Muon Radiography of Volcanoes- Round Table

16:30 Introduction to the round table - Geophysical vs muon imaging techniques applied to volcanoes : advantages, limitations and perspectives
Presenter(s): ZOLLO, Aldo *(Univ Naples)*

16:45 Seismic tomography vs muon radiography to image the structure of volcanoes
Presenter(s): GOT, Jean-Luc *(ISTERRE)*

16:55 Geological and volcanological relevance/potential of muon radiography to investigate and to understand the shallow volcanic processes
Presenter(s): LÉNAT, Jean-François *(UMR 6524 CNRS "Magmas et Volcans")*

17:05 Applications and perspectives of Muon radiography: the experience in Japan
Presenter(s): TANAKA, Hiroyuki *(University of Tokyo)*

17:15 Applications and perspectives of Muon radiography: the experience in Italy
Presenter(s): STROLIN, Paolo Emilio *(Univ. Napoli and INFN)*

17:25 Applications and perspectives of Muon radiography: the experience in France
Presenter(s): GIBERT, Dominique *(Institut de Physique du Globe de Paris)*

Introduction to the round table

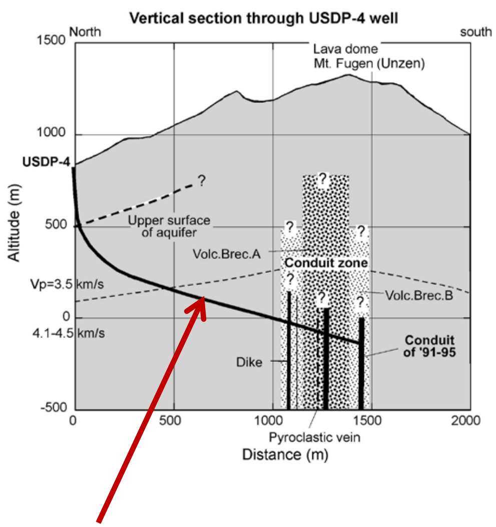
Geophysical vs Muon imaging techniques applied to volcanoes : advantages, limitations and perspectives

Aldo Zollo

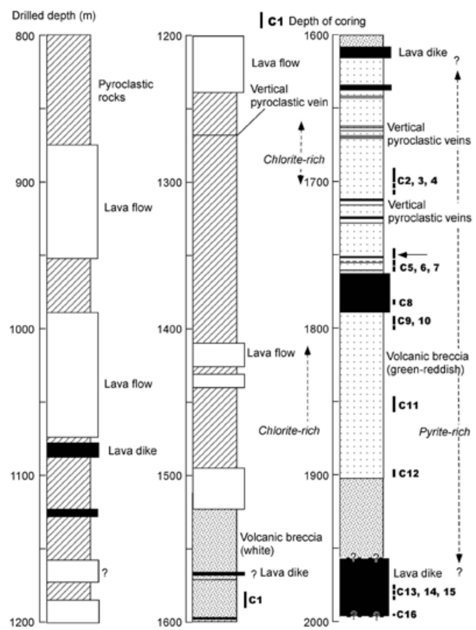
Direct and indirect methods

Direct method

Conduit Drilling in the Unzen (Japan) volcano (Nakada et al., 2005)



The USDP4 well



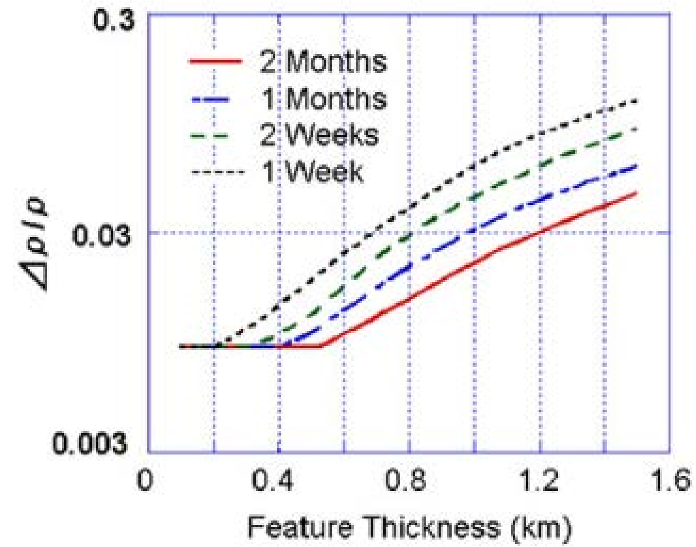
Geologic section along the well

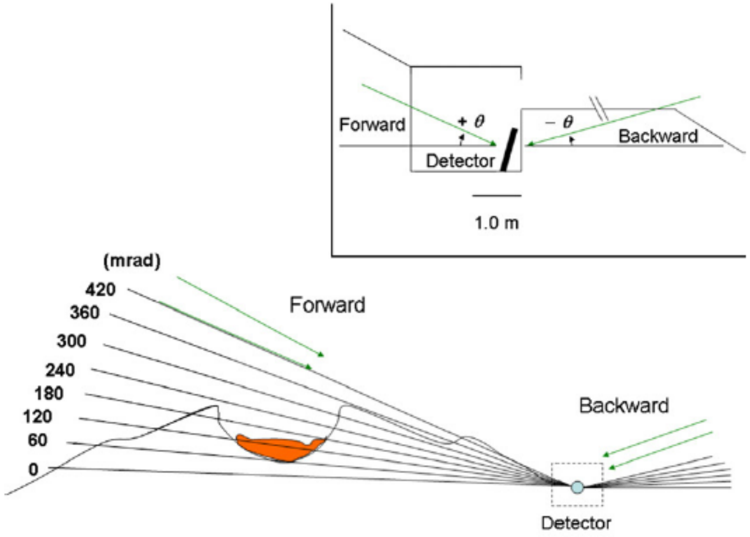
Indirect method

Based on	Geophysical Method
Propagation	Seismic, Ground Penetration Radar
Diffusion	Heat flow, seismic wave scattering
Potential	Electrical, Magnetic, Magnetotelluric, Gravity

Cosmic-ray muon radiography

The principle: muon absorption measurements along different nearly horizontal paths through a solid body are used for the reconstruction of the density distribution in the interior of the object.

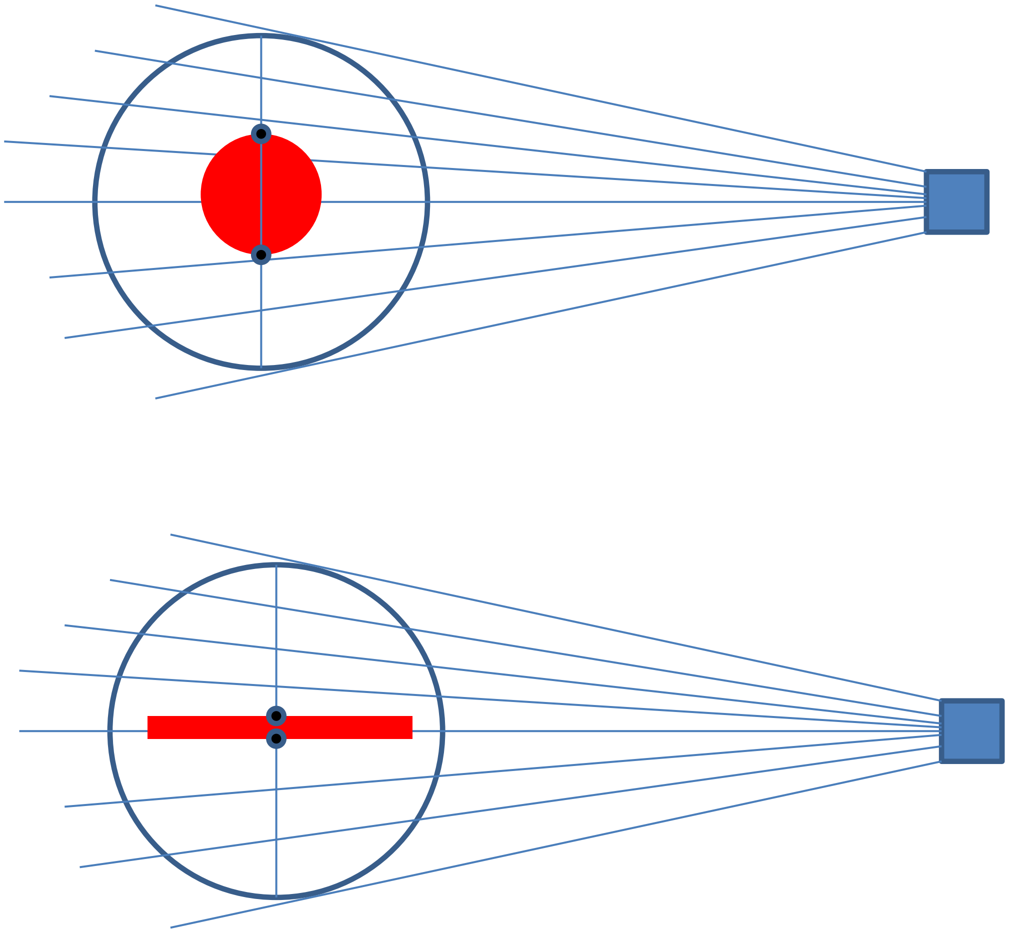




The figure summarizes the tradeoff between observation time and density contrast for features to be resolved to within one standard deviation with a detector with area of 4000 cm^2 located about 1 km from the target (Tanaka et al 2007).

The required observation time is inversely proportional to the area of the detector used.

Pixel resolution

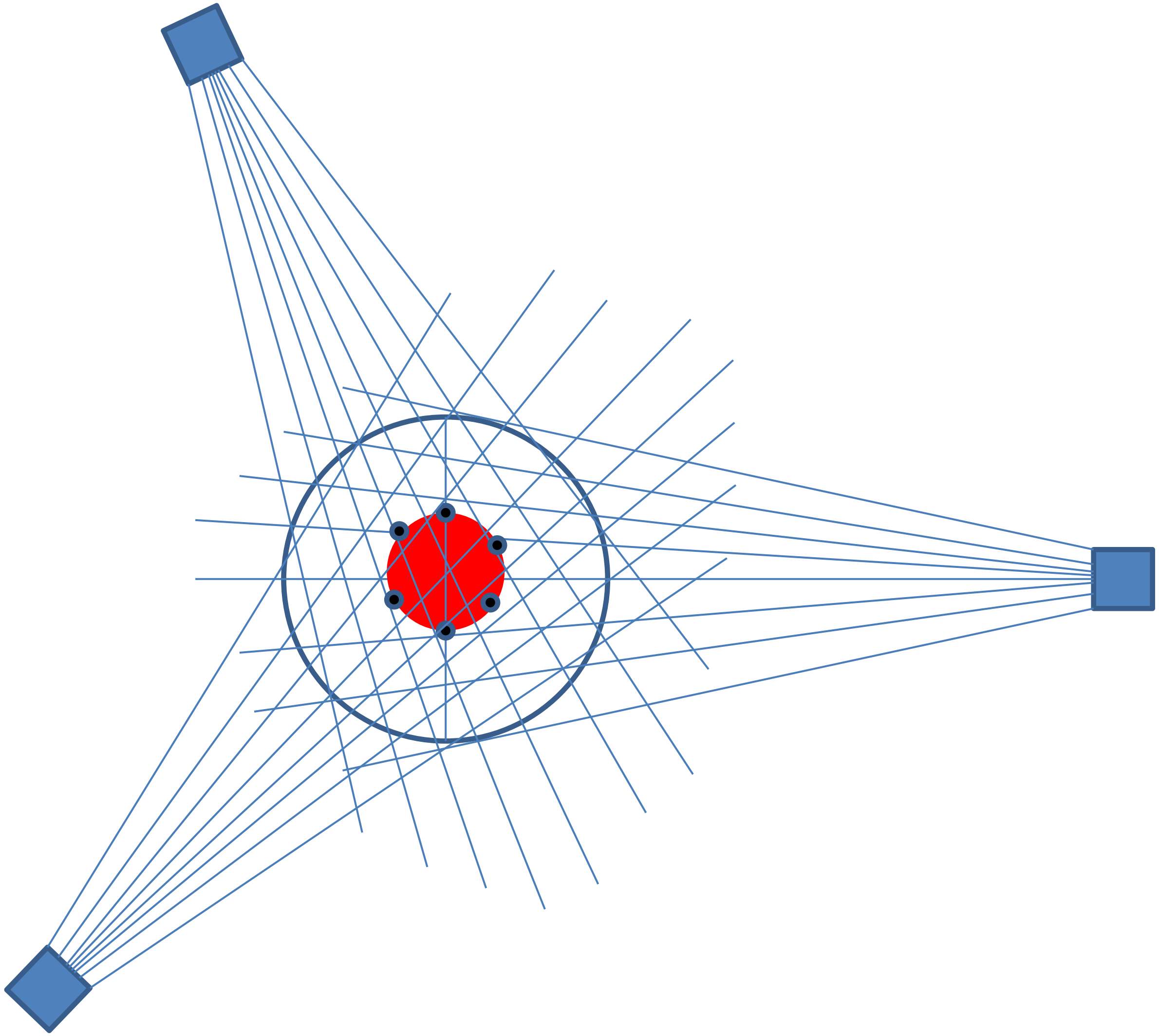


Depends on :

- the muon detector size and distance from the target
- Size and shape of the density anomaly

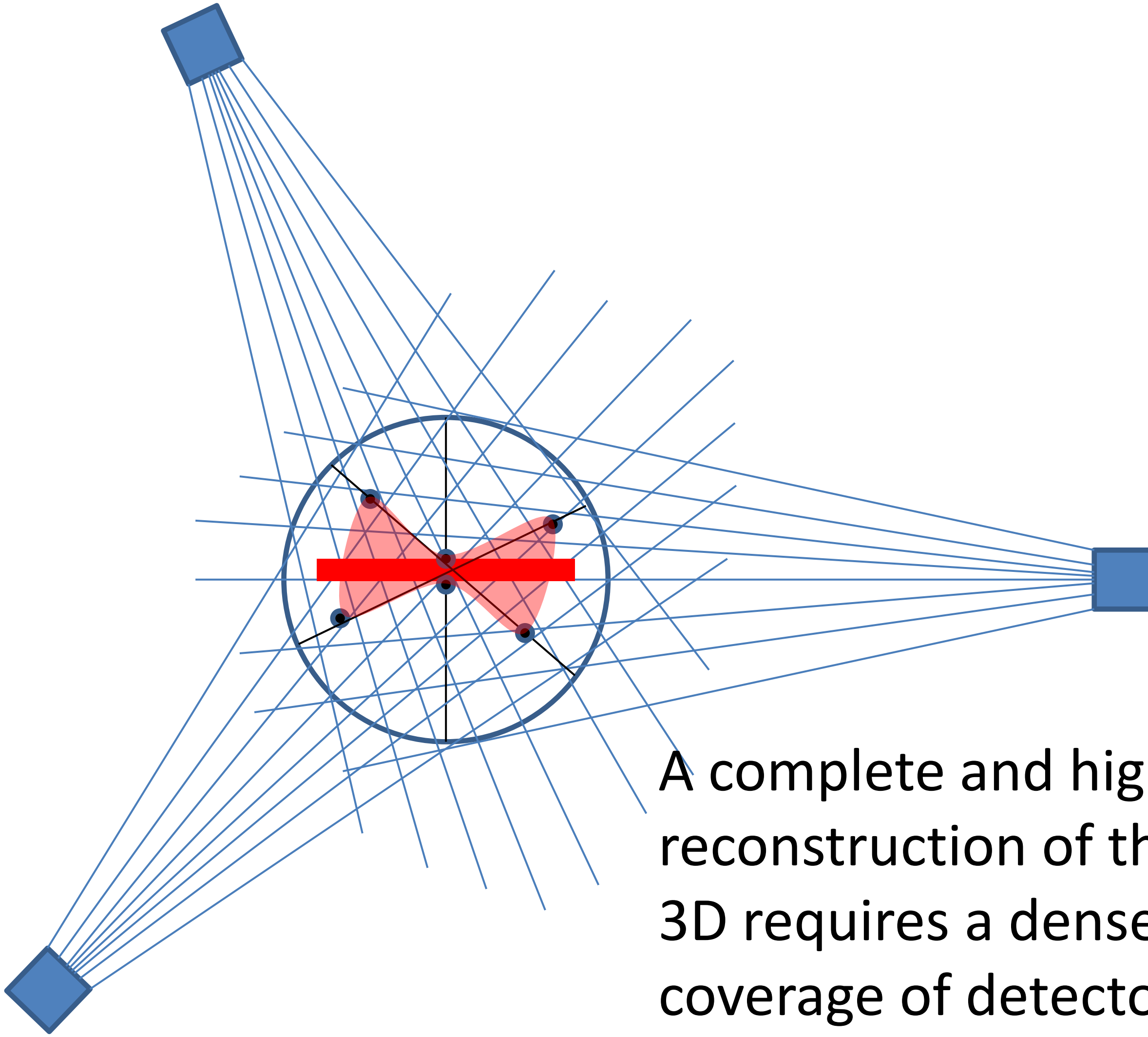
Single muon detector

Pixel resolution



Multiple muon detector

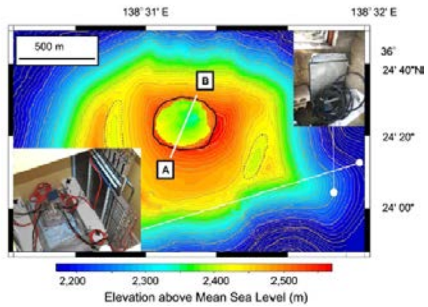
Pixel resolution

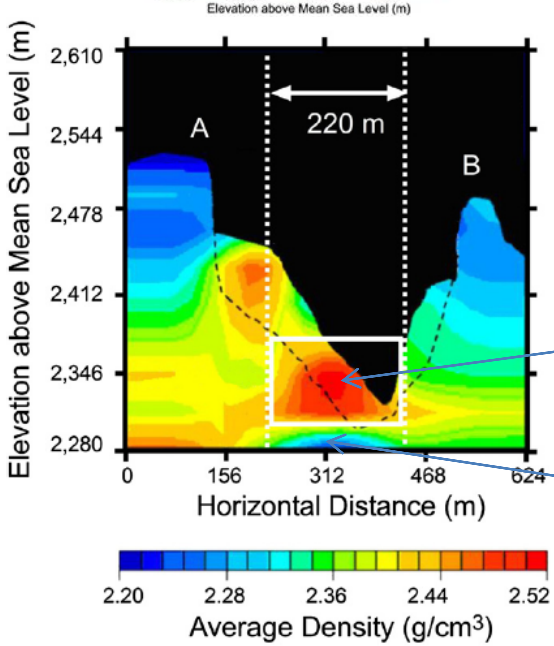


A complete and high resolution reconstruction of the image in 3D requires a dense azimuthal coverage of detectors

Multiple muon detector

Volcanoes images from muography



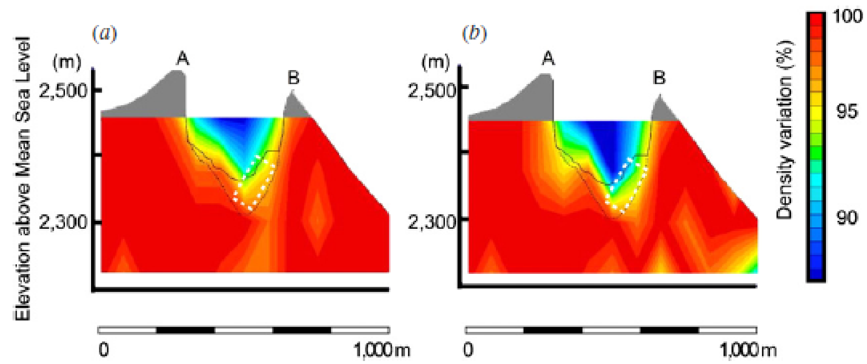


lava mound

porous conduit

Average density distribution projected on the cross-sectional plane parallel to the detector plane including the crater floor of Mt Asama (Japan), (Tanaka et al, 2007).

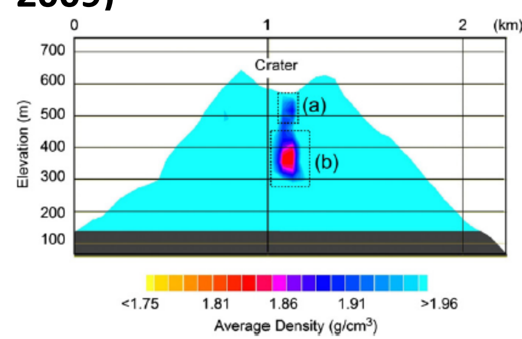
Temporal variations at Mt Asama by muon radiography (Okubo & Tanaka, 2012)

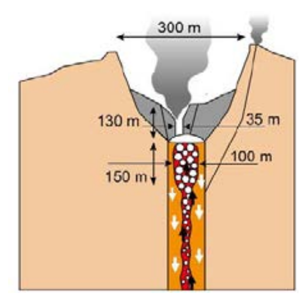


By data collected before the 2009 eruption between 6 January and 1 February 2009.

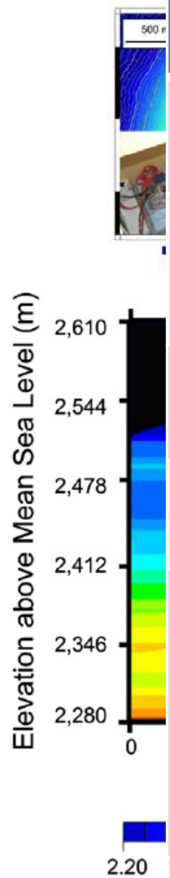
By data collected after the 2009 eruption between 2 February and 5 March 2009.

Average density distribution obtained with the PAC system at Mt Iwodake (Japan) (Tanaka et al. 2009)





Volcanoes images from muography



Muon Radiography	
Physical parameter measured	**Cosmic-ray muon absorption rate through the matter**
Operative physical property	**Density**
Typical source of anomaly	**Rock density contrasts**
Depth of Investigation	**Upper part of volcanoes (the method is limited to horizontal ranges of 2–3 km)**
Pixel resolution	**Depends on observation time and size of the detector. For example using a detector of 4000 cm^2 at 1 km distance from the target, with 2 months of observations, anomalous bodies (1-2% change in <ρ>) can be determined with a vertical resolution of 30 m and a horizontal resolution of 60 m (Tanaka et al, 2007).**
Time for data acquisition	**Depends on target size , from several weeks to few months**
Useful for estimation of temporal changes	**Yes, but for slow variation and long time windows**

Average d
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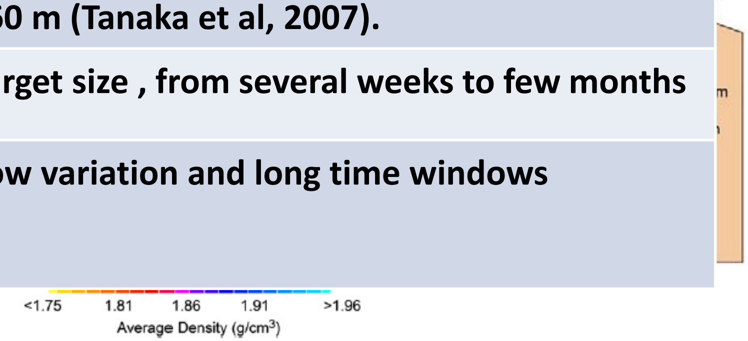
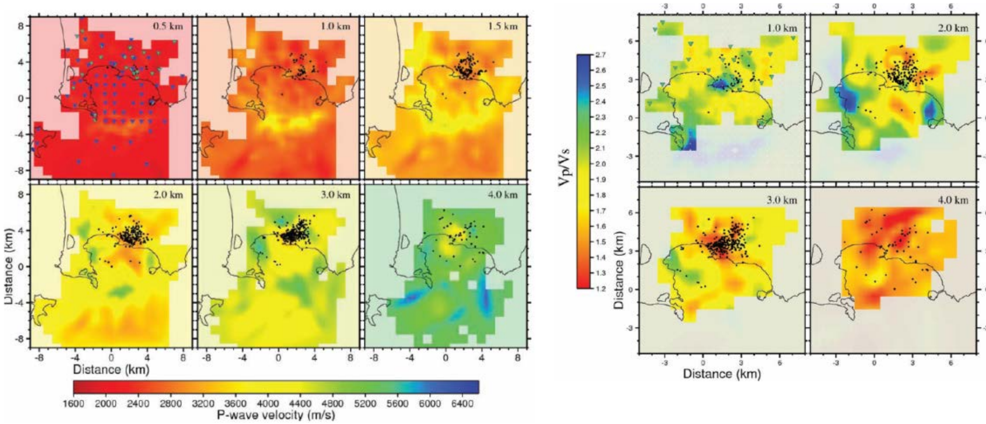
detector p
Mt Asama (Japan), (Tanaka et al, 2007).

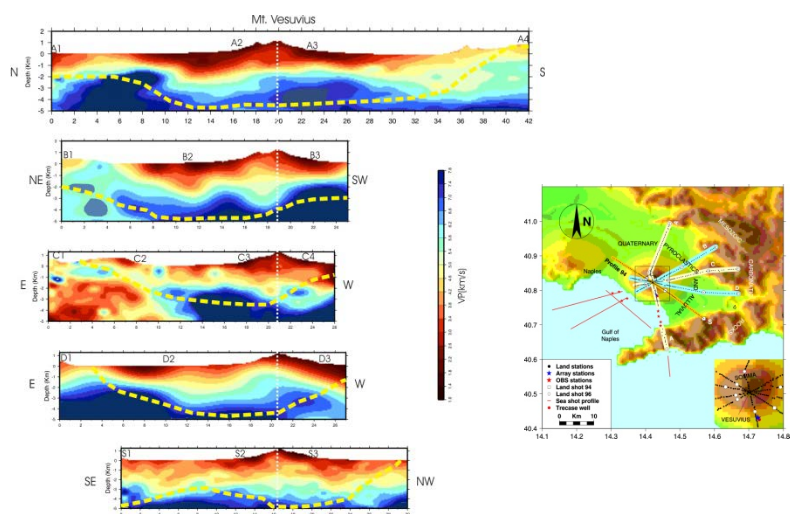


Seismic methods

Active and passive seismic data for 3D tomography of Campi Flegrei caldera in Southern Italy (Battaglia et al., 2008)

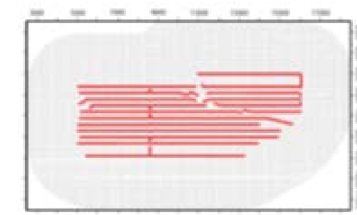


Imaging of the structure of Mt. Vesuvius (Southern Italy) by active seismic data (Zollo et al, 2002)

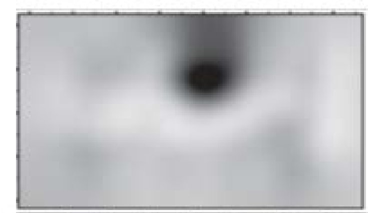


High Resolution Images of Valhall oil field by acoustic full waveform inversion (Etienne et al. 2012)

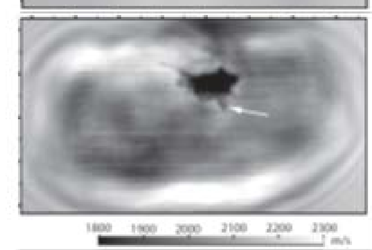
Acquisition Geometry



Initial model



Final model



Seismic methods

Active and passive seismic data for 3D tomography of
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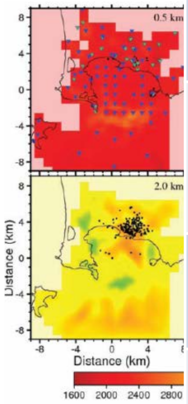

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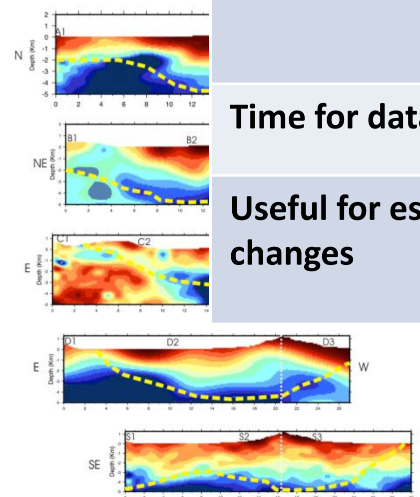
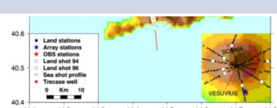
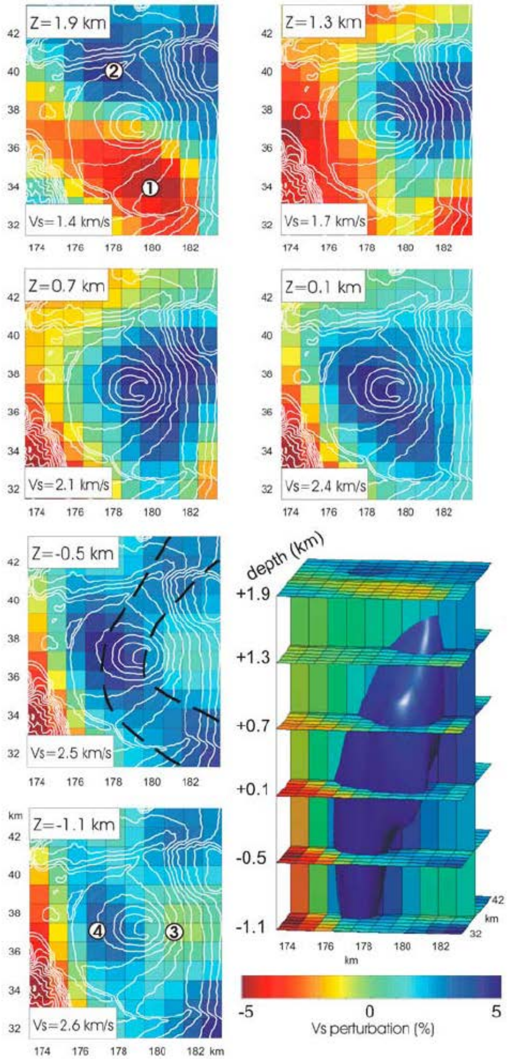


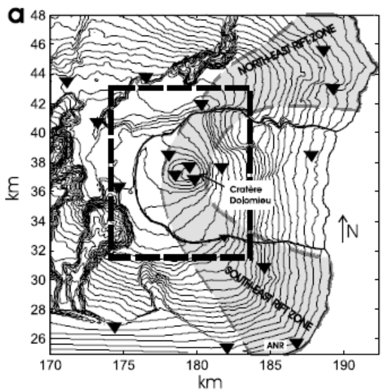


Seismic Methods	
Physical parameter measured	Amplitudes and traveltimes of seismic waves
Operative physical property	Velocity of seismic waves and correlated elastic moduli and density
Typical source of anomaly	Lithology changes, Fracturing and fluid percolation, magma emplacements
Depth of Investigation	All, depends on the acquisition layout
Resolution	Depends on frequency and used method, 2 km for Battaglia model (from checkerboard test), < 100 m (spatial resolution) for the Valahall model
Time for data acquisition	From few hours to few weeks
Useful for estimation of temporal changes	Yes → 4D tomography

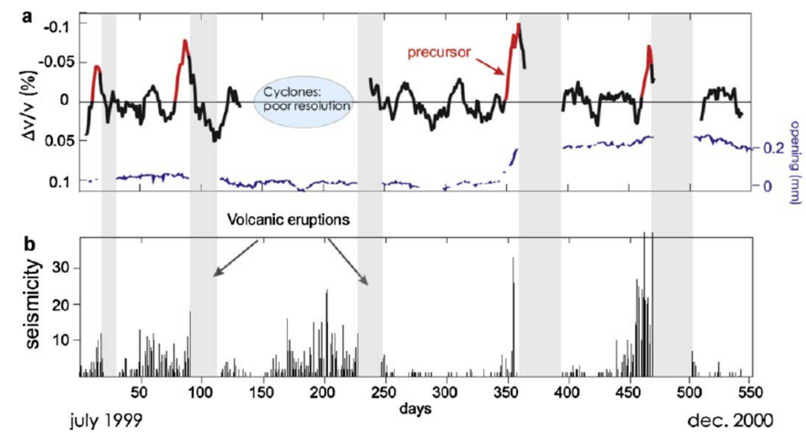
Ambient Seismic Noise

3-D surface wave tomography of the Piton de la Fournaise volcano using seismic noise correlations (Brenguier et al. 2007)





Measurements of temporal changes of Piton de la Fournaise volcano using seismic noise cross-correlations (Brenguier et al. 2011)



Ambient Seismic Noise

3-D surface wave tomography of the Piton de la
Fourna
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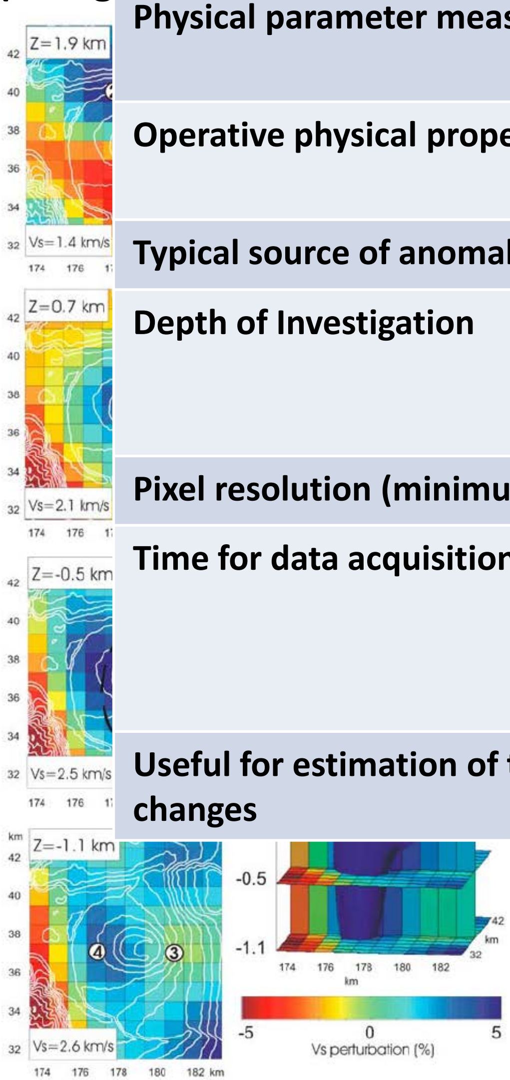
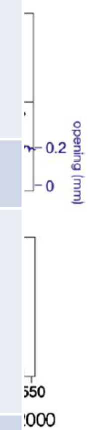
Seismic Ambient Noise Tomography and Interferometric Methods	
Physical parameter measured	**Amplitudes and traveltimes of seismic ambient noise**
Operative physical property	**Velocity of seismic waves and seismic velocity changes**
Typical source of anomaly	**Structures or velocity layers contrasts**
Depth of Investigation	**Few km (for the acquisition geometry used for Piton de la Fournaise), depends on frequency and stations distances**
Pixel resolution (minimum)	**Of the order of few km (spatial resolution)**
Time for data acquisition	**several months for the tomographyc images (18 months of noise data for the Piton de La Fournaise model). For interferometry: small velocity changes (0.1%) with a time resolution as small as one day**
Useful for estimation of temporal changes	**Yes**

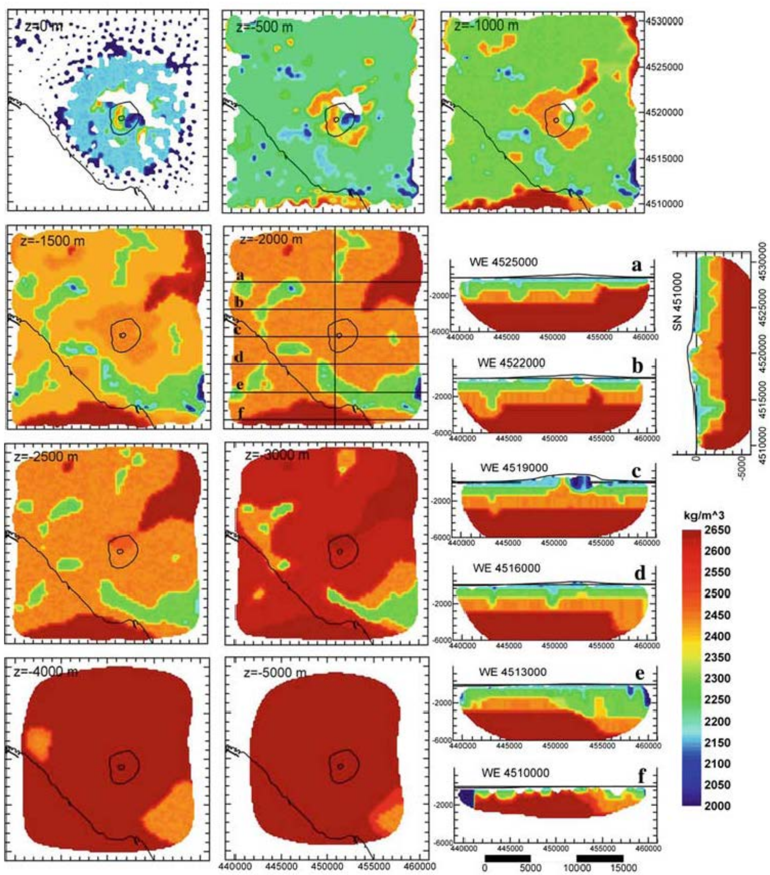


Piton
noise

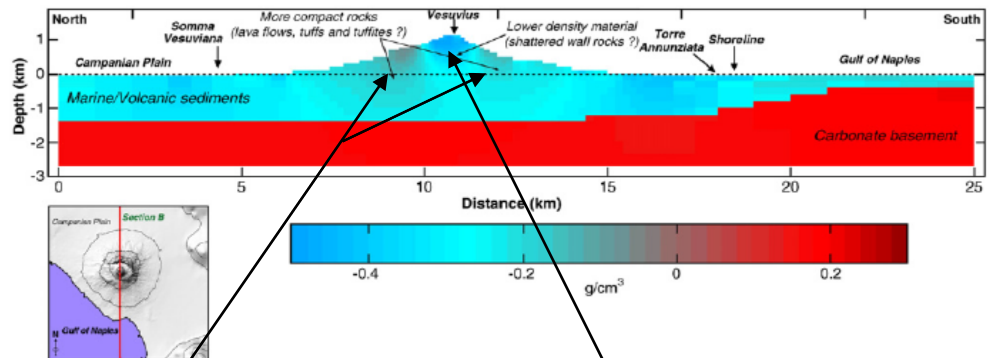


Gravity Method

3D Gravity Inversion at Mt. Vesuvius (Southern Italy) (Berrino et. al, 2008)



Shallow structure of the Somma–Vesuvius volcano from 3D inversion of gravity data (Cella et al. 2007)

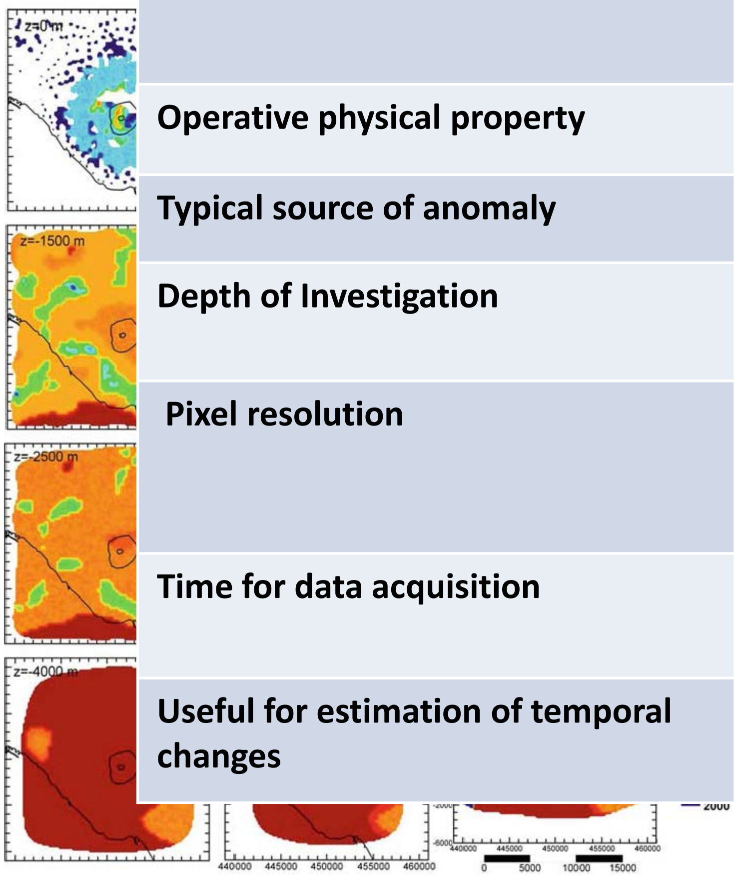


More compact rocks (probably lava flows, tuffs and tuffites)

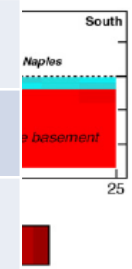
Lower density material

Reference density= 2.4 g/cm^3

Gravity Method

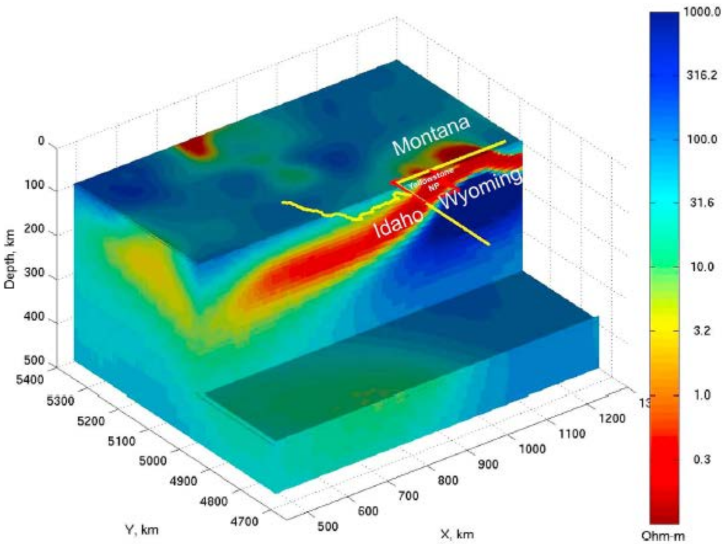


Gravity method	
Physical parameter measured	Spatial variations in the amplitude of the gravity field of the Earth (the vertical attraction of anomalous masses).
Operative physical property	Rock density
Typical source of anomaly	Rock density contrast
Depth of Investigation	All, depends on the profile length or 2D gravity survey surface area
Pixel resolution	Depends on the density of stations, of the order of km (spatial resolution); tradeoff between shape and density amplitude of anomalous body
Time for data acquisition	Depends on the investigated area, from some days to weeks.
Useful for estimation of temporal changes	Yes, but difficult (and costly) to perform

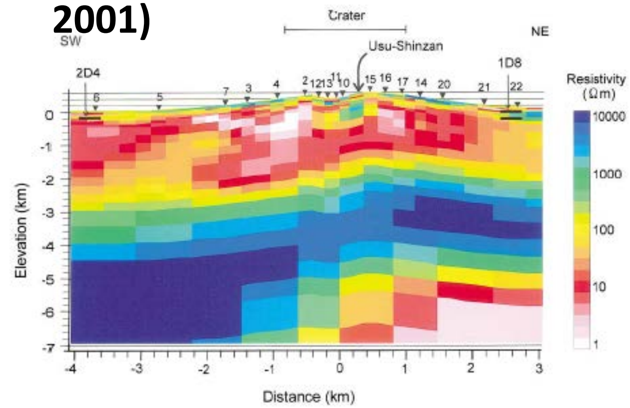


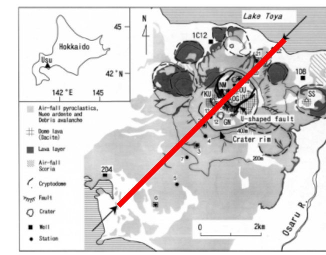
Electromagnetic methods

3D inversion of large-scale magnetotelluric data of the Yellowstone conductive mantle plume (Zhdanov et al., 2011)

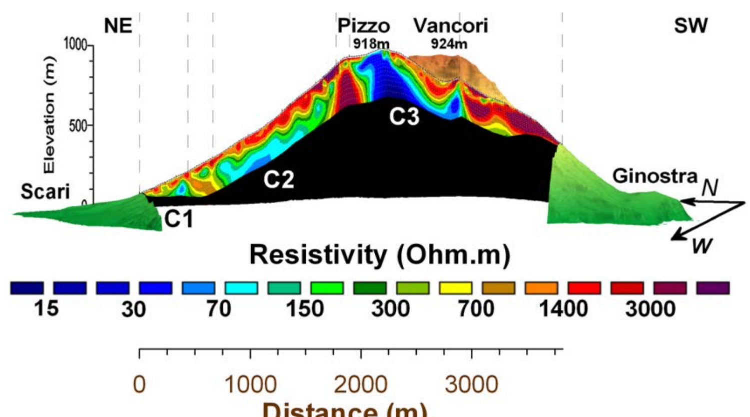


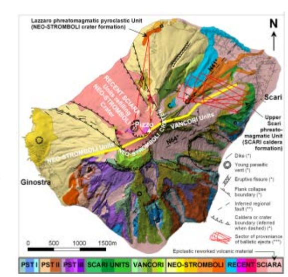
2D image of Usu volcano, (Hokkaido, Japan) using magnetotelluric soundings (Matsushima et al., 2001)





2D image of Stromboli volcano (Italy) by geoelectrical prospecting (Finizola et al., 2006)





Electromagnetic methods

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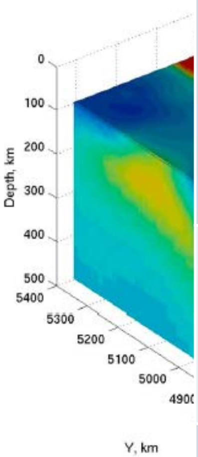

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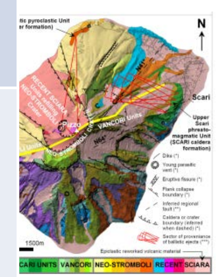

Electromagnetic Methods	
Physical parameter measured	Variations of electrical and magnetic fields
Operative physical property	Rock conductivity and resistivity
Typical source of anomaly	Lateral and vertical changes in conductivity and resistivity
Depth of Investigation	Depends on frequency, of electro-magnetic signals : from 0 m (geoelectrical) down to hundreds of kilometers for MT
Pixel resolution	Depends on the frequency and acquisition layout, spatial resolution of about 100 m on top of Usu model by MT, < 50 m for geoelectrical image of Stromboli. Mostly controlled by presence of fluids and magma
Time for data acquisition	From few hours (for Acoustic MT) to days (geoelctrical and MT measurements) to weeks or more for very deep, very long-period MT measurements
Useful for estimation of temporal changes	Yes

“Muography”: advantages, limits and potential future developments

Strong points

- **high resolution images of low-amplitude gravity contrasts occurring in the shallow part of strato-volcanoes. Complementary and competitive with standard geophysical methods**
- **the method can be remotely operated whilst standard geophysical methods require to be operated on site. This can be difficult due to field conditions, or dangerous due to the volcanic activity.**
- **It can reach extremely high resolutions, depending on the azimuthal coverage of detectors and shape of the anomaly**

Weak points

- **The method is limited to near-surface depths and strongly depends on the nature of the local topography (the detector must be placed on a slope pointing toward a topographically prominent feature of interest, and there will only be results for the volume located above the detector);**
- **the method is limited to horizontal ranges of 2–3 km (which limits the potential targets and pixel resolution)**
- **Not feasible to detect and track rapid density changes within volcanoes (hours to days). Poor depth penetration and resolution.**

Muography: advantages, limits and potential future developments

Next generation Muon observing systems:

- Multiple observations from networks of muon detectors for **high (pixel) resolution 3D volcano images**;
- Reduction of time required to obtain density measurements with reduced statistical and systematic errors → Important for **4D images**, measurements of **temporal variations and for near-real-time monitoring applications**;
- **Borehole** muon detectors, installed at few km depth within the Earth: advanced technologies, not yet available(?)
- Muon detectors **on the seafloor** (difficult process due to density changes in water, the muon tracking process is made more difficult)
- Applications to other geophysical structures/phenomena: will it have the capability to monitor **active fault zones** within the crust?

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