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# MODELING OF RECENT VOLCANIC EPISODES AT PHLEGREAN FIELDS (ITALY): GEOCHEMICAL VARIATIONS AND GROUND DEFORMATION

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## ABSTRACT

Phlegrean Fields (Figure 1) is an active and densely populated caldera structure, located near Naples (Italy). After the last eruptive event (the Monte Nuovo eruption, in 1538) periodic episodes of unrest characterize the evolution of this volcanic district, involving seismic activity and slow ground motion (bradyseism). During the last 35 years, two major episodes of bradyseism have been recorded in the area, in 1969-72 and 1982-84, each one leading to a vertical ground displacement of about 2 m. Since 1985, the caldera has been undergoing a slow subsidence, periodically interrupted by minor and short-lasting uplift phases. Fumarolic activity is also present within La Solfatara crater near the caldera center. Geochemical monitoring, carried out since 1982, revealed how bradyseismic activity is accompanied by remarkable changes in the composition of discharged fluids.

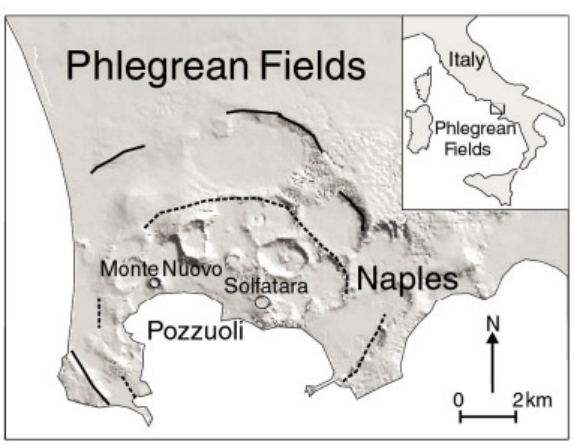


*Figure 1. The Phlegrean Fields caldera, with the location of Monte Nuovo and Solfatara eruptive centers. Lines indicate major collapse structures.*

Understanding the mechanism driving the bradyseismic activity and unravelling the relation between ground deformation and hydrothermal fluid circulation are necessary steps toward an effective hazard assessment in a densely populated area such as Phlegrean Fields.In this work, we present some results of numerical modeling of both the hydrothermal fluid circulation at La Solfatara, and of its effects on rock deformation. In the first case, simulations were performed with TOUGH2, accounting for the presence of water and carbon dioxide; then, the coupled TOUGH-FLAC simulator was applied to study rock deformation arising from changes in pore pressure and temperature. Modeling results show that periods of intensified magmatic degassing explain many features of the recent unrest crises at Phlegrean Fields.

## INTRODUCTION

Recent unrest episodes at the Phlegrean Fields caldera began in 1969, with a first phase of vertical ground uplift that culminated in 1972 (Casertano et al., 1976). A small amount of subsidence followed afterwards, but no remarkable ground level changes were recorded until a new bradyseismic phase began in 1982. The maximum uplift in this case was reached in 1984 and was followed by a slow, aseismic subsidence (Barberi et al., 1984). Since 1984, three minor uplift events were recorded in 1989, 1994, and 2000. Each uplift event was accompanied by variations in the composition of fumarolic gases at La Solfatara (Chiodini et al., 2003, and references therein).

Our attention here is focused on the system evolution since 1982, when both geochemical and geophysical monitoring became particularly accurate. A recent analysis of published geochemical data has shown that each uplift event since 1982 was followed by a sharp increase of the $CO_2/H_2O$ ratio at La Solfatara fumaroles (Chiodini et al., 2003). This evidence supported our working hypothesis, according to which the recent unrest crises at Phlegrean Fields were associated with periods of more intense

magmatic degassing. If degassing from the magma chamber is more intense, a larger amount of deep fluids enters the shallow hydrothermal system. This is expected to modify the composition of fumarolic effluents and, at the same time, generate some degree of ground deformation as the ascending fluids expand, increasing pore pressure, and heating up the surrounding porous medium.

To verify this hypothesis, numerical modeling has been performed, simulating the injection of deep fluids into a hot and shallow hydrothermal reservoir. This was done both by modeling the hydrothermal fluid circulation separately, and by applying the coupled TOUGH-FLAC thermo-hydro-mechanical model, to evaluate the effects of fluid circulation on the porous medium. Simulation of the heat and multi-phase fluid transport was performed with TOUGH2 (Pruess, 1991), accounting for the presence of water and carbon dioxide (EOS2). Early simulations were aimed at describing present system conditions, as inferred from geochemical data (Todesco et al., 2003a). This was accomplished simulating a shallow hydrothermal system heated by a prolonged inflow of deep, magmatic fluids. Such inflow was simulated assigning a fluid source at the bottom of the hydro-thermal system that discharged a hot mixture of water and carbon dioxide. Additional TOUGH2 runs were then carried out to verify whether the observed compositional variations could arise from an increased magmatic degassing. In these simulations, $CO_2$-enriched fluids enter the hydrothermal system at a higher rate during selected periods (Chiodini et al., 2003). Modeling results showed that the observed compositional variations are well reproduced by the model (Figure 2), provided that the high injection rate periods (HIRPs) are chosen appropriately.

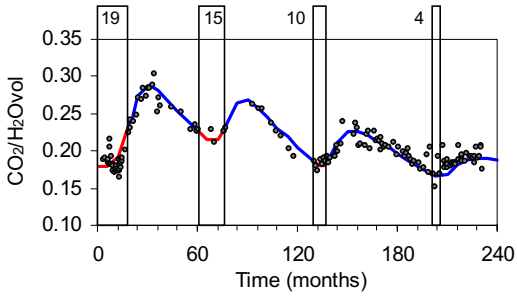


*Figure 2. Observed gas composition since 1983 (dots) and simulated values (line); HIRPs and their duration (months) are high-lighted (Simulation 3x-C). Modified after Chiodini et al. (2003).*

The coupled TOUGH-FLAC simulator (Rutqvist et al., 2002) was then used to model the effects of one single period of enhanced magmatic degassing (lasting 2 years) on the deformation of an elastic porous medium (Todesco et al., 2003b). These simulations only accounted for the shallowest region of the hydrothermal system, and for this reason were not expected to reproduce the entire amount of measured vertical displacement. Nevertheless, results highlighted interesting effects arising from the two-phase nature of the flow, and confirmed that short-duration injection of deep fluids can produce a quick and remarkable ground deformation, followed by a more gentle subsidence when deep degassing is reduced again. This temporal evolution matches the observations well, as shown in Figure 3, where simulated and observed vertical displacement are normalized with respect to their maximum value and compared. These coupled simulations also showed that chemical variations arise in the fumarole source region even if the composition of the injected mixture does not change.

Here we present new results obtained with TOUGH2 and the coupled TOUGH-FLAC simulator. The new simulations performed with TOUGH2 only focus on the role of deep fluid composition, injection rate during HIRP, and duration of HIRP. Coupled thermo-hydro-mechanical simulations investigate the mechanical effects of a gradual reduction of the injection rate, during HIRP, and of a longer HIRP lasting 10 years.

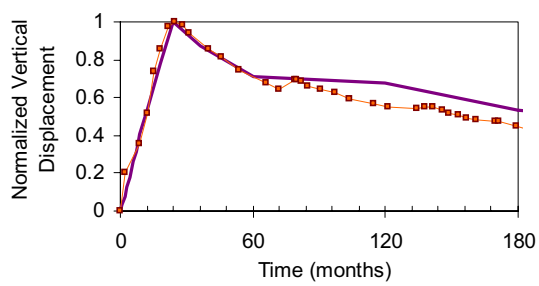


*Figure 3. Normalized vertical ground displacement. Squares: measured data, since 1983; thick line: simulation. Modified after Todesco et al. (2003b).*

Results confirm that an important correlation exists between deformation and chemical variations, and show that the multi-phase, multi-component nature of the processes involved plays an important role in determining the system evolution.

## TOUGH2 SIMULATIONS

Simulations performed with TOUGH2 take full advantage of the simple geometry of the natural system, and were run on a 2D, cylindrical domain (Figure 4). Initial conditions were calculated by simulating a prolonged (4000 year) injection of hot (350°C) water and carbon dioxide at the base of the hydrothermal system. The deep fluid source has the same size as La Solfatara crater (Chiodini et al., 2003), and the composition of the injected mixture

($CO_2/H_2O$ ratio = 0.17 vol) matches the composition of the fumarolic gases at the beginning of 1983. Injection rates (1000 ton/day of $CO_2$ and 2400 ton/day of $H_2O$) were arbitrarily chosen, and match (to within an order of magnitude) the recent estimate of diffuse $CO_2$ degassing through the bare soil at La Solfatara (Chiodini et al., 2001; Todesco et al., 2003a). Prolonged heating leads to the development of a hot two-phase plume, within which a shallow single-phase gas region forms (Figure 5), whose existence and physical conditions match the prediction of the geochemical model proposed for La Solfatara (Chiodini and Marini, 1998). This single phase gas region was interpreted as the source feeding the active fumarolic field at La Solfatara. Its average composition is taken here as representative of fumarolic emissions.

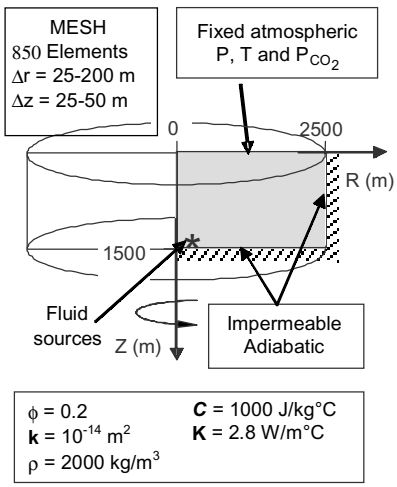


*Figure 4. Computational domain for TOUGH2 simulations. Boundary conditions and fluid source are indicated. Rock physical properties are also shown.*

Three different simulations were run (Table 1), using four HIRPs, chosen as in Figure 2. In the simulation shown in Figure 2, HIRPs are characterized by a fluid injection rate 3 times higher (3x), and by a higher $CO_2/H_2O$ ratio (0.3 vol). In the simulations presented here, the composition of the injected mixture is kept unchanged during the HIRP, while the injection rate is increased by a factor of 3, 5 and 7, respectively.

When the injection rate is increased, the pore pressure near the source at depth also increases, leading to a certain degree of vapor condensation. When the injection rate is reduced again, pore pressures quickly decline, and water boiling takes place where the stronger decompression occurs. These phase changes are responsible for remarkable temperature variations, associated with latent heat effects, which play an important role in rock deformation (as will be shown later).

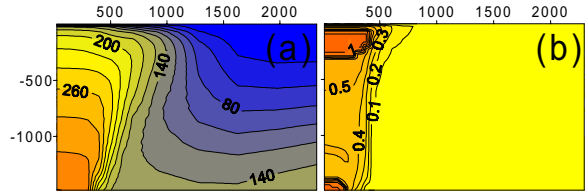


*Figure 5. (a) Temperature (°C) and (b) volumetric gas fraction achieved after a prolonged injection of hot water and carbon dioxide.*

At the same time, they obviously induce changes in gas composition, becoming depleted or enriched in water vapor, according to the current conditions. These changes in gas composition affect initially the deepest portion of the domain, near the fluid source, where pressure variations are more dramatic. However, as the simulation proceeds, the pressure and temperature perturbations induced by the HIRP progressively involve shallower portions of the domain, eventually affecting the single-phase gas region and inducing remarkable variation in the $CO_2/H_2O$ ratio there.

*Table 1. Performed TOUGH2 simulations. Injection rates refer to HIRP*

| Name | $CO_2$ (t/d) | $H_2O$ (t/d) | $CO_2/H_2Ov$ |
|---|---|---|---|
| 3x-C | 5000 | 6700 | 0.30 |
| 3x | 3000 | 7200 | 0.17 |
| 5x | 5000 | 12000 | 0.17 |
| $5x_{HIRP}$ | 5000 | 12000 | 0.17 |
| 7x | 7000 | 16800 | 0.17 |
| 1x-C | 1943 | 1457 | 0.30 |

Simulation results can be expressed again in terms of average $CO_2/H_2O$ ratio within the single-phase gas region, at different times (Figure 6). As the figure shows, each simulation produced a significant $CO_2$ enrichment, with maximum $CO_2/H_2O$ ratios achieved at the end of each HIRP. The higher the injection rate during HIRP, the higher the $CO_2$ enrichment. Higher $CO_2/H_2O$ values are followed by a faster decline when the injection rate is reduced again. The increment in $CO_2$ is controlled not only by the injection rate, but also by the duration of each HIRP: lower values of $CO_2/H_2O$ usually follow a shorter HIRP. However, as the number of HIRPs increases, their effects in terms of composition of the shallow single-phase gas region tend to cumulate, as the fluids injected earlier ascend and reach shallower depth, while new injections occur. The combined effect of multiple HIRPs becomes particularly evident when the injection rate is higher: in simulation 7x, the compositional peak after the 3$^{rd}$ HIRP is almost as high as the previous one, induced by a longer HIRP. The same effect is observed also in the other simulations after the following and even shorter HIRP. Multiple HIRPs also affect the minimum values of the gas ratio that are reached after the fluid injection rate has been reduced.

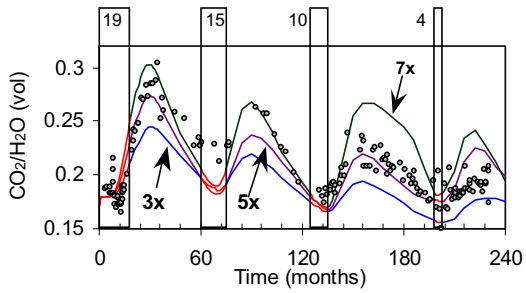


*Figure 6. Measured (dots) and simulated (lines) compositional variations. Different lines refer to different simulations, as indicated. HIRPs and their duration (months) are highlighted.*

Initially, these minimum values are similar for each simulation (and close to the initial composition of the single-phase gas region), but after the 3rd HIRP the gas compositions calculated in the three considered cases differ, with greater $CO_2$ depletion obtained in Simulation 3x, with lower injection rate.

Even if all simulations produced significant oscillation in gas composition, none of the curves plotted in Figure 6 provides a complete match with observed data. To improve data fitting more simulations were performed changing the length of the HIRP, and always keeping the composition of injected mixture unchanged. A better result was obtained with a different choice of HIRPs, as shown in Figure 7, and with a higher increment of the injection rate during the HIRP (Simulation $5x_{HIRP}$).

The match with observed data is fairly good for the first three injections. Afterwards, simulation $5x_{HIRP}$ tends to overestimate the observed data. This is again due to the cumulative effects of subsequent HIRPs. This effect is not observed in Simulation 3x-C (Figure 2), where the match with observed data was provided with a different choice of HIRP, lower injection rate, and $CO_2$-enriched injected fluids. Thanks to the different injection rates and fluid composition, the amount of $CO_2$ injected during the HIRPs in simulations 3x-C and $5x_{HIRP}$ is the same. The high $CO_2/H_2O$ values calculated at the end of simulation $5x_{HIRP}$ derive from the higher amount of water that is injected into the system in this case. Because water is the condensible component, its larger amount has important consequences in terms of pressure and temperature distribution and affects both phase distribution and gas composition. Figure 8 shows a comparison between pressure and gas composition calculated just before the 4th HIRP, for simulations 3x-C and $5x_{HIRP}$. At this time, simulation $5x_{HIRP}$ is characterized by a higher $CO_2$ mass fraction in the gas phase at shallow depths, where the single-phase gas region is present.

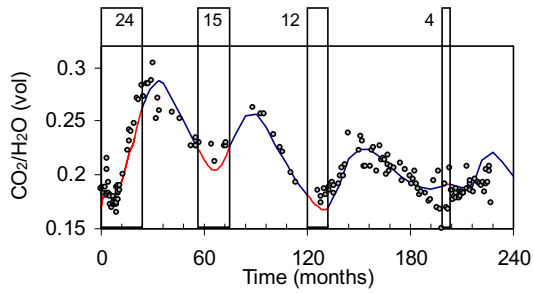


*Figure 7. Simulation $5x_{HIRP}$. Measured (dots) and simulated (line) compositional variations. HIRPs and their duration are indicated.*

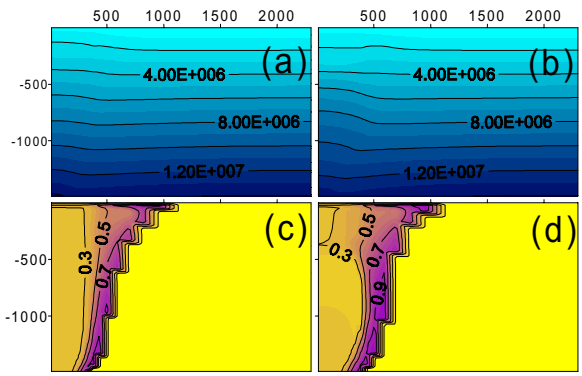


*Figure 8. (a,b) Pore pressure (Pa) and (c,d) gas composition ($CO_2$ mass fraction) after 199 months. Simulations: 3x-C(a,c) and $5x_{HIRP}$ (b,d).*

A further simulation was performed to verify the role of compositional changes at the source level (Figure 9). Simulation 1x-C was run without increasing the fluid injection rate at the source, but only changing the relative proportion between water and $CO_2$, from 0.17 to 0.30 vol, during the HIRPs. HIRPs are chosen as in Figure 2. As Figure 9 shows, also in this case the single-phase gas region undergoes changes in its average composition, but the amplitude of these variations is much lower than observed.

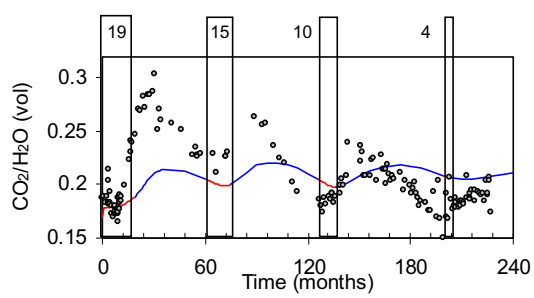


*Figure 9. Simulation 1x-C. Measured (dots) and simulated (line) compositional variations, with unchanged injection rates. Injected fluid composition changes during highlighted periods.*

## COUPLED TOUGH-FLAC SIMULATIONS

The coupled TOUGH-FLAC model applied here links the capabilities of the TOUGH2 geothermal simulator (Pruess, 1991) with the geotechnical analysis of rock and soil performed with FLAC3D, a commercial code for rock mechanics (Itasca Consulting Group Inc., 1997). Both codes are fully described elsewhere, as is their coupling (Rutqvist et al., 2002). Briefly, FLAC3D is an explicit finite difference program applied here to describe the coupled thermomechanical behavior of a continuous elastic medium, as it reaches equilibrium. At this time, only a one-way coupling was considered, in which the pore pressure and temperature fields, calculated with TOUGH2, are fed to FLAC3D, which in turn calculates the stress and strain distribution arising from such changes in pressure and temperature. The porous medium is considered homogeneous and elastic.

The coupled TOUGH-FLAC model was applied to study the mechanical effects potentially induced by intensified magmatic degassing. As in the previous section, system unrest is simulated as a sudden increase in fluid injection rate at the deep source, followed by a longer period during which the injection rate is reduced again. In all coupled simulations the composition of injected fluids does not change and only one single HIRP is imposed at the beginning of the simulation. Simulations have addressed the role of fluid injection rate during HIRPs, and of rock elastic properties (Todesco et al., 2003b). Simulations presented here describe the effects of a gradual reduction of the injection rate during the HIRP, and the role of a 10-year-long HIRP (Table 2). All simulations were performed considering the same injection rates and fluid composition as in Todesco et al. (2003b). Also the 3D computational domain and boundary conditions are the same (Figure 10 ). Preliminary thermo-hydro-mechanic simulations were performed to study the effect of a single HIRP lasting 2 years and followed by a long period of reduced injection (Todesco et al., 2003b).

*Table 2. Coupled TOUGH-FLAC simulations.*

| | $CO_2$ | $H_2O$ | $CO_2/H_2O$ vol |
|---|---|---|---|
| Inj. Rate (HIRP; t/day) | 15000 | 30000 | 0.2 |
| Reduced Inj. Rate | 1500 | 3000 | 0.2 |

| Simulations | HIRP (yr) | Inj. Rate Reduction |
|---|---|---|
| 10x | 2 | Sharp |
| 10x-g | 2+3 | Gradual (since 3rd yr) |
| 10x-l | 10 | Sharp |

As mentioned above, when the injection rate is increased pore pressure is suddenly increased and leads to water condensation. Thanks to the release of latent heat, the source region undergoes significant heating.

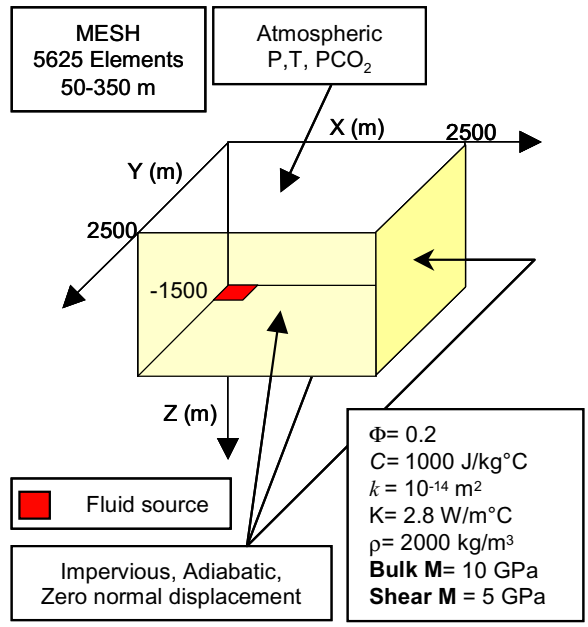


*Figure 10. Computational domain for the 3D coupled simulations with TOUGH-FLAC, with boundary conditions and applied rock properties.*

This pressure and temperature perturbation tends to rise toward shallower levels as fluids slowly propagate from the source outward. System conditions at the end of a HIRP can be conveniently described in terms of pressure, temperature gas fraction and composition (Figure 11). The increment in pressure and temperature near the fluid source is evident. When the injection rate is reduced, a sudden decompression takes place in the source region. There, water can boil, subtracting latent heat, increasing the gas saturation, and modifying the gas composition by increasing the amount of water vapor. Meanwhile, the overpressure generated during the HIRP migrates toward shallower levels, as the heated fluids continue to rise. System conditions 5 years after the injection rate has been reduced are portrayed in Figure 12. The evolution becomes different if, after 2 years, the injection rate is not suddenly reduced, but is gradually decreased during the following 3 years (Simulation 10x-g; Figure 13).

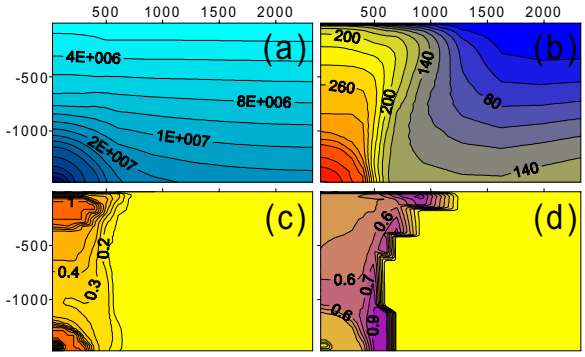


*Figure 11. Simulation 10x: (a) Pressure (Pa), (b) temperature (°C), (c) vol. gas fraction, and (d) $CO_2$ mass fraction in gas, after 2 years of simulation.*

In this case, system conditions at the end of the HIRP are characterized by higher pressure and temperature. At shallow depth, the gas fraction at the base of the single-phase gas region is lower and the gas phase is enriched in carbon dioxide. Five years after the end of the HIRP (i.e.: after 10 years of simulation), system conditions are similar to those obtained with a sharp reduction of injection rate (Figure 12), but some differences exist both in pressure and temperature distribution, and lead to a different phase distribution and gas composition. As will be shown later, such different temperature and pressure distributions will result in a different evolution of ground deformation.

Another simulation was run considering a longer HIRP, lasting 10 years (Simulation 10x-l; Figure 14). The fluid injection rate is again 10 times higher during the HIRP. To compare the effects of such a long period of high injection rate with previous results, Figure 14 illustrates the system conditions 5 years after the injection rate has been reduced (i.e.: after 15 years of simulation). In this case, the longer HIRP provided conditions for a remarkable increment of both pressure and temperature. As a consequence, when the injection rate is relieved a much more evident decompression occurs at depth, and extensive boiling strongly reduces the $CO_2$ mass fraction within the gas phase. In addition to the different pressure and temperature distribution, the most remarkable feature of this simulation is the disappearance of the single-phase gas region. This happens because the pressure wave, caused by the higher fluid injection rate, can propagate upward for a long enough time to reach shallow depths, where the single-phase gas region is located.

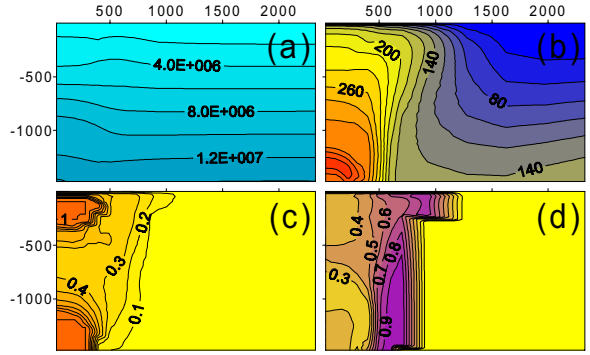


*Figure 12. Simulation 10x (a) Pressure (Pa), (b) temperature (°C), (c) vol. gas fraction, and (d) $CO_2$ mass fraction in gas, 5 years after the injection rate has been reduced (7 years of simulation).*

This generates enough condensation to turn the single-phase gas reservoir into a two-phase region. Condensation does not affect, however, all the water in the reservoir, as half of the gas at shallow depth still is water vapor, due to the high temperature. The different system conditions presented above result in different evolution of the ground deformation.

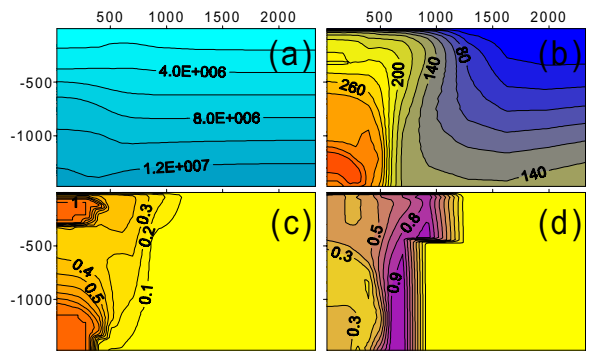


*Figure 13. Simulation 10x-g (a) Pressure (Pa), (b) temperature (°C), (c) vol. gas fraction, and (d) $CO_2$ mass fraction in gas, 5 years after the injection rate has been gradually reduced (10 years of simulation)*

Figure 15 shows the vertical ground displacement, on the XZ plane, calculated after a 2-years-long HIRP. System conditions and ground deformation at this time, are the same in all the simulations described above. The maximum vertical displacement is 0.64 m and it is reached at a depth of 1100 m. Figure 15 also shows how such deformation evolves 5 years after the injection rate is sharply reduced (Simulation 10x).

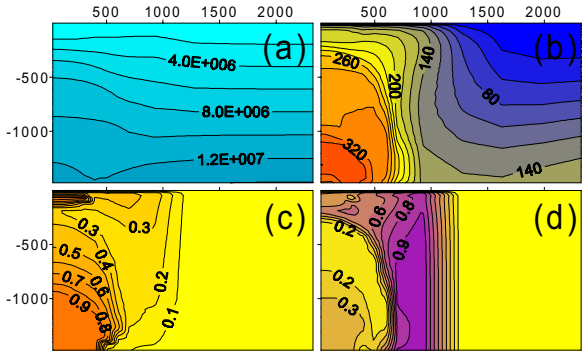


*Figure 14. Simulation 10x-l (a) Pressure (Pa), (b) temperature (°C), (c) vol. gas fraction, and (d) $CO_2$ mass fraction in gas 5 yr after the injection rate has been reduced (15 yr of simulation).*

If the injection rate is gradually reduced, the maximum ground deformation is attained at the end of the HIRP, which in this case is after 5 years of simulation. Figure 16 shows the distribution of the vertical ground displacement at the end of the HIRP (a) and 5 years after (b).

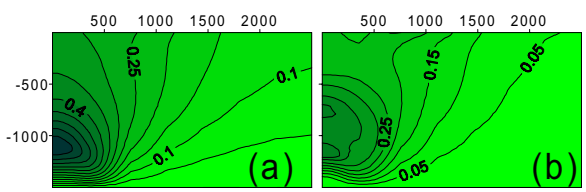


*Figure 15. Simulation 10x. Vertical ground displacement (a) after 2 years of simulation (end of HIRP) and (b) after 7 years (5 years after the HIRP).*

Because of the longer duration of the HIRP, the maximum deformation is slightly higher (0.68 m), and it is achieved later (at the end of the HIRP) and at a shallower depth (800 m). Once the injection rate is reduced, also the vertical displacement declines (Figure 15b). The region affected becomes larger and shallower. A more remarkable ground deformation is calculated when the HIRP lasts 10 years (Figure 17). During such a long period, the maximum vertical displacement not only reaches very high values (1.45 m) but also involves a wide and very shallow region. When the injection rate is finally reduced, both decompression and temperature drop are fast, and within 5 years the rock deformation becomes negligible (Figure 17b). The maximum vertical uplift experienced at the surface in all of these simulations is shown in Figure 18 as a function of time. In each simulation, the maximum deformation is always achieved at the end of the HIRP. As mentioned above, we expected to reproduce only a fraction of the observed ground deformation, as we only model the shallowest portion of the hydrothermal system, and hence we neglect the contribution arising from heating and pressure changes affecting the volcanic system at greater depths.

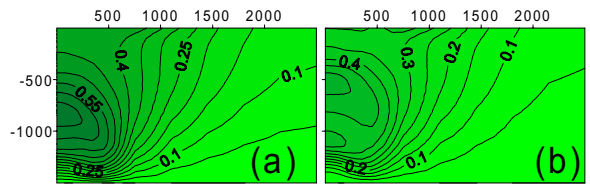


*Figure 16. Simulation 10x-g. Vertical ground displacement (a) after 5 years of simulation (end of a HIRP) and (b) after 10 years (5 years after HIRP).*

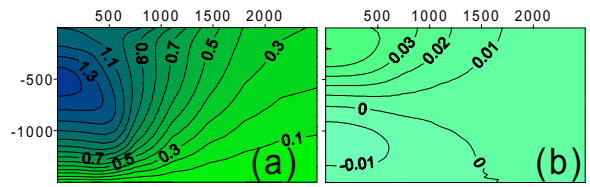


*Figure 17. Simulation 10x-l. Vertical ground displacement (a) after10 years of simulation (end of HIRP) and (b) after15 years (5 years after HIRP).*

If the HIRPs last 2 years only, and then injection rate is sharply reduced, the maximum vertical displacement achieved at the surface is 0.31 m. Afterwards subsidence begins at a slower rate. As shown in Figure 3, the rate of uplift and subsidence well reproduce the temporal evolution of the last big bradyseismic event. When the injection rate is not suddenly reduced, but diminishes gradually during the following 3 years, vertical displacement continues to rise, even though at a progressively smaller rate. Only when injection rate is fixed again at its minimum value, does vertical displacement begin to gradually decline. Subsidence, in this case, is somewhat faster than in the previous case. If the HIRP is continued for 10 years, vertical displacement continues to rise for the entire period, to a maximum value of about 1 m, and then quickly drops when the injection rate is reduced. This is the only case in which subsidence is faster than the uplift phase. In this case, the calculated deformation reaches the same order of magnitude as the observed uplift. The temporal evolution, however, is much different, with the uplift phase being longer than the observed uplift period, and the following subsidence much faster.

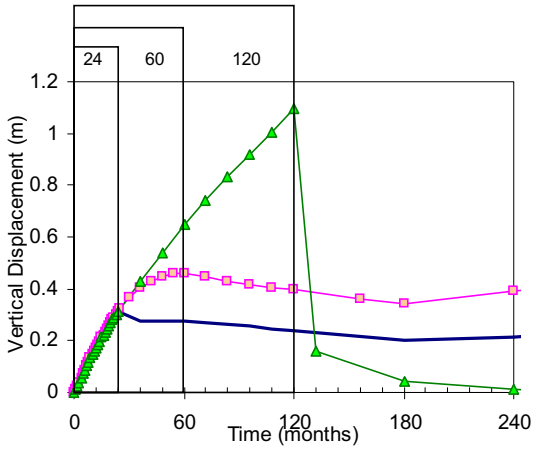


*Figure 18. Vertical ground displacement (m) at the surface, for simulation 10x (line), 10x-g (squares) and 10x-l (triangles)*

## CONCLUSION

We presented some results of numerical simulations of hydrothermal circulation at the Phlegrean Fields, and of its effects on the mechanical behavior of porous rocks. The simulations confirm that periods of intense magmatic degassing induce important changes in the composition of the reservoir that feeds surface fumaroles. Such variations are associated with the different rate at which deep fluids are injected into the shallow hydrothermal system. Important variations also arise even if the composition of the injected mixture is unchanged. Gas composition appears to be controlled by the complex multi-phase and multi-component nature of this system. Recurring periods of more intense magmatic degassing may cause cumulative effects and also play a role in the compositional evolution of the fumarolic field. Coupled thermo-hydro-mechanical simulations showed that periods of higher injection rate can drive significant amounts of rock deformation. The simulated ground deformation matches the observed evolution, describing a fast uplift phase followed by slower subsidence. Simulations also confirm that maximum deformation is always attained at the end of the periods of more intense degassing, while peaks in gas composition are reached only afterwards, several months after the injection rate has been reduced again. If stronger magmatic degassing is to be considered the mechanism driving bradyseismic events, then the role of the geochemical signals as a precursor of system unrest should be carefully evaluated. More work is certainly necessary to better constrain rock properties and system conditions, but the proposed approach effectively captured many important features of the natural system and should represent a first step toward a robust assessment of the recent evolution at the Phlegrean Fields.

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