MAGMA DEGASSING, HEATING AND DEFORMATION AT CAMPI FLEGREI CALDERA

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Introduction. One of the most problematic issues of modern volcanology is the trigger mechanism of unrests at calderas (Newhall and Dzurisin, 1988; Lowenstern *et al.*, 2006; Acocella *et al.,* 2015). Here we focus on Campi Flegrei caldera (CFc) which has recently given clear signs of potential re-awaking (Chiodini *et al.*, 2012). In its history, CFc alternated phases of uplift followed by subsidence periods over a range of different timescales (Rosi *et al.*, 1983; Di Vito *et al.*, 1999; Orsi *et al.*, 2004; Morhange *et al.*, 2006). There are evidences of decades-long inflation prior to the last magmatic eruption, the AD 1538 Monte Nuovo eruption as described in Dvorak and Mastrolorenzo (1991). The Monte Nuovo eruption was followed by a general subsidence which lasted to the early 50s when inflation resumed and culminated into two major uplift, accompanied by an intense seismic activity ("bradyseism"), in 1969-1972 and in 1982-1984, with a total vertical displacement of 3.8±0.2m (Del Gaudio *et al.*, 2010, and references therein). Since 1985, a slow subsiding phase, interrupted only by few minor uplifts, affected CFc until 2005 when a new inflation phase started, with an accelerating trend in the next following years. A maximum vertical displacement of about 31 cm has been attained in August 2015, according to the measurements referred in http://www.ov.ingv.it/ov/it/bollettini. This current inflation is accompanied by a weak seismicity, by a strong increase in the fumarolic activity, and by remarkable compositional variations of the fumaroles of Solfatara, the most active zone of CFc (Chiodini *et al.*, 2012, 2015 and references therein). At Solfatara, thirty years of compositional data of the main fumarolic vent are made available for investigate the causes of the processes controlling the unrest. This long and detailed time series of geochemical data related to hydrothermal fluids released by a caldera is practically unique at global scale. Surprising correlations among the fluid compositions and the geophysical signals, as well as the results of physical numerical modelling, indicate that the ongoing unrest is controlled by repeated injections of magmatic fluids into the hydrothermal system of CFc. The process is

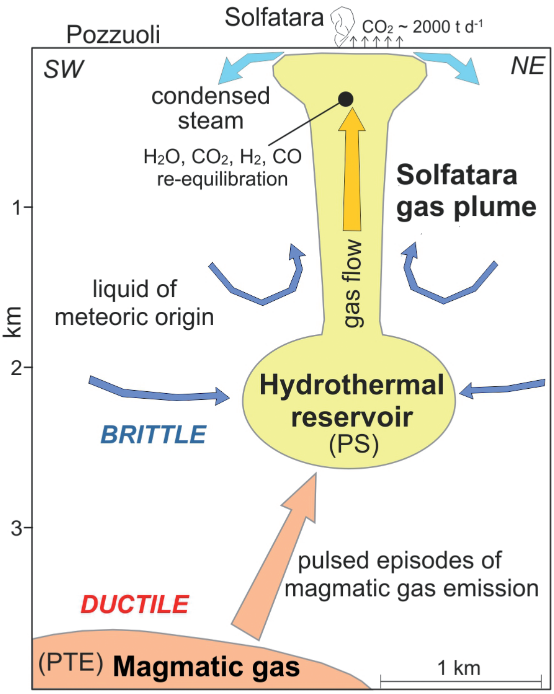

Fig. 1 – Conceptual model involving the release of magmatic fluids from the deeper part of the hydrothermal system (Magmatic gas, PTE) towards the shallower parts (Hydrothermal reservoir PS) below the Solfatara, where these mix with meteoric fluids (modified from Chiodini *et al.*, 2015). See the text for further explanations.

responsible of the heating of the system, which in turn shows the same accelerating trend of ground inflation, thus gaining the role of most likely candidate responsible of the current uplift.

The hydrothermal system feeding Solfatara. The total deeply derived CO_2 released from diffuse degassing processes at Solfatara and surrounding (~1.4 km^2) is estimated to be 1000 to 1500 t/d in the period 1998-2010 (Chiodini *et al.*, 2011). In addition, recent (2012-2015) measurements of the gas flux from the three main fumarolic vents, indicate a total CO_2 output ranging from 350 to 850 t/d (Aiuppa *et al.*, 2013). The total CO_2 flux of 1500-2000 t/d, i.e. the fumarole flux added to the diffuse emission, has to be considered as a minimum estimate of the total hydrothermal CO_2 output because the flux from the numerous minor fumarolic discharges is not taken into account, since it has never been measured.

The sketch of Fig. 1 shows the main features of the hydrothermal system feeding this large degassing process (Chiodini *et al.*, 2015). The system consists of a deep zone of magmatic gas accumulation and a shallower hydrothermal reservoir. The first is located at ~4 km depth (Vanorio *et al.*, 2005) and supplies fluid and heat to the overlying shallower part of the system: it has been hypothesized that it hosts a small batch of magma (De Siena *et al.*, 2010). In the upper part, the hydrothermal reservoir, magmatic fluids mix and vaporize liquid of meteoric origin, forming a gas plume in the subsoil of Solfatara. This scheme, which is derived from geochemical interpretations (e.g. Caliro *et al.,* 2007 and references therein), agrees with the most recent inversion of the ground deformation data observed in the 1982-2013 period (Amoruso *et al.*, 2014). The measured deformation would be in fact controlled by pressure changes in two sources: a pressurized triaxial ellipsoid (PTE) oriented NW - SE and centred at about 4 km depth in the subsoil of Pozzuoli, and a pressurized spheroid (PS) located at ~ 2 km depth below Solfatara crater. PTE and PS are coincident with the deeper magmatic gas and the shallower part of the hydrothermal system depicted in Fig. 1.

Compositional changes of Solfatara fumaroles and the 2005-2013 ground deformation pattern. At Solfatara fumaroles, the proportion of the magmatic component sharply increases during relatively short periods, which can be explained as the results of repeated episodes of magmatic fluid injections into the hydrothermal system (Chiodini *et al.*, 2012). Such episodes are characterized by the decrease of the methane content of the fumaroles due to the low CH_4 content of magmatic fluids and, possibly, the relatively high and transient oxidizing conditions during the process which prevent the formation of CH_4 in the hydrothermal environment (Chiodini, 2009). On the other hand, since the relative abundances of other gases of prevalent magmatic origin, such as CO_2 and He, may increase, ,the ratio of their contents with CH_4 content is a good indicator of the increased flux of the magmatic component. Allowing that,

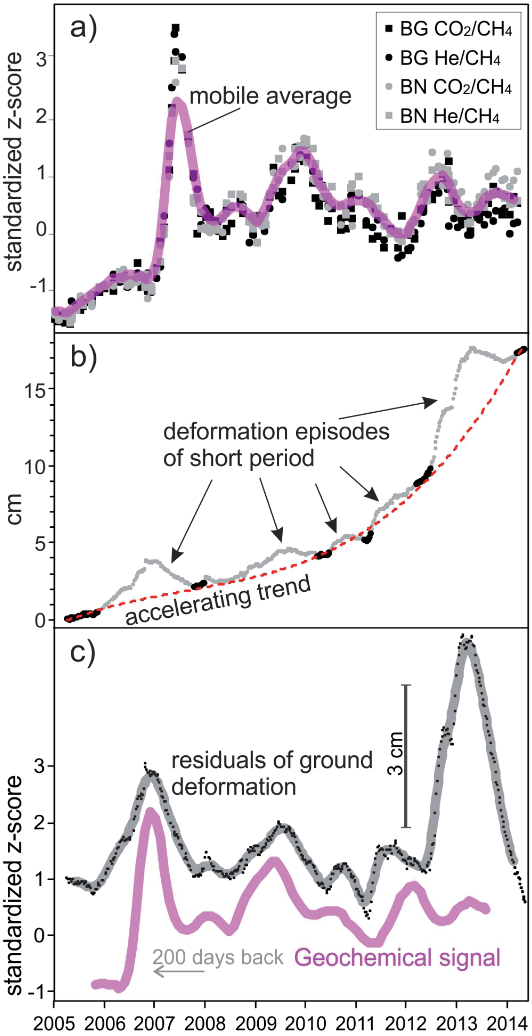

Fig. 2 – a) Measured CO2/CH4 and He/CH4 ratios at fumaroles BG and BN. In order to compare the different signals the measured data were normalized by dividing the difference between each value and the mean by the standard deviation (standardized z-score). The 4 month mobile average of all the data is assumed as the best representation of the geochemical signal; b) 2005-2014 baseline length variation between the ACAE and ARFE CGPS stations (De Martino *et al*., 2014). The data used for the derivation of the 'accelerating trend' curve are reported as black dots (see the text for further explanations); c) the geochemical signal is compared with the 4 month mobile average of the ground displacement residual (redrawn from Chiodini *et al*., 2015).

the six peaks, each lasting about one year, which affected the CO_2/CH_4 and He/CH_4 ratios of the main fumaroles BN and BG in 2007, 2008, 2009-10, 2011, 2012, 2013 (Fig. 2a) correspond to periods of discharge of fluids richer in the magmatic component at the Solfatara fumaroles.

Fig. 2b shows the deformation pattern of CFc during the same period, i.e. from 2005 to 2014. The whole CFc uplifted and expanded producing different total displacements, but following a similar accelerating process (continuous GPS data, CGPS, Fig. 2-4 in De Martino *et al*., 2014). According to Chiodini *et al*. (2015), here we refer to the baseline variations between two CGPS stations of the INGV network [ACAE and ARAFE, see Chiodini *et al*. (2015) for further details]. The deformation curve (Fig. 2b) suggests the overlapping of a general trend of expansion with short periods of dilation (or uplifting) pulses, two of which were particularly important, in 2006-2007, and 2012-2013. Chiodini *et al*. (2015) fitted the CGPS measurements to a third-order polynomial equation considering only the points less affected by these pulses (i.e., the relative minima of the curve; Fig. 2b, black dots). The residuals of the observed data with respect to the curve (Fig. 2c) clearly repeat the same sequence of seven minima and six maxima, highlighted by the CO_2/CH_4 and He/CH_4 fumarolic ratios. The main difference is a time lag of about 200 days, with the geochemical signal following the ground deformation (Fig. 2c).

Excluding an improbable fortuity, this coincidence between two independent data sets can be interpreted as the consequence of pulsed inputs of magmatic fluids into the hydrothermal system feeding Solfatara fumaroles. The pressurization of the deeper part of the system (magmatic gas zone in Fig. 1), which likely anticipates the degassing event, and the pressure variations within the hydrothermal system during the injection episode cause the deformation. The delay of the geochemical signal represent the transient time of the magmatic fluids from the input zone to the fumarolic discharges. Only the last important deformation event (2012-2013) does not correspond to a geochemical peak of comparable intensity. It is worth to note that recently this deformation episode was attributed to magma intrusion at relatively shallow levels rather than to a fluid transfer process (D'Auria *et al.*, 2015).

Analyzing the entire data set of Solfatara fumarolic compositions, we infer that fourteen episodes of magmatic fluid injections affected the CFc from 1983 to 2014 enough to produce measurable geochemical anomalies. Their effects are investigated by physical numerical modelling.

Modelling magmatic fluid injections into the CFc hydrothermal system. Chiodini *et al.*, (2012) applied a physical numerical model [TOUGH2 by Pruess (1991), with an axisymmetric computational domain] to mimic the injection of batches of magmatic fluids into the hydrothermal system, feeding the fumarolic field of Solfatara. The results highlight the occurrence of the new unrest of CFc which apparently culminated in 2012-2013 with the above cited magma intrusion at relatively shallow levels. Repeated injections of hot fluids at the base of the hydrothermal system, i.e. beneath Solfatara crater, are imposed to the model, keeping a fixed H_2O-CO_2 ratio and adjusting the flux through a trial-and-error approach in order to reproduce the H_2O-CO_2 composition measured at the main Solfatara fumaroles. Twelve injections of variable intensity, each involving an amount of deep fluids of the order of the quantities involved in low-medium sized eruptions, well reproduce the compositional changes of the fumaroles in the 1983-2011 period (Chiodini *et al.*, 2012). The cumulative curve of injected fluids (for a total of ~ 25 Mt) clearly shows a change in the slope at the beginning of the 2000's which can be interpreted as the beginning of the new unrest phase at CFc, independently suggested by the inversion in the deformation pattern which, roughly at the same time, passed from a subsidence trend to the new uplift regime.

In the last years, new researches based on the fumarolic inert gas species suggested that the period studied in Chiodini *et al.* (2012) was likely affected by depressurization of the gas-magma separation process (Caliro *et al.*, 2014). This depressurization, which occurred from 1980's to 2011-2015, should have caused an important increase of the H_2O/CO_2 ratio of magmatic fluids because H_2O is more soluble in magma than CO_2. This implies that the hypothesis of a fixed H_2O-CO_2 composition of Chiodini *et al.* (2012) cannot be taken as plausible. We present here the results of new modelling, which accounts for a progressive increase in the water content of the injected fluids.

Recently, several studies were aimed to improve the modeling of the hydrothermal system of CFc. They include, for example, the first definition of a 3-D domain with heterogeneous properties of the rocks derived from the density tomography of the caldera (Petrillo *et al.*, 2013), and the first application to CFc of MUFITS (Afanasyev *et al.*, 2015), a code which deals with high, magmatic temperatures of the fluids.

Here, however, we discuss the results of new modelling performed with TOUGH2 code (Pruess, 1991) and an axisymmetric computational domain, i.e. the same tools adopted in Chiodini *et al.* (2012), in order to compare these new results with the previous ones. TOUGH2 accounts for the coupled transport of heat and a multi-phase (gas and liquid) and multicomponent (water and carbon dioxide) fluid. The used computational domain, discretized in 850 cells of different volume, represents a 5 km diameter and 2 km height cylinder. Bottom and lateral boundaries are impermeable and adiabatic, while the top boundary has fixed atmospheric temperature and pressure. Values of the rock properties (porosity $\Phi = 0.2$; permeability $k = 10^{-14}$ m^2; density $\varrho = 2000$ kg/m^3; thermal capacity $C = 1000$ J/kg °C; thermal conductivity K = 2.8 W/m °C) are equal to those adopted in previous modelling (Chiodini *et al.*, 2012 and references therein).

The initial state is a steady state reached after 2000 years of injection of 3400 td^{-1} of a gas mixture at 350°C with a relatively low CO_2/H_2O molar ratio, and ideally represents the pure hydrothermal component discharged at Solfatara before the 1982-84 crisis. The transient solution is obtained with the pulsed injection into the hydrothermal system of large amounts of a gas mixture, with H_2O-CO_2 composition representing the magmatic fluid. The CO_2/CH_4 anomalies measured at Solfatara fumaroles provide the hint for the number and timing of each injection episode of magmatic fluids (14 in the 1983-2014 period), while the fumarolic CO_2/H_2O

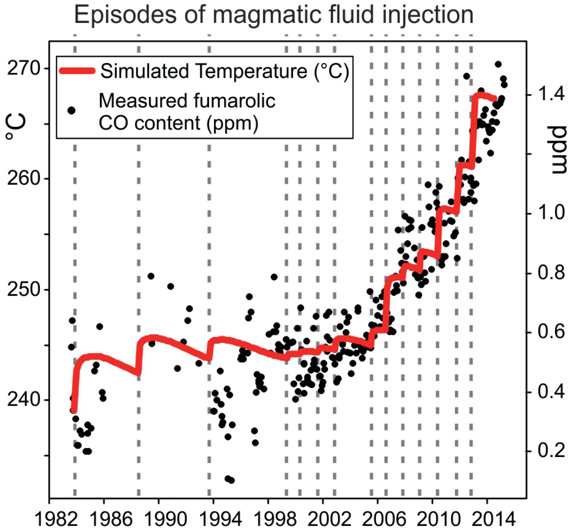

Fig. 3 – Evolution of the average temperature simulated for the deep central part of the computational domain compared with the measured carbon monoxide (CO) content of the fumaroles. The timing of the simulated magmatic fluid injections (dashed lines) were derived by the analysis of the CO_2/CH_4 and He/CH_4 fumarolic ratios (see the text for further explanations).

ratio constrains the total gas amount of each injection episode whit a trial-and-error procedure similar to that adopted in Chiodini *et al.* (2012).

While in Chiodini *et al.* (2012) approach the composition of the injected fluid was constant with time, in this study the H_2O/CO_2 ratio (by weight) of the injected magmatic fluids increases form the value of 0.67, in 1983, to 1.2, in 2012. This increase of the H_2O/CO_2 ratio agrees with the hypothesis of an open magmatic system, which depressurizes in time because of degassing. Practically, we depict one possible, but not unique, scenario previously proposed to explain the evolution of the fumarolic inert gas species compositions (see Fig. 8b in Chiodini *et al.*, 2015).

The results of the new model confirm the beginning of the new unrest phase in earlier 2000's, when the cumulative curve of injected fluids shows an inflection point as already noted by Chiodini *et al.* (2012). There are, however, two major differences with the previous simulations: 1) in order to reproduce the observed fumarolic compositions, the injected amounts of fluids have to be ~30% higher than in previous model; 2) the system is significantly heated during the process, a feature not observed in Chiodini *et al.* (2012). The increase of the H_2O/CO_2 ratio of the injected fluids with time causes, in fact, a remarkable increase of the total amount of steam injected into the system, and in turn of condensation and heating of the whole system.

Fig. 3 shows the evolution of the simulated average temperature in the deep central part of the domain, above the injection point (a cylinder of 1 km diameter and 1 km height). The resulting average temperature remains nearly constant from 1983 to 2005 (240-245 °C), while from 2006 to 2014 it increases from 245°C to 270°C.

The absolute temperature field is in some way controlled by the quite arbitrary choice of the function used to describe the H_2O/CO_2 increase of the magmatic component, which in turn constraints the total amount of injected steam. On the contrary, the time evolution of the temperature increase is much less affected by this choice, being mainly controlled by other constraints, such as the measured fumarolic CO_2/CH_4 ratio (frequency of the injections) and the H_2O/CO_2 ratio (intensity of the injections). It is worth to note that the reliability of the modelled evolution of the temperature finds confirmation on independent observations. The fumarolic content of carbon monoxide, which is the gas specie most sensitive to temperature variations (Chiodini and Marini, 1998), shows the same behavior (Fig. 3). In 2005-2006, concurrently with the beginning of the increase of the simulated temperature, the fumarole of Pisciarelli starts to increase its activity [increase of flow rate and discharge temperature: Chiodini *et al.* (2015)]. Finally, in 2005-2006 CFc starts to expand and uplift with an accelerating trend very similar to the temperature increase.

Conclusion. The almost unique, long time set of fumarolic compositions data at Solfatara highlight important changes in the hydrothermal system feeding the manifestation observed from 1983 to 2015 periods. In particular, during the ongoing unrest of CFc started in 2005, the occurrence of numerous episodes of injection of magmatic fluids into the hydrothermal system are recognized comparing geochemical and geophysical signals. The physical numerical modelling of such episodes, together with several other independent observations, indicates that the large amount of steam involved in the process is currently heating the hydrothermal system through condensation. This heating process, which for the first time is documented to occur with so many details during a caldera unrest, may be one of the main causes of the current deformation phase of CFc. The input of magmatic steam into geothermal systems is potentially a very efficient way both for heating and for deforming the rocks to such an extent that steam injection is used is used in oil industry for heavy oil exploitation (e.g. Dusseault and Collins, 2008; Dusseault, 2011).

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References

Acocella V., Di Lorenzo R., Newhall C., and Scandone R.; 2015: *An overview of recent (1988 to 2014) caldera unrest: Knowledge and perspectives*. Rev. Geophys., article in Press, doi: 10.1002/2015RG000492

Afanasyev A., Costa, A. and Chiodini G.; 2015; *Investigation of hydrothermal activity at Campi Flegrei caldera using 3D numerical simulations: Extension to high temperature processes*. J. Volcanol. Geotherm. Res., **299**, 68-77, doi:10.1016/j.jvolgeores.2015.04.004

Aiuppa A., G. Tamburello, R. Di Napoli, C. Cardellini, G. Chiodini, G. Giudice, F. Grassa and M. Pedone; 2013: *First observations of the fumarolic gas output from a restless caldera: Implications for the current period of unrest (2005–2013) at Campi Flegrei*. Geochem. Geophys. Geosys., doi:10.1002/ggge.20261.

Amoruso A., Crescentini L. and Sabbetta I.; 2014: *Paired deformation sources of the Campi Flegrei caldera (Italy) required by recent (1980-2010) deformation history*. J. Geophys Res. **119**, doi:10.1002/2013JB010392

Caliro S., Chiodini G. and Paonita A.; 2014: *Geochemical evidences of magma dynamics at Campi Flegrei (Italy)*. Geochim. Cosmochim. Acta **132** , 1-15

Caliro S., Chiodini G., Moretti R., Avino R., Granieri D., Russo M. and Fiebig, J.; 2007: *The origin of the fumaroles of La Solfatara (Campi Flegrei, South Italy)*. Geochim. Cosmochim. Acta, **71** (12), 3040-3055

Chiodini, G.; 2009: *CO_2/CH_4 ratio in fumaroles a powerful tool to detect magma degassing episodes at quiescent volcanoes*. Geophys. Res. Lett., **36**, L02302, doi:10.1029/2008GL036347.

Chiodini G. and Marini, L.; 1998: *Hydrothermal gas equilibria; the H_2O–H_2–CO_2–CO–CH_4 system*. Geochim. Cosmochim. Acta, **62**, 15, 2673–2687.

Chiodini G., Caliro S., Cardellini C., Granieri D., Avino R., Baldini A., Donnini M. and Minopoli C.; 2010: *Long-term variations of the Campi Flegrei, Italy, volcanic system as revealed by the monitoring of hydrothermal activity*. J. Geophys Res., **115,** 3, B03205

Chiodini G., Caliro S., De Martino P., Avino R. and Gherardi F.; 2012; *Early signals of new volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and physical simulations*. Geology, **40**, 943–946.

Chiodini G., Vandemeulebrouck J., Caliro S., D'Auria L., De Martino P., Mangiacapra A. and Petrillo Z.; 2015: *Evidence of thermal driven processes triggering the 2005-2014 unrest at Campi Flegrei caldera*. Earth Planet. Sci. Lett. , **414**, 58–67.

Del Gaudio C., Aquino I., Ricciardi G. P., Ricco C. and Scandone R.; 2010: *Unrest episodes at Campi Flegrei: A reconstruction of vertical ground movements during 1905– 2009*. J. Volcanol. Geotherm. Res., **195**, 48–56, doi: 10.1016/j.jvolgeores.2010.05.014.

De Martino P., Tammaro U. and Obrizo F.; 2014: *GPS time series at Campi Flegrei caldera (2000-2013)*. Ann. Geophys., **57**, 2, 2014, S0213; doi: 10.4401/ag-6431

De Siena L., Del Pezzo E. and Bianco F.; 2010: *Seismic attenuation imaging of Campi Flegrei: Evidence of gas reservoirs, hydrothermal basins, and feeding systems*. J Geophys Res, **115**, 1–18.

Di Vito M. A., Isaia R., Orsi G., Southon J., De Vita S., D'Antonio M., Pappalardo L. and Piochi M.; 1999; *Volcanism and deformation since 12000 years at the Campi Flegrei caldera (Italy)*. J. Volcanol. Geotherm. Res., **91**, 221–246.

Dusseault M.B.; 2011: *Geomechanical Challenges in Petroleum Reservoir Exploitation*. KSCE Journal of Civil Engineering **15**, 4, 669-678, doi: 10.1007/s12205-011-0007-5.

Dusseault M.B. and Collins P.M.; 2008: *Geomechanics Effects in Thermal Processes*. CSEG Recorder, June 2008, 20-23.

Dvorak J. J. and Mastrolorenzo G.; 1991: *The mechanisms of recent vertical crustal movements in Campi Flegrei Caldera, southern Italy*. Spec. Pap. Geol. Soc. Am., **263**, 47

Lowenstern, J. B., Smith R. B. and Hill D. P.; 2006: *Monitoring super-volcanoes: Geophysical and geochemical signals at Yellowstone and other large caldera systems*. Philos. Trans. R. Soc. A, **364**, 2055–2072.
Morhange C., Marriner N., Laborel J., Micol T. and Oberlin C.; 2006: *Rapid sea-level movements and noneruptive crustal deformations in the Phlegrean Fields caldera, Italy.* Geology, **43**, 93–96.
Newhall C. G. and Dzurisin D.; 1988: *Historical unrest at large calderas of the world*. U.S. Geol. Surv. Bull., 1855, 1108.
Orsi G., Di Vito M. A. and Isaia R.; 2004: *Volcanic hazard assessment at the restless Campi Flegrei caldera*. Bull. Volcanol., **66**, 514–530.
Petrillo Z., Chiodini G., Mangiacapra A., Caliro S., Capuano P., Russo G., Cardellini C. and Avino R.; 2013: *Defining a 3D physical model for the hydrothermal circulation at Campi Flegrei caldera (Italy)*. J. Volcanol. Geotherm. Res.**264**,172–182
Pruess K.; 1991:*TOUGH2 - A General Purpose Numerical Simulator for Multiphase Fluid and Heat Flow*. L. B. L. Report. LBL, Berkeley, CA, p. 29400.
Rosi M., Sbrana A. and Principe C.; 1983: *The Phlegrean Fields: Structural evolution, volcanic history and eruptive mechanisms*. J. Volcanol. Geotherm. Res., **17**, 273–288.
Vanorio T., Virieux J., Capuano P. and Russo G.; 2005: *Threedimensional seismic tomography from P wave and S wave microearthquake travel times and rock physics characterization of the Campi Flegrei caldera*. J. Geophys. Res., **110**, B03201, doi:10.1029/2004JB003102.