MODELING OF THE GEOTHERMAL ACTIVITY AT VULCANO (AEOLIAN ISLANDS, ITALY)

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ABSTRACT
Since its last eruption (1888-90) Vulcano has been in a fumarolic stage. Present activity includes fumaroles at the crater rim and at the Baia di Levante beach, and soil gas emissions. Physical modeling of heat and fluid flow through a cylindrical porous medium were carried out to study the hydrothermal activity. Simulation results show that a layered permeability distribution, with the more permeable region at the top, is consistent with the thermal gradient observed in the area around the cone. Higher permeability throughout the whole depth of the domain is required to obtain the elevated mass discharge rate and temperature observed at the fumarolic fields. Variations in the permeability distribution are shown to affect the discharge conditions at the surface and outline the importance of such parameters in controlling the fluid flow evolution.

1. INTRODUCTION

Vulcano belongs to the Aeolian Archipelago and is one of the active Italian volcanoes. After its last eruption, the island experienced a continuous fumarolic activity mainly concentrated at the crater rim and at the beach of Baia di Levante (Fig. 1), whose intensity and spatial extent varied with time (Barberi et al., 1991; Todesco, 1994, and references therein). Other manifestations involve gas emanation from the soil and the presence of a thermal component in the shallow phreatic waters, characterized by temperatures as high as 65°C, and by chemical and isotopic anomalies (Panichi and Noto, 1992; Capasso et al., 1993). Variations in the temperature and composition of hydrothermal fluids can be related to changes in the magmatic source, or to variable degrees of interaction between hot volcanic fluids and shallow waters. During the last twenty years, the evolution of the fumarolic activity resulted in an overall increase of the superficial manifestations, with a remarkable enlargement of the exhalative area and a progressive increase of the gas emission rate. A surveillance program was started to provide a continuous monitoring of the system with the double aim of understanding its functioning and detecting any sign that could possibly allude to a new eruptive activity. In order to interpret the information provided by the surveillance it is necessary to develop a reliable model of the present activity. In this work, physical modeling of two-phase fluid circulation at Vulcano was carried out in a cylindrical domain to investigate the role of boundary conditions and different porosity and permeability distribution on the evolution of the hydrothermal activity. The successful results obtained by the more advanced geothermal simulators encourage their introduction in volcanology, which appears to offer many interesting modeling research opportunities. System definition, initial and boundary conditions were selected based on the available literature data The simulation results are consistent with the available information on the underground fluid circulation, and show a strong dependence of the fluid flow patterns on the permeability distribution of the porous **rocks.**

2. THE HYDROTHERMAL SYSTEM

Two sources of information are available to study the hydrothermal system at Vulcano. The first one derives from the drilling of geothermal wells on the island (Fig. 1), which provided useful information on the subsurface system. The second one is related to the study of the superficial manifestations (i.e. fumaroles, thermal waters, gas emission from the soil) which give information on the circulating fluid.

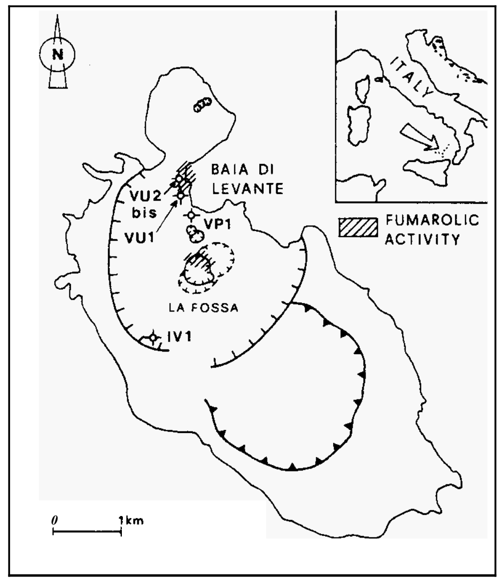

Figure 1. The island of Vulcano (Aeolian Islands). The location of the geothermal wells is indicated along with the areas characterized by fumarolic activity.

2.1 Subsurface

The first geothermal drillings (VU1 and VU2bis) were carried out at Vulcano in the 1950's by AGIP S.p.A. They reached only shallow depths (235m), crossing alternating tuffs and ash layers with minor lava flows. Three productive layers discharged up to 2400 t/day of *dry* steam from the VU1 well and 168 t/day from VU2bis. Diffuse hydrothermal alteration was observed in the core samples of VU2bis involving pyrite and anhydrite, with chlorite and sericite at the bottom hole (Sommaruga, 1984). Two more drillings, with vertical and deviated sections, were performed later by the joint-venture AGIP-ENEL-EMS (Faraone et al., 1986; AGIP, 1987; Barberi et al., 1989; Gioncada and Sbrana, 1991), but despite the high temperature observed, these wells were never productive. The IV1 well was drilled in 1983-84, **SW** of the active cone and reached the maximum depth of 2050 m. In 1987, the last well (VP1) was drilled N of the cone, down to the depth of 1000 m. A monzodioritic intrusion was encountered by the IV1 well at depths of 1360m in the vertical section and at 980m in the deviated one (IV1dir), whereas shallow sub-volcanic bodies were found at the VP1 bottom-hole. Diffuse alteration was found, especially at shallow levels, and evidenced the superimposition of high- and low-temperature hydrothermal circulation. Secondary paragenesis involved chlorite, calcite, clay minerals, anhydrite, pyrite, limonite, and abundant quartz. At greater depths, the intrusive and sub-volcanic bodies were affected by the deposition of garnet, anfiboles, biotite, and epidotes (Faraone et al., 1986; Cavarretta et al., 1988). Fluid inclusions found in hydrothermal anhydrite crystals from the IV1 well showed trapping temperatures scattered over a wide range (180-350°C), with no apparent correlation with the depth of sampling (Cavarretta et al., 1988). In-hole static temperature measurements were performed during well drilling and showed almost constant values of 50-60°C down to a depth of 600-700 m (see Fig. 3d). Similar temperatures are also commonly found in the shallow water wells drilled for domestic use around La Fossa cone (Panichi and Noto, 1992; Capasso et al., 1993). At greater depths, the thermal gradient becomes steeper and temperatures higher than 419°C (zinc melting point) were found at the IV1 bottom-hole. Circulation losses during the drilling mainly affected the shallower portion of the two wells, with total losses concentrated in the first 500 m for the IV1 well, and in the first 900 m in the VP1 well (AGIP, 1987).

The absence of a significant thermal gradient in the first 600 m suggests that at these shallow levels fluid circulation contributes to the heat transfer, whereas at greater depths conduction dominates inducing a steeper gradient. Accordingly, permeability should be higher in the first 600 m and then drop to relatively low values at greater depths. The lack of productivity of the wells and the distribution of secondary phases suggests that fluid flow is confined to fractured zones. The evidence of coexisting high- and low-temperature alteration minerals suggests that the intensity of the hydrothermal activity varied with time. This can be due to variable input from the deep source, but also to a variable system permeability controlling the spatial extent of fluid circulation and the possible inflow of cold "external" water. Several competing effects can modify rock permeability both in space and time. The intense mineral deposition characterizing hydrothermal systems plays an important role in reducing rock porosity and it is responsible for the progressive "self-sealing" of the affected areas. On the other hand, rock fracturing related to seismic activity or to localized overpressure can easily provide new channel-ways for the fluid flow. These features are both common in hydrothermal systems and provide a continuous variation of the rock permeability.

2.1 Superficial Activity

The crater fumaroles discharge up to 1100 t/day of gas (Italiano and Nuccio, 1992), whose composition involves water and carbon dioxide (98vol% of the total mixture), with sulphur compounds, HCl, HF, B, and Br as minor components (Martini et al., 1980; Carapezza et al., 1981; Cioni and DAmore, 1984; Chiodini et al., 1991a). The gas temperature can be different at different fumaroles, and its maximum value underwent dramatic changes throughout this century, outlining periodic system crisis. A fist peak of 615°C was reached in 1923 (Sicardi, 1940, 1955), after which temperatures went back to less than 200°C. Slightly higher values were observed at the end of the 1970's and a new sharp increase was recorded since 1988, and brought the temperature over 600°C in 1991 (Chiodini et al., 1993). Higher temperatures have been usually associated with higher gas/steam ratios (i.e. higher CO_2 content) and mass flow rate. Shallow seismic swarms related to fluid motion have been recorded underneath the crater, with hypocentral depths of 600-1000 m (Montalto, 1994). The presence of enhanced hydrothermal deposition at these depths suggested a relation between self-sealing processes and seismic activity associated with pore pressure increases in plugged conduits. Fumaroles at the Baia di Levante beach are characterized by uniform temperature values of about 100°C, which are kept constant by a shallow boiling aquifer. Their composition differs from that observed at the crater due to the loss of reactive components. System crisis are revealed by higher gas emission rates and by increases of the CO content (Cioni and DAmore, 1984; Martini et al., 1989; Chiodini et al., 1991b). Synchronous variations at the crater and at the beach suggest that the two fumarolic fields are connected at depth by a common source with superficial modifications affecting the fluid composition at Baia di Levante. Gas emanation from the soil has been detected at several locations on the island and involves emission of CO_2, H_2 and He (Badalamenti et al., 1984, 1991; Bertrami et al., 1984; Toutain et al., 1992; Carapezza and Diliberto, 1993). The available data suggest that these gases have a deep origin, related to the hydrothermal activity at Vulcano. During system crisis, the gas emission rate increases and CO_2 can reach saturation. The higher anomalies in gas emanation are usually associated with major tectonic trends on the island, suggesting a strong association between soil degassing and zones of structural weakness. The presence of a hydrothermal influence has also been detected in the shallow water wells drilled for domestic use (Martini, 1980; Brondi and Dall'Aglio, 1991; Panichi and Noto, 1992; Capasso et al., 1993). Variations of temperature, salinity, and composition have been periodically recorded and received different interpretations involving either seasonal variations or a variable input from the volcanic system.

Different origins have been proposed for the hydrothermal fluids (Martini et al., 1980; Carapezza et al., 1981; Cioni and D'Amore, 1984; Chiodini et al., 1991a). A general agreement exists, however, about the presence of two distinct fluid components: one, CO_2-rich, related to a deep (magmatic) origin, and the other, H_2O-rich, associated with a shallower source. Temooral variations in the gas composition and temperature can be associated with variable contributions of these two components. Data from superficial manifestations suggest that fluids preferentially move through fracture systems which account for their fast ascent and for the slight difference among the vents fed by different fractures. Variations in temperature and composition can be related to various degrees of mixing between the volcanic component and shallow waters. Hence the fluid mobility represents an important control parameter for fluid temperature and composition. Deepening of the fracture system could also account for the increase in temperature, as fluids in hotter regions are reached. Variation in the permeability of the system is likely to rule both the temperature and the composition of the fluids, allowing for larger or smaller extents of the fluid circulation and controlling the input of external water.

3. NUMERICAL SIMULATIONS

Numerical simulations were carried out to investigate the effects of different permeability distribution on the fluid flow pattern and on the resulting thermal gradient. The simulations were performed with the TOUGH2 multi-component, multi-phase geothermal simulator (Pruess, 1991). The model adopted here accounts for the transport of heat and pure water through a cylindrical porous domain with a 500 m radius and a depth of 1500 m. The thermo-physical properties of water are obtained from the steam table equations as established by the International Formulation Committee (1967). The fluid phases are assumed to be in thermal equilibrium with the porous matrix. At present, pure water is considered as the only fluid component and the effects of dissolved salts as well as the occurrence of chemical reactions are neglected. More work is in progress to study the effects of CO_2, but it is not presented here. The model does not account for stress evolution and deformation of the solid matrix, or for the presence of fractures. The solution is found with an integral finite difference approach, based on the discretization of the domain into a mesh of control volumes (Edwards, 1972; Narasimhan and Witherspoon, 1976).

The simulations were performed with fixed temperature of 300°C and pressure of 1.5×10^7 Pa at the base of the domain, and 30°C and atmospheric pressure at the top. Both no flow and free flow conditions were imposed for heat and mass fluxes at the vertical boundary. The results showed here refer to no flow conditions. Initial conditions involve a uniform temperature of 30°C over the whole domain and a hydrostatic pressure gradient. Table 1 specifies the rock physical properties which have been kept constant in all the simulations. A first set of simulations was performed to evaluate the effects of the computational grid size. The total number of elements was varied from 85 to 1240, with radius varying from 25 to 100 m, and the vertical dimension from 5 to 100 m. A comparison between the results showed that runs performed with 620 and 1240 elements do not differ significantly. Simulations carried out with non-uniform grids showed that finer resolution near the top and bottom regions does not seriously modify the results, but it allows to better capture some details of the flow. Based on these results, a non-uniform mesh of 480 elements, with a 50 m radial size and vertical dimensions varying from 5 to 50 m, was used in the following simulations.

TABLE 1. Rock physical parameters.

Rock Density (kg/m^3)	2800.
Specific Heat (J/kg°K)	800.
Heat Conductivity (W/m°K)	2.5

Three different permeability distributions were considered (Table 2): uniform (A1); layered, with higher permeability in the upper region (A2); and "channelled", where a preferential high-permeability central channel connects the bottom to the top (A3). A further simulation was camed out, starting from the steady state conditions obtained for the simulation A2, to study the opening of a high-permeability channel across the low-permeability bottom part (A2bis).

In the uniform domain, as the system is heated from below, two major asymmetric convective cells develop at the base of the system. After about 23 years, these cells reach the surface, where heat and fluids (up to 5400 W/m^2 and 1080 kg/day m^2) are discharged from the top boundary. The temperature increase at shallow depths favours the development of a narrow two-phase zone. After 100 years, the system reaches the stable configuration that characterizes the steady state, involving a very steep temperature gradient in the first 100 m and a broad two-phase region, occupying the whole width of the domain to a depth of about 700 m (Fig. 2).

TABLE 2. Simulation parameters. R=radial and Z=vertical distances; @=porosity;k=permeability. See text for discussion.

Name	Type	R (m)	Z (m)		k (m^2)
A1	Uniform	0-500	0-1500	.35	10^{-12}
A2	Layered	0-500	0-600	.35	10^{-12}
			600-1500		10^{-18}
A2 bis	Layered + Channelled	0-500	0-600	.35	10^{-12}
		0-500	600-1500		10^{-18}
		0-100	600-1500		10^{-12}
A3	Channelled	0-100	0-1500	.5	$200.x10^{-12}$
		100-500		.25	10^{-15}

In the second simulation, a permeable shallow zone overlays a low-permeability region located at depths greater than 600 m (A2). Longer times are required for the propagation of the thermal front at depth, and a remarkable pressure increase is induced by the thermal expansion of the less mobile fluid (Fig. 3a). As the thermal perturbation reaches the more permeable zone, however, a single convective cell develops in the shallower region and releases the pressure increase by discharging heat (up to 29 W/m^2) and fluid (up to 10 kg/day m^2) at the surface. At the steady state, the pressure distribution is back to hydrostatic and the upper region is characterized by low temperatures (<100°C). Higher temperatures are present at depth, where the thermal gradient becomes steeper (0.25°C/m, Fig. 3b, 3c). Such temperature profile is in good agreement with the values observed in the geothermal wells, especially those from the VP1 well (Fig. 3d). With respect to the uniform case, the heat and fluid flows are up to 2 orders of magnitude lower and the system evolution does not involve the development of a vapour phase.

The situation changes if, once the system has reached the steady state conditions, a connection is open between the hot bottom of the domain and the shallow permeable zone. In the simulation A2bis, the high permeability of the shallow region was also assigned at depth, to the central portion of the domain. The rapid ascent of heat and hot fluid through the new channel is responsible for a dramatic inflection of isotherms and isobars. The temperature increase leads to the development of a two-phase region that, after 10 years, occupies a funnel-shaped region with a maximum depth of about 800 m (Fig. 4). After 100,000 years the upper part of the system is characterized by high temperatures (up to 200°C at 150 m depth) and slight overpressure in the high-permeability channel at depth. The opening of the channelway resulted in a remarkable increase of the heat and fluid flows at the surface which, at the steady state, are up to 5 and 7 orders of magnitude higher, respectively, than in the A2 simulation.

The third simulation (A3) assumes the presence of a preferential high-permeability channel at the center of the domain, from its bottom to the surface. The fluid heated at the bottom of the domain can quickly rise within the channel, and induces an early development of a superficial two-phase zone (Fig. 5). At later times, the thermal anomaly expands toward the outer boundary and the two-phase region extends uniformly to the depth of 700 m. After 1Ma, a remarkable heat flow (up to $1.7x10^6$ W/m^2) leaves the system surface from the top of the high permeability channel, and accompanies a fluid flow of 10^5 kg/day m^2. Smaller flows (up to 14 W/m^2 and 0.77 kg/day m^2) are observed from the less permeable zone.

Three more simulations were carried out with these same permeability distributions, but with free flow conditions at the vertical boundary. At Vulcano, these conditions could represent a situation where the nearby cold seawater has a free access to the hydrothermal system. In each simulation, the open boundary induces a significant inflow of cold fluid, which enters the domain at depths greater than 600 m, with no dependence on the permeability distribution. A steep pressure gradient develops in the area where the fluid enters the system, and then decreases toward the surface. At steady state, in the uniform system the pressure distribution exceeds the hydrostatic gradient, whereas in the layered case, hydrostatic pressures develop in the permeable shallow zone. In the channelled domain a steep gradient characterizes the vicinity of the high permeability zone at depths greater than 600 m. The inflow of cold water keeps the system temperature to very low values at the steady state, and both heat and fluid flow from the top of the domain are strongly reduced. In the channelled domain only, temperatures as high as 100°C can reach the surface.

4. DISCUSSION

The results obtained from numerical simulations are in substantial agreement with the available data and bear some interesting

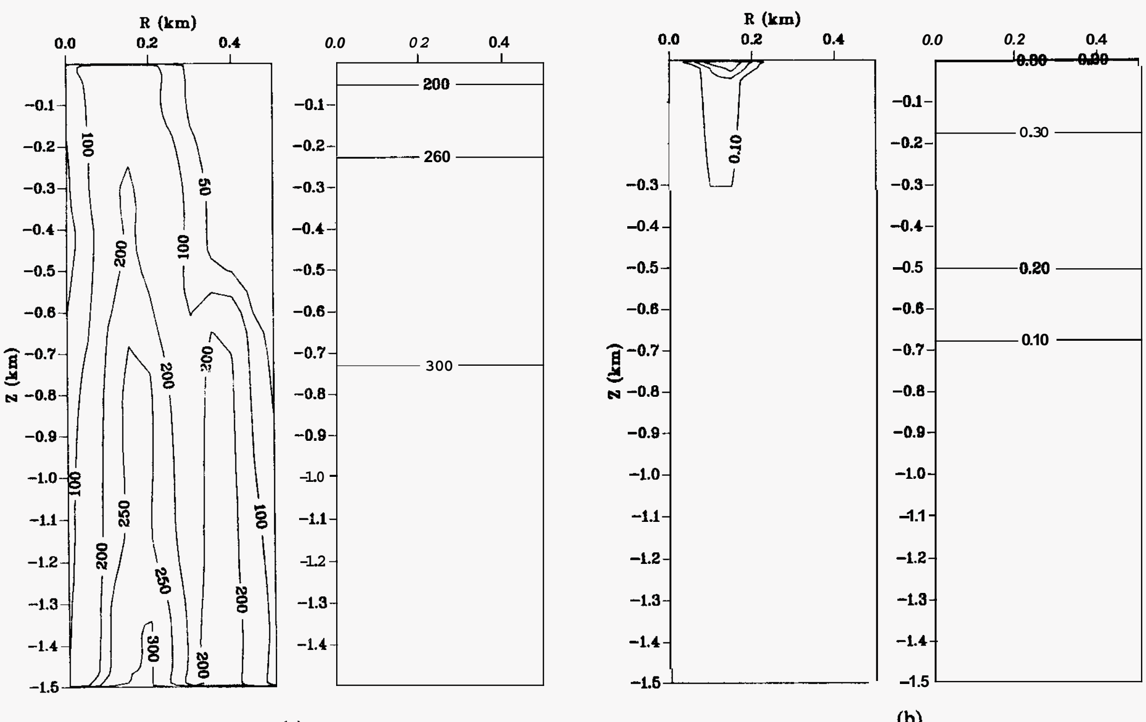

Figure 2. Simulation A1. Temperature (a) and water vapour volumetric fraction (b) distributions after 23 years (left) and 100 years (right) from the beginning of the simulation.

implications. According to the simulation A2, a layered permeability distribution with higher values at the top accounts for the temperatures observed in the shallow water wells around La Fossa cone, and are consistent with the scarce fluid flow observed outside the fumarolic fields. It is interesting to note that the presence of convective cells generates a zone of preferential fluid discharge, even if no structural discontinuities are present. The temperature profile obtained for the layered system is consistent with the data from the geothermal wells (IV1dir in particular, Fig. 3d). Minor discrepancies with some of the data are easily produced in a heterogeneous natural system, where the temperature profiles or the permeability distribution are likely to vary from well to well. Simulation results therefore confirm the "permeable over less permeable" setting for the area around La Fossa cone, with the sharp permeability variation at a depth of about 600 m. Such a discontinuity is approximately located at the same depth as the shallow fluid-related seismic events that could be related to the high pressure gradient induced by the permeability change. The layered permeability distribution produced very slow heating of the deep region, corresponding to only a subtle temperature increase at the surface even if important perturbations were imposed at depth. This implies that such permeability distribution could efficiently mask remarkable changes occuning at depth and whose effects could be seen at the surface only after considerable time, if at all recorded. Preliminary results from simulations with mass injection at the base of the domain confirm such conclusions and suggest that in layered systems the effects of variable fluid injection are mainly confined to the lower layer with negligible variations observed at the top. On the other hand, simulation A2bis showed that rock fracturing at depth can provide significant variations in the temperature and fluid discharge rate from the top, even if boundary conditions at the bottom remain unchanged. Therefore, changes observed at the surface do not necessarily correlate with modification of the deep source (i. e. different magma depth or magma degassing rate), but can simply be the result of a variation in the permeability of the porous rock. Higher permeability throughout the whole system, as in the uniform or in the channelled cases, provide an effective connection between the heat source and the surface, and allow for the discharge of high enthalpy fluids at the top of the domain. This is the case of the fumarolic fields, both at the beach and at the crater, where gases at temperatures above 100°C are discharged with high mass flow rates. At the time of the geothermal drillings the total steam output from the fumaroles was about 1.5×10^5 kg/day m^2 (Italiano and Nuccio, 1992), which is consistent with the results of the A3. Open boundary conditions generate peculiar fluid flow patterns and are responsible for high overpressure at depth. The low temperatures observed at the steady state, however, suggests that free flow conditions are not consistent with the observed thermal gradient. The channelled system only provides surface temperatures as high as 100°C under free flow conditions, and could be representative of the fumarolic area at the beach, where open connections with the seawater are likely to exist.

Better results could be obtained by improving the model and introducing further important features. In particular, this work showed the relevance of permeability distribution in the hydrothermal circulation, and further simulations should include the effects of fractures in the porous medium. Studies involving the effects of carbon dioxide are presently in progress. Moreover, the evolution of the activity at Vulcano since 1988 has been characterized by gas temperatures well above the critical value. This implies that in order to simulate the present state of the system, thermo-physical properties of water at supercritical temperatures should be introduced into the model. Finally, a complete modeling should also account for the effects of dissolved salts, which alter the thennodynamic properties of the fluid and induces important variations in the system porosity and permeability.

5. CONCLUSIONS

In this work the hydrothermal activity at Vulcano has been studied by means of a physical model accounting for two-phase pure water and heat flow through a cylindrical porous medium heated from below. Three different permeability distributions (uniform, layered, and channelled) have been considered in order to reproduce different aspects of the natural system, and both no flow and free flow boundary conditions were adopted for the vertical boundary. Despite major simplifications (such as the absence of other gas components or dissolved salts) the simulation results were shown to be consistent with the present knowledge of the system, and encourage further modeling research. The thermal gradient observed along the geothermal wells and the temperature measured in some shallow water wells are consistent with a layered permeability structure, with the more permeable rocks at the top (simulation A2). Thermal

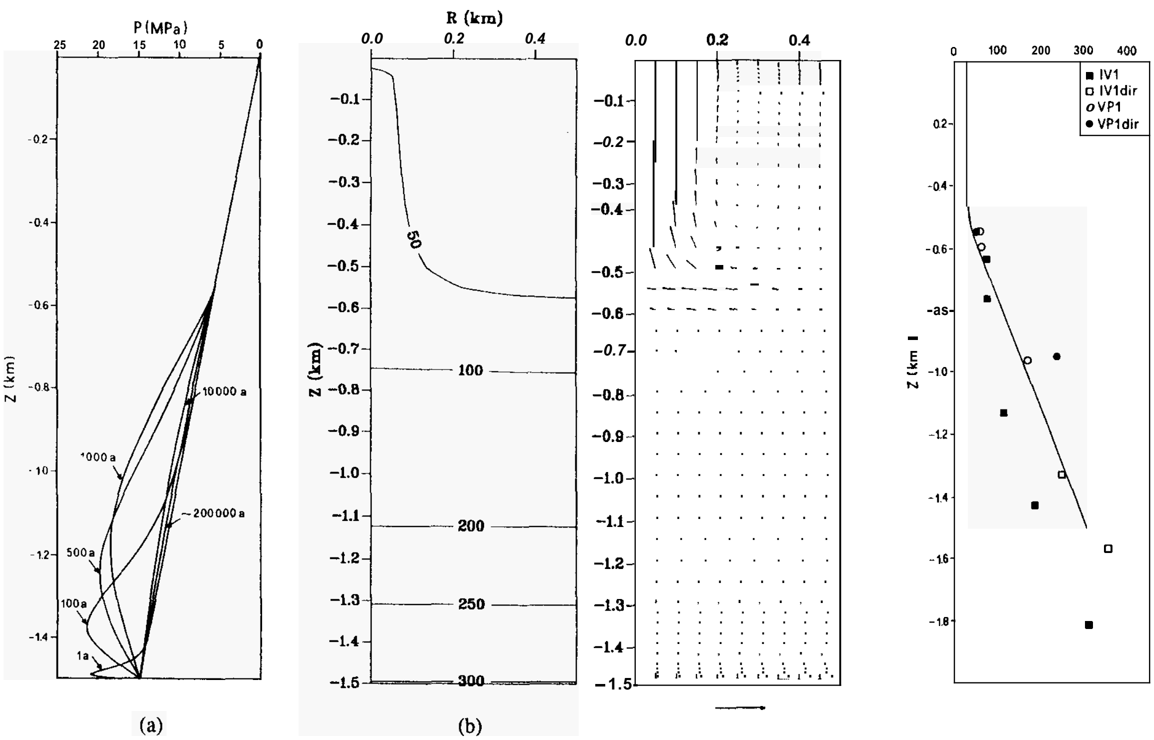

Figure 3. Simulation A2. (a) Pressure distribution with depth at various times from the beginning of the simulation. (b) Temperature (°C) and (c) heat flow (W/m^2) distribution at the steady state (≈188,000 years). Arrows' length is proportional to flux magnitude. The reference arrow corresponds to 0.29×10^2 W/m^2 (maximum value). (d) Temperature distribution with depth at the steady state (line) and temperature data from geothermal wells (points). IV1dir and VP1dir refer to wells' deviated sections.

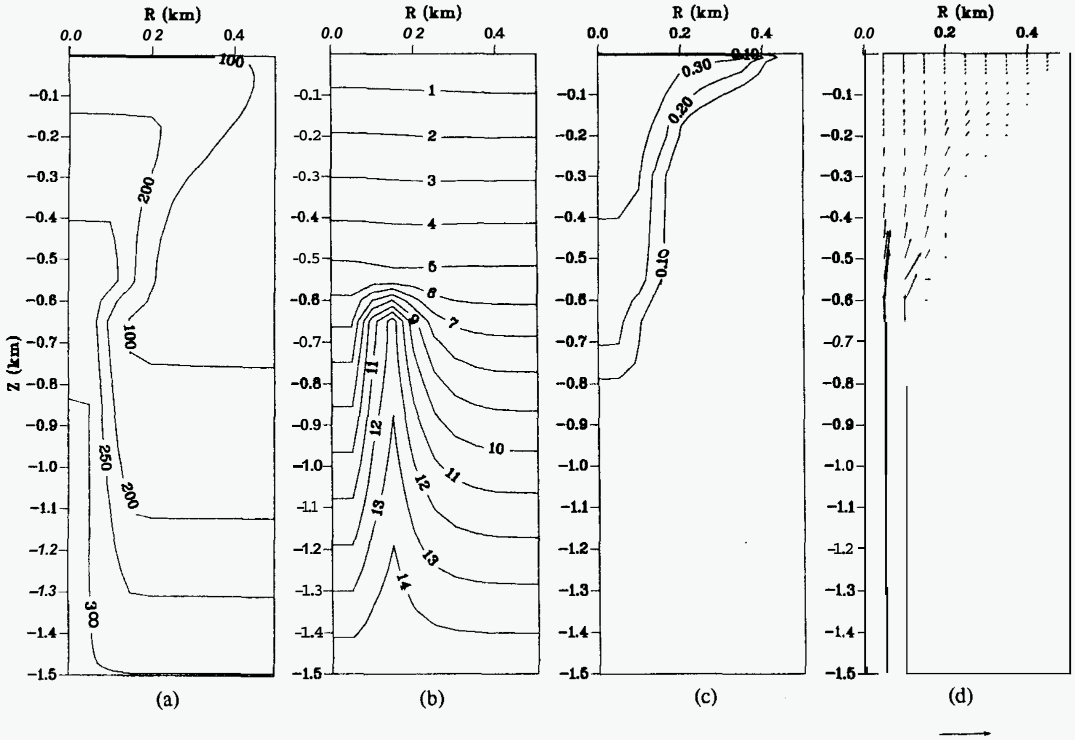

Figure **4.** Simulation A2bis. (a) Temperature (°C); (b) Pressure (MPa); (c) Water vapour volumetric fraction; (d) Heat flow (W/m^2), after 9 years from the beginning of the simulation. Arrows' length is proportional to flux magnitude. The reference arrow corresponds to 0.21×10^5 W/m^2 (maximum value).

perturbations at the base of such a domain induce the development of a "pressure wave" that dissipates as the thermal front reaches the shallower high-permeability zone. The opening of a permeable channel within the bottom region generates effective heating and higher mass discharge rates at the surface, even if boundary conditions at the bottom do not change (simulation A2bis). The areas characterized by fumarolic activity, at the crater or at the Baia di Levante beach, are effectively described by a domain with a high-permeability central channel (simulation **A3).** In this case, higher temperatures and mass emission rates were obtained at the surface, in agreement with the data on the fumarolic fields. Surface temperatures as high as 100°C are obtained even if free flow conditions are imposed at the vertical boundary, as it could be the case for the fumaroles at the

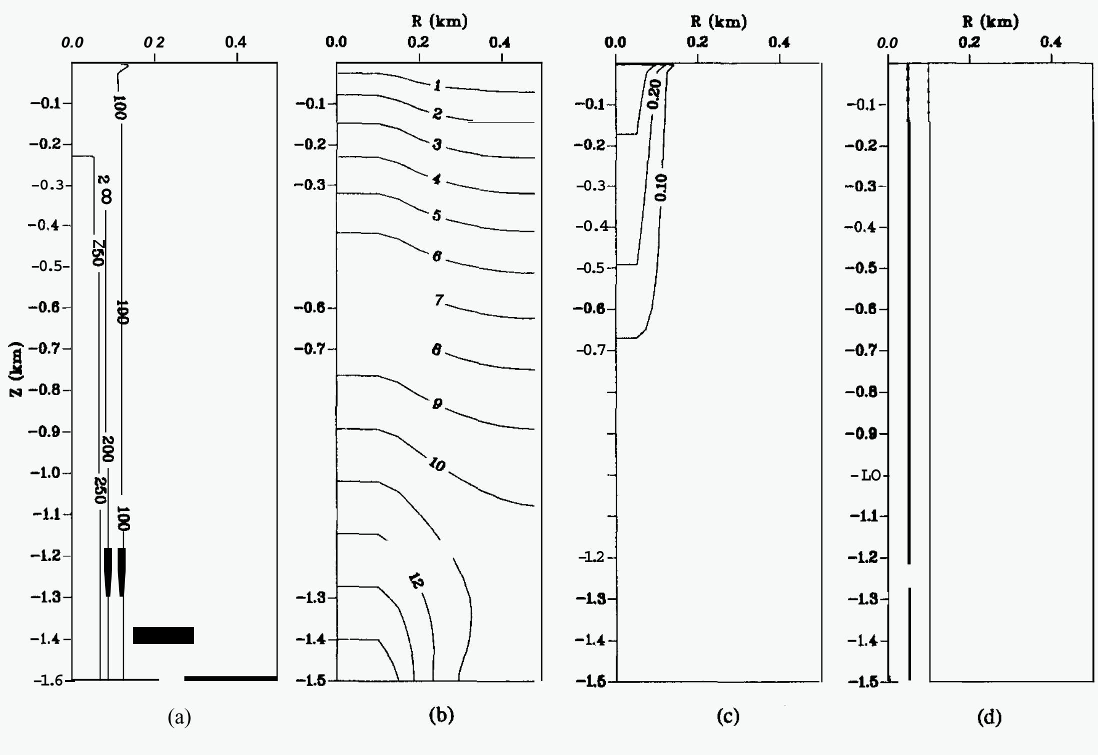

Figure **5.** Simulation A3. (a) Temperature (°C); (b) Pressure (MPa); (c) Water vapour volumetric fraction; (d) Heat flow (W/m^2), after 1 **year** from the beginning of the simulation. Arrows' length is proportional to flux magnitude. The reference arrow corresponds to the maximum value of 0.17×10^7 W/m^2.

beach. The performed simulations showed the primary role of the permeability distribution in the definition of fluid flow patterns. The remarkable effects induced by variations of the permeability distribution invite a careful interpretation of the changes in the fluid temperature and discharge rate observed at the surface. The results obtained in this work establish a set of system parameters that provide a satisfying description of some of the important features of the hydrothermal activity at Vulcano. The successful results obtained suggest that numerical modeling represents a powerful tool to study the physics of hydrothermal circulation in volcanic areas, and should be extensively adopted to contribute to the interpretation of field data. More accurate results will derive from improved physical models but also from the introduction of extensive, modeling-oriented field and laboratory data, which are required to obtain a more reliable description of the natural system.

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