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Magma degassing as a trigger of bradyseismic events: The case of Phlegrean Fields (Italy)

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[1] Phlegrean Fields is an active and densely populated caldera near Naples (Italy). Two major unrest episodes characterized its recent history, each leading to remarkable ground uplift and followed by slow subsidence. Fumaroles near the caldera centre underwent important chemical changes during these volcanic crises. Based on published data we show that a correlation exits between ground displacement and gas composition. Numerical modelling of hydrothermal circulation shows that periods of enhanced fluid injection at the base of the hydrothermal system, are consistent with the observed chemical variations. The model predicts an average increase in pore pressure and temperature within the system, suggesting potential effects on ground deformation. Literature data and simulation results show that periods of intense magmatic degassing could explain most of the features characterizing recent bradyseismic crises and should be considered a potential trigger for the unrest at Phlegrean Fields, as well as at other calderas in the world. *INDEX TERMS:* 3210 Mathematical Geophysics: Modeling; 8424 Volcanology: Hydrothermal systems (8135); 8499 Volcanology: General or miscellaneous. **Citation:** Chiodini, G., M. Todesco, S. Caliro, C. Del Gaudio, G. Macedonio, and M. Russo, Magma degassing as a trigger of bradyseismic events: The case of Phlegrean Fields (Italy), *Geophys. Res. Lett.*, *30*(8), 1434, doi:10.1029/2002GL016790, 2003.

1. Introduction

[2] Calderas are large volcanic depressions that form during major explosive eruptions. Activity may resume inside quiescent calderas, often leading to ground deformation (bradyseism) and seismicity. These crisis sometime prelude to a new eruptive phase, but in other cases, a slow subsidence follows the maximum uplift, with no further consequence [*Newhall and Dzurisin*, 1988]. Understanding the process driving bradyseismic crises bears important consequences for volcanic hazard evaluation. Traditional interpretations involve a pressure build-up inside the magma chamber [*Mogi*, 1958; *Bianchi et al.*, 1987; *Dzurisin and Yamashita*, 1987; *Bonafede et al.*, 1986], but the role of hydrothermal fluids has been also emphasized by some authors [*Casertano et al.*, 1976; *Bonafede*, 1991; *De Natale et al.*, 1991; *Gaeta et al.*, 1998]. Data from Phlegrean Fields show that, even during quiescent times, the hydrothermal circulation represents one of the most relevant processes in the area, both in terms of mass discharged by diffuse degassing, and in terms of associated energy release [*Chiodini et al.*, 2001].

[3] To better investigate the relations between ground deformation and hydrothermal fluid circulation, we focused our study on the Phlegrean Fields caldera (Figure 1). Here, a good geochemical record exists for the last 20 years, and an even longer data set, stretching through the last 2000 years, is available to constrain ground deformation [*Caputo*, 1979; *Dvorak and Mastrolorenzo*, 1991]. These data evidence a secular trend of subsidence, periodically interrupted by short uplift phases, accompanied by seismic activity. Last eruption (Monte Nuovo, in 1538) was preceded by a vertical ground displacement of 7 m [*Dvorak and Gasparini*, 1991]. During the last 30 years, two main uplift phases were recorded: in 1969–1972 and in 1982–1984. In each case, deformation was confined within a radius of 6 km, with maximum values (ca. 2 m in both cases) at the caldera centre. There, the town of Pozzuoli was partially evacuated in 1984, due to the intense seismic activity [*Barberi et al.*, 1984]. Since 1985, a slow subsiding phase began and was interrupted three more times by minor uplifts in 1989, 1994 and 2000 (Figure 2).

[4] Since the unrest in 1982, systematic geochemical monitoring began providing 160 samples (from 1983 to 2002) for the hottest vent (BG, T = 150–164°C), that is here considered representative of the entire fumarolic field. Water vapor is the main component of the fumarolic effluents, followed by CO_2, H_2S, N_2, H_2, and CH_4; acid gases (SO_2, HCl, HF) are virtually absent [*Cioni et al.*, 1984; *Chiodini and Marini*, 1998; *Chiodini et al.*, 2001]. This composition is typical of the hydrothermal environment [*Chiodini and Marini*, 1998], however the involvement of large proportion of magmatic fluids is suggested by the isotopic composition of H_2O, CO_2, and He [*Tedesco et al.*, 1990; *Allard et al.*, 1991; *Panichi and Volpi*, 1999]. Strong variations involving both main and minor gas species were observed during the last bradyseismic crises in 1982–1984, 1989, 1994, and 2000 [*Cioni et al.*, 1984; *Tedesco and Scarsi*, 1999].

[5] According to the current interpretation [*Barberi et al.*, 1984; *Cioni et al.*, 1984], bradyseism is preceded by an

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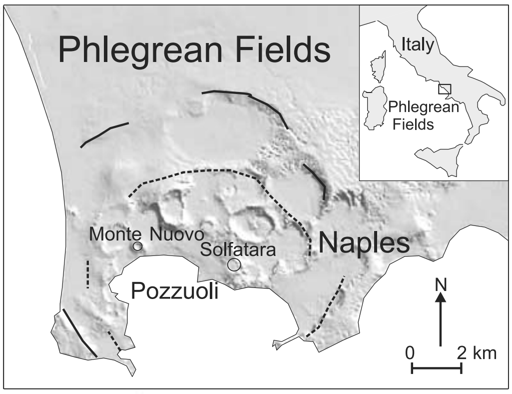

Figure 1. The Phlegrean Fields caldera. Major structural features and the location of La Solfatara and Monte Nuovo eruptive centres are indicated.

increase in water vapor in fumarolic gases. Such an increase derives from a higher degree of water boiling, due to additional heat transferred to the hydrothermal system [*Cioni et al.*, 1984]. This, in turn, would result from a new magmatic intrusion, traditionally called upon to explain the observed ground deformation. A different approach to the published geochemical data allowed us to gain further insights on the driving process and to reach a different interpretation.

2. A New Perspective on Published Data

[6] Chemical variations recorded during the last 20 years can be summarized as chronograms, where appropriate ratios of main gas components (CO_2/H_2O, CO_2/H_2S and N_2/H_2O) are plotted versus time. The temporal evolution of these ratios can be compared with elevation changes measured at the caldera centre since 1983 (Figure 2). Each gas ratio show four asymmetric peaks during the considered time span. Each peak is due to a sharp increase of each gas ratio, followed by a more gentle decline. Interestingly, compositional peaks systematically follow the corresponding maximum uplift, with a delay of the order of few hundreds days. Our data analysis also shows that a high correlation exists among chemical compositions and measured ground displacement. If chemical data are shifted back in time, so that each compositional peak corresponds to the associated maximum uplift, the correlation between chemical composition and ground elevation is strongly highlighted. Figure 3 shows the gas composition as a function of ground elevation, after such temporal shift. The highest correlation coefficient ($R^2 = 0.89$) is obtained for the N_2/H_2O ratio, but also the other gas ratios reached R^2 values high enough to exclude a fortuitous correlation. Such high correlation suggests that changes in ground deformation and chemical composition are driven by the same process. We hypothesize that the injection of deep fluid (likely magmatic), enriched in CO_2 and N_2, at the base of the hydrothermal system, could explain the compositional evolution of the system and its temporal relation with the ground deformation. To check this hypothesis we analysed the behaviour of a hydrothermal system undergoing the injection of hot fluids from a deep external source.

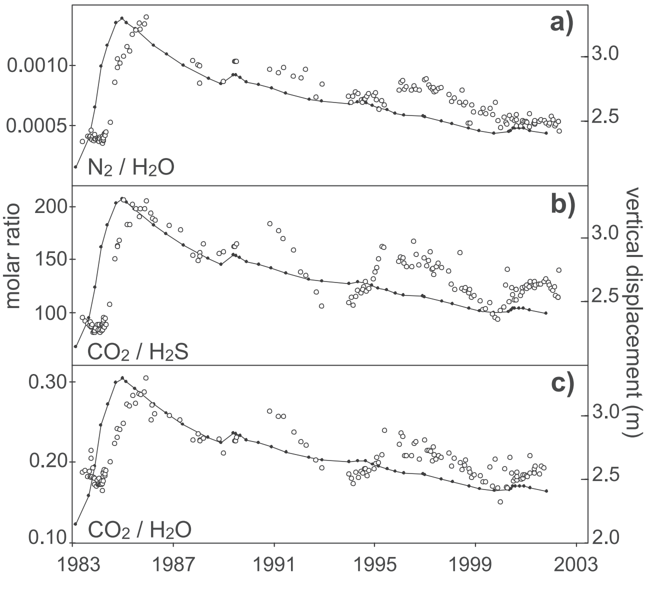

Figure 2. Temporal evolution of chemical composition at La Solfatara fumarole BG, and vertical ground displacement, as recorded at benchmark 25 (in Pozzuoli). (a) N_2/H_2O molar ratio; (b) CO_2/H_2S molar ratio; (c) CO_2/H_2O molar ratio.

3. Physical Modeling of Fluid Circulation

[7] Physical modelling was here applied to verify whether the observed, chemical evolution could derive from

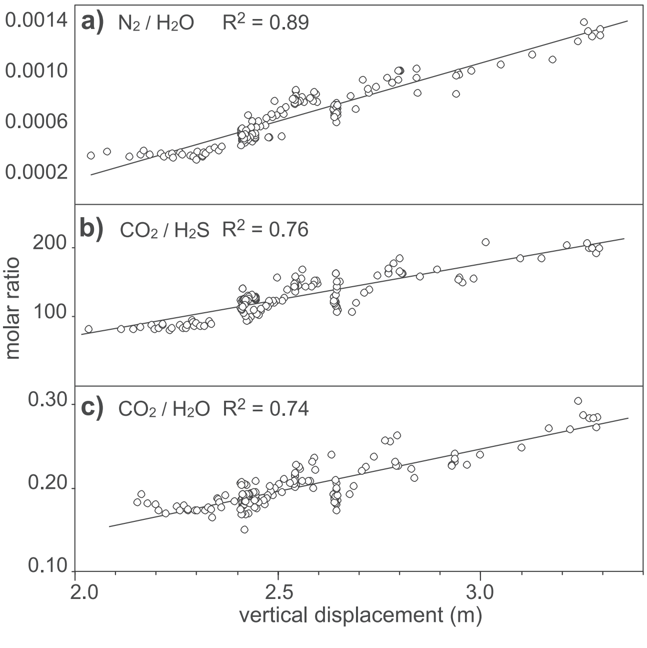

Figure 3. Chemical composition versus ground deformation and corresponding correlation coefficients (R^2). Chemical composition are shifted back in time to match uplift phases (see text for discussion). In parenthesis, the temporal shift assigned to reach the best correlation: (a) N_2/H_2O molar ratio (260 days); (b) CO_2/H_2S molar ratio (280 days); (c) CO_2/H_2O molar ratio (230 days).

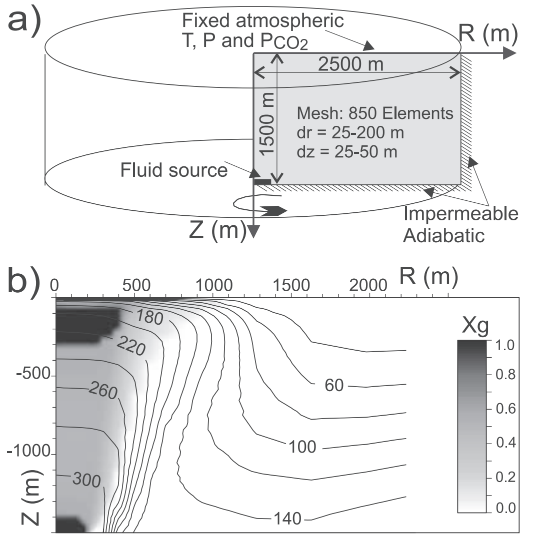

Figure 4. (a) Computational domain and boundary conditions for numerical simulations. Applied rock properties: porosity = 0.2; thermal capacity = 1000 J/kg°C; density = 2000 kg/m^3; permeability = 10^{-14} m^2; thermal conductivity = 2.8 W/m°C; (b) Initial conditions: temperature (°C, black lines) and volumetric gas fraction (Xg) (see text).

periodic injections of hot CO_2-rich fluids at the base of a shallow hydrothermal system. To this purpose, we applied a well known geothermal simulator (TOUGH2 [*Pruess*, 1991]). The simulator accounts for the coupled transport of heat and of a multi-phase (gas and liquid) and multi-component (water and carbon dioxide) fluid. It was recently applied to the study of diffused degassing at La Solfatara, and successfully reproduced some of the main features of the natural system [*Todesco et al.*, 2003].

[8] The conceptual model that we adopt here is similar. We consider the hydrothermal system at La Solfatara and assume that it has been heated by a prolonged and continuous injection of hot fluids, arriving from a greater depth (Figure 4a). Only the shallowest portion of the hydrothermal system was considered, to keep the simulation within a temperature range compatible with modelling capabilities. Rock physical properties applied in the simulations are based on literature data, and are briefly reported in Figure 4a, together with boundary conditions. Initial conditions were computed by simulating more than 4000 years of injection of a mixture of carbon dioxide and water at 350°C, at the base of the hydrothermal system. The composition of the injected fluids (CO_2/H_2O = 0.17 vol) was selected in order to match the gas composition measured right before the 1982–84 bradyseismic crises. The order of magnitude of the corresponding injection rates (1000 ton/day of CO_2 and 2400 ton/day of H_2O) were established based on measured CO_2 diffuse degassing rate. System conditions thereby achieved are consistent with the results of *Todesco et al.* [2003]: a plume of hot fluids develops and extends toward the surface, where a shallow single-phase-gas region forms (Figure 4b). The existence of such region and its physical conditions meet the prediction of the geochemical model independently proposed for La Solfatara [*Chiodini and Marini*, 1998]. This is the region that feeds the fumarolic activity at the surface, and that here we consider representative of the high-temperature fumaroles composition. The simulation also reproduces the observed degassing rate and the energy budget recently estimated at La Solfatara.

[9] Aim of the simulations presented here was to study the evolution of this heated hydrothermal system during bradyseismic crises, here simulated as periods during which both the injection rate of deep fluids and their carbon dioxide content are increased. Simulations were planned to verify whether this mechanism can produce the chemical variations recently observed at Phlegrean Fields. During the simulated bradyseismic crises, the injection rates were increased to 5000 ton/day of CO_2 and 6670 ton/day of H_2O. These new values correspond to a CO_2/H_2O ratio of 0.30vol, that is the maximum value measured at La Solfatara during last big bradyseismic event. Fluid temperature remains unchanged. After some time, the injection rate and injected fluid composition return back to their initial values. Several high-injection-rate-periods (HIRP), of variable duration, were simulated over a time span of 20 years. Results presented here only refer to a selection of HIRP, whose frequency and duration were chosen to match observed chemical variations.

[10] The increased injection rate and the different CO_2 content cause an increase in temperature and pressure within the hydrothermal system. Furthermore, the composition of the single phase gas region changes, leading to the emission of CO_2-enriched fluids. Once the injection rate returns to the initial, lower value, also gas composition shift to lower values of the CO_2/H_2O ratio. Compositional variations, however, do not follow immediately the changes in injection rate and some time is necessary before chemical changes are observed at the surface. As a consequence, the maximum CO_2 enrichment is observed at the surface some time after the injection rate is lowered again. After the maximum value is reached, the CO_2 content undergoes a smooth decline, that closely resembles the observed trend (Figure 5). As the figure shows, the periods of high injection rate (HIRP), chosen to match chemical data, roughly correspond to the observed uplift phases. Modelling results confirm that periodic phases of

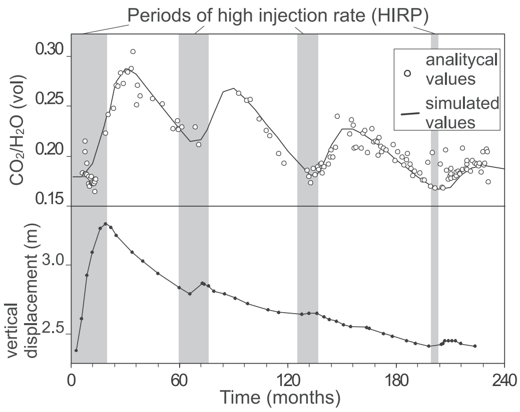

Figure 5. (a) Comparison between observed (open dots) and simulated (solid line) gas composition expressed as CO_2/H_2O (molar ratio). Shaded area highlights periods of enhanced fluid injection (HIRP); (b) Ground deformation.

intense magmatic degassing can generate the observed chemical changes. The model also predicts a delay (and its order of magnitude) between the beginning of the crisis and the occurrence of chemical changes in fumarolic gases.

4. Discussion and Conclusion

[11] We here propose a new mechanism to explain the recent bradyseismic crises at the Phlegrean Fields, based on a careful review of literature data and modeling results. We hypothesize that periods of intense magmatic degassing drive both chemical changes of fumaroles and ground deformation during unrest crises.

[12] It is recognized that hydrothermal fluids can induce or enhance rock deformation [*Bonafede*, 1991; *De Natale et al.*, 1991; *Gaeta et al.*, 1998] by increasing the pore pressure (and hence modifying the effective stress) and rock temperature (inducing thermal expansion). In the case of Phlegrean Fields, the fluid and heat transport associated with hydrothermal circulation is known to be particularly relevant. Two specific campaigns (in 1998 and in 2000) showed that up to 1500 tons of carbon dioxide are daily released from the small Solfatara crater (0.5 km^2) [*Chiodini et al.*, 2001; *Todesco et al.*, 2003]. Associated shallow steam condensation is expected to release ca. 100 MW of thermal energy. This amount of energy is one order of magnitude higher than the energy released by heat conduction through the entire caldera, and several times higher than the energy associated with recent seismic crises and ground deformation [*Chiodini et al.*, 2001]. Even more fluids and energy are expected to be released during unrest crises. These estimates imply that hydrothermal circulation could be reasonably considered a potential driving mechanism for ground deformation.

[13] The model applied here does not account for rock deformation, but it describes the evolution of temperature and pore pressure resulting from such injections. As expected, these two variables progressively increase during the entire duration of the HIRP, and then gently decline. A deformation induced by such changes is therefore expected to reach its maximum value at the end of each HIRP. Figure 5 shows a very good correspondence between the end of each HIRP (chosen to match chemical data) and the observed maximum uplift phases.

[14] This hypothesis also provides an explanation for the different time at which chemical changes and maximum uplift are recorded. Rock deformation at the Phlegrean Fields is expected to be elastic [*De Natale et al.*, 1991] and hence it follows immediately the fluid injection into the hydrothermal system. On the contrary, injected fluids require some time to reach the surface, so that fumarole composition is affected only at later times.

[15] Our hypothesis is consistent with the observed temporal evolution of bradyseism and with geochemical data. We believe that periods of intense magmatic degassing could potentially trigger unrest phases also at other similar caldera, such as Long Valley, Yellowstone and Rabaul.

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