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InSAR Permanent Scatterer analysis reveals fault re-activation during inflation and deflation episodes at Campi Flegrei caldera

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ABSTRACT

Permanent Scatterers Synthetic Aperture Radar Interferometry (PSInSAR) and Global Position System (GPS) are applied to investigate the most recent surface deformation of the Campi Flegrei caldera. The PSInSAR analysis, based on SAR data acquired by ERS-1/2 sensors during the 1992–2001 time interval and by the Radarsat sensor during 2003–2007, identifies displacement patterns over wide areas with high spatial resolution. GPS data acquired by the Neapolitan Volcanic Continuous GPS network provide detailed ground velocity information of specific sites. The satellite-derived data allow us to characterize the deformation pattern that affected the Campi Flegrei caldera during two recent subsidence (1992–1999) and uplift (2005–2006) phases. PSInSAR results show the re-activation of the caldera ring-faults, intra-caldera faults, and eruptive fissures. We discuss the results in the light of the available volcanological, structural and geophysical data and propose a relationship between the structures activated during the recent unrest episodes and those responsible for the recent (<3.8–4 ka) volcanism. The combined interpretation of the collected data show that (a) the caldera consists of two sectors separated by a N–S striking faulting zone and (b) the intra-caldera NW–SE faults and eruptive fissures in the central-eastern sector re-activated during the studied unrest episodes and represent possible pathways for the ascent of magma and/or gas to the surface. In this sector, maximum horizontal strain, recent volcanism (3.8–4 ka), active degassing and seismicity concentrate. The fault re-activation is related to the dynamics of the caldera and not to tectonic stress. The deformation fields of the uplift and subsidence episodes are consistent with hydrothermal processes and degassing from a magmatic reservoir that is significantly smaller than the large (~40 km^3) magma chamber responsible for the caldera formation. We provide evidence that the monitoring of the horizontal and vertical components of deformation improves the identification of active, aseismic faults. Accordingly, we suggest that future ground deformation models should include the re-activation of the detected structures.

1. Introduction

Spaceborn interferometric synthetic aperture radar (InSAR) technique is increasingly used to monitor volcanic deformation (Ohkura & Shimada, 2001; Lundren et al., 2001; Kwoun et al., 2006a,b; Manzo et al., 2006; Wicks et al., 2006; Tizzani et al., 2007; Trasatti et al., 2008; Finnegan & Pritchard, 2009). The high spatio-temporal sampling achieved by this technique increases the chances to detect and analyze ground deformation signals. In volcanic areas, this is particularly important because ground deformation may reflect changes in the magmatic system related to an increased potential for eruption. Moreover, the improvement of the resolution in measuring the surface deformation patterns at different spatio-temporal scales is relevant to understand the surface and inner structure of active volcanoes, and to decipher the precursor signals of an eruption.

Campi Flegrei (Italy), Long Valley (California), and Rabaul (Papua New Guinea) were restless in 1980s and affected by ground uplift, earthquakes and increased degassing (Lowenstern et al., 2006). Rabaul did not erupt until September 1994, whereas Campi Flegrei and Long Valley caldera experienced further unrest episodes without erupting. At Rabaul, intra-caldera faults and ring-faults were activated before the eruption (Saunders, 2005). At Campi Flegrei, the role of ring-faults in accommodating the uplift and subsidence during unrest episodes is a still open question (De Natale & Pingue, 1993; Orsi et al., 1999; Amoruso et al., 2007; Trasatti et al., 2008). Such examples highlight (a) the ambiguity of precursor signals (e.g. uplift) of an eruption, which reflects the complexity of volcanic systems, and (b) the need of well constrained structural models for volcanoes.

Campi Flegrei caldera is listed among the supervolcanoes of the world (Sparks et al., 2005), lastly erupted in 1538 AD, and suffered ongoing unrest episodes. Studies on Campi Flegrei and other calderas are abundant (e.g., Rosi & Sbrana, 1987; Orsi et al., 1999; Lowenstern et al., 2006; Bodnar et al., 2007; Gottsmann & Battaglia, 2008, and references therein), however, an integration of geological,

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volcanological, and deformation data from satellite platforms is, in many cases, lacking.

In this study, we merge structural, volcanological, geophysical, and satellite data with the aim to: (a) detect the structures activated during uplift and subsidence episodes: (b) recognize sectors of the caldera characterized by a different eruptive and deformation behaviour: and (c) provide a structural and volcanological framework for the unrest episodes. The results prove that this approach provides information on the short and long term dynamics of volcanic areas. We demonstrate that both the caldera ring-faults and the intra-caldera faults were re-activated during uplift and subsidence. Results put constraints on the still debated question on whether pre-existing structures respond to inflation and deflation episodes in caldera settings (e.g. Saunders, 2005; Geyer & Martì, 2009), and, in particular, on how the tectonic structures that affect a caldera may react to inflation and deflation episodes originated by a magmatic/hydrothermal system clearly different from the one that originated the caldera structure.

2. Volcanological setting and recent dynamics

The Campi Flegrei caldera was defined after the Campanian Ignimbrite (40 ka) and the Neapolitan Yellow Tuff eruptions (15 ka), which produced sub-circular collapses (Fig. 1). NW–SE, NE–SW, and N–S striking faults occur within the Neapolitan Yellow Tuff caldera (NYTC) (Fig. 1). The NW–SE and NE–SW strikes are those of the main regional lineaments of the area (Rosi & Sbrana, 1987; Orsi et al., 1999; Bruno, 2004; Acocella, 2008). N–S and NW–SE eruptive fissures younger than 15 ka are concentrated in the westernmost and eastern NYTC sectors, respectively (Fig. 1). Faults and eruptive fissures with a preferred NW–SE strike concentrate in the central-eastern sector (CES) of NYTC, whereas fewer NE–SW striking faults affect the central-western sector (CWS) (Fig. 1). The N–S striking faults outcrop in the central and westernmost sectors of the caldera.

In the last 15 ka, 70 eruptions occurred in distinct epochs of activity up to the last event of Monte Nuovo (1538 AD) (Fig. 1; Di Vito et al., 1999; Isaia et al., 2009). Within the CES, multiple plinian to strombolian, phreatomagmatic and lava dome events erupted magmas of different composition (shoshonite, latite, trachyte, and trachyphonolite; D'Antonio et al., 1999; Di Vito et al., 1999). CWS was characterized by scarce and lower energy eruptions of trachytic to trachyphonolitic magmas. In particular, 14 of the 16 eruptions of the last 4 ka occurred from the CES (Isaia et al., 2009). The other two eruptions were phreatomagmatic events from the CWS.

Offshore, CES and CWS are separated by a set of structural discontinuities (Sacchi et al., 2009) whose on-land propagation is highlighted by N–S and NNE–SSW striking faults located in the central sector of NYTC (Fig. 1). These faults overlap a high, N–S elongated, up to 2 km deep, Qp anomaly that is associated with the intense hydrothermal alteration (de Lorenzo et al., 2001). A high Vp/Vs anomaly also characterizes the upper 2 km in this area and reflects the occurrence of fluids due to steam condensation. Below, at 3 km depth, is characterized by a low Vp/Vs anomaly, which suggests a gas-rich rock volume (Chiarabba & Moretti, 2006). The preferred orientation of the fast S waves polarization indicates that this volume is affected by N–S striking cracks (Bianco & Zaccarelli, 2009).

NYTC suffered repeated ground deformations that are more pronounced in the central sector (La Starza marine terrace; Fig. 1), where an uplift of at least 100 m was estimated in the last 10 ka. Slow ground movements (bradyseism) periodically occurred during the last 2000 years. Two significant historic unrests (1970–72 and 1982–84) occurred in the last 40 years. A ground uplift of 3.5 m between 1970 and 1984 was accompanied by thousands of earthquakes, while only part of the displacement (<1 m) was aseismically recovered throughout the subsequent ground subsidence. After the 1982–84 crisis, the general subsidence was interrupted by episodes of 'micro-uplift' with displacement of a few cm. This last occurred in 2004–2006.

Geochemical and geophysical data show that peaks in CO_2/CH_4 in fumaroles during micro-uplifts occurred some months after shallow (<3 km depth), long-period and volcano-tectonic earthquakes. The epicenters of these earthquakes roughly aligned along a NNW–SSE to NW–SE strike (Fig. 1; Cusano et al., 2008; Chiodini, 2009). A decrease of CO_2/CH_4 accompanied the subsidence phase. Migration of

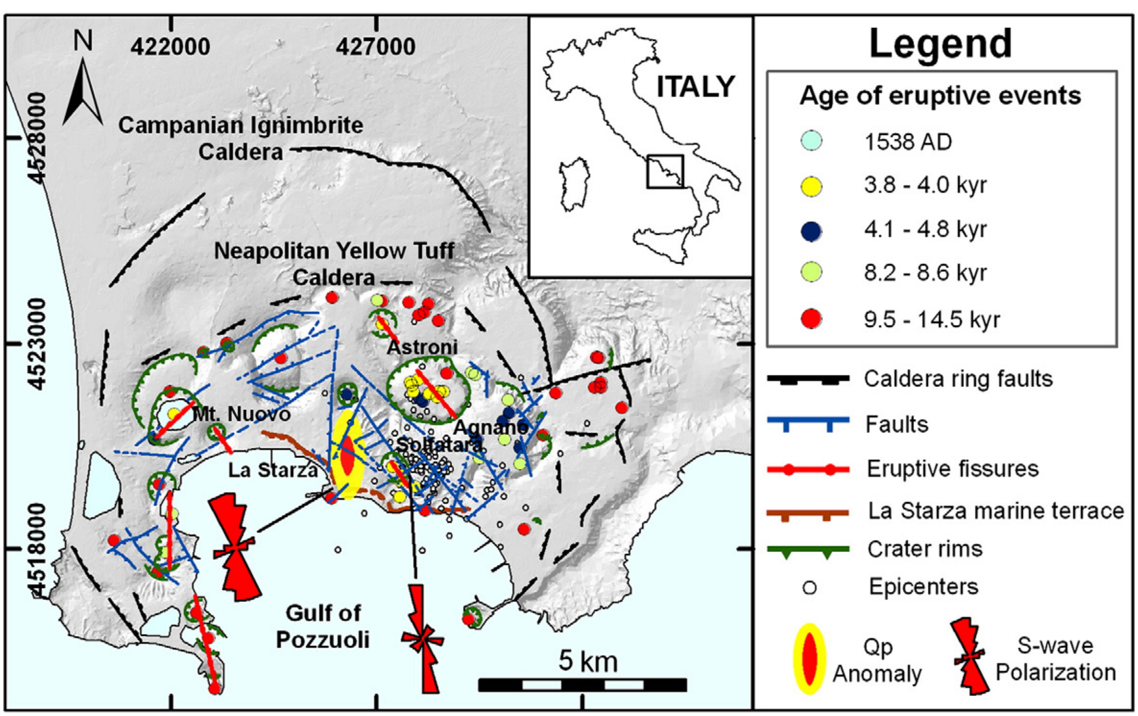

Fig. 1. Structural sketch map of the Campi Flegrei caldera. In the figure are also shown: the eruptive vents for the four main activity epochs; the seismicity associated with uplift episodes in 2000 and 2005–2006; and the area of higher attenuation values for the uppermost 2 km. The preferred orientation of the fast S-wave polarization is also reported.