A rock physics and seismic tomography study to characterize the structure of the Campi Flegrei caldera

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Abstract: The Campi Flegrei (CF) caldera experiences dramatic ground deformations unsurpassed anywhere in the world. The source responsible for this phenomenon is still debated. With the aim of exploring the structure of the caldera as well as the role of hydrothermal fluids on velocity changes, a multidisciplinary approach dealing with 3-D delay-time tomography and rock physics characterization has been followed. Selected seismic data were modeled by using a tomographic method based on an accurate finite-difference travel-time computation which simultaneously inverts P-wave and S-wave first-arrival times for both velocity model parameters and hypocenter locations.
The retrieved P-wave and S-wave velocity images as well as the deduced Vp/Vs images were interpreted by using experimental measurements of rock physical properties on CF samples, to take into account steam/water phase transition mechanisms affecting P-wave and S-wave velocities. Also, modelling of petrophysical properties for site-relevant rocks constrains the role of over-pressured fluids on velocity. A flat and low Vp/Vs anomaly lies at 4 km depth under the city of Pozzuoli. Earthquakes are located at the top of this anomaly. This anomaly implies the presence of fractured over-pressured gas-bearing formations and excludes the presence of melted rocks. At shallow depth, a high Vp/Vs anomaly located at 1 km suggests the presence of rocks containing fluids in the liquid phase. Finally, maps of the Vp*Vs product show a high Vp*Vs horse-shoe shaped anomaly located at 2 km depth. It is consistent with gravity data and well data and might constitute the on-land remainder of the caldera rim, detected below sea level by tomography using active source seismic data. For a more exhaustive description of the utilized methodologies, of synthetic tests for spatial resolution and uncertainty assessment and, the interpretation of results, the reader may refer to the paper Vanorio et al. (2005).

INTRODUCTION

As with many calderas, CF periodically experiences notable unrest episodes which include ground deformations, seismic swarms and increases in the degassing activity (Barberi et al., 1984). However, unlike other calderas, ground deformations in CF may reach values unsurpassed anywhere in the world (Newhall and Dzurisin, 1988). Based on historical records, the uplift phase may precede a new eruptive event as occurred in 1538 (Dvorak and Gasparini, 1991). Nevertheless, short uplift phases may also interrupt the secular subsidence as occurred in 1970-1972, 1982-1984, 1989, 1994 and, 2000 without culminating in an eruption. Mechanisms accounting for these phenomena have generally involved pressure generation exerted either from a magma chamber (Bianchi et al., 1987; Bonafede, 1986) or from hydrothermal reservoirs (Oliveri del Castillo and Quagliariello, 1969; Casertano et al., 1976; Bonafede, 1991). Modelling of ground deformation data shows that any of the possible sources responsible for the recurrent uplift and subsidence has to be placed between 1.5 and 4 km depth, in order to fit both the magnitude and the narrow bell-shape of the recorded displacement (Bianchi et al., 1987; Bonafede, 1991). The presence of a magmatic reservoir underneath the CF caldera has been proposed as a possible interpretation of both P-S converted phases at 4 km depth (Ferrucci et al., 1992) and temperature data inferred by Qp models (de Lorenzo et al., 2001). However, no evidence for magma bodies having volumes larger than 1 km^3 has been found down to 4-5 km by the recent 3-D P- wave tomography performed in the Gulf of Naples and Pozzuoli (Zollo et al., 2003). Furthermore, no variation of isotopic ratios of magma-derived species has been found in fumaroles during the 1982-1984 unrest that could serve as evidence for the magmatic origin of the crisis (Allard et al., 1991).

The possibility that hydrothermal fluids play a fundamental role in triggering activity at CF often attracts attention because a correlation between ground displacement and gas emission rate has been found (Barberi et al., 1984; Chiodini et al., 2003). No signatures indicating cap-rock formations, which are required to build up pore fluid pressure within reservoirs, have yet been detected. Under the hypothesis of pore fluid pressure generation, the assessment of cap-rock formations constitutes evidence constraining the depth of the triggering source. Thus, many questions still remain unresolved and mechanisms responsible for the CF activity not well constrained.

The Rationale of this work

Why a new Seismic Tomography in the CF from micro-earthquake travel times?

Local Earthquake Tomography constitutes a basic tool to assess the 3-D velocity structure in seismically active areas (Thurber, 1992). Although, velocity images from the inversion of passive data (earthquakes) may suffer from a lower resolution in very shallow layers compared to that of active data (shots), Local Earthquake Tomography both shows the advantage of imaging the velocity structure during a seismic crisis and of providing also an S- wave field. The assessment of a reliable S wave velocity structure is crucial, especially in a geothermal field, to overcome ambiguities deriving from the interpretation of the P-wave velocity field alone. In the CF area, a previous joint tomographic and earthquake location study using Micro-earthquake travel-times was performed by Aster and Meyer (1988) who used 228 events occurring during the 1982-1984 crisis. They reported both a high Vp/Vs ratio at 1 km depth that was interpreted as a region of highly water saturated fractured rocks and a cessation of seismicity at approximately 4 km. In this new seismic tomographic study, the 1982-1984 dataset from January 1st through April 15th, 1984 has been upgraded and entirely re-picked so largely increasing the number of P-wave and S-wave time readings compared to the previous study (Aster and Meyer, 1988). The picking of the waveforms from the temporary network (21, 3-component digital short-period seismometers) deployed by the University of Wisconsin (WS) was operated by some URs participating to the project: UR1, UR3, UR4 and UR5. However, the analysis of this distributed and collective picking showed us that a homogeneous re-picking was necessary to achieve the resolution we wanted. Consequently, the UR6 has performed together with G. Russo (UR1) a new and more accurate picking and checked its consistency by Wadati diagram analysis. Also, during the same period, two networks were complementing the WS one: the network maintained by the Vesuvian Observatory (VO) and by AGIP (Azienda Generale Italiana Petroli, AG) consisting of 25 vertical seismic stations. Consequently, the UR6 has performed together with G. Russo (UR1) a new and more accurate picking and checked its consistency by Wadati diagram analysis. We added P- picking data coming from the VO and AGIP database, verifying consistency (see Figure 2 for the network configuration).
The dataset consists of 1209 micro-earthquakes occurring from January 1st through April 15th 1984 which provided 7,264 P- and 3,121 S- arrival time readings. Arrival times measured from digitized seismograms were estimated to be accurate in the range of 0.02-0.05 s for P- and 0.02-0.1 s for S- waves. A preliminary hypocenter location was determined by using the 1-D P velocity model resulting from the active seismic experiment performed in the Bay of Pozzuoli (Zollo et al., 2003). From the initial data set, we selected earth-

quakes that had at least 6 P- and 4 S- phases read, azimuthal gaps smaller than 180° and RMS time residuals smaller than 0.5 s. This selection provided a final database consisting of 462 events with a number of P- and S- readings of 3,447 and 2,289, respectively.

Why Rock Physic Characterization in the CF caldera?

The anomalies of the P-wave and S-wave velocity structure need to be interpreted on a physics base. Rock Physics plays the role of connecting the inferred changes in seismological parameters to properties and conditions occurring at depth. Therefore, to improve the interpretation of the retrieved anomalies, we modelled the role of hydrothermal fluids on P-wave and S-wave velocities via effective medium modelling.
Both laboratory measurements on site-relevant lithologies under controlled conditions of pressure (Vanorio et al., 2002; Vanorio, 2003) and the comparison with results obtained on other lithologies under pressure and temperature conditions (Ito et al., 1979; Wang and Nur, 1989) constrained the modelling results. The combined approach afforded in this study brings new clues useful to assessing the CF caldera structure and, in turn, its activity.

Methods

The inversion strategy

We used a linearized, iterative tomographic approach as proposed by many authors (Spakman and Nolet, 1988; Aster and Meyer, 1988; Hole, 2000; Benz et al., 1996; Latorre et al., 2004, among others) in which P- and S- first arrival times are simultaneously inverted for both earthquake locations and velocity model parameters at each step of the inversion procedure. The importance of coupling earthquake hypocenter parameters (locations and origin time) on the one hand and velocities on the other has been discussed by Thurber (1992) who emphasized that all required parameters should be mutually consistent to avoid significant bias in the derived models.
Inherently, the final solution of a tomographic inversion depends strongly on the a priori choice of the 1-D reference model (Kissling et al., 1994). As a first approach, we used the 1-D P-wave velocity model resulting from the tomographic inversion of 77,000 first P wave arrival times collected during the active seismic experiment performed in the CF caldera (Zollo et al., 2003). The initial S- velocity model was derived from the P- velocity model using a Vp/Vs ratio of 1.7 estimated from Wadati diagrams. However, due to the inherent difference in the geometry of the passive and active experiments and to the elapsed time between the acquisition of the two datasets (~20 years), we veri-

fied the accordance between the initial 1-D velocity model (Zollo et al., 2003) and earthquake data. The elapsed time is a significant factor because of changes occurring in geothermal systems. A statistical study based on RMS time residuals was inferred from 400 initial 1-D models, randomly generated within two extreme 1-D velocity bounds. The upper and lower velocity bounds were chosen to have the 1-D reference model of Zollo et al. (2003) as average. The outcome of this procedure indicated that the mach between earthquake data on the one hand and the 1-D velocity model on the other, revealed an overestimation of the reference 1-D velocity. This could affect velocity estimates in the final models. On account of that, we made a more restrictive selection on the 1-D reference model by choosing, as a reference model, the average one resulting from the initial models showing the lowest RMS residuals (< 0.2 s). This selection provided a final 3-D solution showing a lower RMS (0.07 s) (which means a reduction of 46% from the initial RMS value of 0.13) and a zero-centered distribution of travel time residuals.

The rock physics modelling

We theoretically reproduced the effect of higher temperatures and pressures on Vp/Vs via modelling as proposed by Dvorkin and Nur (1996). Since our intention was to model sediments with a non-zero stiffness of the dry matrix, we used the upper Hashin-Shtrikman bound to appropriately model the elastic moduli. Once the moduli and density of the dry matrix are computed (Dvorkin and Nur, 1996 and Dvorkin et al., 1999a GRL for details), the computation in the low-frequency domain (i.e. fluid and solid motions are in phase) of the bulk and shear moduli of the saturated sediment come from Gassmann's equation (Gassmann, 1951). In the reported modelling, pore fluid is described by a mixture of water and carbon dioxide (20% of carbon dioxide and 80% of water) whose bulk modulus and density were computed (Batzle and Wang, 1992) for a constant temperature of 350°C and by only varying pressure conditions. Modelling computed the variation of Vp/Vs as a function of pore fluid pressure: the modelled rock bears a lithostatic pressure of 70 MPa (c.a. 4 km depth) and a pore fluid pressure varying from 5 MPa to 45 MPa. The results of modelling (Figure 1) showed that the increase of pore fluid pressure leads to a decrease in pore fluid compressibility (i.e. vapour-liquid transition is simulated) and, as a consequence, the Vp/Vs ratio increases.

Figure 1 also shows the expected variation in Vp/Vs in the case where an increase of pore fluid pressure leads the bulk rock porosity to increase by 5% (**Φ**=25%, dashed black line in the figure). The line connecting rock models having different porosity describes the result of computation by slightly increasing porosity by steps of 1%. Figure 1 shows that in gas-bearing rocks, crack opening leads the Vp/Vs ratio to decrease as a function of pore pressure.

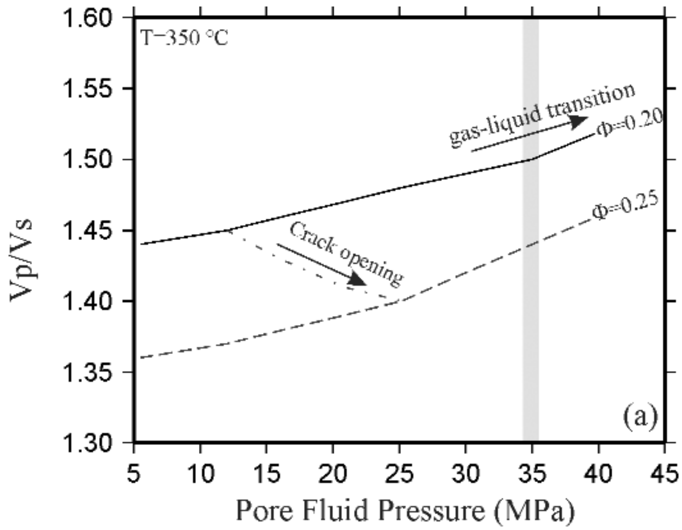

Fig. 1. Theoretical modeling of pore pressure effects on Vp/Vs ratios in a tuffite at 350° C.

Results

- At shallow depth, we found similar velocity trends to those reported in the previous tomographic study of Aster and Meyer (1988). However, our augmented database allowed an improved resolution of the tomographic images at depths between 4 km and 5 km where we found an anomalously low Vp/Vs ratio (Figure 2).
- Several P-wave and S-wave velocity logs have been extracted from the 3-D model that indicate reversal trends (Figure 2) (e.g. velocity values decrease with depth) which weaken moving radially away from the center of the caldera (the city of Pozzuoli and Solfatara zone) towards more external sites (Agnano, Arco Felice, Montagna Spaccata Quarto). This result marks departures of the effective stress from normal compaction trends.
- The modelling of rock physical properties as well as the reversal trends led us to interpret the low Vp/Vs anomaly at 4 km depth as the top of formations enriched in gas under pressure. Transient fluid pressure events induced by episodical self-sealing processes (Batzle and Simmons, 1977) represent a significant mechanism in hydrothermal environments which have been noted in other inflating calderas as Long Valley Caldera (Farrar et al., 1995; Sanders et al., 1995; Hill et al., 1990) and Yellowstone (Husen et al., 2004). In CF, reversal trends gather in the center of the caldera and imply a localized pressure source as suggested by the narrow bell shape of the recorded displacement. The signature of a low Vp/Vs ratio at 4 km depth excludes the presence of melted rocks at 4 km whose assessment

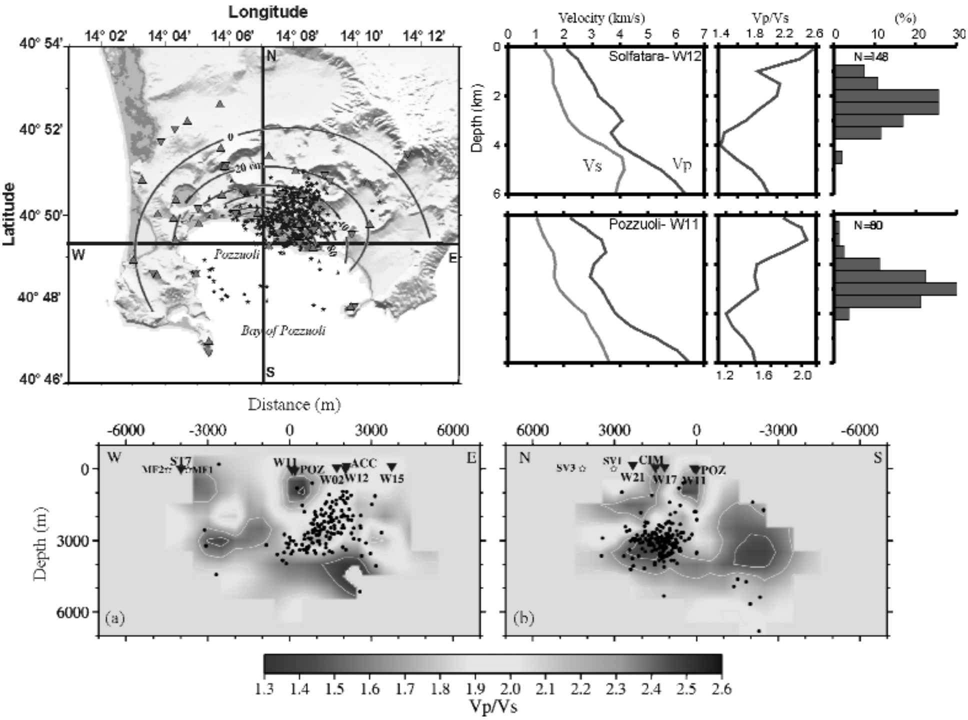

Fig. 2. *Top left panel* – Map of the CF caldera showing seismometer stations (triangles) and final earthquake locations (stars). The map also reports the elevation contours (black lines) for the 1982-1984 uplift. *Top right panel* – Reversal trends on vertical velocity profiles, Vp/Vs and, histograms showing earthquake distribution along profiles (radius equal to 0.5 km). *Bottom* – Vp/Vs vertical cross-sections and earthquake distribution (black points) along the directions reported in the map. Stars and triangles indicate wells and stations, respectively.
You can see this figure in color on page 205.

would instead require high Vp/Vs ratios. The absence of melt formations down to 4-5 km depth is also in accordance with the results reported in Zollo et al. (2003).

– Earthquake locations are mostly distributed on the top of velocity reversals and within the low Vp/Vs anomaly. Our results from the CF caldera suggest that storage of supercritical fluids at depth has to be tracked to monitor the caldera activity and to prevent risks.

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