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Tectonic stress and renewed uplift at Campi Flegrei caldera, southern Italy: New insights from caldera drilling

Stefano Carlino [a,*], Christopher R.J. Kilburn [b], Anna Tramelli [a], Claudia Troise [a], Renato Somma [a], Giuseppe De Natale [a]

[a] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Sezione di Napoli, Osservatorio Vesuviano, Via Diocleziano 328, Naples, 80124, Italy
[b] Aon Benfield UCL Hazard Centre, University College London (UCL), Gower St, London WC1E 6BT, UK

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ABSTRACT

Deep drilling is a key tool for the investigation of active volcanoes in the modern Earth Sciences, as this provides the only means to obtain direct information on processes that occur at depth. Data acquired from drilling projects are fundamental to our understanding of volcano dynamics, and for mitigation of the hazards they pose for millions of people who live close to active volcanoes. We present here the first borehole measurement of the stress field in the crust of Campi Flegrei (southern Italy), a large active caldera, and one of the highest risk volcanoes worldwide. Measurements were performed to depths of ~500 m during a pilot study for the Campi Flegrei Deep Drilling Project. These data indicate an extensional stress field, with a minimum horizontal stress of *ca.* 75% to 80% of the maximum horizontal stress, which is approximately equal to the vertical stress. The deviation from lithostatic conditions is consistent with a progressive increase in applied horizontal stress during episodes of unrest, since at least 1969. As the stress field is evolving with time, the outcome of renewed unrest cannot be assessed by analogy with previous episodes. Interpretations of future unrest must therefore accommodate the possibility that Campi Flegrei is approaching conditions that are more favourable to a volcanic eruption than has previously been the case. Such long-term accumulation of stress is not expected to be unique to Campi Flegrei, and so might provide a basis for improved forecasts of eruptions at large calderas elsewhere.

1. Introduction

Understanding how volcanoes work is crucial to the management of the risk associated with their eruptions. To improve the knowledge of active volcanic systems, modern research has been addressed to the investigation of volcano-tectonic processes that occur at depth through deep scientific drillings (Harms et al., 2007). This allows the determination of the *in-situ* properties of the solid materials and fluids, and the local stress field, along with the verification of the geophysical models that can be inferred from surface observations.

In the framework of the International Continental Scientific Drilling Programme (ICDP; www.icdp-online.org), different projects are focused on the study of caldera systems that have experienced multiple collapse and large eruptions, and which might occur again in the future. In particular, the assessing of the local stress fields at depth inside large active calderas is crucial to an understanding of the interplay between tectonic and magmatic processes and the critical conditions for rock failure.

Campi Flegrei is an active volcanic caldera that is 13 km across and borders the western suburbs of Naples, in southern Italy. It is one of the highest risk volcanic areas in the world, because there are nearly 2.5 million people who will be vulnerable to an eruption, which particularly includes the 350,000 who live within the caldera itself. The caldera is underlain by a primary zone of magma storage that is 1.2 km to 1.5 km thick, and which has a top that is *ca.* 7.5 km below the surface (Zollo et al., 2008); there is also a possible smaller magma source at a depth of 3 km to 4 km (Bianchi et al., 1987; Carlino and Somma, 2010; Woo and Kilburn, 2010).

Campi Flegrei caldera last erupted in 1538, after a century of net uplift of at least 15 m that was centred around the port of Pozzuoli (Fig. 1; Bellucci et al., 2006). Following more than 400 years of quiescence, intermittent uplift began in the late 1950s (Del Gaudio et al., 2010). Most of the recent uplift occurred during two episodes, in 1969–1972 and 1982–1984, which resulted in

* Corresponding author.
E-mail address: stefano.carlino@ingv.it (S. Carlino).

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a maximum net uplift at Pozzuoli of more than 3 m (Bellucci et al., 2006). This second episode was accompanied by elevated rates of local seismicity, which produced more than 16,000 earthquakes with recorded magnitudes between 0 and 4 (De Natale et al., 1995, 2006). This persistent seismicity damaged the older buildings in Pozzuoli, and eventually led to the evacuation of some 40,000 people (Barberi et al., 1984). The most recent episode of uplift began in 2005, and by the time of writing in 2014, this had raised Pozzuoli by an additional *ca.* 0.23 m (Fig. 2; Istituto Nazionale di Geofisica e Vulcanologia, 2014). Although this has been 30 times slower than the two previous crises, it represents the first episode of sustained uplift since 1984.

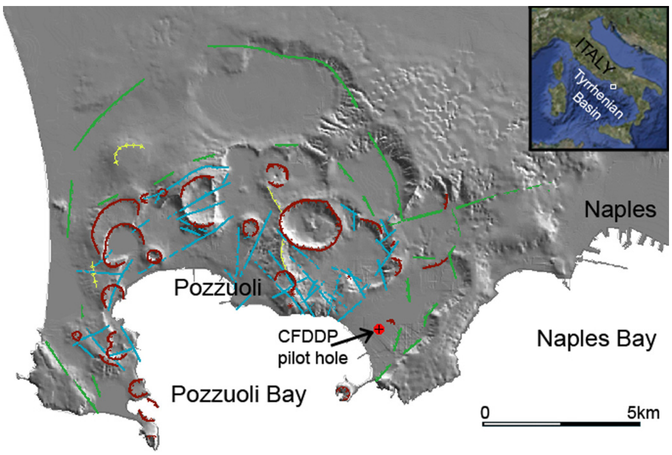

Fig. 1. Digital map of the Campi Flegrei caldera showing the caldera rim (*green*), main faults (*blue*), principal post-caldera cones and craters (*brown*), and relict structures (*yellow*). The red circle is the location of the CFDDP, https://sites.google.com/site/cfddpproject/ pilot hole at Bagnoli. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The potential for major crustal failure during renewed uplift increases with the amount of stress that has already been accumulated in the crust. Such failure would favour the onset of seismic swarms, and if magma is available at shallow depth, also the onset of a volcanic eruption. A continuing concern, therefore, is whether the stress driving the uplifts has been accumulating in the crust or has been partially relaxed between the rapid unrest episodes. To address this concern, we have measured the current stress field as part of the Campi Flegrei Deep Drilling Project (CFDDP), which is a part of the ICDP. These data provide the first direct stress measurements for Campi Flegrei, and they are consistent with an accumulation of stress at least since the uplift of 1969–1972, so that the potential for eruption appears to be increasing with successive episodes of unrest.

These data also extend the database of deep borehole studies in volcanic districts, which include Iceland (Haimson and Rummel, 1982), Long Valley caldera in California (Moos and Zoback, 1993), Hawaii (Morin and Wilkens, 2005) Unzen in Japan (Nakada et al., 2005), and Krafla caldera in Iceland (Elders et al., 2011). Furthermore, they reinforce the importance of borehole data for investigating the structure and evolution of magmatic systems, as well as geothermal processes (Eichelberger and Uto, 2007; Harms et al., 2007). This type of investigation represents a new frontier in modern Earth Science research, as deep drilling provides the only means to obtain direct information on the processes that operate at depth.

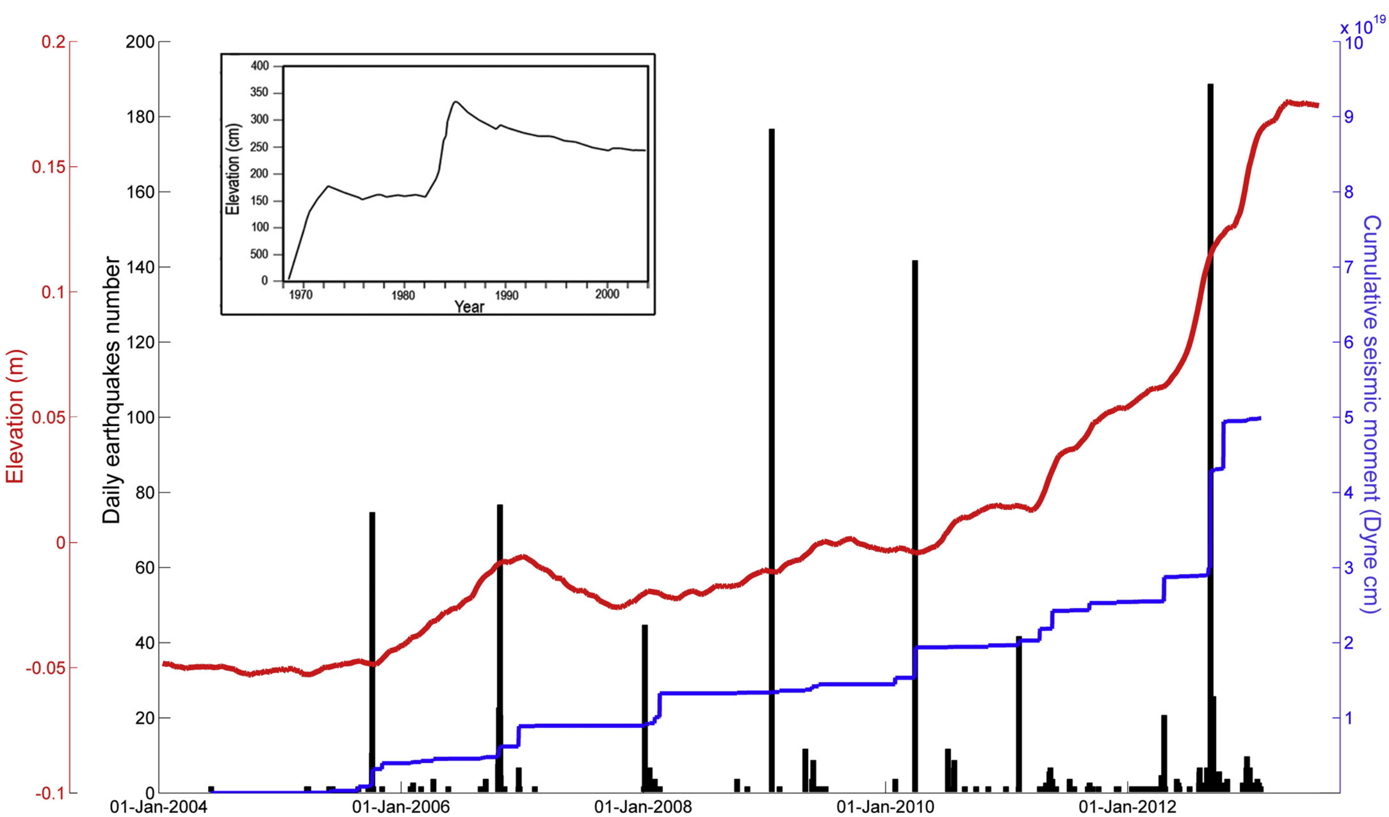

Fig. 2. Ground uplift (*red line*), cumulative seismic moment (*blue line*), and daily earthquake numbers (*black lines*) at Campi Flegrei caldera from 2004 to the present time. The seismic activity during this period has generally occurred as swarms, with maximum magnitudes <2.0. The unrest that started in 2005 is ongoing, and the latest period of uplift (July 2014) occurred at a rate of about 1.5 cm/month. The insert on the top left is the recorded uplift from 1970 to 2004 (data from the INGV seismic and ground deformation database; www.ov.ingv.it). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)