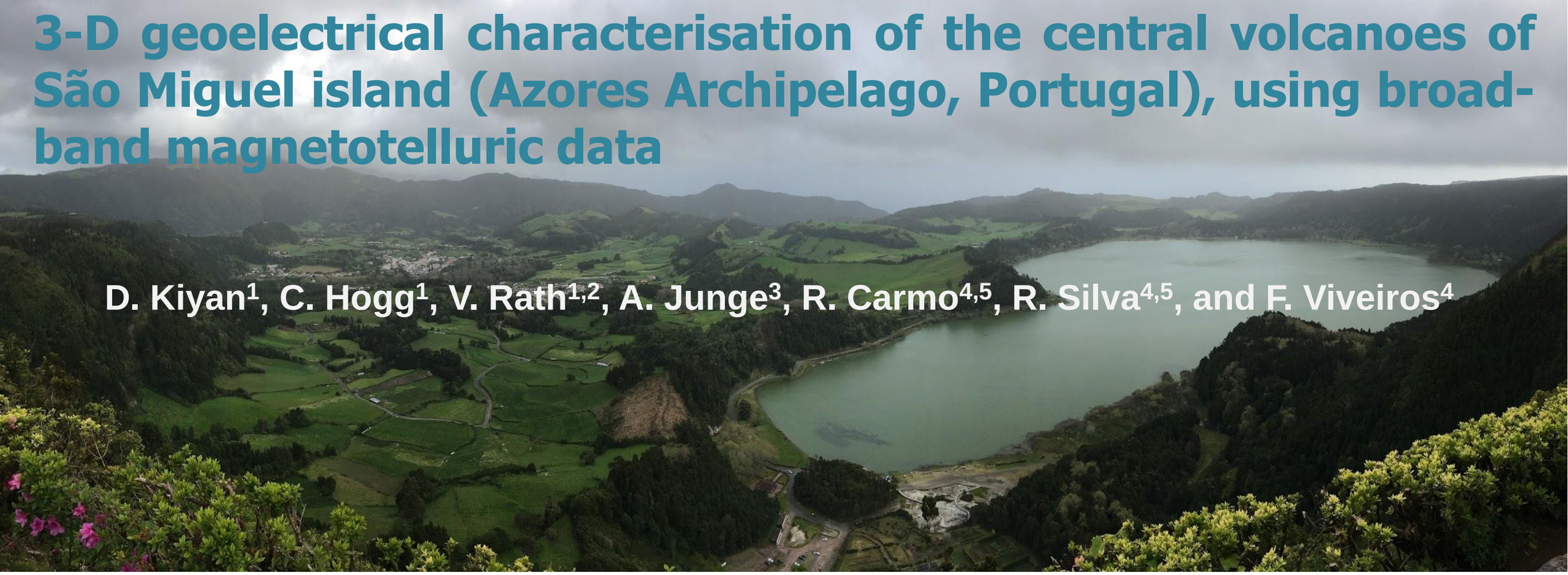
3-D geoelectrical characterisation of the central volcanoes of São Miguel island (Azores Archipelago, Portugal), using broad-band magnetotelluric data



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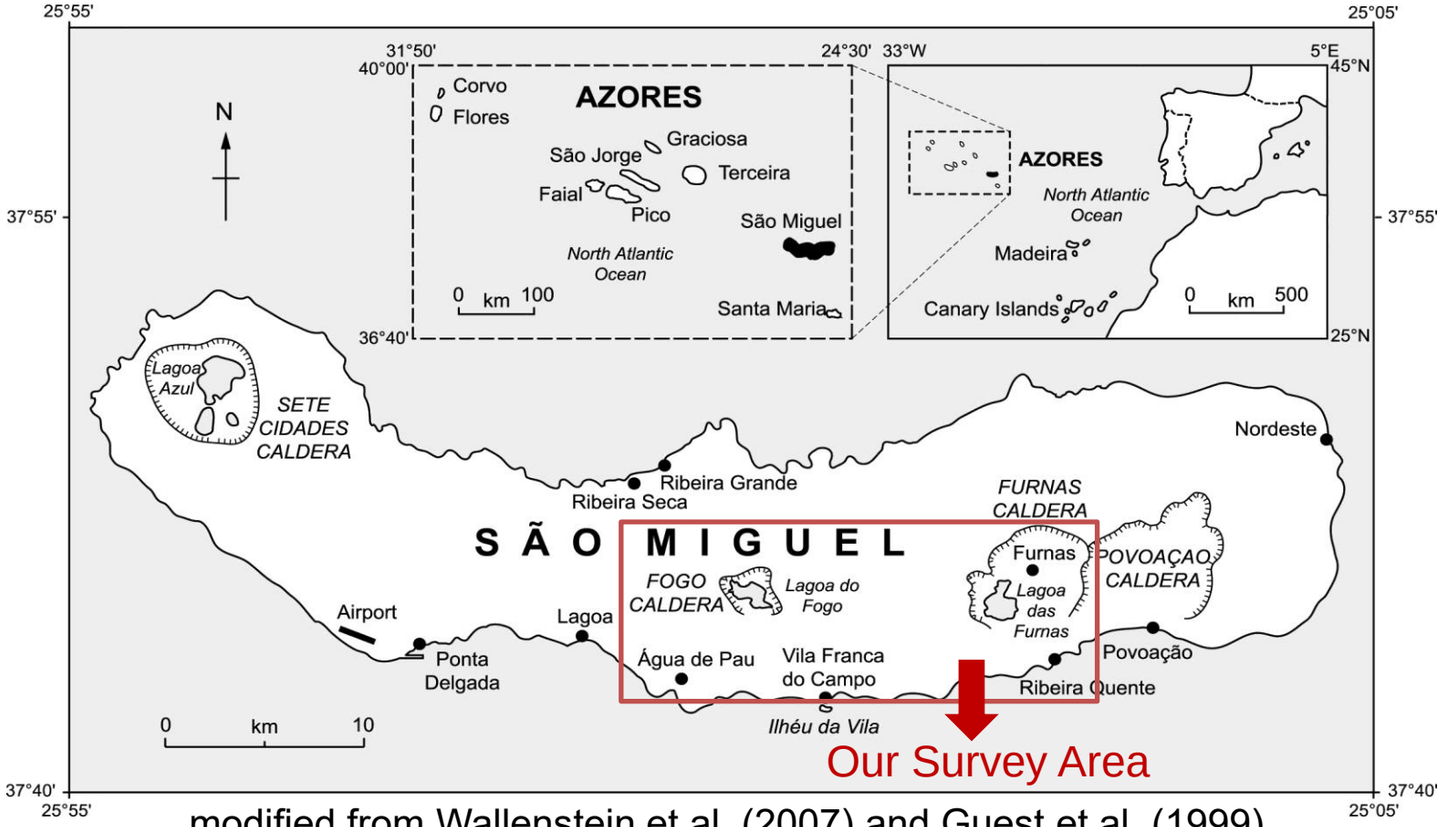
Outline

- Introduction to São Miguel island
- Motivation
- Magnetotelluric assessment of the Fogo and Furnas volcanoes
- On-going research

Azores Archipelago: a brief introduction



modified from Wallenstein et al. (2007) and Guest et al. (1999)

Furnas Volcano

Fogo Volcano

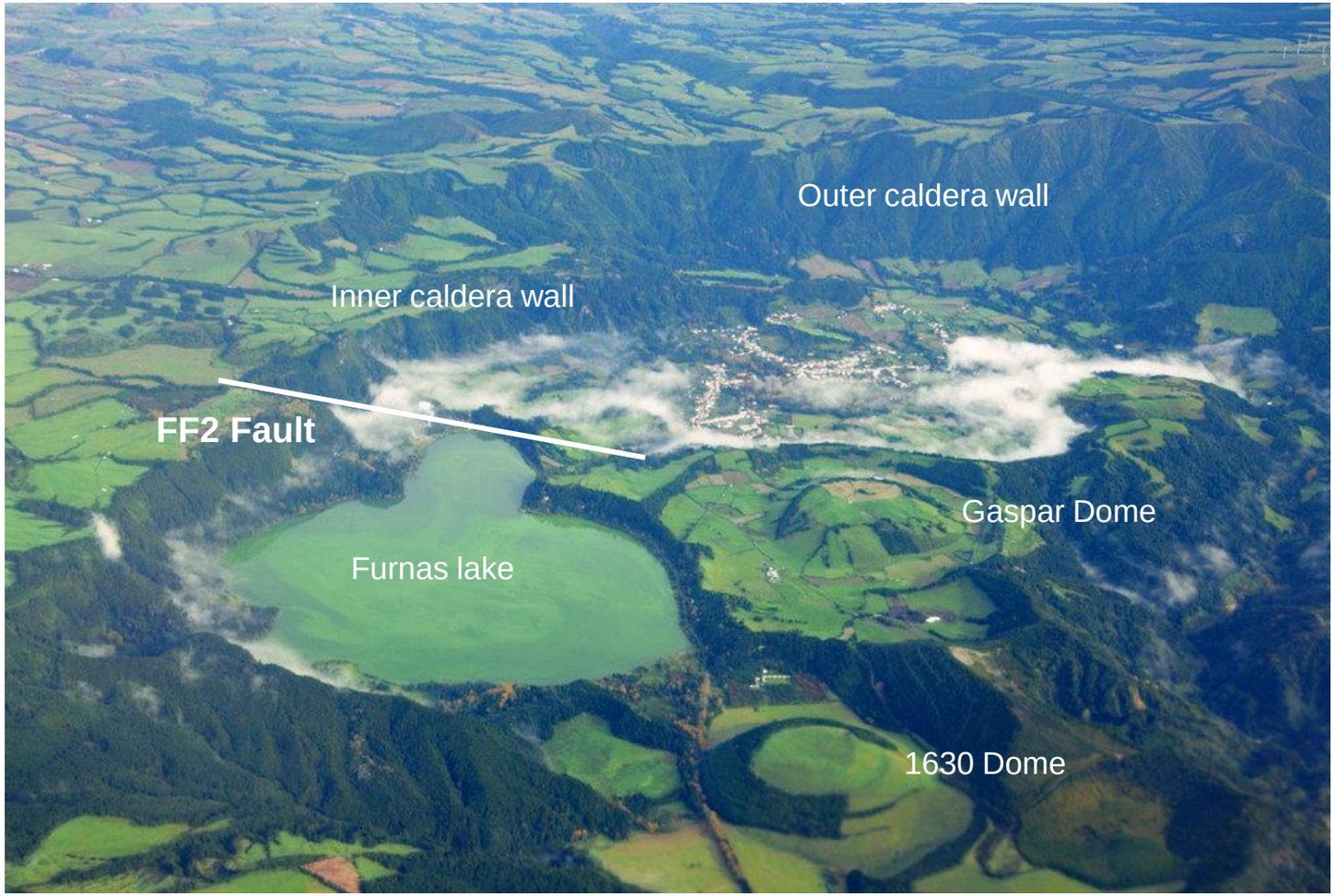
Azores Archipelago: 9 volcanic islands

Triple junction where the Eurasian,

the North American, and the Nubian Plates meet!

São Miguel Island: 3 volcanic centres: Sete Cidades, **Fogo** and **Furnas**

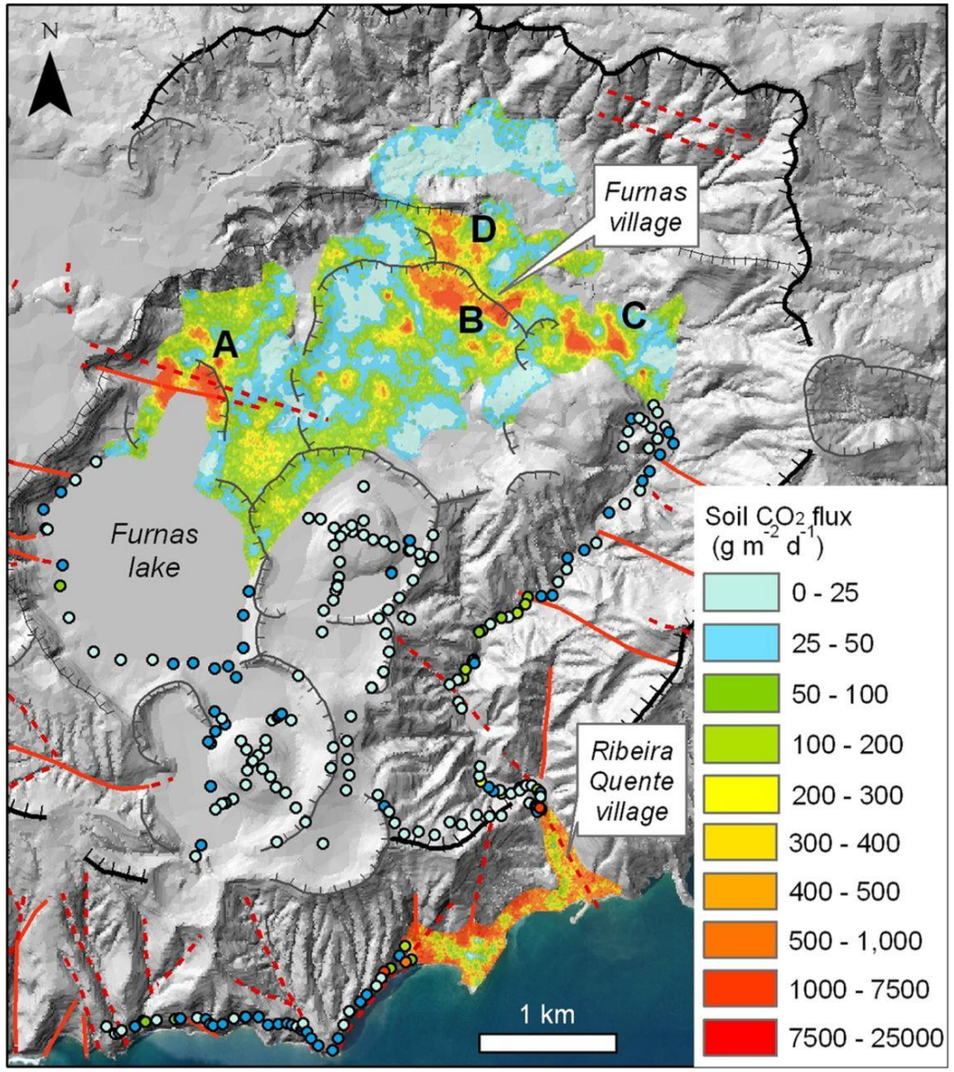
Survey Area I: Furnas Caldera



- Caldera complex
- Outer caldera 8 km x 5 km, and
  Inner caldera 6 km x 3.5 km
- WNW-ESE trending dip-slip faulting crosses the volcanic edifice (so called FF2 Fault)
- Two recent big eruptions 1439-43 AD, and 1630 AD produced volcanic domes

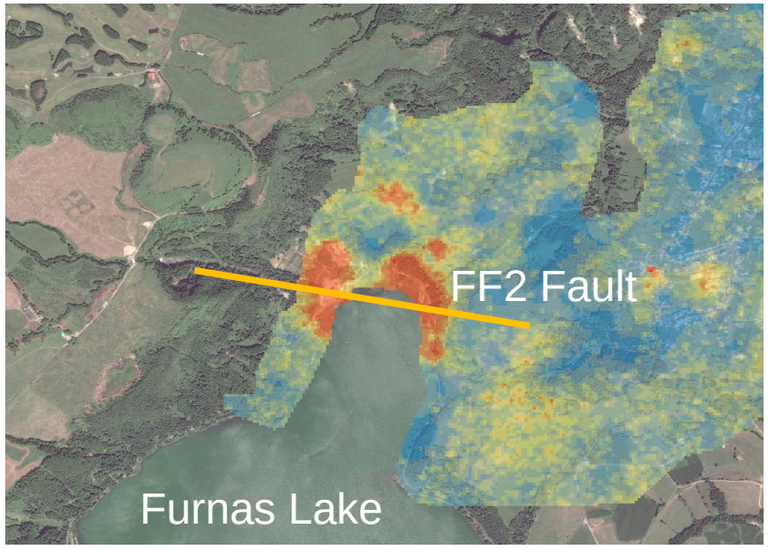
Survey Area I: Furnas Caldera

- Intensive CO_2 / Radon outgassing



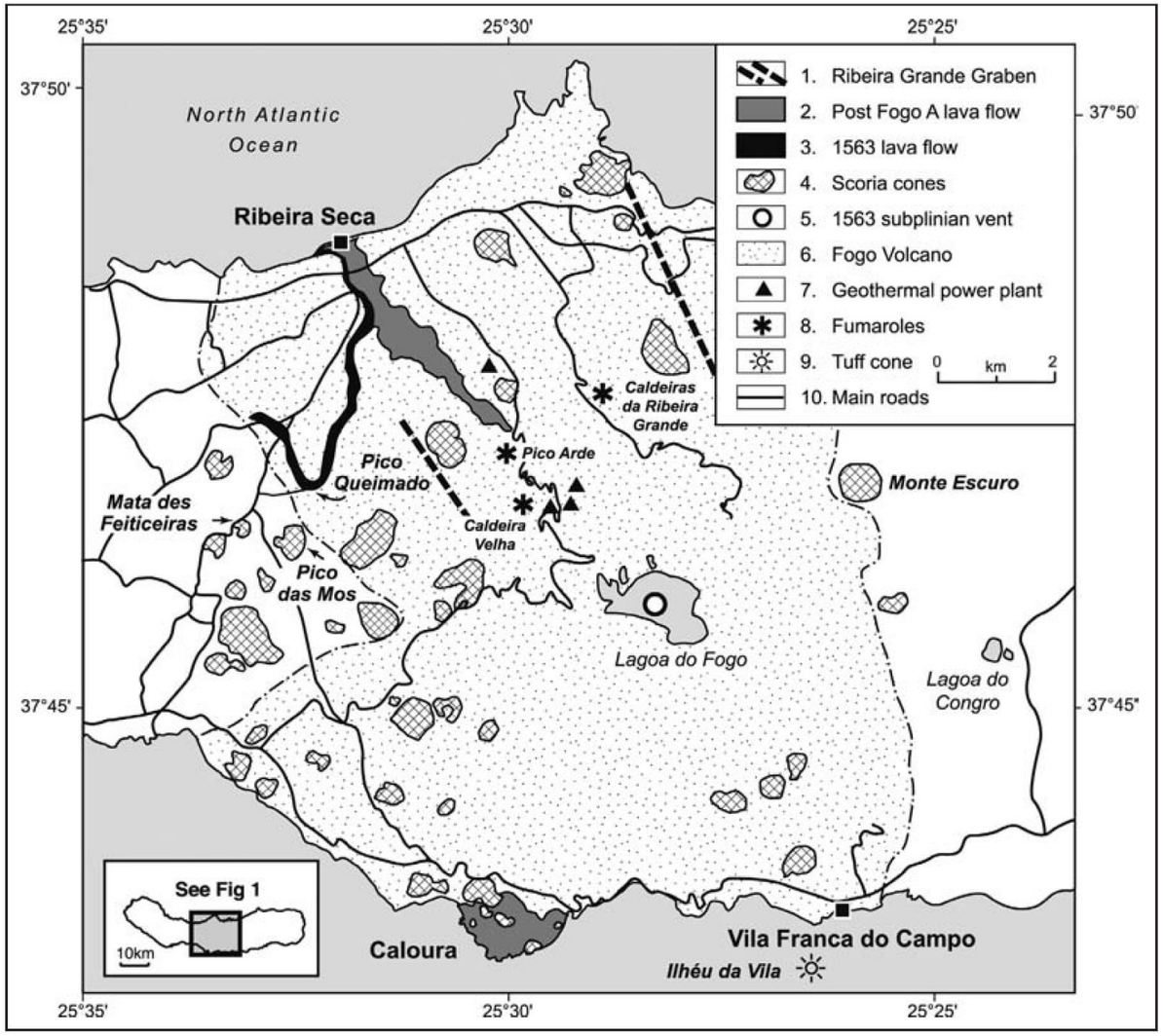
(Viveiros et al. 2010)

Zoom into region A



(modified after Viveiros et al. 2010)

Survey Area II: Fogo-Congro region



Volcanic structures and geothermal surface manifestations in the Fogo volcano (from Wallenstein, 2007)

- Fogo Volcano, also known as Agua de Pau, is the largest of the three central volcanoes.
- The volcano is considered to be dormant but still dominates the topography of the island.
- It exhibits geothermal manifestations including fumarole fields, hot springs and soil diffuse degassing areas, with the main features being present at Pico Vermelho (near Pico Arde), Calderia Velha and Caldeiras da Ribiera Grande on the northern flank of Fogo Volcano.

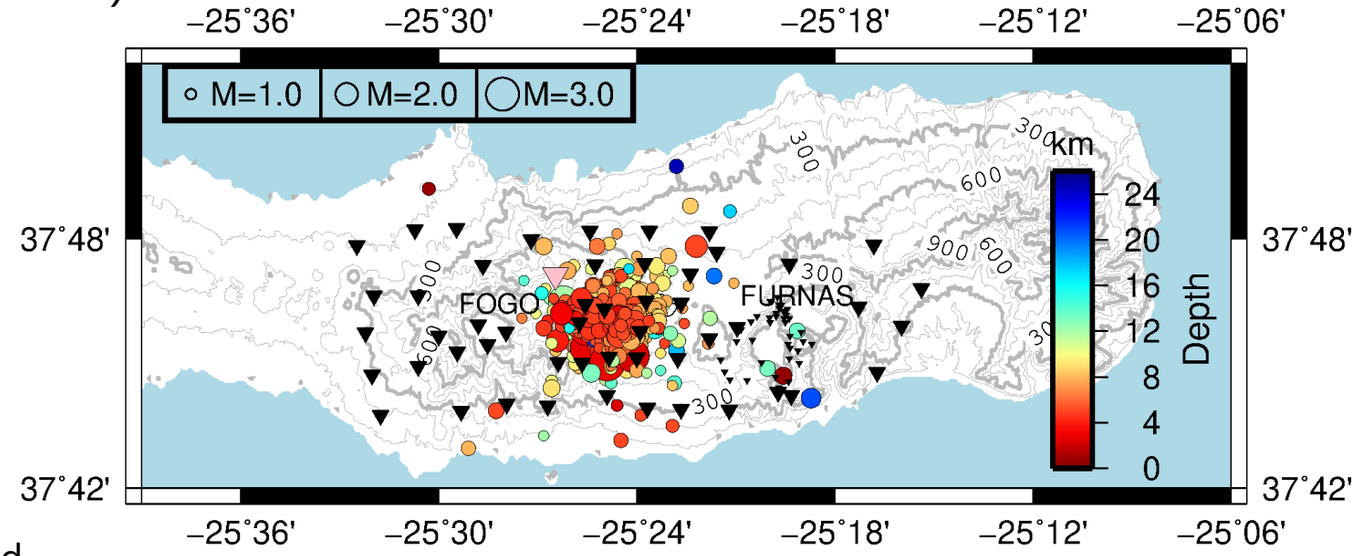
Scientific Objectives

Furnas volcano:

- Characterise the 3-D geoelectrical structure of the volcano
- Investigate the relationship between fault systems and gas/fluid (CO_2 & Radon gas) concentrations / pathways
- Understand the roles of fluids and clay material within the volcano-hydrothermal system

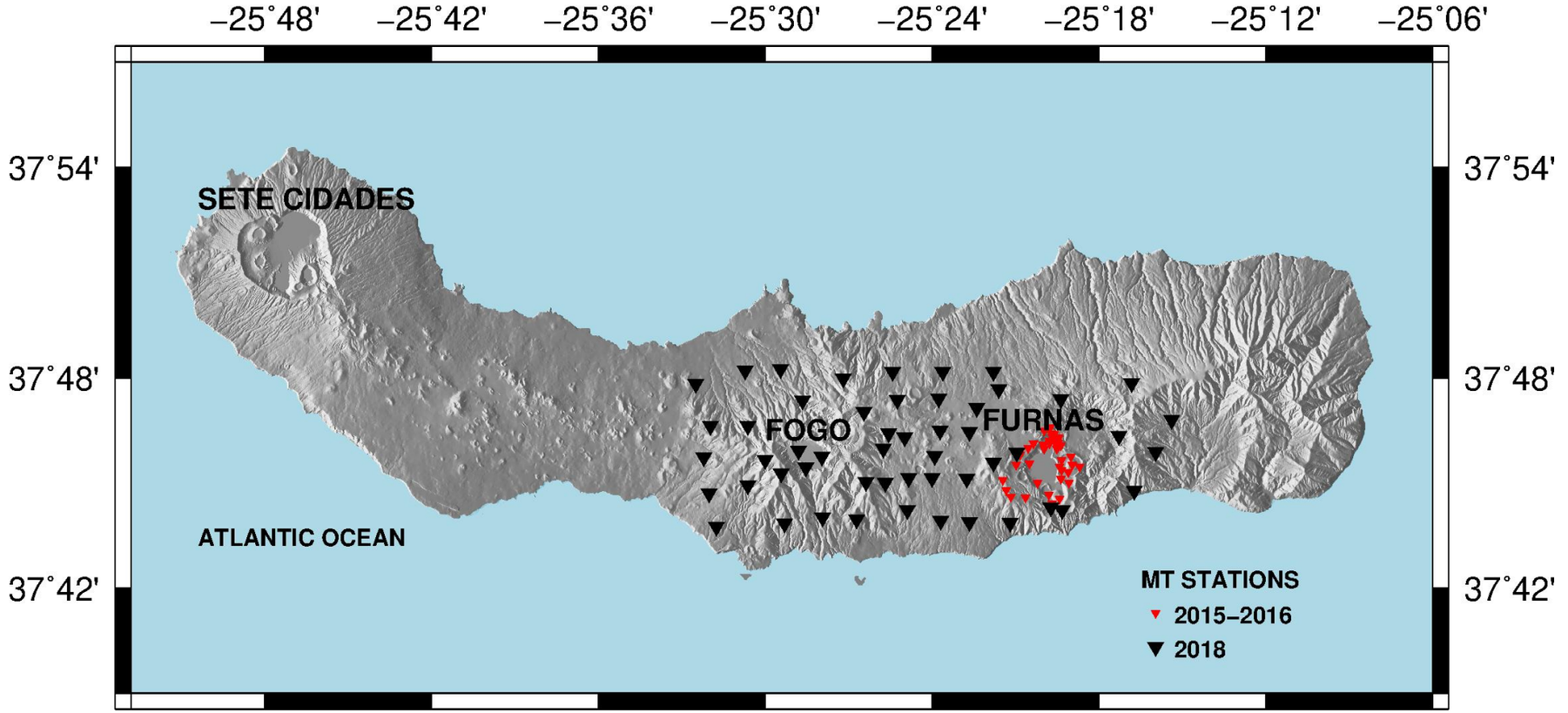
Fogo volcano:

- Geoelectrical characterisation of Fogo volcano and the Congro Region, where swarms of seismic activity occur (as recent as February 2018!)



Seismic activity (February 2018) on Fogo/Congro. Black inverted triangles represent the MT stations.

Magnetotelluric (MT) Data

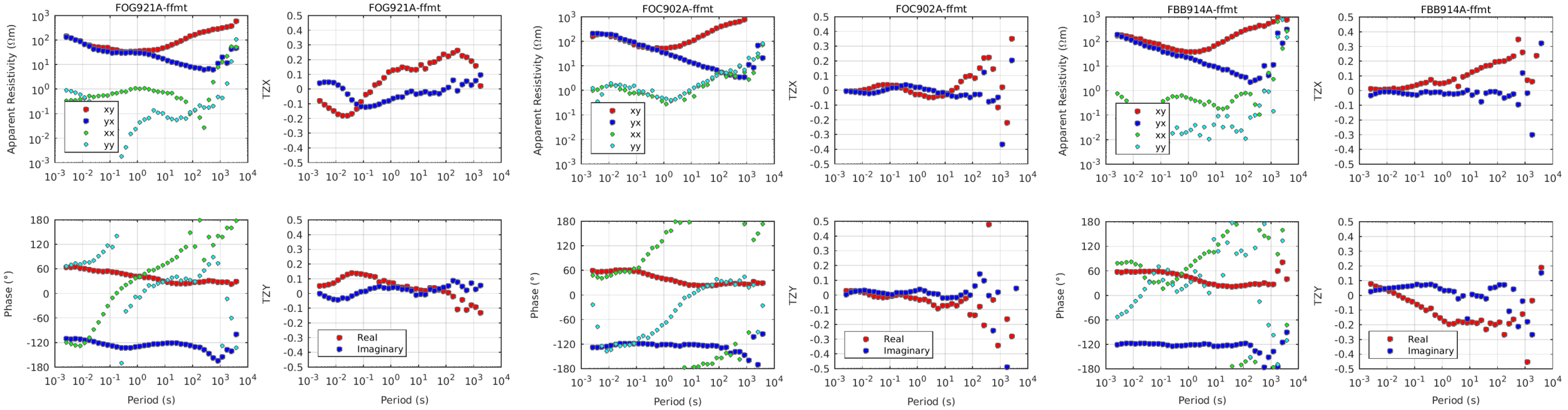


- Phase I field Campaign in 2015-2016: a total of 39 high-frequency MT stations and 15 broad-band MT stations
- Phase II field Campaign in 2018: a total of 55 broad-band MT stations
- Full Tensor MT data & vertical magnetic field data were recorded at all stations
- Very good data quality 1000 Hz – 1000+ s

MT Data

Sample Data curves from Fogo-Congro region

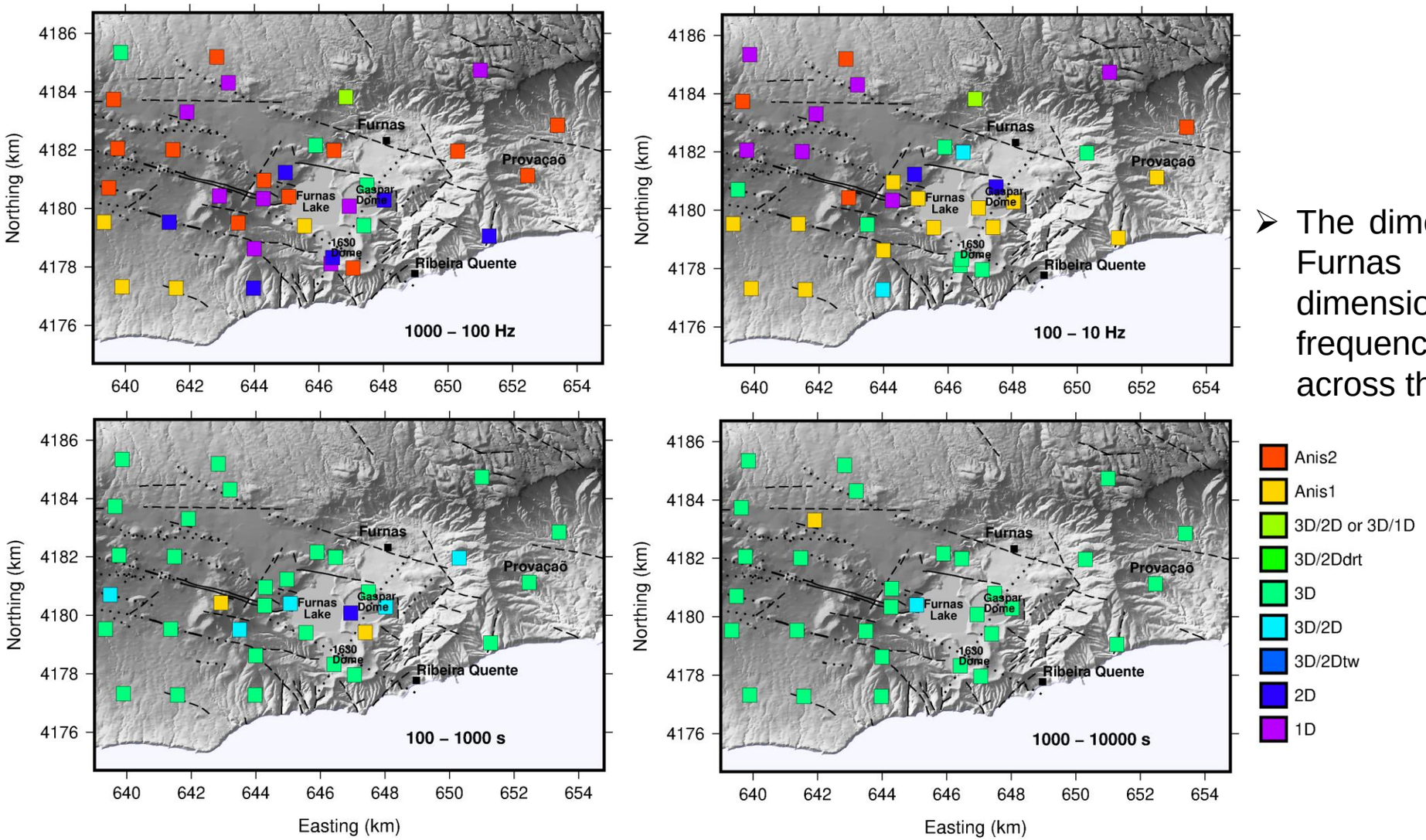
Data curves from Furnas



- MT data have been processed with three different processing codes: Phoenix processing code (based on Jones & Jödicke (1984), Egbert processing code (Egbert, 1997) and EGstart code (Hering 2019) developed by the University of Frankfurt.

- Three processing codes have yielded similar results, however, EGstart (presented above) yielded the far superior result with a significant improvement in the Tipper data.

Furnas Volcano: MT data

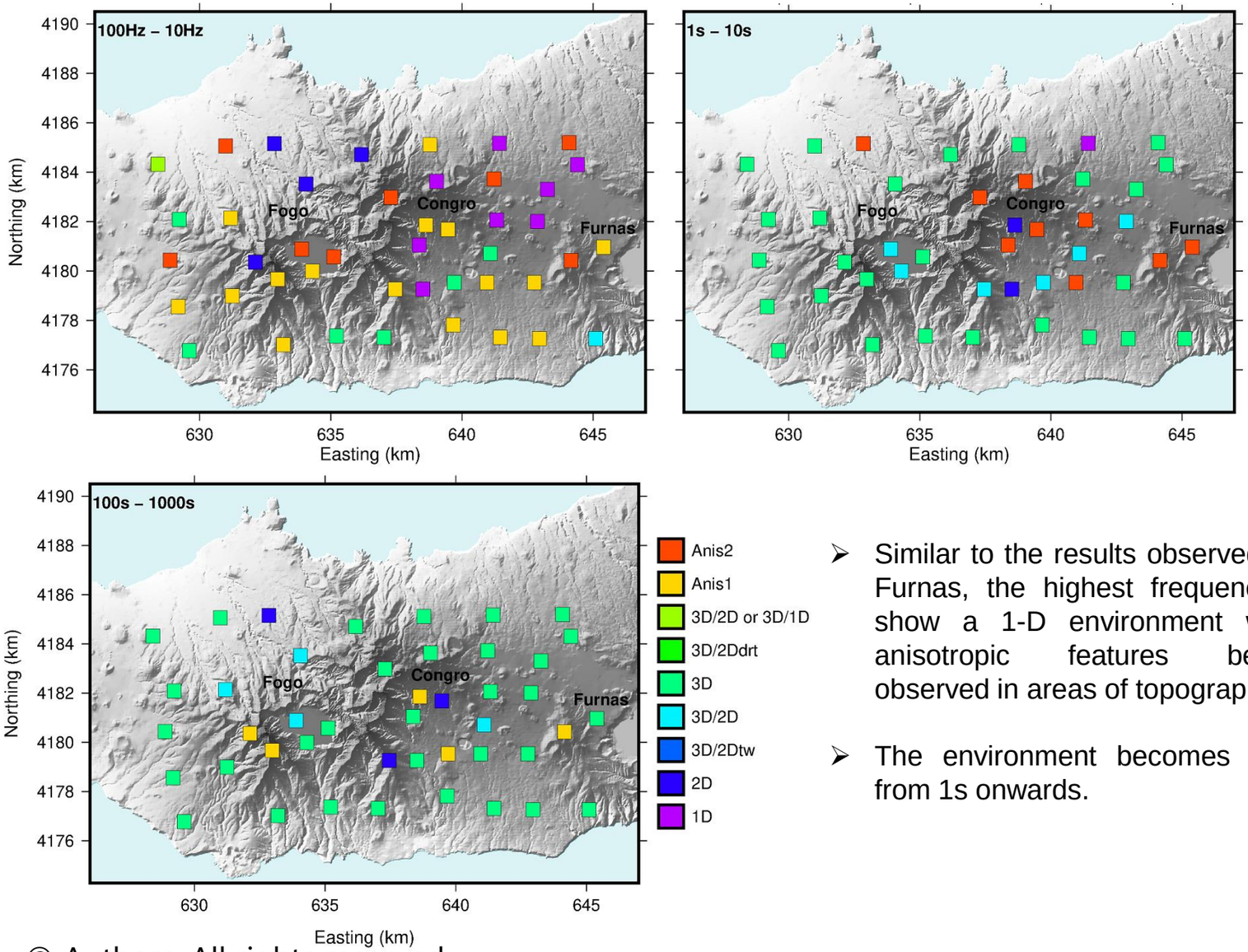


- The dimensionality analysis indicate that Furnas volcano is complex, with dimensionality ranging from 1-D (high-frequency range) to 3-D (100 – 10,000 s) across the frequency bands.

WALDIM (Martí et al., 2009) dimensionality analysis

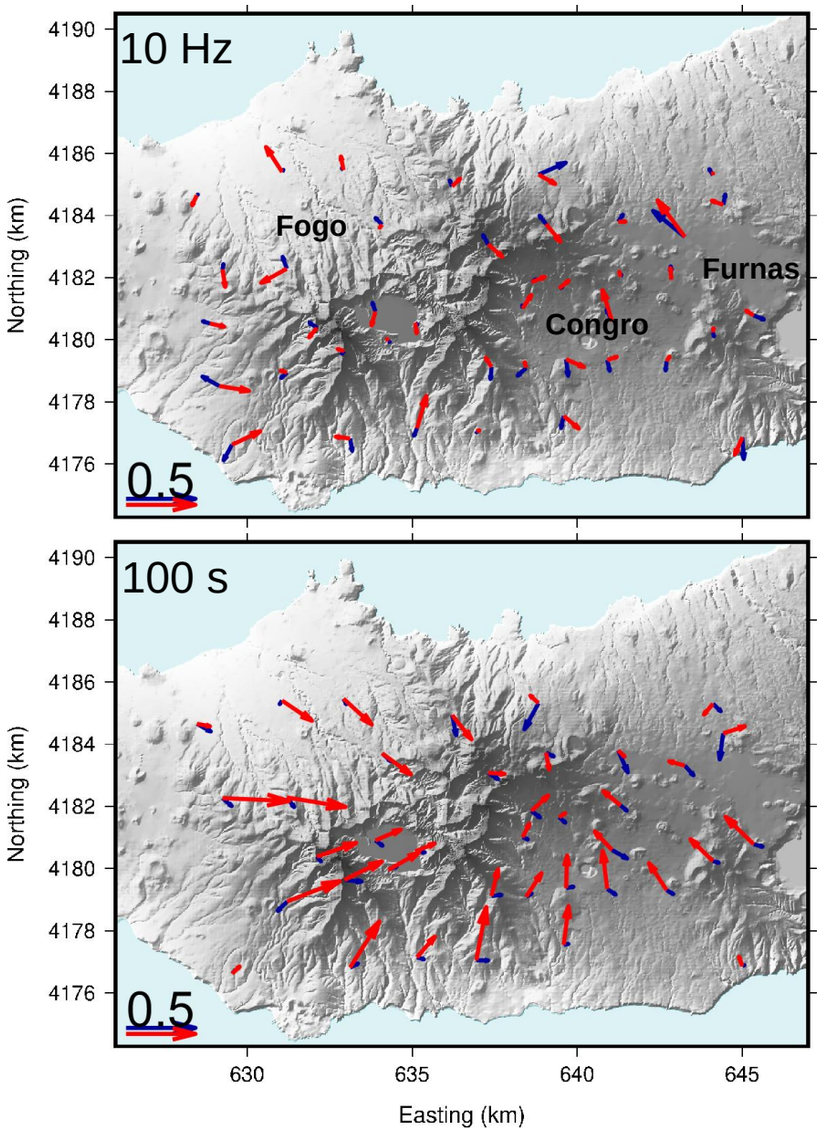
Fogo Volcano: MT data

WALDIM dimensionality analysis



- Similar to the results observed at Furnas, the highest frequencies show a 1-D environment with anisotropic features being observed in areas of topography.
- The environment becomes 3-D from 1s onwards.

Tipper Data (Wiese convention)



3-D MT Inversion

3-D MT Inversion Code, ModEM (Meqbel, 2009; Egbert and Kelbert, 2012; Kelbert et al. 2014)

Furnas Volcano (current) MT Model

3-D mesh set-up:

- 91 (N-S) x 113 (E-W) x 156 (vertical) (plus 10 air layers)
- horizontal cell size 200 m x 200 m
- thickness of the first layer is 50 m
- topography and bathymetry data are included
- starting model resistivity is set to 100 Ωm

Input Data:

- off-diagonal components of the impedance tensor data in the period range of 0.001 s – 5,000 s
- 35 MT sites, and 28 frequencies per site were used.
- error floors were set as an absolute value of 3% of |Zij| for Zxy and Zyx

Note: Inversions with ZZ, ZT, ZZT data are currently being performed..

Fogo Volcano preferred MT Model

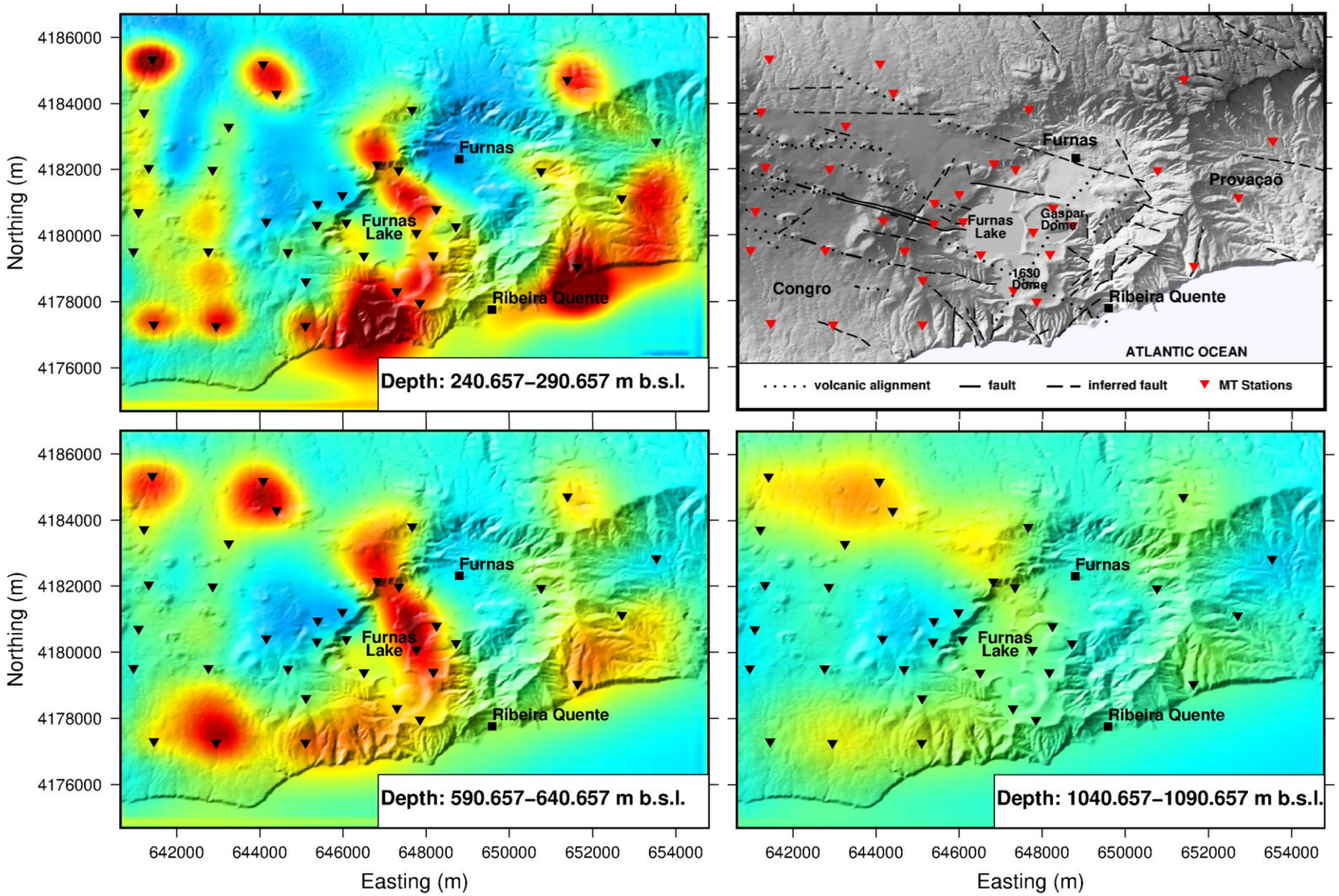
3-D mesh set-up:

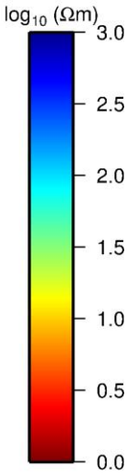
- 93 (N-S) x 135 (E-W) x 152 (vertical) (plus 10 air layers)
- horizontal cell size 200 m x 200 m
- thickness of the first layer is 50 m
- topography and bathymetry data are included
- starting model resistivity is set to 100 Ωm

Input Data:

- simultaneous inversion of full impedance tensor and tipper data in the frequency range of 1,000 Hz – 1Hz
- 44 MT sites, and 11 frequencies per site were used.
- error floors were set as an absolute value of 3% of $(|Zxy \times Zyx|^{1/2})$ for Zxx, Zxy, Zyx, and Zyy; for vertical transfer functions, a constant error of 0.02 was used.

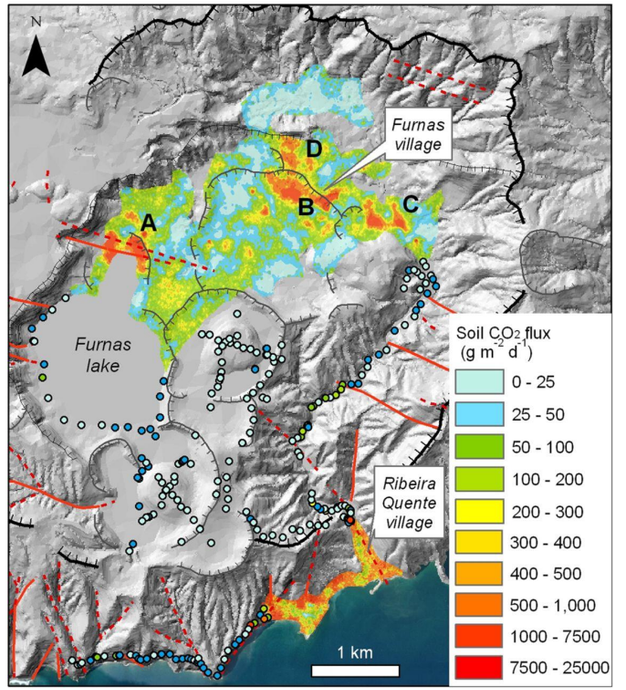
3-D MT Inversion Results – Horizontal Depth Slices: Furnas Volcano





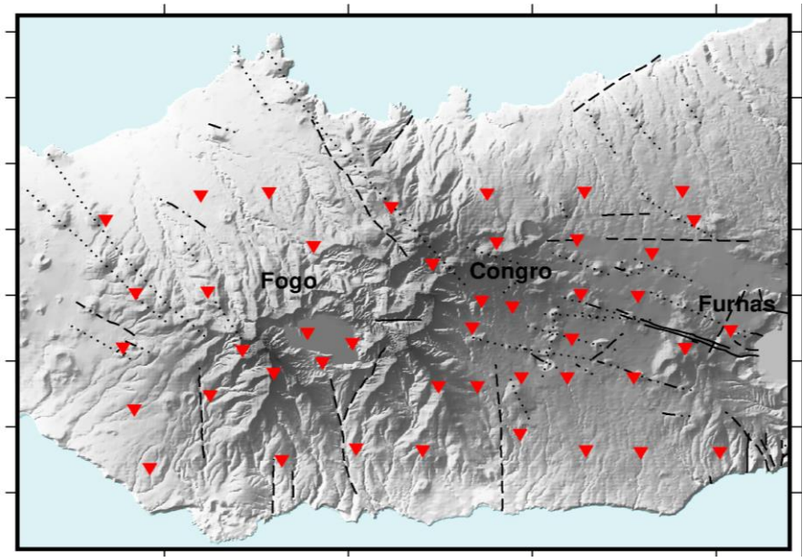
Previously imaged volcano-hydrothermal system using the high frequency MT data (Hogg et al., 2018) extends across the outer-caldera to regions where there are elevated CO_2 gas emissions.

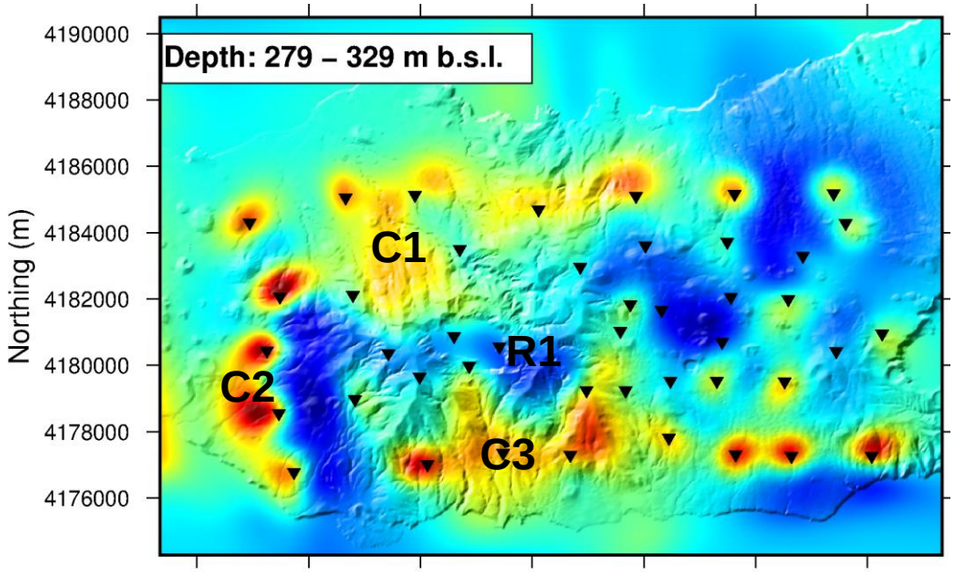
At Ribeira Quente, significant gas anomalies correlate with the fractures that cross the caldera. However further modelling studies will be required to assess if these areas are linked.

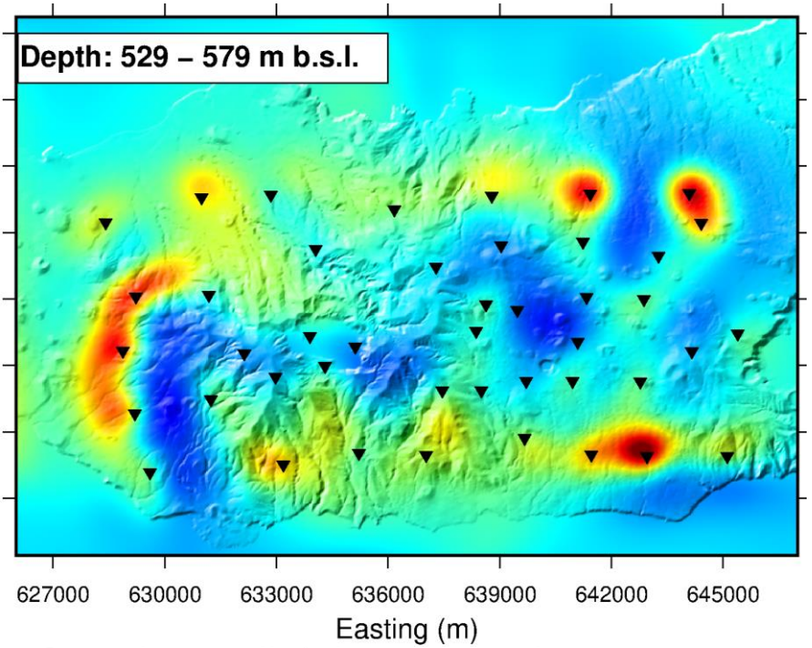


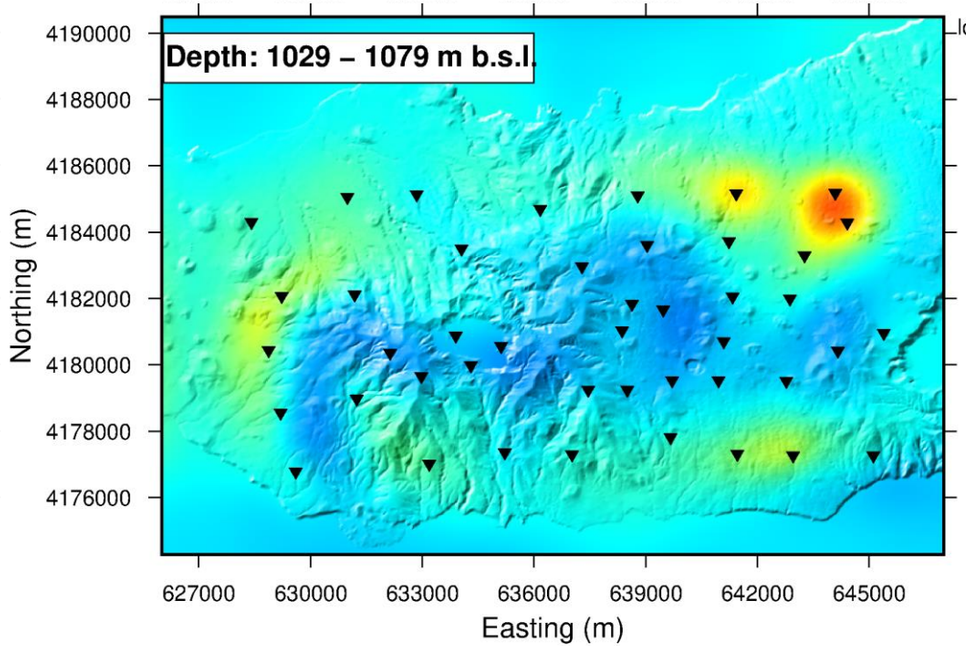
(Viveiros et al. 2010)

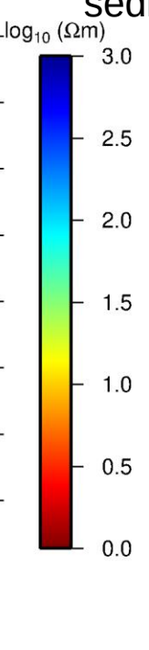
3-D MT Inversion Results – Horizontal Depth Slices: Fogo Volcano











C1: correlates well with the Ribeira Grande geothermal system, which is a high temperature system with temperatures up to 245°C, hosted by volcanic rocks, mainly pyroclastic units and lava flows (Franco, 2015)

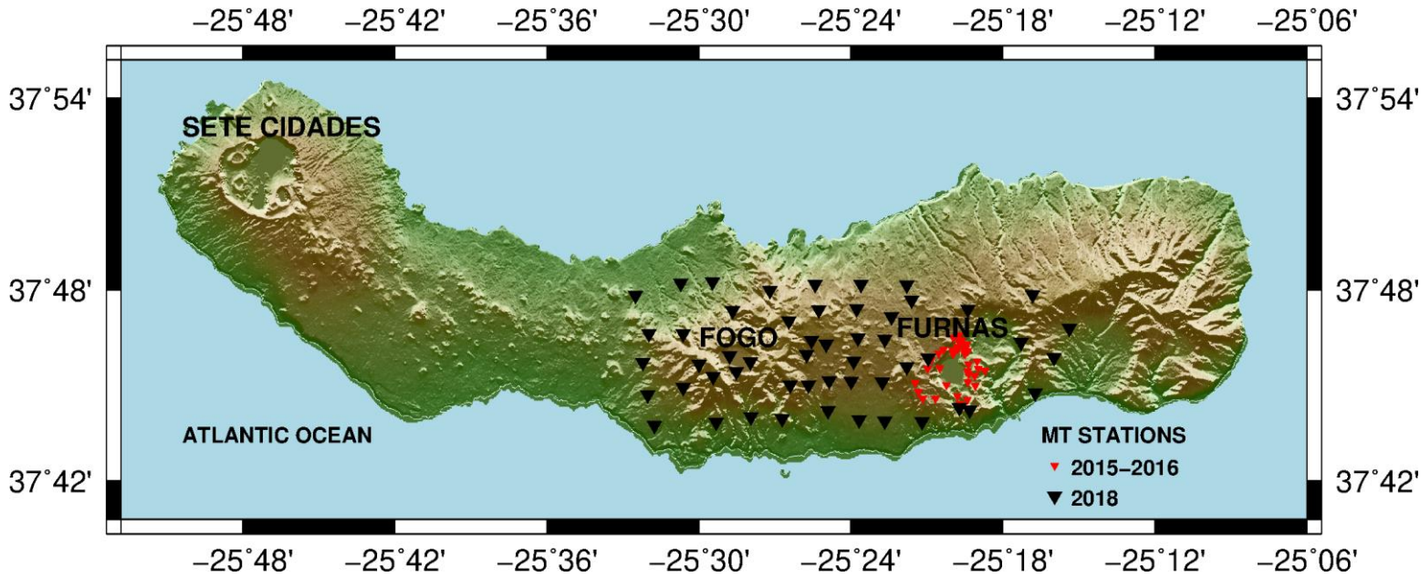
C2: is definitely present, possibly fault controlled

C3: possible geothermal resource in the south, however could be saturated sediments, land slides?

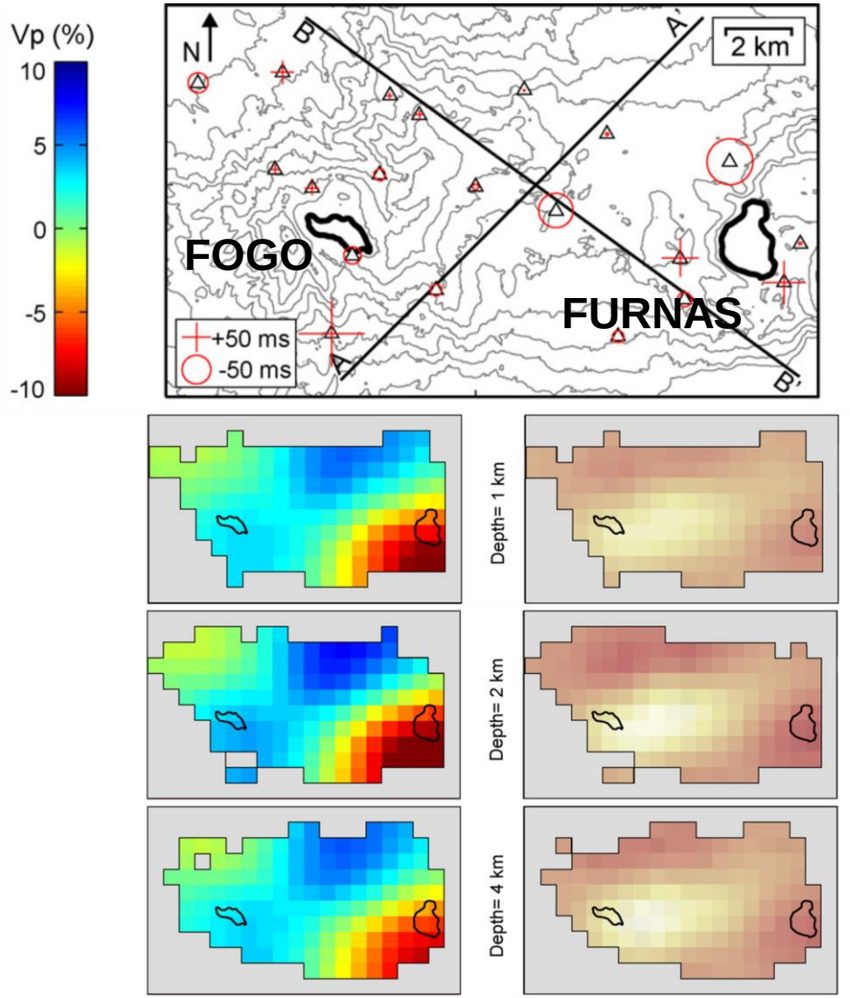
R1: resistive core, which extends towards Congro region, where the majority of seismicity occurs, and towards Furnas

On-going Research

- 3-D inversion of Furnas MT data with tipper data included
- Interpretation of the conductivity structures obtained in the 3-D models
- Performing forward simulations on the detectability of the magma source proposed at 3 - 6 km depth beneath Furnas through geochemistry, magnetic and seismic tomography (Zandomeneghi et al., 2006)



Velocity Models



Tomographic inversion of P and S travel times (after Zandomeneghi et al., 2006)

THANK YOU!

Acknowledgements

This multi-year research has been primarily financed by the Dublin Institute for Advanced Studies. Patrick Cannon, Franz Martinez, Ernesto Sousa, and Victor Sousa are thanked for their full support during the field campaign in 2018. The Irish Centre for High Performance Computing (ICHEC) is thanked for availing the Kay cluster to carry out the numerical computations. Finally, we thank Gary Egbert, Anna Kelbert, and Naser Meqbel for making their ModEM code available to us. Some of the figures are plotted using the GMT of Wessel and Smith (1991) and Wessel and Smith (1998).

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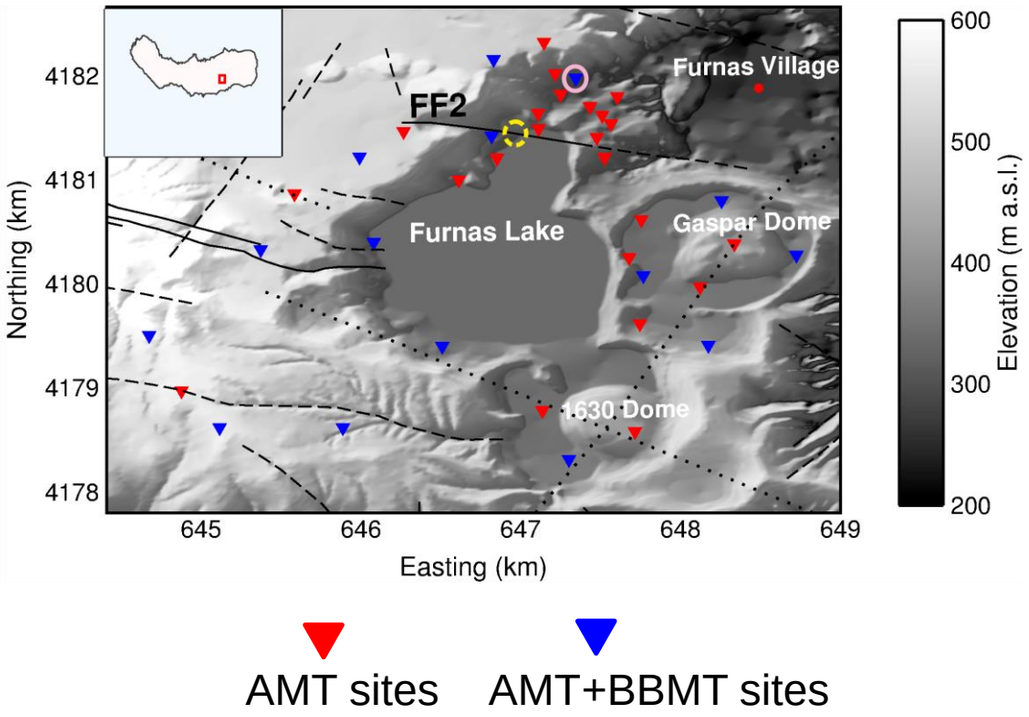
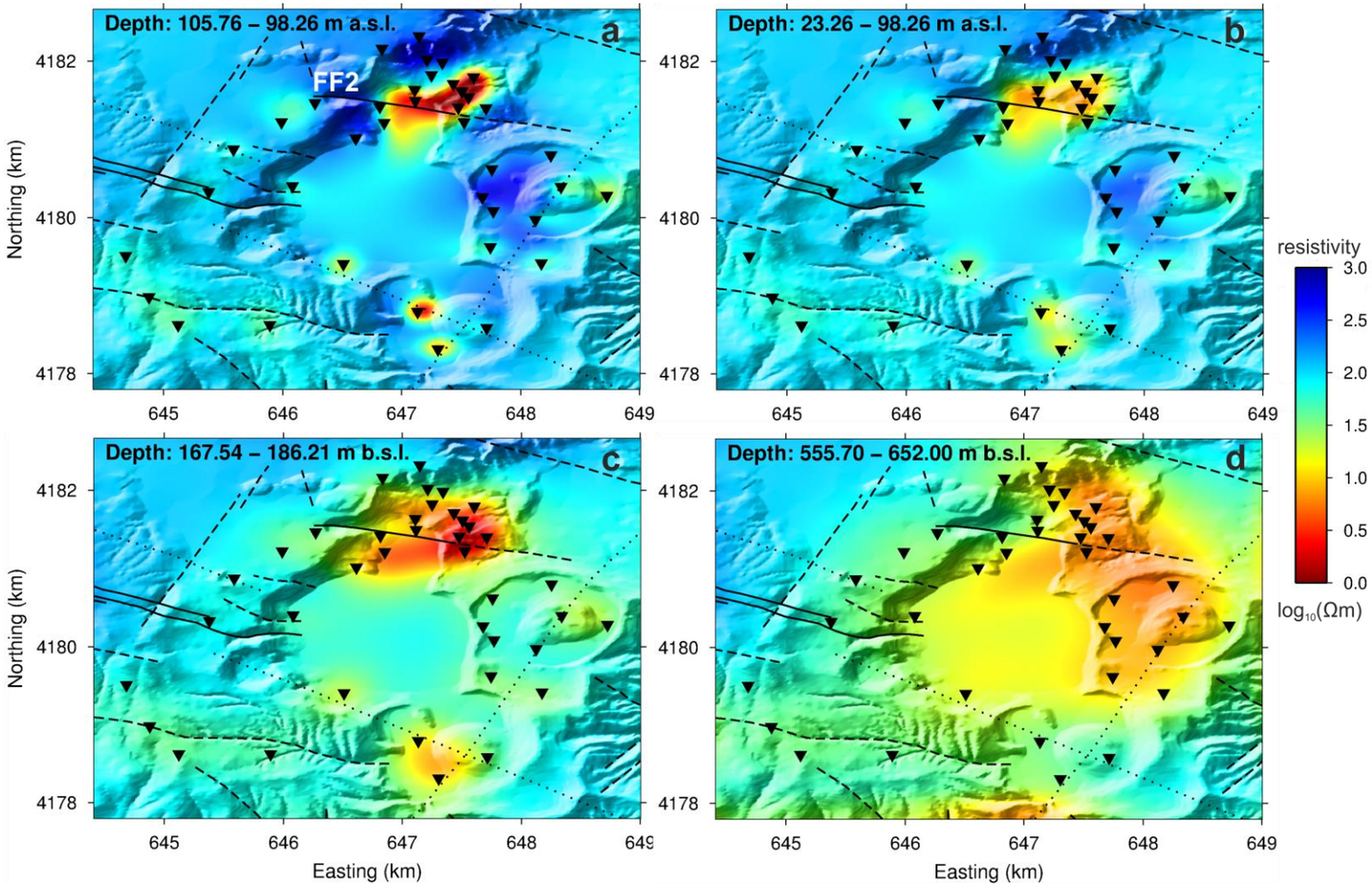
Shallow hydrothermal system of Furnas Volcano using high- frequency MT data





Horizontal slices of the final resistivity model at various depth

(Hogg et al., 2018)