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# Aquifers and groundwater within active shield volcanoes. Evolution of conceptual models in the Piton de la Fournaise volcano

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**Abstract**

The uncertainty regarding hydrogeological models that have been proposed for describing active volcanoes results from the difficulty of prospecting deep groundwater bodies. In the case of the Piton de la Fournaise volcano located in Reunion Island, recent geophysical exploration using deep electromagnetic (EM) prospecting tools has provided new geostructural and hydrogeological information. This paper introduces yet a new hydrogeological model, using a direct modeling approach, which then serves as a numerical tool for testing our most recent geological findings and for consolidating our understanding of the hydraulic behavior of the massif. For this purpose, the 3D Femwater finite element code has been implemented. The model is built to represent the global structure of the volcano defined by four main volcanic units as hydrogeological layers. While each layer is characterized by an average homogeneous hydraulic property, the boundary conditions correspond to the yearly groundwater recharge spatially distributed into homogeneous recharge zones, and constant head conditions correspond to the sea or rivers which form the edge of the modeled area. The numerical flow simulation provides piezometric heads reaching a height of 1800 m a.s.l. in the vicinity of the volcano summit. The computed piezometric surface is consistent with the shape of the saturated zone inferred by geophysical soundings, and the model simulated groundwater discharge is consistent with the observed main spring discharge identified within the deepest valleys or along the shoreline. This simulation gives hydraulic confirmation of a continuous aquifer conceptual model. High water levels in active volcanoes are thus not necessarily a result of perched or dike confined aquifers. These results indicate the presence of a central groundwater dome similar to those observed in the Canary or Azores islands, where volcanic terrains are much older. Our model implies potentially new kinds of interactions between groundwater and volcanic activity. In particular, we focus on the importance of water pressure distribution within the volcano. By itself, the three-dimensional

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groundwater model provides a guide for a better understanding of the structure and the eruptive dynamics of active volcanoes.


*Keywords:* shield volcano; hydraulic properties; groundwater; 3D modeling; Piton de la Fournaise

## 1. Introduction

Hydrogeology often plays an important role in the study of volcanic systems. For example, Mastin (1997) shows that groundwater can significantly interact with eruptive activity. The location of volcanic aquifers is also taken into account in geothermal or in water/rock interaction studies (Savin et al., 2001; Ingebritsen and Scholl, 1993; Carvalho Martins, 1988). Groundwater is also considered as an important factor in most mass wasting phenomena affecting volcanoes. The work of Iverson (1995) suggests that large groundwater head gradients may be a major agent in the gravitational destabilization of volcano flanks. However, hydrogeological models of shield volcanoes are generally poorly constrained and contrasting models have been proposed in different areas. For example, divergent models have been proposed for Teide volcano on Tenerife island (Custodio et al., 1988; Ecker, 1976). Cruz and Silva (2001) stress the existence of conflicting conceptual hydrogeological models for volcanic islands. They distinguish two main categories: (i) the Hawaiian model (Peterson, 1972; Mac Donald et al., 1983), and (ii) the Canary Island model (Custodio, 1978, 1989). Recently, Izuka and Gingerich (2003) note that the Hawaiian model cannot apply to the SE part of the island of Kauai (Hawaii).

This divergence, and the uncertainty that surrounds these conceptual groundwater models can be explained by the relative difficulty of studying groundwater within active volcanoes. This can hamper volcanological studies requiring a thorough understanding of hydrogeology.

On Reunion Island, a multidisciplinary program of water resource development has been conducted on the Piton de la Fournaise volcano since 1995. The study involves geophysical, geological and hydrological surveys that provide new data and a better understanding of the groundwater conditions in active shield volcanoes.

This paper presents the results of the study employed in developing a new model of the hydrogeological system of Piton de la Fournaise volcano. This model is then discussed and compared to field observation.

## 2. Geographical and geological setting

Reunion Island is located at 21°07′S and 55°32′E in the western part of the Indian Ocean, 800 km east of Madagascar. This small island forms a cone rising above the oceanic floor, from depths exceeding 4000 m, and culminating at about 3000 m above sea level. The island, elliptical in shape (50 * 70 km) with a NW–SE strike, is composed of two volcanoes: Piton des Neiges and Piton de la Fournaise. While Piton des Neiges, 3069 m a.s.l., is a dormant and deeply eroded volcano, Piton de la Fournaise is one of the most active basaltic volcanoes in the world. This shield volcano, 2631 m a.s.l., is partly incised by deep valleys (Rivière des Remparts, Rivière de l'Est and Rivière Langevin) (Fig. 1).

The morphology of Piton de la Fournaise is characterized by three sub-concentric nested calderas opening out to the sea on their eastern side (Chevallier and Bachèlery, 1981). The oldest caldera, to the west, is visible at the head of the amphitheatre-shaped valley formed by the Rivière des Remparts. Eastward, the youngest caldera, Enclos, is the major site of recent volcanic activity. Eruptions produce essentially basaltic lava and most aspects of the morphology and of the volcano's historical activity are now well-defined (Gillot and Nativel, 1989). In the evolution of Piton de la Fournaise, four distinctive building stages are used to define four volcano-structural units. Each stage produces a roughly concentric caldera, progressively smaller than the caldera of the previous stage. This structural classification corresponds to the geological map, but it may be simplified by regrouping

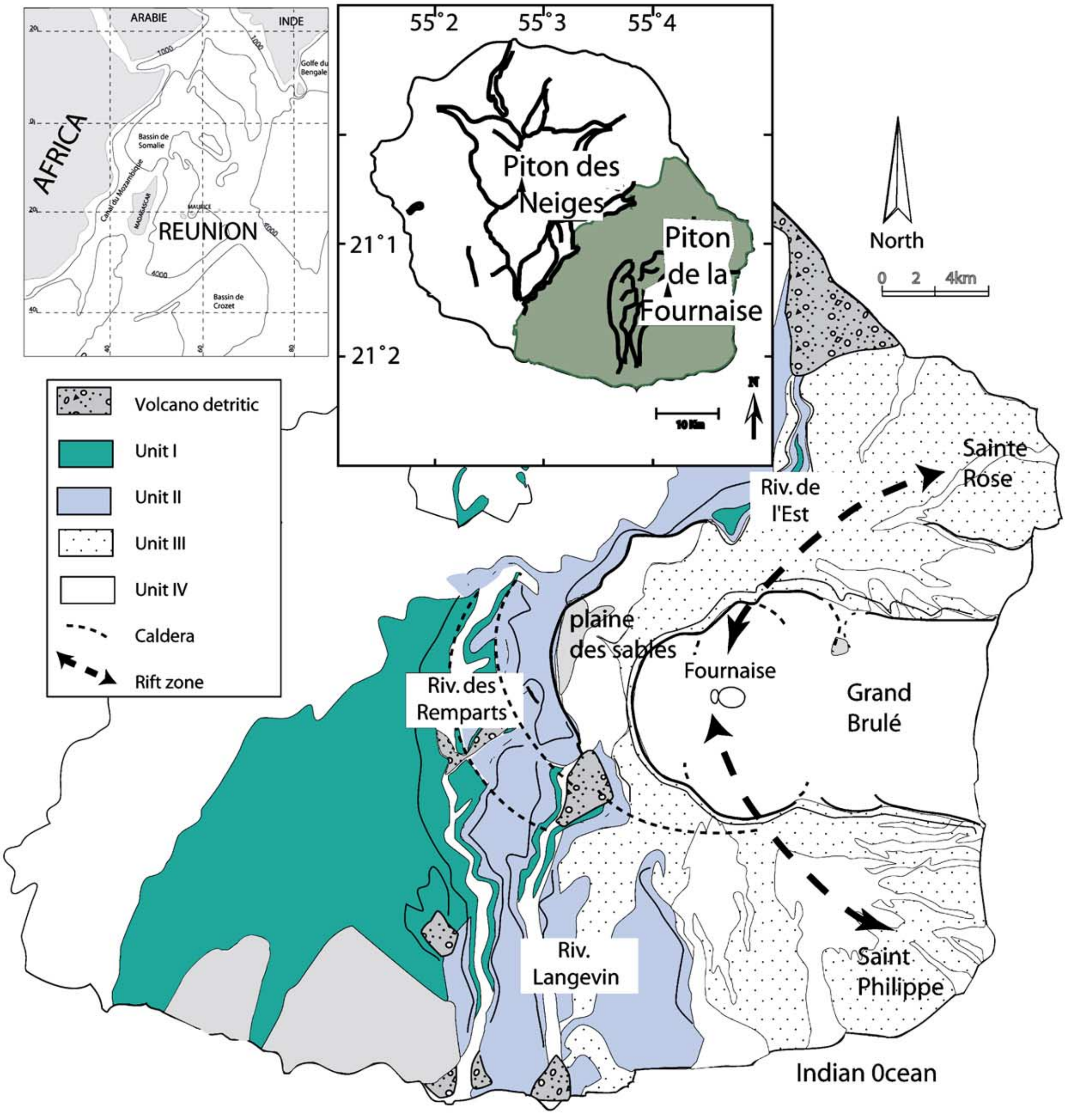


Fig. 1. Simplified geological map of the Piton de la Fournaise volcano.

units. For example, Bachèlery and Mairine (1990) and Bachèlery and Lenat (1993) distinguish two main groups: the first, "the old shield volcano" (Unit I), being at least 500,000 years old and forming the outer western slopes of the existing edifice and the second, "the recent shield volcano" (Units II, III, IV), dating from 150,000 years to present and corresponding to three calderas, Morne Langevin (150,000 years old), Plaine des Sables (65,000 years old), and Enclos (5000 years old).

The climate in Reunion is intertropical and characterized by a hot, rainy season from December to April and a temperate, dry season from May to November. Wind direction and topography induce large variations in the rainfall on the island. The eastern windward side of Piton de la Fournaise massif shows the maximum rainfall rate, with over 12,000 mm/year (Barcelo and Coudray, 1996).

## 3. Hydrogeological background

As in the case of numerous high volcanic islands, the question of groundwater conceptual models is still controversial in Reunion Island. This is particularly obvious in the interior of the island where the depth of aquifers, added to the rugged topography, precludes borehole prospecting. Until recently, groundwater exploitation has been mainly developed in the "basal coastal aquifer". Farther inland, groundwater exploitation is limited to natural spring catchments, which are principally located in the walls of the major valleys and cirques, at altitudes ranging from 800 to 1200 m.

Most wells (82%) are located between 0 and 110 m a.s.l., their average depth being above 100 m. In the last 10 years, borehole investigations have been extended farther inland, up to 200 m a.s.l. Above this altitude, investigations become more risky and boreholes are scarce (less than 3%). Due to the steep slopes of the volcano, 88% of the wells are located within a 4 km wide coastal band. Hence, the encountered water level is very close to sea level. The major proportion of the wells (77%) have a piezometric level under 6 m a.s.l. Those having a piezometric level higher than 15 m a.s.l. (12%) are generally situated in specific hydrogeological settings, often in relationship with alluvial aquifers.

The piezometric slope ranges from 0.5 to 3 m/km, the highest values characterizing a connection with alluvial aquifers. Transmissivity values obtained from well tests and from model results are higher than $1 \cdot 10^{-1}$ $m^2/s$ for 57% of the wells. The specific modal discharge is equal to $50 \cdot 10^{-2}$ $m^3/s/m$. It can reach 0.7 $m^3/s/m$. These results are very close to those characterizing Hawaiian volcanoes in similar geological contexts (Peterson, 1972; Ingebritsen and Scholl, 1993).

Two different hydrogeological models of Piton de la Fournaise have been proposed (Coudray et al., 1990; Violette et al., 1997), and both suggest a basal aquifer restricted to a coastal fringe. These respective authors suppose that groundwater "cascades" in the center part of the massif without forming extended aquifers and that high altitude springs are the result of "tile flows" or dike-impounded systems. Violette et al. (1997) suggest that flow pattern in the Piton de la Fournaise is similar to that observed at Kilauea in Hawaii (Ingebritsen and Scholl, 1993). In both cases, the volcanic terrains are supposed to be either impervious (impounding dikes, "tiles structures", or hydrothermal core) or highly conductive (values deduced from well tests along the coastal fringe). These models, referenced as the "Hawaiian conventional type" (Izuka and Gingerich, 2003), do not take into account any variation of hydraulic conductivity within the volcanic terrains. Their authors assume a kind of quasi-binary distribution of conductivity within the volcano, as suggested by proposed schematic cross section (Ingebritsen and Scholl, 1993; Mac Donald et al., 1983). Custodio (1989), while working on the Canary Islands, notes that this widely used conventional classification is hydraulically unclear. He proposes a single regional aquifer, one which is continuous from the gently sloping water table in the high permeability coastal area to the steeply sloping inland water table, and corresponds with a decrease in permeability. As a consequence, the water table forms a highly elevated groundwater dome across the island (Fig. 2).

Join and Coudray (1993) classify the hydrogeological context of springs in the high inland zones of Reunion Island, into three categories (Fig. 2):

(i) superficial water tables in relation with subsurface flows in aquiferous layers of very limited extent,
(ii) perched water tables of limited extent, where flows are channeled through paleo-valleys or spread over extensive ash layers,
(iii) a basal water table observed in entrenched amphitheatre-shaped valleys providing the main groundwater resources.

This classification (Fig. 2) is supported by a geochemical survey covering 243 springs on the

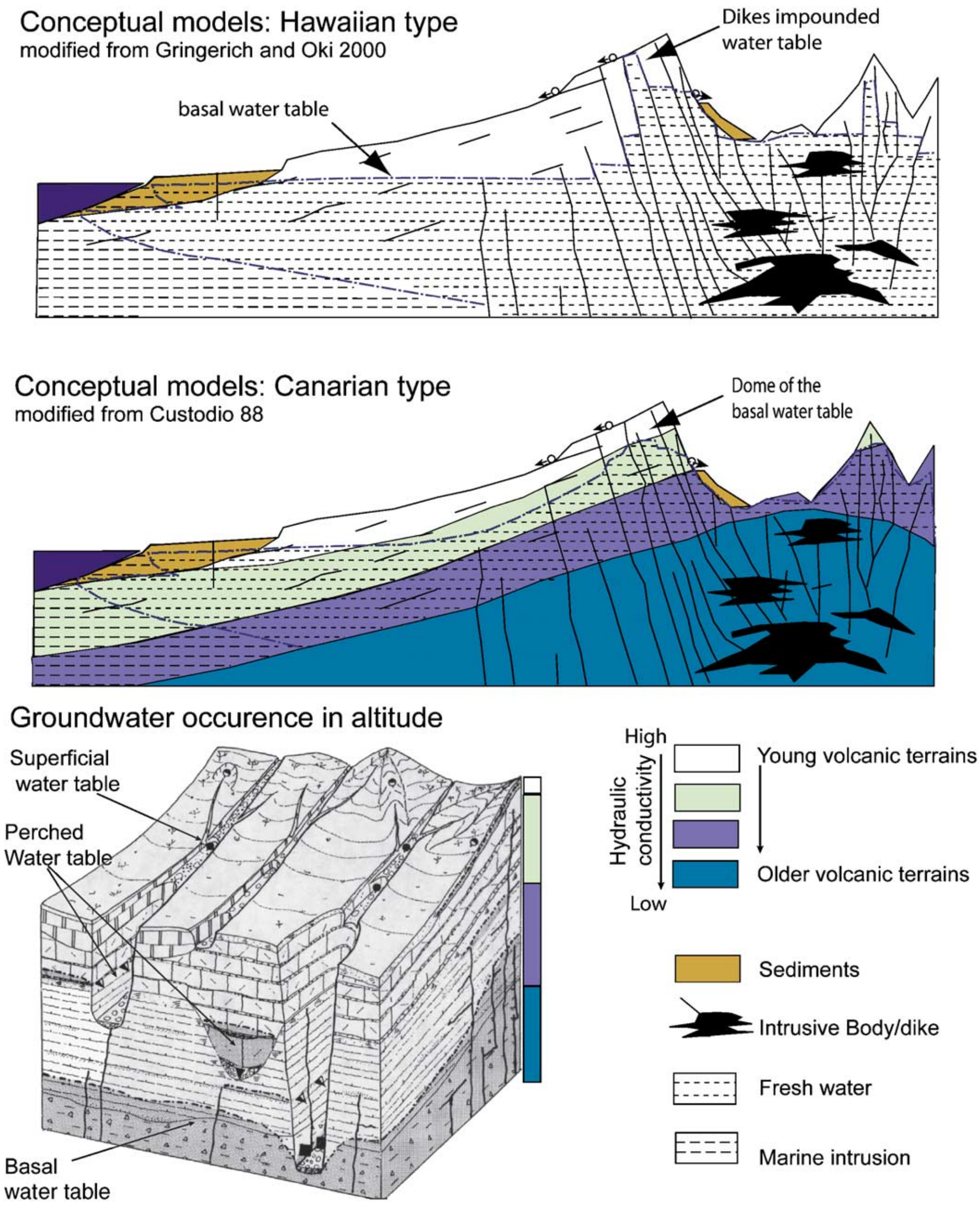


Fig. 2. Conceptual models of groundwater in volcanoes.

island (Join et al., 1997). Altogether, the sampled springs of Piton de la Fournaise massif correspond to low temperature and slightly mineralized freshwater.

To improve a new conceptual model of groundwater in Reunion Island, the authors suggest taking into account a progressive decrease of hydraulic conductivity, between the surface and the deepest terrains. Folio et al. (1999) point out that the determination of hydraulic conductivity distribution in the Piton de la Fournaise volcano is critical in establishing a model of its groundwater circulation.

## 4. Hydrogeological investigation of the Fournaise volcano

The sizeable depth (several hundred meters) of the water level in the interior of the island precludes the use of drilling as a prospecting method. Indirect methods are therefore to be used, and geophysical surveys were thus conducted. Additional works, such as detail geological and hydrological surveys of specific zones or field measurements of the hydraulic conductivity, have been carried out (Folio, 2001).

### 4.1. Structural investigation

Building a hydrogeological model on the scale of a volcanic edifice requires a preliminary structural

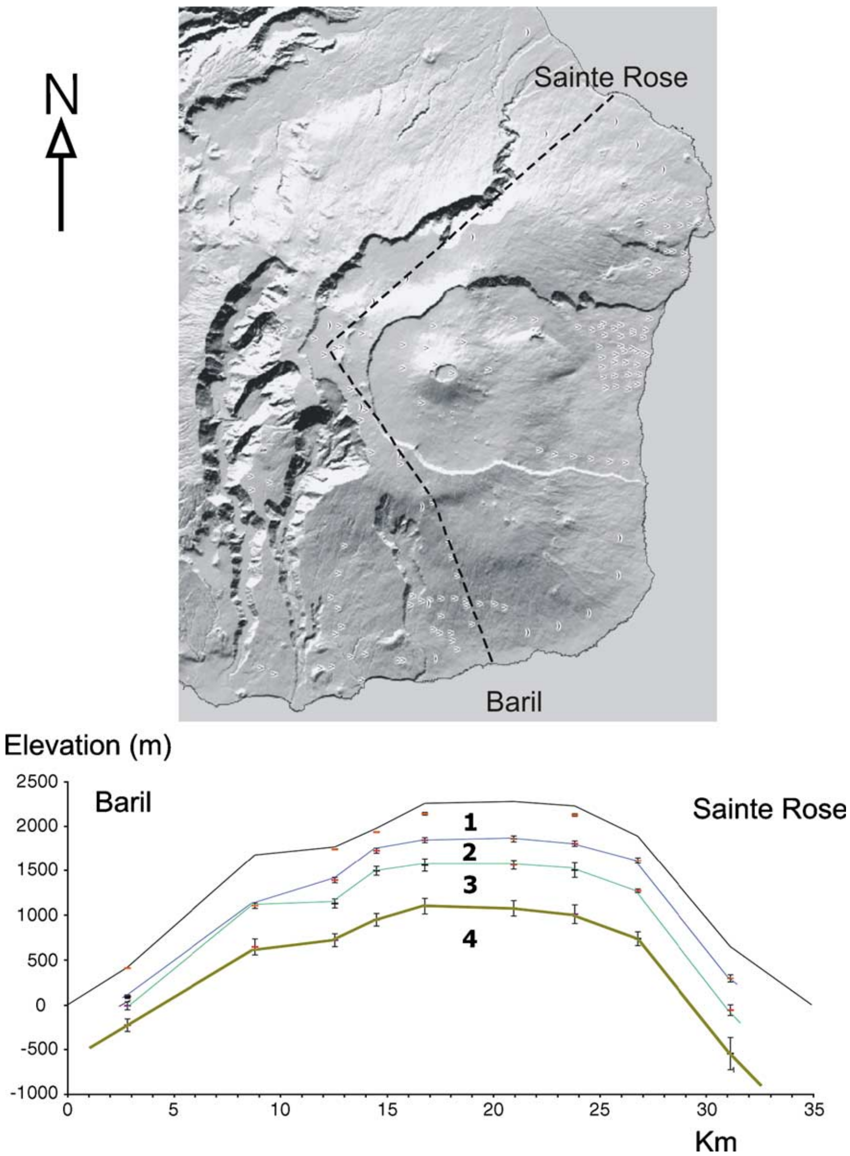


Fig. 3. Geoelectrical structure inferred from EM soundings. Map—dot: EM station; dashed line: geoelectrical cross section. Cross section—1: 2000 to 10,000 Ω m; 2: 100 to 900 Ω m; 3: less than 100 Ω m; 4: conductive basement (less than 10 Ω m).

and volcanological model. Courteaud et al. (1997) and Folio et al. (2000) have demonstrated the capability of electromagnetic (EM) methods in determining the depth of the water saturated zone at Piton de la Fournaise. Several EM methods have been applied (MT, AMT, CSAMT, TEM) for a total of more than 200 EM soundings in the last 10 years over the entire Piton de la Fournaise massif (Fig. 3). A synthesis of these EM surveys (Courteaud et al., 1997; Lenat et al., 2000; Folio, 2001), combined with new geological data, is used to provide reliable information—as to the geological structures, the extent of low permeability layers and, in some cases, the location of water tables. Comparisons between the geoelectric layers and the lithologic logs exposed in the deep valleys walls are in overall accordance. The following four-layer model summarizes the general geoelectrical pattern of the Piton de la Fournaise massif (Fig. 3):

1. A resistive surface layer (2000 to 10,000 Ω m; values typical for dry basaltic rocks) is identified as the recent, unsaturated volcanic series (Unit III and Unit IV).
2. A moderately resistive layer (100 to 900 Ω m) is interpreted as the water saturated zone in the upper volcanic series.
3. A conductive layer (<100 Ω m) corresponds to the top of the saturated old volcanic series (Unit II and Unit I).
4. A highly conductive saturated basement (<10 Ω m) not observed at the surface.

The lithology of this conductive basement has been discussed by several authors (Courteaud et al., 1997; Lenat et al., 2000). Hoareau (2001), on the basis of a petrological study of the oldest formations of Piton des Neiges, establishes the correlation between the conductive basement and the hydrothermal alteration front within subaerial lava flows.

From this geoelectrical information, we have extracted the inferred structural interfaces, regrouping the first and second layers, to evaluate the 3D geometry of the geological units. The inferred water saturated interface (between the first and second layers) constitutes the hydrogeological information to be compared to the results of the simulation.

### *4.2. Hydraulic conductivity distribution*

The hydraulic data, derived from pumping tests on existing boreholes, characterize the hydraulic properties of the younger volcanics (Unit III and Unit IV) that constitute most of the coastal aquifer. Hydraulic conductivity, $K=1\cdot 10^{-2}$ m/s, represents an average value for the two youngest units of the volcano. Farther inland, the hydraulic characteristics of the deep formations of the Piton de la Fournaise massif are virtually unknown. The few borehole hydraulic tests available show conductivity values significantly lower than those delivered by pumping tests in the coastal areas. This indicates a genuine decrease of permeability with depth. This is also consistent with the decrease of resistivity in geoelectrical models. To confirm this distribution of hydraulic conductivity, field surveys have been conducted in the deepest formations. They have been carried out on outcrops on the walls of the deepest valleys of Piton de la Fournaise. Such walls form natural cross sections, exposing more than 500,000 years of the geological history of the volcano. The permeability of the massive part of a lava flow on these outcrops is estimated from statistical analysis of the cooling fractures and its translation in the equivalent porous media (Khaleel, 1989; Folio et al., 1999). The permeability of the scoriaceous interlayers is estimated using a mini gaz permeameter (Folio et al., 1999; Folio, 2001). More than 400 in situ measurements on 17 different outcrops show that for both massive lava flows ($k_L$) and scoria ($k_{Sc}$), data remains roughly homogeneous, at the scale of a pile of lava flow, in the same volcanic unit. The global hydraulic conductivity of a porous equivalent medium of the pile of massive lava and scoria is estimated using algebraic estimators, valid for layered media:

$$\mathrm{Kh}_{eq} = \frac{E_{Sc}K_{Sc} + E_L \mathrm{Kh}_L}{E_{Sc} + E_L}$$

$$\mathrm{Kv}_{eq} = \frac{E_{Sc}K_{Sc} \times E_L \mathrm{Kv}_L}{(K_{Sc}E_L) + (\mathrm{Kv}_L E_{Sc})}$$

where: $\mathrm{Kh}_{eq}$ = horizontal hydraulic conductivity, $\mathrm{Kv}_{eq}$ = vertical hydraulic conductivity, $K_{Sc}$ = isotropic hydraulic conductivity of scoria interlayers,

Table 1
Evaluation of hydraulic conductivity in the oldest units of Piton de la Fournaise (from Folio et al., 1999; Folio, 2001)

| Parameters | Unit I | Unit II | Units III and IV |
|---|---|---|---|
| $Kh_L$ 1 (m/s) | $10^{-4}$ | $10^{-4}$ | $10^{-2}$ (average value from pumping test) |
| $Kv_L$ 1 (m/s) | $2 \cdot 10^{-4}$ | $2 \cdot 10^{-4}$ | |
| $K_s$ (m/s) | $10^{-7}$–$10^{-5}$ | $10^{-4}$–$10^{-3}$ | |
| $Kh_{eq}$ (m/s) | $5 \cdot 10^{-5}$–$8 \cdot 10^{-5}$ | $10^{-4}$–$3 \cdot 10^{-4}$ | |
| $Kv_{eq}$ (m/s) | $4 \cdot 10^{-7}$–$4 \cdot 10^{-5}$ | $2 \cdot 10^{-4}$ | |
| Model values | $10^{-6}$ | $10^{-4}$ | $10^{-2}$ |

$Kh_L$=horizontal hydraulic conductivity of lava flows, $Kv_L$=vertical hydraulic conductivity of massive lava flow, $E_{Sc}$=average thickness of scoria inter layers (0.6 m), $E_L$=average thickness of massive lava flow layers (2–2.25 m).

The results are given for Unit I and Unit II (Table 1).

Despite the uncertainty of this estimation, a drastic decrease of the hydraulic conductivity in the oldest units of Piton de la Fournaise volcano is obvious. It is assumed that the volcanic units can be considered as homogeneous hydrological layers, with a reasonable estimation of the conductivity in the modeling process.

### 4.3. Regional water balance appraisal

In order to enhance knowledge of the hydrology of the area, the initial rain gauge network, managed by the national meteorological survey (Météo France), was expanded by adding new rainfall recording stations (Barcelo and Coudray, 1996). Atmospheric and topographic elements influencing spatial rainfall variations were thus better constrained and a new isohyet map has been proposed. Moreover, hydrometric equipment, set up on experimental watersheds, have contributed in improving water balance and infiltration rates on the volcano flanks. This hydrological study provides a new assessment of the water budget of Piton de la Fournaise (Barcelo, 1996), developing a new cartography of annual infiltration rates on the volcano. The total precipitation is estimated at approximately 2300 $Mm^3$/year and the estimated total annual groundwater recharge is approximately 68 $m^3$/s.

## 5. Groundwater modeling

### 5.1. Geometry

In the study area, the elevation varies from 0 to 2300 m a.s.l. and the Piton de la Fournaise volcano has an average surface slope of 15%. Water tables inferred from geophysical soundings show a rising piezometric gradient in the central part of the massif. This implies a strong vertical component in the flow of the groundwater. Therefore, a three-dimensional (3D) groundwater flow model is needed to compute flow and pressure levels in the Piton de la Fournaise massif. The modeling is accomplished by using the Femwater code (Yeh, 1987), a 3D density-driven, flow and transport model, of both saturated and unsaturated finite elements. A graphical interface, GMS (Owen et al., 1996), is used with the Femwater program for pre and post processing. The groundwater flow is computed for an unconfined aquifer in steady-state condition.

The geometry of the model is determined by taking into consideration (i) the geometry of the volcanic series interpolated from geophysical interpretation and (ii) the volcano-structural scenario as defined by Chevallier and Bachèlery (1981) and Bachèlery and Montaggioni (1983), refined by Bachèlery and Mairine (1990) and Courteaud et al. (1997). The lower layer of the model corresponds to a conductive basement, the extension of which can be generalized to the whole massif of Piton de la Fournaise. This geoelectrical basement, interpreted as a hydrothermal alteration front, is developed principally in the volcanic unit I. Landward, the top of this basement rises more or less regularly until it reaches an average altitude of +1500 m a.s.l., beneath the Plaine des Sables. The 3D mesh is realized using spatially extrapolated synthetic cross sections, taking into account the main structural features, e.g. the inferred downthrow of caldera faults. The average thickness of the main volcano-structural units within this framework is presented in Table 2.

The volume to be modeled is discretized in 15,782 elements with 9534 nodes corresponding approximately to a 1 mm planar cell size of the mesh. The volcano-structural units are chosen as the hydrogeological layers of the model (Fig. 4).

Table 2
Average thickness of volcano-structural units

| | Thickness within the caldera | Thickness outside of the caldera |
|---|---|---|
| Unit IV | 150 m | 50 to 100 m (Grand Brûlé) |
| Unit III | 300 m | 50 to 100 m |
| Unit II | 400 to 500 m | 200 to 400 m |
| Unit I | Vary with the position of the hydrothermal alteration front | |

Due to numerical instability, the estimated anisotropy of hydraulic conductivity has not been taken into account in this simulation. An average value for isotropic hydraulic conductivity is defined and the following conductivity values are assigned: $1 \cdot 10^{-2}$ to Units III and IV, $1 \cdot 10^{-4}$ to Unit II, $1 \cdot 10^{-6}$ to Unit I and $1 \cdot 10^{-7}$ m s$^{-1}$ to the base layer. We were not able to take into account the role of dikes in local changes in permeability. Depending on their orientation, dikes can act as barriers, capable of confining groundwater locally (Peterson, 1972; Bret et al., 2000). Note also that the low hydraulic conductivity value of the basement is arbitrary, since this layer has never been observed either on outcrop or in boreholes. Nevertheless, several authors (Courteaud et al., 1997; Lenat et al., 2000) assume this layer constitutes a low permeability substratum for groundwater.

### 5.2. Boundary conditions

On the modeled domain, groundwater recharge is assigned as a Neumann type flux boundary condition. The average yearly infiltration rate is distributed into multiple homogeneous recharge zones. This subdivision of the domain area is made according to the isohyet map, combined with the annual infiltration coefficient distribution map proposed by Barcelo (1996) over the entire massif of the Piton de la Fournaise volcano. Due to the existence of heavy, episodic rainfall and to the presence of highly permeable subsurface volcanic formations, the infiltration rate is of major importance. In the study area, this parameter varies from 1000 mm year$^{-1}$ to more than 10 000 mm year$^{-1}$ (Folio, 2001).

Because of the size of the domain and in order to simplify the resolution of the flow problem, the model does not take into consideration density driven flow, to simulate the seawater intrusion on the coastal boundary. Nevertheless, the Ghyben Herzberg conditions have been accounted for, assigning to the ocean exit face the apparent freshwater transmissivity that corresponds to the freshwater thickness (density) observed in coastal areas. By so doing, it is assumed that the interface of seawater acts essentially as an impermeable flow barrier, and the discharge faces of the model have been restricted to the depth of the freshwater–saltwater interface. The discharge zones therefore have a thickness of 100 m, a value that is consistent with the average depth of the freshwater–saltwater interface observed in coastal boreholes or prospected by geophysical methods (Folio, 2001; Albouy et al., 2001; Robineau et al., 1997). Dirichlet boundary conditions correspond to a specified head condition of 0 m a.s.l. assigned to nodes belonging to these exit faces. Custodio et al. (1988), while modeling the volcanic island of Tenerife, show that this approximation introduces a negligible error with regard to t inland piezometric gradients.

The remaining boundaries on the west side of the modeled domain correspond to a specified head boundary provided by the cell's altitude, which corresponds to the bordering streams of Riviere de l'Est, Riviere Langevin, and upper tributaries of Rivière des Remparts (Fig. 4).

## 6. Results and discussion

The simulation provides a steady-state flow model of the Piton de la Fournaise massif. It describes the groundwater flow constrained by (i) the spatial repartition of mean annual infiltration rates, (ii) the hydraulic conductivity distribution and (iii) the outlet boundaries corresponding to specified heads. In the absence of calibration procedures and sensitivity tests specific to the classical operational groundwater models, this simulation does not claim to be a forecasting tool for groundwater resource management. Our objective is to present the hydraulic behavior of the massif, compatible with up-to-date hydrogeological assumptions.

The computed solution provides a simulated groundwater pressure and velocity for each node of

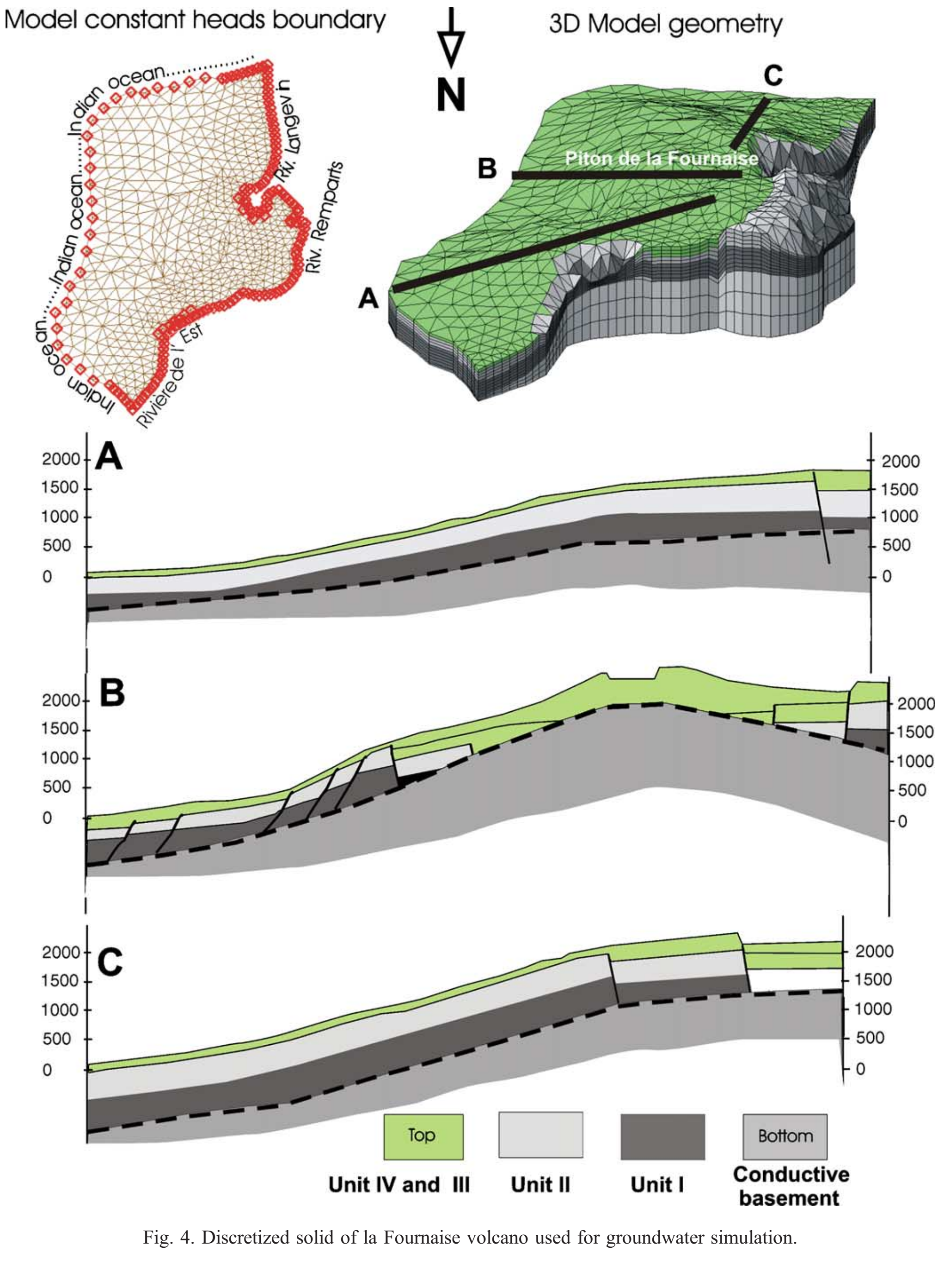


Fig. 4. Discretized solid of la Fournaise volcano used for groundwater simulation.

the 3D mesh. These values are used to define the distribution of groundwater flux within the volcano. The analysis of the flow velocity distribution reveals two modes. The first forms a homogeneous group corresponding to the velocities in the upper units ($1 \cdot 10^{-5}$ to $7 \cdot 10^{-5}$ m/s). Velocities in the second group are more dispersed, but still very low, varying from $1 \cdot 10^{-11}$ to $1 \cdot 10^{-7}$ m/s and correspond to groundwater flows in the low permeability substratum. As a consequence, most of the groundwater flow occurs in the upper layers.

The map of simulated piezometric contours is in accordance with the water level contours of the saturated zone inferred from geophysical soundings (Fig. 5).

Piezometric heads reach 1800 m a.s.l. in the vicinity of the volcano summit. In the coastal zone, low hydraulic gradients conform with those observed at existing boreholes. The extension of this flat water table appears limited to a coastal fringe approximately 2 km wide. When one moves towards the core of the volcano, the hydraulic gradient increases proportionally with altitude. In general, the middle high external slopes of the volcano correspond to zones of high hydraulic gradients.

In cross section, the pressure head distribution reveals interesting results: (i) the vertical component of the flow increases near the summit zone, (ii) in the vicinity of the summit, the water level remains beneath the top of the low permeability basement (Fig. 5).

The distribution of model simulated discharges is compared to the location of the main springs of the massif (Fig. 6). The major discharge points of the model are in accordance with the known subaerial and submarine coastal springs. On the western edge of the volcano, the simulated water table is mostly drained in the upstream part of the large rivers. On the right bank of the Rivière de l'Est, the significant simulated outflow corresponds precisely to a group of large springs that are tapped as electrical power sources. In the Langevin River, principal simulated outflows are equally well-correlated with the main springs of this area. This confirms that the simulated high water level can explain the occurrence of large springs on the steep banks of rivers that drain the volcano.

The analogy between computed outflow flux vectors and springs exists on the coast as well. The model simulated outflows correspond nicely to the principal marine springs, evidenced by infrared thermography (Coudray et al., 1990). The "Grand Brulé" area, in the collapse area, is confirmed as a major outlet for groundwater. The sector is filled by the youngest, highly conductive lava flows, which act as a drain for groundwater. On the other hand, a clear diminution of groundwater outflow is observed in the sectors of "Sainte Rose" and "Saint Philippe". In our model, this result is namely a consequence of topographic watersheds inducing groundwater divides (Fig. 6). Chevallier and Bachèlery (1981) describe these sectors as an effect of rift zone processes. In this case, further appraisal of conductivity decrease, due to magma injection, will obviously enhance this simulated trend.

It therefore appears that our general model, taking into account the main geological structures and reasonable estimations of infiltration and hydraulic properties, is suitable to explain the main observed features of the groundwater flow on the scale of the massif.

The resulting conceptual model bears similarity with the one proposed by Custodio et al. (1988) for the Teide volcano (Canary Islands). The main difference with previous models for Piton de la Fournaise is that this model implies the presence of a continuous water table rising in dome-like geometry, in the center of the edifice. Comparable hydrogeological patterns have been recognized in several other oceanic volcanoes, such as Karthala in the Comoros archipelago (Savin et al., 2001), Mauritius Island (Join et al., 2000), Pico Island in the Azores archipelago (Cruz and Silva, 2001), or on the Hawaiian archipelago (Izuka and Gingerich, 2003).

From a general point of view, our new model, defined for the active volcano of Piton de la Fournaise, leads us to a conceptual model that is very close to the one previously validated in much older volcanic systems, as in the Canaries (Custodio, 1989). Hence, we may suggest a flow pattern continuum, from the active to the oldest oceanic volcanoes, forming high islands. In fact, the main differences between the old and the young systems lie (i) in the permeability range of the different volcano units, (ii) in the thickness of non-saturated volcanic terrains, and (iii) in the contrast between the hydraulic conductivity of the altered core system and that of more recent volcanic layers. The regional water table, becoming progressively higher and smoother, may perhaps best illustrate the hydrologeologic evolution as a function of an increasing alteration of the massif. In the long run, the water table comes closer to the surface whereas erosion and landslides simultaneously reduce the relief (Bret et al., 2003). The groundwater system itself can play a major role in these processes. As we

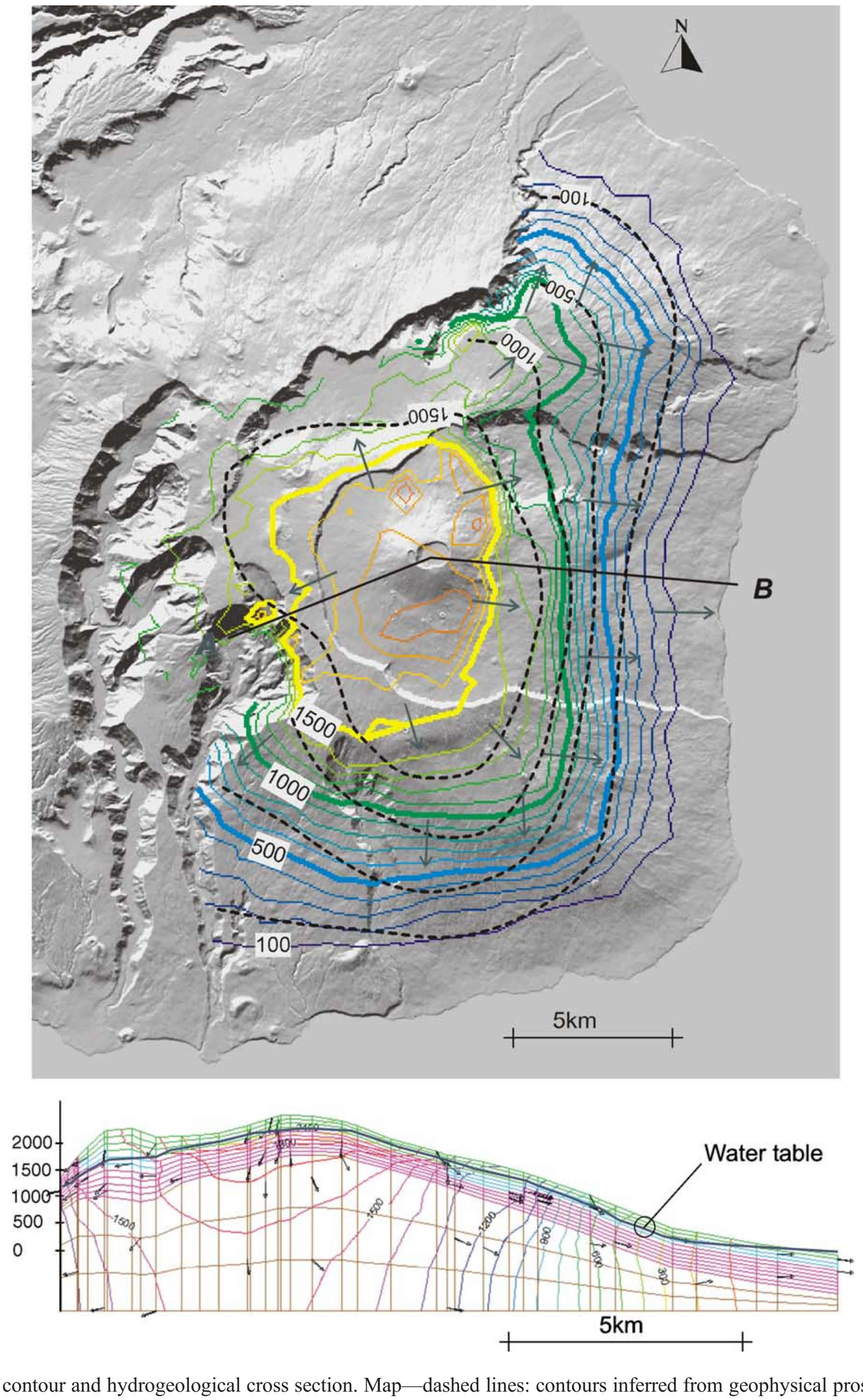


Fig. 5. Piezometric contour and hydrogeological cross section. Map—dashed lines: contours inferred from geophysical prospecting; grey lines: simulated piezometric contours. Cross section—arrow: groundwater flow direction; labelled lines: pressure head in meter.

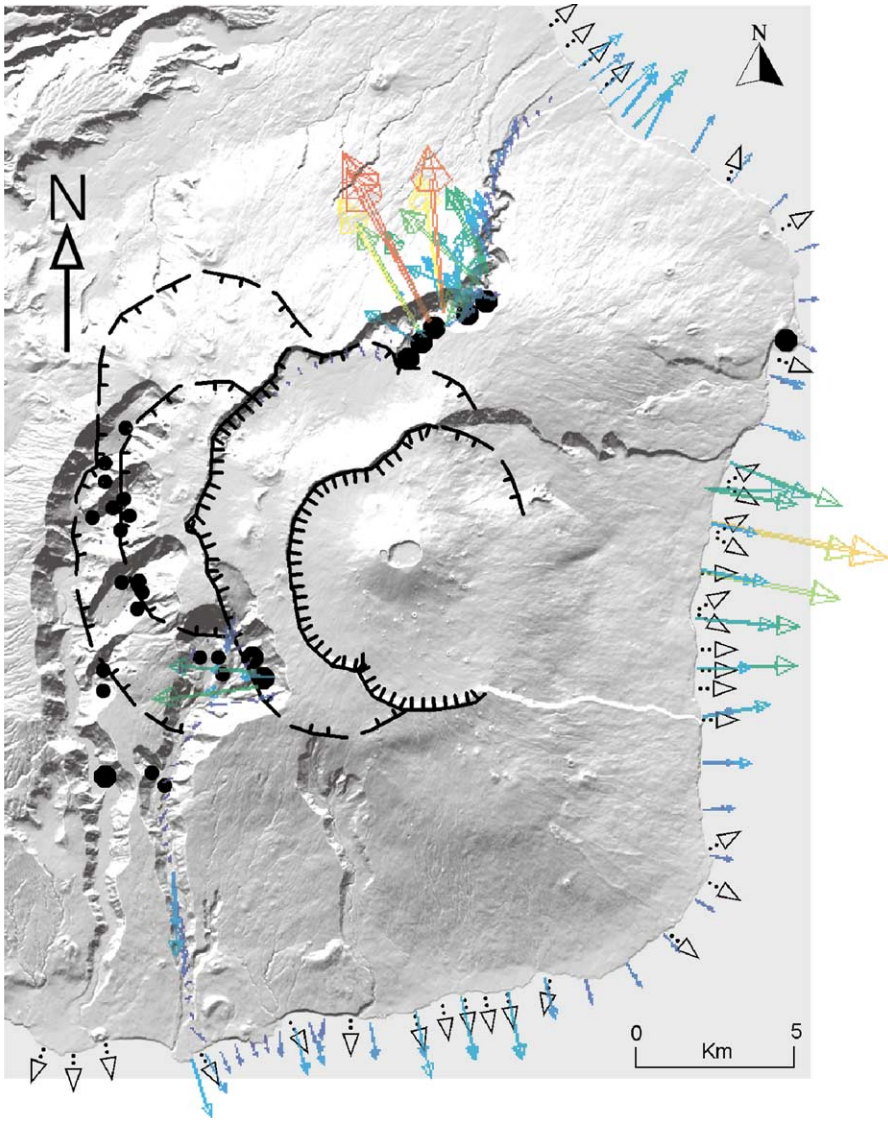


Fig. 6. Outflow distribution model and field observation. Dot: identified springs (size is proportional to discharge); shaded arrows: computed outflow (size and shade proportional to discharge); black arrows: infrared traces of marine springs.

have shown in this simulation, the morphology of the water table represents the base level for the main river drainage system. Below the saturation level, water pressure increases in low permeability terrains and may significantly contribute to the physical conditions that are favorable in triggering landslides (Iverson, 1995). Thus the determination of the saturation level is critical in assessing the mechanical state of the interior of volcanoes.

## 7. Conclusion

Previous multidisciplinary investigations of the Piton de la Fournaise massif have produced a fairly good estimation of the groundwater recharge distribution, the 3D geometry of the main volcanic units, and their hydraulic properties. By using these three sources of data and considering the constant head boundary of the volcano, a first direct modeling approach has been applied in order to test the hydraulic behavior of our most recent geological view of the entire massif.

According to the pseudo layered 3D structure as proposed by the volcanologists working on the Piton de la Fournaise volcano, the simulation provides a physical solution for groundwater flow that supports the concept of a single groundwater system within a shield volcano. As main result, the computed water heads define the general shapes of the water table: very flat near the coast, the water table forms, in the central part, a dome rising 1800 m asl. Despite the lack of any calibration procedure, this "one step" simulation appears to be consistent with both the geophysically inferred water table and the main recognized springs of the massif.

Up to now, according to conventional Hawaiian conceptual models, the occurrence of high water levels at Piton de la Fournaise was interpreted as disconnected groundwater bodies impounded by dikes or perched on local impervious layers. This study demonstrates that the geological structure of such active shield volcano provides sufficient hydrogeologic conditions to produce a high water table in the interior of the island. This general shape can be obviously enhanced by low permeability barriers such as magma intrusions. A sharp appraisal of hydraulic characters and the geometrical extension of local discontinuities presents a new challenge for us to go further in validating a volcanologic groundwater model. In fact, this simulation does not act as a predictive water resource tool, but the concept of a continuous groundwater body within the massif provides a new framework for our physical approach towards understanding the role of groundwater in shield volcanoes. Namely, this concerns the assessment of the conditions of equilibrium for various dynamic processes (phreatic eruption, mass landslides), depending on the water content and on the hydrostatic pressure.

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