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MODELING OF GAS COMPOSITION AND GRAVITY SIGNALS AT THE PHLEGREAN FIELDS CALDERA

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ABSTRACT

Hydrothermal systems are known to play an important role in the evolution of active calderas: these volcanic systems periodically undergo dramatic unrest crises, commonly involving ground deformation, seismic activity and important changes in several geophysical and geochemical parameters monitored at the surface. These unrest crises may, or may not, culminate with a renewal of the eruptive activity, but in any case they bear important consequences in densely populated regions. Early warning and a prompt evaluation of the state of evolution of the volcanic system are therefore essential to ensure proper mitigation measures. A proper interpretation of monitoring data, however, is only achieved within the framework of a robust conceptual model of the system. Recent research work carried out at the Phlegrean Fields shows that the recent evolution of the caldera is consistent with the presence of a pulsating magmatic source, periodically discharging CO_2-enriched fluids into a shallow hydrothermal system. Such pulsating degassing affects the amount of heat and fluids entering the hydrothermal system, the distribution of fluid phases throughout the system, and their composition. As a consequence, degassing controls not only the composition of fluids discharged at the surface, but also ground displacement and gravity residuals. In this work, the TOUGH2 code has been applied to study how different degassing scenarios could affect the composition of discharged fluids and the gravity signals recorded at the surface.

UNRESTS AT THE PHLEGREAN FIELDS CALDERA

The Phlegrean Fields (Figure 1) caldera is an active volcanic center located in the urban area of Naples (Italy). The last eruptive event (Monte Nuovo) occurred in 1538, following several decades of ground deformation, culminating with a 7 m uplift, a few days before the eruption (Di Vito et al., 1987; Rosi and Sbrana, 1987; Orsi et al., 1999). More recently, two non-eruptive unrest crises occurred in 1969 and 1982. Each time, remarkable ground uplift (up to 1.8 m in Pozzuoli) was reached within a couple of years, and was accompanied by seismic activity, gravity changes, as well as geochemical variations at Solfatara fumaroles. Since 1985, a slow subsidence is taking place, periodically interrupted by minor, short-lasting uplift episodes (Barberi and Carapezza, 1996, Orsi et al., 1999; and references therein). Figure 2 illustrates some typical changes in geophysical and geochemical parameters recorded since 1982.

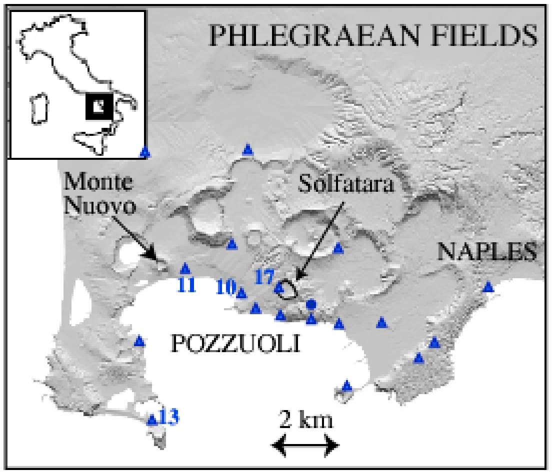

Figure 1. The Phlegrean Fields caldera and the Solfatara crater. Blue triangles indicate the location of gravity stations. Blue numbers refer to the stations considered in the present study (10: Serapeo; 11: Arco Felice; 13: Miseno; 17: Solfatara).

Radiocarbon dating of fossil marine organisms, found within Roman ruins in Pozzuoli, revealed that submersion of the famous Roman pillars was interrupted three times by uplift episodes, thelast of which led to the 1538 eruption. These new data imply that non-eruptive unrest episodes are rather the rule than the exception in the complex deformation history of the caldera (Morhange et al., 2006).

Unrest crises of active volcanoes are commonly ascribed to magma ascent toward the surface, or to its emplacement at shallow crustal level. Recent research, however, emphasizes the role of hydrothermal fluids in the evolution of quiescent volcanoes. Measurements carried out to quantify mass and energy budgets associated with the ascent and condensation of hot hydrothermal fluids revealed impressive figures, with up to 100 MW of thermal energy being released through diffuse degassing at Solfatara (Chiodini et al., 2001, Chiodini et al., 2005). A proper evaluation of the volcanic hazard therefore requires a good understanding of the mechanisms controlling the hydrothermal system during unrest periods.

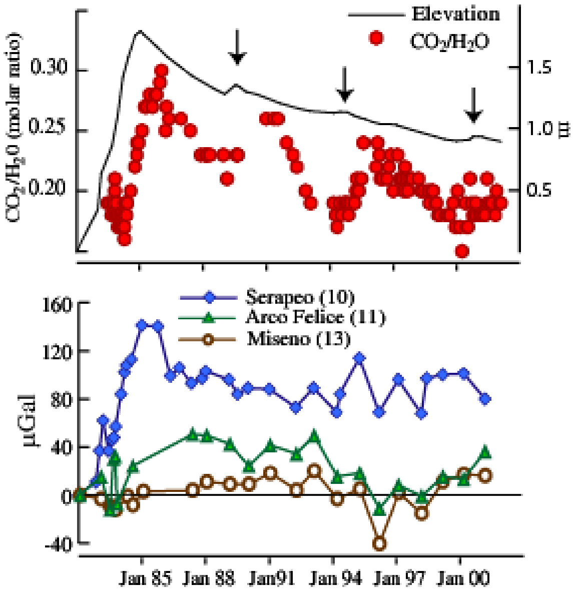

Figure 2. Vertical ground displacement (m) at the caldera centre, and fumarolic gas composition at Solfatara. Arrows indicate periods of minor uplifts (upper diagram); gravity residuals at three different stations (location in Fig.1), since 1982 (lower diagram).

Physical modeling of hydrothermal fluid circulation showed that the compositional changes observed at Solfatara during unrest crises are consistent with periods of increased magmatic degassing (Chiodini et al, 2003). Coupled thermo-hydro-mechanical modeling also showed that heating and pore pressure build-up, associated with the ascent of hot hydrothermal fluids, can generate important amounts of ground deformation (Todesco et al., 2004). This further emphasizes the role of the hydrothermal system in uplift episodes, already suggested by various authors (Casertano et al., 1976; Bonafede, 1991; Gaeta et al., 1998; 2003; Battaglia et al., 2006). More recently, physical modeling was carried out to evaluate gravity changes arising from the hydrothermal fluid circulation. Todesco and Berrino (2005) showed that a hydrothermal system fed by a pulsating magmatic source is characterized by continuous change of fluid composition and phase distribution. As a result, the variation of the average fluid density generates a gravity change that can be recorded at the surface. Comparison with observed gravity data showed that hydrothermal fluids reaching the surface are responsible for the anomalous data set recorded at Solfatara. Simultaneous matching with geochemical data provided new constraints for the definition of the initial and boundary conditions (Todesco and Berrino, 2005).

In this work, physical modeling of heat and fluid flow is applied to study the most recent evolution of the hydrothermal system at Solfatara. Simulation results are compared with both geochemical and gravity data, following Todesco and Berrino (2005).

MODELING OF HYDROTHERMAL SYSTEM AT SOLFATARA

According to the conceptual model proposed by Chiodini et al. (2003), the hydrothermal system at Solfatara is fed by a magmatic source, which releases variable amounts of hot fluids, mostly water and carbon dioxide. The recent evolution has been dominated by short periods of increased magmatic degassing, followed by longer periods, during which both the amount of fluids entering the shallow hydrothermal system, and their CO_2/H_2O ratio are reduced. Numerical modeling of fluids (CO_2+H_2O) and heat transport through a homogeneous and shallow hydrothermal system was performed with TOUGH2 (Pruess, 1991). Hydrothermal fluid circulation is fed by a fluid source located at the base of the system (Figure 3).

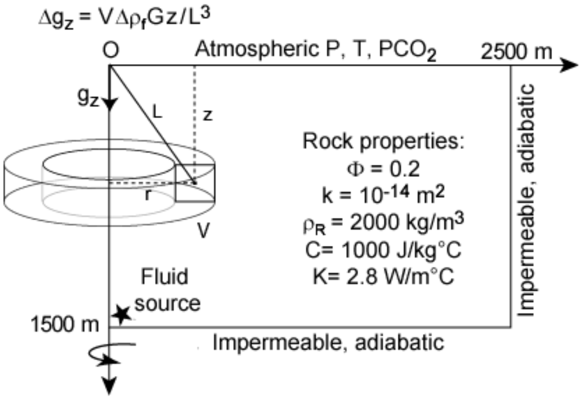

Figure 3. Computational domain, boundary conditions, and rock properties employed in all simulations. One of the grid blocks is highlighted to illustrate its contribution Δg_z to the vertical component of gravity change at point O: V, block volume, $\Delta\rho_f$, change in average fluid density; G, universal gravitational constant; z, block depth; L, block distance from O (from Todesco and Berrino, 2005).

Hot gases rise toward the surface and form a hot two-phase plume, with a shallow dry-gas region, whose composition can be considered representative of the fumarolic fluids. Modeling results (Figure 4) showed that an appropriate choice of the duration of crisis and quiet periods allows reproduction of the observed compositional variations (Chiodini et al., 2003).

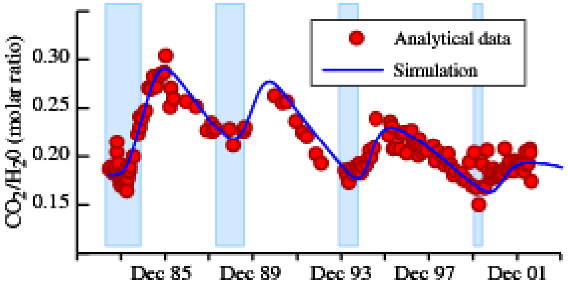

Figure 4. Gas composition at Solfatara (dots) and simulation results (line). Blue bars represents subsequent unrest periods during which larger amounts of CO_2-rich fluids enter the hydrothermal system (modified after Chiodini et al., 2003).

Further modeling showed that a good match with the observed composition is also achieved with different choices of fluid composition and injection rate at the source, and different duration of crisis and quiet periods (Todesco et al., 2004).

To better constrain fluid source and system crises, modeling results were used to calculate gravity changes associated with the simulated evolution of the hydrothermal system (Todesco and Berrino, 2005). During unrest periods, higher amounts of hot fluids, with higher CO_2/H_2O ratio, are injected into the system. As a consequence, fluid composition and phase distribution change during the simulation, modifying fluid density distribution. Modeling results were used to calculate the vertical component of gravity as a function of the average fluid density in every element of the computational domain (Figure 3). The gravity change arising from the repeated unrest crises is characterized by an overall decline, associated with the progressive enlargement of the two-phase region as large quantities of non-condensable gas are added to the system. This overall decline is interrupted during unrest crises, when minor gravity increments signal the larger fluid injection rate. Figure 5 shows gravity residuals recorded at the caldera center (Serapeo, blue diamonds) and at Solfatara (pink squares). Data recorded at Solfatara differ from those recorded at Serapeo and nearby stations, and differences are usually ascribed to the presence of hydrothermal fluids that reach the surface at Solfatara. Todesco and Berrino (2005) performed a new set of simulations, in order to obtain a gravity change, associated with the hydrothermal circulation, consistent with the gravity data observed at Solfatara. Satisfactory results were achieved considering different (hotter) initial conditions, a higher CO_2/H_2O ratio during system crises and shorter unrest periods. Modeling results are shown in Figure 5, where the green dashed line was obtained by adding the simulated hydrothermal contribution (blue line) to the gravity data observed at Serapeo (blue diamonds). A reasonable match is shown with data observed at Solfatara (pink squares).

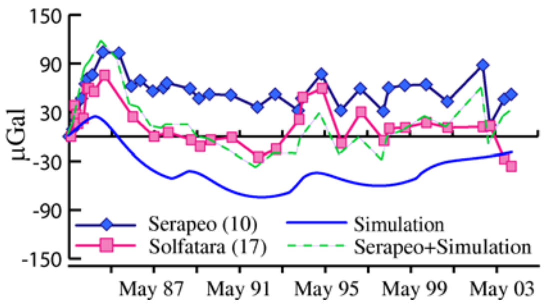

Figure 5. Observed and simulated gravity changes: blue diamonds, Serapeo (10); pink squares, Solfatara(17); blue solid line, gravity changes generated by the simulated evolution of the hydrothermal system; green, dashed line; effects of simulated hydrothermal system superimposed to data at Serapeo (modified after Todesco and Berrino, 2005).

The new simulation also provides a good match with the observed compositional variations (Figure 6).

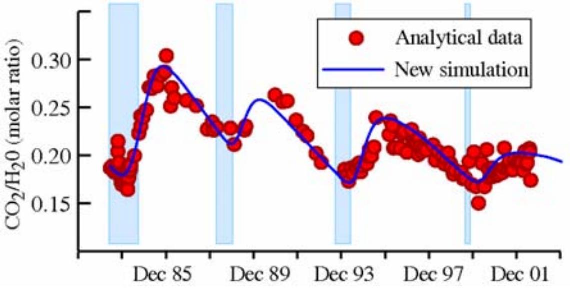

Figure 6. Observed (red dots) and new simulated (blue line) compositional changes at Solfatara (after Todesco and Berrino, 2005).

Contemporaneous matching of two independent parameters, such as gravity change and compositional variations, provided a robust confirmation of the proposed conceptual model and allowed to better constrain fluid source and initial conditions.

New data, however, suggest that something has changed within the system, as a new trend is recognizable both in geochemical and in gravity data (Figure 7).

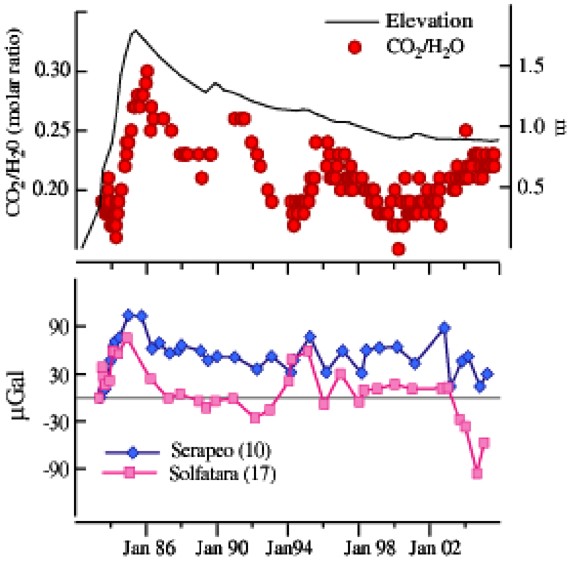

Figure 7. Ground deformation, gas composition and gravity residuals from June 1983 to April 2005.

Beginning in 2005, the rate of subsidence has declined, and new uplift has begun. Gas composition is continuously increasing since 2000, showing a more gentle and longer enrichment with respect to previous unrest periods. At the same time, significant drop in gravity residuals implies the presence of larger amounts of gas below Solfatara. New simulations were performed to describe these new trends, considering different number and duration of unrest crises, different fluid compositions and injection rates at the source, and different source sizes (Table 1).

Table 1. Performed simulations. Data on gas composition and injection rate refer to the 4th (or 5th) unrest crisis only. During quiet periods, gas composition is 0.41wt%, fluid injection rate is 4600 t/d for S-1, and 3400 t/d everywhere else.

	CO_2/H_2O (wt%)	Injection rate (t/d)	Duration (months)	Source radius (m)
C-1	0.5	12100	3	150
C-2	1.0	12100	3	150
5th -1	0.5	12100	3	150
5th -2	1.0	12100	3	150
I-1	1.0	6800	3	150
I-2	1.0	17000	3	150
S-1	1.0	12100	3	175
D-1	1.0	12100	2	150
D-2	1.0	12100	5	150

All simulations begin at the end of the third quiet period (June 1999), and involve the fourth crisis and the following period. Two simulations (5th-1 and 5th-2) were performed considering a fifth unrest crisis, corresponding to the summer 2000, whereas in simulation S-1, from August 2000 on, the source radius increases. Some preliminary results are presented in Figure 8.

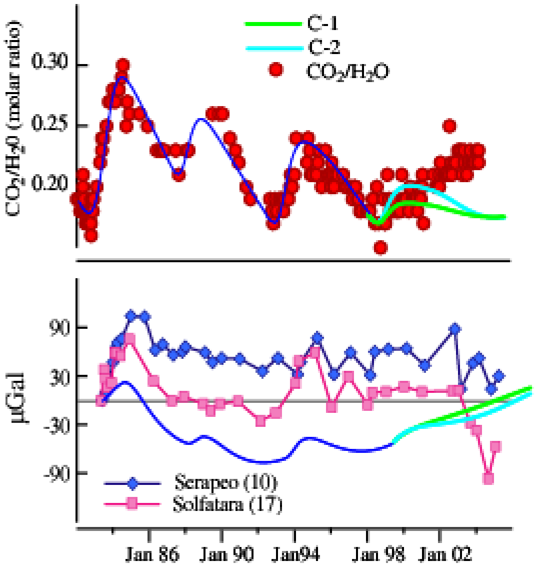

Figure 8a. Results from simulations C1-C2, compared with observed gas composition and gravity residuals.

Although different conditions were considered, modeling results show that the recent evolution cannot be described as a simple sequence of unrest and quiet periods, as previously done.

All simulations are characterized by a different degree of CO_2 enrichment, but the observed trend is not properly described. The increment of the CO_2/H_2O ratio is either too fast or too slow, and it is always followed by a decline that is not observed in the data. Gravity changes are characterized by increasing trends, or by rather constant values, which are not consistent with the significant drop in gravity residuals recorded at Solfatara.

The mismatch between modeling results and observed data is not surprising. Simulations presented here describe the evolution at Solfatara in terms of progressively shorter unrest crises, all characterized by the same fluid composition and injection rates. The model describes a homogeneous system whose rock properties never change during unrest episodes. On the contrary, geochemical and gravity data suggest that the mechanism feeding fumaroles at Solfatara has probably changed through time.

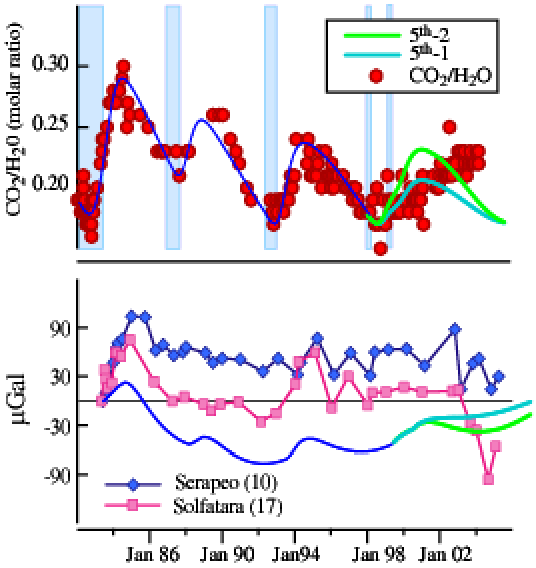

Figure 8b. Results from simulations 5th1-2, compared with observed gas composition and gravity residuals.

The magmatic contribution, and hence the CO_2/H_2O ratio during unrest crises, has probably changed with time. Rock permeability is certainly affected by the repeated episodes of unrest, last of which involved seismic swarms in August 2000 (Bianco et al, 2004), and October 2005.

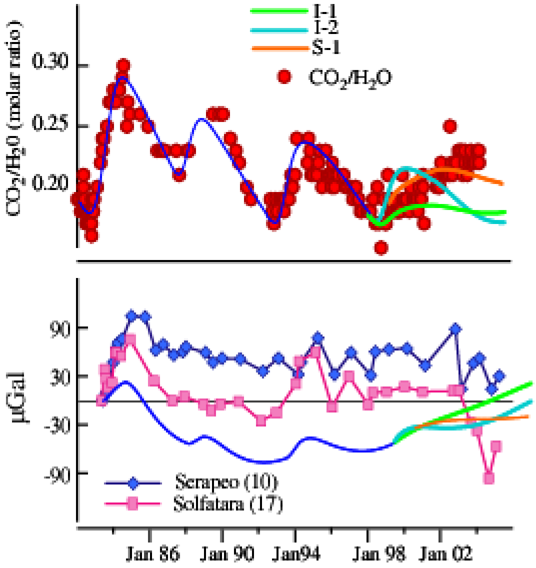

Figure 8c. Results from simulations I1-I2 and S1, compared with observed gas composition and gravity residuals.

Modeling results suggest that last few years have been probably characterized by a wider source region, and by frequent and shorter unrest crises. However, fluid composition and average density are not uniquely determined by the conditions assigned to the last unrest period, but do derive from the entire simulated evolution. A better match with observations will require new simulations considering again the entire observed period, since 1983, with a careful definition of each unrest crisis, in terms of composition of injected fluids, fluid injection rates, timing and duration. A more detailed description of subsurface rock properties, their spatial distribution and temporal evolution will also contribute to improve the model calibration.

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