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Muon tomography and volcanoes study

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Abstract. Space-time visualization of the volcanoes internal density composition improves the understanding of underlying volcanic processes and the volcanic hazards assessment. Muography is an innovative imaging technique using cosmic-ray muons which are elementary particles naturally produced in the atmosphere. They are highly penetrating particles and some of them are able to cross matter over kilometers before being absorbed. Muography visualizes the density structure in large-scale structures by tracking of the penetrated muons —similarly to how X-raying is used for imaging in the human body. The recent progress in the development of muon detector technologies has allowed us to operate instrumentation in harsh and varying environments surrounding volcanoes and use muography for passive, remote and non-destructive imaging of the internal density structure of volcanoes. The present paper gives a short overview of muography features and gives somes examples.

1. Introduction

From the early investigations of L. Alvarez performed in the Egyptian Chephren [1] to the recent results of the ScanPyramids project (1) and the discovery of a new gallery within the Great Pyramid, muons have gained in popularity not only in the archaeology domain but also in geosciences and among industrial manufacturers. Muons are elementary particles and usually belong to the “high energy physics” (HEP) scientific world but they also represent the largest proportion of charged particles reaching the surface of the Earth since they are secondary products of primary cosmic rays (high-energy protons and light nuclei) interacting with the atmosphere.

Muon imaging has emerged as a powerful method to complement standard tools in Earth Sciences. The general features of this technique are nowadays quite popular and they basically rely on the detection of flux of atmospheric muons after they cross a given structure. Their rather low interaction cross-section with matter ensures that not only may they reach the Earth’s ground level but furthermore may they significantly penetrate large and dense structures that one would like to scan. At the same time, their sensitivity to the atmosphere conditions in which they are produced may provide valuable information on some not so easily accessible parameters such

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(1) `http://www.scanpyramids.org/`

as, *e.g.*, the temperature at the top of the stratosphere. Therefore the range of applications of muography may be very large, which is one of the main reasons of today's domain expansion.

2. Muography basics: direct and inverse problem

Detecting and simulating atmospheric muons: the direct problemtemplate

The starting point of muography is of course the detection of muons, the "direct problem". This detection is quite simple since atmospheric muons are charged leptons. As they cross matter, they will interact with the charges (electrons and nuclei) of the medium. This will result in a loss of a fraction of their total energy and also in a deviation of their trajectory. These properties, sensitive to the density of the target (and to a lower extent to its Z/A ratio between the number of protons and the total number of nucleons), are exploited in the two different modes of muography called "absorption muography" and "scattering muography". Therefore the knowledge of the muons flux (both in rate and shape) is one of the key features of the analysis. Since muons are natural products, their flux must be modeled either from analytical formulas or from Monte Carlo algorithms, constrained on experimental data. This flux is sensitive to various effects: geomagnetic field, altitude/longitude/latitude, atmospheric thermodynamics, etc. Detailed studies carried out within the CORSIKA framework are available in [2]. An example of muons spectrum confronted with experimental data is displayed in fig. 1.

Atmospheric muons at ground level have an average energy usually ranging close to the minimum of ionization (see [3]). The energy deposit of the muons crossing the detectors may be converted into various types of signals which constitute the basic "hits": charges avalanches in gaseous detectors such as Resistive Plate Chambers (RPC) or Micro-Megas, silver atoms in nuclear photographic emulsions or photons in scintillation detectors (see [4]). The hits left by the muons in the detectors are collected together to build their trajectory. The muography detectors belong to the "trackers" category. The absorption mode is the same as for the X-ray medical imaging. One infers the mass distributions inside a given target from the measurement of the reduced muons flux due to their interaction with the matter of the target. The scattering mode allows the reconstruction of the mass distributions from the measurement of the muons trajectory deviation angles upstream and downstream the target. It is usually restricted to small targets while the absorption mode is well suited for large-volume imaging.

The minimal requirements on the detection devices used for muography are therefore the tracking capabilities, whose performance is measured in terms of spatial (and/or angular) resolution, usually driven by the size of the detectors segmentation or pixels, and in terms of timing resolution. The standard configuration for a tracker is to have parallel detection planes (more than 3) with XY resolution. This allows the minimal track reconstruction in the event-building procedure. Good spatial and

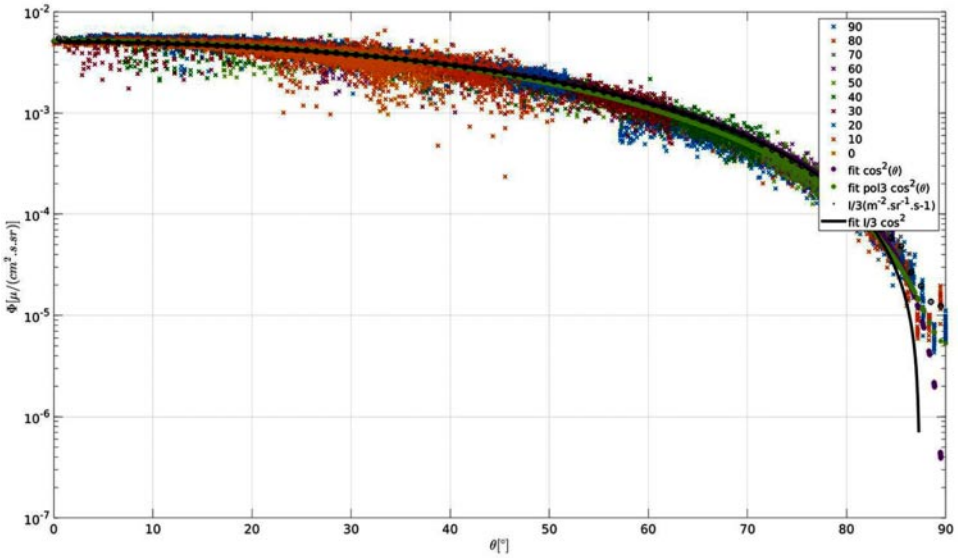

Fig. 1. – Integrated muon fluxes plotted as a function of the zenith angle θ. The crosses represent the measured data for different inclinations of the detector. The red line is a linear fit using $\cos^2(\theta)$ on the total measured flux. The black line represents the simulated flux with CORSIKA.

angular resolutions are absolutely necessary if one wants to scan precisely details in rather small objects. These requirements are less stringent for large structures, such as volcanic domes where the measured fluxes are strongly reduced because of the target's opacity. For such measurements the important parameter is the detector's acceptance, *i.e.* its capability of collecting the maximal number of muons for a given active surface as described in [5]. Larger matrices offer a larger detection area which reduces the acquisition time for a given angular resolution as detailed in [6]. Good timing performances are also required for background reduction and time-of-flight measurements. The background rejection is important for outdoor applications where one needs to eliminate random coincidences and requires fine timestamps, of the order of the nanosecond or below. As its name implies, time-of-flight measurement consists in measuring the time taken by the muon to cross the detector and discriminating whether it was propagating downwards or upwards. This is absolutely vital if one wants to assess whether the muon crossed the target or if it belongs to background. In this case a sub-nanosecond resolution is required for meter-scale detectors.

Figure 2 illustrates a particular implementation of the direct problem where the muon detector (figure on the left column) is located on the slope of an active volcanic dome (the Soufrière of Guadeloupe, Lesser Antilles, France). The trackers use plastic scintillators as detection medium and have been operated within the Diaphane project (2). The sketch in the bottom left column represents all muons trajectories falling into the detectors acceptance.

(2) `https://diaphane-muons.com/`

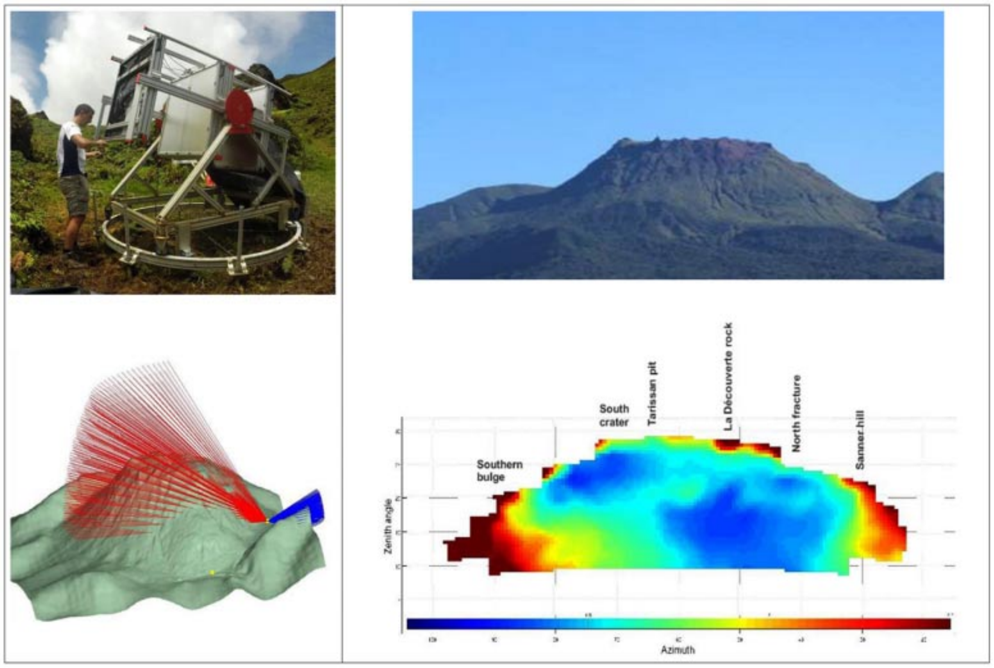

Fig. 2. – Example of a scintillator muon tracker of the Diaphane project (top, left) and sketch of the muon trajectories falling into their acceptance (bottom, left). Right: picture of the dome (top) and apparent density map measured from the East side (bottom). The blue regions correspond to negative density anomalies while the red regions correspond to positive density anomalies.

From data to images: the inverse problem

The most difficult step in muography is the so-called "inverse problem", when going from raw data to reconstructed mass distributions. For a general presentation of these general features, see [7]. Indeed muography is not suited for standard imaging techniques, like a Radon transform widely used in medical imaging, for example. One of the main reasons is the limited statistics, imposed by the natural atmospheric muons flux. On top of the statistical limitation, there are intrinsic ambiguities for single-point measurement in absorption mode since the detector measures the attenuation of the muon flux integrated all over the path $\mathcal{L}$ of the muons inside the studied target of density ρ, *i.e.* its "opacity" ϱ defined as

$$\varrho = \int_{\mathcal{L}} \rho \, \mathrm{d}l .$$

It is clear from this definition that a single measurement of a muon deficit (negative anomaly) or a muon excess (positive anomaly) w.r.t. a given model leads to an infinite number of possibilities as to the precise location of this anomaly along the path $\mathcal{L}$. Going from an opacity map to a density map requires therefore a model or more generally an "inversion technique" that provides the most probable mass distribution functions inside the target (for a review, see [6]). The inverse problem needs to be constrained by the available "a priori" information (in the Bayesian language) but also driven by the data quality. And this imposes the requirements on the detector performance in terms of acceptance, resolution, stability in operation, duty cycle, etc.

A typical apparent density may is displayed in fig. 2 for the case of the Soufrière of Guadeloupe. One can see that the structural image exhibits a highly heterogeneous structure for this dome, from the low-density regions (in blue on the map) in the center and below the South-East crater (the most active zone of the volcano, where vents are recorded at high velocity) to the high-density regions close to the edges of the dome mainly constituted by basaltic rocks.

3. Volcanoes studies: from structural to functional imaging

On volcanology, there are well-established collaborations for muon imaging of volcanoes, which led to huge progress in the understanding of the internal structure and magma dynamics. The obvious advantage of muography is the possibility to perform target's scanning from remote positions and in an autonomous way, without on-site operators as for *e.g.* ERT measurements. The technique is also well suited for continuous 24/7 measurements essential for monitoring purposes. Given the dangerousness of many active domes, those features make muography a perfect tool for volcanological surveillance.

Recent progress in methodological developments are impressive and have been obtained mainly in the volcanological applications. A non-exhaustive list of the most visible achievements is given here:

- structural imaging of a volcanic dome from one or more different points of view: Idowake, Ontake, Showa-Shinzan, etc. in Japan, Stromboli, Etna, Vesuvius, etc. in Italy (fig. 3), Puy-de-Dôme (fig. 4), Soufrière of Guadeloupe in France (fig. 2), Mayon in the Philippines, etc.
- 3D density structure of a lava dome [8, 9] in complete coincidence with the 3D structure obtained with ERT techniques [10],
- identification of huge mass and energy transfers associated with the hydrothermal activity [11, 12],
- simulation and rejection of the upward muons flux effects [13],
- simulation and subtraction of the muon diffusion at the surface of the volcano effects [14],
- joined muon-gravimetry inversion to perform 3D reconstruction of the dome [9],
- combined measurements of muography and seismic noise data [12].

In the following we focus on particular projects chosen among 3 major collaborations in Japan, France and Italy.

Pioneering works in Japan

Early applications of muography applied to volcanology have been led by the ERI group of Pr. Tanaka using different types of detectors: nuclear emulsions and

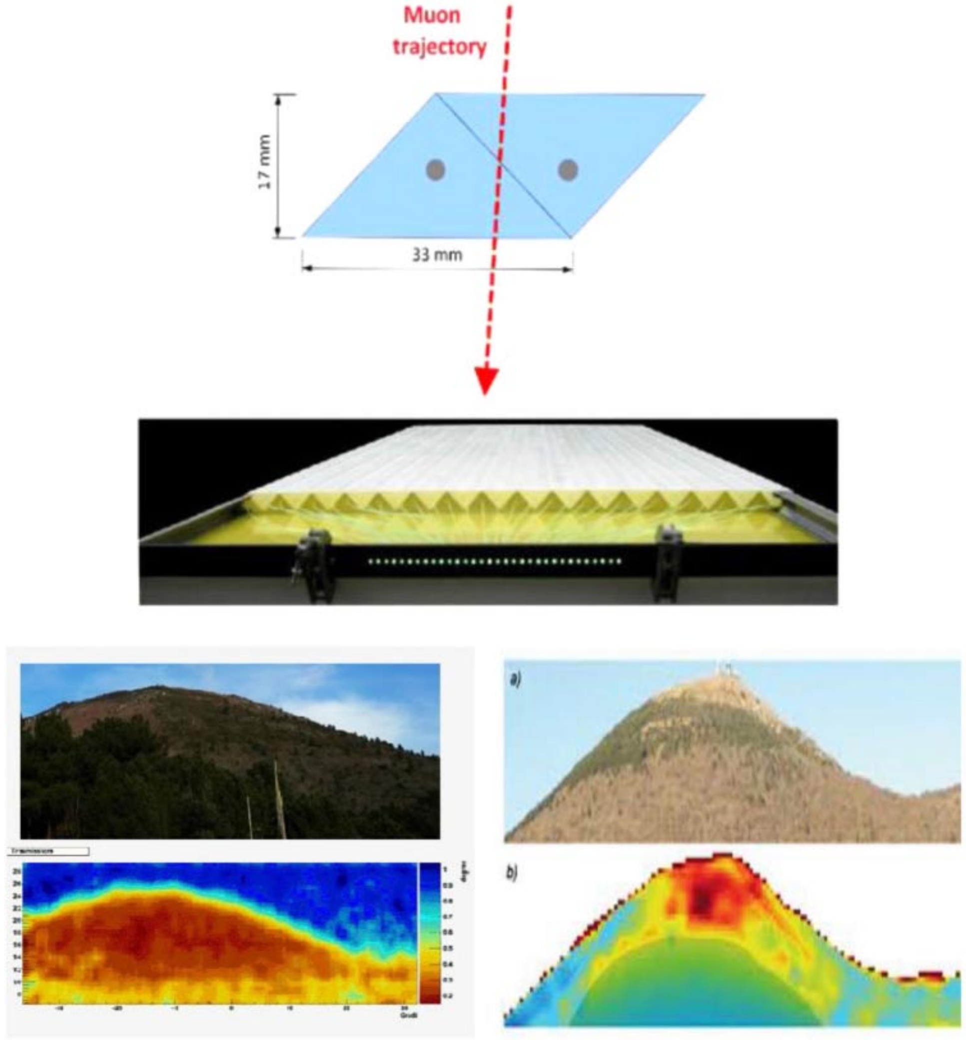

Fig. 3. – Top: MURAVES scintillators, schematics and detection plane. Lower left: MURAVES structural imaging of the Vesuvius (Italy). Lower right: map of the scaled transmission through the Puy de Dôme as seen over seven months from the Grotte de la Taillerie (France).

scintillators (see [15–17] and references therein). For instance Mt. Asama was the first volcano which was imaged with muography in 2006 [15] using the so-called Emulsion Cloud Chambers (ECC) developed in the scope of the neutrino oscillations searches experiments, see *e.g.* OPERA [18]. After its eruption in 2004, the Mt. Asama could not be accessed, making impossible the use of conventional geophysical methods, such as electromagnetic and seismic techniques. The ECC's detection area was $0.4\,\mathrm{m}^2$ and they were located inside a 1 meter deep vault at 1 km of the crater's summit, giving an overall 10 meter image resolution. The data analysis requires emulsion films development and readout with a microscope to build the tracks.

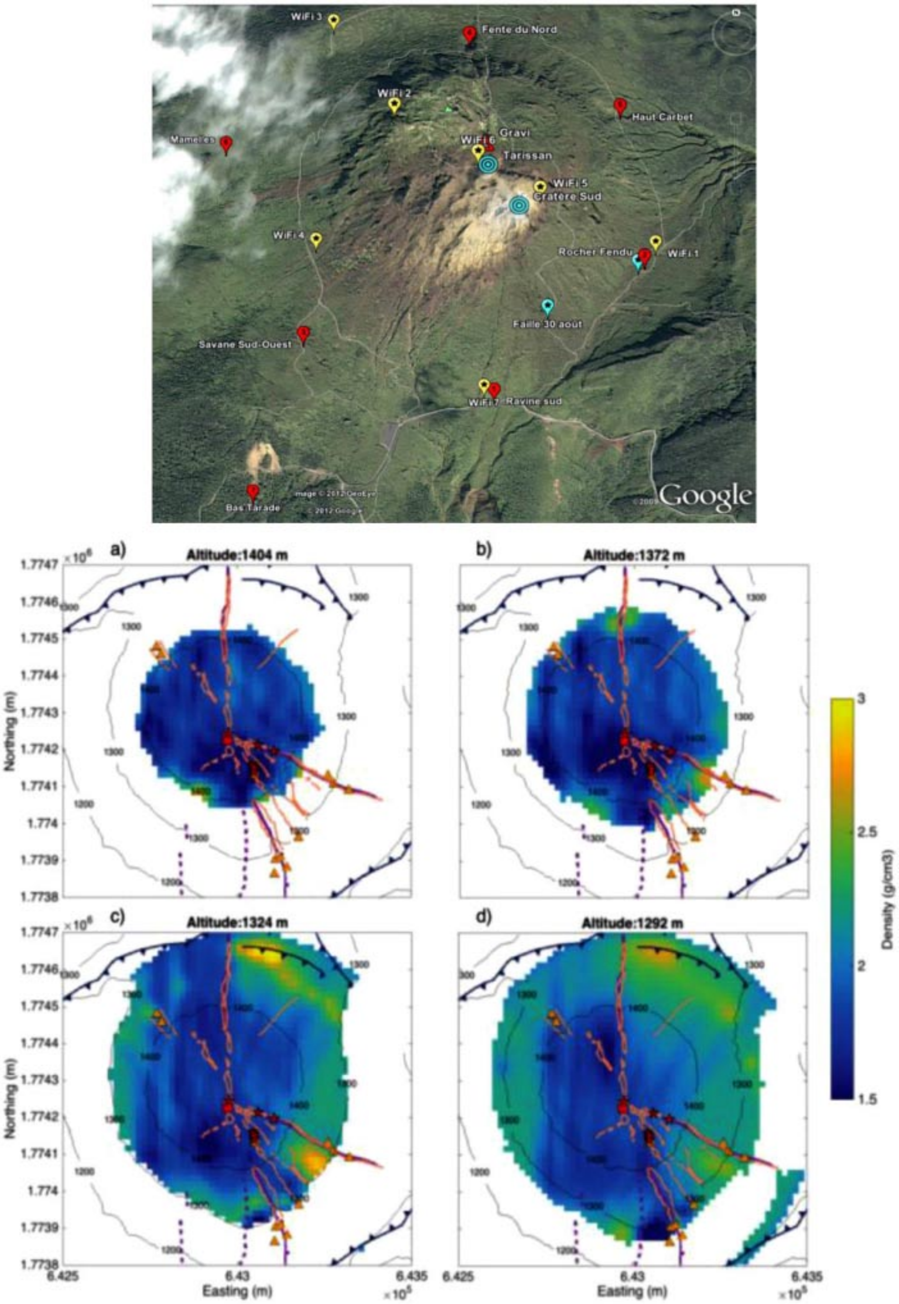

Fig. 4. – Top: summary of the experiments on the Soufrière of Guadeloupe with 6 muon detectors operated around the dome (red flags). The blue circles represent the location of the CG3 gravimeter for the monitoring. The yellow flags represent the WiFi relays necessary to establish the link between the telescope and the volcano observatory where the data are stored in real time. Bottom: 3D reconstruction of the Soufrière of Guadeloupe's dome: slices of constant altitude. The results have been obtained by coupling muography data and gravimetry data in a process of joined inversion for the density.

MURAVES (Vesuvius) & TOMUVOL (Puy-de-Dôme)

As mentioned before, many techniques are used to detect muons. Here we present two original techniques: plastic scintillators with a triangular shape and a SiPM readout for the MURAVES collaboration and Glass-Resistive Plate Chambers (GRPCs) for the TOMUVOL one.

MURAVES is a collaboration between INGV, INFN, UCL and UGent, that runs three detectors located on the Vesuvius slopes in Italy, one of the most dangerous volcanoes in Europe [19]. This project was initiated long ago with the MURAY project of collaborative efforts around methodological and instrumentation developments [20]. Interesting features are the use of triangular-shaped scintillator bars, obtained by extrusion in the Fermilab laboratory. The combination of information from two adjacent bars allows to increase the spatial resolution by weighting the amount of light collected (fig. 3, top).

TOMUVOL (TOmographie MUonique des VOLcans) is an interdisciplinary collaboration initiated in 2009, joining particle physicists and volcanologists from three French laboratories: LMV and LPC, located in Clermont-Ferrand, and the IP2I Lyon. The project benefits from a reference site located near Clermont-Ferrand: the Puy de Dôme (alt. 1464 m a.s.l.), an extinct 11 000-yr-old volcanic dome in the Massif Central, south-central France [21]. It has a remarkable structure with two domes originating from two subsequent eruptions, which occurred within a short time interval. Its density structure is therefore expected to be complex with large variations. This site has interesting bench-marking features for methodological developments in geosciences imaging. The TOMUVOL muon tracker is made of parallel planes of GRPCs, operated in avalanche mode. This technology allows a high segmentation, in 1 cm^2 cells. GRPCs are rather cheap, robust, highly efficient ($\sim$ 95%), with a detection rate up to 100 Hz and a low noise level, less than 1 $\mathrm{Hz\,cm}^{-2}$. A typical mass distribution map obtained during the first data taking campaign is displayed in fig. 3 (lower right).

The previous review is not exhaustive of course and there are other collaborations covering other volcanoes: Etna [22, 23], Stromboli [24], just to quote Italian volcanoes. But it gives an overview of methods and detection techniques used to perform structural and dynamical imaging of volcanic domes.

Methodological developments on the Soufrière of Guadeloupe

The Soufrière of Guadeloupe is a phreatic volcano with a young dome ($\sim$ 500 y). Since its last eruption in 1976, the volcano is under active surveillance through a permanent observatory. Since 2015, a french collaboration, Diaphane, between particle physicists of the CNRS-IN2P3 institute (IP2I Lyon) and geophysicists of the CNRS-INSU institute (Géosciences Rennes, IPG Paris) has been developing tools and methods to contribute to the volcano's surveillance through muography. These collaborations built several scintillator-based trackers based on the concept of distributed

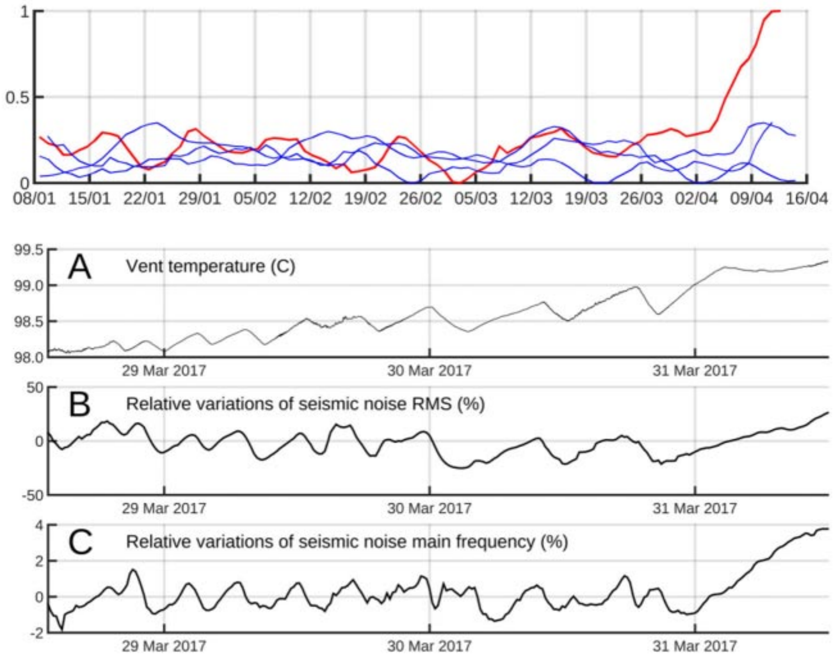

Fig. 5. – Top: time variations of the muon flux across different domains of the lava dome. The red curve is for the bundle of lines of sight covering the seismic source zone. The blue curves are for adjacent areas. Oscillation amplitudes are arbitrarily set to a common value. Bottom: time variations of vent temperature (A), seismic noise RMS (B) and dominant frequency (C).

smart sensors, adapted to harsh environmental conditions in totally autonomous modes and used them to make continuous muon tomography experiments for more than 10 years on the Soufrière of Guadeloupe volcano, in the Lesser Antilles, making this volcano the most equipped in the world with a network of 6 telescopes simultaneously taking data in the 2017–2020 period (figs. 2 and 4).

The collaborations were the first to perform a 3D joined inversion of muography and gravimetry data (fig. 4), in perfect agreement with the 3D inversion model of the dome from ERT measurements [10]. The joined inversion in that particular case is straightforward, since both methods measure the same observable, density. Technically one has to invert the following problem:

$$G\begin{bmatrix}\boldsymbol{\rho}_\mu\\ \boldsymbol{\Delta}_\rho\end{bmatrix}=\begin{bmatrix}G_{\mathrm{g}}\\ G_\mu\end{bmatrix}\begin{bmatrix}\boldsymbol{\rho}_\mu\\ \boldsymbol{\Delta}_\rho\end{bmatrix}=\begin{bmatrix}\boldsymbol{d}_{\mathrm{g}}\\ \boldsymbol{d}_\mu\end{bmatrix}=\boldsymbol{d},$$

where G is the forward kernel, $\boldsymbol{d}$ the data vectors, subscripts g and μ denote the gravity and muon case, respectively, $\boldsymbol{\rho}_\mu$ is the density distribution, and $\boldsymbol{\Delta}_\rho$ accounts for a possible density offset between the gravity- and muon-inferred models.

The Diaphane collaboration obtained a less obvious and promising result by combining muography and seismic data from geophones distributed at the summit of the

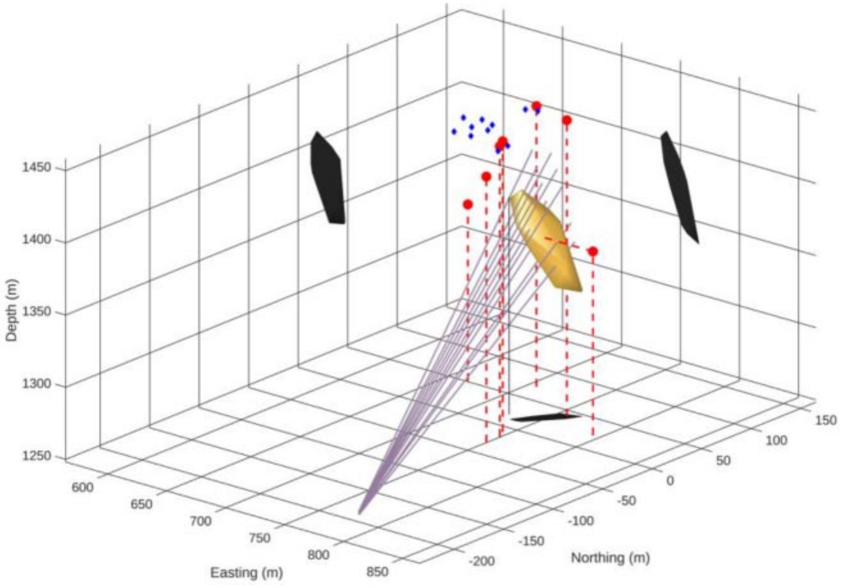

Fig. 6. – Location of the seismic noise source volume. The yellow body represents the 3D convergence zone of the wavefronts back-propagated from the geophones located on top of the lava dome (blue dots). The red dots represent the presently main active vents. The black patches are the projections of the source volume onto the faces of the 3D block diagram. The fan-like bundle of straight lines represents the lines of sight of the telescope measuring the flux increase in fig. 5.

Soufrière [12]. They found the signature of an active hydrothermal focus located 50–100 m below the summit of the volcano, by observing the coincidence between a 2-day sequence of oscillations of both amplitude and dominant frequency of the seismic noise followed by a sharp decrease of the bulk density visible as an augmentation of the muon flux crossing the active zone. This is illustrated in fig. 5 where the sequence of seismic and muon events is displayed. Figure 6 indicates the reconstructed location of the seismic noise source volume.

A spectral coherency analysis of the seismic noise followed by a bandpass filtering allowed to localize the seismic source by an unconstrained back-propagation algorithm, which pointed towards a rather small volume of about 10^4 m^3. This convergence zone falls in the sub-acceptance of the muon detector which “sees” the sharp flux increase, in coherence with the seismic activity (fig. 5).

Besides their pure scientific interest, these results are of much importance from a volcanological point of view to constrain flank destabilization models and risk assessment [25, 26] and represent an interesting perspective for a time analysis of the volcanological dynamics.

Those methodological developments and successful results have attracted the industrial sector’s attention for non-invasive/non-destructive controls of large and/or inaccessible structures like *e.g.* blast furnaces [27], nuclear power plants [28], storage silos, etc.

4. Conclusions

This paper presented general features of muography applied to geosciences, focusing on volcanology. With various detection techniques, many collaborations around the world succeeded to scan the inner part of active volcanoes domes providing unprecedented inputs to volcanological models. The real-time measurements capabilities of the muography techniques open the field of monitoring [29,30], so powerful in the context of risks mitigation and hazards management. The success of the method opens the door to a large number of applications, from Earth Sciences and archaelogy to non invasive and non destructive controls in the industry. With the technological improvements, detectors compactifications and miniaturization, a lot of yet unexplored domains will be explored, either with underground measurements or with open-air measurements, the two main operation modes that we have illustrated with examples in geology and volcanology.

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