio et al., 2002; Rabaute et al., 2003; Giberti et al., 2006; Peluso and Arienzo, 2007; Piochi et al., 2014; Montanaro et al., 2017). This integrated database has become fundamental to constrain the various fluid-dynamical models developed to understand the caldera behaviour (e.g., Todesco et al., 2004; Troiano et al., 2011; Hurwitz et al., 2007; Carlino et al., 2015).

## 2. Geological setting

The Campi Flegrei caldera (Fig. 1), one of the highest volcanic risk areas worldwide, is a ca. 10 km diameter volcanic depression (Rosi and Sbrana, 1987) showing signs of unrest over the past few decades (Corrado et al., 1977; Del Gaudio et al., 2010; D'Auria et al., 2011; Chiodini et al., 2016; Kilburn et al., 2017).

The caldera-formed depression is filled mostly by pyroclastic and epiclastic deposits (Rosi and Sbrana, 1987; Piochi et al., 2014). Tuff and tuffite sequences, made of coarse and fine ashes that may include variable amount of dm-to-mm sized pumices, scoria fragments and rare lava clasts, are widespread. The Campanian Ignimbrite is likely the most important tuff deposits, with widespread distribution within and outside the caldera; it is at the base of the marine sequence that testifies to marine invasion at ca 39 ka (Rosi and Sbrana, 1987; Piochi et al., 2014). Temperature up to 350 °C has been detected at 3000 m depth inside the caldera (Fig. 1) while geothermal gradients range between 100 °C $km^{-1}$ and 250 °C $km^{-1}$ (AGIP, 1987; Rosi and Sbrana, 1987; Corrado et al., 1998; Carlino et al., 2012). Saline fluids and a huge release of $CO_2$ (~1500–3000 t $d^{-1}$) and thermal energy (minimum of 100 MW) characterize the caldera (De Vivo et al., 1989; Chiodini et al., 2001, 2016).

The caldera has experienced several unrest phases following 15 ka of frequent volcanic activity including most recently in the 1538 CE Monte Nuovo eruption (Piochi et al., 2014). Volcanic epochs, the last of which dated between ca. 5 and 3.5 ka, interrupted of up to thousands of years. Major unrest phases in 1970–72 and 1982–84 recorded ca. 3 m of maximum cumulative uplift and >16,000 earthquakes (Bianchi et al., 1987; Del Gaudio et al., 2010; D'Auria et al., 2011, 2015). After a period dominated by slow subsidence, the uplift resumed in 2006, with 5 cm/year to 1.5 cm/month of inflation (D'Auria et al., 2011). Ground dislocation has also been documented prior to the 1538 CE eruption (Parascandola, 1947; Di Vito et al., 1987; Dvorak and Gasparini, 1991) and identified in the uplifted La Starza sequence for the last 5 ka, where marine sediments are now ca. 20 m asl (Rosi and Sbrana, 1987; Piochi et al., 2014 for a review). These phenomena have been modeled as due to small magma intrusions into the shallow crust (Berrino et al., 1984; Woo and Kilburn, 2010; D'Auria et al., 2015) and/or disturbance of geothermal fluids, possibly driven by deeper magma (De Natale et al., 1991; Bodnar et al., 2007; Todesco et al., 2004, 2010; Troiano et al., 2011; Gottsmann et al., 2006; Chiodini et al., 2016).