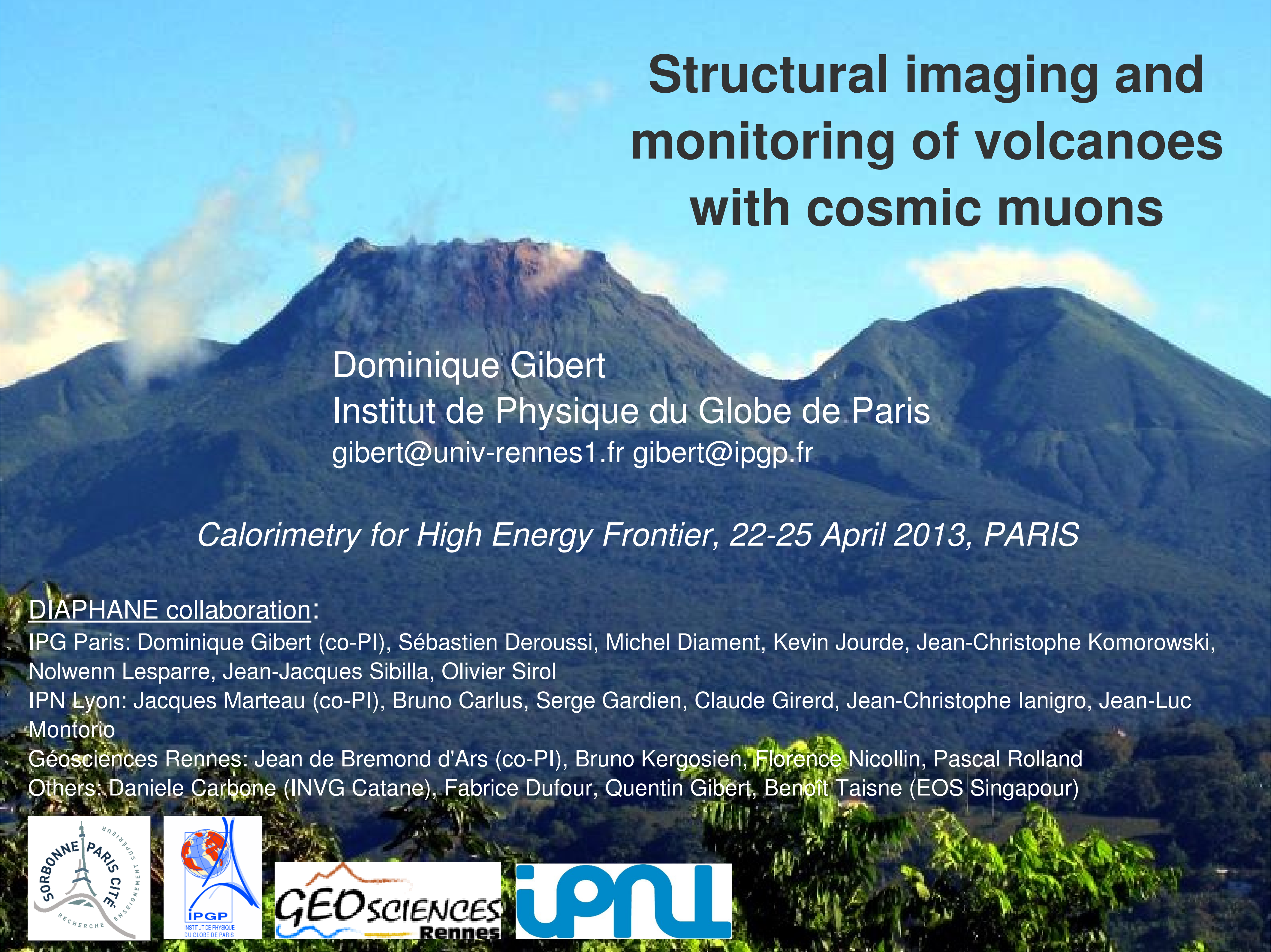

Structural imaging and monitoring of volcanoes with cosmic muons

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Outline

- Volcano hazards and usefulness of muon tomography
  - Types of hazards and the role of imaging methods
  - Comparison of muon tomography and other geophysical methods
- Design of field detectors for volcanoes
  - Technical constrains
  - Performances
- Examples of applications: La Soufrière of Guadeloupe
  - Structural imaging / comparison with other methods
  - Monitoring
- Summary

Volcano hazards

Various hazards with different physical causes and magnitude

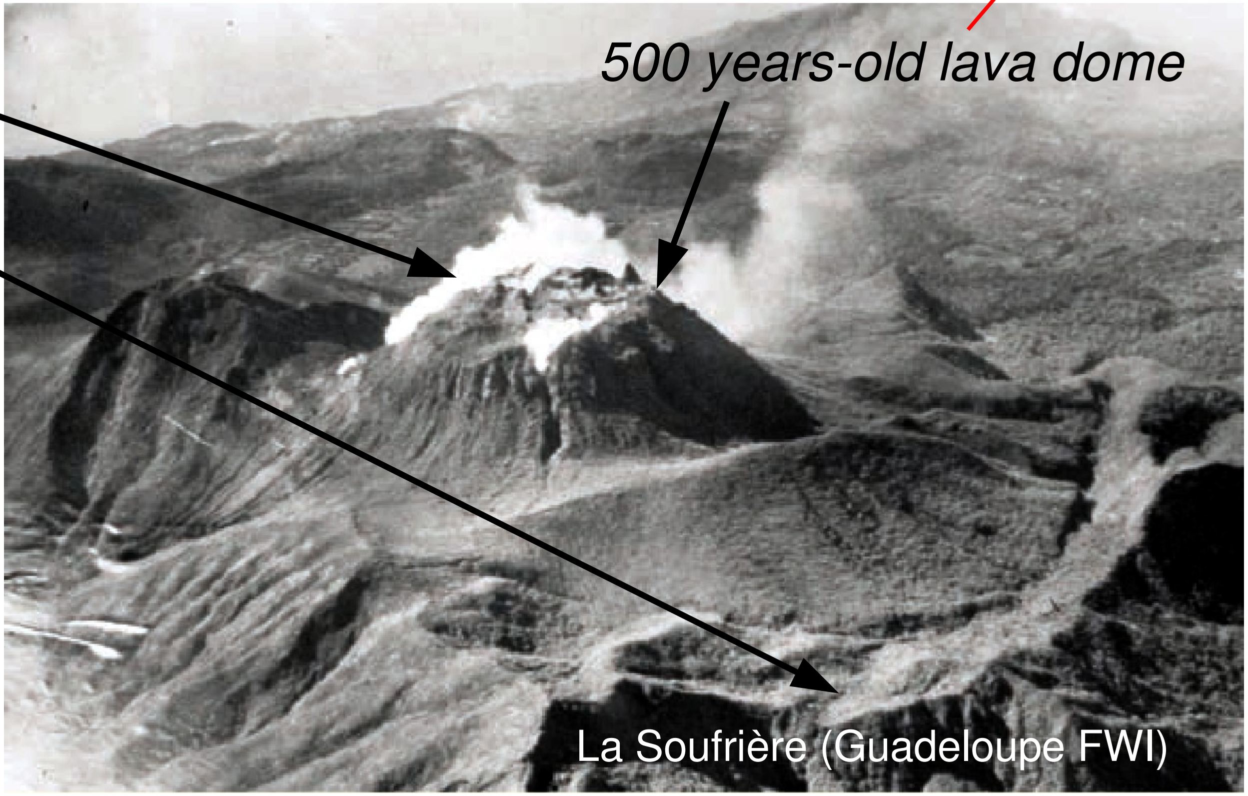
- Phreatic explosion, landslide and flank collapse
- Phreato-magmatic explosion

Active vents during phreatic eruption

Remains of ancient volcanoes

500 years-old lava dome


Mount St Helens (USA)


La Soufrière (Guadeloupe FWI)

Volcano hazards

Phreatic eruption and flank collapse are the most likely hazards for La Soufrière (and many volcanoes of this type)

- Phreatic eruption = release of thermal energy contained in the hydrothermal reservoirs (energy is present, we need the trigger)
- Flank collapse may be triggered by internal overpressure, earthquake

Active vent during 1976 phreatic eruption

(c) 1976, M. Bof

… the same in 2010

2010, Q. Gibert

Volcano hazards

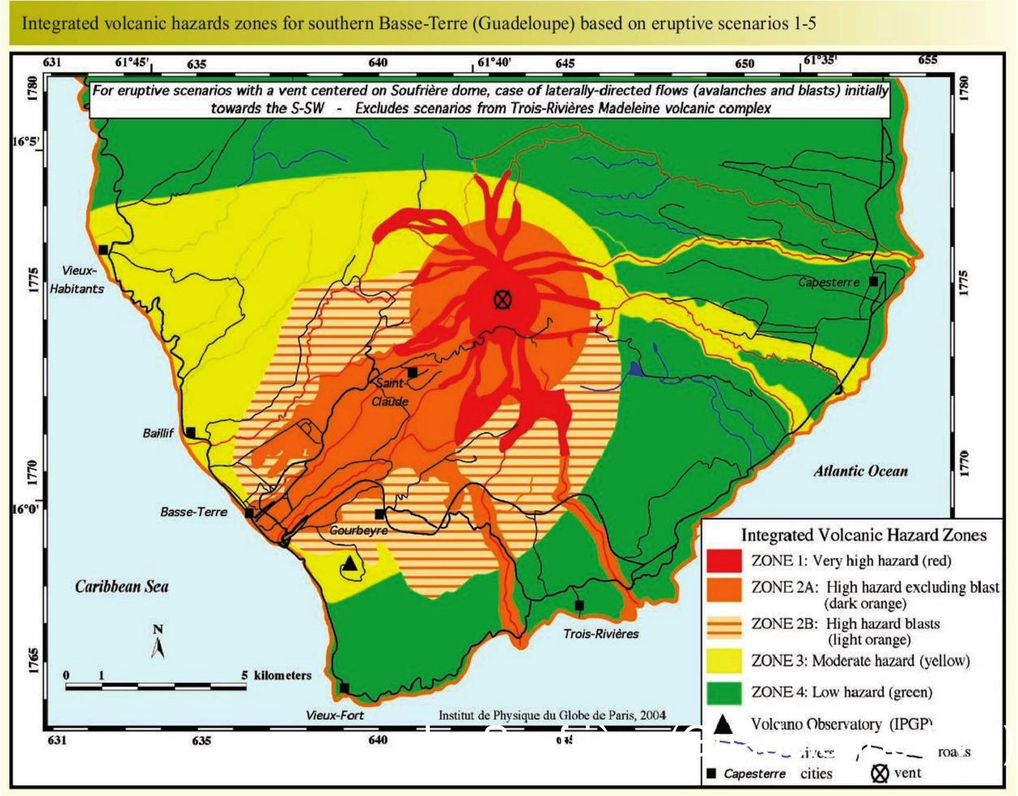
Hazard level depends on present-day state of the volcano

- Degree of alteration *(mechanical integrity)*
- Volume of reservoirs *(stored energy)*
- Internal changes *(liquid/vapor transition)*
- Channels and conduits

Tomography methods
play a leading role

- Electrical conductivity
- Seismic waves velocity
- Density

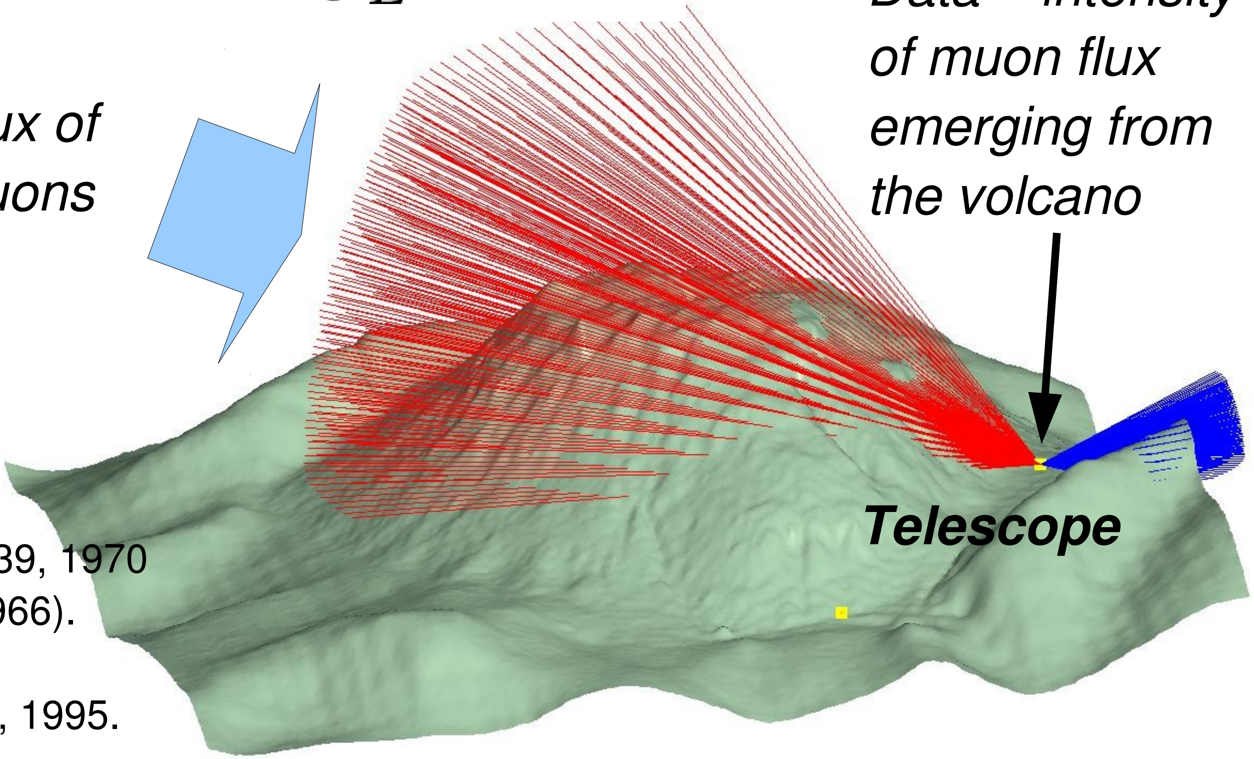
Komorowski, J.C. et al., Volcanic Atlas of the Lesser Antilles, 2005.



Muon tomography

Measure the flux of muons across the volcano to determine its density structure

- Basic information = opacity $\varrho(L) \equiv \int_L \rho(\xi)\mathrm{d}\xi,$



Incident flux of cosmic muons

Data = intensity of muon flux emerging from the volcano

Telescope

Precursory work:
Alvarez, L.W. et al., *Science*, 167, 832-839, 1970
(see also *Physics Today*, 78-80, Sept. 1966).
Renew of interest:
Nagamine, K. et al., *NIMA*, 356, 585-595, 1995.
Short review:
Saracino G. & C. Cârloganu, *Physics Today*, 60-61, Dec. 2012.

Muon tomography

Advantages

- Determination of density *via* a straight-ray geometry
  - Simple inverse Radon transform
  - Curved paths seismic and electrical tomography => non-linear inverse problem
  - Volume integral in gravity measurements
- Wide angle remote imaging => study of active volcanoes

Limitations

- Cannot see « below » => restricted to the top part of volcanoes
- Need to have sufficient statistics => « slow » monitoring with a weekly or monthly timescale

Field telescopes

Constrains

- Modular with elements < 50 kg to allows use of rope access techniques
- Low power consumption (< 50W) including all devices (WiFi, …)
- Rugged design to support heavy rain, strong winds, ash fall, acid gas
- Robustness to support shocks (up to 20 g) during hauling
- Repairable on the field
- Remotely controllable (power control, reboot, data download,...)
- Acceptance large enough to image 1 km of rock in reasonable time
- Angular resolution 1° to 2°
- 3 (or more) planar detectors to suppress fake tracks
- High-resolution (1 ns) clock

Field telescopes

Scintillator strips (1x5x80 cm^3) provided by FermiLab

Shifting fibers: Bicron BCF-91A

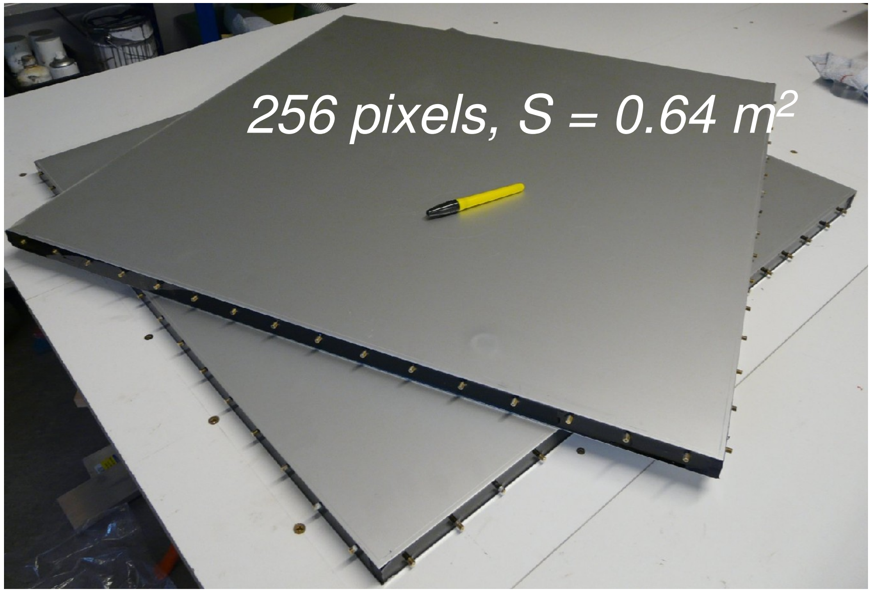
Multichannel PM H8804-200 MOD-5 Hamamatsu

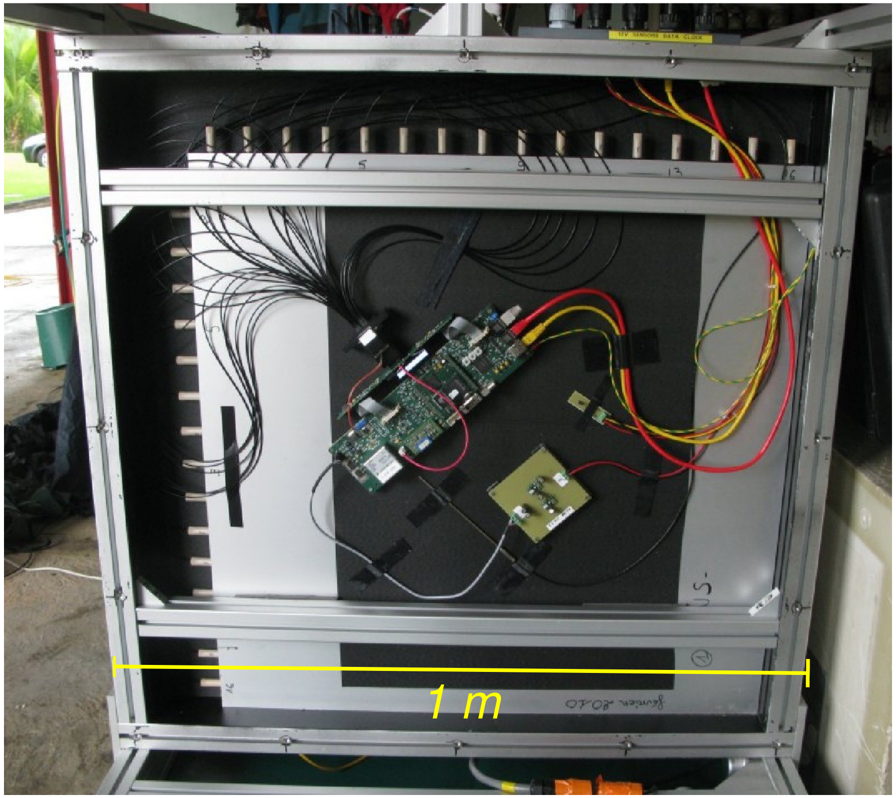
SiPM S10362-13-050C Hamamatsu

Main board: CAMEROP from OPERA

Clock resolution: 1 ns

SiPM Front end developed by IPNL





Field telescopes


Etna 2012


Soufrière 2012

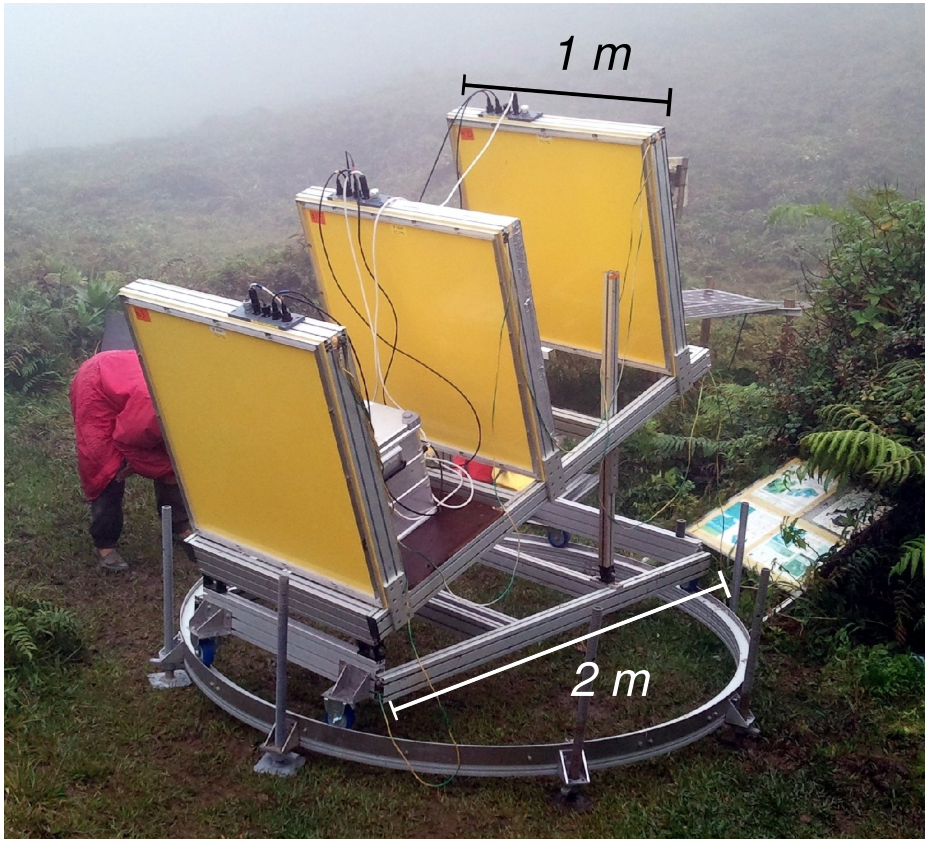
Photovoltaic panels (800 W), wind turbine, fuel cells

Total mass: 200 to 600 kg

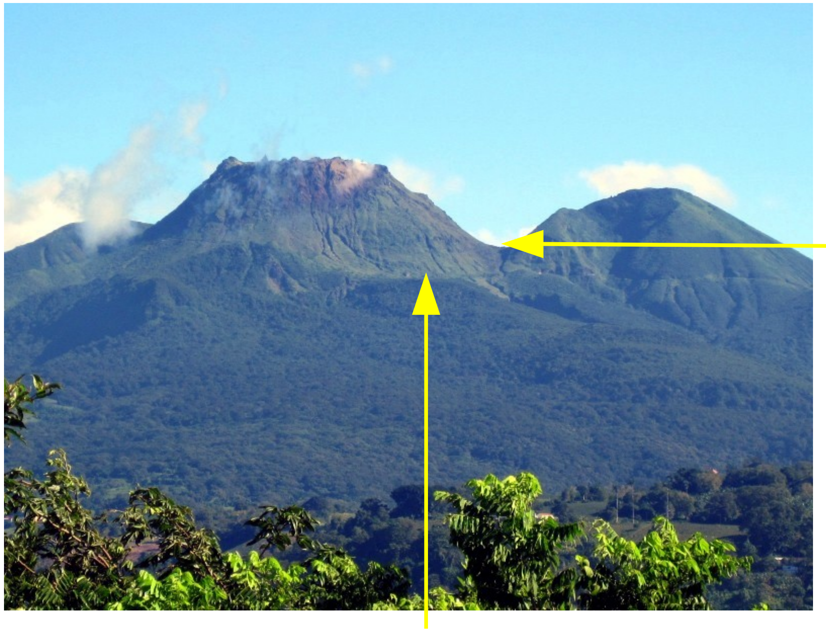
Angular aperture 30° - 60°

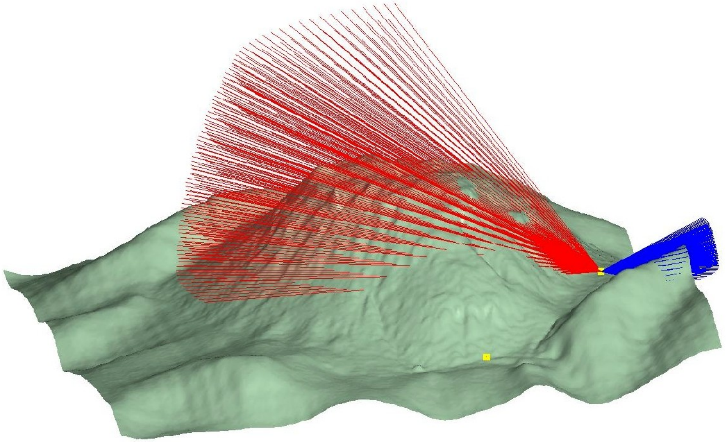
Angular resolution 1° - 2°


Etna Sept. 2010



La Soufrière structural imaging





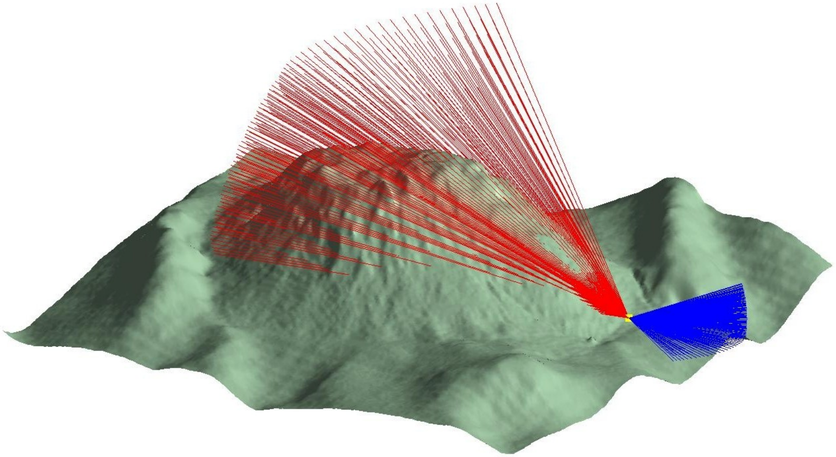
Typical acceptance = 12 sr.cm^2

More than 2.5 years of on-field operation

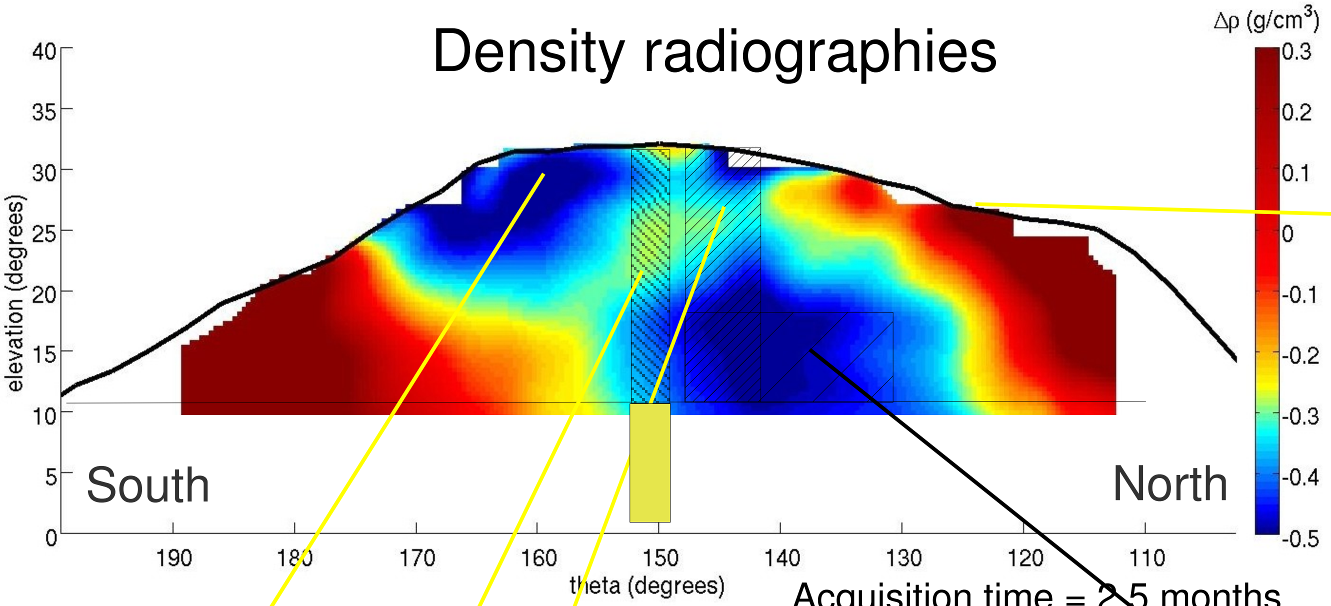
Angular aperture = 60° (res = 2°)

Voxel 25 m at lava dome center

3 hurricane seasons (cumul rain = 10 m)



La Soufrière structural imaging



Acquisition time = 2.5 months

Steep slopes with dense andesitic lava

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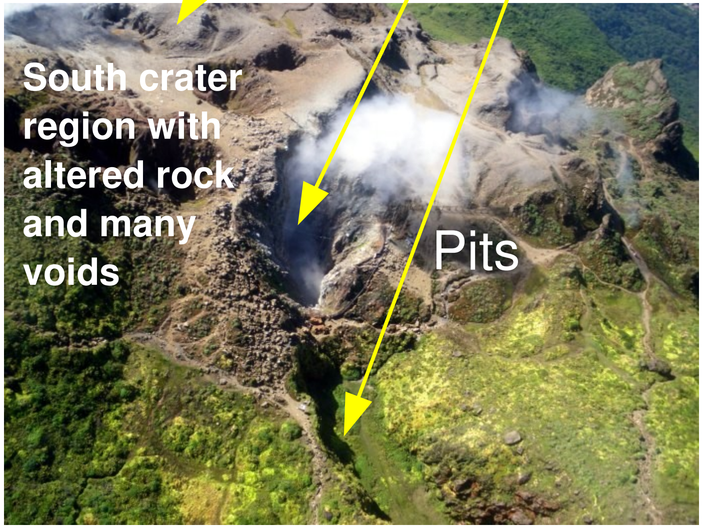
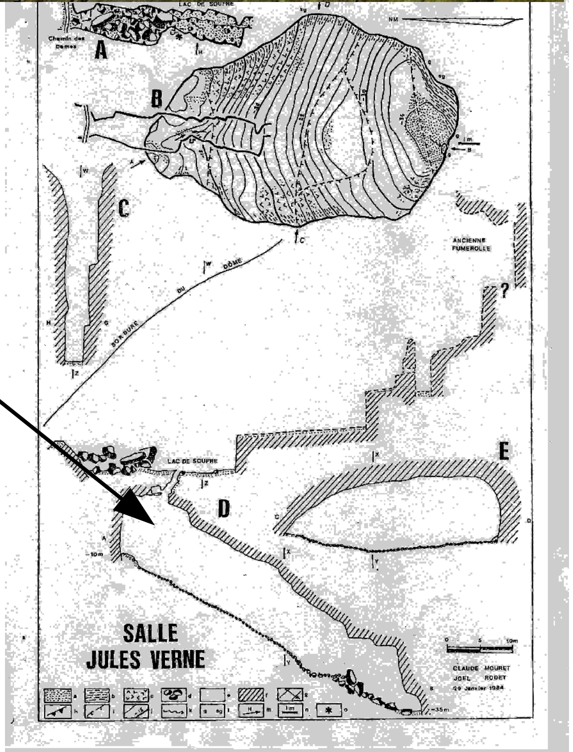


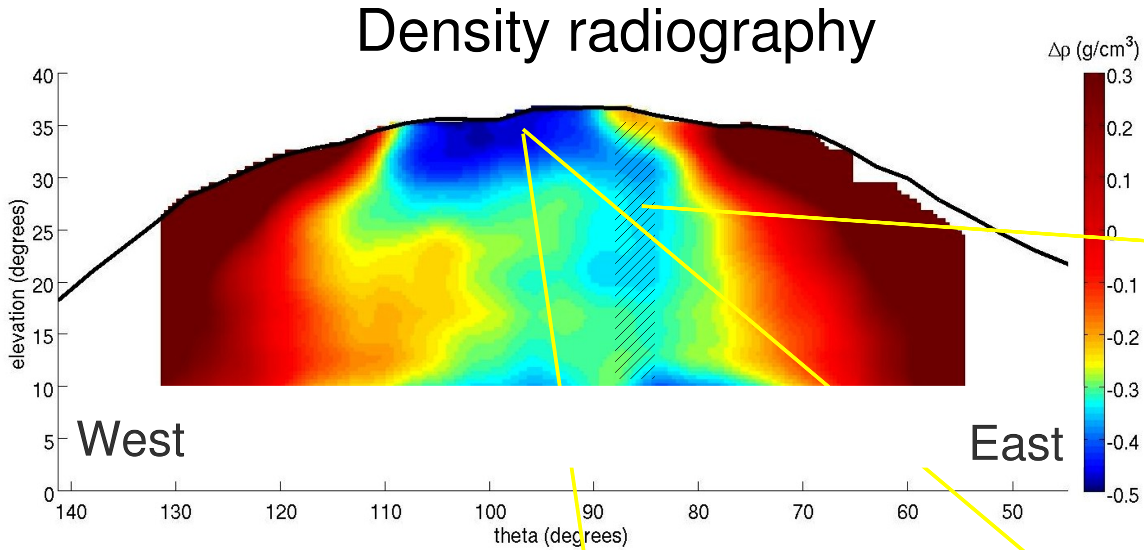
South crater region with altered rock and many voids

Pits

Low density region might be the Spallanzani cave described in ancient texts. No more accessible.

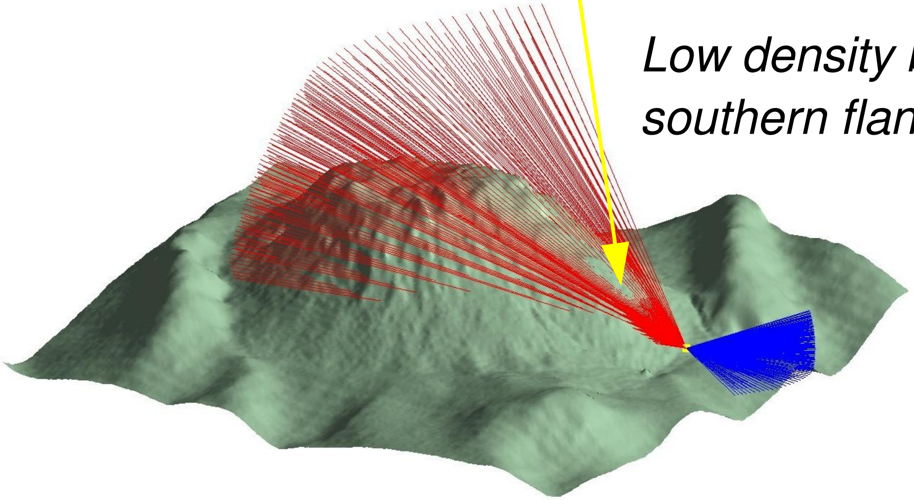


La Soufrière structural imaging



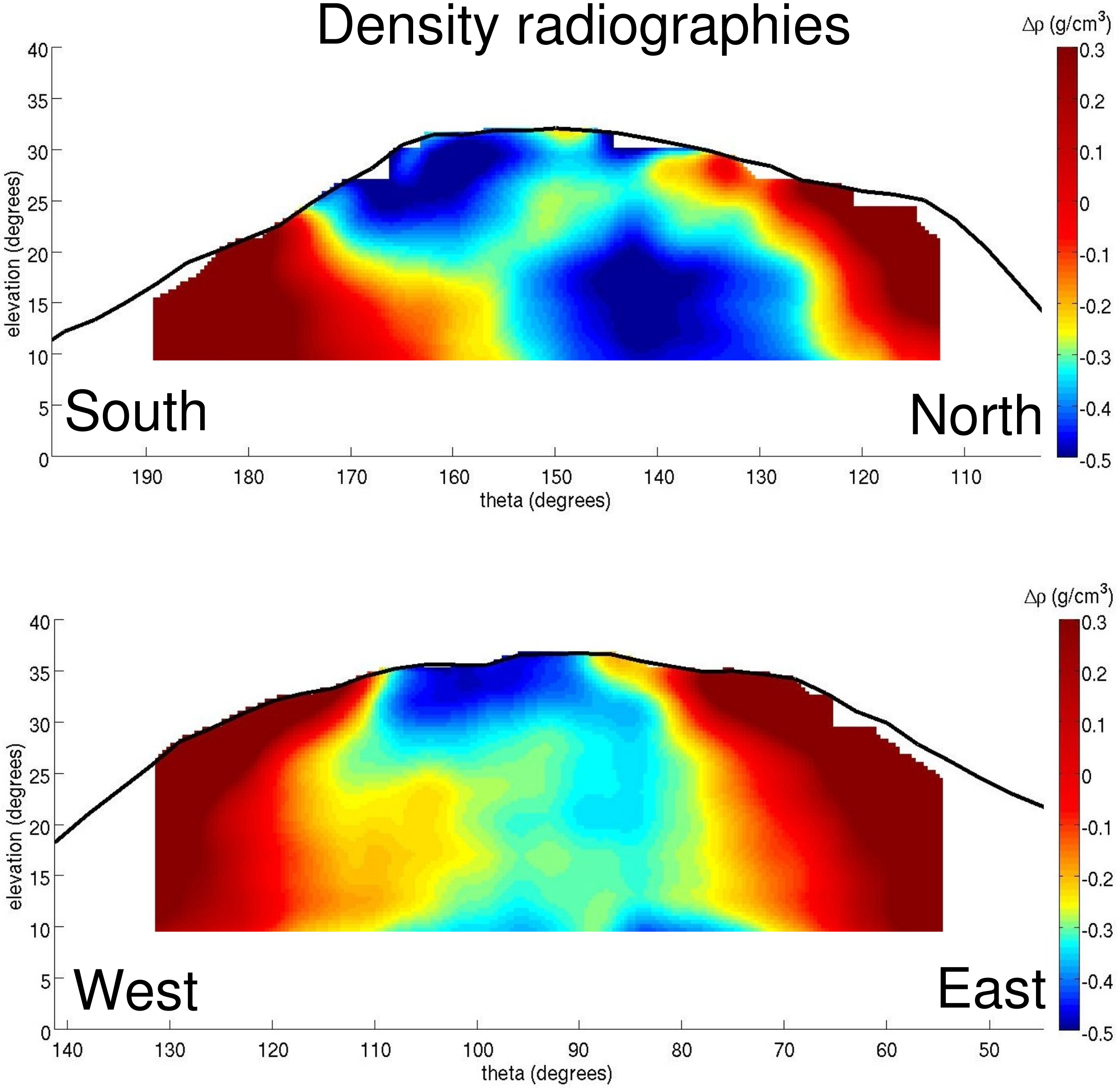
Acquisition time = 2 months

Low density bulge on southern flank



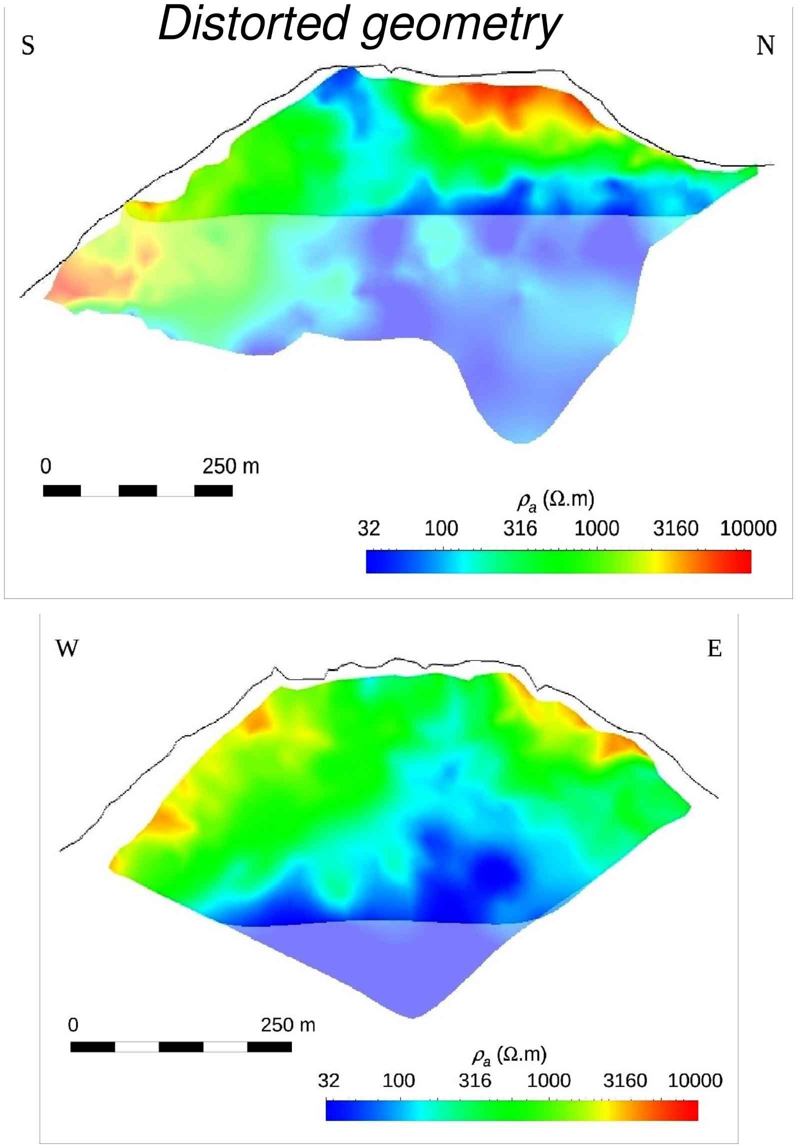
La Soufrière structural imaging

Density radiographies

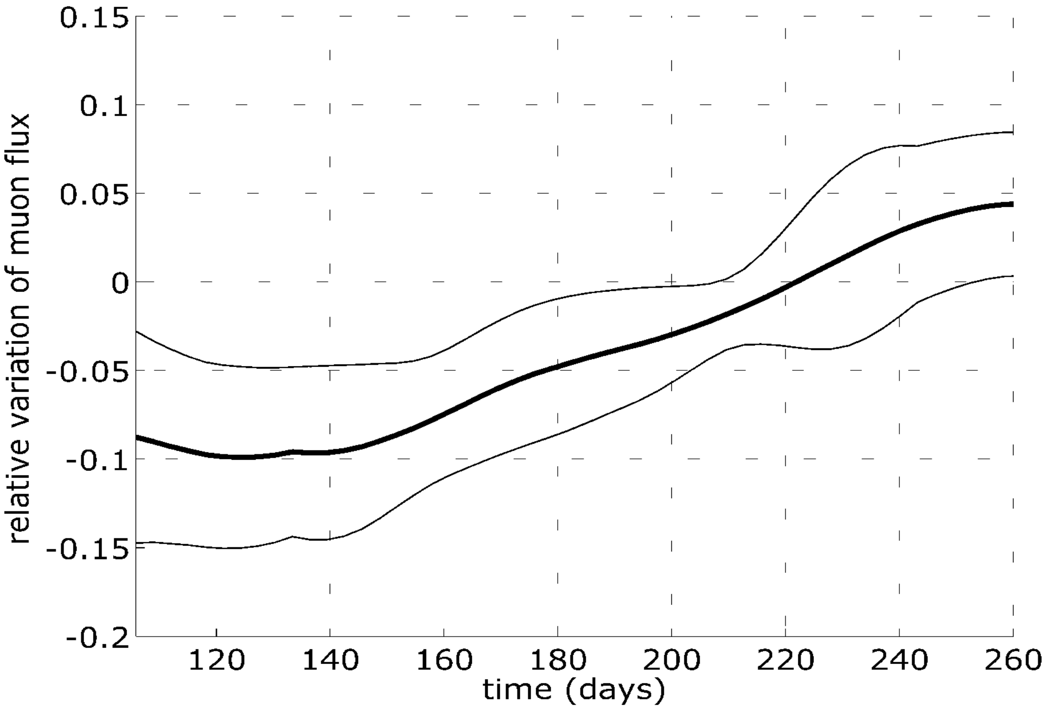


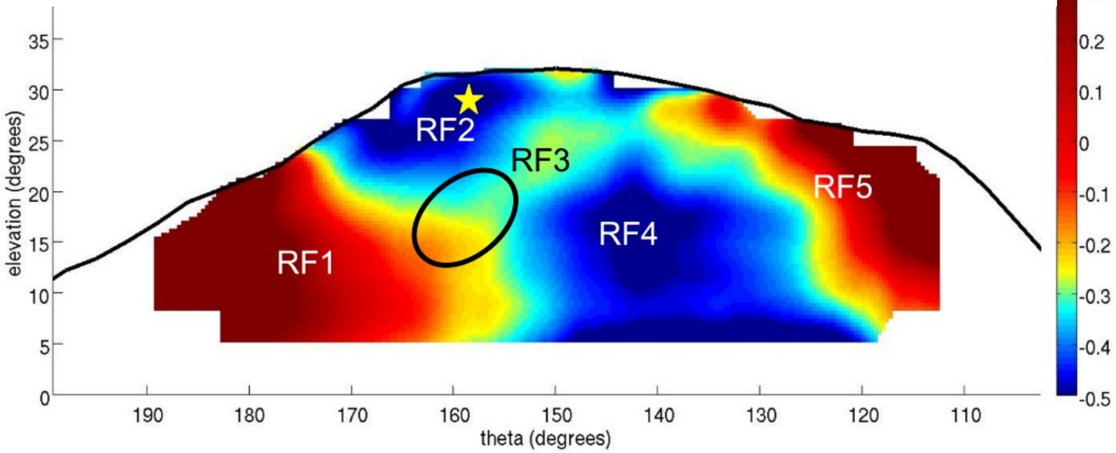
Electrical resistivity

Distorted geometry



La Soufrière monitoring





Monitoring performed during the first semester of 2012 revealed an increase of the flux of muons (i.e. decreasing density) in the bottom part of the South crater reservoir.

This preceded the appearance of new active vents at the summit.

Summary

- Density muon tomography may be considered operational
  - Structural remote imaging
  - Monitoring at timescales of month
- Field telescopes proved adapted to harsh field conditions
  - Heavy rains, strong winds (Soufrière), cold and hot (Etna)
  - Acceptance is sufficient for rock thickness < 1000 m
  - Larger thickness => augment acceptance by coupling several telescopes
  - Design telescopes for monitoring during eruption (Etna)
- Publications → www.ipgp.fr/~gibert/Publications.html

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