# MODELING OF HYDROTHERMAL CIRCULATION APPLIED TO ACTIVE VOLCANIC AREAS. THE CASE OF VULCANO (ITALY)

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## 1. Introduction

Modeling of fluid and heat flows through porous media has been diffusely applied up to date to the study of geothermal reservoirs (Pruess, 1990). Much less has been done to apply the same methodology to the study of active volcanoes and of the associated volcanic hazard. Hydrothermal systems provide direct information on dormant eruptive centers and significant insights on their state of activity and current evolution. For this reason, the evaluation of volcanic hazard is also based on monitoring of hydrothermal activity. Such monitoring, however, provides measurements of surface parameters, such as fluid temperature or composition, that often are only representative of the shallower portion of the system. The interpretation of these data in terms of global functioning of the hydrothermal circulation can therefore be highly misleading. Numerical modeling of hydrothermal activity provides a physical approach to the description of fluid circulation and can contribute to its understanding and to the interpretation of monitoring data. In this work, the TOUGH2 simulator (Pruess, 1991) has been applied to study the hydrothermal activity at Vulcano (Italy). Simulations involved an axisymmetric domain heated from below, and focused on the effects of permeability distribution and carbon dioxide. Results are consistent with the present knowledge of the volcanic system and suggest that permeability distribution plays a major role in the evolution of fluid circulation. This parameter should be considered in the interpretation of monitoring data and in the evaluation of volcanic hazard at Vulcano.

## 2. Geological Setting

Vulcano is an active volcanic center in Southern Italy (Fig.1), whose last explosive eruption took place at the end of last century (1888-1890). Since then, the island has experienced a continuous fumarolic activity, both at the crater rim, where the highest temperatures are observed, and near the Baia di Levante beach (Todesco, 1994 and ref. therein). The intensity of fumarolic activity varied with time, and periodic system crises have been evidenced by changes in gas temperature, composition and emission rate. These crises are often accompanied by shallow seismic activity, related to fluid motion, and ground deformations within the area of the active cone. Gases emitted at the crater fumaroles mainly consist of water and carbon dioxide, with sulphur compounds, HCl, HF, B, and Br being minor components. Gas emission at the crater fumaroles can reach 1100 ton/ day. Higher mass flow rates are usually associated with higher temperatures, higher carbon dioxide contents, and gas/steam ratios. Gas temperature changes with time and at different vents, ranging from 200°C to about 700°C. Fumaroles at the Baia di Levante beach show constant gas temperature of 100°C and are characterized by the loss of reactive components with respect to gas composition at the crater. Changes in mass flow rate and in gas composition affect simultaneously crater and beach fumaroles (Martini *et al.*, 1989; Chiodini *et al.*, 1991a). Thermal waters, with temperatures up to 60°C (Panichi & Noto, 1992; Capasso *et al.*, 1993) and diffuse gas emanations from the soil (Badalamenti *et al.*, 1984; Carapezza & Diliberto, 1993) are among other surface manifestation of the hydrothermal activity at Vulcano and characterize the area around the La Fossa cone.

More information derives from the geothermal wells (Fig.1) drilled on the island during the '50s (VU2bis) and '80s (IV1 and VP1). In-hole temperature distributions are showed in Table 1. The VU2bis well reached the depth of 200 m and produced wet-steam for two years, attesting the presence of a boiling aquifer feeding the beach fumaroles (Sommaruga, 1984). The other wells, IV1 and VP1, reached greater depths (1000 m and 2000 m, respectively), but were never productive. The study of cuttings and core samples evidenced low permeability and the presence of enhanced hydrothermal alteration at shallow levels, both recent and fossil (Faraone *et al.*, 1988; Barberi *et al.*, 1989; Gioncada & Sbrana, 1991).

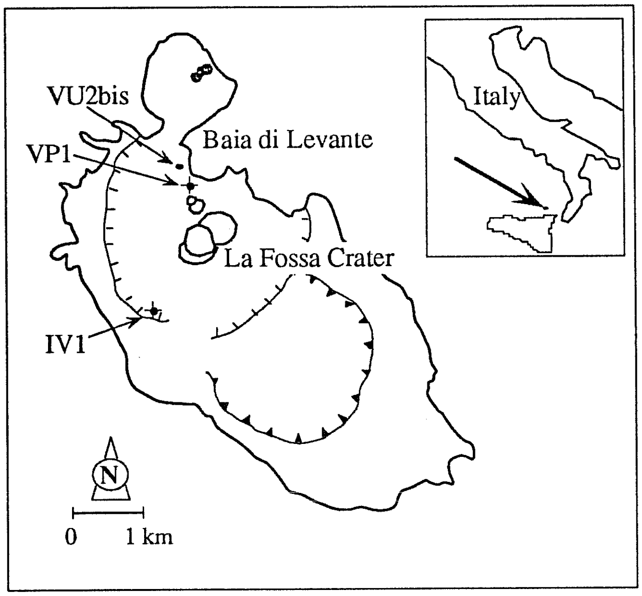


**Figure 1.** The Island of Vulcano (Aeolian Islands, Italy). The active crater and the position of the main geothermal wells are indicated.

**Table 1.** Temperature distribution in the geothermal wells.

| VU2bis | | IV1 | | VP1 | |
|---|---|---|---|---|---|
| m | °C | m | °C | m | °C |
| 15 | 101 | 200 | 60 | 600 | 60 |
| 100 | 136 | 650 | 75.6 | 1000 | 168 |
| 236 | 198 | 770 | 76.5 | | |
| | | 1160 | 112 | | |
| | | 1500 | 180 | | |
| | | 2000 | 419 | | |

During the last twenty years, gas temperature and emission rates increased significantly and synchronous variations of gas composition were observed. The areal extent of fumaroles increased and new fractures opened at the crater rim (Barberi *et al.* 1991). These phenomena and the associated seismic activity created some concern among the population (15,000 people during summer times) living at the base of the active cone. The interpretation of the observed changes plays a major role in hazard evaluation, as they may arise either from changes within the magma chamber (and could therefore prelude to new magmatic activity) or from variations within the hydrothermal system. In this latter case, more attention should be paid to hazards associated with fluid circulation, such as toxic gas emissions or phreatic explosions. The understanding of fluid circulation at Vulcano is therefore necessary to achieve a satisfactory hazard mitigation on the island.

## 3. Physical Modeling

The simulations presented here were carried out to investigate the effects of permeability distribution, and carbon dioxide on the evolution of the hydrothermal system. The TOUGH2 numerical simulator (Pruess, 1991) was used with the EOS1 and EOS2 modules, to describe the coupled multiphase and multicomponent fluid and heat flows. The simulations were carried out on a cylindrical domain with a radius of 500 m and depth of 1500 m, heated from below by fixing the bottom temperature at 300°C. The computational mesh is formed by 480 elements (48 layers of 10 elements each), with a constant radial size of 50 m, and variable vertical dimension ranging from 5 m (near the top and bottom boundaries) to 50 m. Initial and boundary conditions are listed in Table 2, and the rock physical parameters are showed in Table 3.

The effect of porosity and permeability was investigated by running some simulations with pure water on a uniform domain, with porosity of 0.25 and 0.35 and permeability ranging from $10^{-21}$ to $10^{-9}$ $m^2$. These simulations showed that the onset of fluid circulation is strongly dependent on the average value of rock permeability. Narrow plumes develop when rock permeability is higher than $10^{-18}$ $m^2$, and fluid convection enhances the system heating also at shallow levels. A two-phase region forms after a time span that depends on the given permeability (k), and may range from few days (if $k=10^{-9}$ $m^2$), to few years (if $k=10^{-12}$ $m^2$), to thousands of years (if $k=10^{-15}$ $m^2$). For permeability lower than $10^{-18}$ $m^2$, heating of the system is much less efficient due to the scarce fluid mobility, and the resulting temperature and pressure distribution are not consistent with the development of a vapor phase. Higher rock porosity slightly enhances the development of rising plumes, leading to a faster heating and to an earlier development of the two-phase zone.

**Table 2.** Initial and Boundary Conditions.

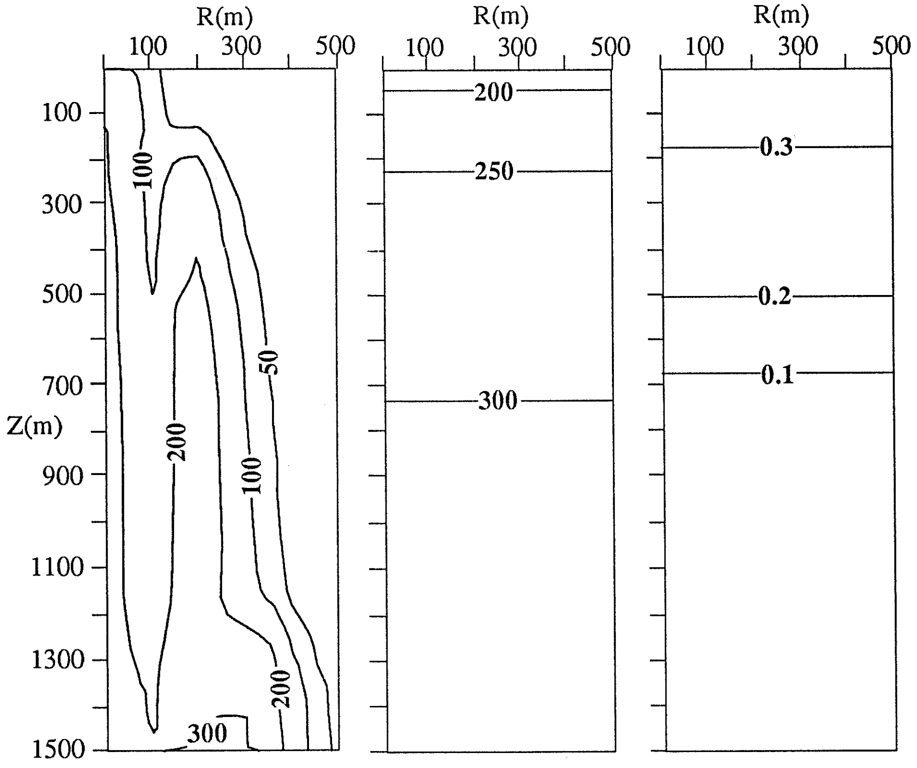
| | |
|---|---|
| Initial Temperature | 30°C everywhere |
| Initial Pressure | Hydrostatic Pressure |
| Top Boundary | Fixed T=30°C<br>Fixed P=$1.0132\times10^5$Pa |
| Bottom Boundary | Fixed T=300°C<br>Fixed P=$0.14\times10^8$Pa |
| Vertical Boundary | No Flow |

**Table 3.** Rock Physical Properties.

| | |
|---|---|
| Density | 2800 kg/ $m^3$ |
| Specific Heat | 800 J/ kg°K |
| Heat Conductivity | 2.5 W/ m °K |

**Table 4.** Performed Simulations.

| | Permeability ($m^2$) | Fluid |
|---|---|---|
| 1 | $10^{-12}$ z=0-1500m | $H_2O$ |
| 2 | $10^{-18}$ z<5m<br>$10^{-12}$ z>5m | $H_2O$ |
| 3 | $10^{-12}$ z<600m<br>$10^{-18}$ z>600m | $H_2O$ |
| 4 | $10^{-12}$ z=0-1500m | $H_2O+CO_2$ |
| 5 | $10^{-12}$ z<600m<br>$10^{-18}$ z>600m | $H_2O+CO_2$ |



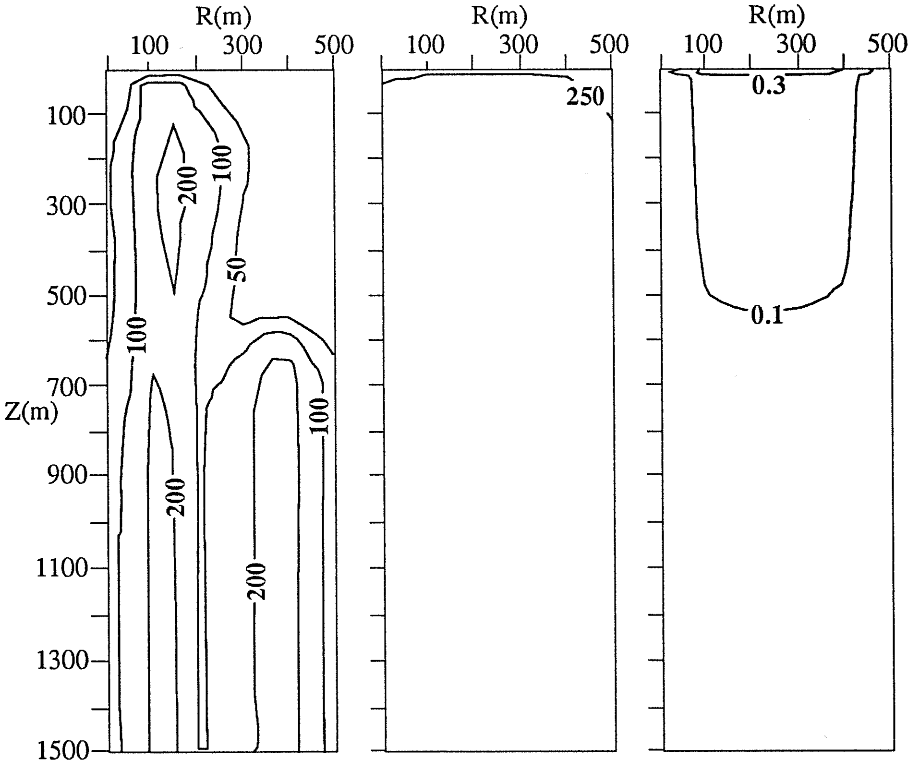
(a) (b) (c)

**Figure 2.** Simulation 1. Temperature distribution (°C) after 10 years (a) and 100 years (b) from the beginning of the simulation; gas volumetric fraction after 100 years (c).

The simulation with permeability of $10^{-12}$ $m^2$ and porosity of 0.35 was then chosen as reference case for the following work devoted to the study of non-uniform permeability distribution and of two-component fluid. A list of the simulations described below is given in Table 4.

## 4. Results

The evolution of a system with uniform permeability is given in Figure 2 for the case of $k=10^{-12}$ $m^2$ (Simulation 1). After 10 years form the beginning of the simulation, hot rising plumes reach the surface (Fig. 2a) and after 100 years the system is uniformly heated (Fig.2b) and a broad two-phase region with maximum gas saturation of about 0.4 extends to the depth of 700 m (Fig. 2c). Simulations 2 and 3 investigated different permeability distributions. In Simulation 2, low permeability ($10^{-18}$ $m^2$) was assigned to the first 5 m depth, to verify the effects of a partially sealed cap. Temperature field and gas saturation are shown in Figure 3. The heat flow at the surface is reduced by the low permeability cap that limits the discharge of the warm fluid through the top of the domain. As a consequence, the system is heated more efficiently, as it appears from a comparison between Figure 2 and 3. Since the surface fluid discharge is inhibited, a narrow zone of fluid downflow develops and separates the larger rising plumes (Fig. 3a). The shape of the two-phase zone and the temperature distribution after 100 years (Fig. 3b,c) also reflect the presence of downflow regions. Pressure distribution is also affected by the low-permeability at the top, that induces a steeper pressure gradient. Figure 4a shows that the pressure at the top after 100 years is about 40 times higher than the atmospheric value. The pressure distribution for Simulation 1 is also shown for a comparison.

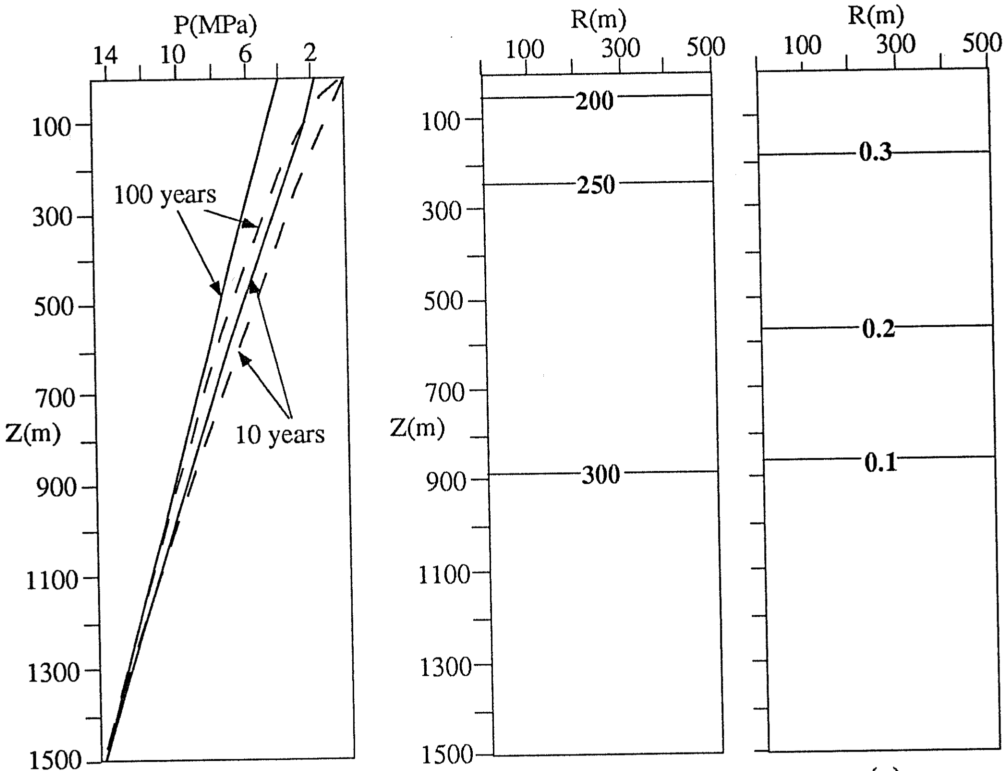


(a) (b) (c)

**Figure 3.** Simulation 2. Temperature distribution (°C) after 10 years (a) and 100 years (b) from the beginning of the simulation; gas volumetric fraction after 100 years (c).

In Simulation 3, low permeability was imposed to the bottom region, at depths greater than 600 m, and resulted in a much slower system evolution. As the thermal perturbation reaches the more permeable region, a convective cell develops and provides a continuos recharge of cold fluid from the top of the domain. Low uniform temperatures from 50 to 60°C characterize the shallow region (Todesco, 1995). This temperature distribution is consistent with the data from the geothermal wells, and it does not allow a vapor phase to develop.

Two more simulations were carried out to evaluate the effects of the presence of carbon dioxide on the system evolution. The carbon dioxide partial pressure was initially taken at the atmospheric value (about 33 Pa), and a partial pressure of $0.15x10^7$ Pa was imposed at the bottom of the domain. A first case (Simulation 4) was run with the same uniform permeability distribution of Simulation 1. Figure 4b,c shows the temperature and gas volumetric fraction after 100 years from the beginning of the simulation. A comparison between Figures 2b,c and 4b,c shows that carbon dioxide tends to enlarge the two-phase region to the depth of 800 m and to slightly reduce temperature. The following Simulation 5 was run with the same initial and boundary conditions as Simulation 4, but with a layered permeability distribution, as in Simulation 3. Under these conditions, the two-phase zone does not develop and the carbon dioxide is completely dissolved in water. In this case, the presence of carbon dioxide does not affect significantly the pressure and temperature distribution in the system.



(a) (b) (c)

**Figure 4.** (a) Pressure distribution with depth after 10 and 100 years from the beginning of the simulation for Simulation 1 (dashed lines) and Simulation 2 (solid lines). (b) Temperature distribution (°C) and (c) gas volumetric fraction after 100 years (Simulation 4).

## 5. Conclusions

Modeling of two-phase, two-component fluid and heat circulation was carried out to simulate the hydrothermal activity at Vulcano (Italy). Results showed that temperature and pressure distributions within the system are highly dependent on the overall rock permeability. The evolution of a system can be strongly modified by changes in the permeability distribution even if boundary conditions remain unchanged. High rock permeability throughout the domain allows a rapid temperature increase and an early development of a liquid-dominated two-phase zone. Rock permeability lower than $10^{-18}$ $m^2$ induces a much slower heating and the resulting temperature distribution is not consistent with the development of a vapor phase, both in the case of uniform and layered permeability structure. The presence of a low-permeability cap at the top of the domain reduces the heat and fluid outflow at the surface. As a consequence, the system undergoes a faster heating and a significative pressure increase at shallow levels. Results also show that the presence of carbon dioxide can increase the size of the two-phase region by enhancing the development of the gas phase.

Some insight on the hazard evaluation at Vulcano can derive from the performed simulations. Results show that higher permeability is responsible for higher temperature and mass discharge rates at the surface. This suggests that the observed variations at the fumarolic fields could derive from changes in rock permeability, even in absence of significative modification of the magmatic source. Processes leading to variation in rock permeability should be emphasized in the interpretation of monitoring data. In particular, self-sealing processes at shallow levels should be monitored due to the potential risk of phreatic explosion triggered by overpressure.

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