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Muons tomography applied to geosciences and volcanology

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ABSTRACT

Imaging the inner part of large geological targets is an important issue in geosciences with various applications. Different approaches already exist (e.g. gravimetry, electrical tomography) that give access to a wide range of information but with identified limitations or drawbacks (e.g. intrinsic ambiguity of the inverse problem, time consuming deployment of sensors over large distances). Here we present an alternative and complementary tomography method based on the measurement of the cosmic muons flux attenuation through the geological structures. We detail the basics of this muon tomography with a special emphasis on the photo-active detectors.

1. Introduction and motivations

Monitoring natural events such as earthquakes, volcanic eruptions, landslides and tsunamis has immense importance, both scientific and societal. The interest of volcano radiography arose in the last decades in Japan [1–4], which has a large volcanic and seismic activity, like other places in the world such as Italy and Iceland in Europe or the Antilles belt in the Atlantic ocean. Because of the possible vicinity of populated areas, volcanoes require careful monitoring of their activity and precise modelling of their geophysical evolution.

Consider for instance Lesser Antilles, a subduction volcanic arc with a dozen of active volcanoes located in populated areas. The volcanoes of Martinique (La Montagne Pelée), Guadeloupe (La Soufrière), and Montserrat (The Soufrière Hills) presented an eruptive activity since the beginning of the 20th century. It is therefore crucial to evaluate their eruptive evolution in the near future to and quantify the associated risk for surrounding inhabitants. Reaching these goals requires accurate imaging of the volcano's inner structure and quantitative estimates of the related parameters (variations of volume, density, strain, or pressure) associated with fluid transports (magma, gas, or water) or physical and chemical evolution of the volcanic materials. La Soufrière of Guadeloupe, an andesitic volcano whose lava dome is about five hundred years old [5], is particularly relevant since it presents a diversified number of hazards including phreatic eruption, flank collapse and explosive magmatic eruption [6]. Its dome is very heterogeneous, with massive lava volumes embedded in more or less hydrothermalized materials [7]. Given the constant erosion of the volcano due to the tropical intensive rain activity, the evolution of such a lacunary structure may be rapid, with formation of cavities, that may be filled with pressurized and likely very acid fluids, resulting in flank destabilization. On top of that present structural models show that the dome sits on a 15° N–S inclined plane, leading to an overall very unstable structure (Fig. 1). This particular example shows that a precise knowledge of the dome's internal structure is a key issue for the global modelling and understanding of the volcanoes. For this reason, La Soufrière has been chosen as priority target for muon imaging [8], which constitutes one of the most promising tools to obtain direct information on the density distribution inside geological objects.

2. Tomography basics

The interest of muon tomography for Earth Sciences purposes soon arose after the discovery of cosmic rays and of the muon. The cross-section of that particle at those typical energies makes it a perfect probe since it is able to cross hundredths of metres of rock with an attenuation related to the amount of matter along its trajectory [9]. Since it is a charged particle, its detection is quite straightforward. The first studies relevant to tomography in geosciences, were motivated by the need to characterise the geological burden overlying underground structures, in particular laboratories hosting large particles experiments aimed at detecting rare events in a silent environment (the so-called "cosmic silence" [10]). This type of "underground tomography" is pursued nowadays in the applications of long-term storage where detailed knowledge is

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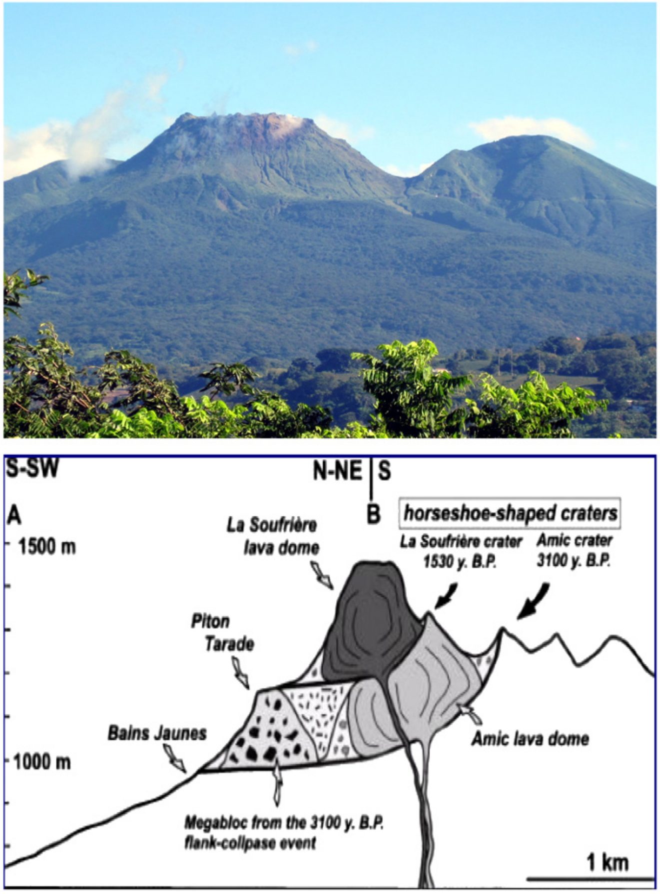

Fig. 1. La Soufrière of Guadeloupe: picture and model.

required on the geological environment (nature and borders of various layers) and for mining geophysics. Applications other than those directly related to underground physics require smaller, modular, autonomous detectors movable on the field and able to reject efficiently the background. The pioneering archaeological investigations performed in the Egyptian Chephren pyramid by Alvarez et al. in 1970s [11], looking for some hidden room inside the pyramid, reveal the feasibility of the method.

A muon radiography uses the same basic principles than a standard medical radiography: measuring the attenuation of a beam (cosmic muons versus X-rays) when crossing matter (rock vs human flesh) with a sensitive device. A detailed discussion of all parameters is given in Ref. [12]. The measurement gives access to the opacity ϱ of the geological structures by comparing the muons flux Φ after crossing the target to the incident open sky flux, Φ_o. Various models give analytical expressions of the muon flux from the two-body decays of pions and kaons and assuming a primary proton flux spectrum roughly following a power law $\approx E_p^{-2.7}$ [13–15]. The opacity is converted to density ρ by inverting the integral equation: $\varrho(\text{kg m}^{-2}) \equiv \int_L \rho(\xi)\text{d}\xi$,$L$ denoting particles trajectory with local coordinate ξ. The muons energy loss (and potential absorption) on their way through rock accounts for the standard bremsstrahlung, nuclear interactions, and e^-e^+ pair production physical processes, taken as:

$$-\frac{\text{d}E}{\text{d}\varrho}(\text{MeV g}^{-1}\ \text{cm}^2) = a(E) + b(E)E \qquad (1)$$

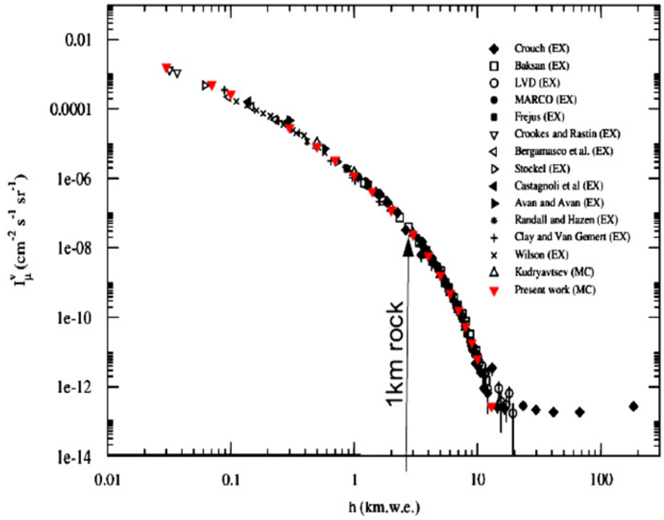

Fig. 2. Integrated flux computed as a function of the standard rock thickness L in metres-water-equivalent (m.w.e.) compared to experimental points.

where the functions a and b depend on the crossed material properties [16]. The flux of muons emerging from the target is the integral of Φ over the energy, ranging from $E_{\min(\varrho)}$, the minimum initial energy necessary to cross given opacity ϱ, to infinite (Fig. 2). This flux is influenced by various environmental parameters such as altitude, geomagnetic cut-off, solar modulation, atmospheric variations to be accounted for in the simulation models. Finally the number of detected muons is the convolution of the muons flux crossing the target, the data taking duration and the telescope acceptance, which is the key experimental parameter that one may evaluate from the simulation and/or from the data themselves.

3. Photo-active detectors for tomography

3.1. The DIAPHANE project

DIAPHANE is the first European project of tomography applied to volcanology. It started in 2008 with a collaboration between three French institutes: IPG Paris, IPN Lyon and Géosciences Rennes to promote muon tomography in the French Earth Science and Particle Physics communities [8]. The first objectives of the project were to make technological choices for the muon telescopes and to define a design suitable for the difficult field conditions encountered on the Lesser Antilles volcanoes. The detector's design: plastic scintillator, optical fibres, pixelized photomultipliers and triggerless, smart, Ethernet-capable readout electronics, is based on the state-of-the-art opto-electronics technology, known for its robustness and stability in extreme working conditions. Modularity and limits in weight are also imposed by transportation constraints, some positions on the flank of the volcanoes being accessible only by helicopter. A standard detector (or "telescope") comprises three independent *XY* detection planes with autonomous and low power consumption readout system recording and timestamping their own hits in auto-trigger mode. The event-building is performed quasi online, via software procedures, by sorting all raw data in time and looking for time coincidences between hits passing the various trigger cuts. Data are transferred continuously via Ethernet wifi and are directly accessible remotely. No shift on-site are needed (concept of the unmanned sensors). The detector is powered through solar panels. Weight, power consumption, robustness and costs have been optimized to the best achievable compromises for that type of field operating detector [17].

Detection matrices: Two layers (*X* and *Y*) scintillator bars are glued between 1.5 mm thick anodised aluminium plates. The scintillator bars were provided by Fermilab with a rectangular