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Geoscientific Instrumentation Methods and Data Systems
Discussions

Inner structure of the Puy de Dôme volcano: cross-comparison of geophysical models (ERT, Gravimetry, Muonic Imagery)

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Abstract

Muon imagery of volcanoes and geological structures are presently and actively developed by several groups in the world. It has the potential to provide a 2-D or 3-D density distribution with an accuracy of a few percent. However, at this stage of the development of the method, comparisons with the results from established geophysical methods are necessary to validate its results. An experiment is currently carried out at the Puy de Dôme volcano involving the concurrent acquisition of muon imagery, electrical resistivity (2-D tomography) and gravity survey. Here, we present the preliminary results for the last two methods.

North-south and east-west resistivity sections have been obtained in June 2011 and May 2012. These electric data allow to model of the distribution of the resistivity values down to the base of the dome. The dome and its surroundings are now mapped with more than 300 gravity stations measured during a detailed gravity survey carried out in March and May 2012. The computed Bouguer anomaly can be interpreted by models of the density distribution within the dome. This will be directly comparable with the results from the muon imagery. Our ultimate goal is to derive a model of the dome using the joint interpretation of all the sets of data.

1 Introduction

Puy de Dôme is a 11 000 yr old and 400 m high trachytic dome situated in the central part of La Chaîne des Puys volcanic field (Massif Central, France). Its morphology suggests the presence of two distinct units (Fig. 1), with the second one emplaced in the scar of a sector collapse in the former one (Boivin et al., 2009). Puy de Dôme construction was accompanied and followed by significant fumarolic and hydrothermal activity, as shown by hydrothermal alteration features on summit outcrops. A late phreato-magmatic eruption of weak amplitude marked the end of activity of the dome (Miallier et al., 2010).

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The dual morphology of the volcano is clearly evidenced by the high precision (50 cm resolution) LiDAR survey (Fig. 1).

The ToMuVol (Muon Tomography of Volcanoes) collaboration, involves geological (Laboratoire Magmas et Volcans, LMV) and physical (Laboratoire de Physique Corpusculaire, LPC) researchers and is aimed at developing muon tomography for studying and monitoring volcanoes. The Puy de Dome was selected as an experimental site because of: (1) its geological and morphological characteristics (i.e. simple external shape but probably complex inner structure), (2) its proximity with the laboratories in Clermont-Ferrand and (3) its very good accessibility. In addition to muon imagery, two geophysical surveys have been carried out on the Puy de Dôme: electrical resistivity tomography measurements (June 2011 and May 2012) and a high resolution gravity survey (March and May 2012).

The objective of this work is first to compare models from electrical and gravity measurements, then to compare models from these classical geophysical methods with muonic models and later to define inner structures of the Puy de Dôme volcano and validate the muon approach.

2 Methodology

2.1 Electrical Resistivity Tomography (ERT)

The ERT method provides images of the distribution of electrical properties in the soil. In the case of the Puy de Dôme volcano, field measurements used multi-electrode systems based on a quadripole method that works by injecting an electric current using two electrodes and then measuring the resultant potential with the remaining two electrodes. The injected current generates an electric field that is dependent of the distribution of the ground conductivity. An apparent electrical resistivity is deduced using Ohm laws.

The rock resistivity depends on the fluid content and nature (usually water), the permeability and the alteration of the rocks. Geological interpretations can be ambiguous because different lithologies can have similar resistivities and also because of the non-uniqueness of the models. On the other hand, the resistivity of rocks within a structure such as the studied dome, may vary significantly (several orders of magnitude) and therefore the method has a high potential to differentiate volcanic structures.

Figure 2 shows the location of the electrical acquisition lines. We used an ABEM SAS 4000 system with 64 electrodes with electrode spacing of 35 m for the entire volcano, and 5 m in the summit area. Both Wenner (vertical sensibility) and Wenner-Schlumberger (vertical and horizontal sensibility) protocols were used for the measurements.

Res2Dinv software, developed by Loke (Loke and Barker, 1996), was used to obtain 2-D models. Prior to inversion, the raw data were filtered out. The datasets along each profile comprise the data from both 35 m and 5 m electrode spacing lines and the topography is taken into account.

2.2 High resolution gravity survey

The method allows to map the gravity field variations due to the uneven density distribution in the geological target. We used a Scintrex CG-5 Gravimeter (INSU, CNRS). This instrument measures the relative gravity value between gravity stations. The absolute value was obtained at stations where the absolute gravity value has been previously determined. Station spacing in our survey (Fig. 2) was around 250 m in the distal zone (between 1 and 2 km far from the summit) and 80 m in the proximal zone (1 km around the summit). Absolute gravity bases and secondary bases established during the survey were measured during each daily prospect. Typically, 50 % of the station and base measurements were repeated twice during each prospect in order to have an optimum control on the quality of the data.

For structural prospecting, the interpretation is usually based on the Bouguer anomaly that represents the difference between theoretical values for a homogeneous

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Earth and measured values. It is calculated from gravity data after (1) instrumental and tide drift corrections, (2) theoretical gravity value calculation (or latitude correction), (3) free air correction, (4) plateau correction (depending on density correction value ρ_{cor}) and (5) topography correction (also with ρ_{cor}). This anomaly reflects the density variations in the ground.

3 Results

3.1 Resistivity distribution models of Puy de Dôme volcano

The inversion of the electrical data provides 2-D models of the distribution of the resistivity. The two models shown on figure 3 have an accuracy of 7 % for the north-south section and 20 % for the east-west model. The data from the summit detailed electrical survey (5 m electrode spacing) were added to the 35 m electrode spacing data, thus allowing to obtain a better image of the superficial structures.

The models show a general heterogeneity of the Puy de Dôme. Parts with resistivity higher than 5 kΩ m suggests massive, unaltered or poorly altered rocks of the dome extrusion. Alternatively, they could also be low permeability, dry breccias or pyroclastites. Low resistivity parts ($\rho < 5\,\mathrm{k\Omega\,m}$) probably correspond to wet or intensely altered or brecciated rocks, or rocks containing conductive minerals (clay for example).

Superficial zones with high resistivity values are observed along the Puy de Dôme slopes. These formations have low thickness (tens of meters). Recent geological observations suggest that these structures could be actual lava flows emitted by a summit vent (D. Miallier and P. Boivin, personal communication, 2012).

At the periphery of the Puy de Dôme, high resistivity formations coincide with strombolian cones constituted by trachy-basaltic scoriae (Petit Puy de Dôme, Puy Lacroix).

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3.2 Bouguer anomaly map

The Bouguer anomaly is often correlated with the topography if the density of correction is too different from that of the rocks that create the topography. The Nettleton test determines the correction density that minimises the topography-anomaly correlation (Nettleton, 1939). In the case of the Puy de Dôme, we found that a density correction of $2.0 \times 10^3\,\mathrm{kg\,m^{-3}}$ minimizes the topography-anomaly relation. This value is in good agreement with density measurements made on samples of the Puy de Dôme rocks (D. Miallier, personal communication, 2012, i.e., in the range $1.6–2.2 \times 10^3\,\mathrm{kg\,m^{-3}}$).

The local anomaly was calculated by subtracting a regional component (first degree surface estimate). The resulting residual Bouguer anomaly with a density correction of $2.0 \times 10^3\,\mathrm{kg\,m^{-3}}$ is used for the modelling.

The gravity models were obtained using an inversion package, GROWTH2.0, developed by Camacho et al. (2011). Figure 4 shows density sections of the models of the Puy de Dôme. A high heterogeneity is visible in the volcano structure. A dense core is identified under summit area and is probably rooted bellow 500 m into the volcano. On both sides of this core, low density structures form a ring-like pattern (assuming an axial symmetry). Beneath the lower slopes of Puy de Dôme volcano, we observe formations with low density values that can also be identified in some places with known strombolian cones. These structures are mainly composed of low density scoriaceous material.

4 Discussion

4.1 Comparison of resistivity and density models

The comparison of these two types of geophysical models along the north-south direction (Fig. 5a and b) shows both similar and different structures. Among the similar structures, R10 and R11 (high resistivity) on the one hand and D5 and D3 (low density)

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clearly match with two strombolian cones: the Petit Puy de Dôme at the north and Puy Lacroix towards the south. Inside the dome, the correlation between resistivity and density structures is not clear. Indeed, D1 structure (dense core) has no resistivity equivalent when we would expect that massive intrusions would have both resistivity and density values higher than that of the other deposits such as pyroclastites and breccias. In the case of Puy de Dôme volcano, the correlation between physical properties of rocks and their nature appears to be more complex. In our opinion, the density model is robust enough to interpret D1 as a massive trachytic structure. The variable resistivity of this structure can probably be inferred to fracturing processes that make possible the alteration of rocks by giving way to water and fumaroles circulations. Obviously, the joint comparison of the resistivity and density structures has to be further investigated in the case of the Puy de Dome. For this, we plan to study the physical properties of rock samples from the dome. This will help to understand the resistivity and density structures and will provide robust constraints to compute new geophysical models.

4.2 Comparison of gravity and muonic models

Using Fig. 5b and c we can compare the initial results from muonic imagery with density models obtained from gravity measurements. The Fig. 5c presents a preliminary model of the absorption coefficient distribution of the Puy de Dôme along a north-south section. Such an image integrates the signal of muons crossing the dome along the west-east direction. Since muon attenuation is linearly linked with the rock density, comparisons with the gravity data can be attempted, keeping in mind that Fig. 5b represents a section in a 3-D model and Fig. 5c an image of the muon signal across the dome.

The two models show a dense core located beneath the top of the volcano. This constitutes a strong validation of both methods. For the rest of the dome, where it is well investigated by the muon imagery (i.e. excluding the thick base of the dome where the muon signal is too small), more structures are observed. At this stage, we have not carried out a detailed analysis of these, because the preliminary muon image still needs to be improved. However, we note the preliminary image provides a good insight of the capabilities of the muonic imagery.

In the future, we intend to perform a joint inversion of the gravity and muonic data to obtain better constrained models. This approach has already been applied by Nishiyama et al. (2012) for Mt. Showa-Shinzan lava dome.

5 Conclusions

This study aims to compare different geophysical models: ERT and gravity on the one hand, and a comparison of these methods with muonic tomography on the other hand. Our goal is to develop a method to study the interior of volcanoes with muon tomography alone or with the addition of other conventional geophysical methods.

Our preliminary results on the Puy de Dôme volcano illustrate the complex correlation between different parameters.

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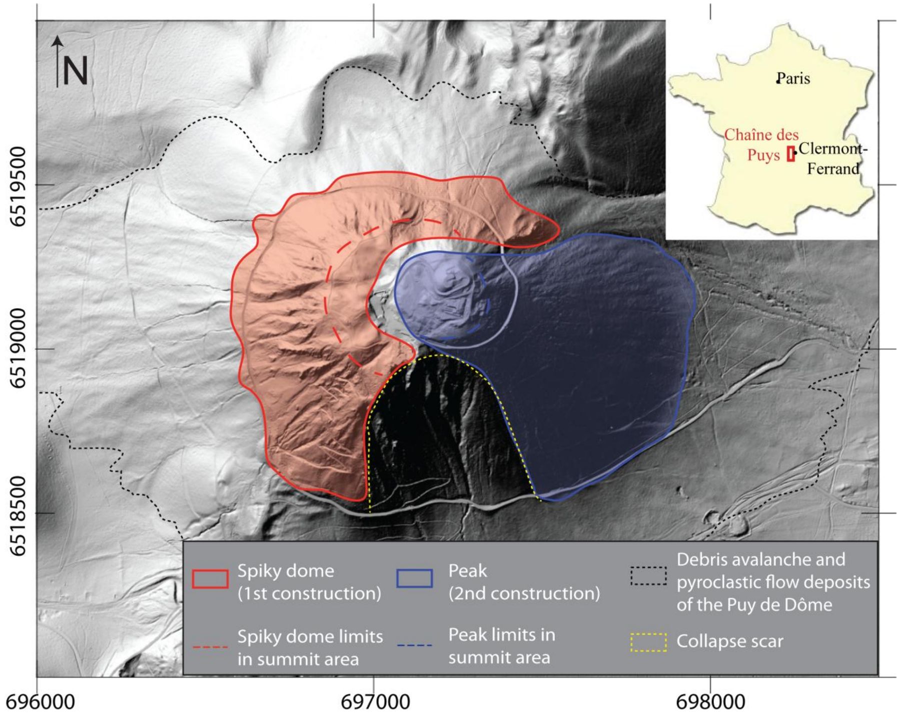

Fig. 1. High resolution LiDAR DEM of the Puy de Dôme (50 cm resolution, CRAIG – GeoPhenix 2011). The two constructional units of the volcano are identified: the first construction is a spiky dome to the west, whereas a peak forms the second construction and its deposits form very regular slopes at the East. A collapse scar is identified in the southern part of the dome.

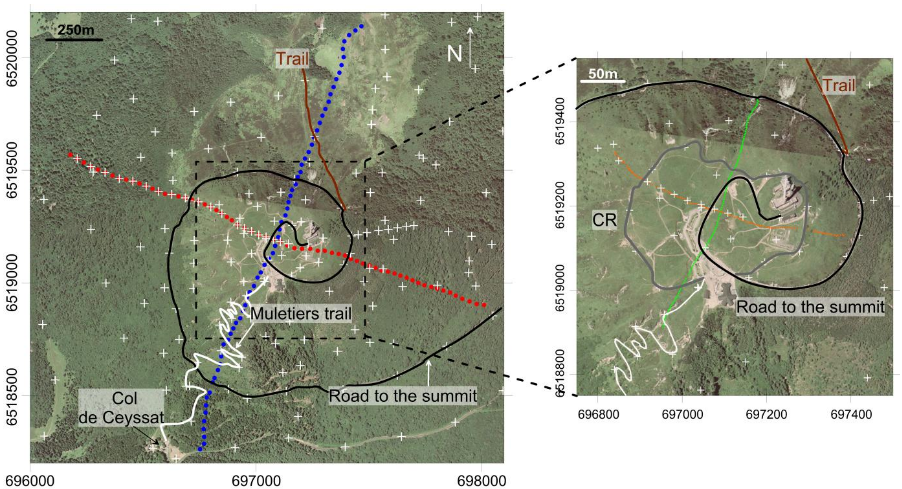

Fig. 2. Location of the ERT lines and gravimetric stations on the Puy de Dôme volcano. (Left panel) ERT lines in N–S direction (blue dots) and E–W direction (red dots) are composed of 64 electrodes with 35 m electrode spacing; (right panel) ERT lines in the summit area (electrode spacing 5 m) in N–S (green dots) and E–W (orange dots) directions. White cross represent gravity stations (more than 300 stations).

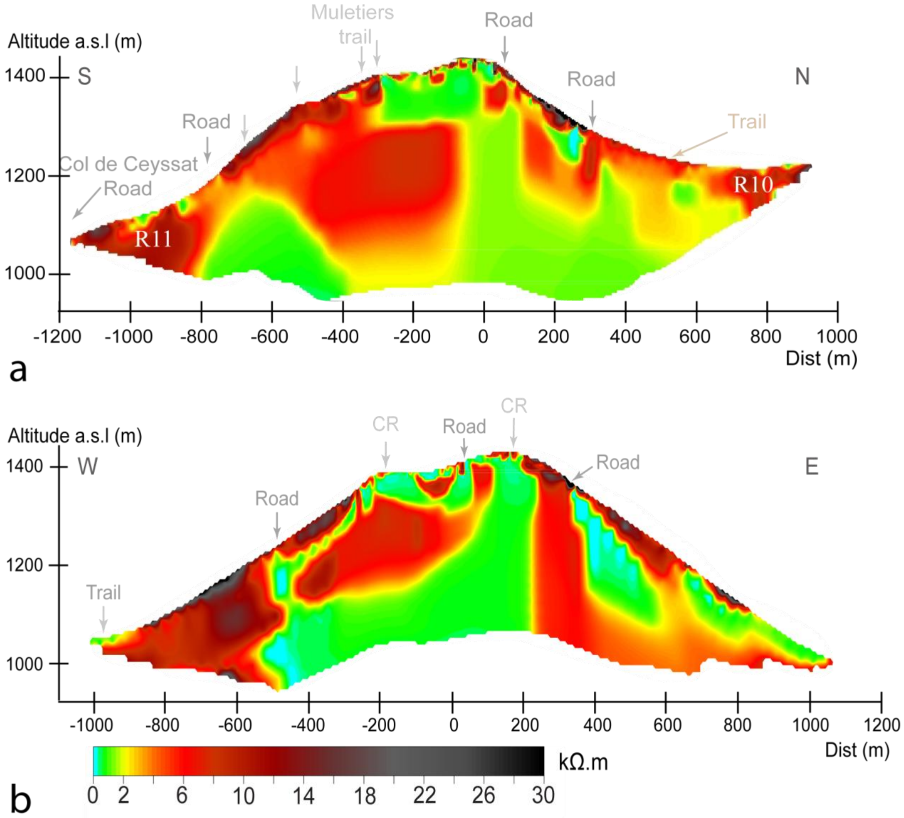

Fig. 3. 2-D resistivity models. **(a)** north–south direction; **(b)** west–east direction.

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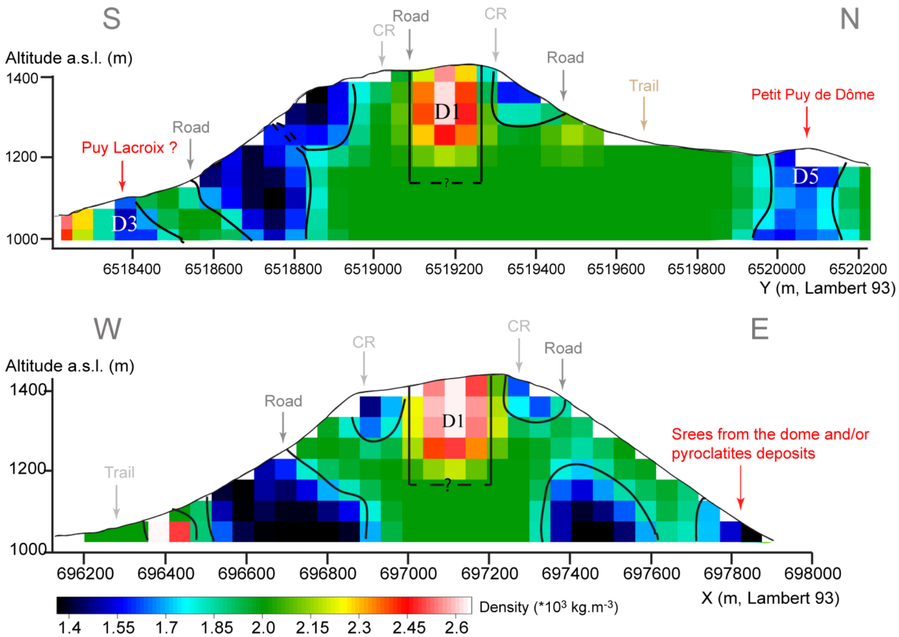

Fig. 4. Sections in the 3-D density models of the Puy de Dôme volcano.

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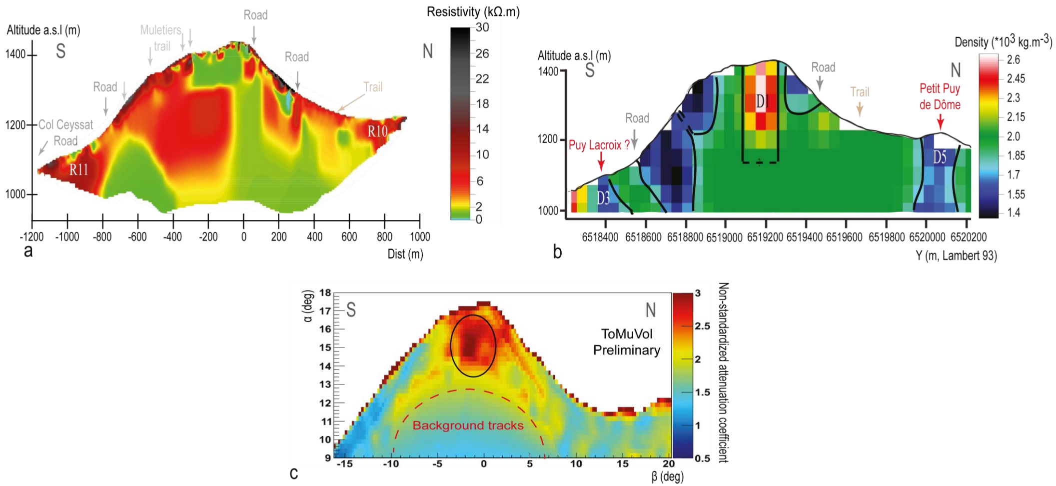

Fig. 5. Comparison of geophysical models along north-south direction. **(a)** 2-D resistivity model; **(b)** 3-D density model from gravimetry and **(c)** non-standardized attenuation coefficient model from muonic tomography.

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