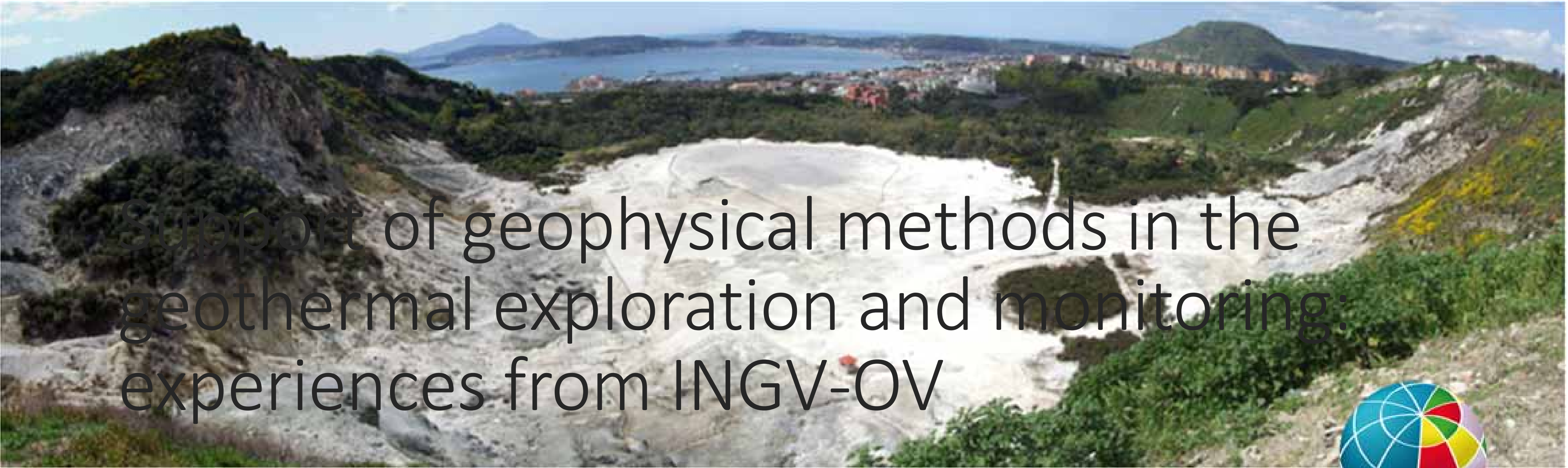


Support of geophysical methods in the geothermal exploration and monitoring: experiences from INGV-OV

TOMMASO PIVETTA, ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA- OSSERVATORIO VESUVIANO (INGV-OV)
tommaso.pivetta@ingv.it

CONTRIBUTORS: STEFANO CARLINO, MARIA GIULIA DI GIUSEPPE, ANTONIO TROIANO, ROBERTO ISAIA, UMBERTO RICCARDI

Outline

- Activities at INGV-OV: volcano monitoring, research in geophysics and volcanology
- Role of geophysics in defining some physical parameters and geometries of the underground medium. Applications and study cases
- Monitoring a geothermal fields through geophysical methods: experiences from the INGV

National Institute of Geophysics and Volcanology-Osservatorio Vesuviano (INGV-OV)

Osservatorio Vesuviano: one of the oldest Volcanological Observatories in the world (estabished in 1841)

Part of the National Institute of Geophysics and Volcanology (INGV)

INGV-OV in charge of monitoring three active volcanoes in the Neapolitan area:
- Vesuvius
- Campi Flegrei
- Ischia

About 100 researchers and technical stuff involved in **studying and monitoring volcano processes**, **geothermal** systems, **geodynamics**…

Geothermal projects at INGV-OV

GEISER: Geothermal Engineering Integrating
Mitigation of Induced Seismicity in Reservoirs
FP7-ENERGY-2009-1 (ended 2011)

Exploitation permissions (2014-2016)
(ISCHIA ISLAND “Forio”,
agreement with IschiaGeotermia Company)

Campi Flegrei Deep Drilling Project CFDDP
(first phase concluded in December 2012)

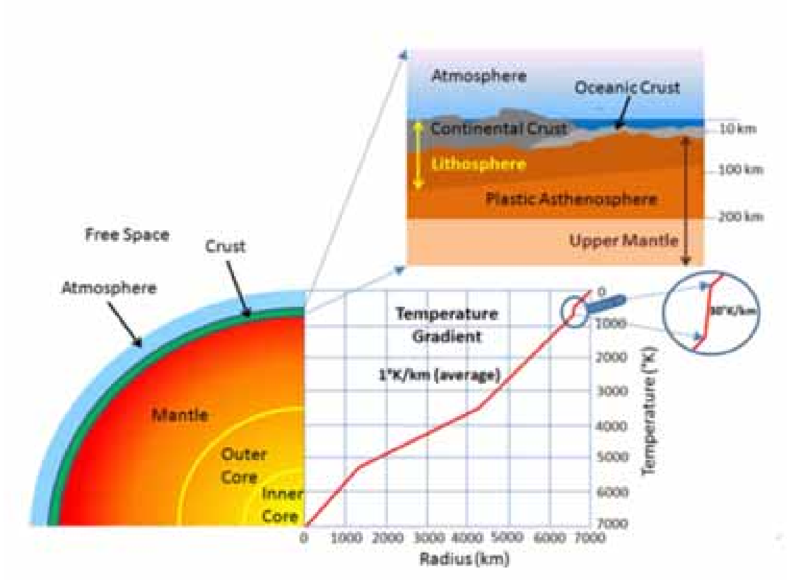
IRGIE – inventory of geothermal research in Eolian islands (ongoing)

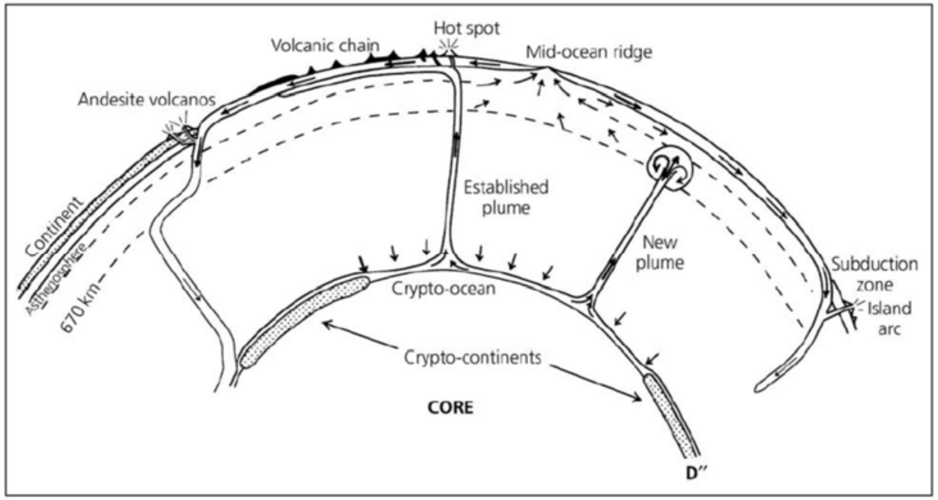
PANTAREI- assessment of the geothermal potential in Pantelleria Island (ongoing)

Geothermal energy: source

Earth is «slowly» dissipating internal heat mostly through convection and conduction.

Heat dissipation is the engine of geodynamics. Understanding geodynamics gives hints on the heat flow distribution





Turcotte and Schubert, 2014

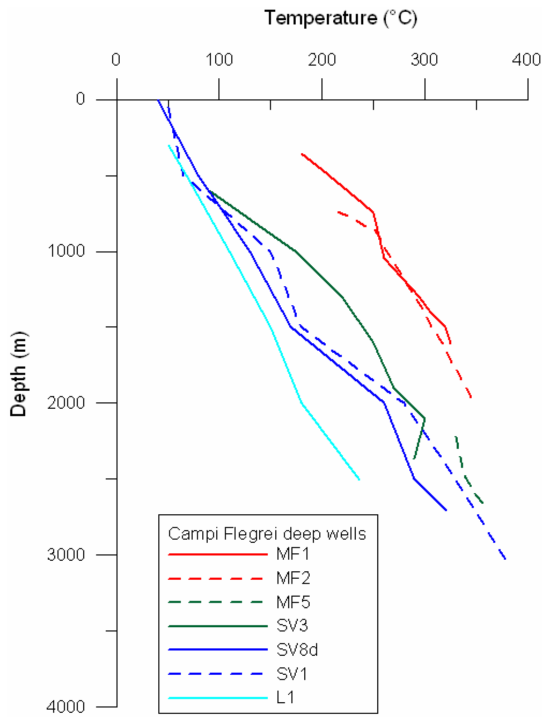
Heat flow and temperature gradients

Heat flow (**q**): heat per unit of area and per unit of time which is transmitted by heat conduction from the Earth's interior.

$$\mathbf{q} = -\lambda \,\mathrm{grad}\, T = -\lambda \,\nabla T .$$

λ = thermal conductivity (rocks dependent)

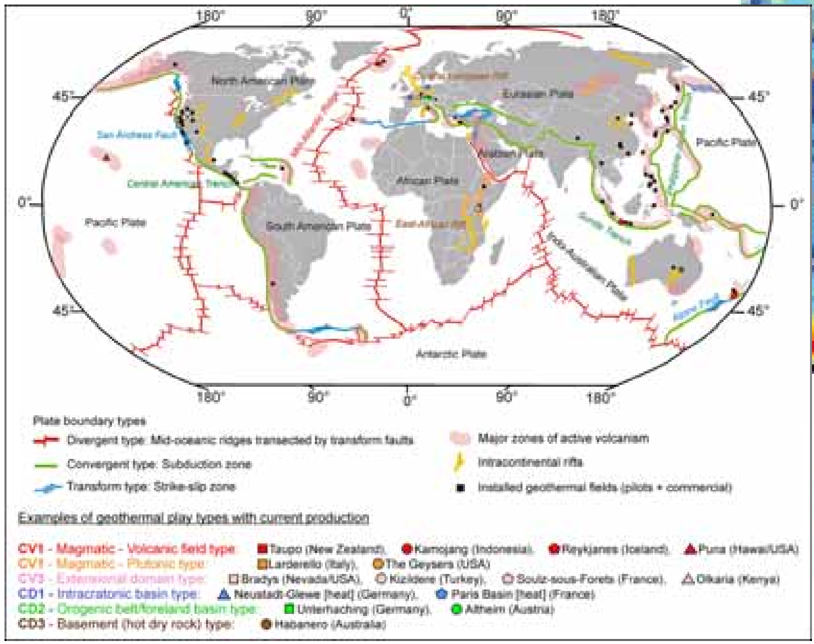
Heat flow may be estimated by measuring the vertical temperature profile (i.e. in a well), knowing the thermal conductivity of the rocks.

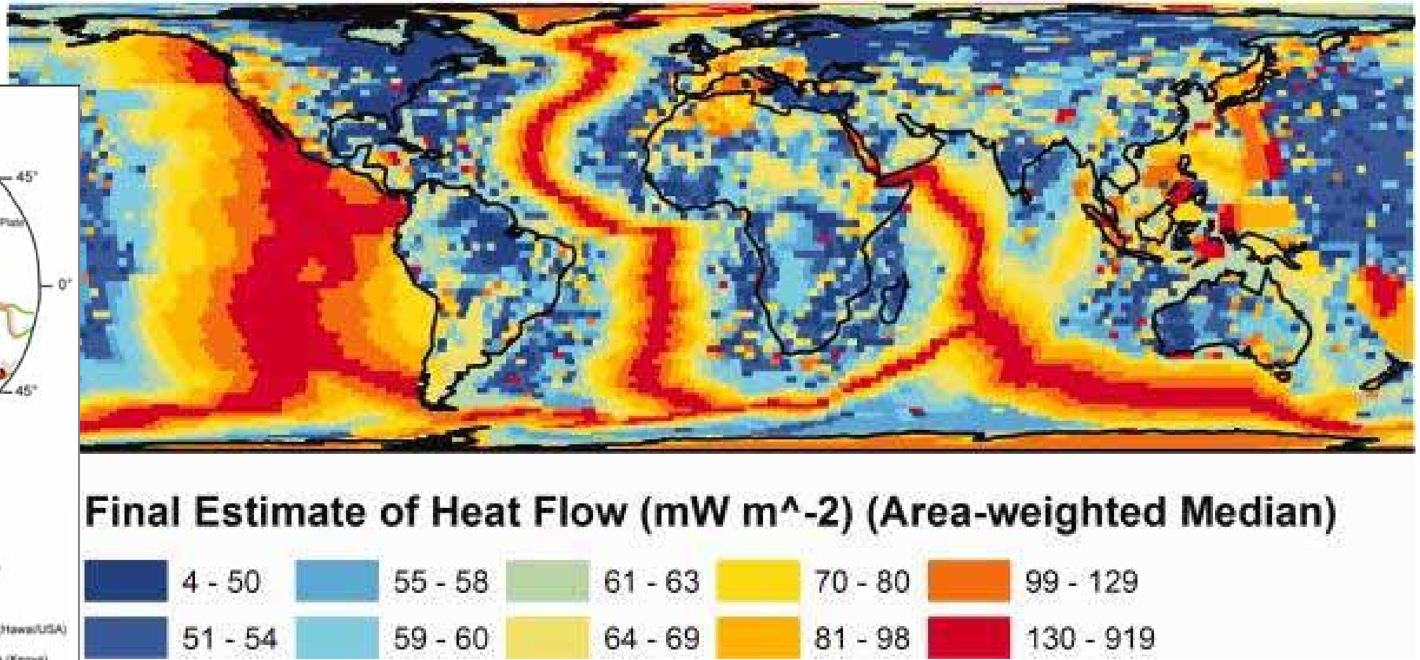


Temperature profiles in Campi Flegrei; Carlino et al., 2012

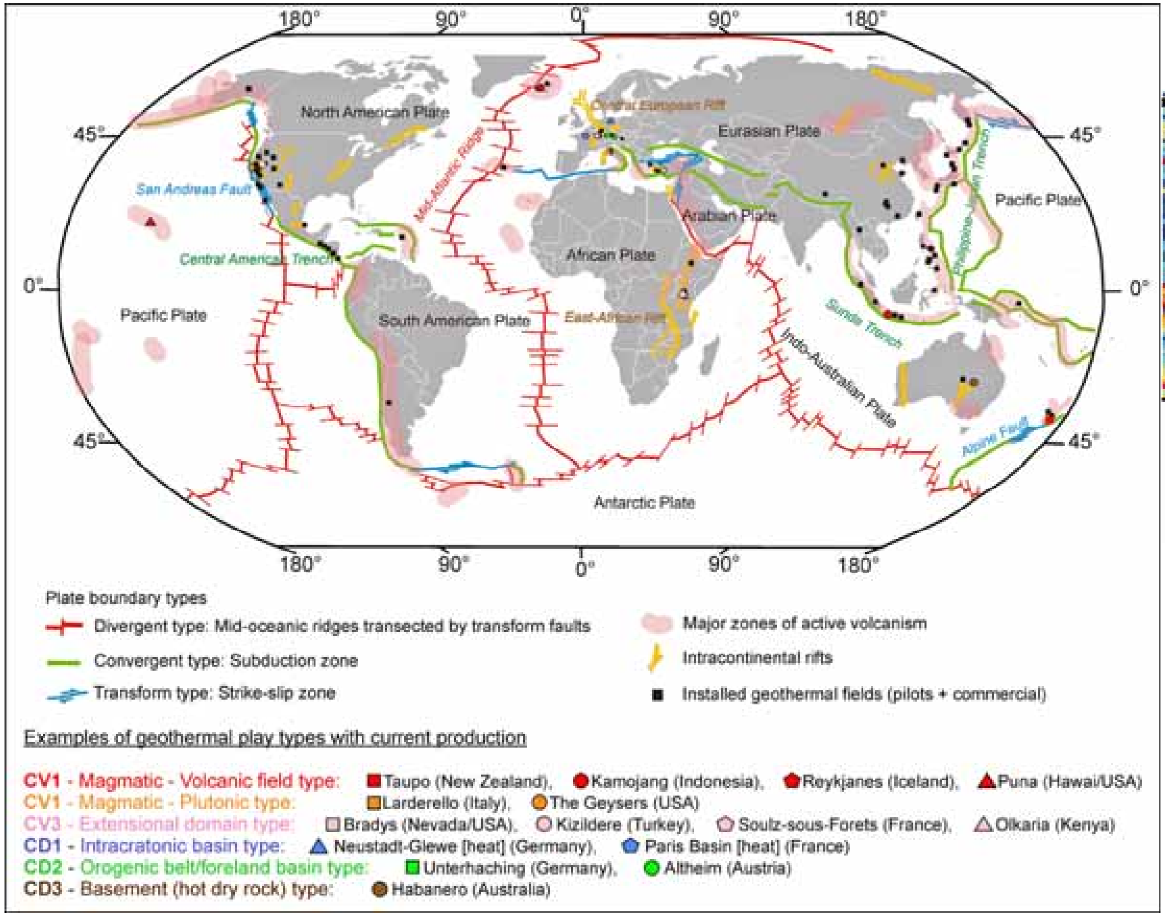
Spatial variations of heat flow on Earth surface

Average HF is: 45-50 mW/m^2



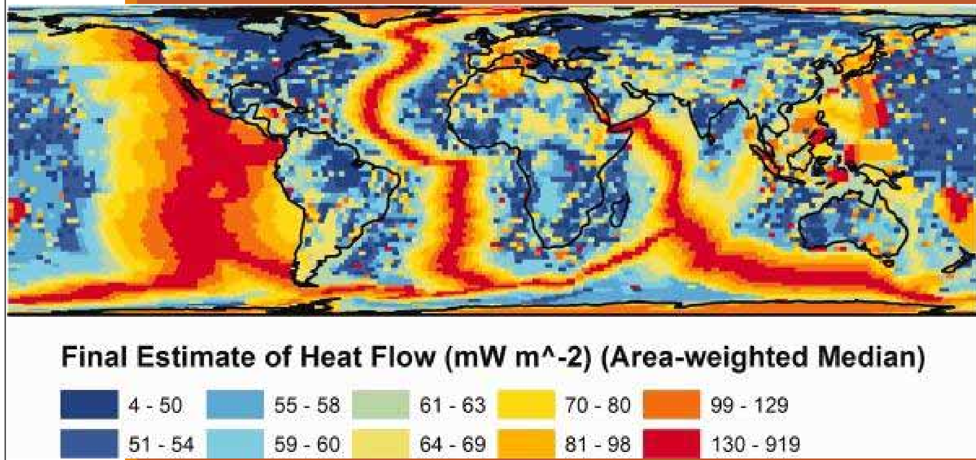


http://www.heatflow.und.edu



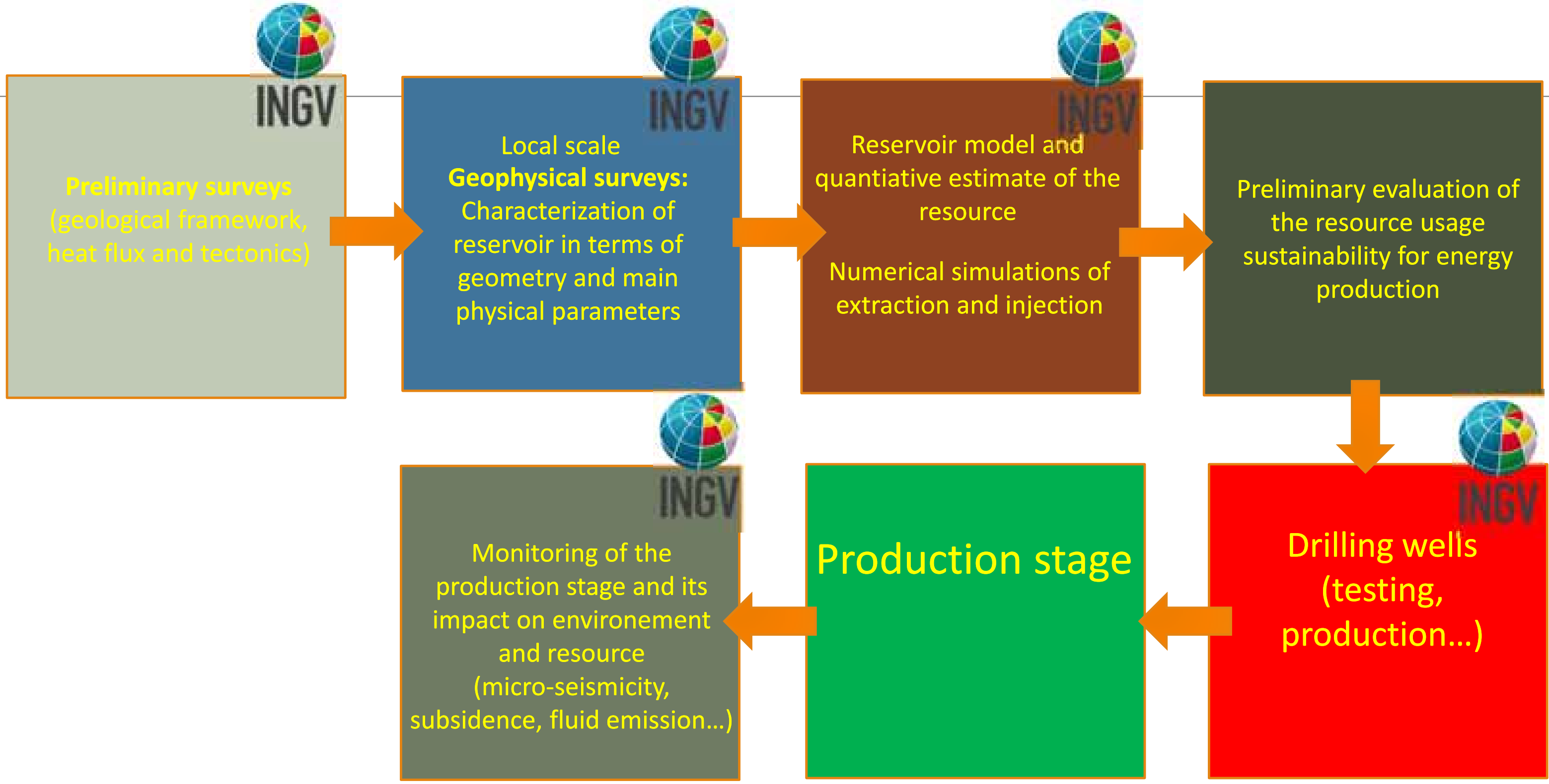
Moeck, 2014

http://www.heatflow.und.edu



Spatial variations of heat flow - Geologic controls on heat flow

Geophysics contribution in phases of geothermal exploration and exploitation



Geothermal systems

> "A geothermal system is any localized geologic setting where portions of the Earth's thermal energy may be extracted from a circulating fluid and transported to a point of use".

In this definition important concepts:

- «localized geologic setting»: calls for some favourable geologic conditions that allow to have an heat source at disposal (relatively shallow depths?)

- «portions of the Earth's thermal energy»: suggests that given the geologic structure we have access to a «deeper» energy source

- «circulating fluids»: fluids are the used to transport energy/heat. Requires, a part the presence of a fluid, also conditions of fluids to circulate

«Geothermal play»

reservoir rock and trap [6]. Translated to geothermal systems, a play type might be defined by the heat source, the geological controls on the heat migration pathway, heat/fluid storage capacity and the potential for economic recovery of the heat. Ultimately the geological

Geothermal plays (Moeck, 2014)

Important to:

- characterize the heat source (heat flow & temperature gradients)
- understand main geological controls → favourable geologic conditions for exploitation
- assess underground fluids content and underground water/fluids paths

Heat

Rock properties

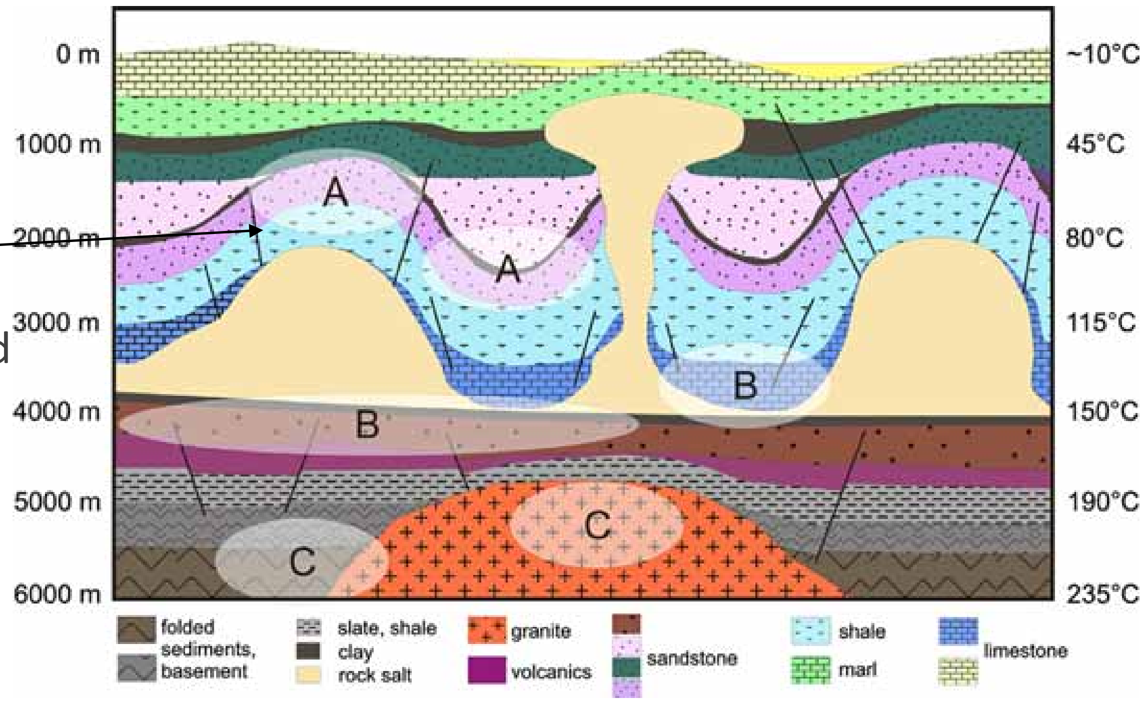
Fluids

Role of geophysics in assessing the «geothermal play»

- Define the geological structures that create high heat flow conditions at different scales: from crustal and lithospheric structures to the local features that allow fluid accumulation (syn/anticlynes)

- Constrain fluid presence and underground fluid's path

- Provide estimates for physical parameters crucial for numerical modelling (e.g. porosity, fluids content)



Geothermal plays (Moeck, 2014)

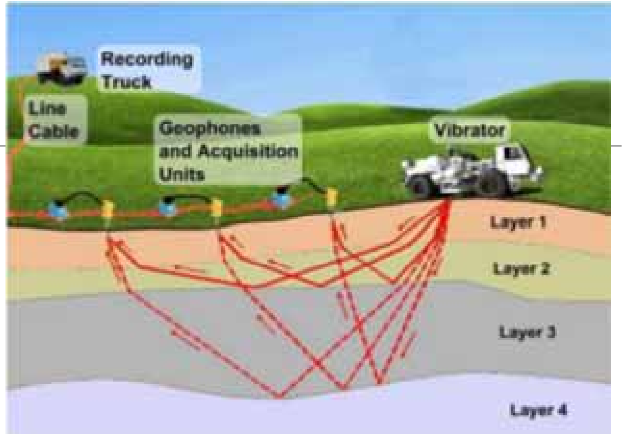
Geophysical methods

Methods that use measurement of physical properties to map underground geological structures

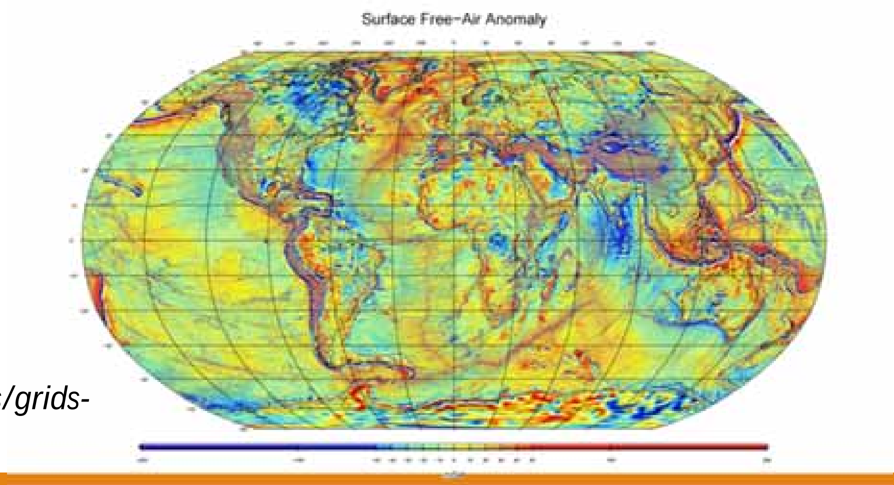
Geophysical methods:

- **Active**: we provide a source (electric current, seismic source…) and measure the response of the earth to this **known** source

- **Passive**: we measure some spatial/temporal variations of physical parameters naturally present in Earth (gravity and magnetic fields)



Active seismic experiment (Dorma Kana et al., 2014)



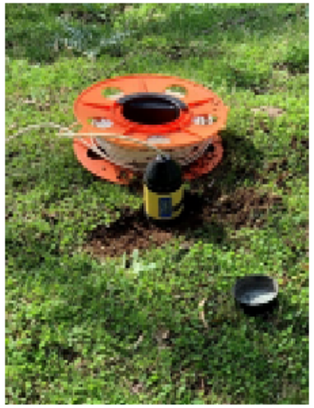
Gravity map: https://bgi.obs-mip.fr/data-products/grids-and-models/wgm2012-global-model/

Geophysical techniques useful for geothermal play assesment

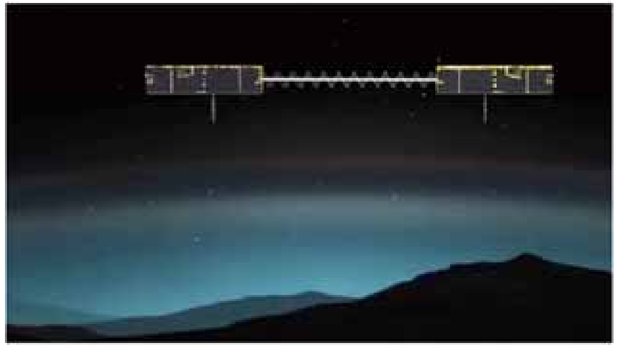
- seismic surveys (reflection, tomography, passive seismics…)
- potential field methods (gravimetery and magnetometry)
- electromagnetic methods: electrical resistivity tomography, magnetotellurics…

- remote sensing (satellite imagery, satellite gravimetry…) → **important especially for preliminary investigations**!

- borehole geophysics (borehole seismic, thermal measurements) → **important after first wells have been drilled!**



MT equipment



GRACE Satllite gravimetry principle

Important: every geophysical method is sensitive to a specific underground parameter (gravity to density; geoelectric to resistivity) → depending on the scope of the work different methods or a combination of them should be evaluated

Geophysical methods-1

Seismic methods

- recontstruct the underground structures by studying the arrival times of seismic waves produced by artificial/natural sources

- for **geothermal exploration:** structural setting definition, fluids detection (Vp/Vs)

Geo-Electrical methods

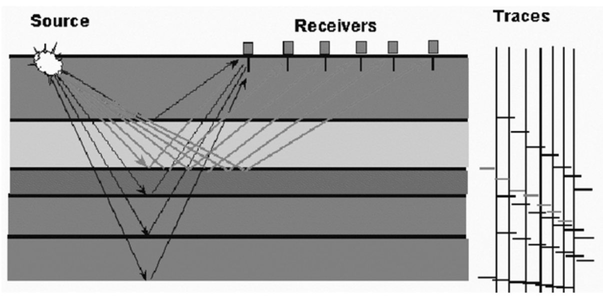
- resistivity model of the underground using source (ERT) or using natural variations of the electromagnetic field (Magnetotelluric)

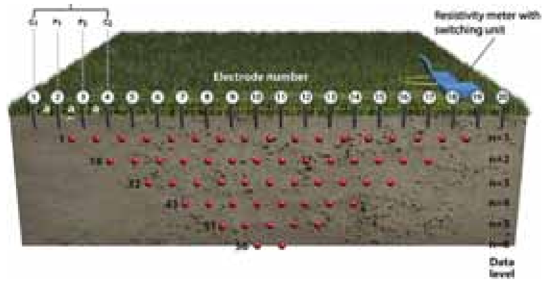
- **For geothermal exploration:** identification of fractures and fluids

Gravimetry

- density model of the underground measuring the small spatial variations of the gravity field

- For **geothermal exploration**: structural setting, deep crustal characterization





Array of electrodes (Loke et al., 2013)

Scintrex CG5 gravimeter

Geophysical methods-2

Magnetometry

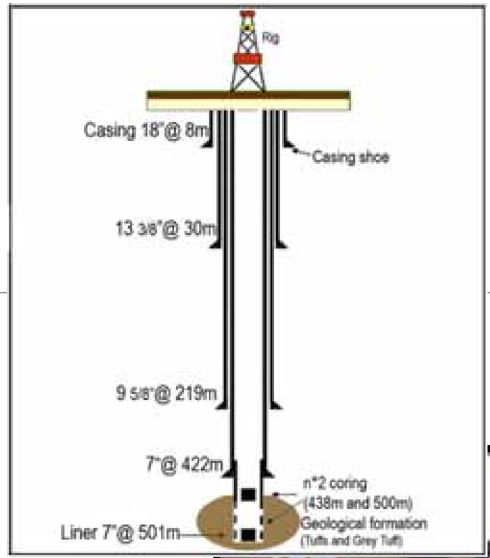
- mapping magnetic rocks (i.e. magmatic rocks). Important: Curie temperature (about 600°C) → loss of magnetic properties of rocks

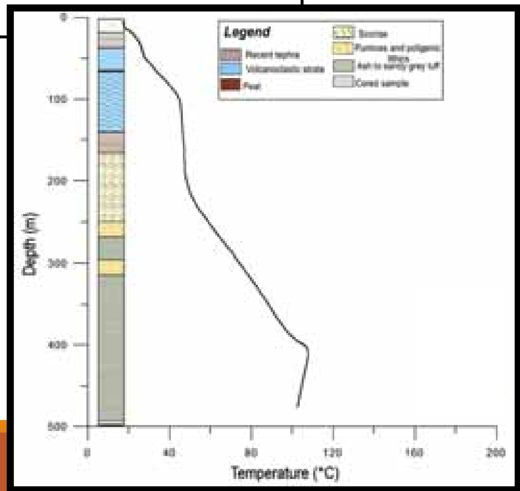
- for **geothermal exploration: mapping cooled dykes.** Curie depth may be estimated by magentic data

Borehole geophysics

- measurement in wells of properties of rocks and fluids through different sensors

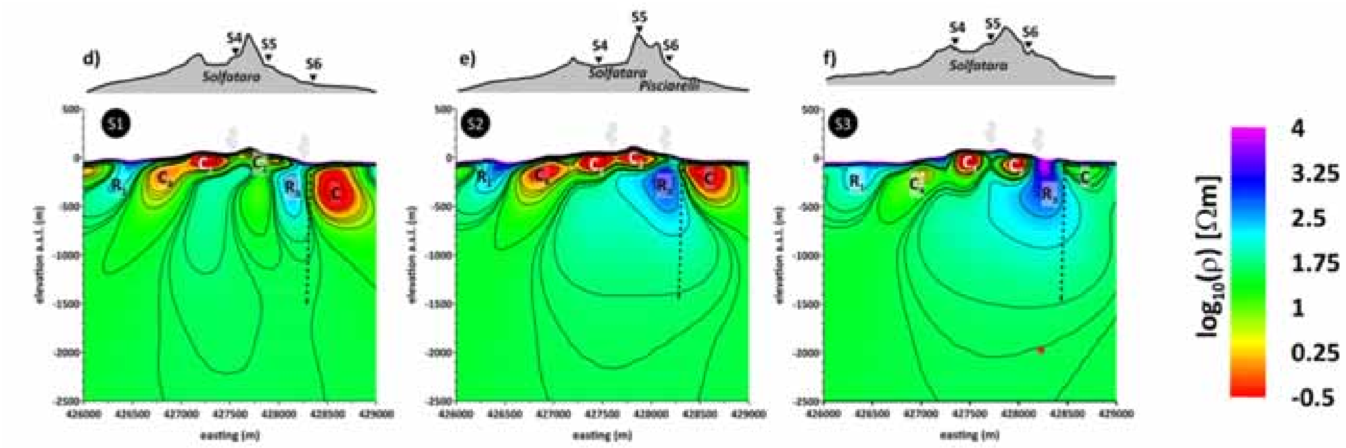
- for **geothermal exploration: temperature profiles; resistivity & density logs for fluid characterization;**



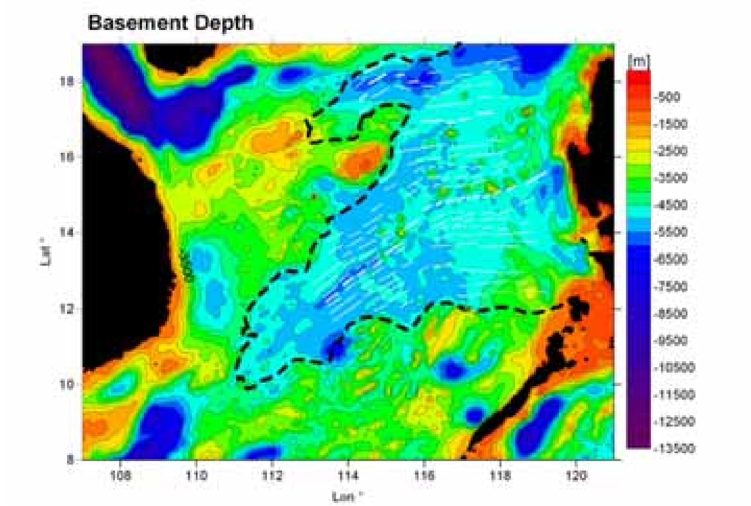


Geophysical methods- outputs

- Application of geophysical methods allows the production of sections, maps or even 3D and 4D datasets of the underground distribution of the physical property



Resistivity sections in the Campi Flegrei area (Troiano et al., 2022)



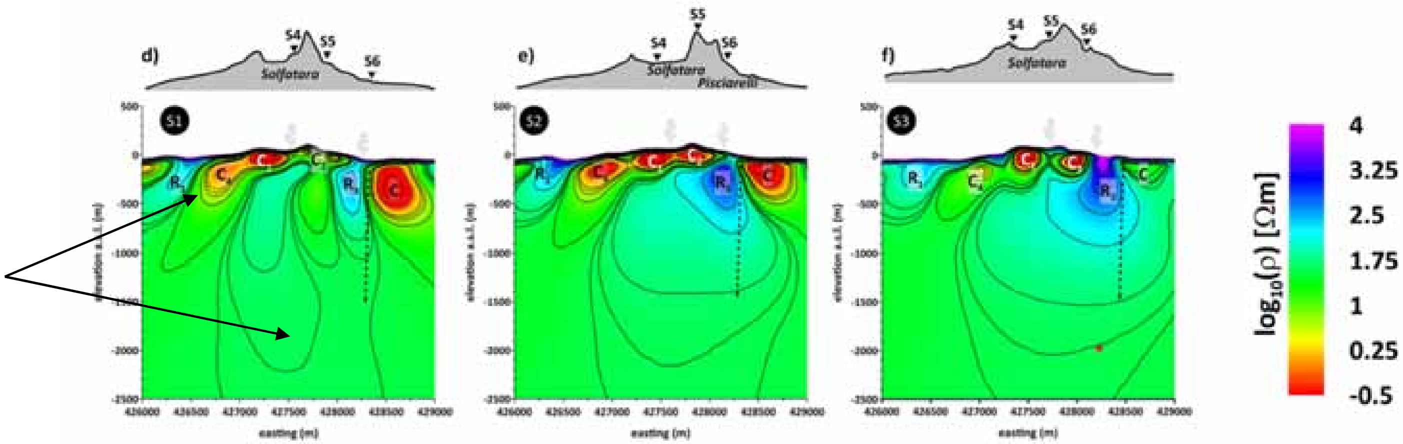
Basement depth in the South China sea from gravity data (Braitenberg et al., 2006)

Resolution- depth of investigation

- Resolution→ smallest feature observable in a geophysical survey

- Since most of the geophysical data are acquired on the surface or even at higher quotas, we usually have a decrease of resolution (**detail**) with depth

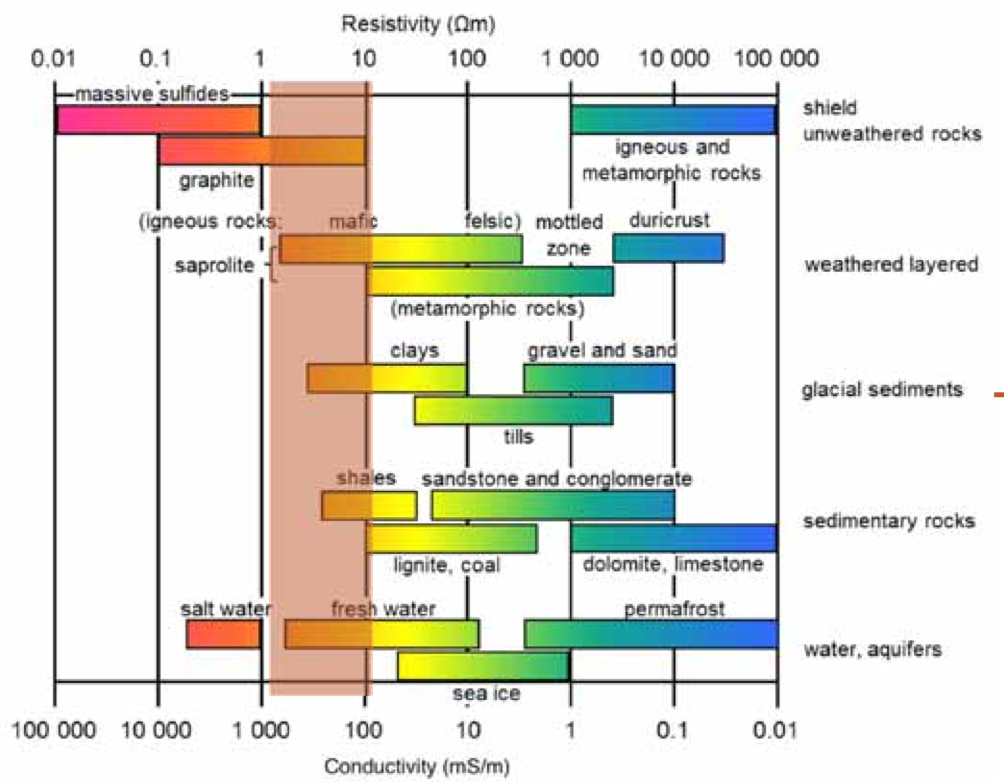
- Set up of acquisition scheme is fundamental: for **ERT resolution** is function of the electrode distance while **depth of investigation (DOI)** is dependent on the maximal distance between the electrodes



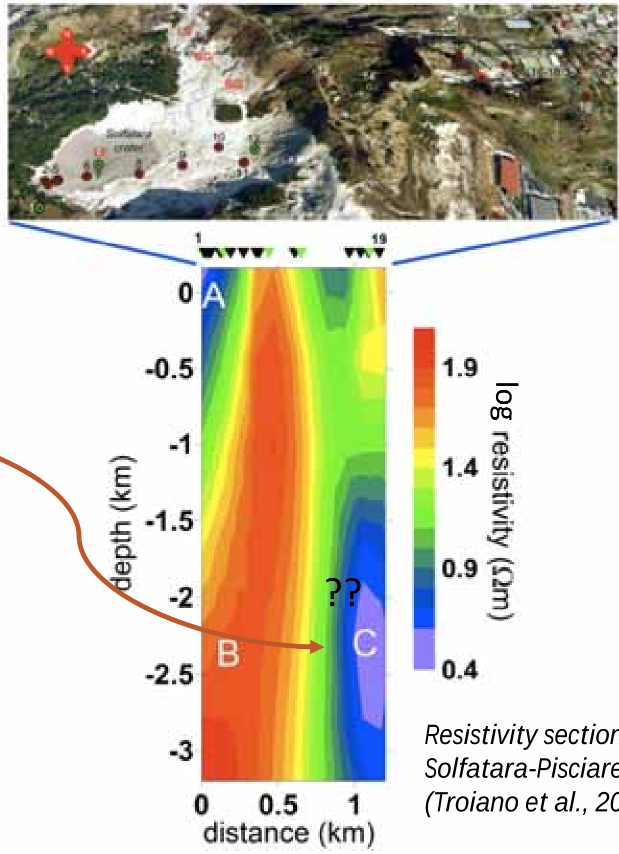
Resistivity sections in the Campi Flegrei area (Troiano et al., 2022)

- there is typically a trade-off between resolution and DOI

Geophysical methods: importance of integration

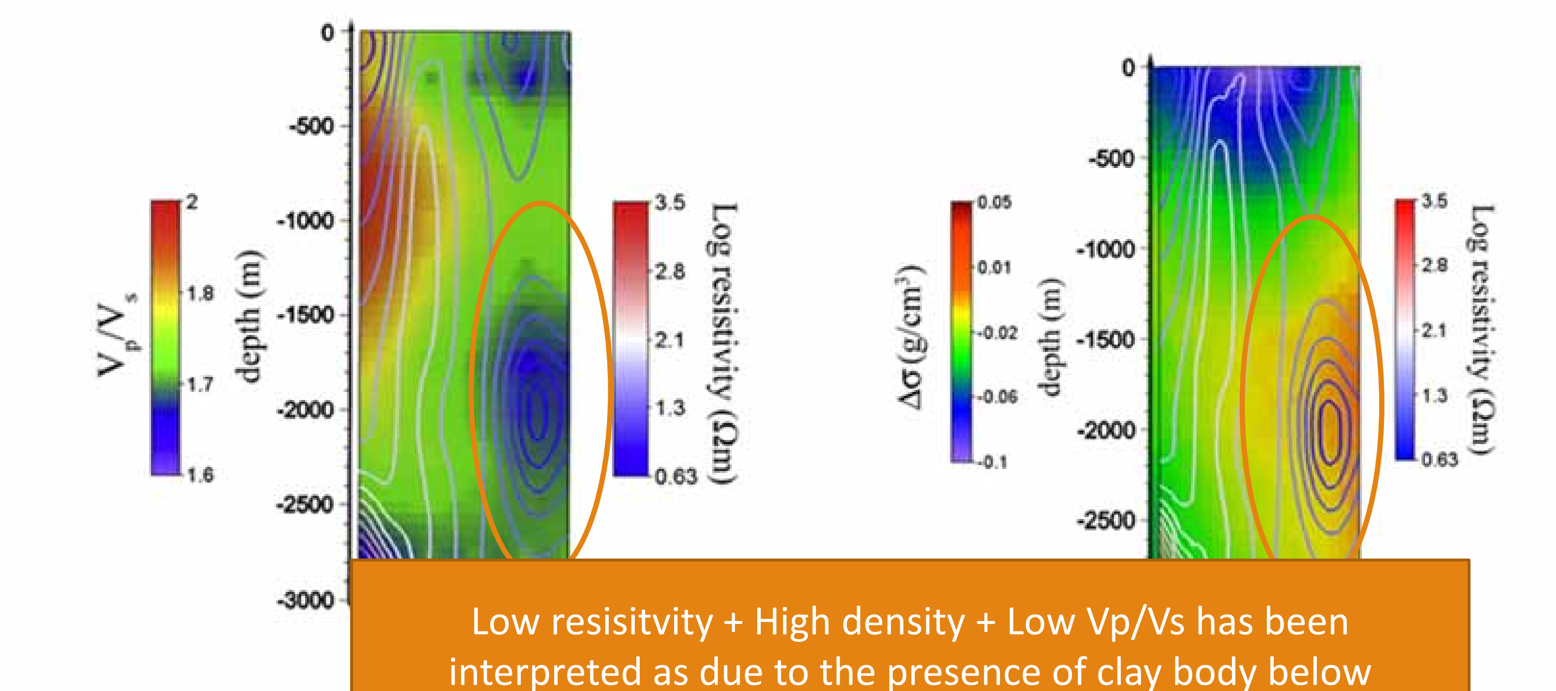


https://em.geosci.xyz/content/physical_properties/electrical_conductivity/electrical_conductivity_values.html



Resistivity section at Solfatara-Pisciarelli (Troiano et al., 2014)

Integration of geophysical datasets reduces the ambiguity



Low resisitvity + High density + Low Vp/Vs has been interpreted as due to the presence of clay body below Pisciarelli-Solfatara area

Contours of resistivity superposed on Vp/Vs ratio (left) and density variations (right).

Vp/Vs from seismic tomography

(Troiano et al. 2014)

Among the various types of prospections, those based on electrical resistivity emerge as some of the most proficient sources of information aimed at understanding the role and distribution of geothermal fluids, their interactions with meteoric recharge, and the main structural lineaments, together with the effects of their circulation on the surrounding rock.

Target \ Physical property	Density	Magnetic susceptibiity	Electrical resistivity	Dielectric permittivity	Seismic velocity
Porosity	Strong	None	Strong	Moderate	Moderate
Permeability	None	None	Weak	Weak	Weak
Water content	Moderate	None	Strong	Strong	Moderate
Water quality	None	None	Strong	None	None
Clay content	Weak	None	Strong	Weak	Moderate
Magnetic mineral content	Moderate	Strong	Weak	None	None
Metallic mineral content	Strong	None	Strong	None	Moderate
Mechanical properties	Moderate	None	Moderate	Weak	Strong
Subsurface structure	Moderate	Moderate	Moderate	Strong	Strong

Strong | Moderate | Weak | None

Degree of relationship

METHOD	PROS	CONS
Seismic	- Detailed reconstruction of underground structures in sedimentary contexts (High resolution)	- Challanging interpretation in volcanic and heterogeneous areas - Logistically demanding - Expensive
Electrical methods	- Sensitivity to fluids content (salinity, temperature) - Depth of investigation - Cheap and logistically easy	- Low spatial resolution - Ambiguity on interpretation (requires intergation with other geophysical techniques)
Gravimetry	- Depth of investigation (crustal characterization) - Distinguish dense rocks, relevant for geothermics (magma intrusions…) - Cheap and logistically easy	- Low spatial resolution - Ambiguity on interpretation (requires intergation with other geophysical techniques)
Magnetometry	- Distinguish rocks with high Fe content (relevant for geothermics) - Cheap and logistically easy	- Ambiguity on interpretation (requires intergation with other geophysical techniques)
Borehole geophysics	- Full and detailed characterization of the geothermal resource along the depth	- Very expensive - Very limited resolution on the horizontal scale

Summary of geophysical methods capabilities for geothermal exploration

Exploration Target \ Methods	Geology	Geochemistry	Geophysics: Gravity	Geophysics: MT	Geophysics: Passive Seismic
Heat Source	Strong	None	Weak	Strong	Strong
Reservoir Host Rock	Strong	Moderate	Weak	Weak	Weak
Permeability Indication	Moderate	Weak	Weak	Moderate	Strong
Upflow - Outflow	Weak	Strong	Weak	Strong	Weak
Top of Reservoir	None	None	None	Strong	None
Reservoir Boundary	None	None	Weak	Strong	None
Resource Size	Weak	None	Weak	Strong	None
Regional/Local Structure	Strong	None	Strong	Moderate	Weak

Degree of Capability: None, Weak, Moderate, Strong

Study case 1: Contribution of satellite gravimetry to understand rifting structures

Case History

Gravimetry and petrophysics for defining the intracratonic and rift basins of the Western-Central Africa zone

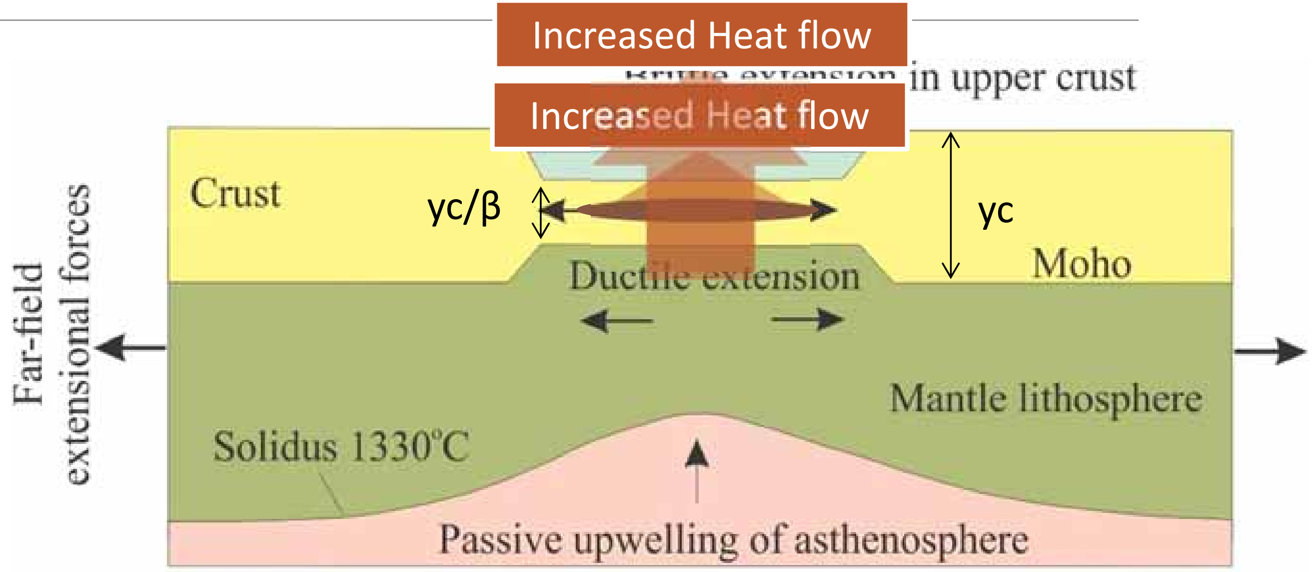
Francesca Maddaloni[1], Tommaso Pivetta[1], and Carla Braitenberg[1]

GEOPHYSICS (2021),86(6): B369

https://doi.org/10.1190/geo2019-0522.1

Importance of crustal characterization for geothermics

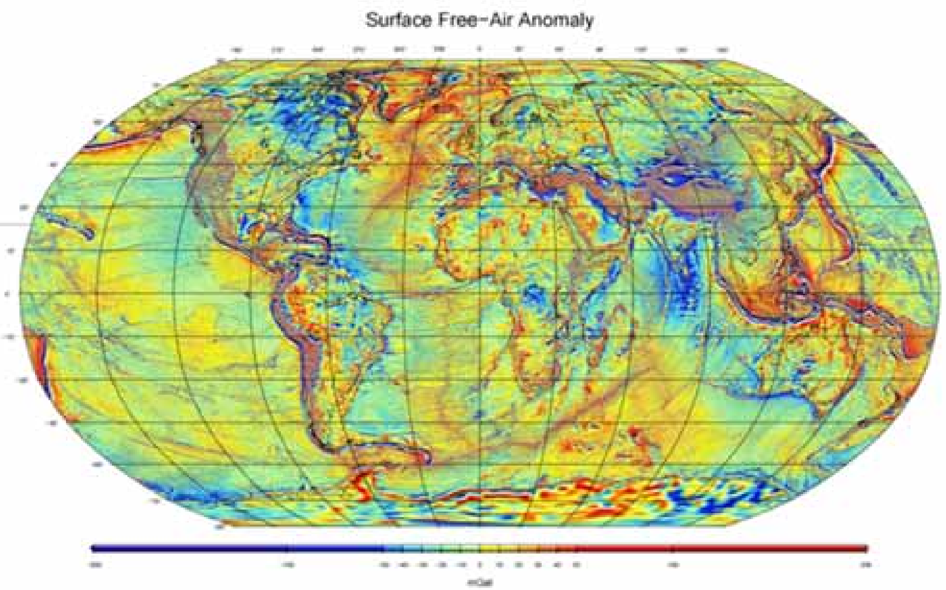
- Crustal thickness is one of the main factors controlling on heat flow
- Emplacement of shallow magmatic intracrustal bodies may further increase heat flow
- Example of preliminary studies necessary to assess the geothermal resource



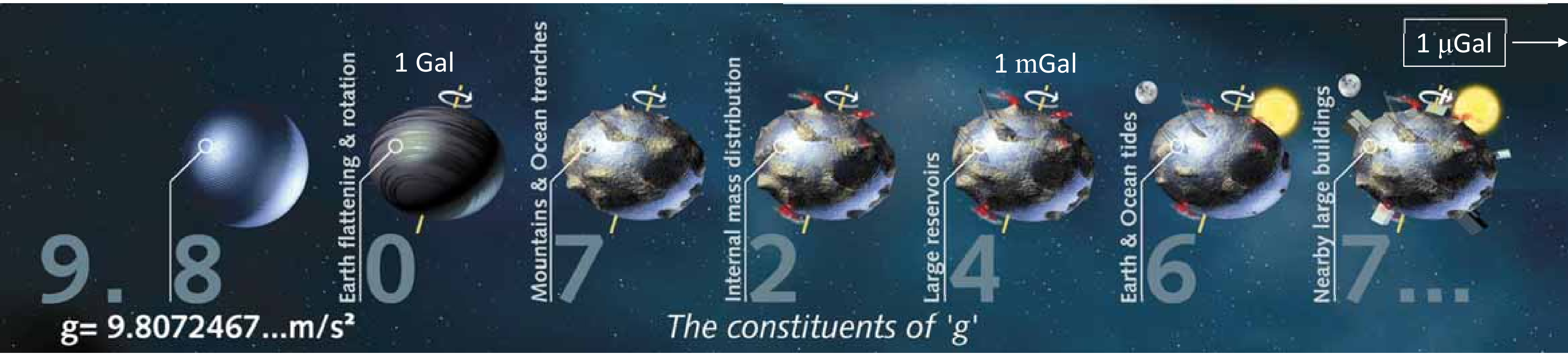
β = stretching factor

Gravimetry

- Lateral variations of density within the Earth cause slight variations of the gravity acceleration (1-10^2 mGal)
- By measuring these spatial variations (anomalies) we obtain map of gravity field variations

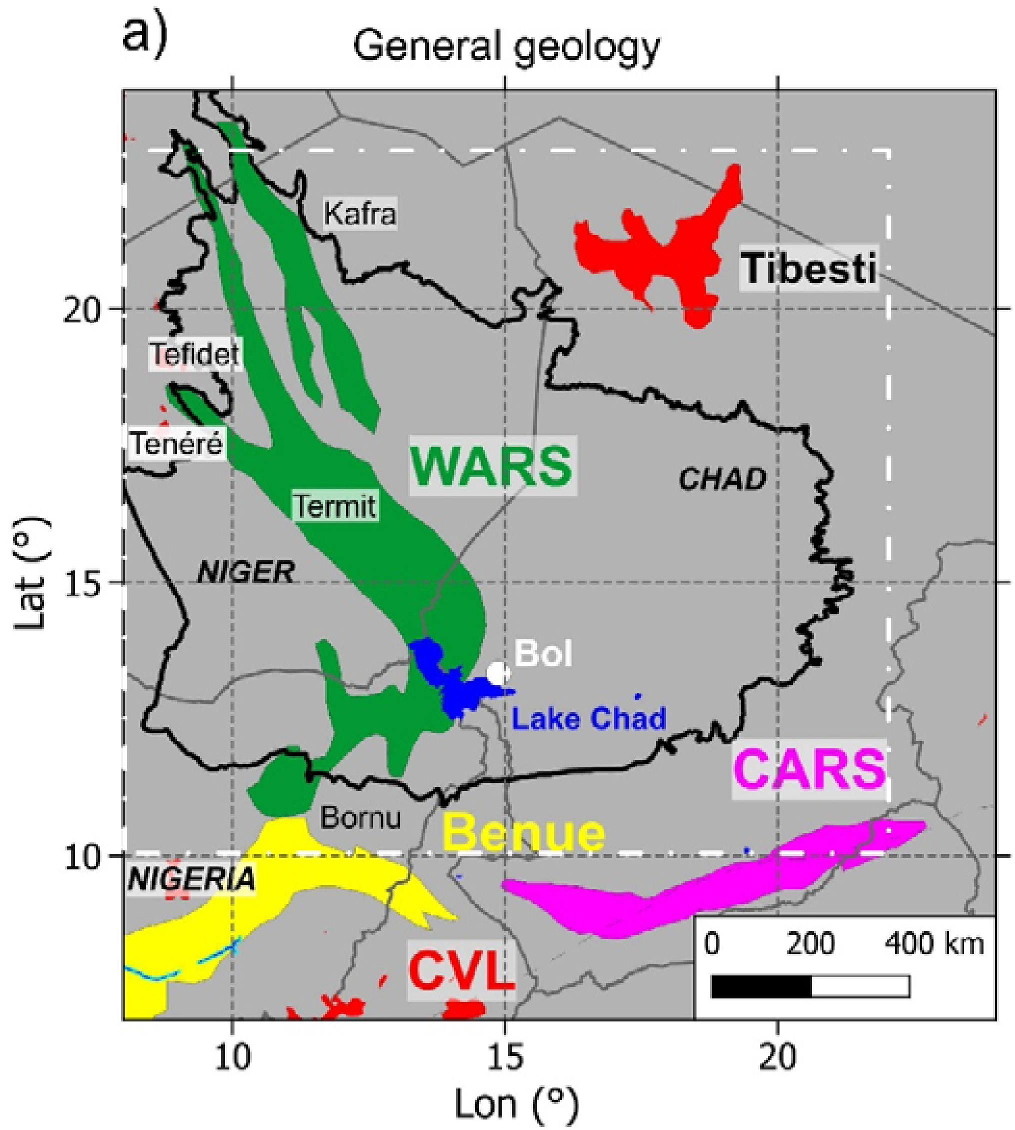


Gravity map: https://bgi.obs-mip.fr/data-products/grids-and-models/wgm2012-global-model/



Study area

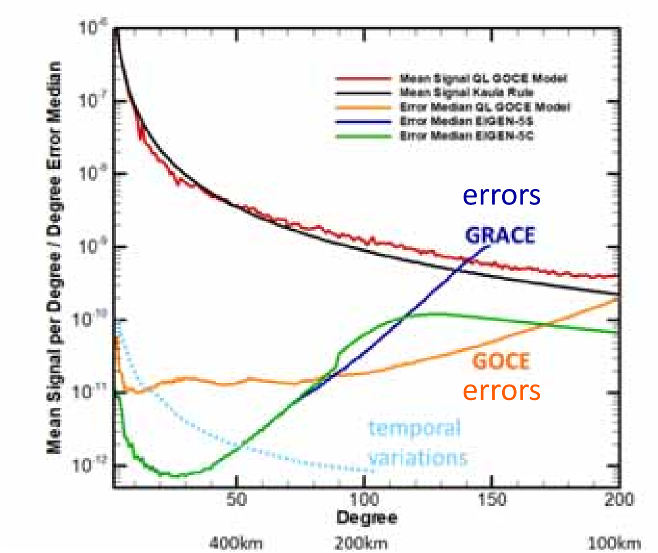
- West and Central African system (WARS and CARS)
- Aborted rift basins
- Remote area with scarce constraints on the crustal structures
- Ideal for testing satellite gravity products



Satellite gravimetry

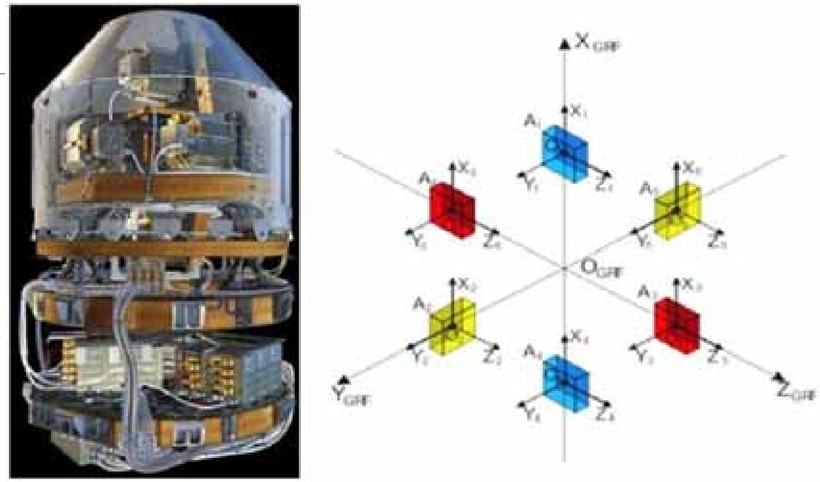
Satellite gravimetry observations:

- Spatial resolution of the products = 80 km
- Ongoing development of new sensors



Increasing spatial resolution →

Rummel, 2020

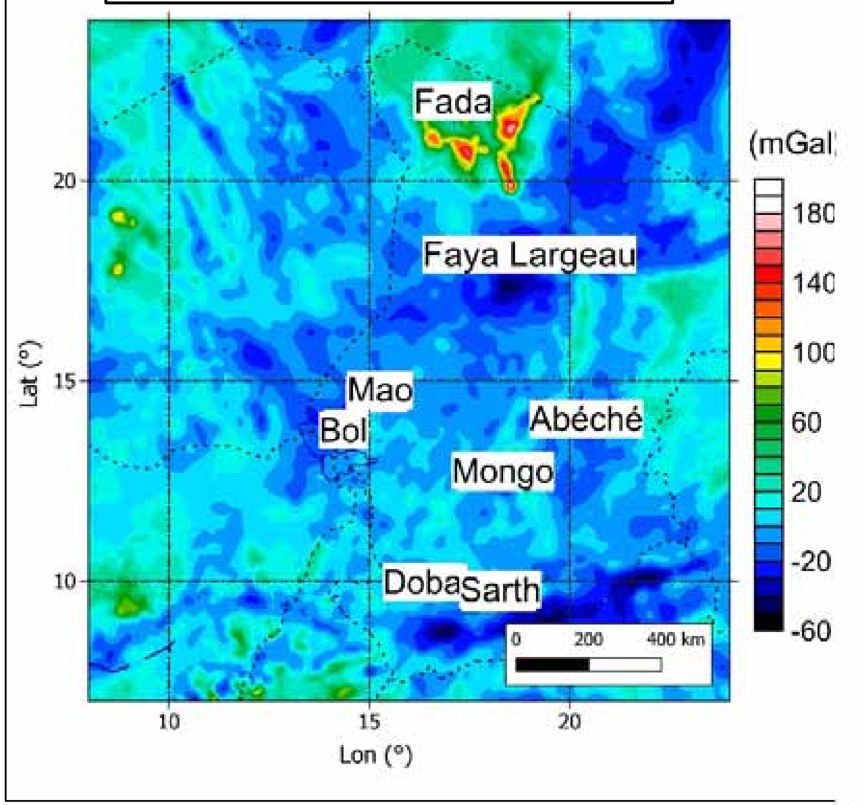


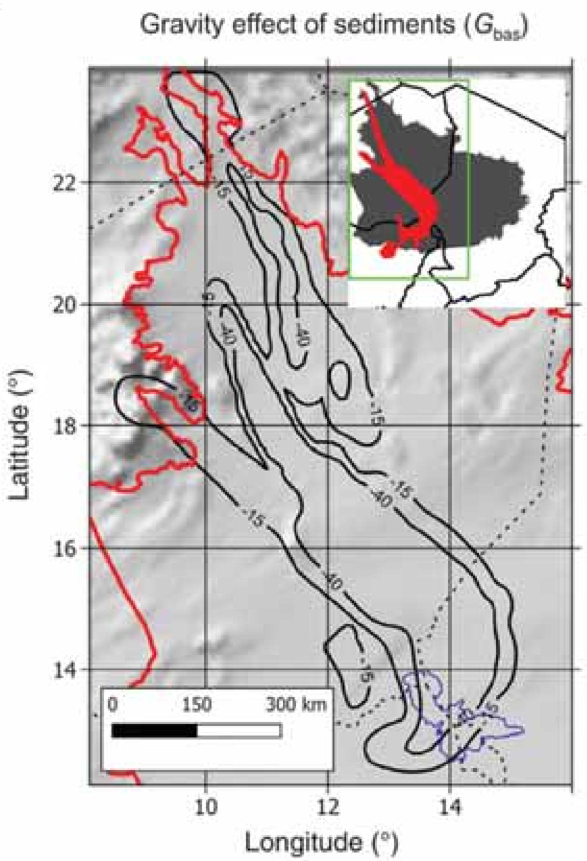
GOCE satellite measurement principle

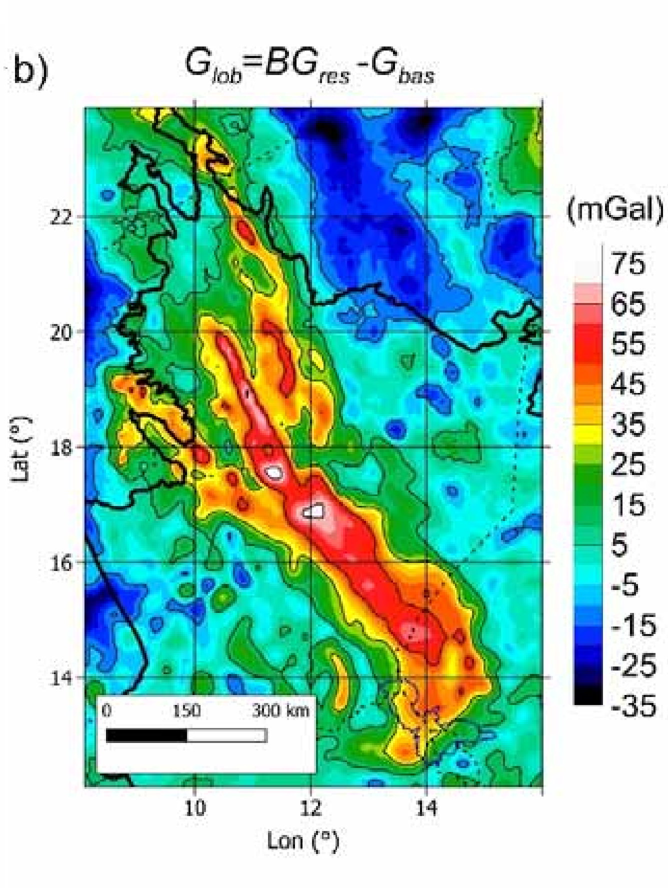
Importance of Satellite Gravimetry: allows global coverage even in remote areas.
<u>Uniform error globally and no problems with reference frames!</u>

Gravity data and processing

Global model of gravity anomalies

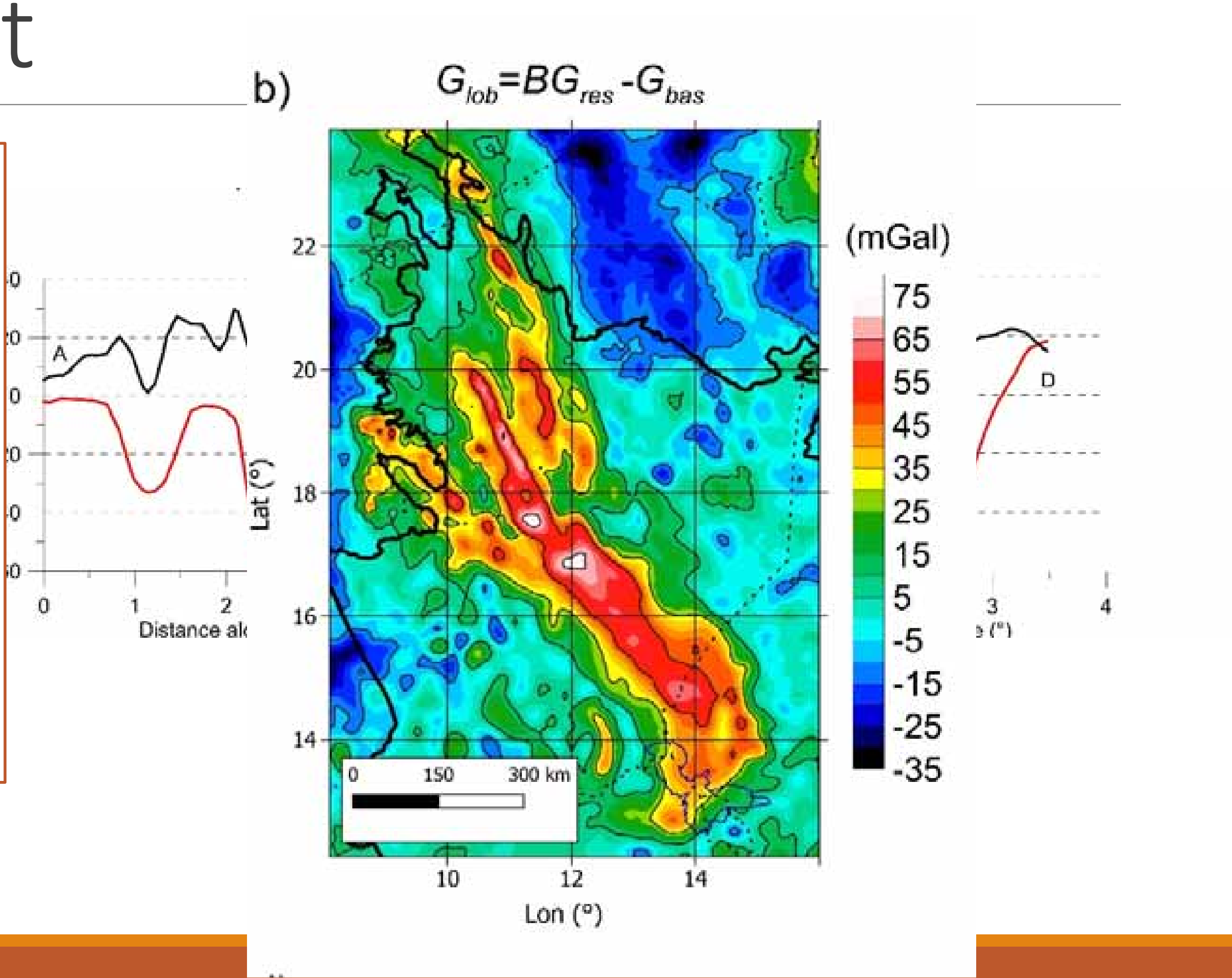




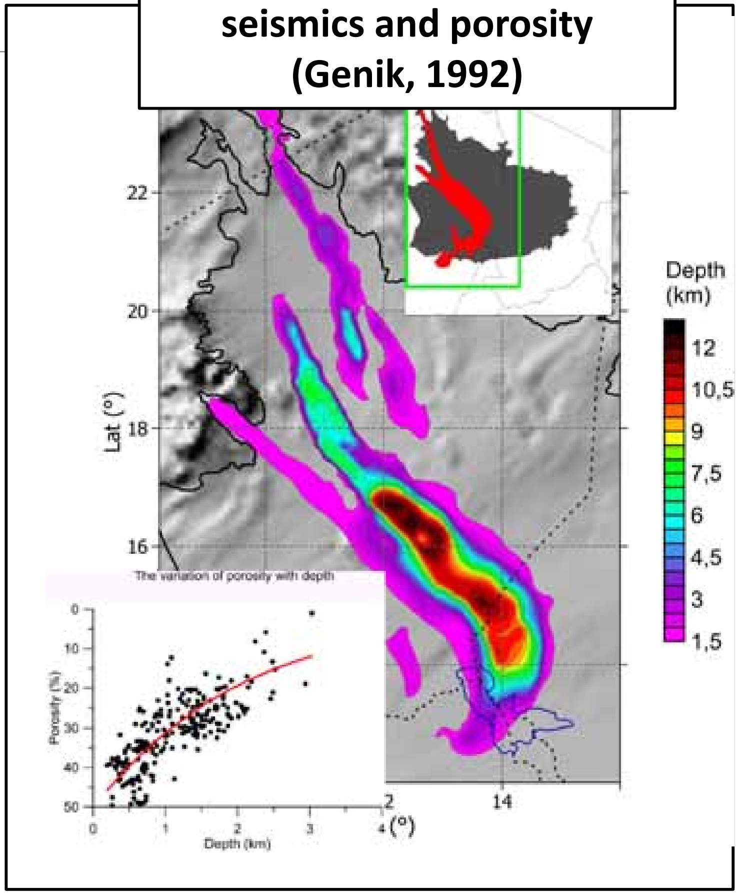


Processing of gravity- removal of sediments effect

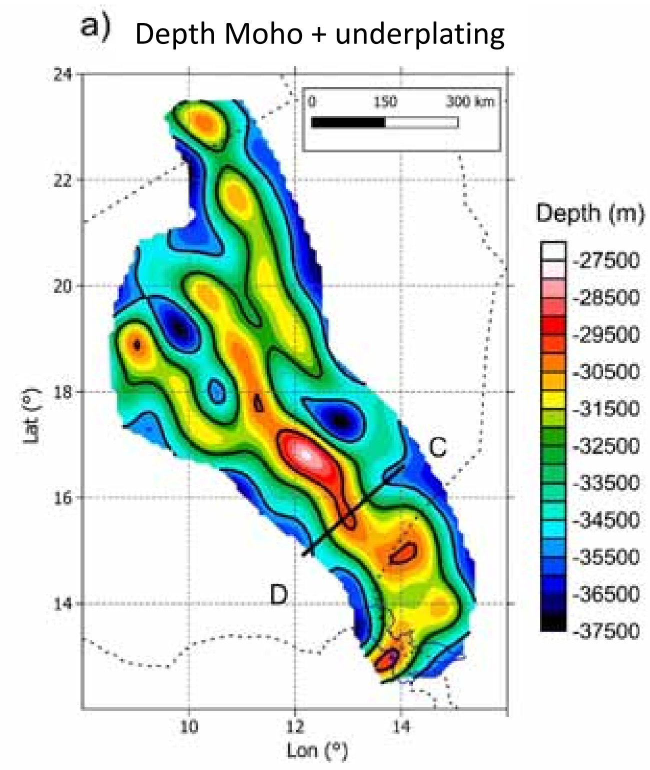
After correcting the gravity observations of the satellite for the effect of the sediments we obtain a map with large positive gravity anomaly

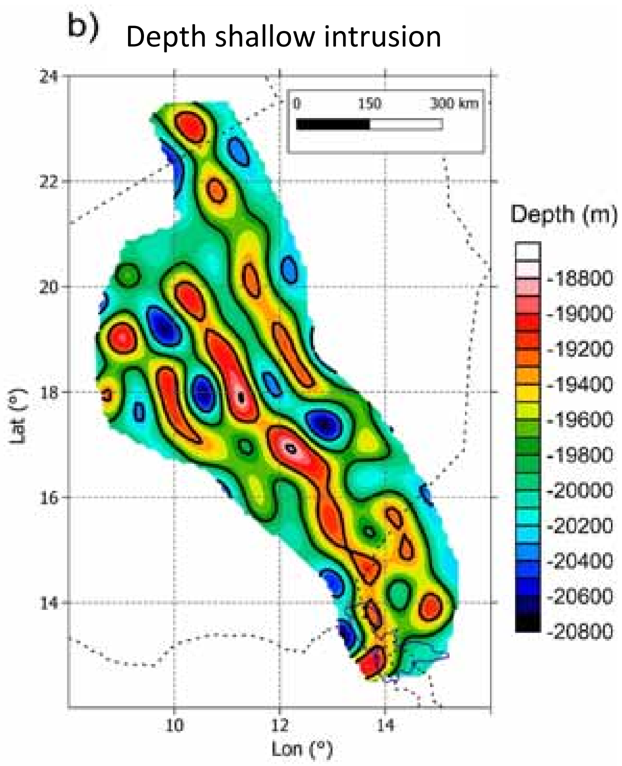


Depth of basement from seismics and porosity (Genik, 1992)



Gravity inversion: two sources crustal thinning and shallow intrusion



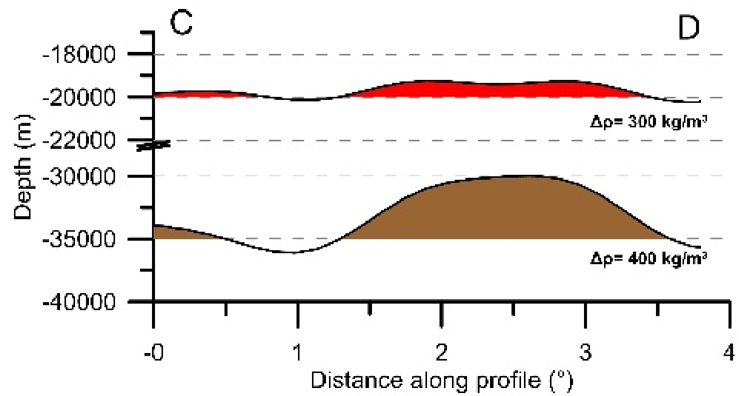


Shallow source approximately 1-1.5 km thick

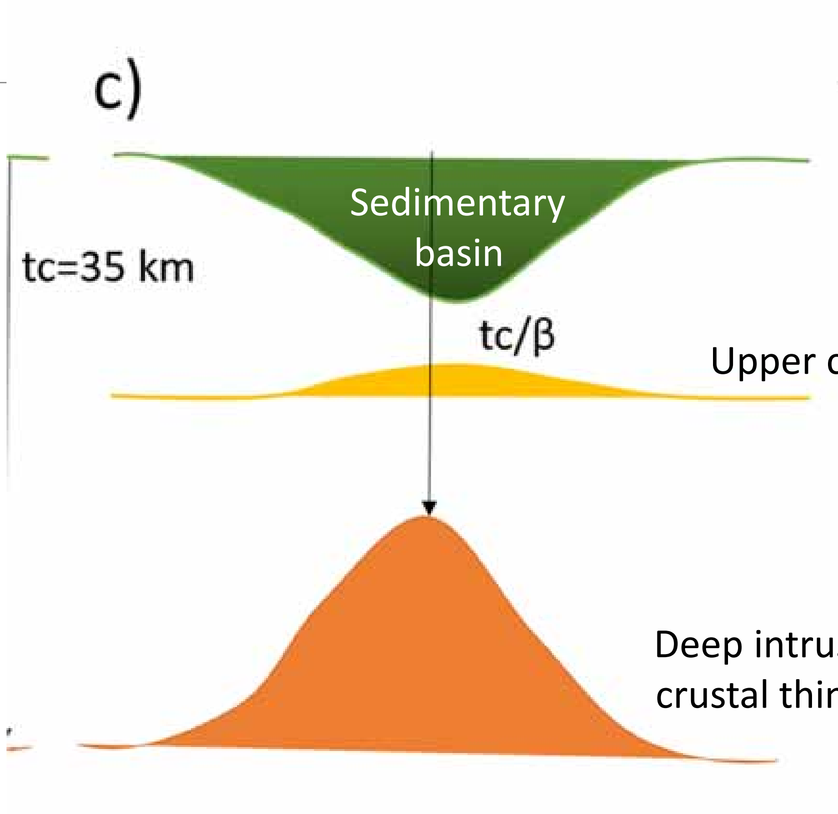
Deeper source 7 km thick: interpreted as a combination of crustal thinning and underplating

We calculated a stretching factor to be about 1.4, in accordance with a basin analysis study (Heine et al., 2013):

Our estimate of β would also imply an uniform stretching factor



Conceptual model of the WARS



Upper crustal intrusion

Deep intrusion/
crustal thinning

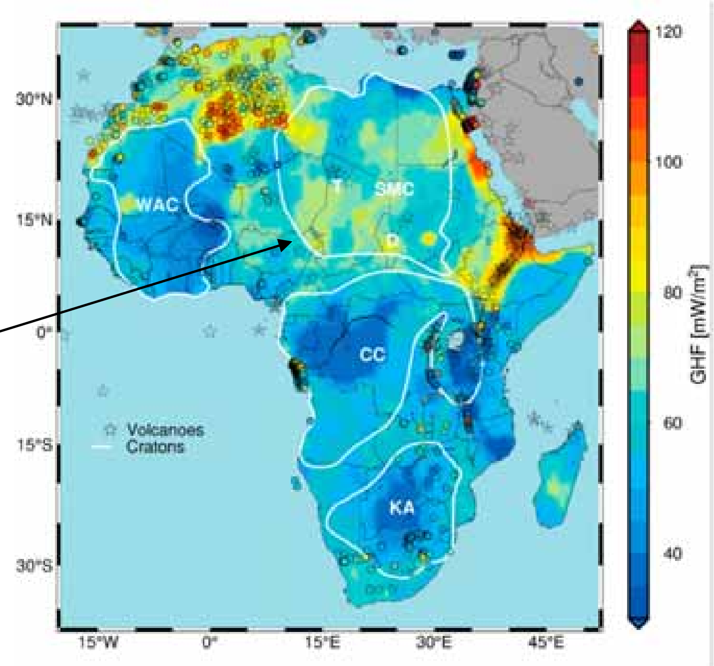
Stretching of lithosphere
causes Moho thinning.

Conclusions – WARS study

In WARS: uniform stretching of crust + production of melts that migrated towards the surface ponding into a shallow magmatic chamber

Combination of stretching and magmatic activity may explain the relatively high **heat flux** inferred for this area

The study showed the potential of the recent global gravity models for crustal characterization



Al-Aghbary et al., 2022

Study cases 2: Geoelectric methods for characterizing hydrothermal systems- examples from Ischia & Campi Flegrei

Bull Volcanol (2017) 79: 85
https://doi.org/10.1007/s00445-017-1170-4

CrossM

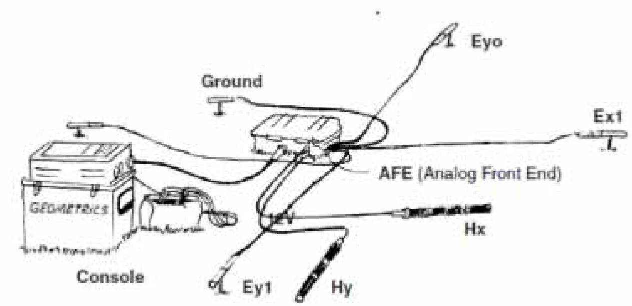
RESEARCH ARTICLE

Magnetotelluric imaging of the resurgent caldera on the island of Ischia (southern Italy): inferences for its structure and activity

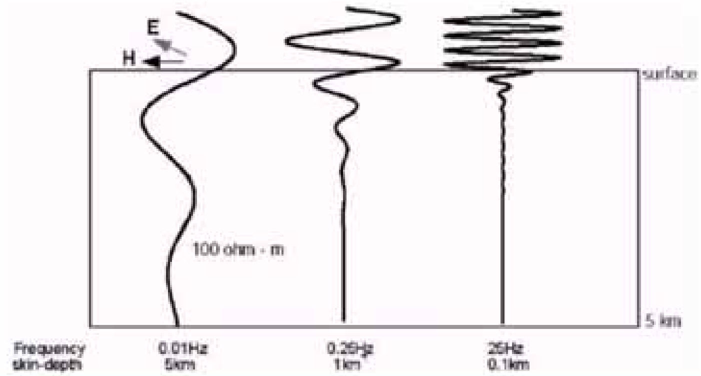
M. G. Di Giuseppe[1] · A. Troiano[1] · S. Carlino[1]

Magnetotelluric method (MT)

- MT is a passive geophysical methodology, that reconstructs the electrical resistivity spatial distribution by the simultaneous measurement of the time variations of the electric and magnetic fields induced in the subsoil by different external sources

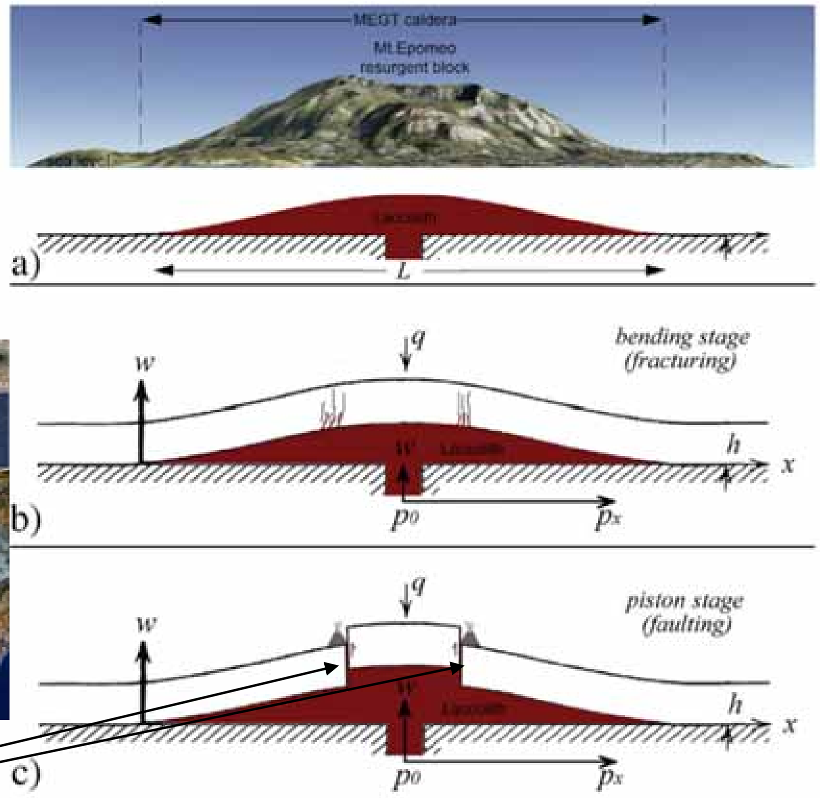


- Investigation depth ranges from tens of meters, recording higher frequencies, up to hundreds of km with long-period surveys.



Ischia- resurgent block

- Example of a resurgent block within a caldera (> 800m!)
- Resurgence caused by emplacement of a laccolith
- Volcanic activity + resurgence allowed an exhumation of the geothermal system
- Very high heat flow at the boundaries of the Mt. Epomeo



Model of evolution of the resurgent block of Mt. Epomeo (Ischia) (Carlino et al., 2006)

90 wells at Ischia Island: geothermal gradient

Deep wells >200m

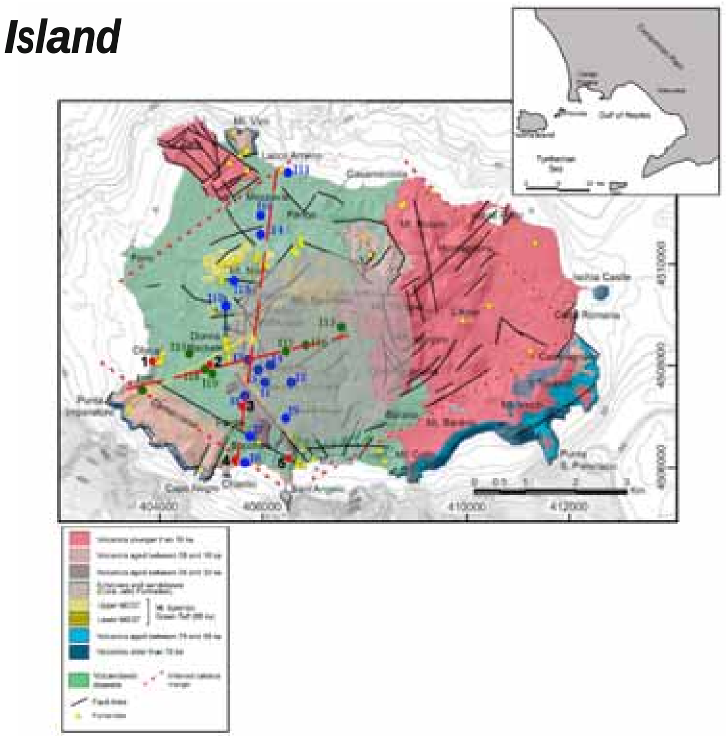
Shallow wells <200m

Deepest well 1156 m

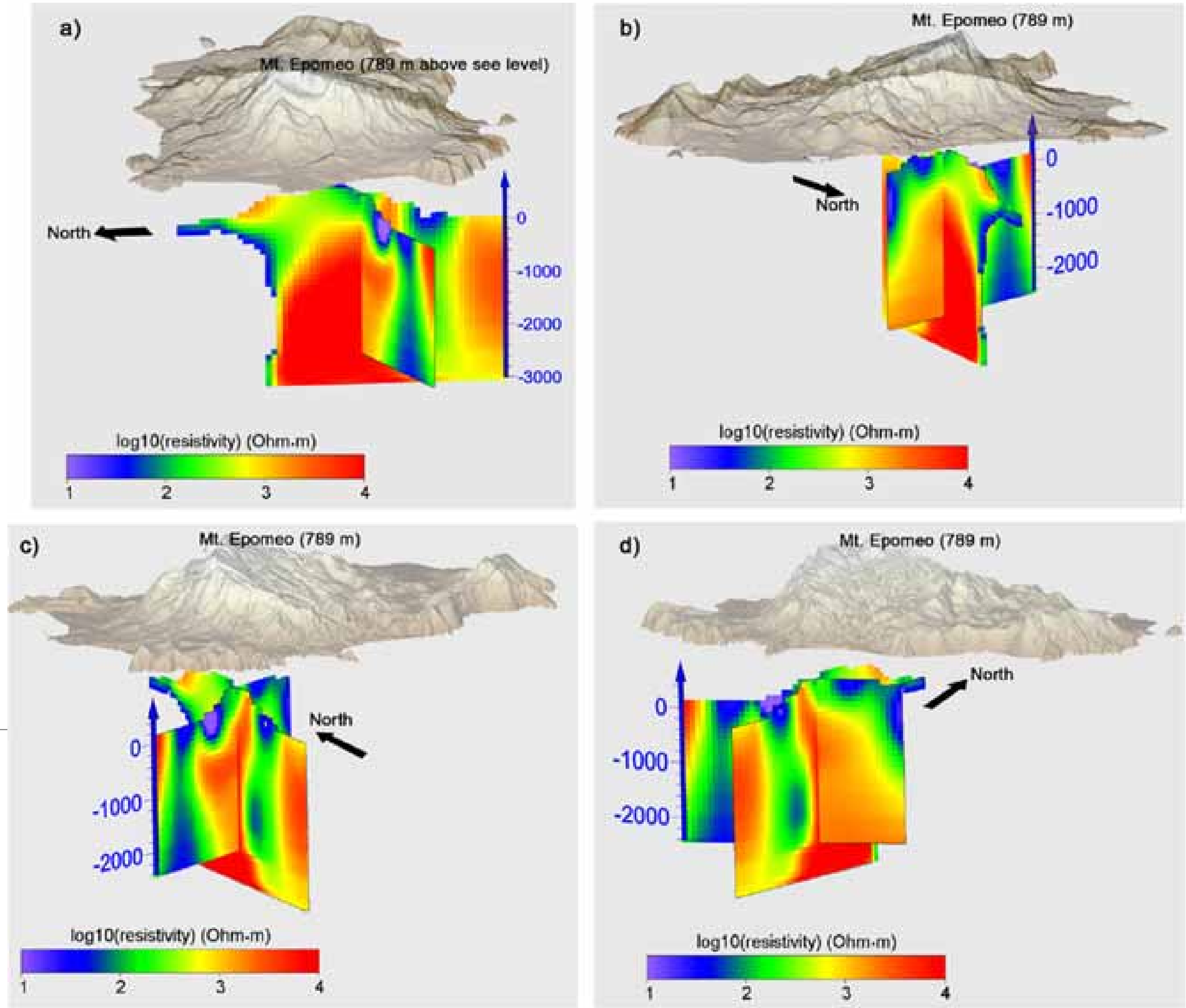
Geothermal Gradient

140/220 ° Ckm^{-1}

Ischia Island

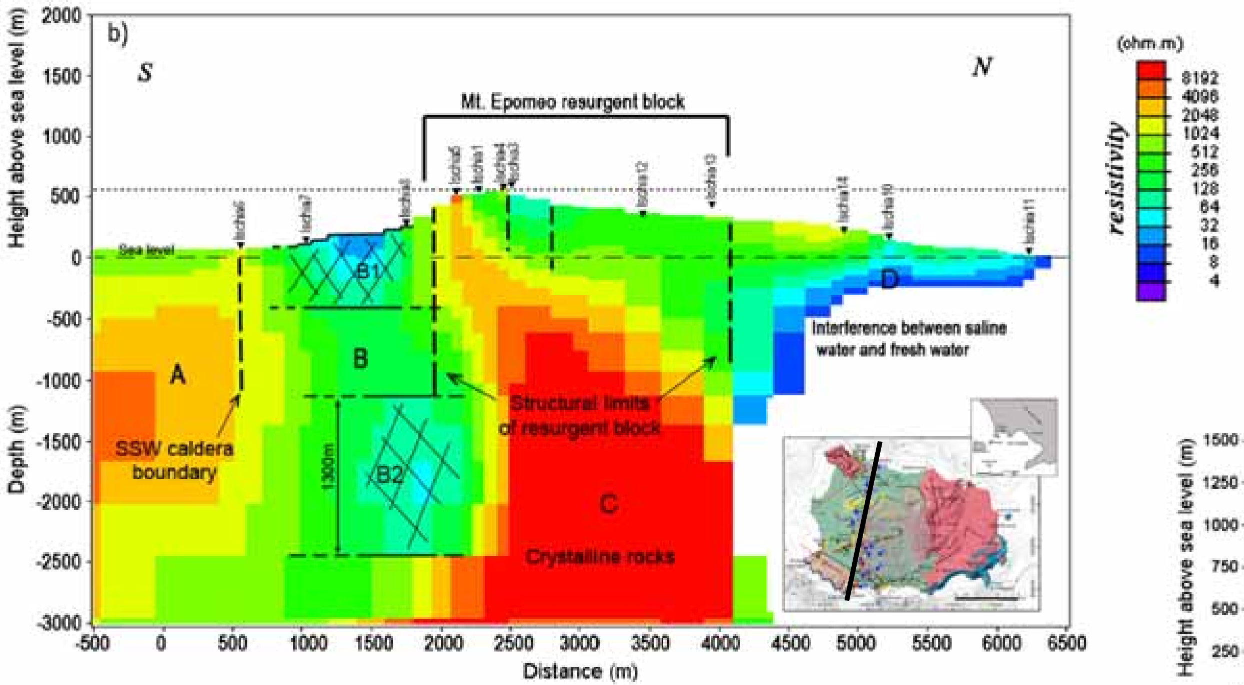


A magnetotelluric (MT) survey of the island was carried out along two main profiles through the central-western sector, providing 2D electrical resistivity sections to a depth of 3 km.

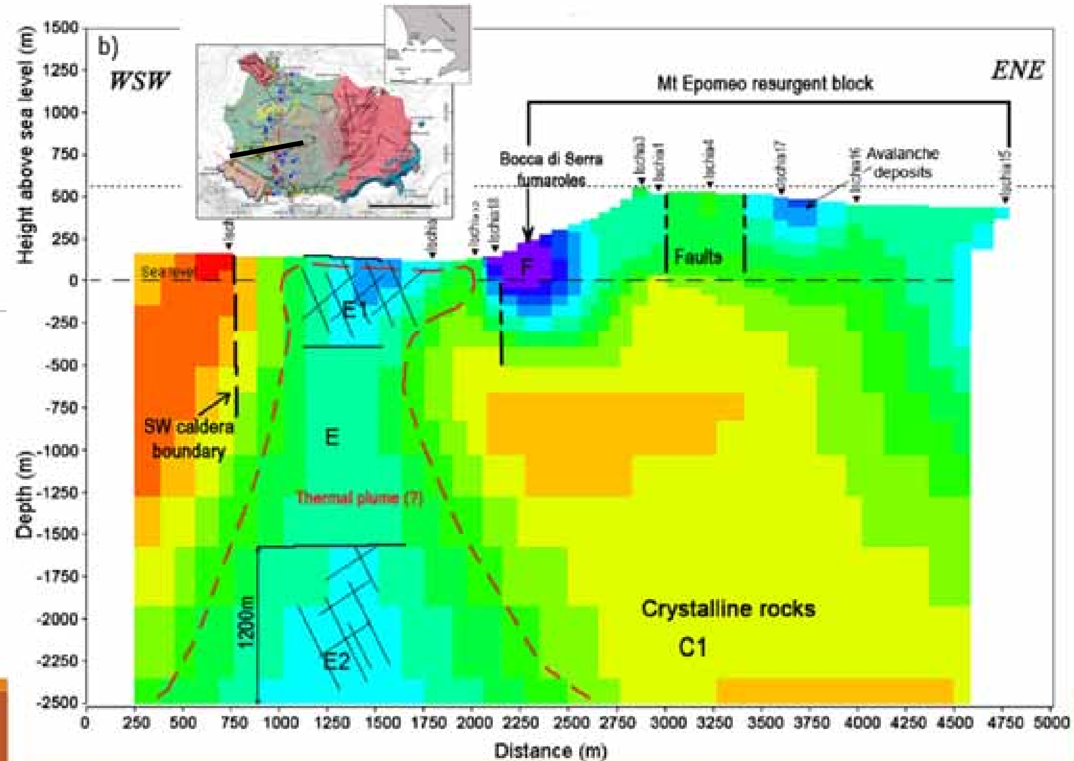


Di Giuseppe, M. G., Troiano, A., & Carlino, S. (2017). Magnetotelluric imaging of the resurgent caldera on the island of Ischia (southern Italy): inferences for its structure and activity. Bulletin of Volcanology, 79, 1-17. doi.org/10.1007/s00445-017-1170-4

Ischia Island

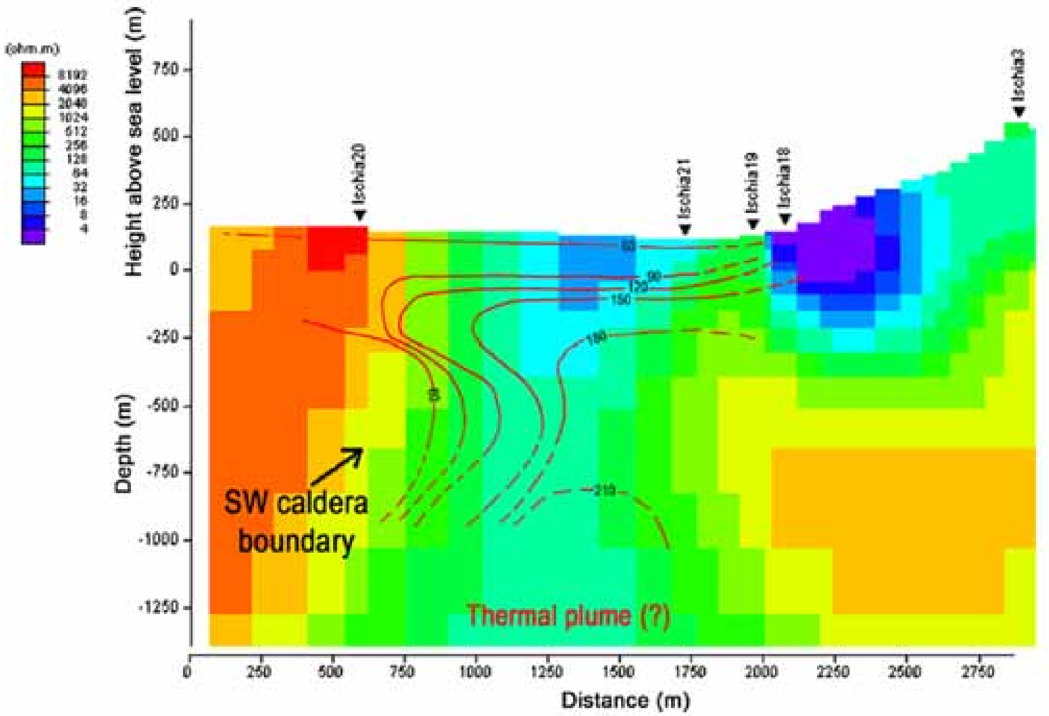


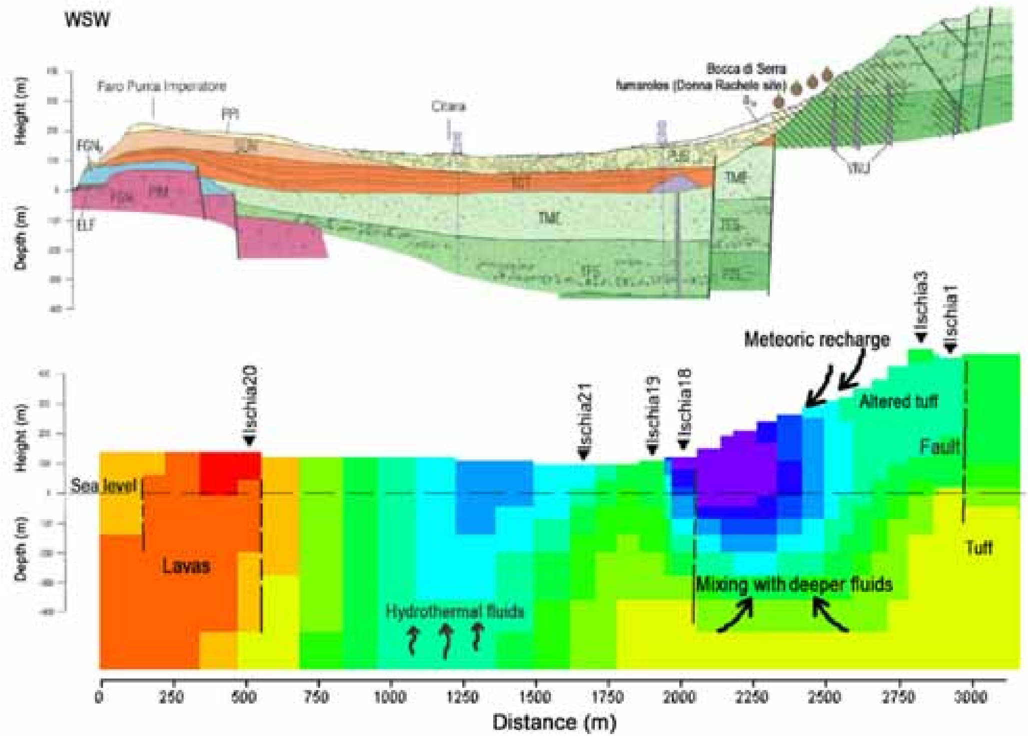
The main feature of the resistivity images is the occurrence of a high-resistivity zone (>1000 Ωm) in both the N-S and WSW-ENE sections This anomaly (C-C1) is delimited by the faults bordering the resurgent block of Mount Epomeo .



The presence of two major hot aquifers (B&E), hypothesized by geochemical studies, has been detected in the SW sector of the caldera. The aquifers reside at different depths, with the depths being controlled by tectonic movements, which have caused deformation of the resurgent block.

Ischia Island

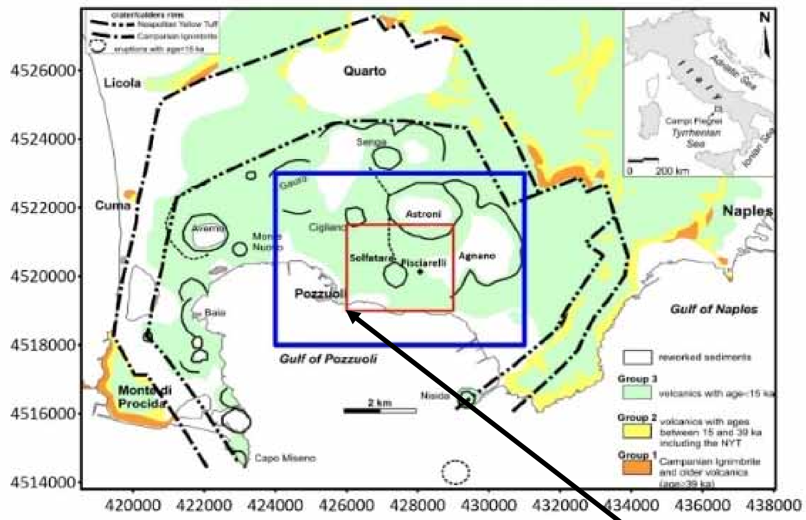


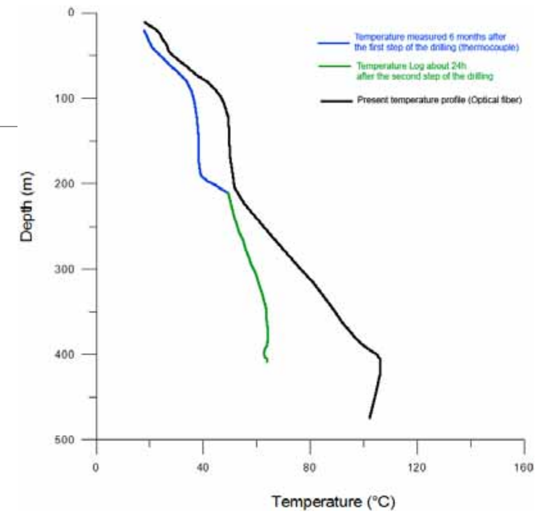


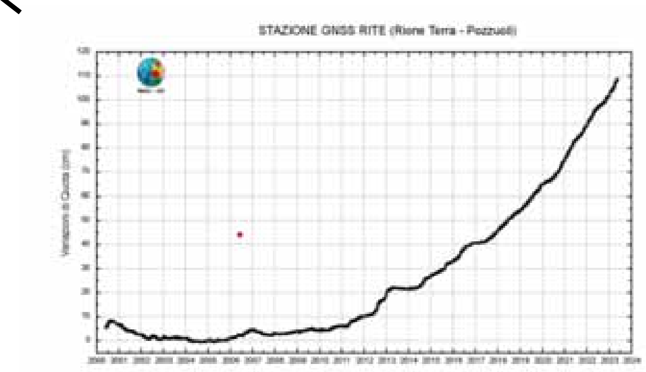
The shape and location of the whole channel exhibiting low resistivity is possibly reconcilable with a thermal anomaly (a plume) associated with advection of hydrothermal fluids.

This is an interpretation also supported by drill hole data and by the presence of fumaroles and a hot-spring field (with temperatures up to 100 °C).

Campi Flegrei

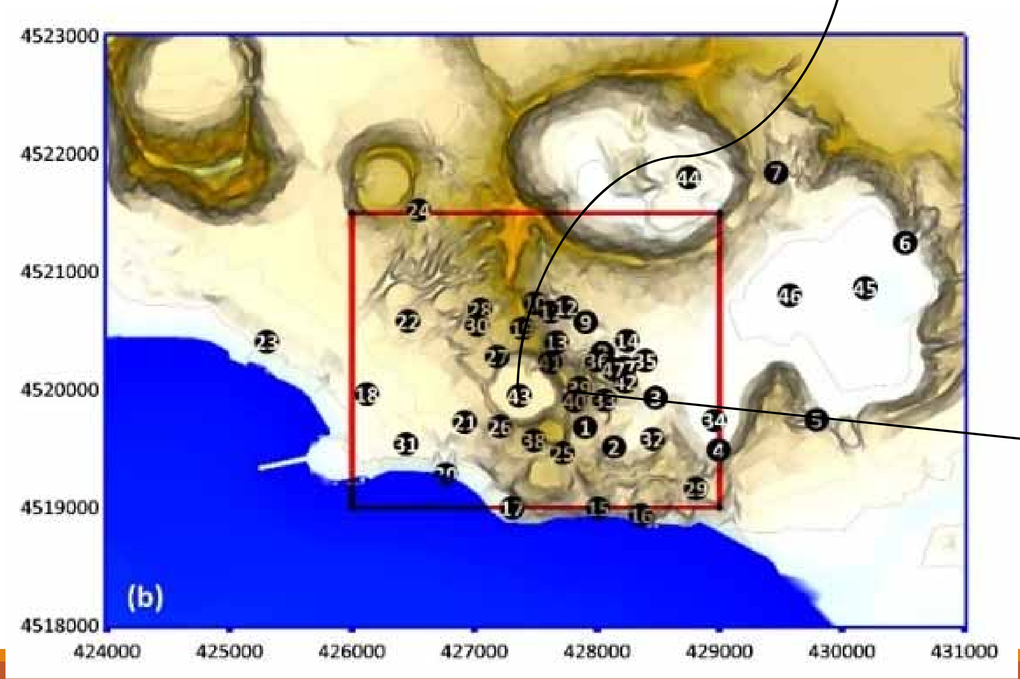






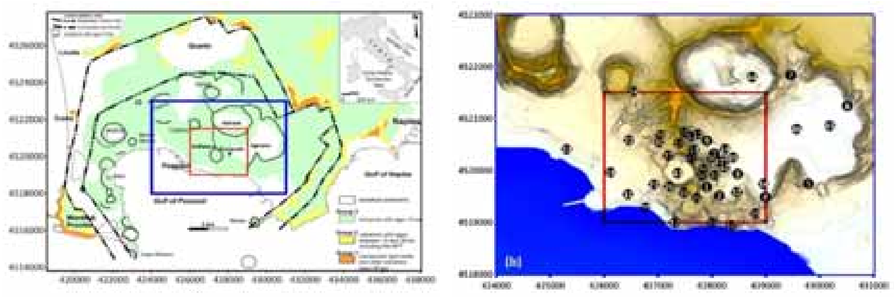
- an active volcanic field within a caldera
- well developed hydrothermal system with active fumaroles
- presently in a unrest phase

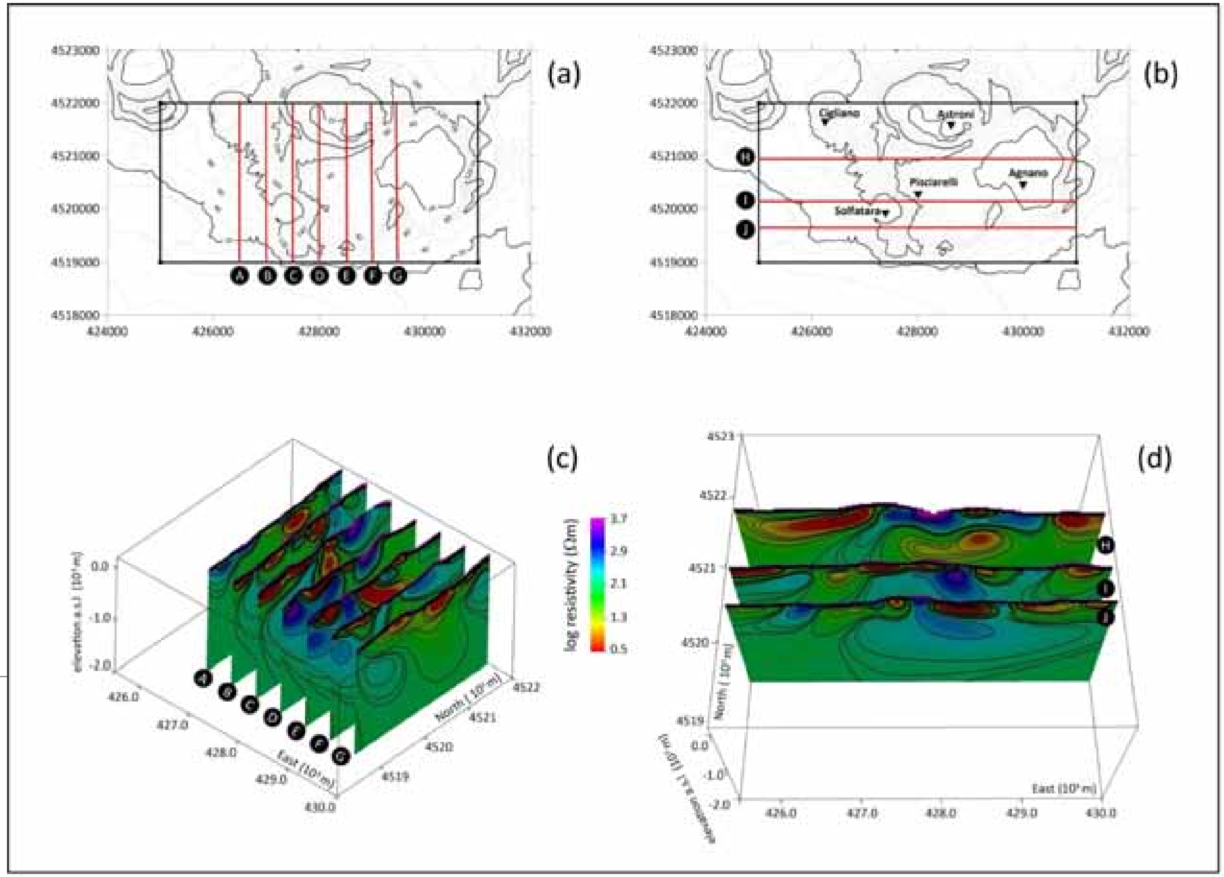

Solfatara


4523000
4522000
4521000
4520000
4519000
4518000
424000
425000
426000
427000
428000
429000
430000
431000
(b)


Pisciarelli

Campi Flegrei Central Sector



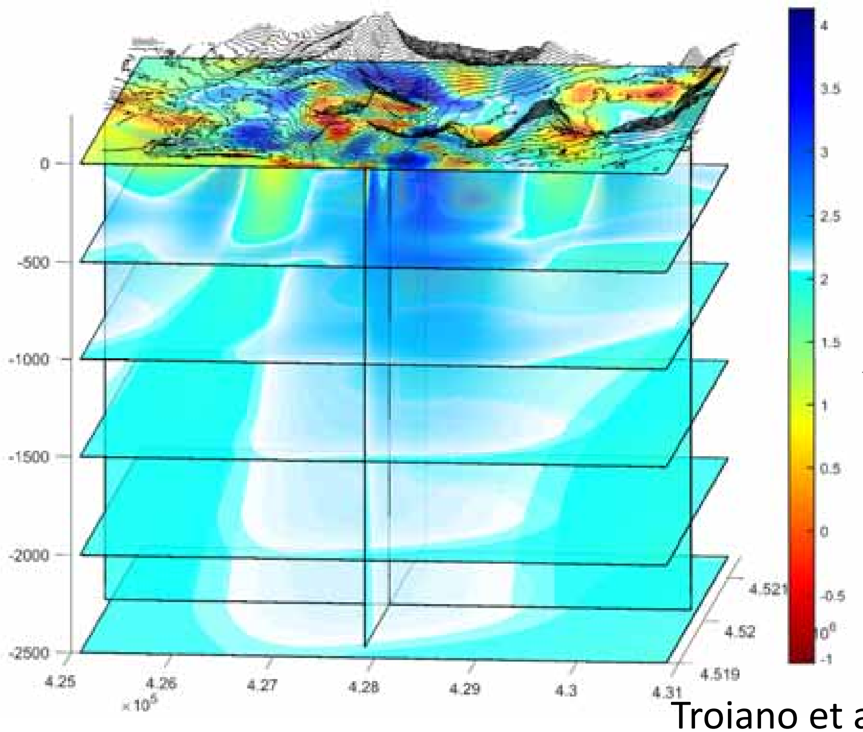
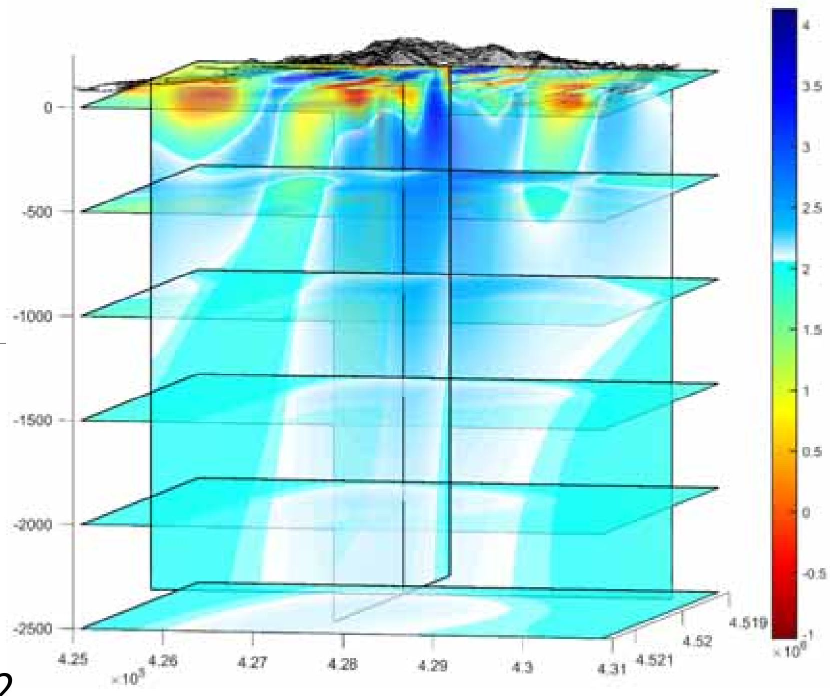


- To solve the open question on the deeper feeding system of the Pisciarelli hydrothermal field, its relation to the Solfatara system, and the main structures governing the fluid rising.
- The previous MT soundings in the area involved 2D applications.

Troiano, A., Di Giuseppe, M.G. & Isaia R. (2022). 3D structure of the Campi Flegrei caldera central sector reconstructed through short-period magnetotelluric imaging. Scientific Reports 12, 20802 (2022). doi.org/10.1038/s41598-022-24998-6

Campi Flegrei Central Sector

A new 3D survey overcomes the limitations of the past magnetotelluric investigations carried out in the sector. Results furnish an electrical resistivity image in the first 2.5 km of depth through the acquisition of electromagnetic data in the 47 measurement sites. The resulting 3D resistivity model unveils multiple findings enforcing the knowledge regarding the relationship between the Solfatara and the Pisciarelli feeding systems and the neighboring structures.

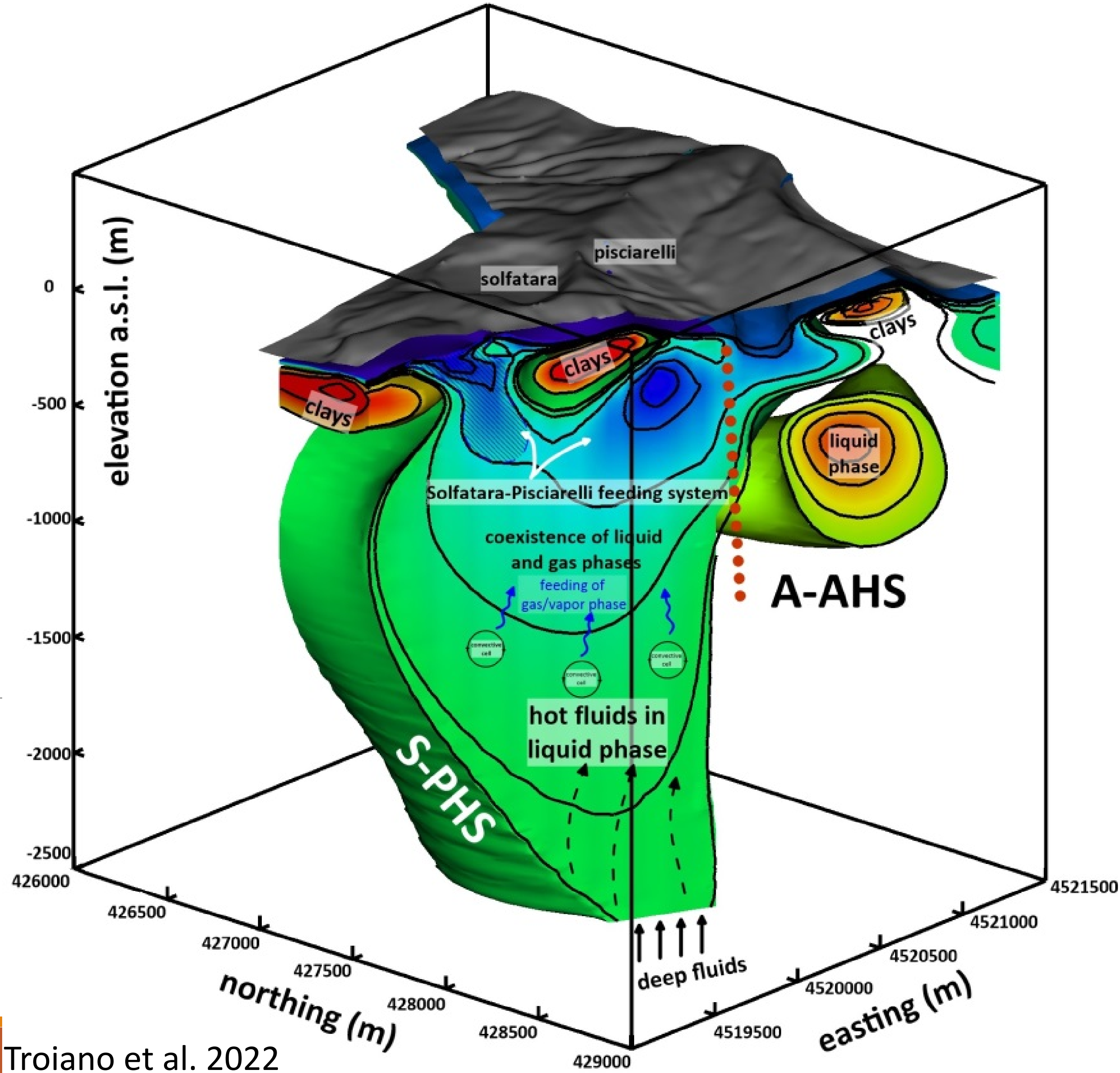
Troiano et al. 2022

Campi Flegrei Central Sector

i. The uppermost conductive block of fewer than 500 m of thickness.

ii. The underlying resistive volume of about 1300 m of thickness, which can be associated with the main geothermal reservoir of the Solfatara-Pisciarelli sector, permeated by a mixture of fluids in coexisting liquid and vapor phases.

iii. A deeper zone characterized by an electrical resistivity of tens of Ω m.



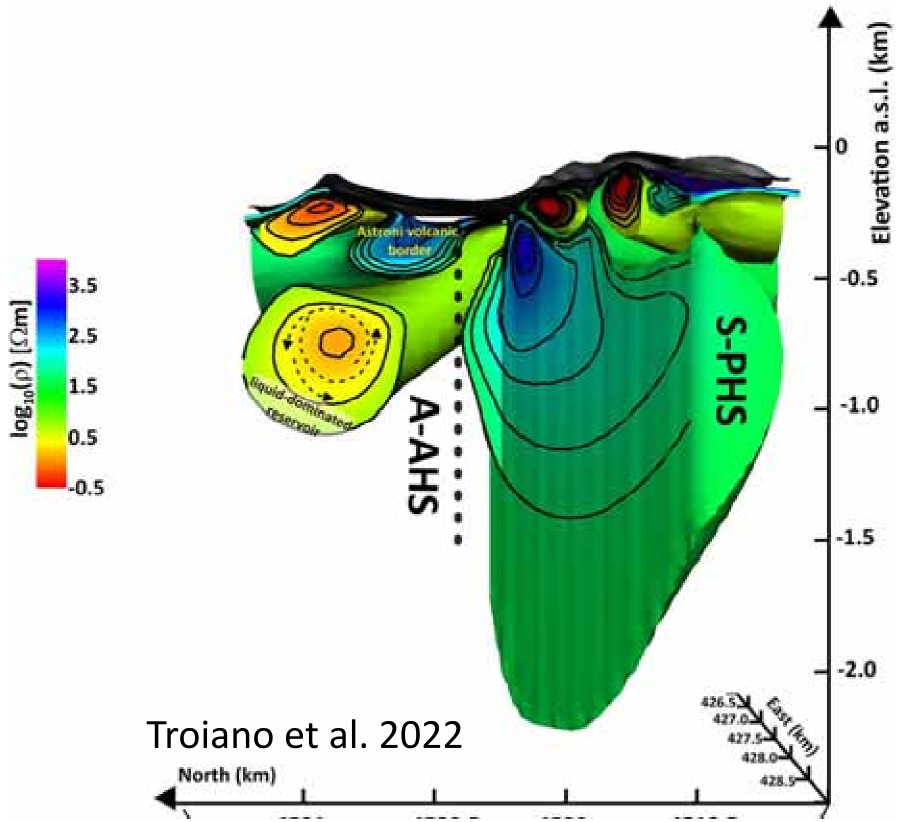
Troiano et al. 2022

Conclusions- exploration

Geophysical methods have an important role in all the phases of geothermal exploration and exploitation.

In our study cases:

- satellite products (potential field methods) are important in the first phases when few constraints are available → crustal characterization
- Electrical methods are particularly apt when a detalied characterization of the reservoir is required
- Importance of integration to reduce ambiguity inherent in every geophysical technique



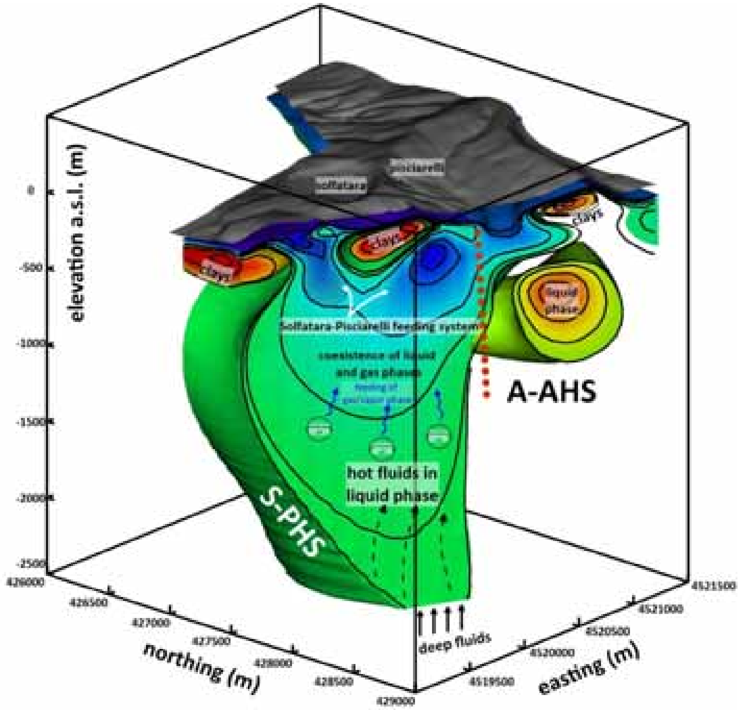
Troiano et al. 2022

Monitoring geothermal fields: experiences of INGV-OV in active volcanoes

Volcanic areas are geothermal areas

- Monitoring volcanoes shares some similarities with monitoring geothermal fields:
  - Large mass of underground fluids involved
  - Occurrence of seismicity induced by fluid circulation
  - Deformation associated with fluid injection and withdrawal

Campi Flegrei: a volcanic system presently in unrest



- Bradyseism: slow underground movements related to the hydrothermal and magmatic system below the Campi Flegrei

- Source of present unrest still debated between pure hydrothermal (no involvment of a deep magmatic component) and an hybrid source with magma rising involved

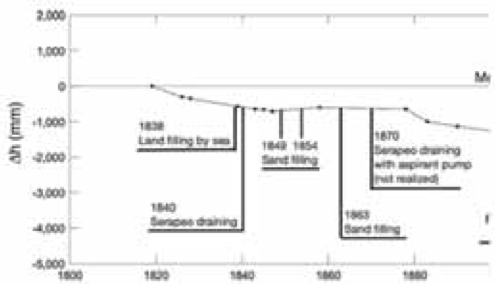
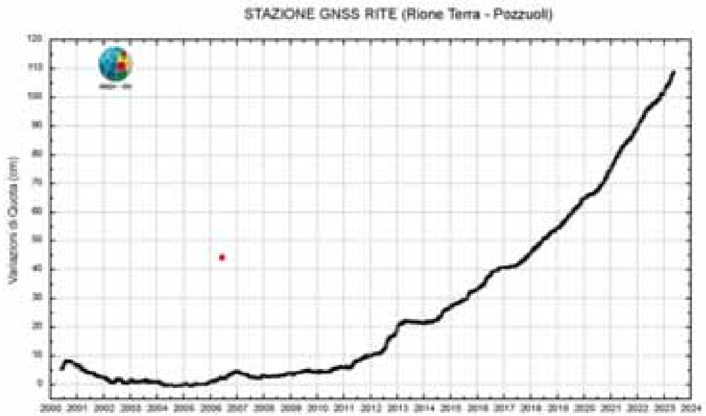


Fig. 11 Height variation of the Serapeo marble floor in th
(2010)

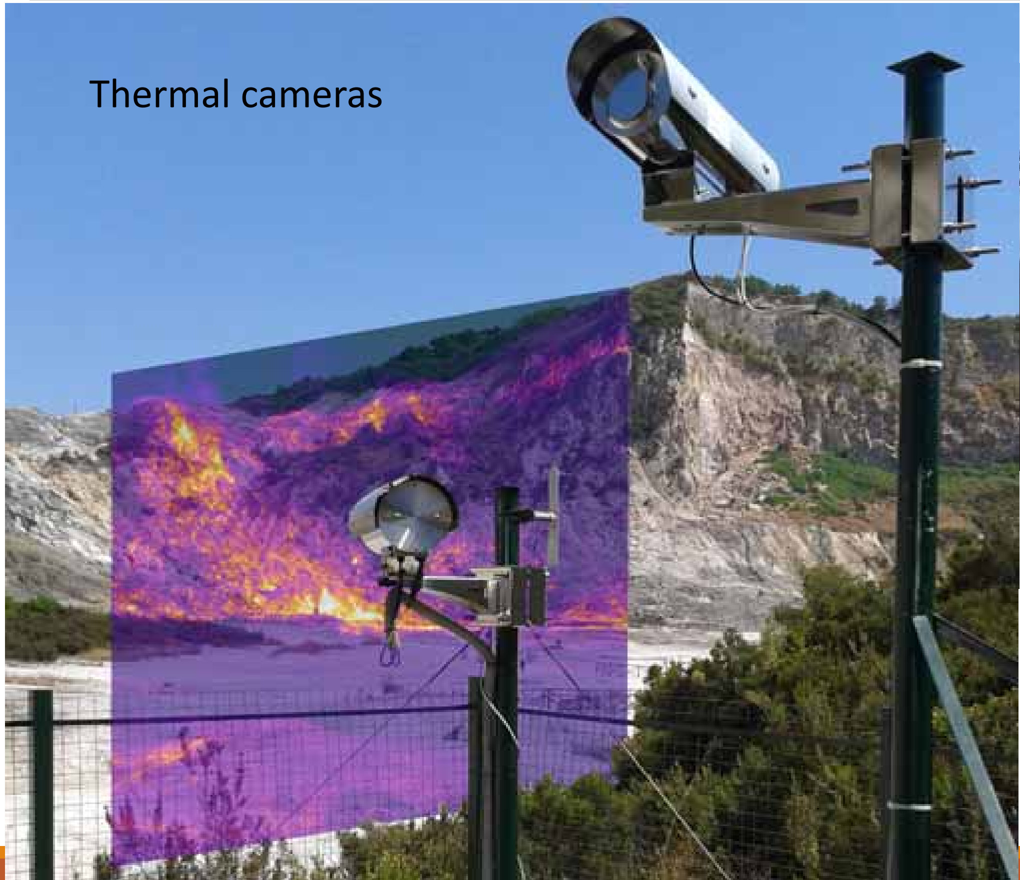


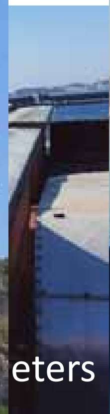
Vesuvius: a quiescent volcano

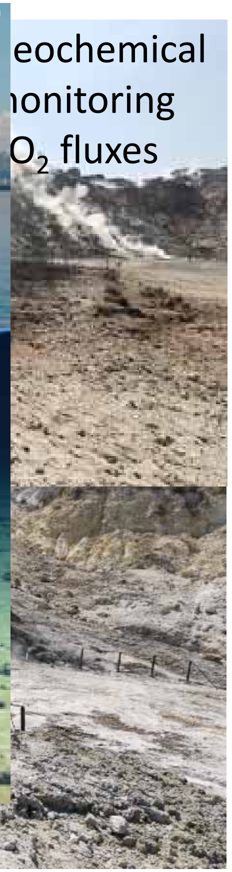
- Last volcanic activity in 1944

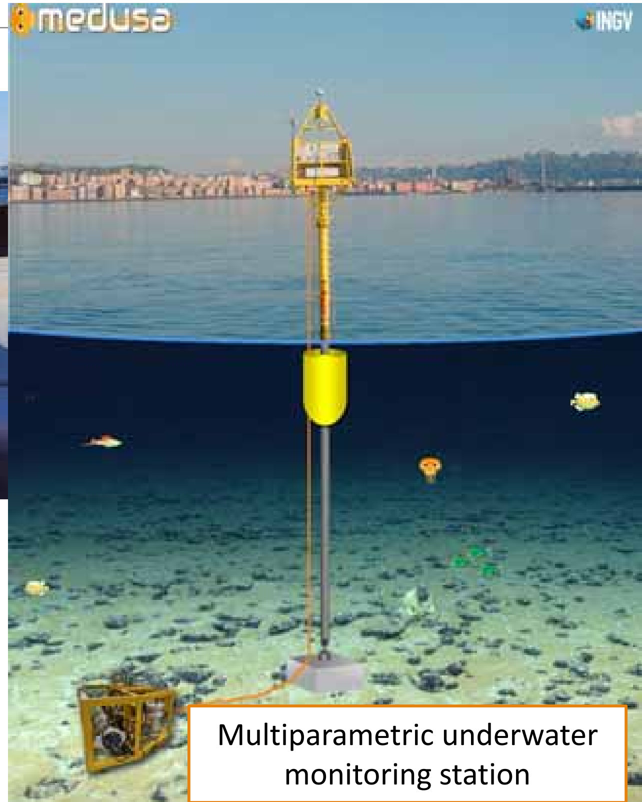
- interaction between hydrothermal and magmatic systems testified by:
  - Fumarole activity
  - Seismic activity (i.e. swarms)
  - Geodetic transients (tiltmeters and gravimetry)

Monitoring systems in the Neapolitan volcanoes





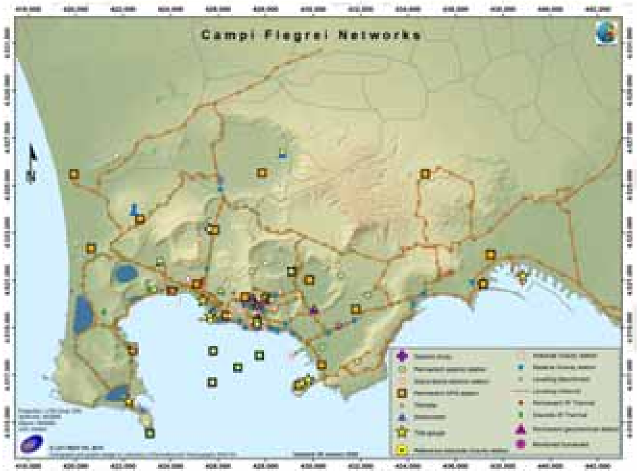




Monitoring activities at INGV-OV

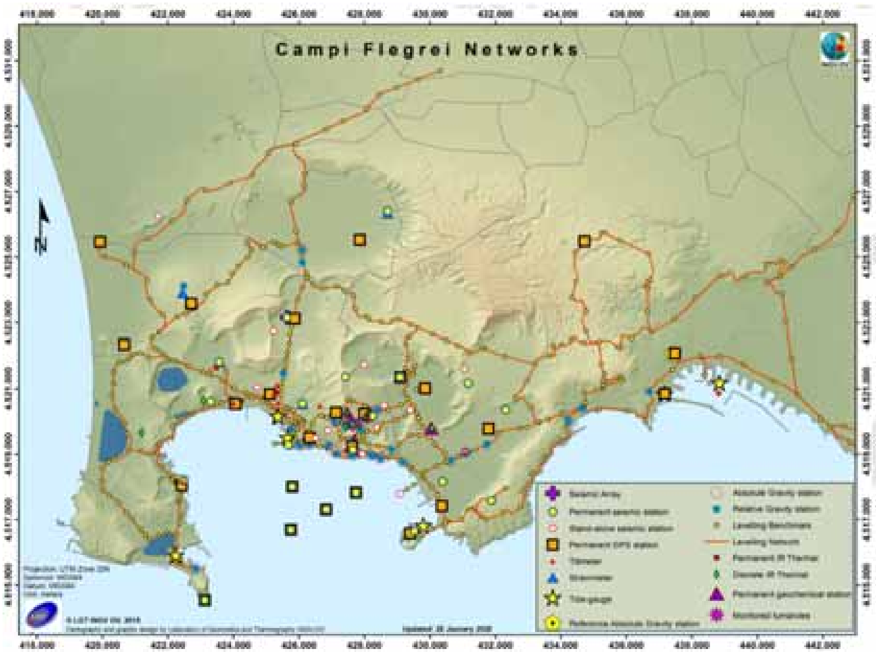
INGV-OV leading insititution in:
- developing instrumental networks and strategies for volcano montitoring

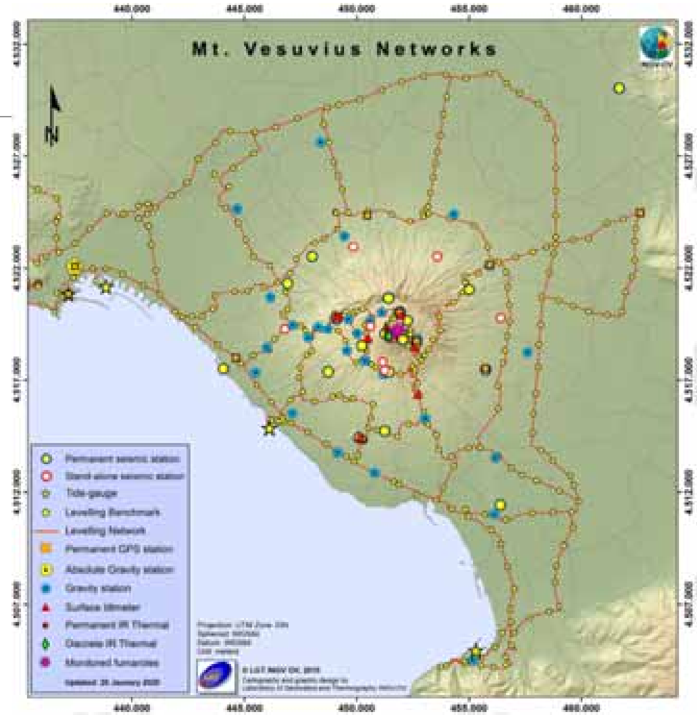
- acquiring and processing geophysical and geochemical data



- studying volcano processes through integration of geophysical geochemical data

Geophysical parameters monitored by INGV-OV

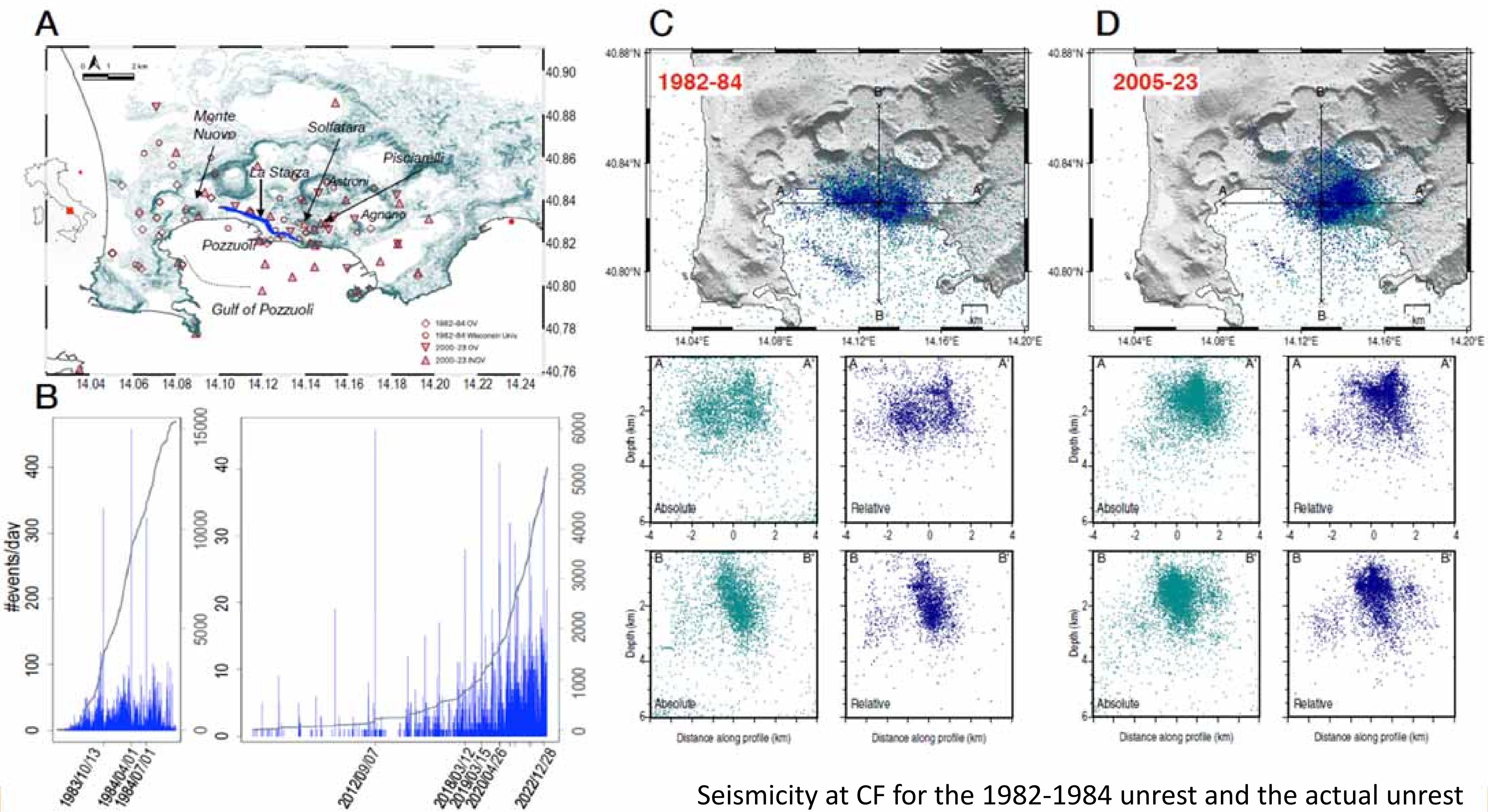




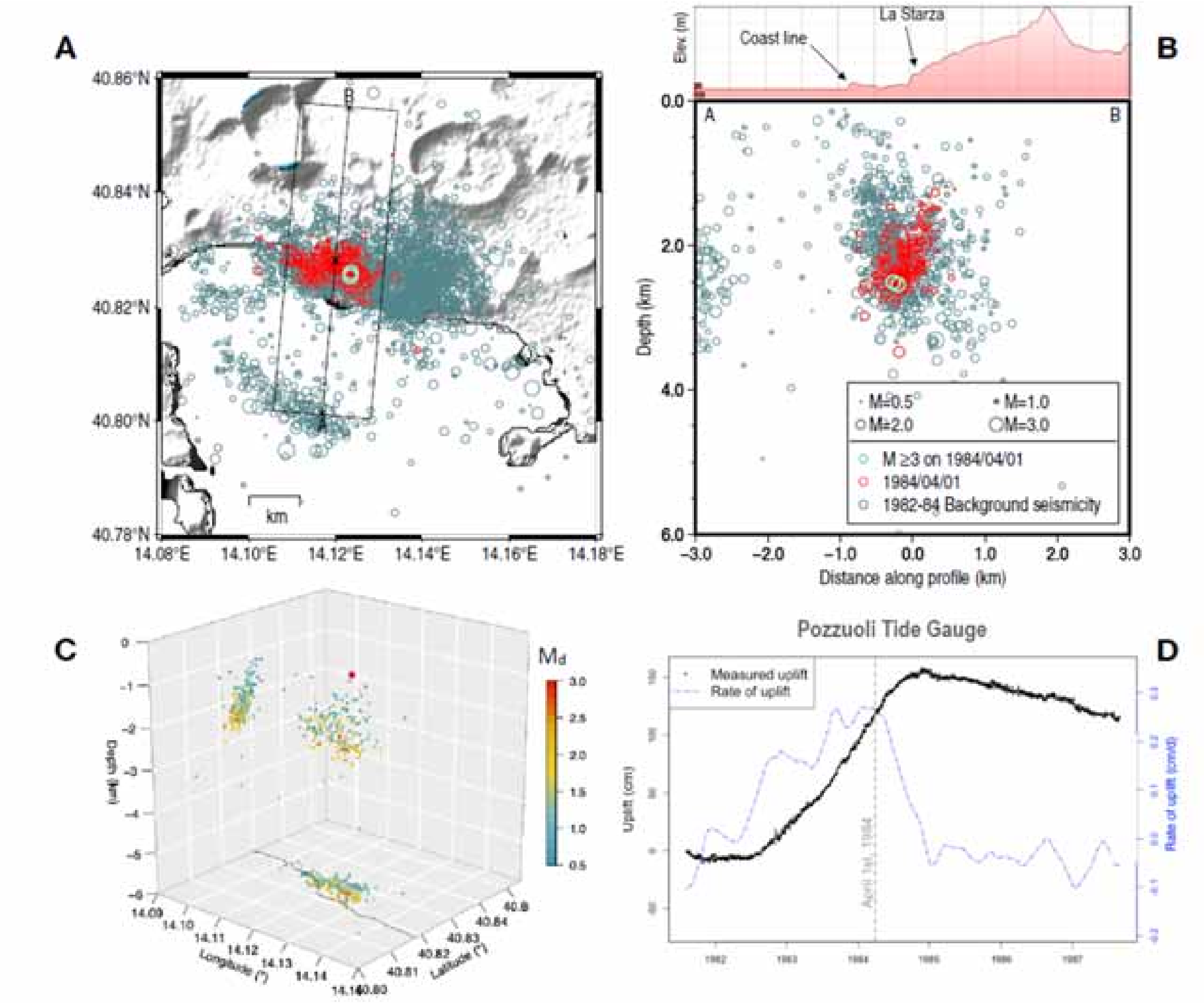
- Seismicity: 27 stations (inland and onshore)
- Deformation: 25 cGNSS, 10 tiltmeters, 4 borehole strainmeters
- ΔMass: 1 cGravimeter and periodic time-lapse observations
- Thermal and geochemical monitoring of fumaroles

- Seismicity: 18 stations (inland and onshore)
- Deformation: 8 cGNSS, 7 tiltmeters
- ΔMass: periodic time-lapse observations
- Thermal and geochemical monitoring of fumaroles

Seismic Monitoring



Seismicity at CF for the 1982-1984 unrest and the actual unrest



A
B
C
D
40.86°N
40.84°N
40.82°N
40.80°N
40.78°N
14.08°E
14.10°E
14.12°E
14.14°E
14.16°E
14.18°E
km
Elev. (m)
Coast line
La Starza
Depth (km)
Distance along profile (km)
M=0.5
M=1.0
M=2.0
M=3.0
M ≥3 on 1984/04/01
1984/04/01
1982-84 Background seismicity
Md
Depth (km)
Longitude (°)
Latitude (°)
Pozzuoli Tide Gauge
Measured uplift
Rate of uplift
Uplift (cm)
Rate of uplift (cm/d)
April 1st, 1984

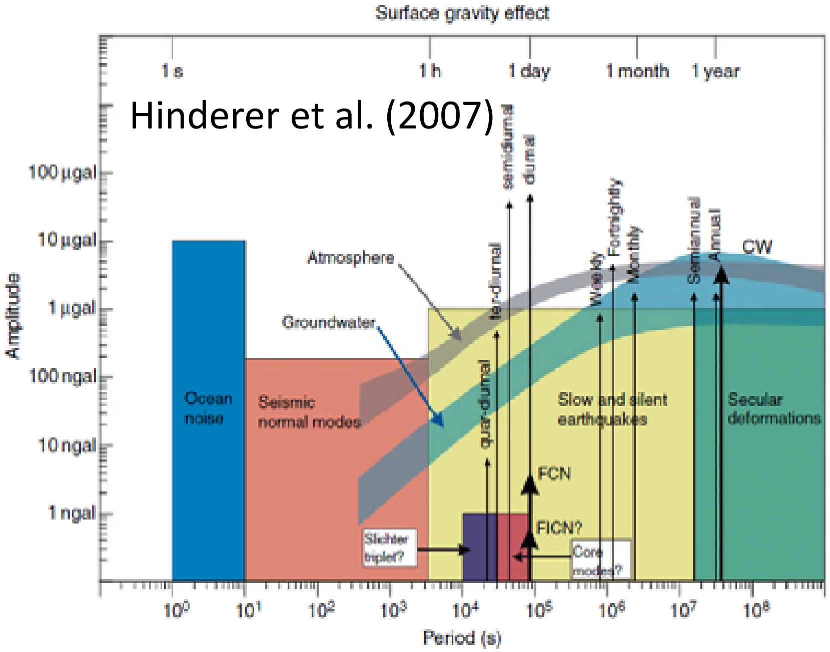
Geodetic Monitoring of hydrothermal systems

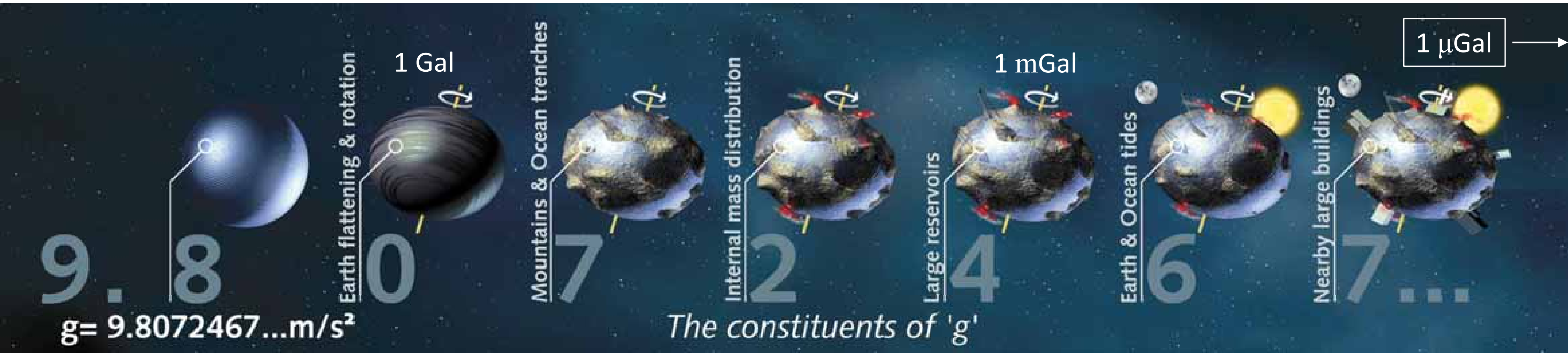
Gravimetry

Every mass redistribution occurring inside and on the surface causes gravity variations

Time lapse monitoring →4D image of the mass variations

Geophysical phenomena responsible of temporal variations:



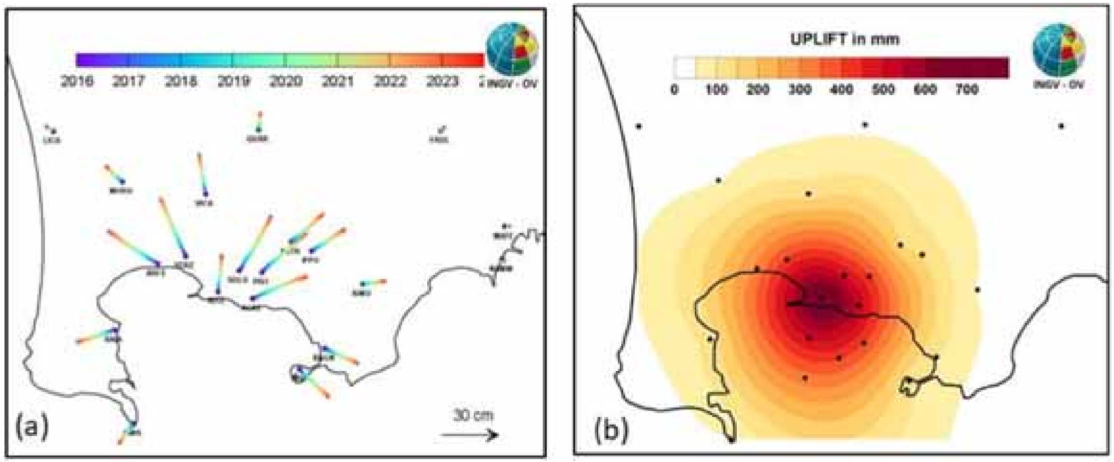


GNSS monitoring

- Continuous GNSS stations provide high quality observations of the deformation

- daily solutions with millimetric precision of horizontal and vertical components

- products: maps of deformation, maps of strain rate

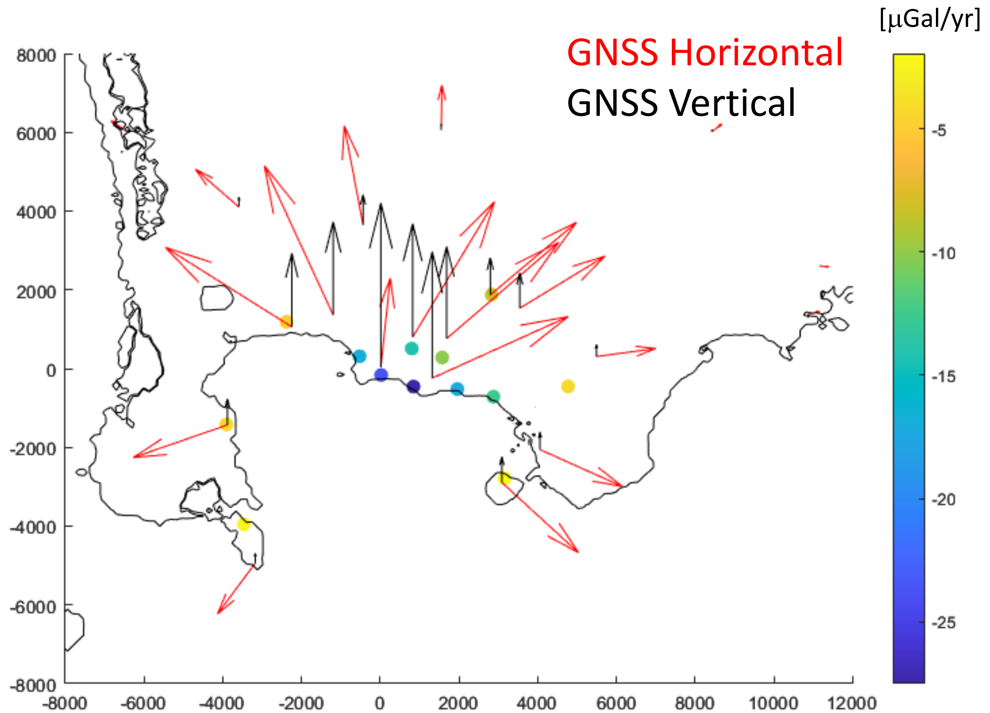


Geodetic monitoring of reservoirs

Monitoring deformation is fundamental:

- extraction and injection induce shallow ground deformations, in a similar way as a volcano in unrest

Gravity monitoring is also fundamental since it senses mass variation related to fluid movements



Campi Flegrei present unrest

Geodetic monitoring of CF- modelling

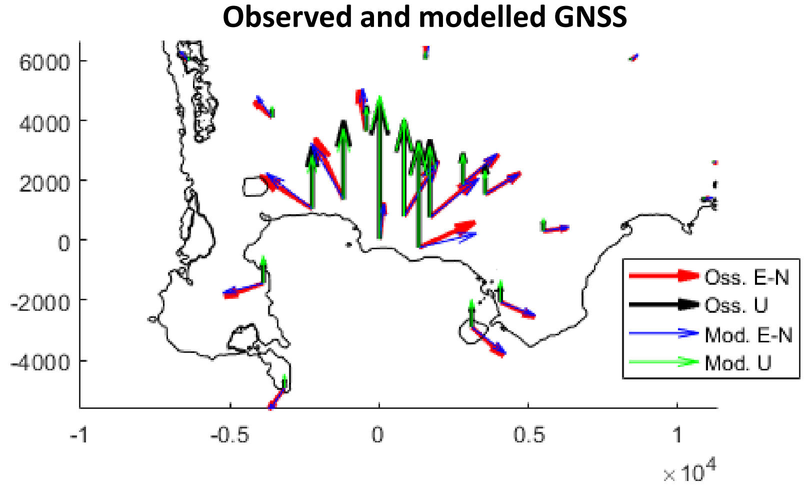
- spatial patterns of deformation help in locating the depth of the source and provide constraints on the pressure difference → in a geothermal system this can be checked through numerical modelling

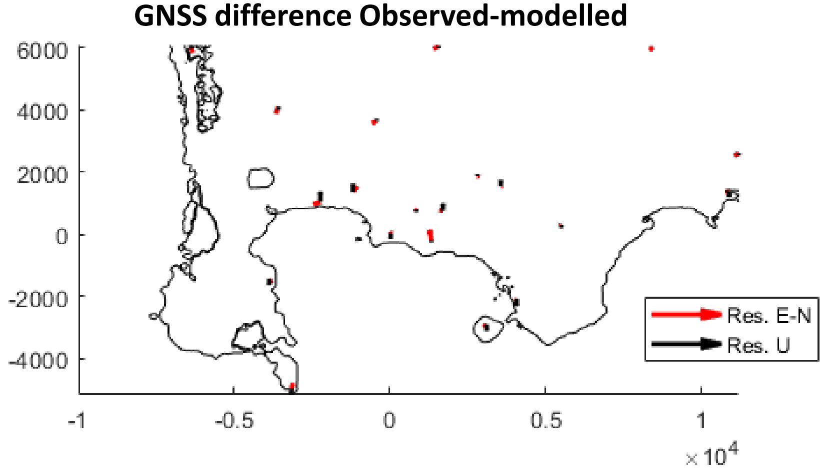
- simple sources of overpressure allow a very good fit of the observations

- we know analytical or semi-analytical formulations for surface deformation due to overpressure in spherical, ellipsoidal sources → fast inversion routines

	X0 [m]	Y0 [m]	Z [m]	Ax1 [m]	Ax2 [m]	Ax3 [m]	dP [Pa]
fECM	-51	-578	2520	568	512	622	$55\ 10^6$

Inverted parameters of an ellipsoidal source of overpressure that fits the CF GNSS observations





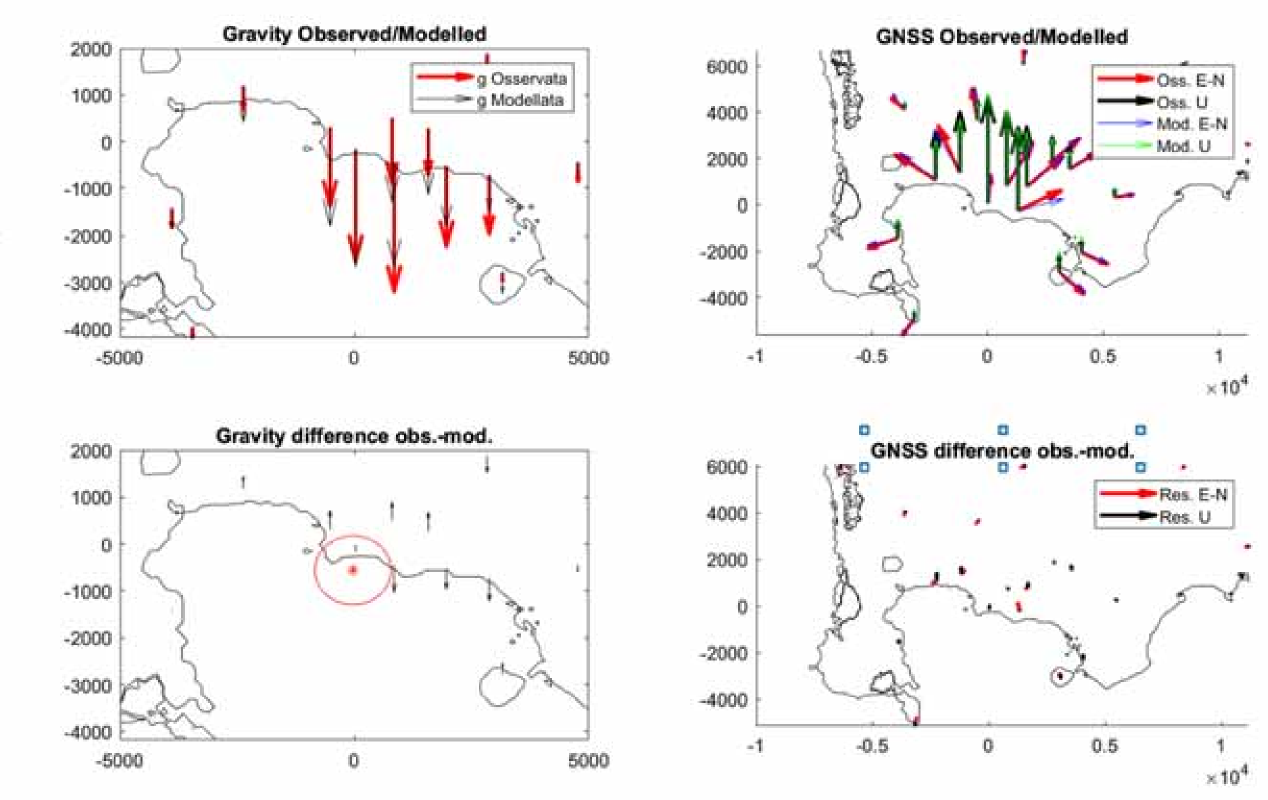
Gravimetric observations

-Information on the mass changes through time: mass fluxes

- Combination of continuous gravity stations and time-lapse measurements

- complements the deformation monitoring done by GNSS and/or SAR

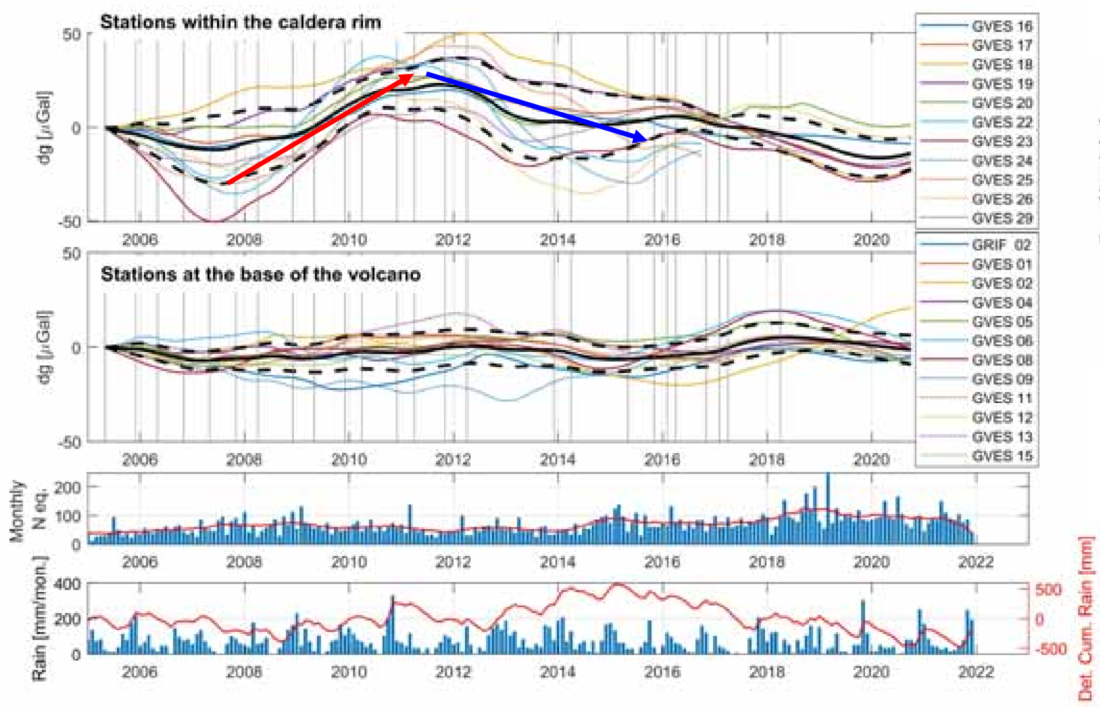
- joint inversion: information on mass flux and/or density of fluids



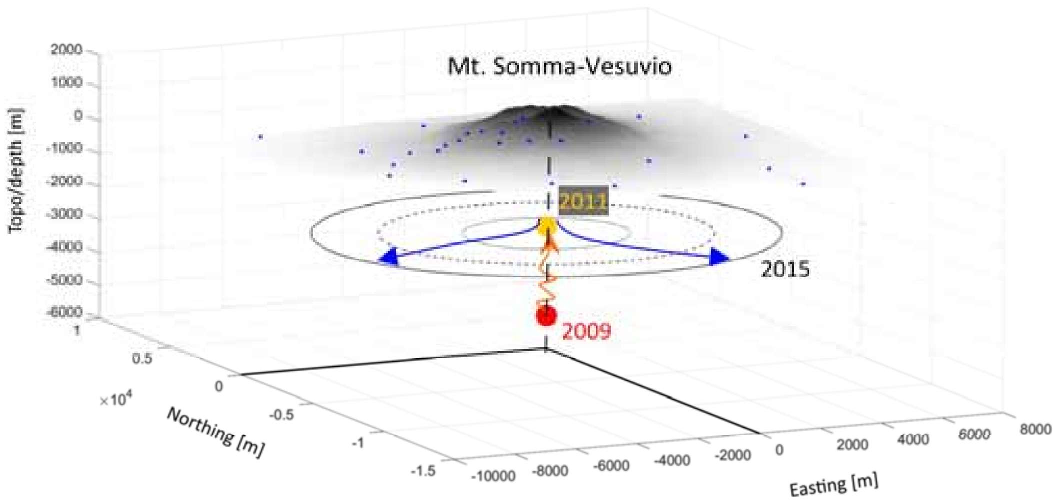
Inverted parameters of an ellipsoidal source of overpressure that fits the CF GNSS & gravity observations

	X0 [m]	Y0 [m]	Z [m]	Ax1 [m]	Ax2 [m]	Ax3 [m]	dP [Pa]	Mass [kg]
fECM conj.	-28	-556	2428	814	733	935	$18\ 10^6$	$6\ 10^9$

Vesuvius –gravity monitoring of hydrothermal system



Pivetta et al., in revision in GJI



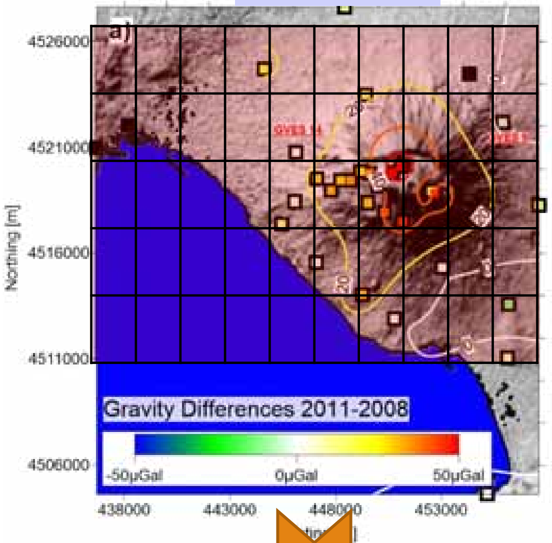
Interpretation: Fluid movements associated with the deep hydrothermal circulation.

<u>1 stage</u>: gravity rise → rise of fluids from deep reservoir up to the hydrothermal system

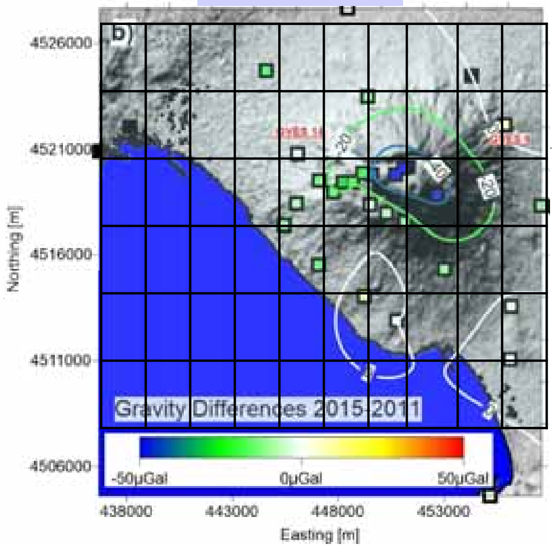
<u>2 stage</u>: diffusion of fluids within the hydrothermal system

“Rising” & “Decreasing” gravity on the volcano

2011-2007



2015-2011



$$M = \frac{1}{2\pi G}\sum_{i=1}^{N}\Delta g_r(x,y)\Delta x\Delta y$$

Gauss theorem applied to 2007-2011 and 2011-2015 fields provides similar masses for the increase and decrease phases (+5.7 10^{10} kg and -4.0 10^{10} kg);

with ρ=1000kg m^{-3}, V= +5.7 10^7 m^3 & -4.0 10^7 m^3

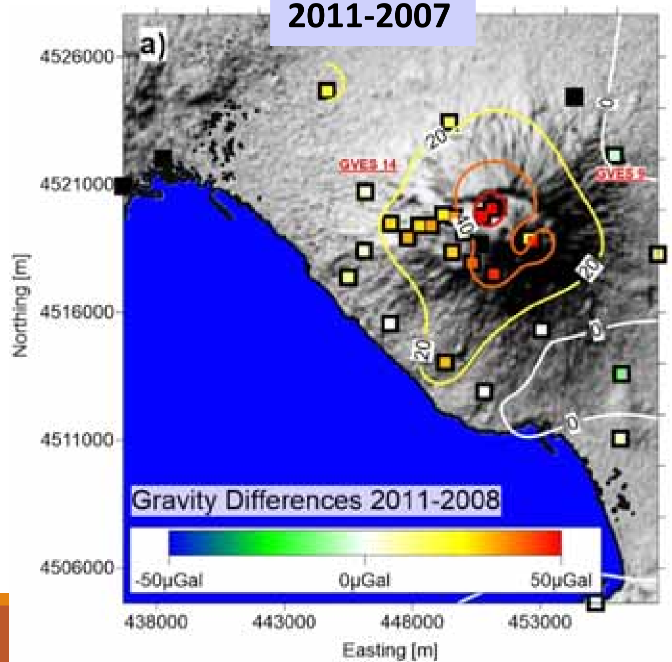
Inversion & modelling of 2007-2011 dg

We invert for depth and volume of a spherical source filled with a fluid with ρ= 1000 kg m^{-3} by minimizing an objective function through the **Nelder-Mead simplex method**
Matlab *fminsearch* function (Unconstrained nonlinear optimization)

The cost function to be minimized

$$f(\boldsymbol{x}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(g_{obs}^{i} - g_{mod}^{i}(\boldsymbol{x})\right)^{2}}$$

2011-2007

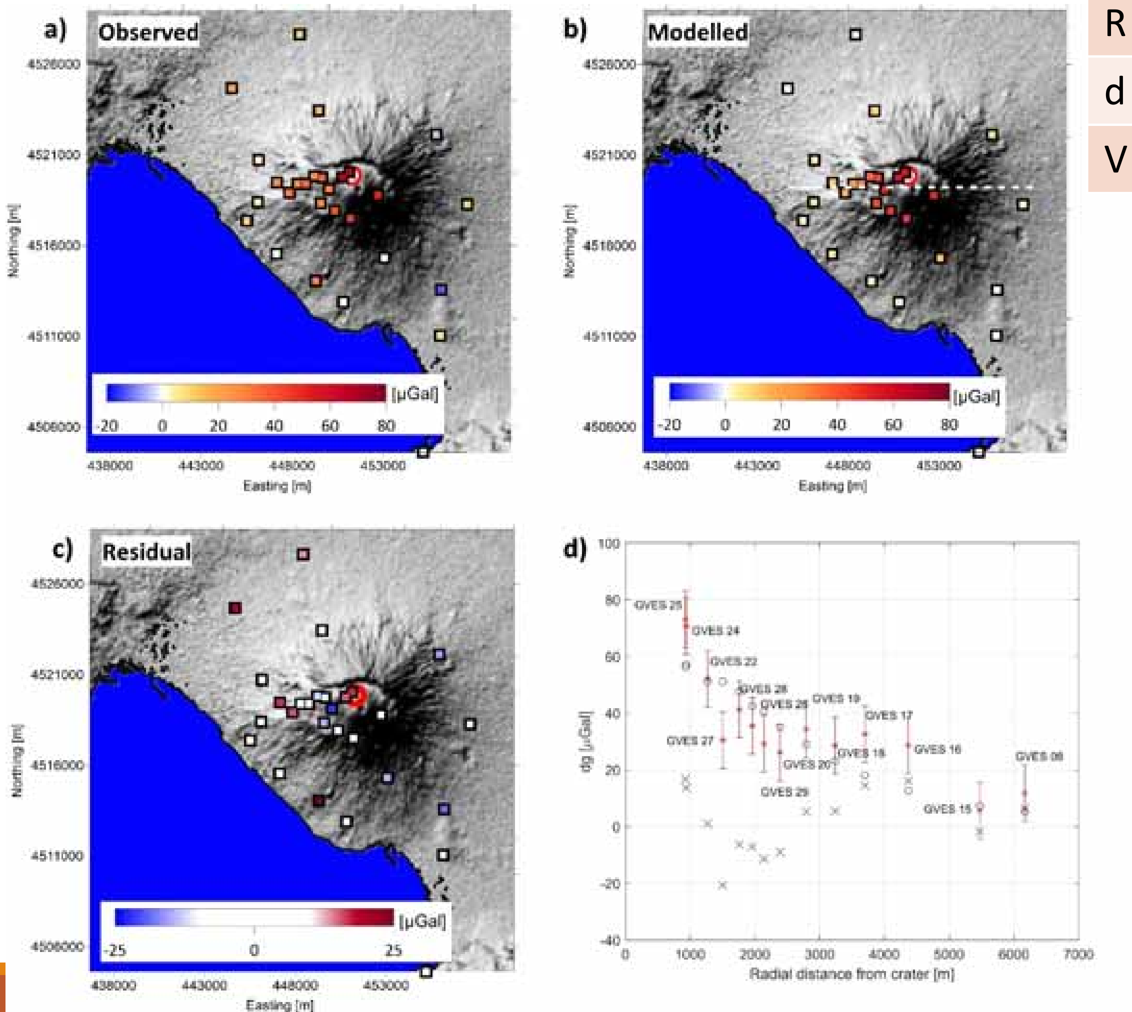


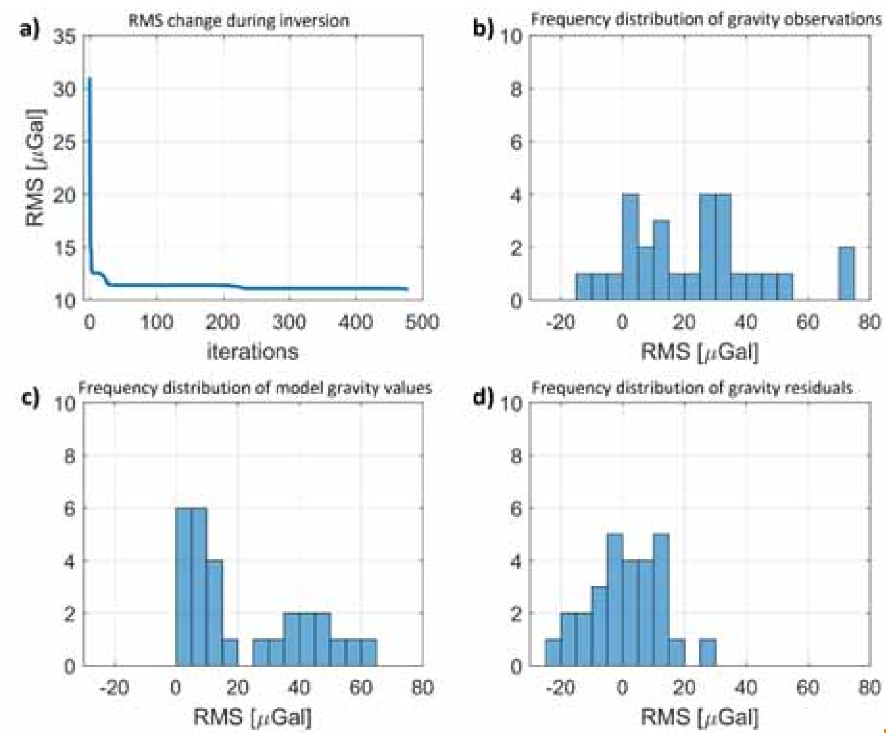
Quality of the inversion

Sphere	
R (m)	285±30
d (km)	2.3±0.8
V (m^3)	$9.5 \cdot 10^7$

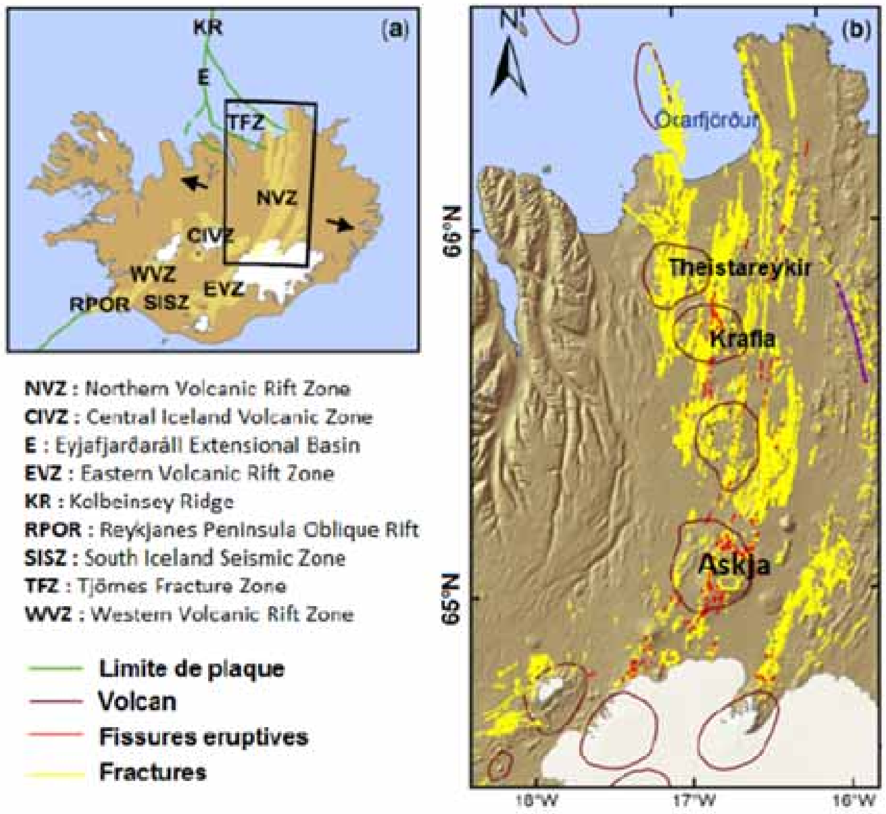
V is in the same order of magnitude as from the Gauss theorem

The inversion reduces the energy of the observations > 60%, RMS reduces from > 30 mGal to ~10 mGal





Geothermal applications of geodetic monitoring



Theistareykhir (Iceland)

Geothermal field in the Icelandic Northern Volcanic Zone (NVZ)

Power plant: 90 MWe with 2 X 45 MWe turbines in operation since autumn 2017 and spring 2018, respectively

13 wells (~ 2 km deep) are using to **extract** the geothermal fluid

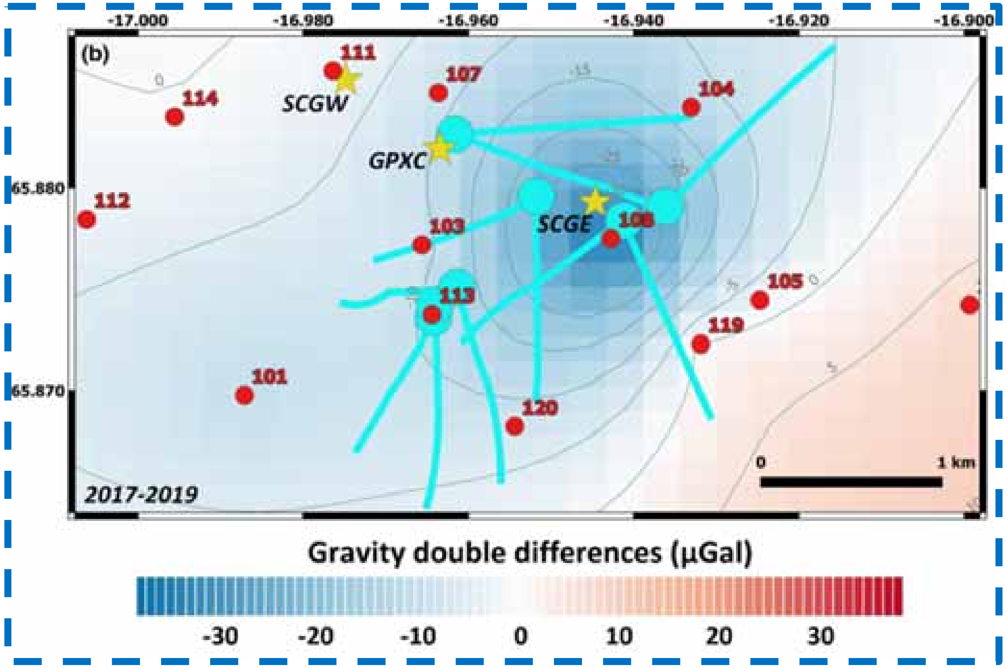
3 collocated wells the geothermal fluid is **reinjected** at around **450 m depth** (ThN-01, ThR-12 and ThN-02).

Main Goal: short-term mass redistribution induced by geothermal production.

Courtesy of Umberto Riccardi

Geothermal applications of geodetic monitoring

Gravimetry has been used in a similar way as in the Vesuvius area to detect mass variations due to injection/extraction of fluids



RESULTS:

Residual gravity **decrease** in 2018 and 2019 with respect to 2017 in the **production area** of the Theistareykir geothermal field.

No gravity variation is observed nearby the injection area

no substantial recharge of the reservoir in this initial period of time after start of exploitation

Courtesy of Umberto Riccardi

Conclusions

Monitoring system:

- Geophysical monitoring (seismicity, ground deformation, mass changes) of the reservoir can help in evalutes current practies of exploitation
- Geodetic moniotring → information on where mass and pressure changes occurr within the reservoir during extraction
- Monitoring Mass fluxes over time may have important implications on sustainability
- Geodetic monitoring of reservoirs in active areas provide information on the geothermal system→ exploration

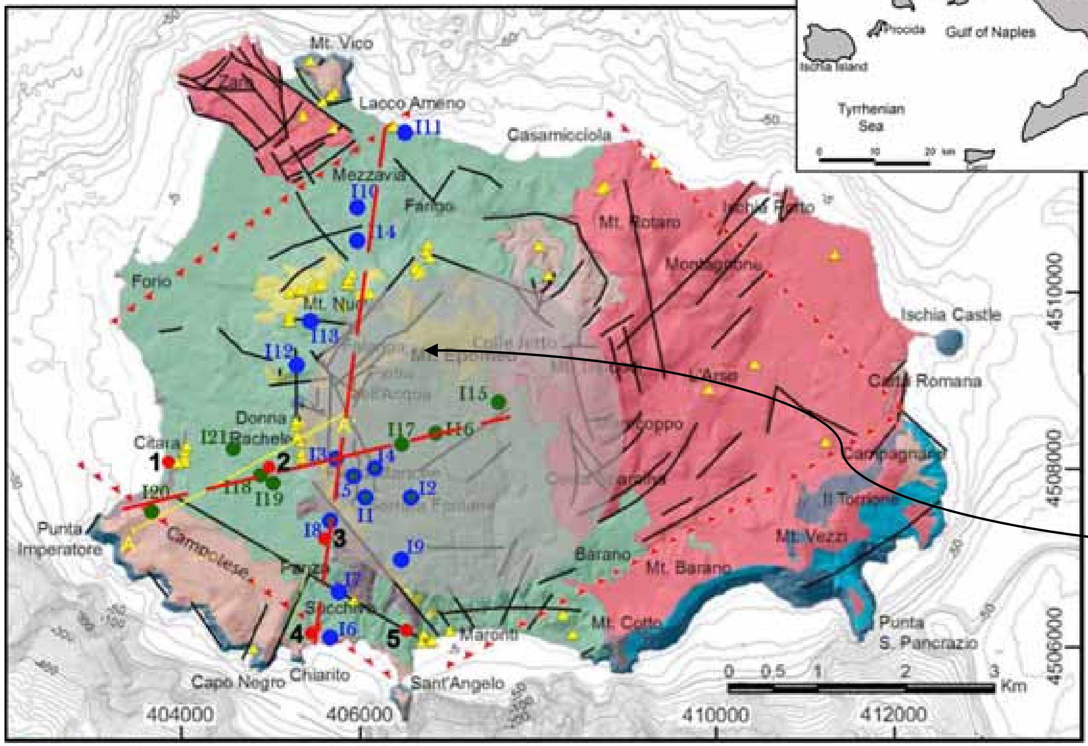
Thanks for the attention!

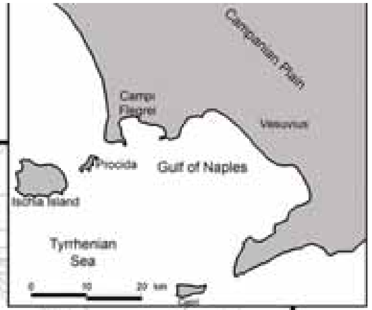
Tommaso Pivetta
Istituto nazionale di Geofisica e Vulcanologia- Osservatorio Vesuviano (INGV-OV) tommaso.pivetta@ingv.it

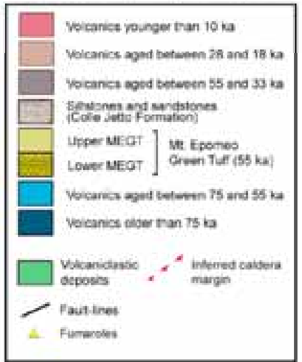
INGV

SUPPLEMENTARY

Project ISCHIA ISLAND “Forio”,







The MT measurement stations along the N-S profile blue points, the MT measurement stations along the WSWENE profile are the green points, and drilling sites are given as red points numbered 1 to 5. The dotted red lines indicate the resistivity section profiles

Objectives

- Improve the understanding of the caldera’s structure and present activity
- Characterize the structures of the hydrothermal system through a **Magnetotelluric survey** complemented with drilling data:
  - Fractures faults
  - Fluids path

What we did in detail:

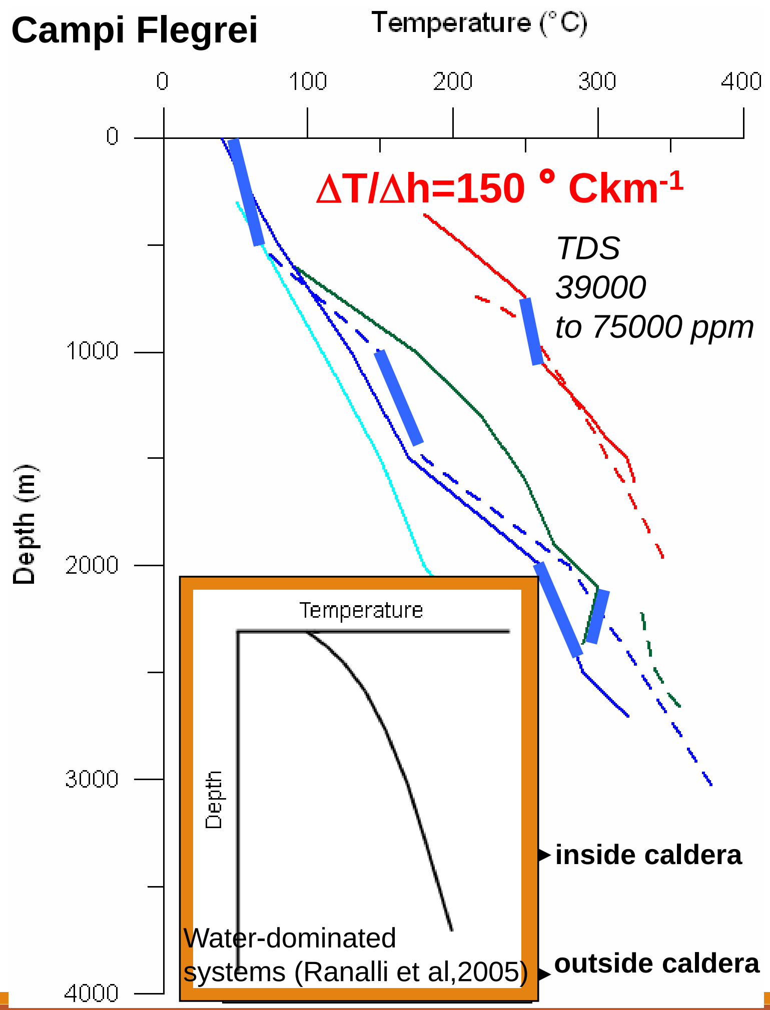
Characterizing structure of Ischia Island through:

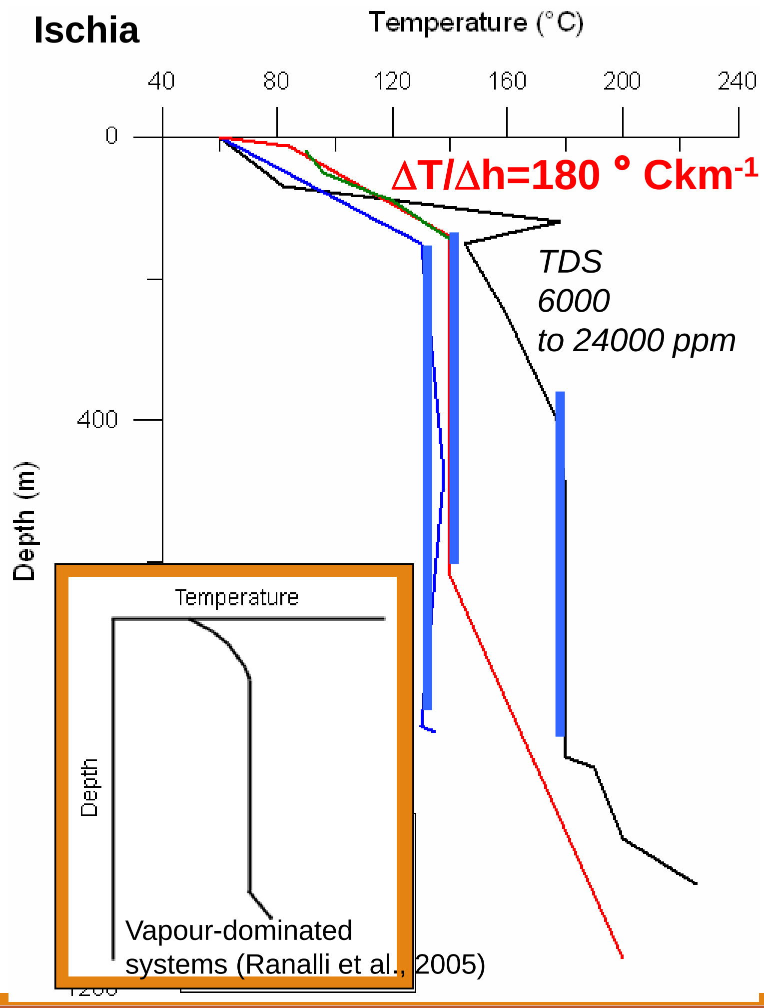
- Drilling data (stratigraphy, rocks mechanics, fluids composition, temperature, pressure);
- Geophysical survey (geoelectric, magnetotelluirc, seismic, ground deformation)

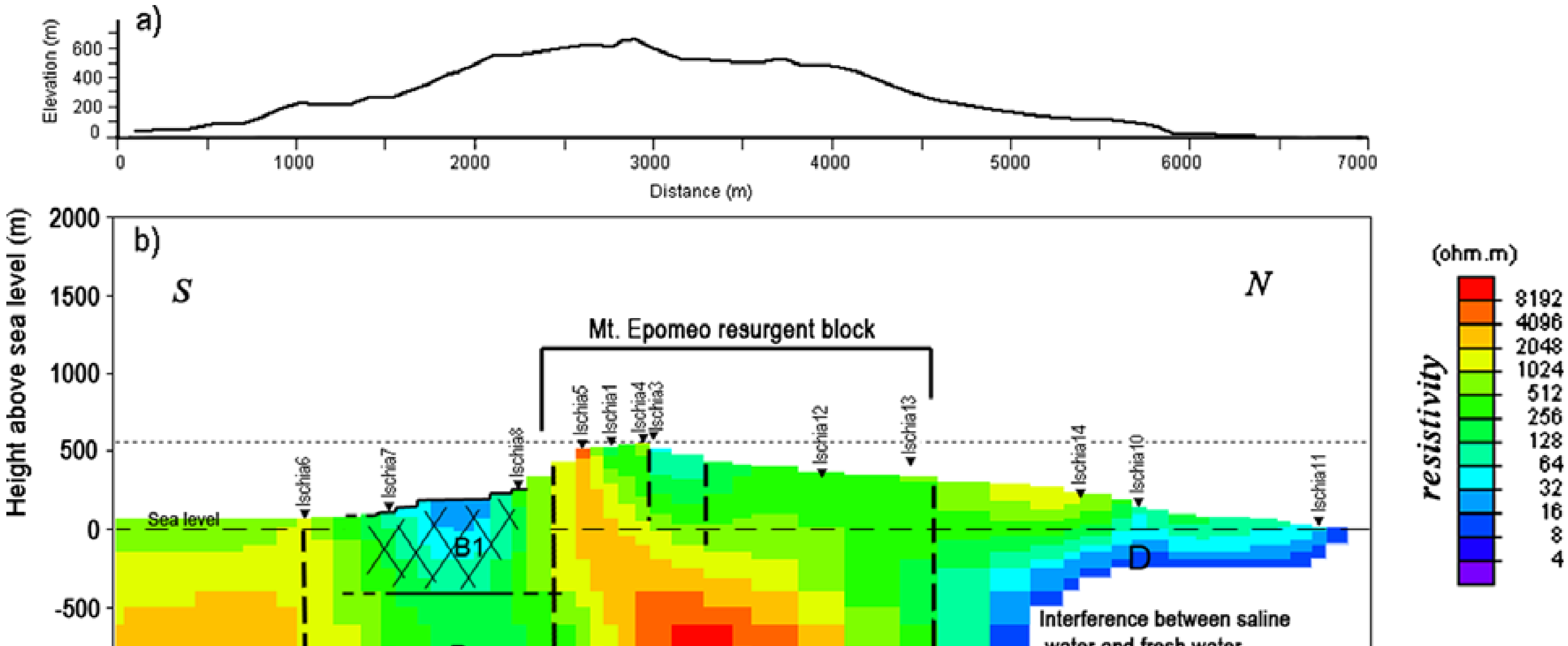
Numerical modelling to:

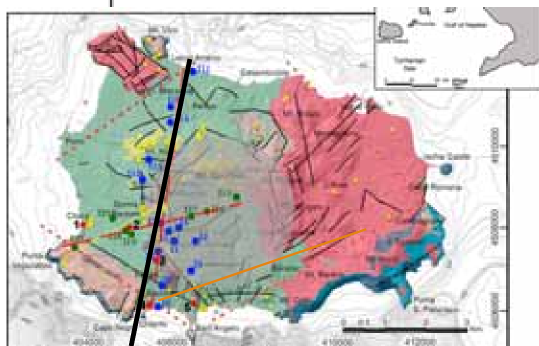
- Evaluate of pressure and thermal perturbations induced by fluids withdrawal and reinjection;
- Sustainability assessment of geothermal exploitation (depletion, induced seismicity);

Temperatures vs. depth of Phlegrean district

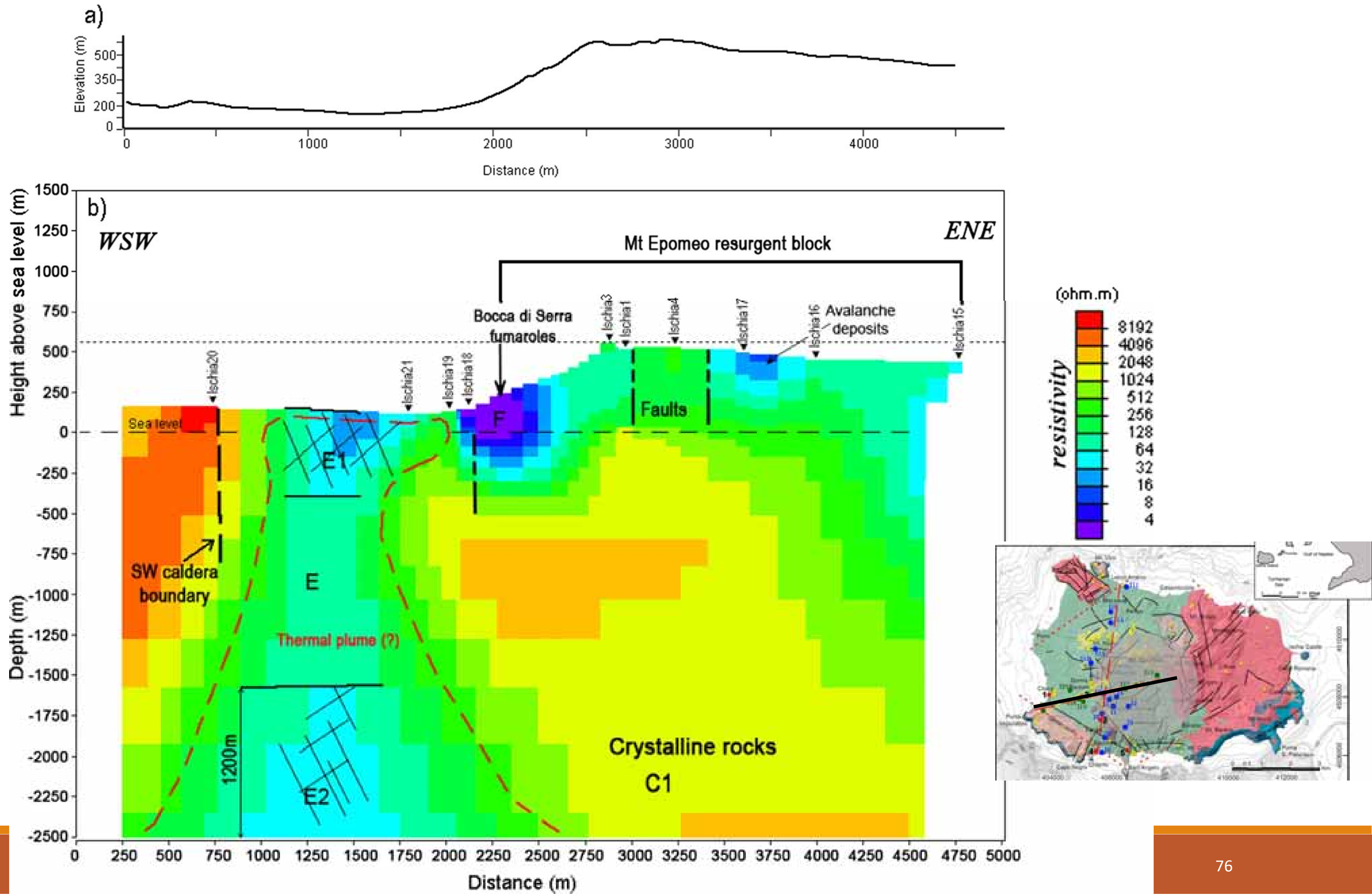


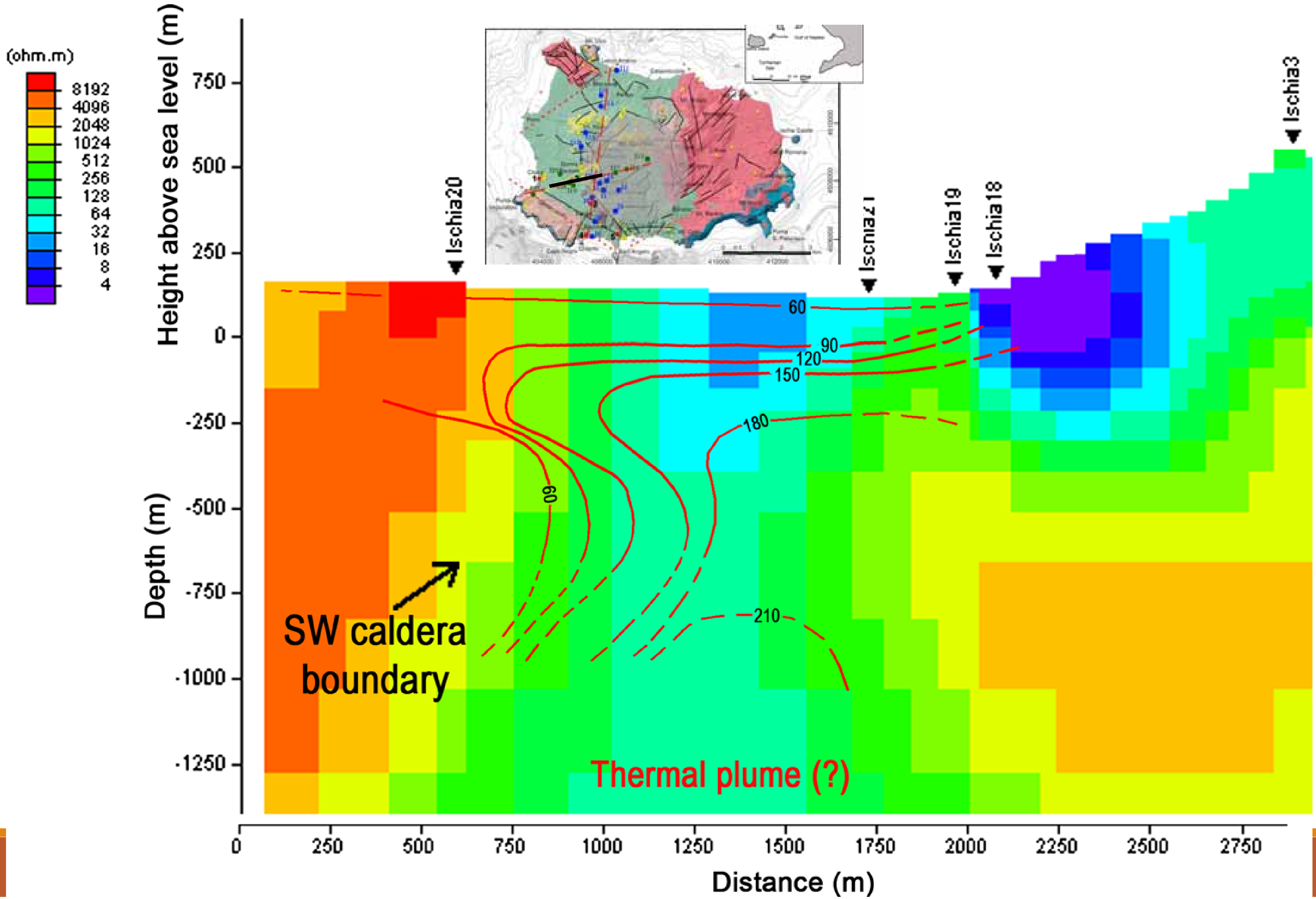


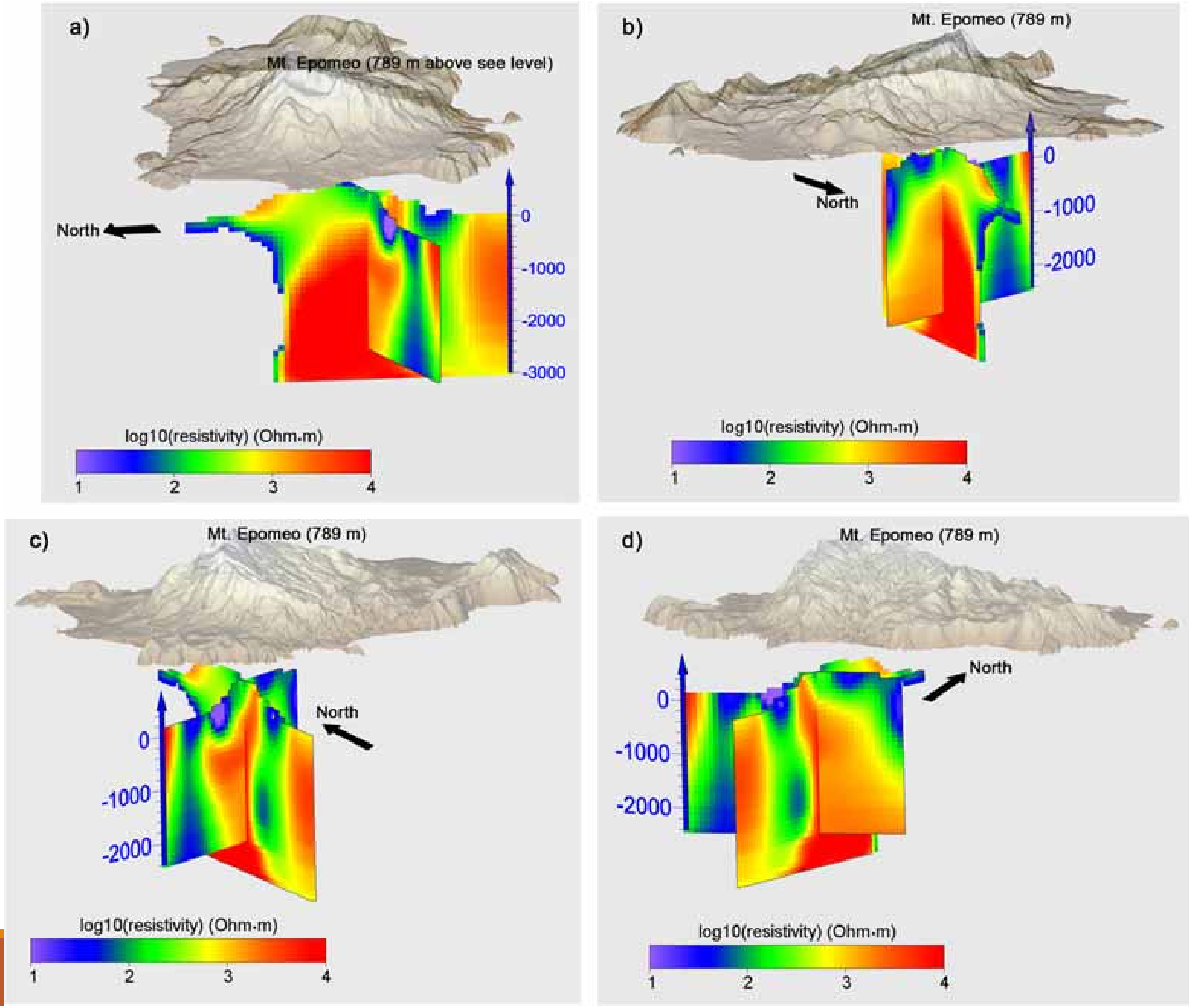




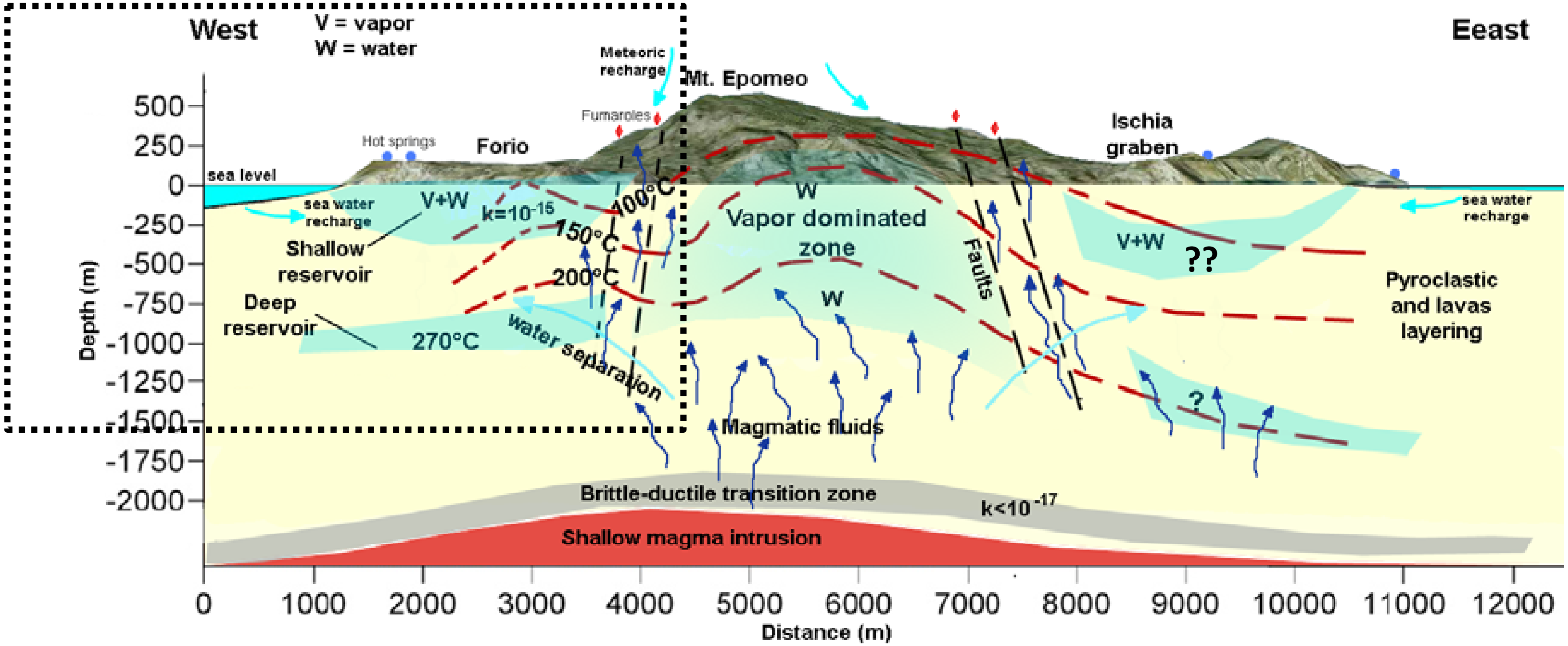
Understand hydrothermal system, which is constituted by different aquifers


a)
Elevation (m)
Distance (m)
b)
WSW
ENE
Mt Epomeo resurgent block
Bocca di Serra fumaroles
Avalanche deposits
Ischia20
Ischia21
Ischia19
Ischia18
Ischia3
Ischia1
Ischia4
Ischia17
Ischia16
Ischia15
Sea level
Faults
F
E1
E
E2
SW caldera boundary
Thermal plume (?)
1200m
Crystalline rocks
C1
Height above sea level (m)
Depth (m)
Distance (m)
(ohm.m)
resistivity


(ohm.m)
8192
4096
2048
1024
512
256
128
64
32
16
8
4
Height above sea level (m)
750
500
250
0
Depth (m)
-250
-500
-750
-1000
-1250
Ischia20
Ischia21
Ischia19
Ischia18
Ischia3
60
90
120
150
180
210
60
SW caldera boundary
Thermal plume (?)
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
Distance (m)


a)
Mt. Epomeo (789 m above see level)
North
0
-1000
-2000
-3000
log10(resistivity) (Ohm-m)
1
2
3
4
b)
Mt. Epomeo (789 m)
North
0
-1000
-2000
log10(resistivity) (Ohm-m)
1
2
3
4
c)
Mt. Epomeo (789 m)
North
0
-1000
-2000
log10(resistivity) (Ohm-m)
1
2
3
4
d)
Mt. Epomeo (789 m)
North
0
-1000
-2000
log10(resistivity) (Ohm-m)
1
2
3
4

Ischia Island



Conceptual model of geothermal reservoir of the island

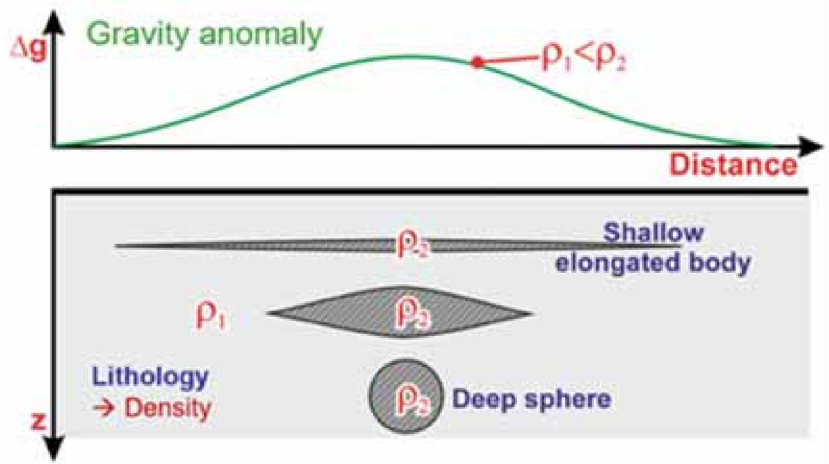
Limits of some geophysical methods: non uniquness of the inverse problem

Superposition of gravity effects of different sources:

- Non unique solution to the inverse problem: when an anomaly is surely linked to a unique source, then inversion can be performed to retrieve density ***OR*** geometry. Inversion for both parameters is not feasible

Solution:

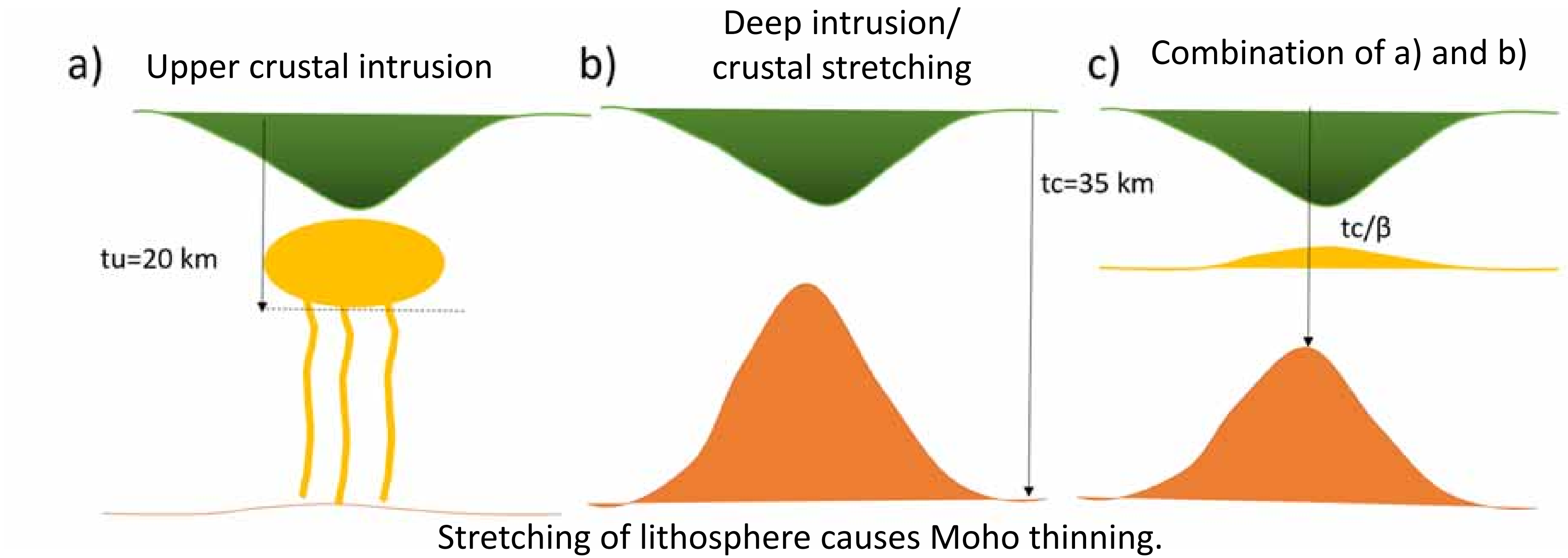
- requires implementation of other constraints to make the inversion unique



Non uniqueness of the inversion problem:
3 different bodies cause same anomaly on surface (from IGMAS+ manual)

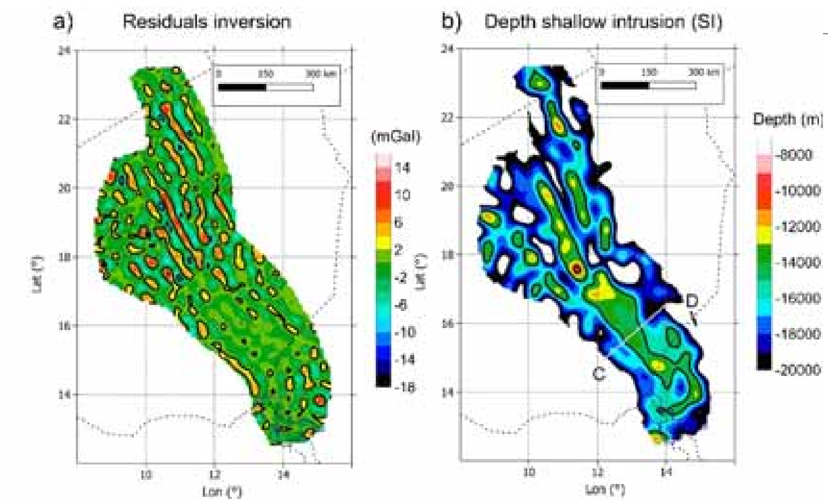
Explaining the positive anomaly of WCARS

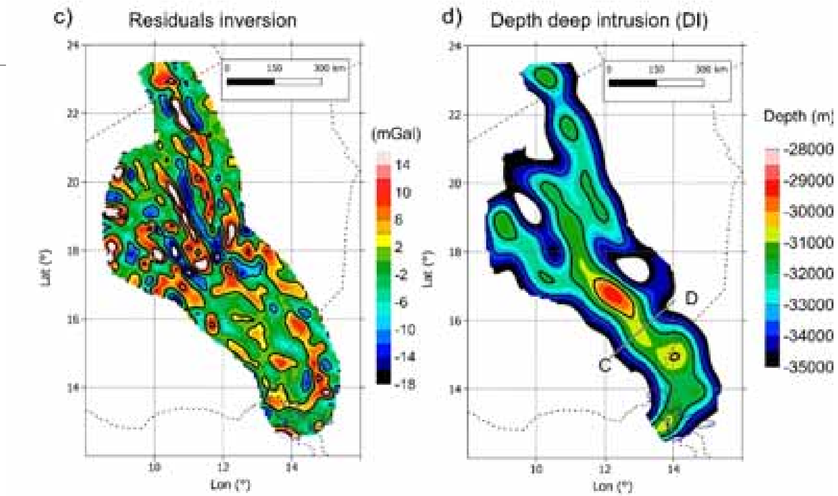
3 Scenarios evaluated: 2 end-member models (a and b) and a combination of them



Stretching of lithosphere causes Moho thinning.
Stretching can be defined by β=tc/tc1

Inversion results: end member models





- Shallow intrusion (SI) with reference depth= 20 km and $\Delta\rho = 300\ \mathrm{kg/m^3}$: magmatic chamber up to 10 km thick.
- PRO: Able to exaplain also high frequency content in the residuals. Compatible with the geodynamic context
- CON: is it reasonable a10 km thick magmatic body?

For deep intrusion (DI): reference depth= 35 km and $\Delta\rho = 400\ \mathrm{kg/m^3}$: 6-7 km thickness

PRO: Compatible with a crustal thinning and/or magmatic underplating

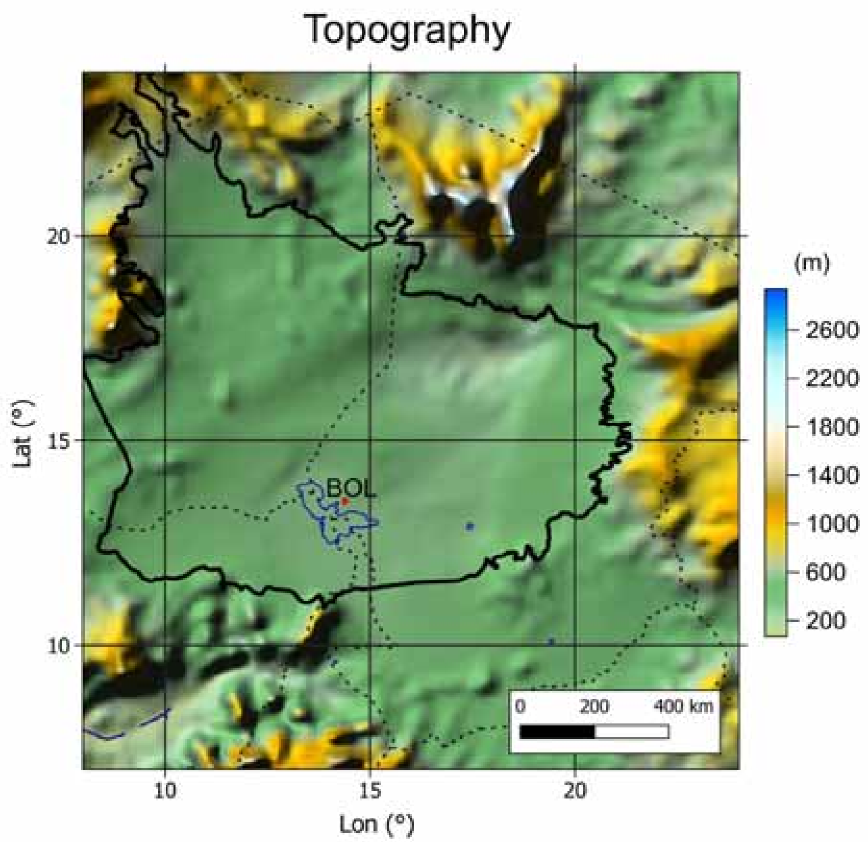
CON: hard to explain the high frequency gravity residuals with such deep source

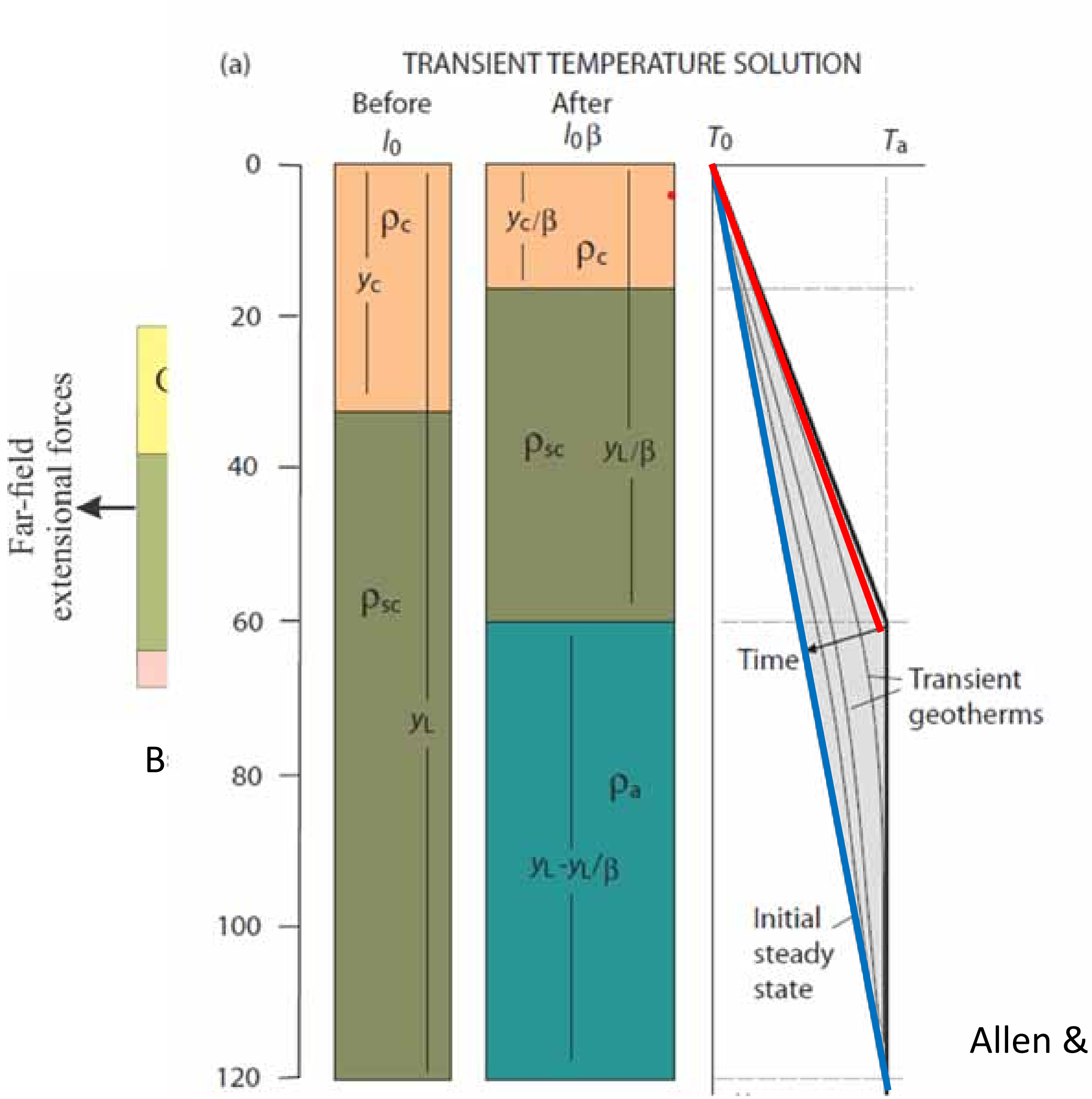
Objectives

Obtain a **3D crustal model** for the WARS region using most recent satellite gravity products

Verify presence of **deep magmatic intrusions** related to the rifting activity

Further demonstrate **usefulness of global satellite gravity products** in studying large scale rifting processes in remote and poorly constrained areas





Allen & Allen, 2013

Rift basin-crustal and thermal structure