Geophysical characterization and numerical modelling of the summit hydrothermal system of Stromboli volcano, Aeolian islands, Italy.

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Abstract :
The characterization of convective circulations in natural media is a major concern for geothermal industry.
The present study aims at characterizing hydrothermal circulations, in active volcanic environments (summit hydrothermal system of Stromboli volcano). Two approaches are initiated: (1) mapping the convective circulations with geophysical methods and (2) quantify the heat released using numerical simulations.
The methodology used in the study consists of a geophysical characterization in the field – measurements of self potential (SP), temperature (T) at 30 cm depth, CO_2 flux and Electrical Resistivity Tomography (ERT) measurements and numerical modelling of thermal convection in fractured porous media where fractures are considered as discrete objects.
To understand the role of such structural boundaries on the flow (velocity, heat flux), a numerical approach is developed for the analysis of natural thermal convection in discrete fractured porous media in 3D setting. This approach is an extension of that previously used for the study of transport properties of fractured porous media [Bogdanov et al. 2003]. The influence of the fracture density and fracture transmissivity on the heat transfer and on the behaviour of the convective field is investigated. The results are compared with simulations in homogeneous porous media with corresponding effective transport characteristics, in order to validate the approach of effective properties in determining of the heat evacuated by the active system. Indeed, the effective approach is numerically cost-effective, but as the comparison of models shows, it is efficient only in a limited number of situations.
In the near future, we hope to integrate all assumptions deduced from geophysical prospecting in a 3D thermal convection model of Stromboli.

Introduction :
The presented study is focused on the summit hydrothermal system of Stromboli volcano. This hydrothermal system has already been emphasized by several studies (Finizola et al. 2002, Finizola et al. 2003, Revil et al. 2004). All these studies attest the presence of an active hydrothermal system. A preferential pathway for up flowing fluids is also brought out, around a structural limit : the upper part of the Rina Grande sector collapse, forming the crest of the studied area (Figure 1).
The dataset designed for the characterization of this system is composed of 13 profiles of self potential (SP) measurements, Temperature (T) at 30 cm depth, CO_2 flux and Electrical Resistivity Tomography (ERT) measurements.
In the first section we present the dataset. The second section is dedicated to the ERT models and all the added value we can provide for the accuracy of such models. The final section will present preliminary results in fractured porous media, and the outlooks we hope to implement for the characterization of such hydrothermal systems.

Acquisition :
11 ERT profiles were achieved with a 5 m spacing between electrodes, and the 2 others profiles, with a 2 m spacing. All in situ measurements (SP, T and CO2 flux), were performed using 2.5 m and 1 m spacing during three different field campaigns occurring in May 2006, May 2008 and May 2013.

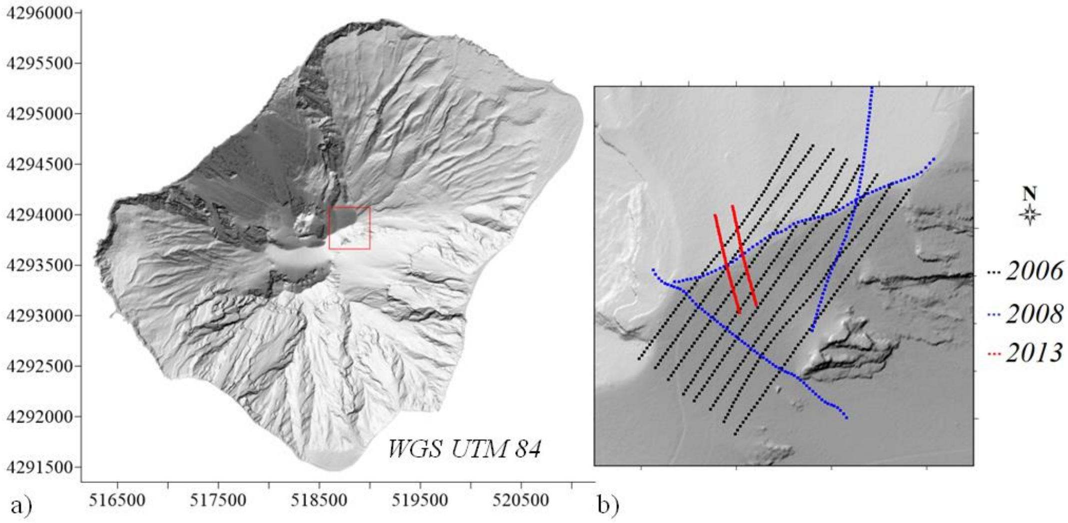

Figure 1 : a) Stromboli island, the area of interest is surrounded in red . b) Zoom on the area of interest and location of the 13 geophysical profiles.

As it is shown on Figure 1, the profiles are disposed along particular directions (parallel or cutting structural boundaries) and are located on an area of steep slopes. These reasons lead us to use an ERT inversion code (ERESI, [Fargier, 2011]) able to take into account topography and non-gridded profiles. Results obtained with this code are presented in the next section.

3D ERT models :

It is obvious that the more the dataset is complete, the more the model is constrained. However, inversing simultaneously field campaigns occurring at different time may also produce some artefacts in models. In order to reduce possible artefacts, we propose to compare the simultaneous inversion, to a cascade inversion.

Cascade inversion is a new procedure we opt for, allowing to combine without amalgam every measurement. In other words, we take the inverse model of one campaign, and use it as the initial model for the inversion of the next campaign.

First we present this procedure using synthetic case (not shown here) to show the accuracy of the method. We simulate a cone shaped volcano with a hydrothermal system (more conductive cylinder below the summit). A first hypothetical field campaign is achieved in the dry season, and the second one, right after a raining event, causing a surface layer more conductive. We then inverse simultaneously the two profiles, and in a second time, we inverse them following the cascade procedure.

The simultaneous inversion is clearly not able to take into account the complexity of the dataset, unlike the cascade inversion which reproduces correctly the internal structure of the volcano.

It is important to note, that the RMS error for both models is equivalent, even if the models are obviously different.

Thus, we propose other quality criterion for real model, as DOI (Depth of investigation (Oldenburg and Li, 1999).

Figure 2 shows the 3D resistivity model of 2008 field campaign. The 2008 cascade inversion was made using the 3D resistivity model of 2006 as the initial model.

We can see that major differences are located in areas constrained by the 2006 acquisition and not by the 2008 acquisition (Figure 1). Resistivities beneath 2008 profiles are quite equivalent, which is not the case between profiles. Note that the RMS error of the cascade inversion is

5.3% and 8.9% for the regular inversion, but the cascade inversion takes into account four times more inversion parameters.

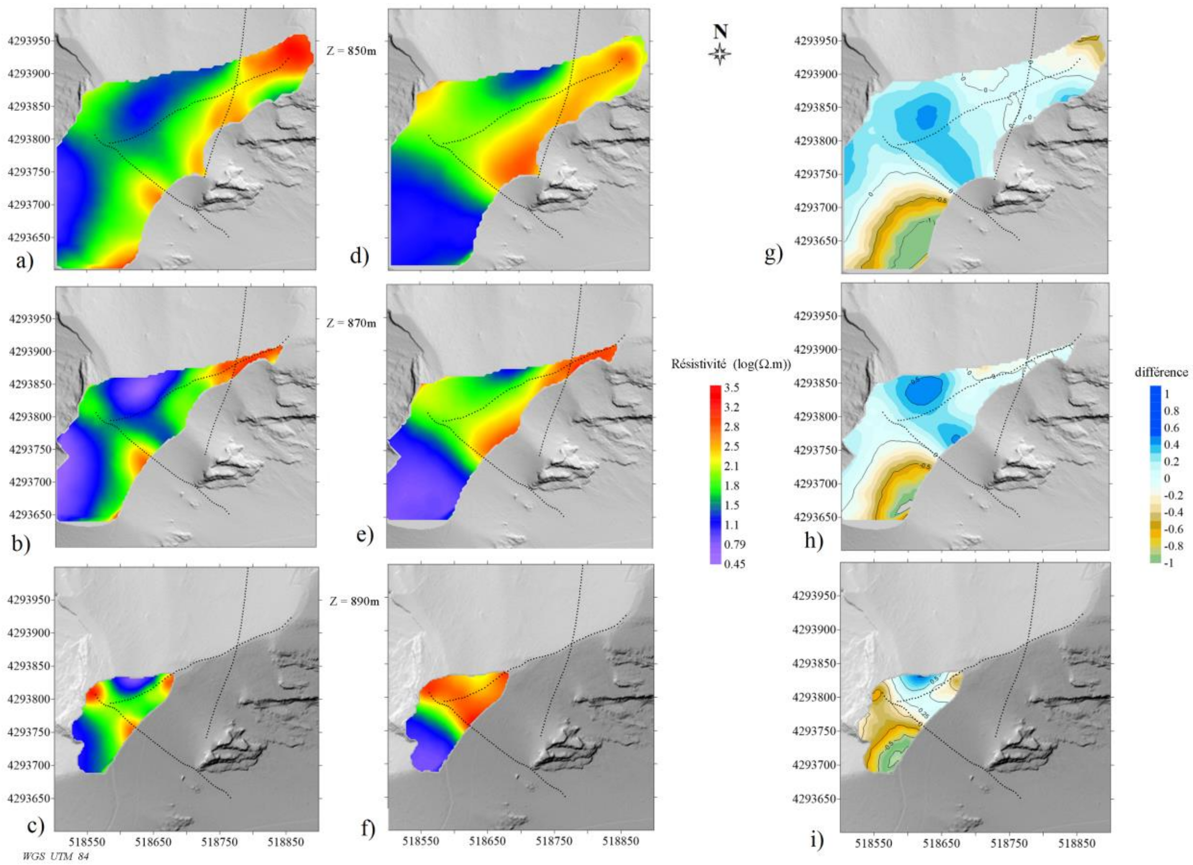

Figure 2 : Horizontal slides of the 3D resistivity model of 2008: a, b and c represent the cascade inversion (2006 model provides the initial model) at 850 m, 870 m and 890 m a.s.l., respectively. d, e and f represents the model for the regular inversion of the 2008 campaign at the same depth. g, h and i represent the normalized difference between the cascade and the simultaneous inversion.

The more conductive areas are associated with porous medium with hot fluids saturating (at least partially) the pores, and resistive areas are associated with porous medium with air filling the pores.

Simulation of natural convection in discretely fractured media:

All these geophysical measurements provide useful informations for the location of up flowing fluids. In order to give a quantitative dimension to these results, we simulate natural thermal convection in fractured porous medium.

It is obvious that the simulation of discrete fractures networks is expensive in terms of computation time. That is why this work is focusing on the accuracy of the model of homogeneous porous medium with transport properties equivalent to those of the fractured porous one.

We focus on the influence of the fracture density (Figure 3) and fracture transmissivity on the output heat flux, characterized by Nusselt number (Nu). For each sample of fractured porous medium two effective characteristics – medium permeability and thermal conductivity – are evaluated numerically. The simulations results are compared to those obtained with models with homogeneous porous medium, described by these effective parameters in order to determinate, in which cases these models can provide reliable predictions.

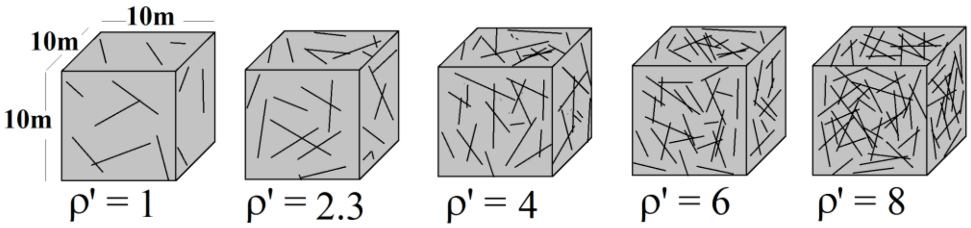

Figure 3 : Schematic view of differently fractured porous medium

Preliminary results show two behaviours displayed in Figure 4: (1) the output flux growth logarithmically with respect to the fracture transmissivity (Figure 4.b), and (2) the predictions of the homogeneous medium approach seem to be satisfactory for poorly fractured media and for highly fractured systems (Figure 4.a). As it can be seen in Figure 3.a, in isotropic systems moderately fractured, the difference between the discrete and the homogeneous approach is less than 20%.

These two observations are quite intuitive, but to our knowledge have not been described in literature, probably because only few studies treat isotropic fractured network.

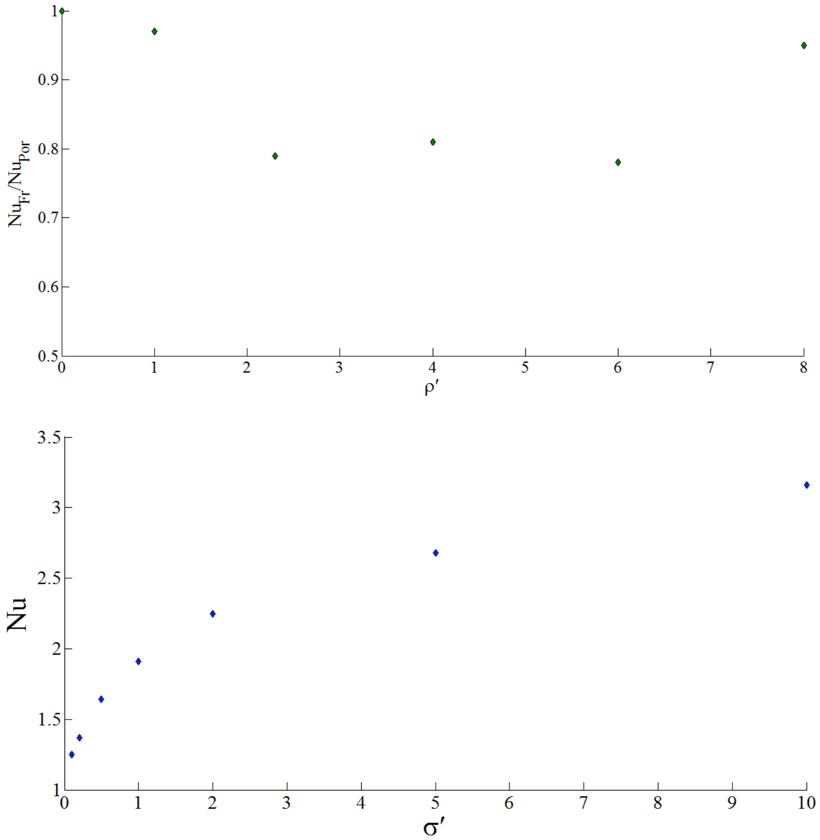

Figure 4 : a) Nu in fractured porous medium normalized to Nu in porous medium of the same effective properties as a function of the adimensionnal density of fractures. b) Nu in fractured porous medium as a function of the adimensionnal transmissivity of the fractures for a network of ρ' = 4, the Ra_{mat} is the same in every simulations.

Conclusions :

Using cascade procedure, ERESI seems more able to incorporate huge dataset of several fields campaigns in steep areas. By combining ERT models to sub-surface geophysical measurements, we hope to produce a sufficiently constrained 3D model of the hydrothermal system of Stromboli, to be inserted in a model of thermal convection.

Preliminary numerical results of thermal convection in isotropic fractured porous media tend to show that the approach with effective properties of the medium is only valid in a media that are poorly or densely fractured. Sensitivity studies of anisotropic networks are planned for the next months.