The puzzle of the Neapolitan volcanoes

Aldo Zollo
University of Naples Federico II

MasterClass Senior #4 : Interaction onde-structure, les enjeux de l’imagerie crustale

vendredi 8 avril 2022 - 09h00

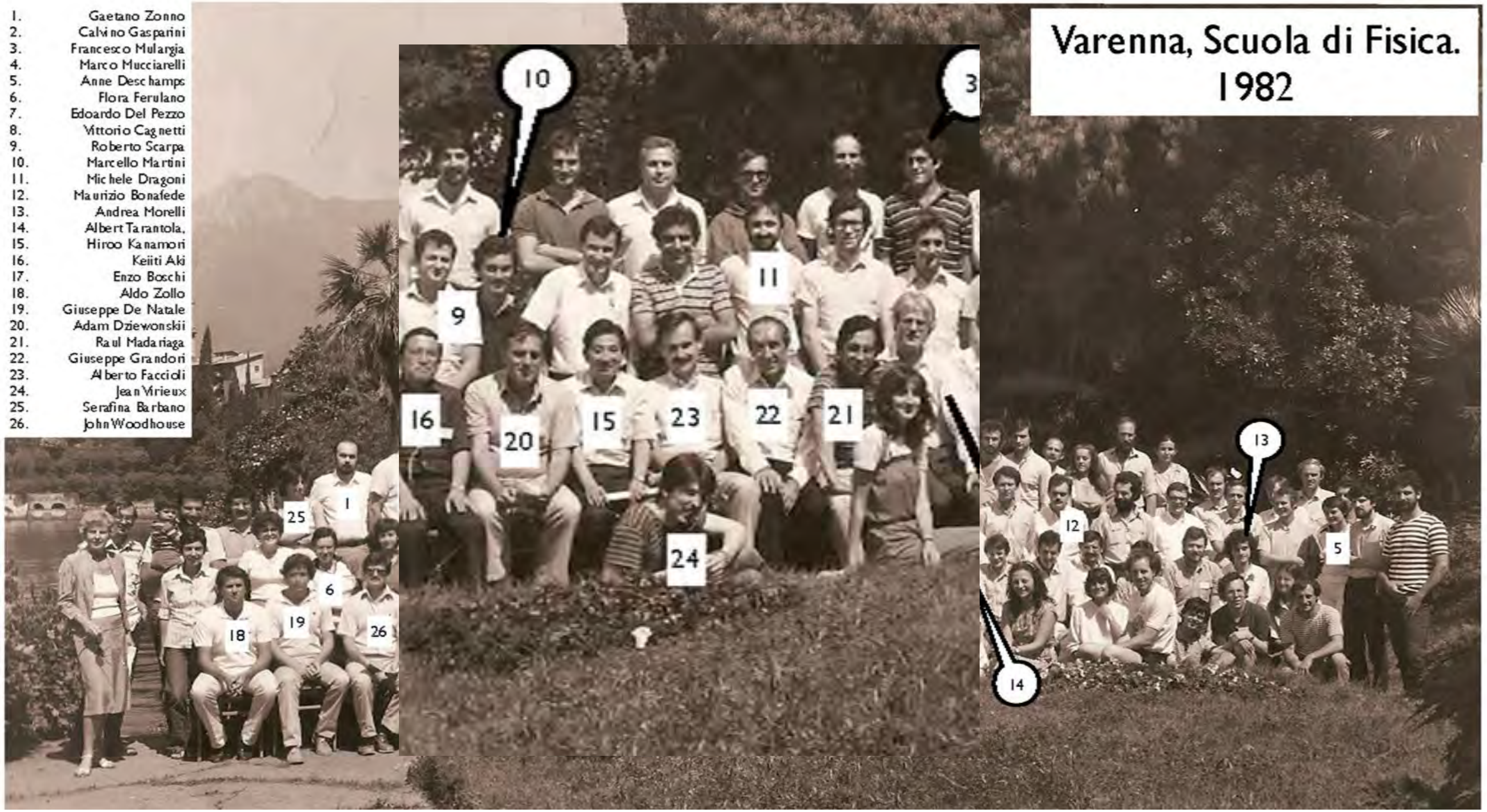
Jean Virieux - ISTerre

Equipe organisatrice : Grands Séminaires ISTerre

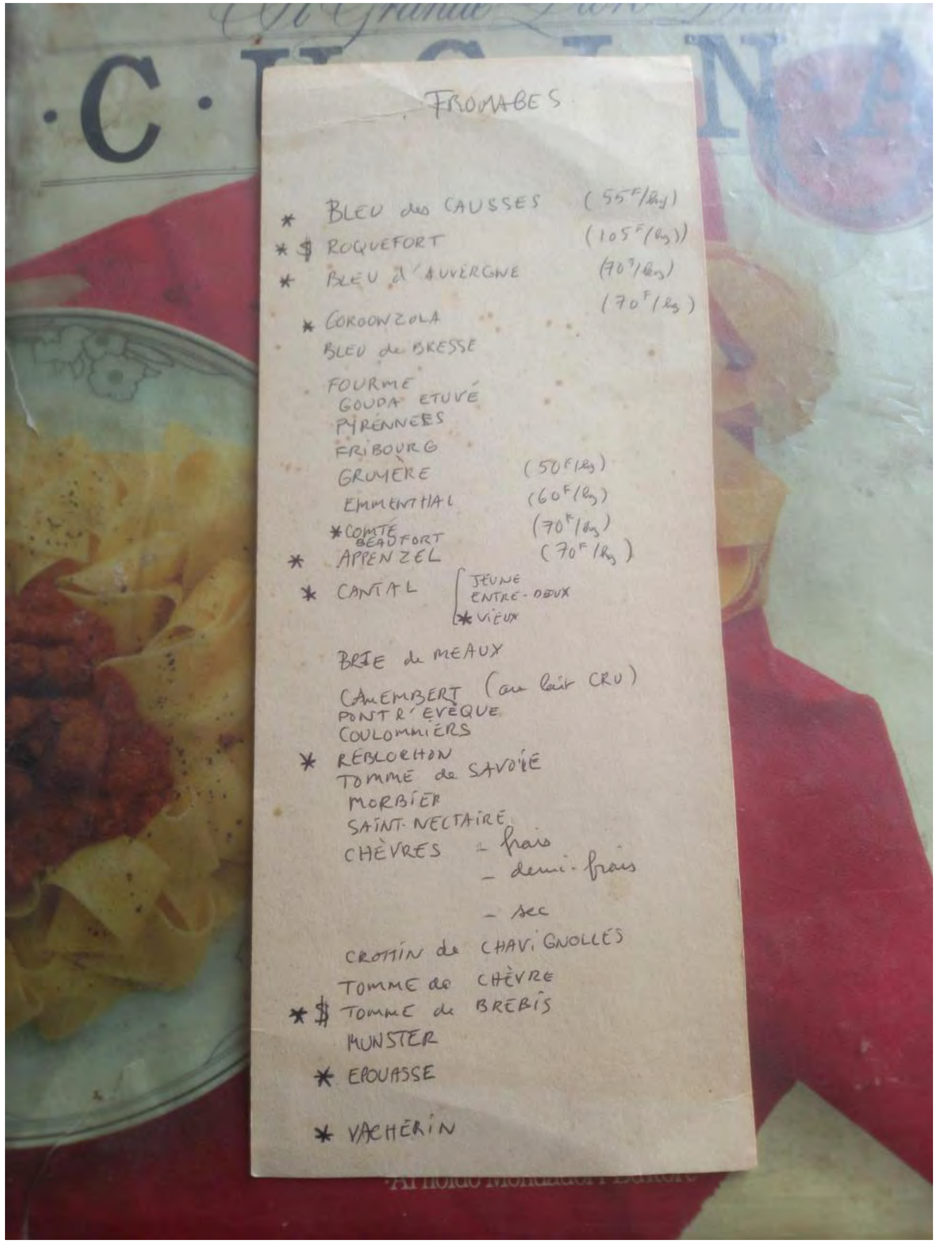
Amphithéâtre Killian, Maison des Géosciences, 38400 Saint Martin d'Hères

Prologue

La premiere rencontre Varenna, 1982



The laboratory life at IPG in Paris in the late eighties



Many scientific ideas and collaborations arise around the table in the lab's coffee room.

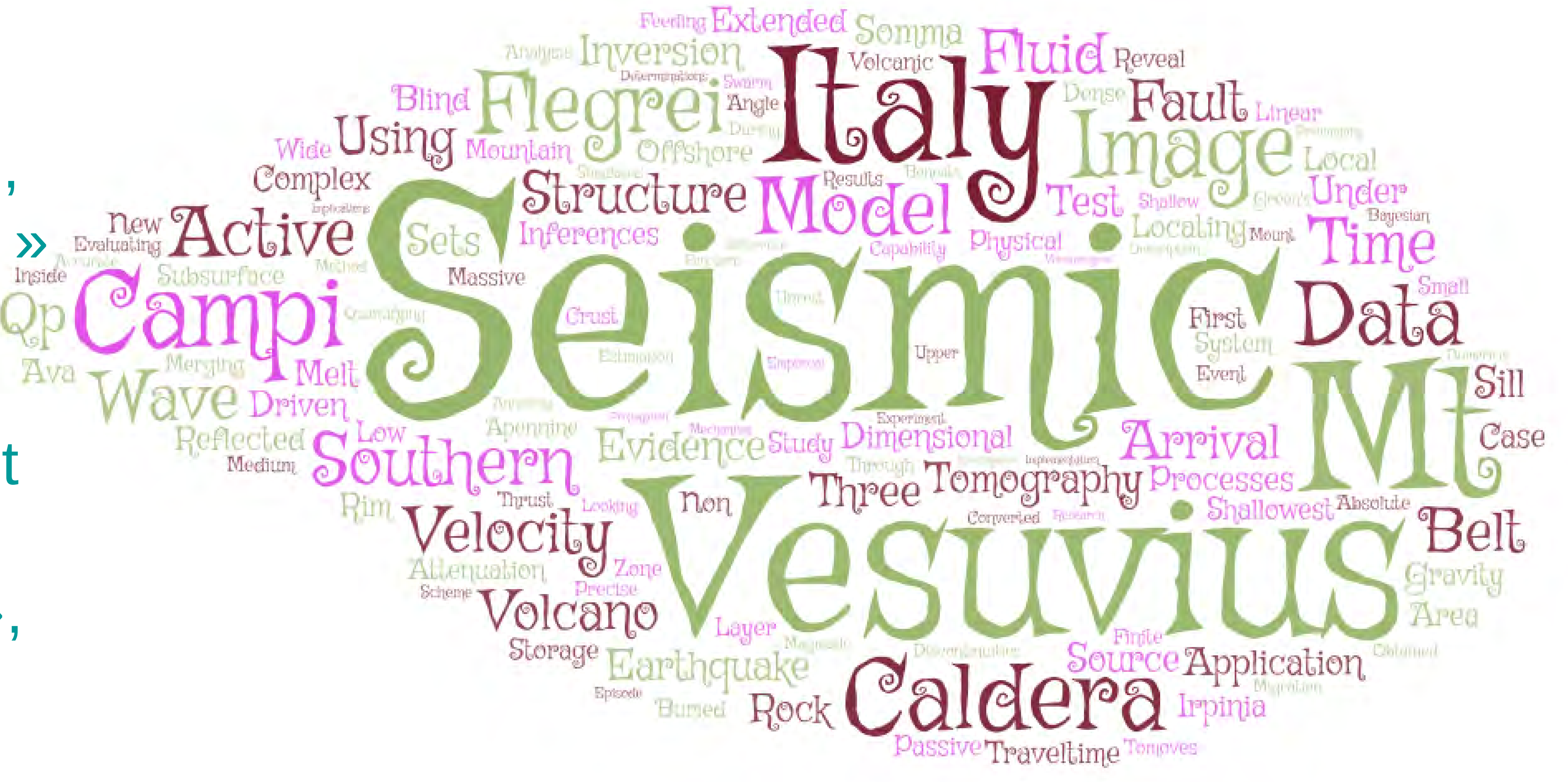
The scientific collaboration through the articles that we have co-authored

Authors	Title	Year	Source title
Bianco F. et al.	Seismic and Gravity Structure of the Campi Flegrei Caldera, Italy	2022	Active Volcanoes of the World
Amoroso O. et al.	From velocity and attenuation tomography to rock physical modeling: Inferences on fluid-driven earthquake processes at the Irpinia fault system in southern Italy	2017	Geophysical Research Letters
Serlenga V. et al.	A three-dimensional QP imaging of the shallowest subsurface of Campi Flegrei offshore caldera, southern Italy	2016	Geophysical Research Letters
Amoroso O. et al.	Seismic imaging of a fluid storage in the actively extending Apennine mountain belt, southern Italy	2014	Geophysical Research Letters
Priolo E. et al	The Campi Flegrei blind test: Evaluating the imaging capability of local earthquake tomography in a volcanic area	2012	International Journal of Geophysics
Battaglia J. Et al	Merging active and passive data sets in traveltime tomography: The case study of Campi Flegrei caldera (Southern Italy)	2008	Geophysical Prospecting
Zollo A. et al.	Seismic reflections reveal a massive melt layer feeding Campi Flegrei caldera	2008	Geophysical Research Letters
Zollo A. et al.			ers
Auger E., Virieux J., Zollo A.			ational
Zollo A. et al.			ational
Improta L. et al.			ational
Auger E. et al.			
Lomax A. et al.			ational
De Matteis R. et al.			cs
Zollo A. et al.	An image of Mt. Vesuvius obtained by 2D seismic tomography	1998	Journal of Volcanology and Geothermal Research
Gasparini P.,et al.	Looking Inside Mt. Vesuvius	1998	Eos
De Matteis R., Zollo A., Virieux J.	P-wave arrival time inversion by using the T - P method: Application to the Mt. Vesuvius volcano, southern Italy	1997	Geophysical Research Letters
Zollo A. et al.	2D seismic tomography of Somma-Vesuvius: Description of the experiment and preliminary results	1996	Annali di Geofisica
Courboulex F. et al.	Source investigation of a small event using empirical Green's functions and simulated annealing	1996	Geophysical Journal International
Zollo A. et al.	Seismic evidence for a low-velocity zone in the upper crust beneath mount vesuvius	1996	Science
De Natale G. et al.	Accurate fault mechanism determinations for a 1984 earthquake swarm at Campi Flegrei caldera (Italy) during an unrest episode: implications for volcanological research	1995	Journal of Geophysical Research
Coutant O., Virieux J., Zollo A.	Numerical source implementation in a 2D finite difference scheme for wave propagation	1995	Bulletin - Seismological Society of America

List of co-authored articles : 22 in 26 years (about 1 article per year, since 1995 to now)

The cloud-of-words from titles of co-authored papers

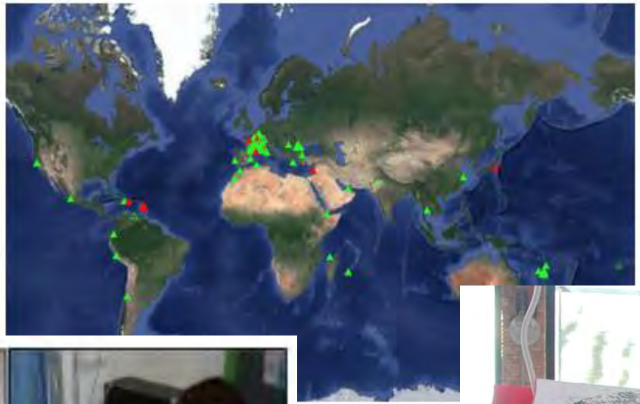
« Seismic », of course!
« Mt Vesuvius »,
« Campi Flegrei »
« Caldera » and then
« Fluid », « fault image »,
« tomography »,
...

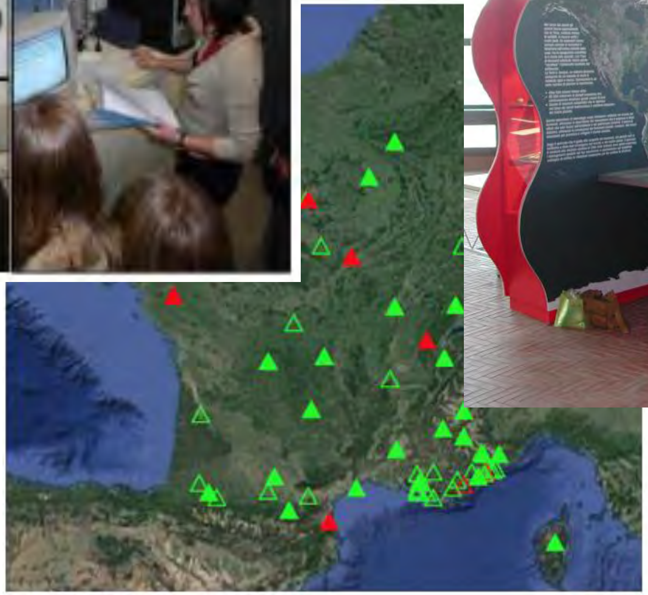


Educational Seismology

EduSeis
The Educational Seismograph Project

EduSeis,
not publishable,
but a valuable
works oriented to
the society





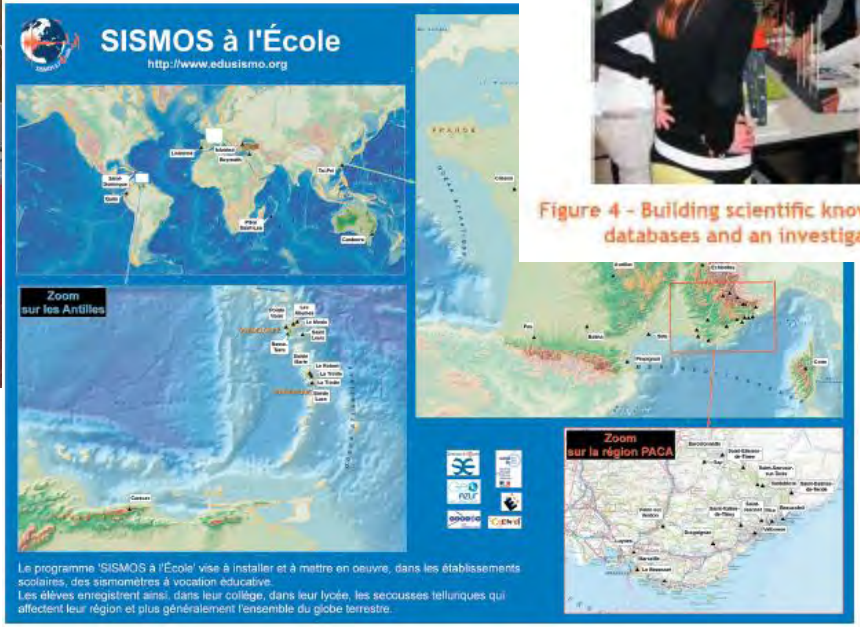
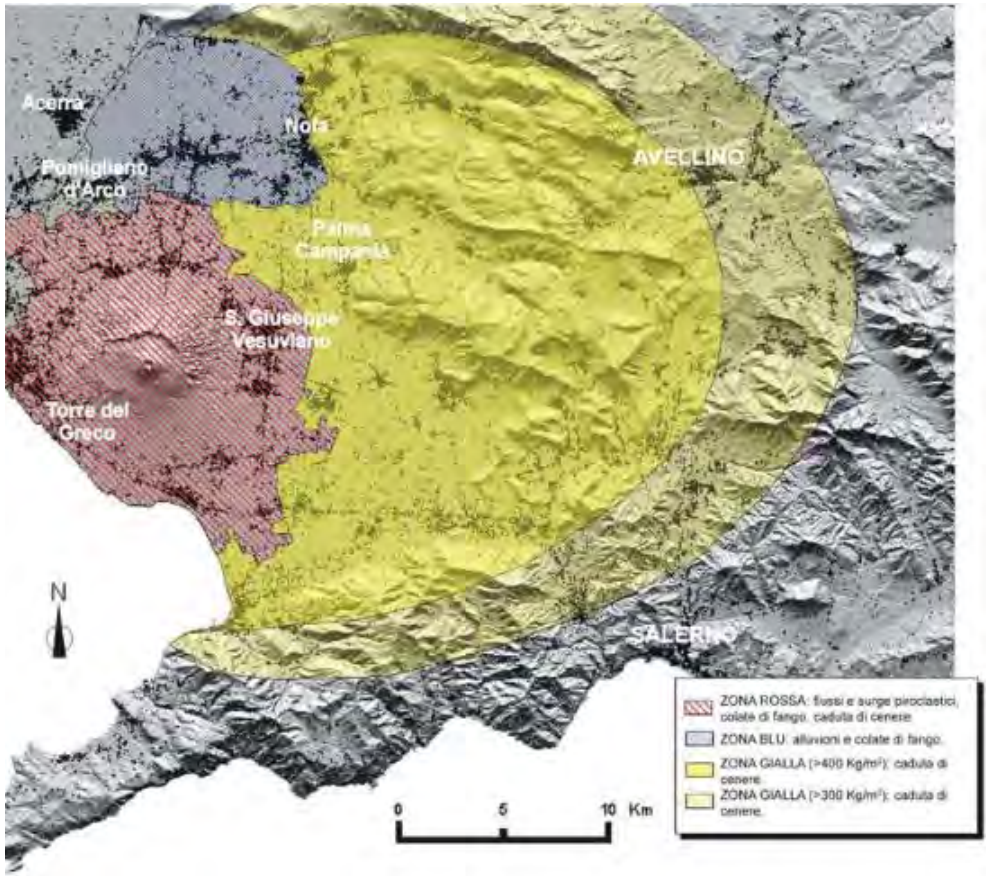


Figure 4 - Building scientific know-how, between mining databases and an investigational approach.

The long story of searching for the magma chamber beneath Mt Vesuvius and Campi Flegrei volcanoes

The volcanic risk of Neapolitan volcanoes

(G. Orsi et sl., website OV-INGV)



Carta del rischio vulcanico dal piano di emergenza "Vesuvio".

Carta di rischio vulcanico per scorrimento di flussi piroclastici nella caldera flegrea. (Agenzia di Protezione Civile).

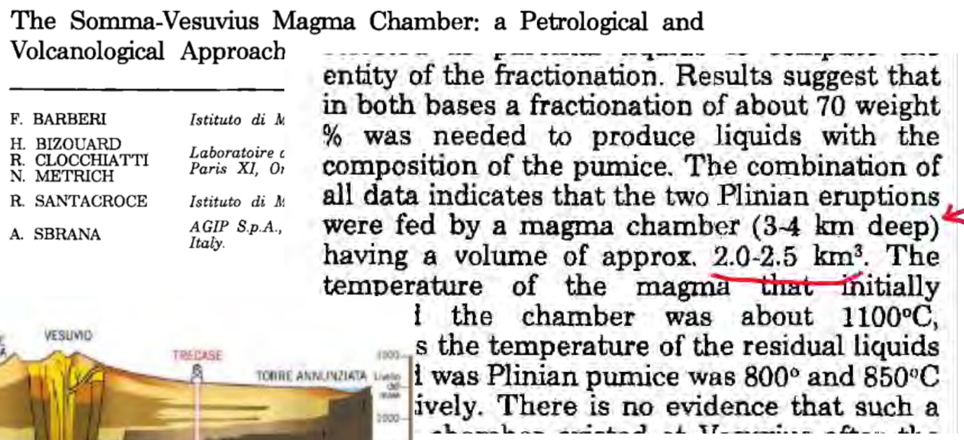
What is the depth, shape and size of the magma chamber feeding Mt Vesuvius and Campi Flegrei volcanoes?

- In 1993 the idea of conducting a series of active/passive seismic experiments

- Target: obtain accurate models of the volcanic structure and magma chamber to develop realistic/reliable future eruptive scenarios to be used for emergency plans.

- To foster a close cooperation and interaction in Italy btw experimental geophysicists and volcano modelers

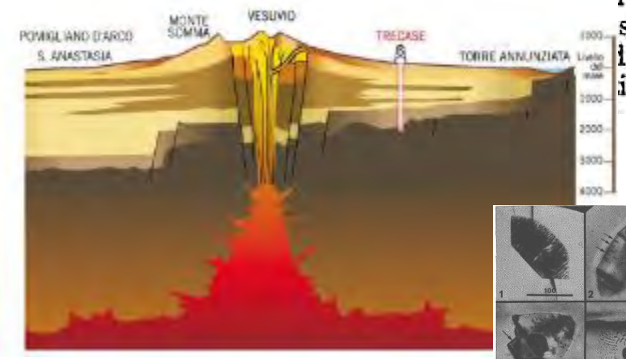
Previous knowledge of the magma chamber at Mt **Vesuvius ...**

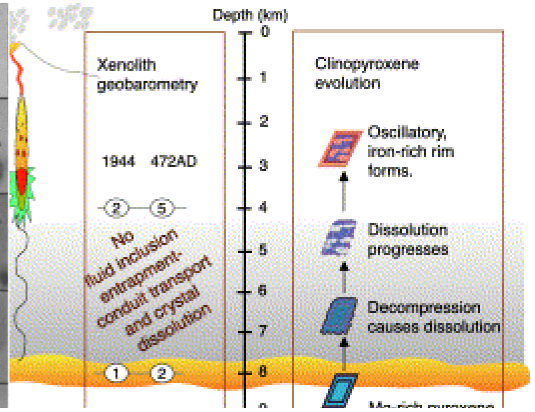

The Somma-Vesuvius Magma Chamber: a Petrological and Volcanological Approach

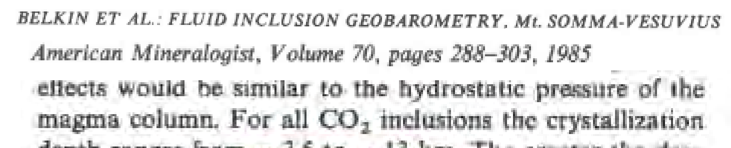
F. BARBERI — *Istituto di M*
H. BIZOUARD, R. CLOCCHIATTI, N. METRICH — *Laboratoire d Paris XI, Or*
R. SANTACROCE — *Istituto di M*
A. SBRANA — *AGIP S.p.A., Italy.*

entity of the fractionation. Results suggest that in both bases a fractionation of about 70 weight % was needed to produce liquids with the composition of the pumice. The combination of all data indicates that the two Plinian eruptions were fed by a magma chamber (3-4 km deep) having a volume of approx. 2.0-2.5 km³. The temperature of the magma that initially the chamber was about 1100°C, s the temperature of the residual liquids l was Plinian pumice was 800° and 850°C ively. There is no evidence that such a

- Most of the information on the origin, evolution of magma → petrological and geochemical researches
- Minimum depth of about 3km from the mineral equilibria of metamorphic carbonate ejecta
- Fluid inclusions (CO2 and H2O-CO2) → 4 to 10 km depth
- Inferred volume of 2-3 km^3 in a closed system condition ...
- .. but isotopic data were not compatible with a closed system, revealing new batch of magma coming from the depth during the same eruption episode.






BELKIN ET AL.: FLUID INCLUSION GEOBAROMETRY, Mt. SOMMA-VESUVIUS

American Mineralogist, Volume 70, pages 288–303, 1985

effects would be similar to the hydrostatic pressure of the magma column. For all CO_2 inclusions the crystallization

... **and** Campi Flegrei

- Most of the information on the origin, evolution of magma → petrological and geochemical researches
- Magma chamber beneath the caldera , likely located at shallow depth 4–5 km
- Petrological and isotopic data showed that the magmatic system in the last 50 ka has behaved as an open system being refilled many times.

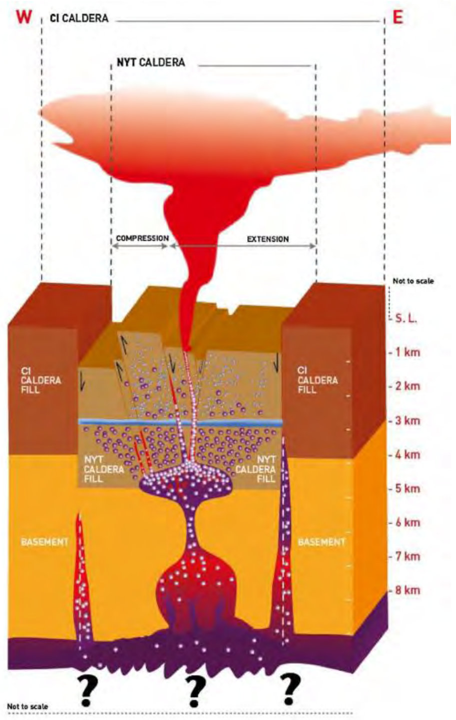
ELSEVIER
Journal of Volcanology and Geothermal Research 91 (1999) 381–414
www.elsevier.com

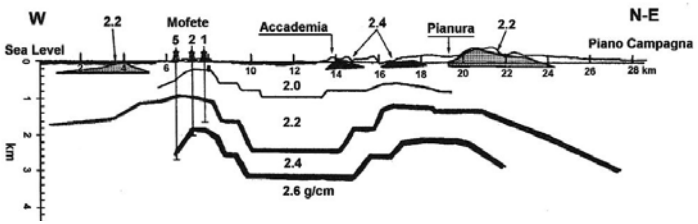
Thermal evolution of the Phlegraean magmatic sys

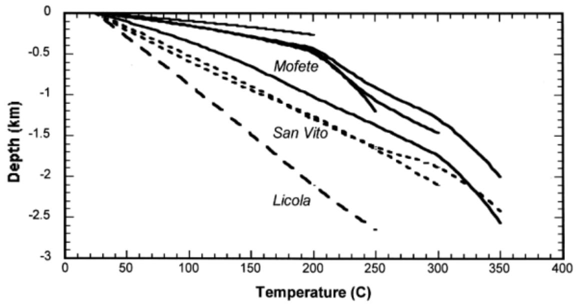
Kenneth Wohletz [a,*], Lucia Civetta [b], Giovanni Orsi [b]
[a] Earth and Environmental Sciences, Los Alamos National Laboratory, Los Alamos, NM, USA
[b] Dipartimento di Geofisica e Vulcanologia, Università of Napoli Federico II, Naples, Italy

Barberi et al., 1984, 1989; Orsi et al., 1999, this volume). The existence of a magma chamber beneath the caldera has been postulated by Barberi et al. (1978), Armienti et al. (1983), Di Girolamo et al. (1984), Rosi and Sbrana (1987), Villemant (1988) and Civetta et al. (1991), and is likely located at shallow depth (4–5 km) (Ortiz et al., 1984; Ferrucci et al., 1992; De Natale and Pingue, 1993). Petrological and isotopic data (D'Antonio et al., 1999, this volume; Pappalardo et al., 1999, this volume) show that the magmatic system in the last 50 ka has behaved as an open system being refilled many times. Orsi et al. (1992, 1995) have shown that the reservoir was refilled by variable batches of magma before the NYT eruption.

The aim of this paper is to demonstrate numerical







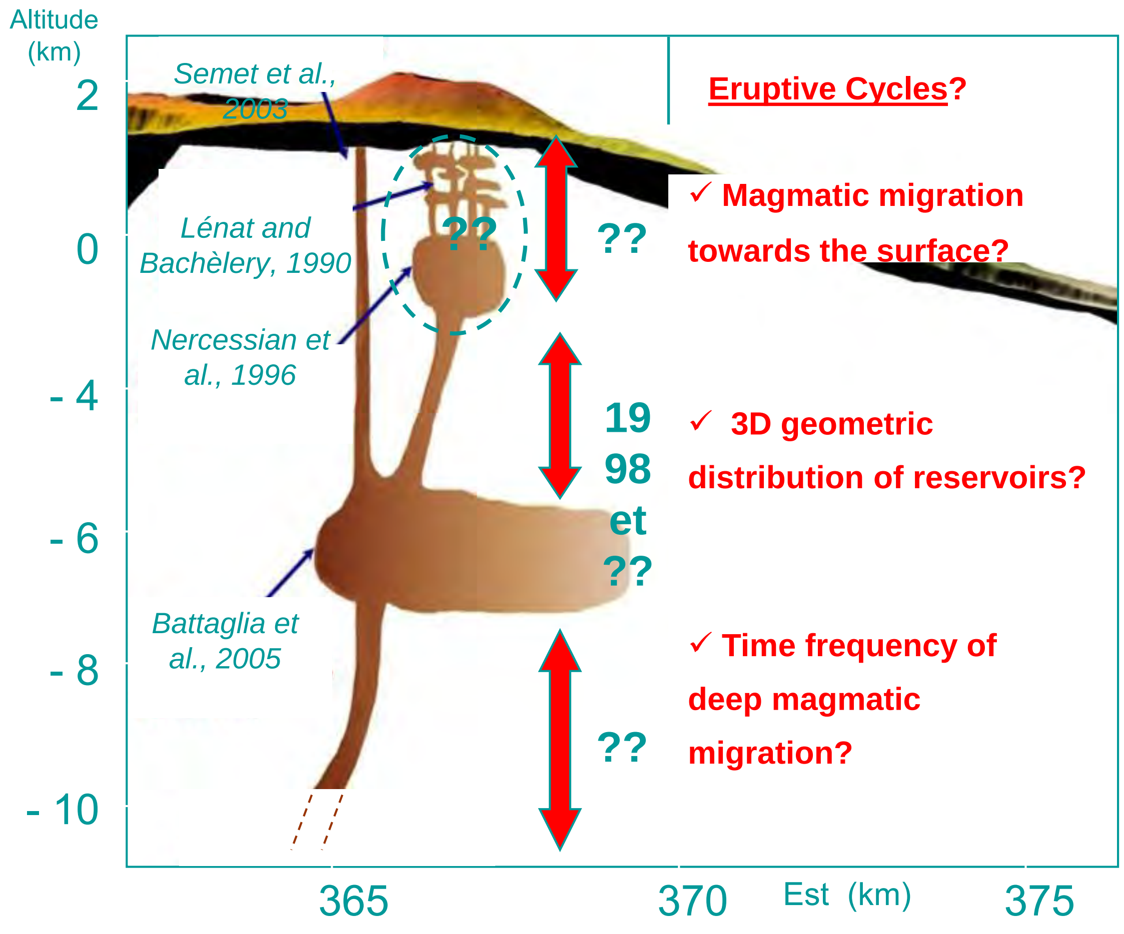
The Complexity of Volcano internal structure

- Strong heterogeneity of their internal structure, in terms of spatial variation of rock physical properties
- Variety of thermo-mechanical processes which may precede and accompany the magma rise and eruption.

→ Need for a reliable three-dimensional model of physical rock properties to better understand and simulate the processes of magma rising and eruption

→ ... But also, to detect and track changes in the volcanic medium properties possibly indicating the volcano unrest.

Island « La REUNION » VOLCANISM



From Aline Peltier after Ferrazzini et Bachèlery, 2004

Seismic Imaging of Volcanoes: Research Developments during last 40 yr

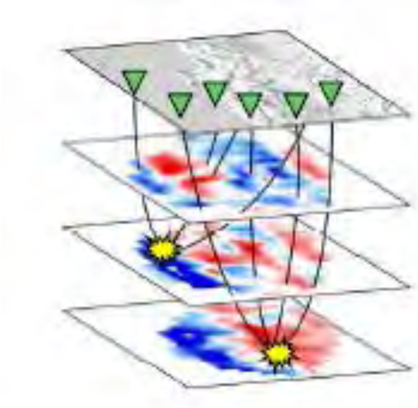
1980

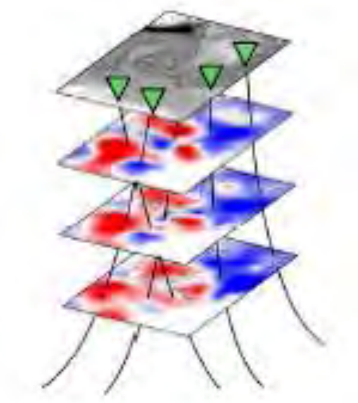
2020

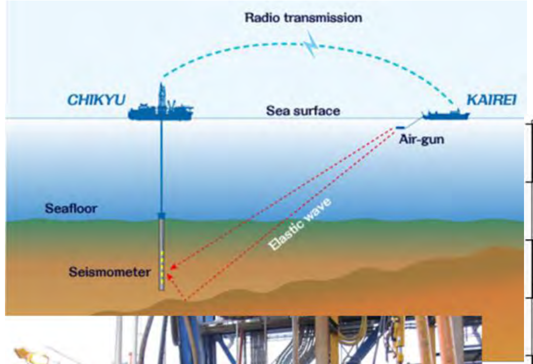
Research Developments	Topic
Technological Developments	Since '80s: digital seismic networks on volcanoes. Last decade: dense, portable, three-component broadband seismic arrays with high dynamic range and digital telemetry
Local Earthquake Tomography	Refined subsurface volcano images (with spatial resolution of few km) mostly using local earthquake tomography
Broadband volcano seismology	Identification and physical interpretation of the large variety of broad-band volcanic seismic signals (tremors, low frequency events, tornillos,..)
Joint use of active and passive sources	The use of active sources minimizes the usual complications which originate from the natural tradeoff among the unknown source (especially the depth) and medium parameters
Reflected/Converted/Diffracted wavefield analysis	Both converted and coda waves sample more efficiently the medium than direct arrivals and, therefore, they are more sensitive to small structure changes. Noise tomography.
4-D monitoring	Changes in the volcanic structure are detected and tracked by repeated seismic measurements over the same target volume (time-lapse or 4-D seismics, noise tomography, coda wave interferometry.)

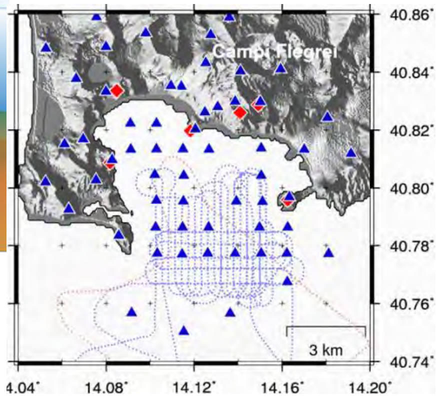
Experimental set-up - Sources

Sources	
Active	Shooting In-land explosions/vibroseis Off-shore explosions/airguns
Passive	
	Local earthquakes
	Teleseisms
	Ambient noise







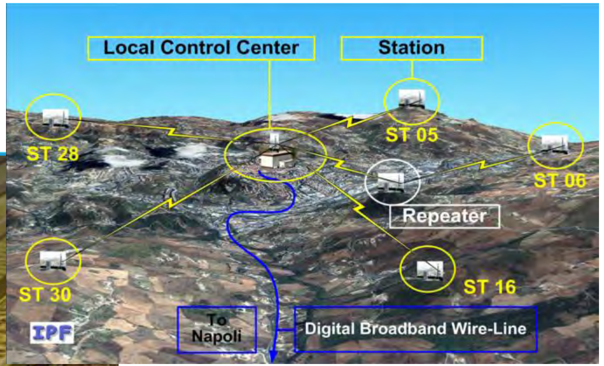


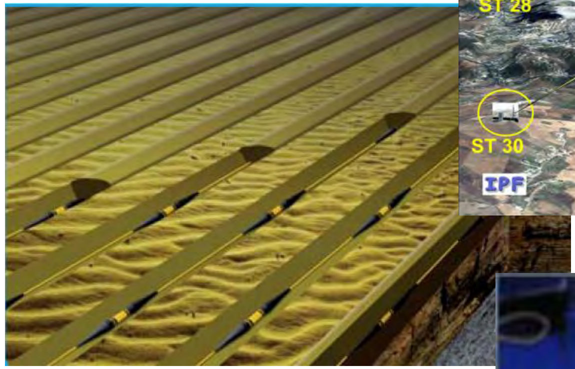
Experimental set-up - Receivers

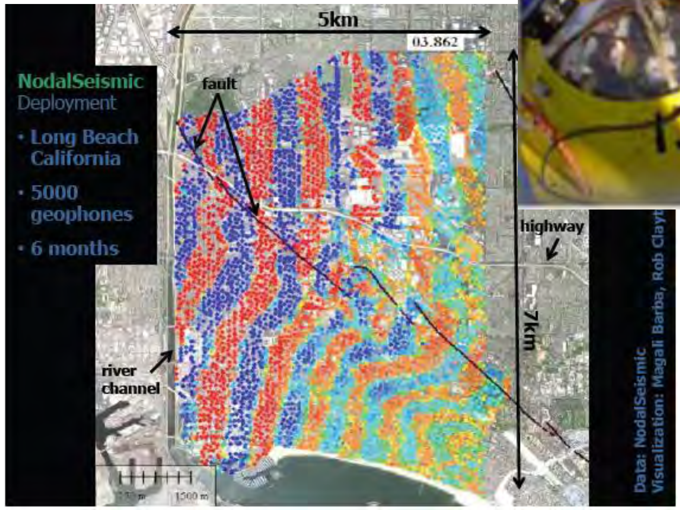
1980

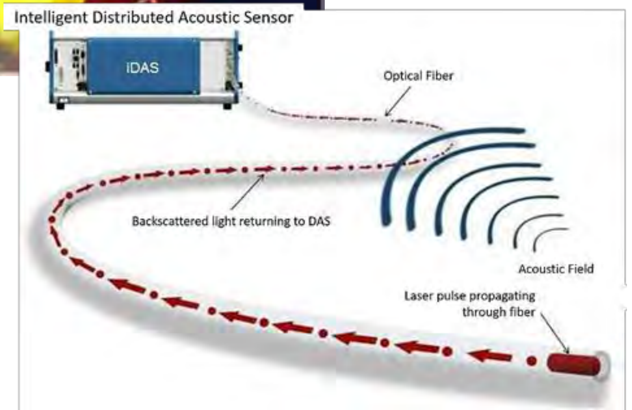
2020

- ❑ 3D arrays of stations inland
- ❑ Ocean Bottom Seismograph (OBS) deployment at the sea-bottom
- ❑ Ocean Bottom Cables (OBC, MEMS technology)
- ❑ Dense seismo-acoustic antennas (large-N)
- ❑ Borehole in-depth vertical arrays
- ❑ DAS fiber optical systems









Method’s development

Times

↓

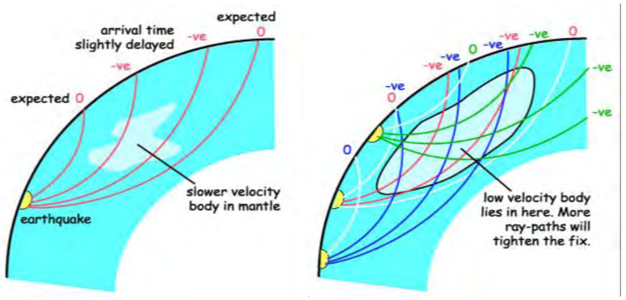
Phase amplitude

↓

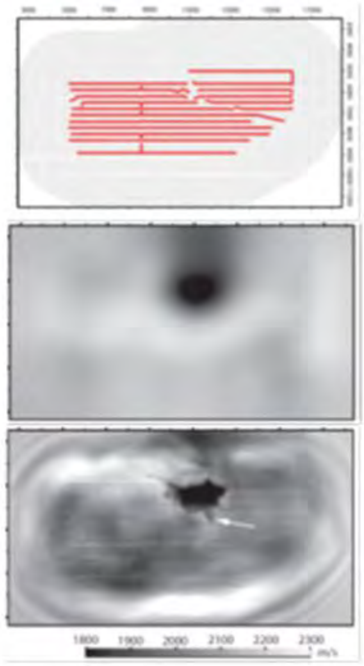
Complete waveform

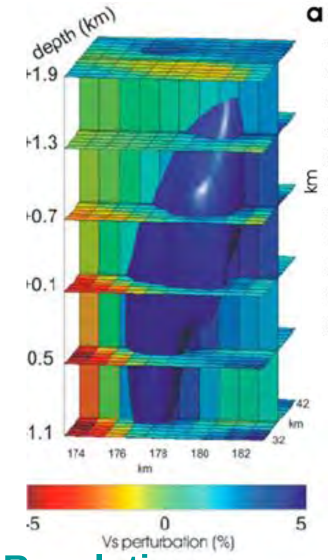
↓

- Body-waves travel time tomography
- Reflected/Converted phase tomography.
- 4D velocity/attenuation tomography , rock-physical modelling
- Ambient noise tomography
- Full-waveform tomography
- AI (ML,DL) methods for event detection, phase picking, eqk location, 4D seismicity tracking

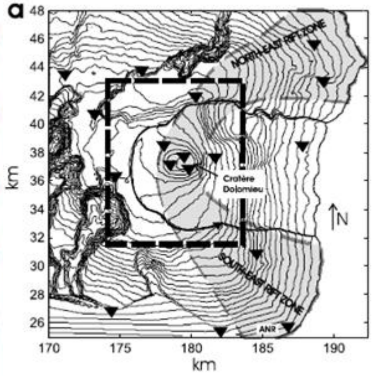


3D Tomography concept: Anomaly detection by backprojection of delay-times along the rays within the earth





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



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

Seismic investigation of the internal structure of Mt. Vesuvius and Campi Flegrei

A huge acquisition effort over 7 years

- **TomoVes 94**:
- on land, 2D source and station arrays
- **TomoVes 96**:

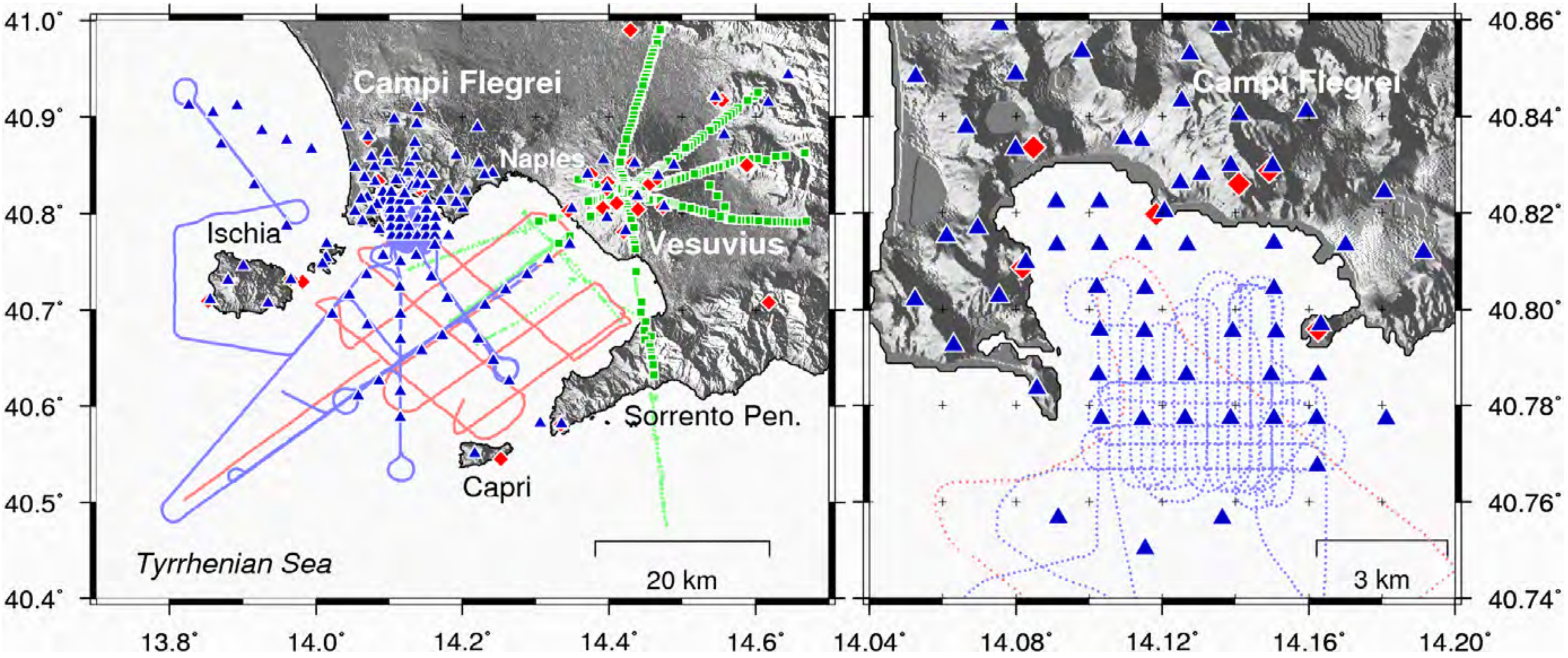
on land, multi-2D source and station arrays

- **MareVes 97**:

offshore, 3D source array at sea, receivers on land

- **Serapis 2001**:

offshore, 2D-3D source arrays at sea, OBS and stations on land



Basic ideas: transfer of knowledge, new approaches and technologies

Know-how Transfer

- From the geophysical exploration of oil and gas reservoirs to the internal volcano structure imaging

Big Challenges

- Densely populated area around the volcanoes
- Strongly heterogeneous structure, possibly high-attenuating medium
- Limitation on the of use explosive charges

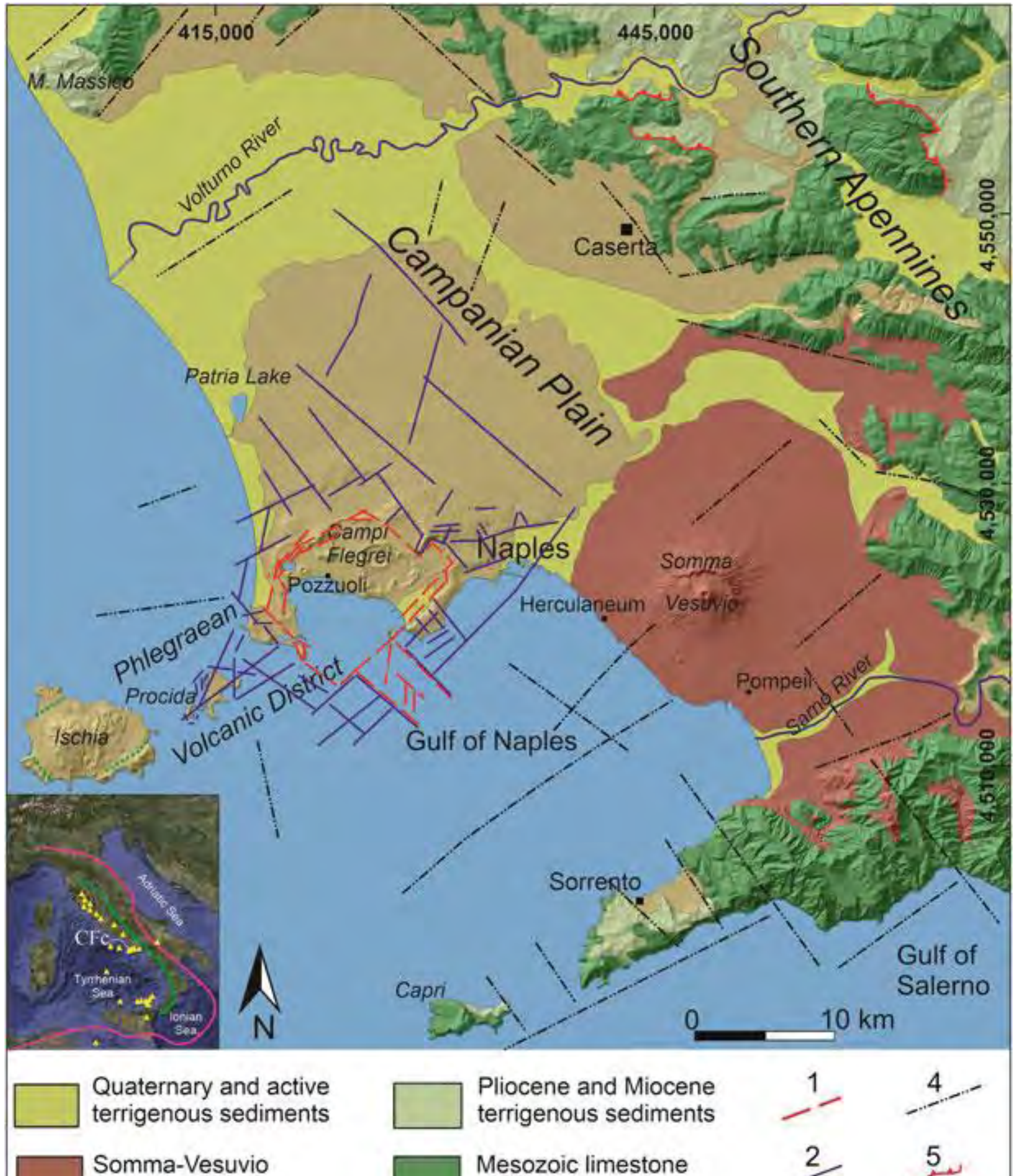
Expected Gain

- Locate at depth the magma reservoir feeding the past and potentially the future eruptive activity
- Reconstruct a reliable 3D model that would have improved the accuracy of location, magnitude determination, source mechanism of earthquakes
- S&T: test and apply innovative technologies and methodologie to be exported on other italian and worldwide volcanoes

Immagine da satellite dell'area napoletano-flegrea in cui è evidenziata l'urbanizzazione.(Telespazio) (G. Orsi et sl., website OV-INGV)

Geological and structural map of the southern Campanian Plain

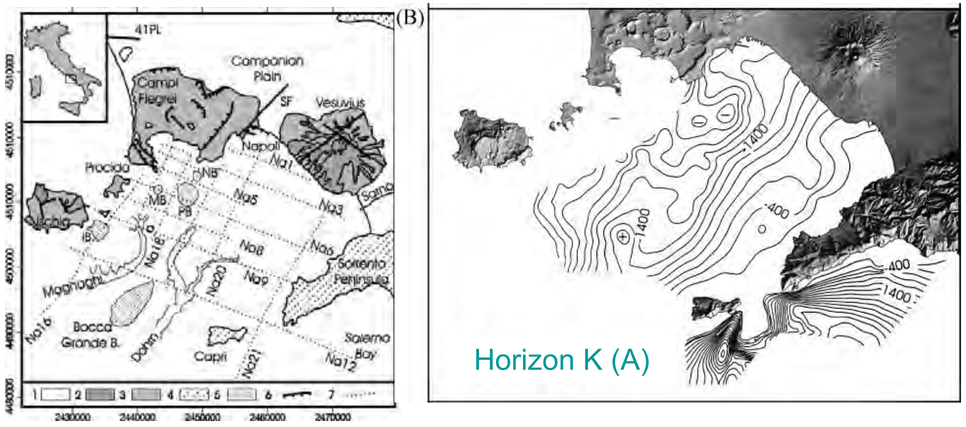
1 Features active during the Neapolitan Yellow Tuff eruption.
2 Features active during the Campanian Ignimbrite eruption.
3 Features active during the Mount Epomeo Green Tuff.
4 Regional faults.
5 Overthrusts



Previous information on the volcano internal structure

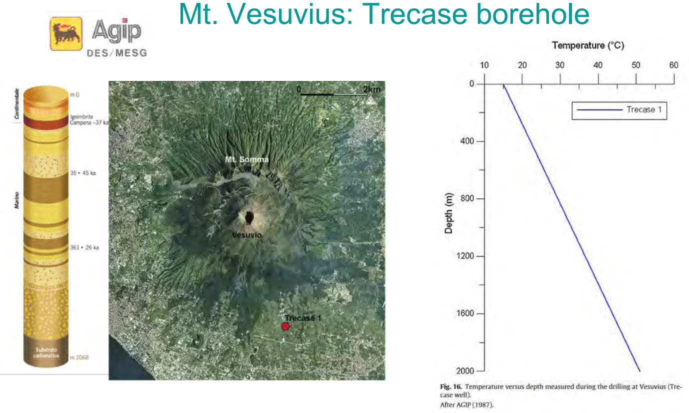
- High resolution off-shore seismic reflection survey (1977)
- AGIP-ENEL joint venture to explore the feasibility of exploiting geothermal energy at Mt Vesuvius and Campi Flegrei (late 70s and early 80s)
  - Boreholes down to about 3 km depth

Finetti & Morelli,1973; Bruno et al, 2003



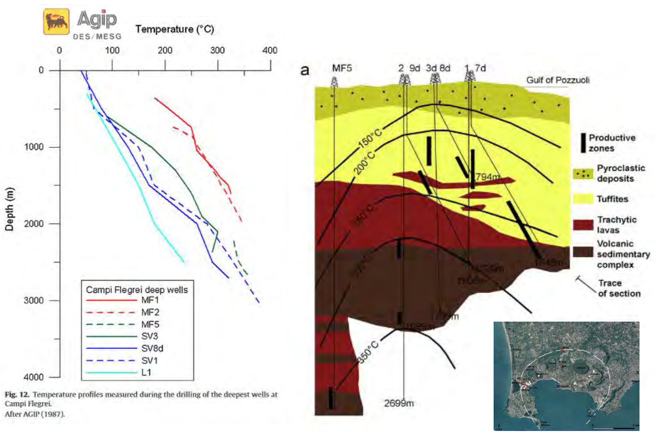
Horizon K (A)

Mt. Vesuvius: Trecase borehole



De Natale et al, Campi Flegrei Deep Drilling Project, 2012; Carlino et al., 2011

Campi Flegrei : Mofete boreholes



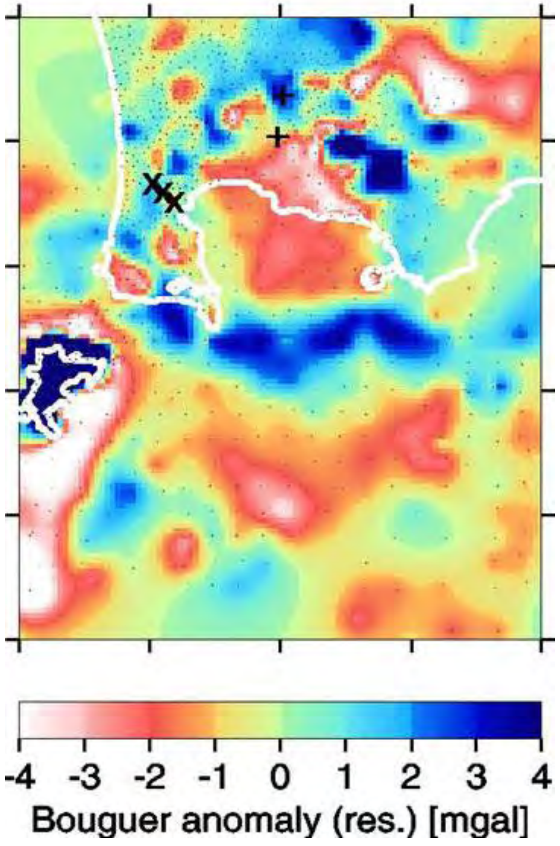
Rosi and Sbrana,1987; Carlino et al., 2011

Previous information on the volcano internal structure

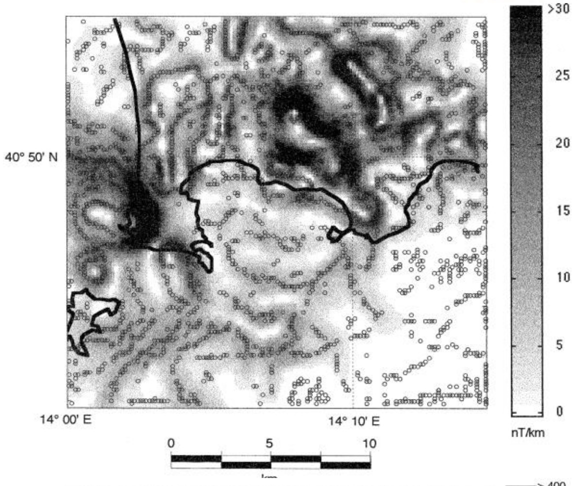
- Gravity, aeromagnetic, geoelectrical surveys (late 70s)
- Deep seismic experiment (late 80s), offshore explosions targeting the Moho discontinuity beneath the bay area (35 km beneath mt Vesuvius and 25 km beneath campi Flegrei).

Campi Flegrei: gravity and aero-magnetic soundings

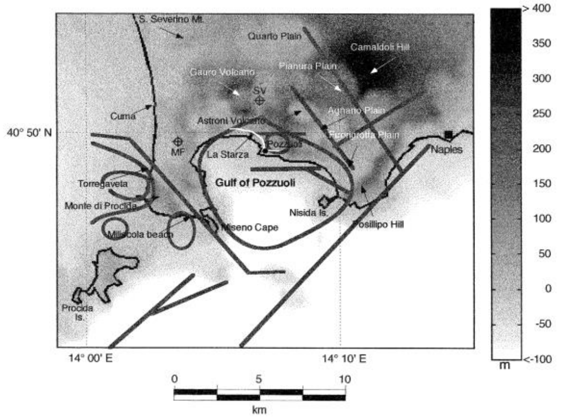
Agip DES/MESG



Capuano and Achauer, 2003



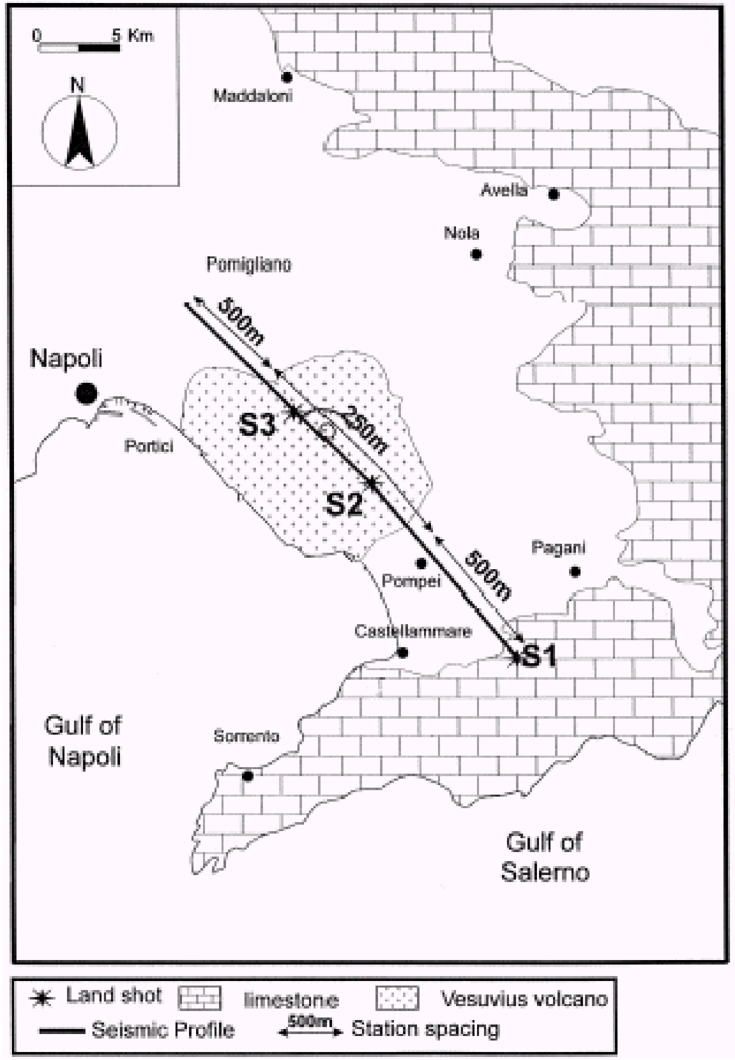
Horizontal derivative map of the aeromagnetic field and sourse boundaries



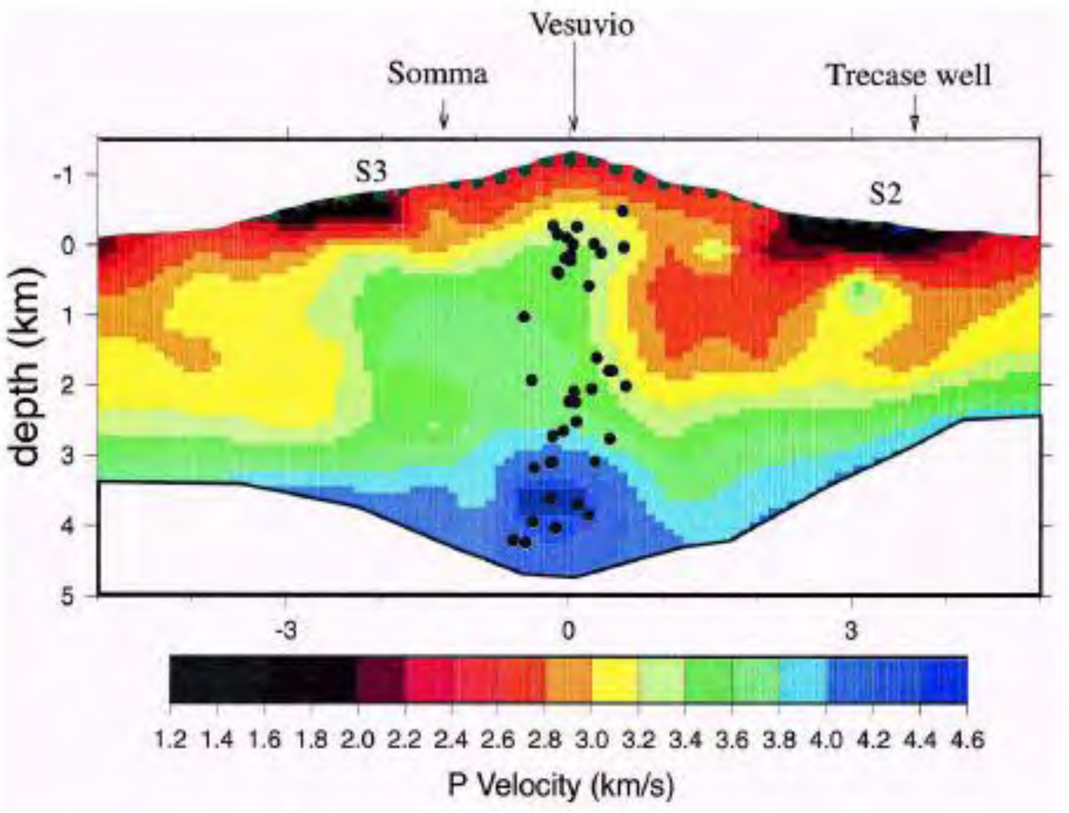
Florio et al. 1999

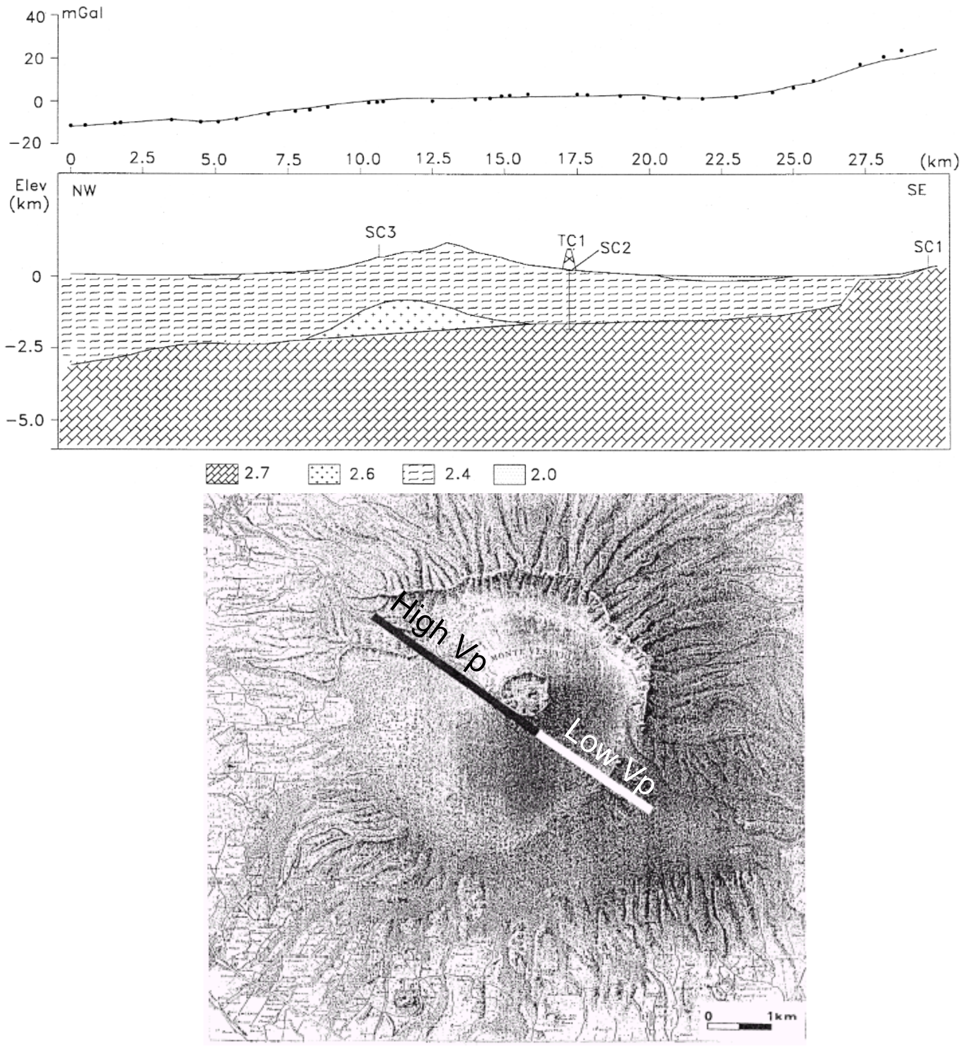
1994, the first experiment: a single profile , 3 shots across the volcano

- Scope of the experiment
  - Testing the use of explosive charges
  - Testing the max travelling distance, penetratig depth
  - Testing the evidence of reflections



The first 2D image





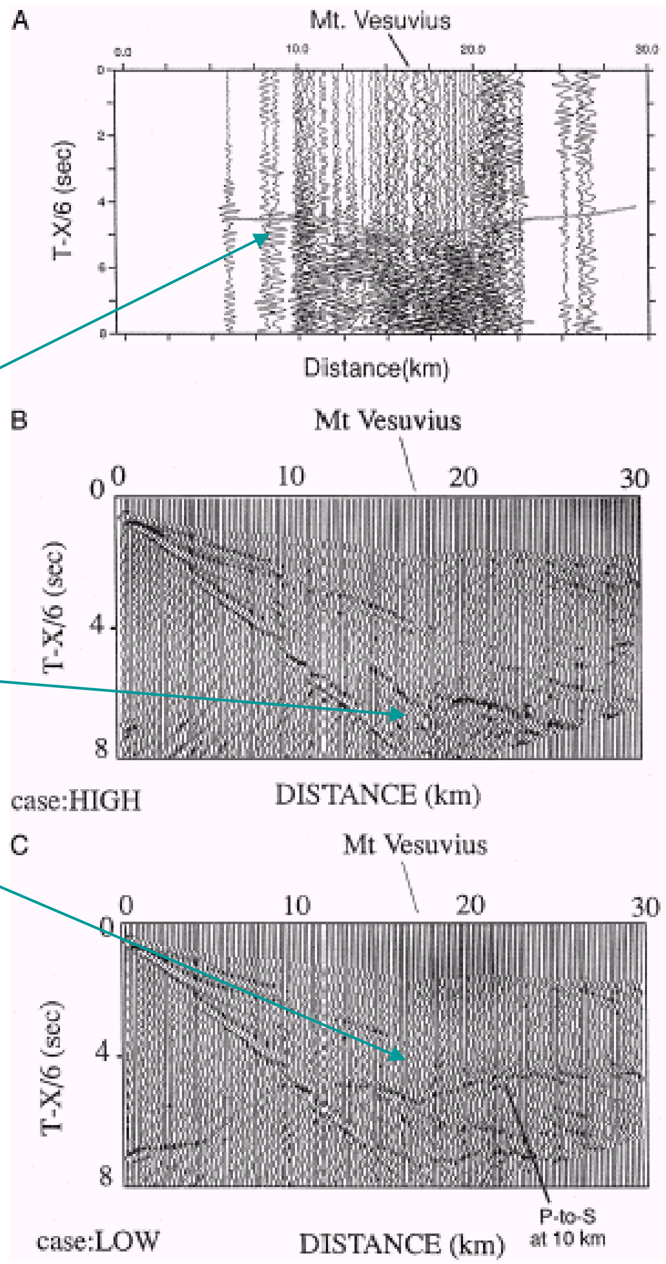
“A high-velocity body Vp s 3.5–4 . kmrs was identified at about 2 km beneath the Somma-Caldera. It is likely to represent a sub-volcanic structure, formed by a dense network of solidified dikes.”

Zollo, A. et al 1998. Journal of Volcanology and Geothermal Research

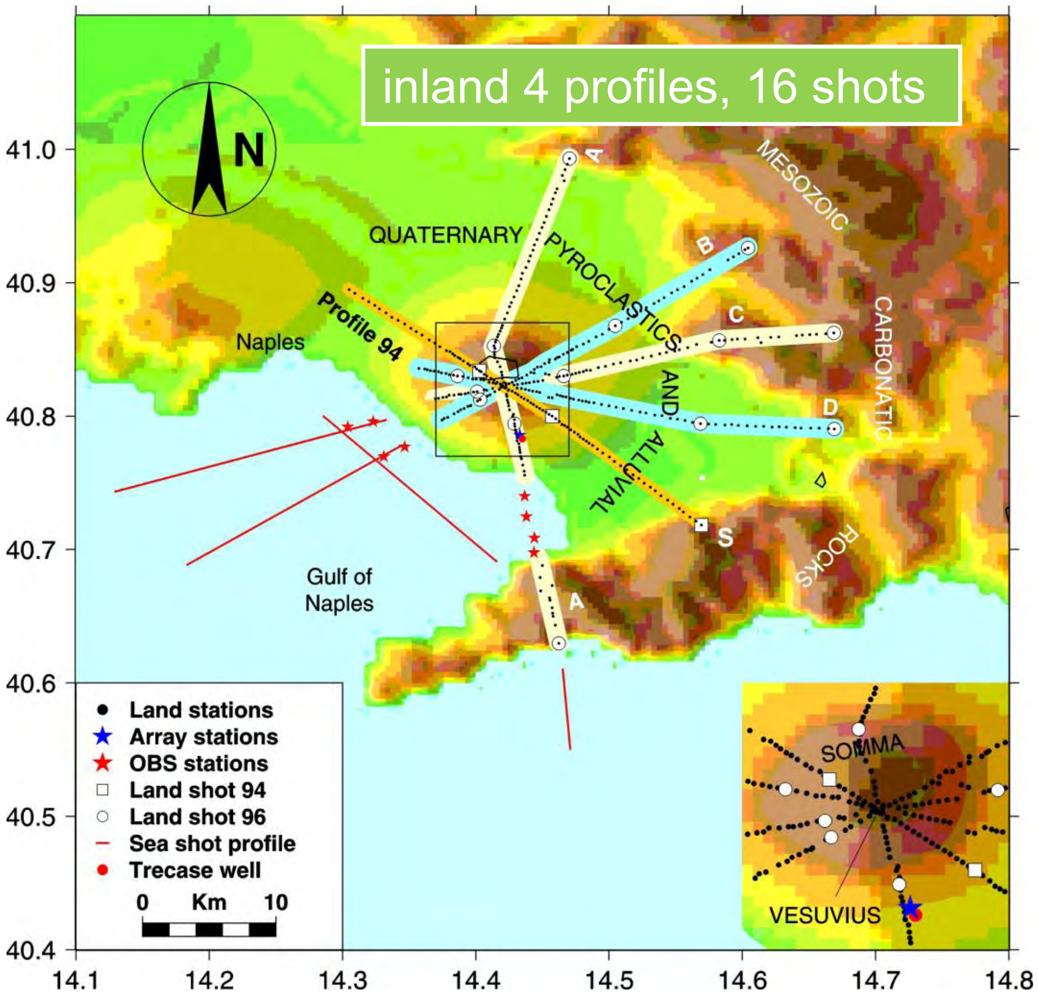
Evidence for the LALA phase: a P-to-S conversion at about 10 km depth

LALA → Large Amplitude Late Arrivals

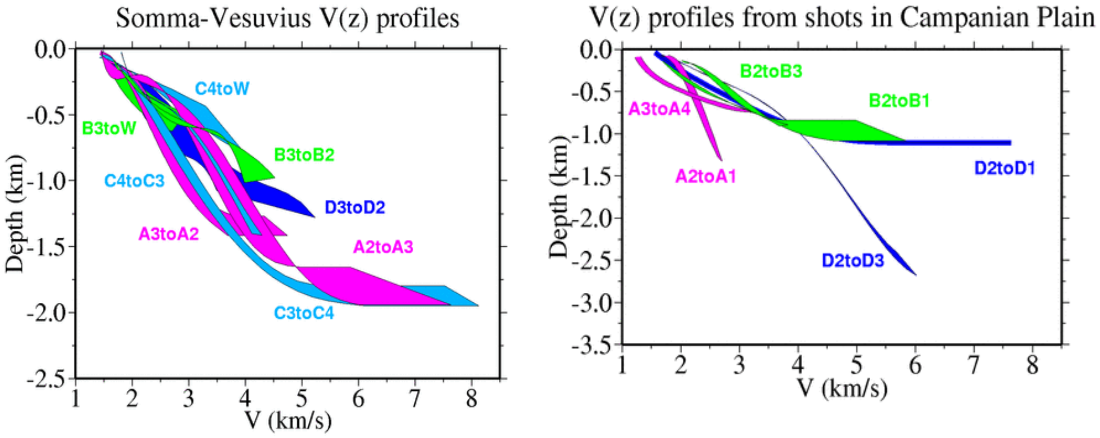
"A prominent converted P-to-S phase at about 10 km of depth indicates the occurrence of a sharp transition to a very low-velocity zone. This may represent the top of an extended magmatic reservoir."

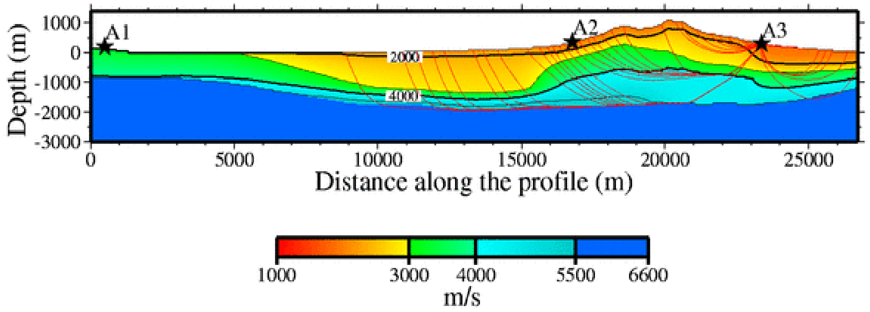


1996, Multi-2D experiment: The shallow structure

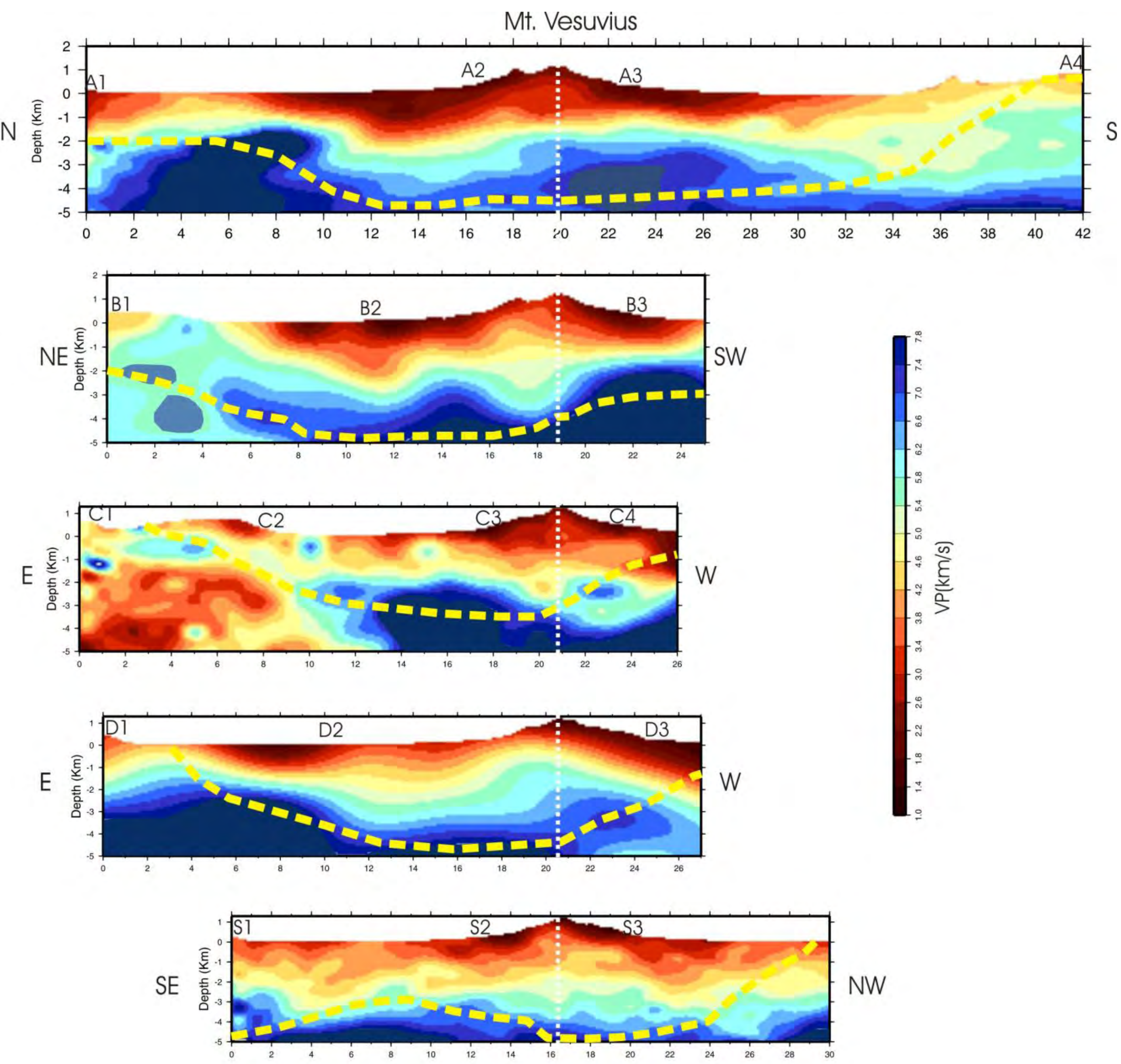


1D P-wave velocity models using the Tau-P method at the scale of a volcano (De Matteis et al, 1997)





De Matteis, R., Latorre, D., Zollo, A., Virieux, J., 2000. Pure Appl. Geophys.



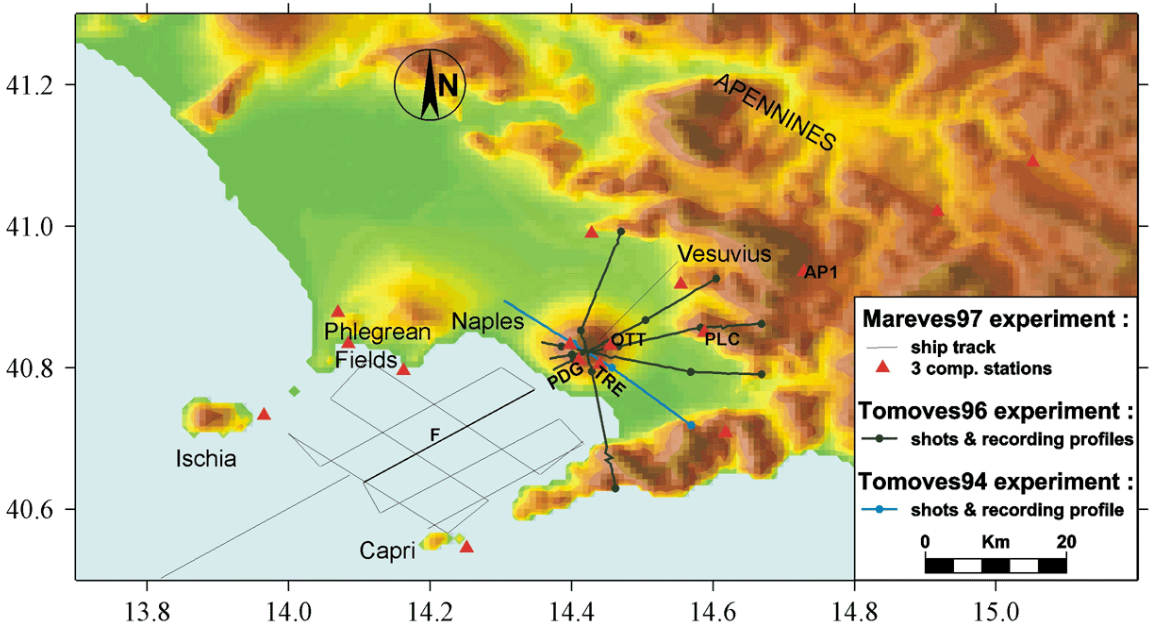
Multi 2-D P-velocity models using a bayesian tomographic method

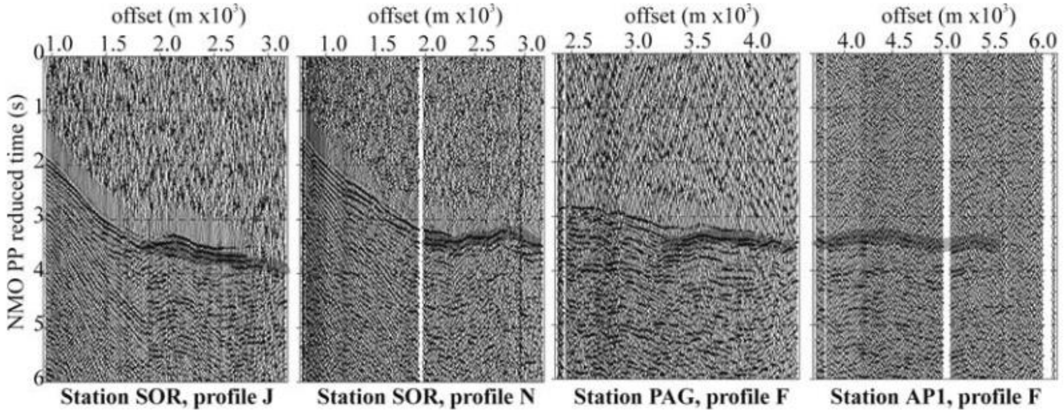
- Model Parametrization
  - Cubic splines interpolation
  - Multi-scale inversion strategy
- Forward Problem
  - Numerical integration of ray equation
  - Two-point ray-tracing
- Inverse Problem
  - Bayesian formulation
  - Genetic + Simplex Algorithms

Zollo, A., D'Auria, L., De Matteis, R., Herrero, A., Virieux, J., Gasparini, P., 2002. Geophysical Journal International

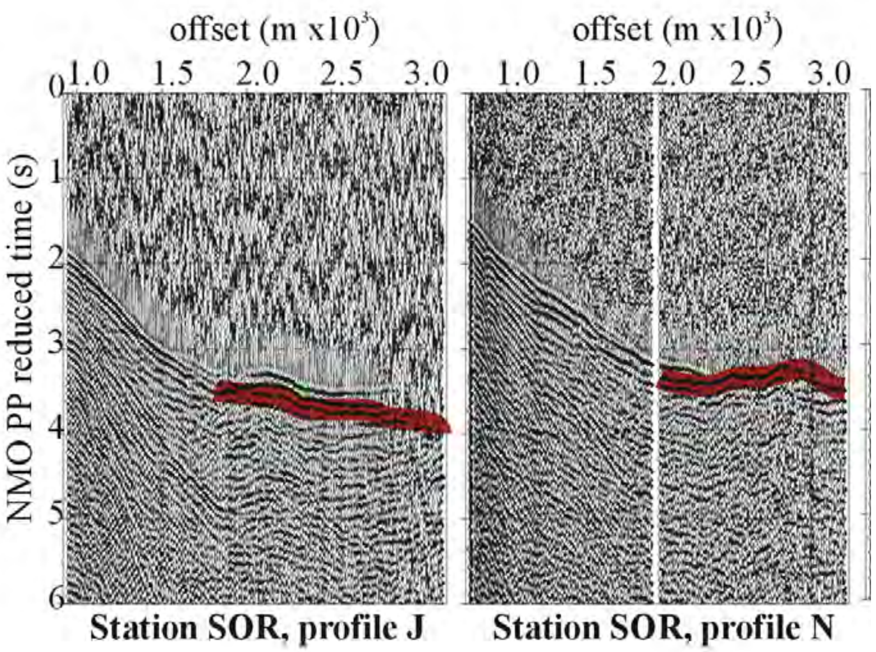
1996 (onshore) & 1997 (offshore): Looking at seismic reflections

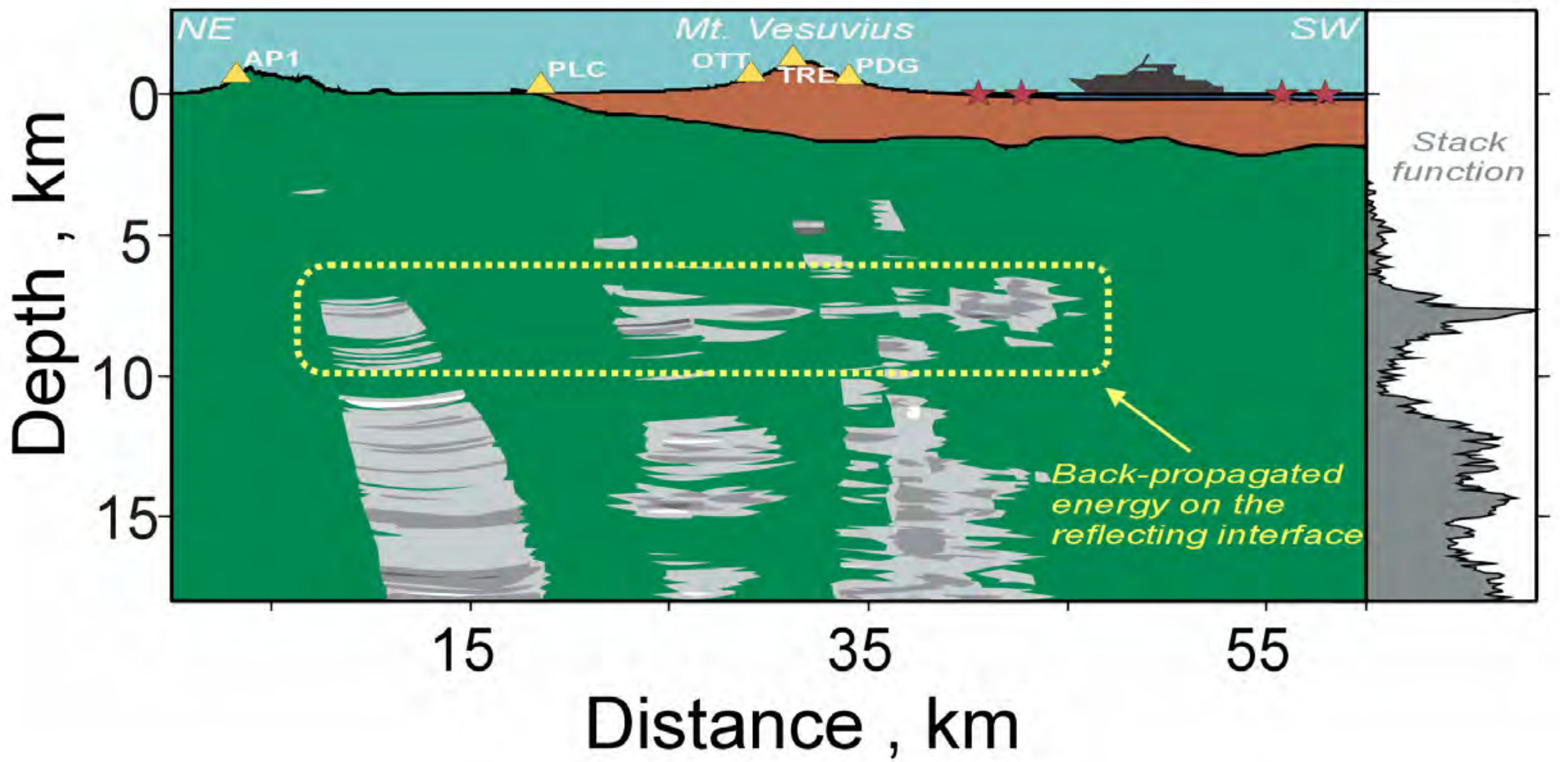
- Seismic Evidence for a low-velocity zone in the mid-crust beneath Mt. Vesuvius (Science, 1996) (Zollo et al., 1996)
- The evidence for a magmatic sill under Mt Vesuvius (Science , 2001) (Auger et al., 2001)
- Locating and quantifying the seismic discontinuities by migration and AVA analysis of refl/conv phases, Auger et al., 2003 GJInt
- Confirmation of a mid-crustal discontinuity beneath Mt Vesuvius from local earthquake records (Nisii et al., 2004)
- Crustal structure deduced from receiver functions via single-scattering migrations , the BROADVES experiment





The mid-crustal magmatic sill at Mt Vesuvius

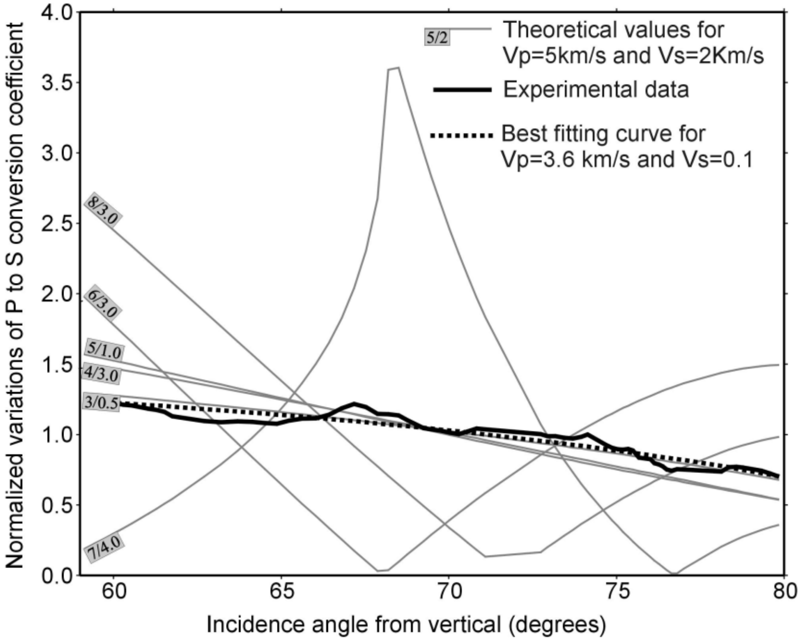




- A pre-stack, depth migration technique is used to locate the reflecting interface

Auger, E., Gasparini, P., Virieux, J., Zollo, A., 2001. Seismic Evidence of an Extended Magmatic Sill Under Mt. Vesuvius. Science 294, 1510–1512.

The impedance contrast at the sill interface



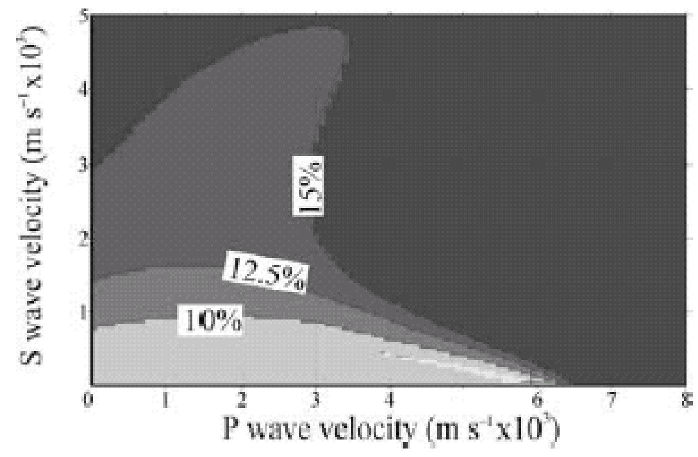
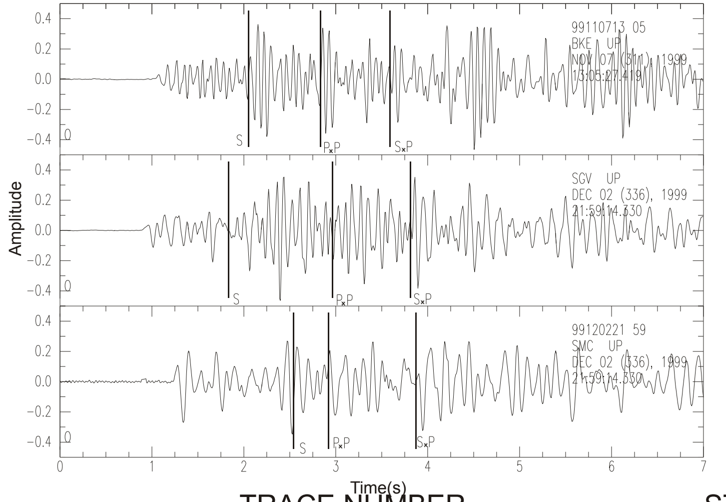


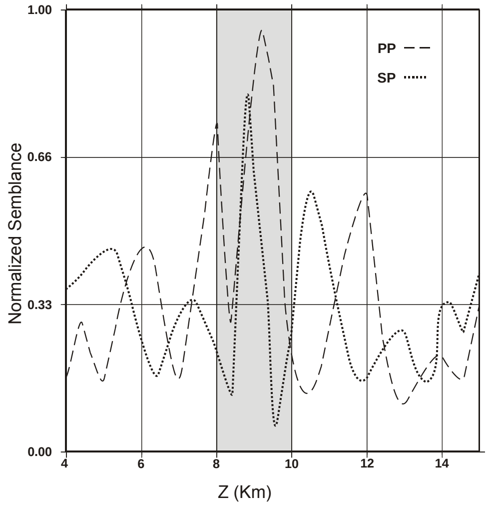
Figure 11. Relative misfit between experimental and theoretical normalized variations of the *P*-to-*S* conversion coefficient as a function of the *P* and *S* velocity assumed in the medium underlying the LALA interface. Only very low *S* velocities, less than 1000 m s^{-1}, are associated with a relative error of less than 10 per cent.

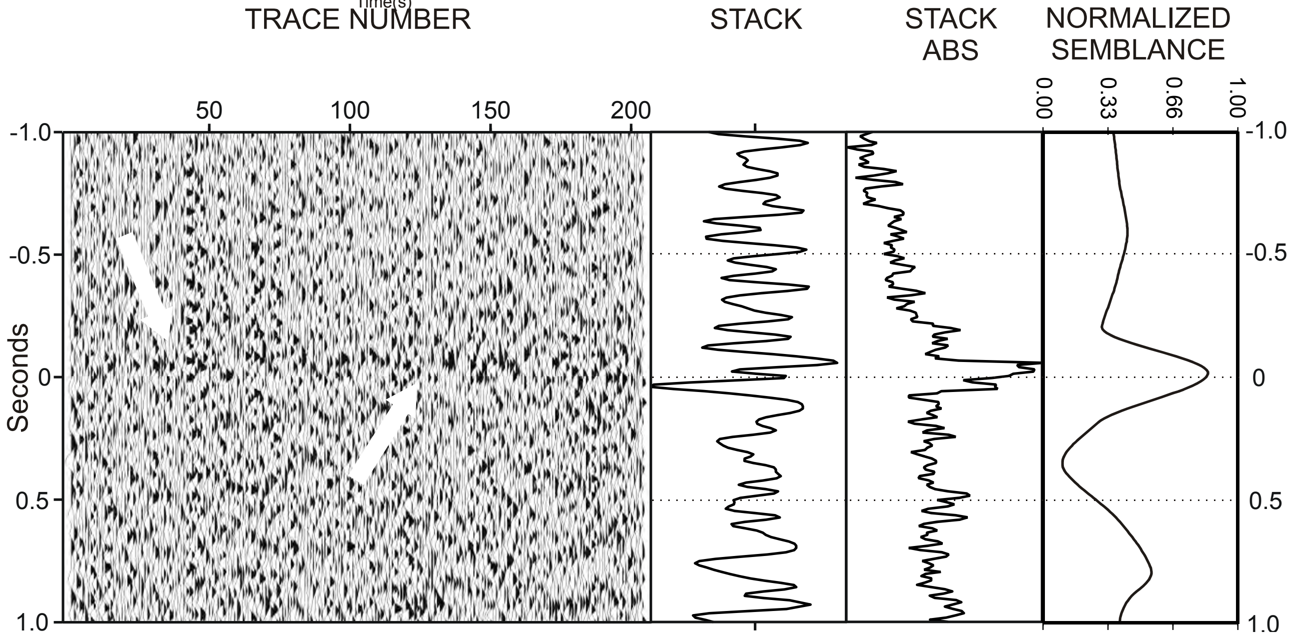
The variation of normalized amplitude vs the incidence angle allows to constrain the P and S velocities below the interface (Vs < 1 km/s; Vp< 5 km/s)

Auger, E., Virieux, J., Zollo, A., 2003.. Geophysical Journal International

Evidence for the mid-crustal sill from local earthquake records





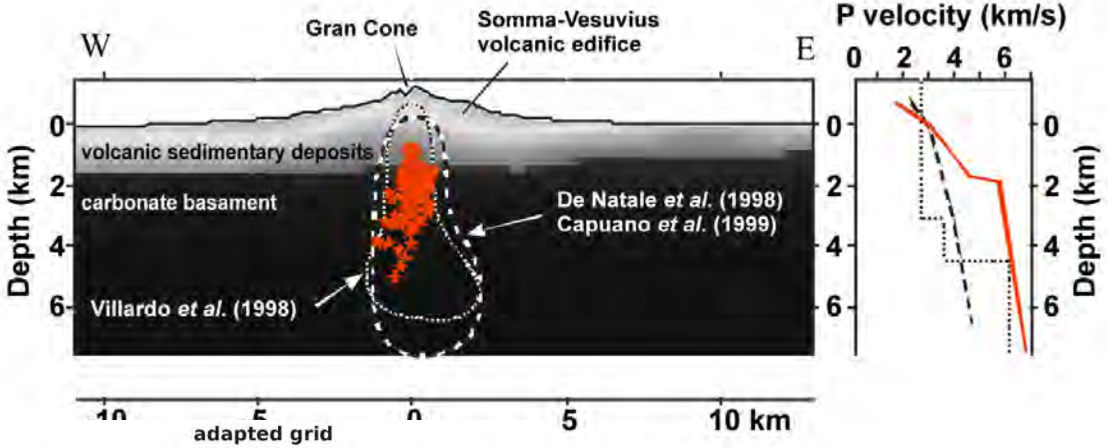


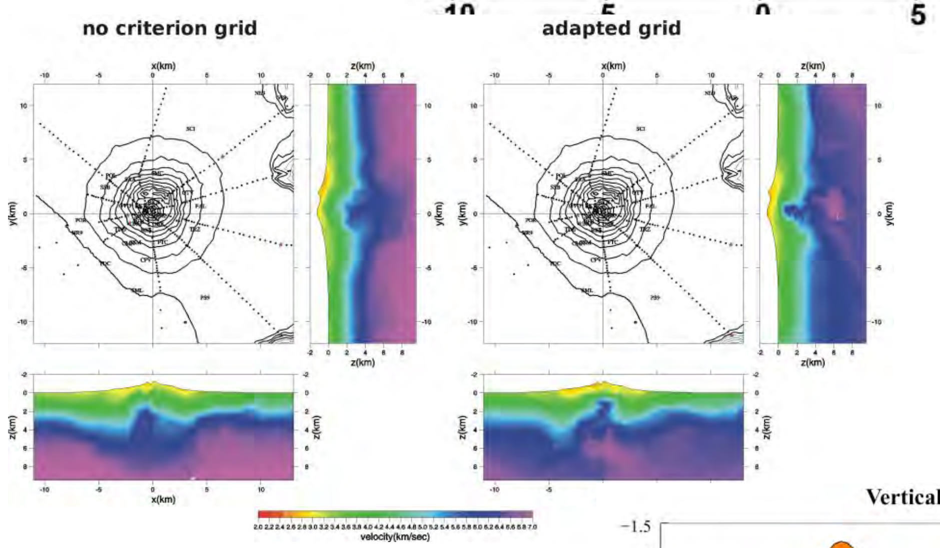
- 24 events, 200 records
- NMO correction and stack
- P-to-P and S-to-P phases
- Interface at 8-10 km depth

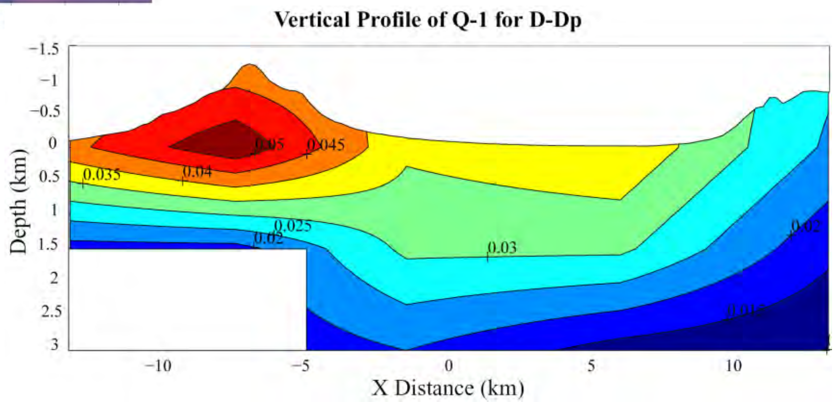
V. Nisii, et al., 2004 Depth of a Midcrustal Discontinuity beneath Mt. Vesuvius from the Stacking of Reflected and Converted Waves on Local Earthquake Records. *Bulletin of the Seismological Society of America* 2004

Other related researches

- Precise, absolute eqk location and focal mechanisms, (Lomax et al, 2001)
- 3D linearized delay time tomography (Montelli et al., 2003)
- Inversion of seismic attributes at Mt vesuvius, (Nowack & Virieux, 2003)



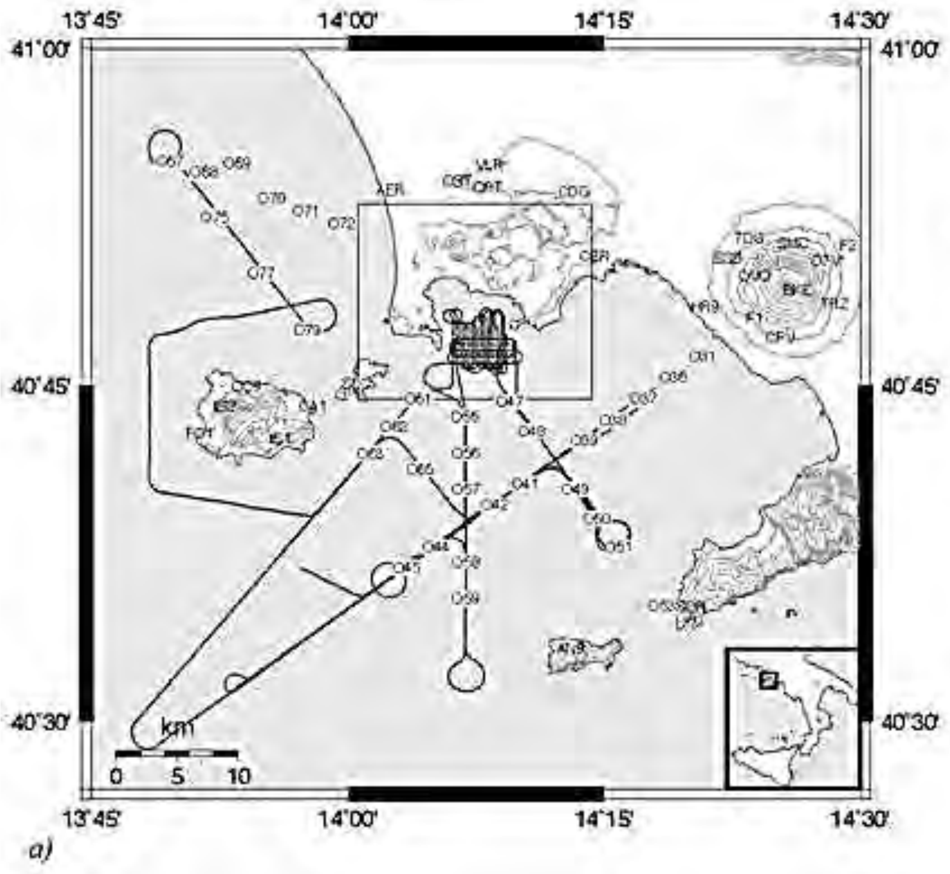


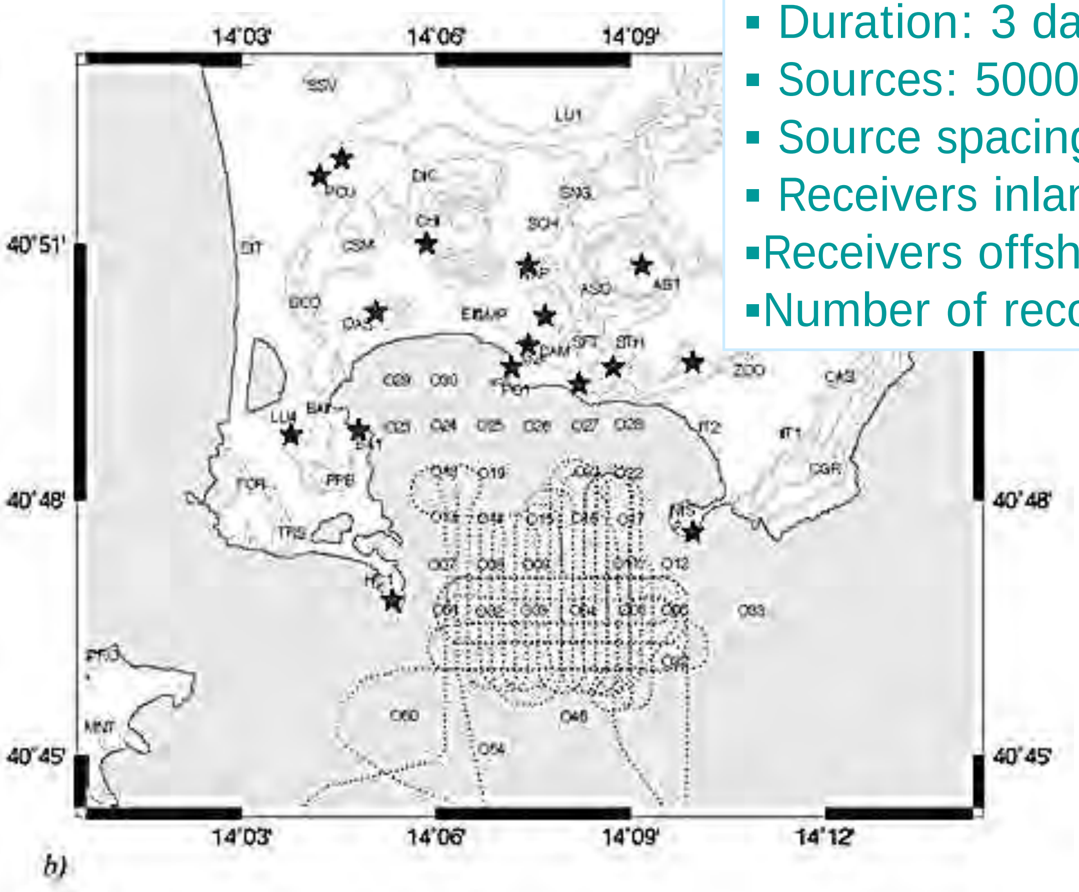


Seismic exploration of the Campi Flegrei caldera structure

SERAPIS (SEismic Reflection Acquisition Project for Imaging Structures) - 2001

The experiment SERAPIS (September,2001)

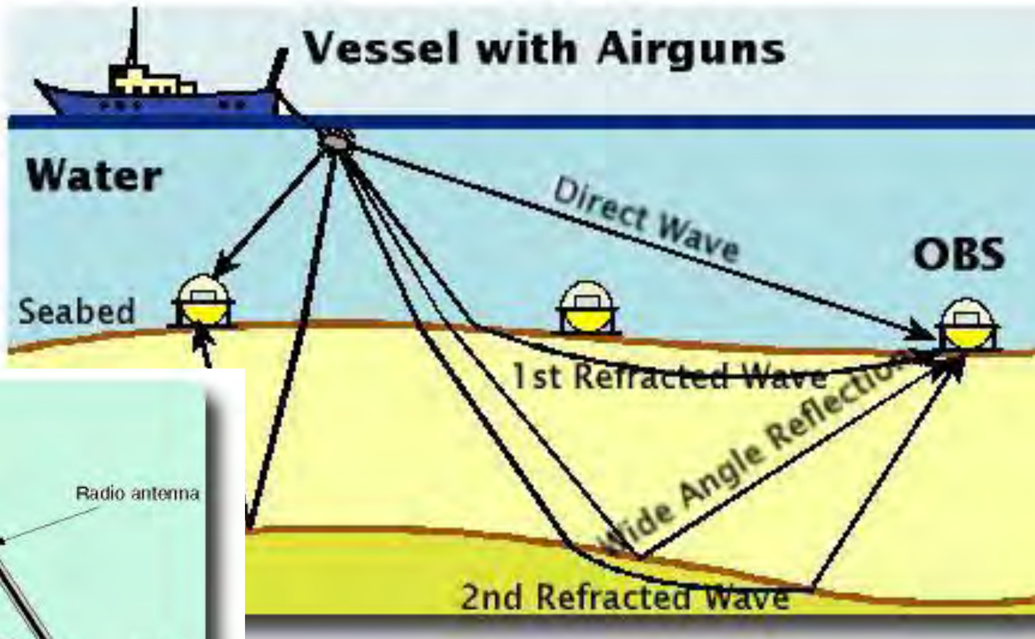


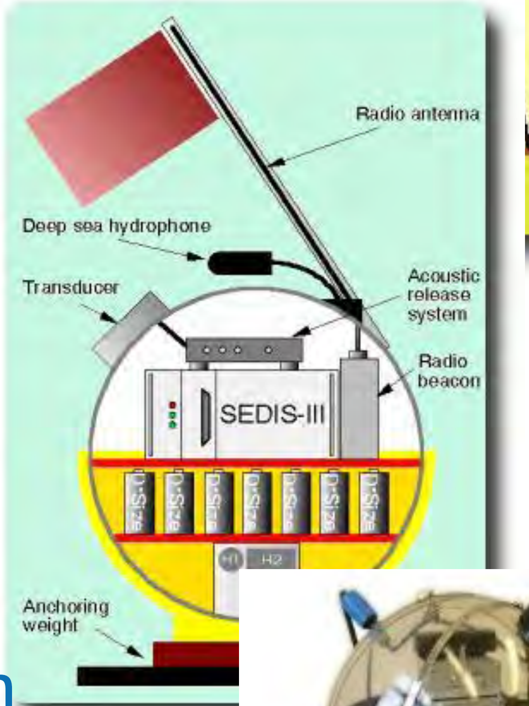


SERAPIS' Numbers

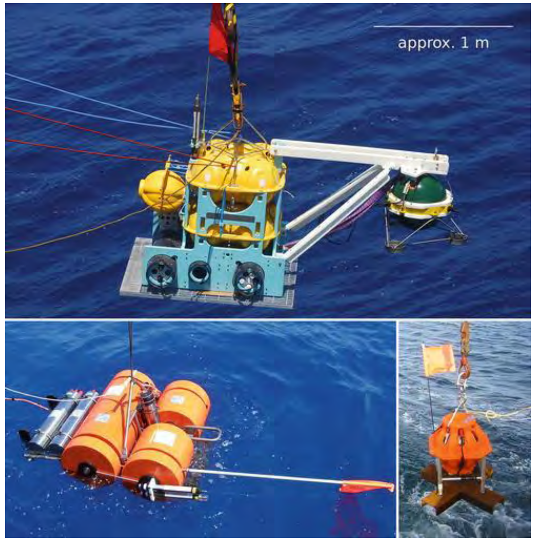
- Duration: 3 days
- Sources: 5000 airgun shots
- Source spacing: 125 meters
- Receivers inland : 72 3C station
- Receivers offshore: 60 3C OBS
- Number of records/P-picks: 77000

The oceanographic vessel NADIR of IFREMER

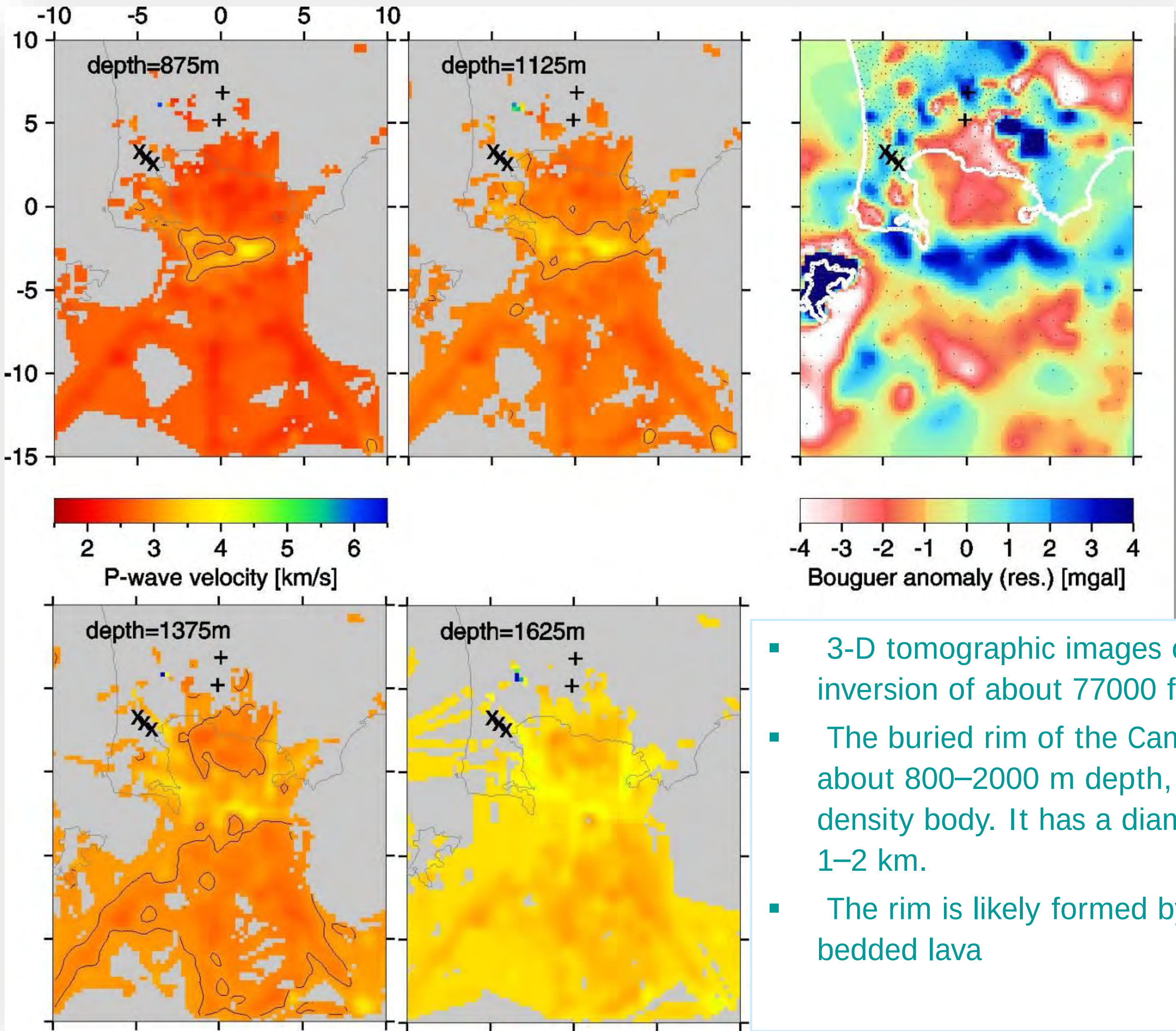


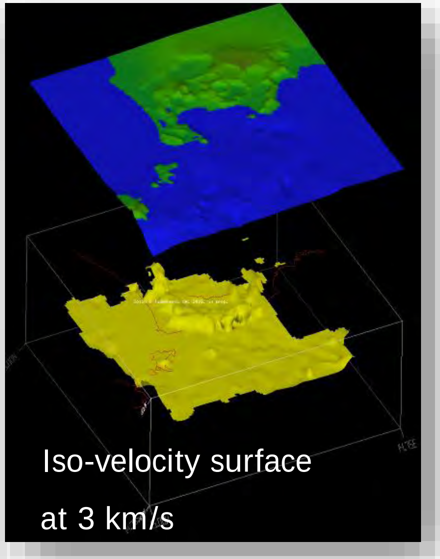


The Ocean Bottom Seismograph SEDIS of GeoPro



The buried rim of Campi Flegrei caldera





- 3-D tomographic images of the shallow caldera structure from the inversion of about 77000 first P arrival times
- The buried rim of the Campi Flegrei caldera is clearly detected at about 800–2000 m depth, as an anular high P-velocity and high density body. It has a diameter of about 8–12 km and a height of 1–2 km.
- The rim is likely formed by solidified lavas and/or tuffs with inter-bedded lava

Zollo, A., et al, 2003, Evidence for the buried rim of Campi Flegrei caldera from 3-d active seismic imaging, *Geophys. Res. Lett.*,

Merging active and passive data sets in traveltime tomography

- 606 earthquakes recorded in 1984 and 1528 shots produced during the SERAPIS experiment in 2001
- finite-difference traveltime computation and a simultaneous inversion of both velocity models and earthquake locations.
- confirm the presence of a high P velocity ring in the southern part of the bay of Pozzuoli and extends its trace inland as compared to previous results. This annular anomaly represents the buried trace of the rim of the Campi Flegrei caldera.
- in good agreement with the location of hydrothermalized lava inferred by gravimetric data modelling

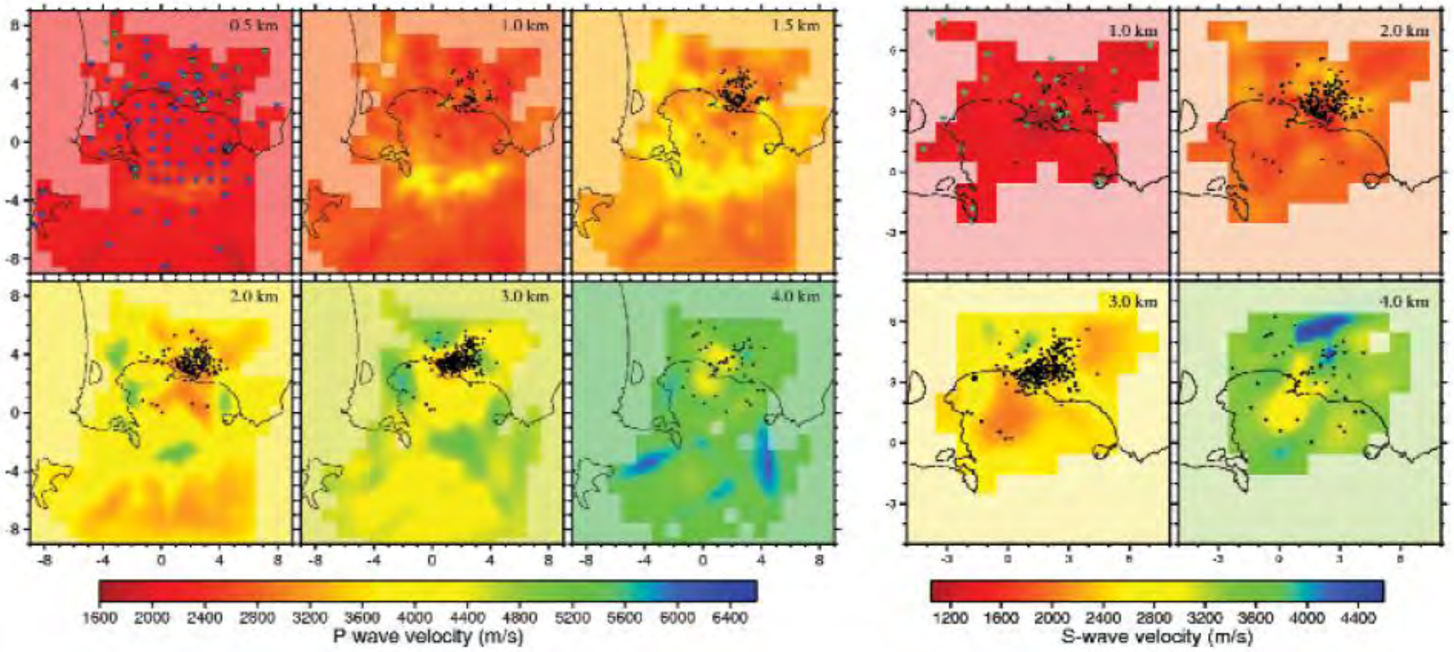
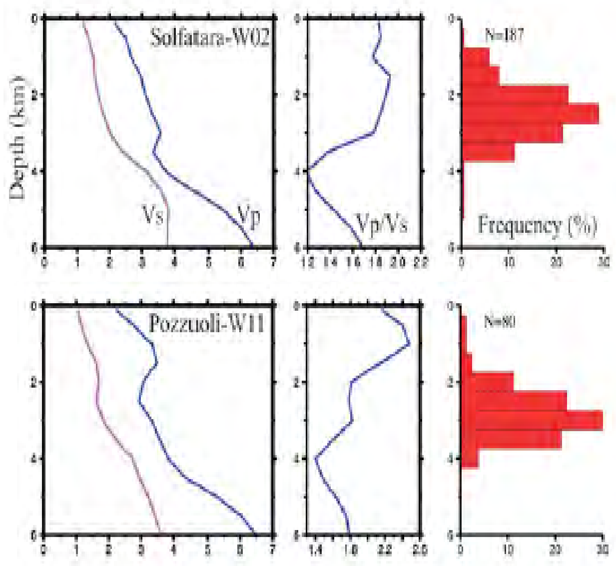


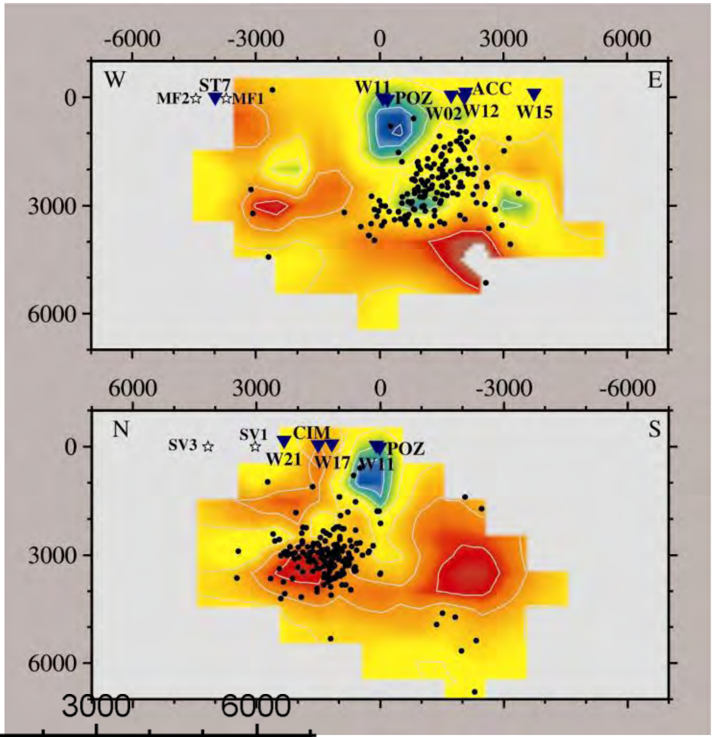
Fig. 5. Tomography results: (left) horizontal sections of the P velocity model. (right) horizontal sections of the S velocity model. Cells not sampled by any ray are shown in lighter colors.

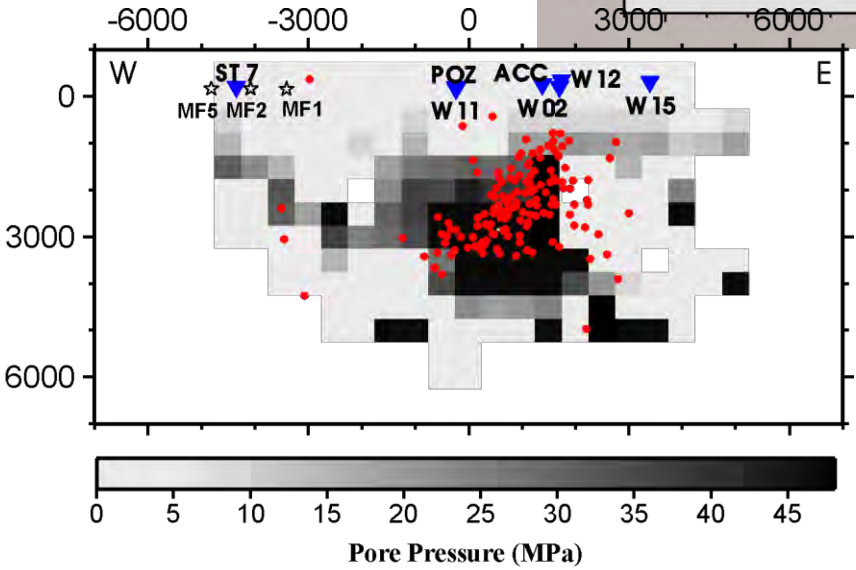
Battaglia, J.,et al.,2008), Merging active and passive data sets in traveltime tomography: The case study of Campi Flegrei caldera (Southern Italy). Geophysical Prospecting,

3-D tomography and rock physics characterization

- Earthquakes are located just on the top of the low Vp/Vs anomaly implying the presence of gas-bearing rocks.
- The origin of gas is matter of speculation: steam or CO_2 probably related to decarbonation reactions due to thermometamorphic processes within the carbonatic basement
- Translation of velocity images into lithology, porosity and pore filling phase images through rock physics effective-medium modeling (Dvorkin et al 1999).
- Earthquakes occur in the high pore-pressure, gas-bearing formations and the presence of melted rocks at these depths is excluded.

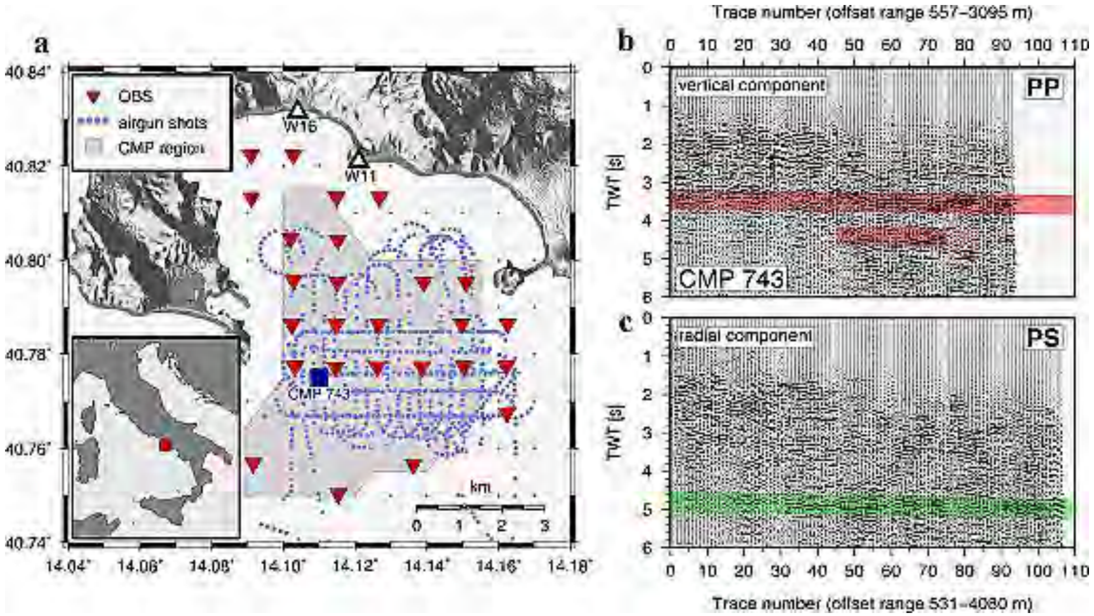


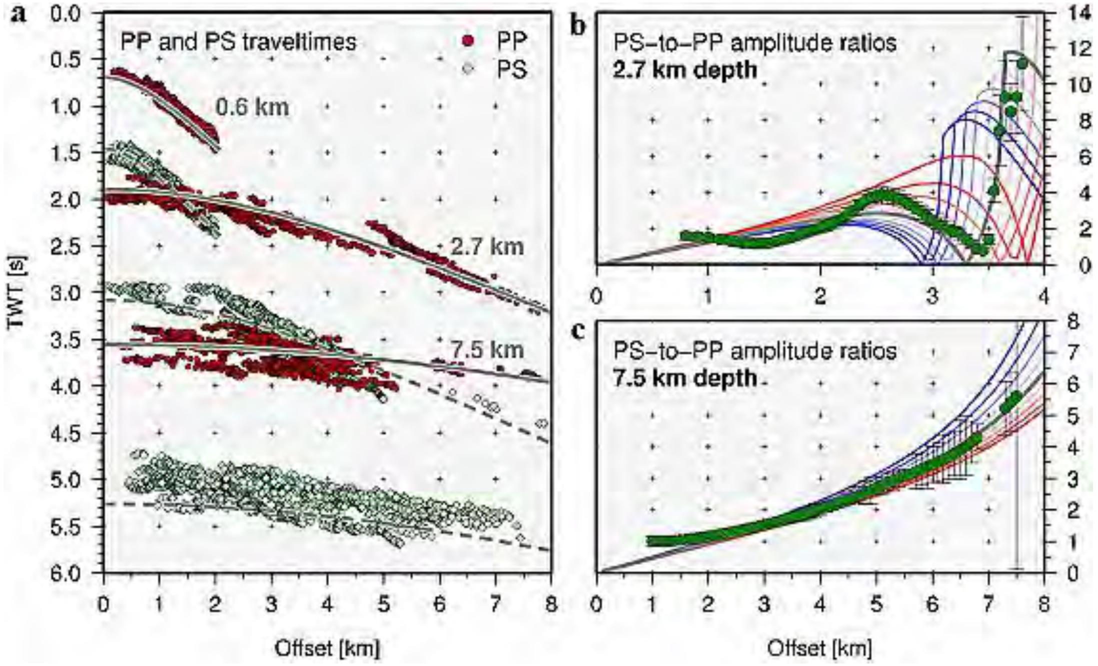




Vanorio, T., Virieux, J., Capuano, P., and Russo, G. (2005), Three-dimensional seismic tomography from *P* wave and *S* wave microearthquake travel times and rock physics characterization of the Campi Flegrei Caldera, *J. Geophys. Res.*,

Seismic reflections reveal a mid-crustal magma sill beneath Campi Flegrei



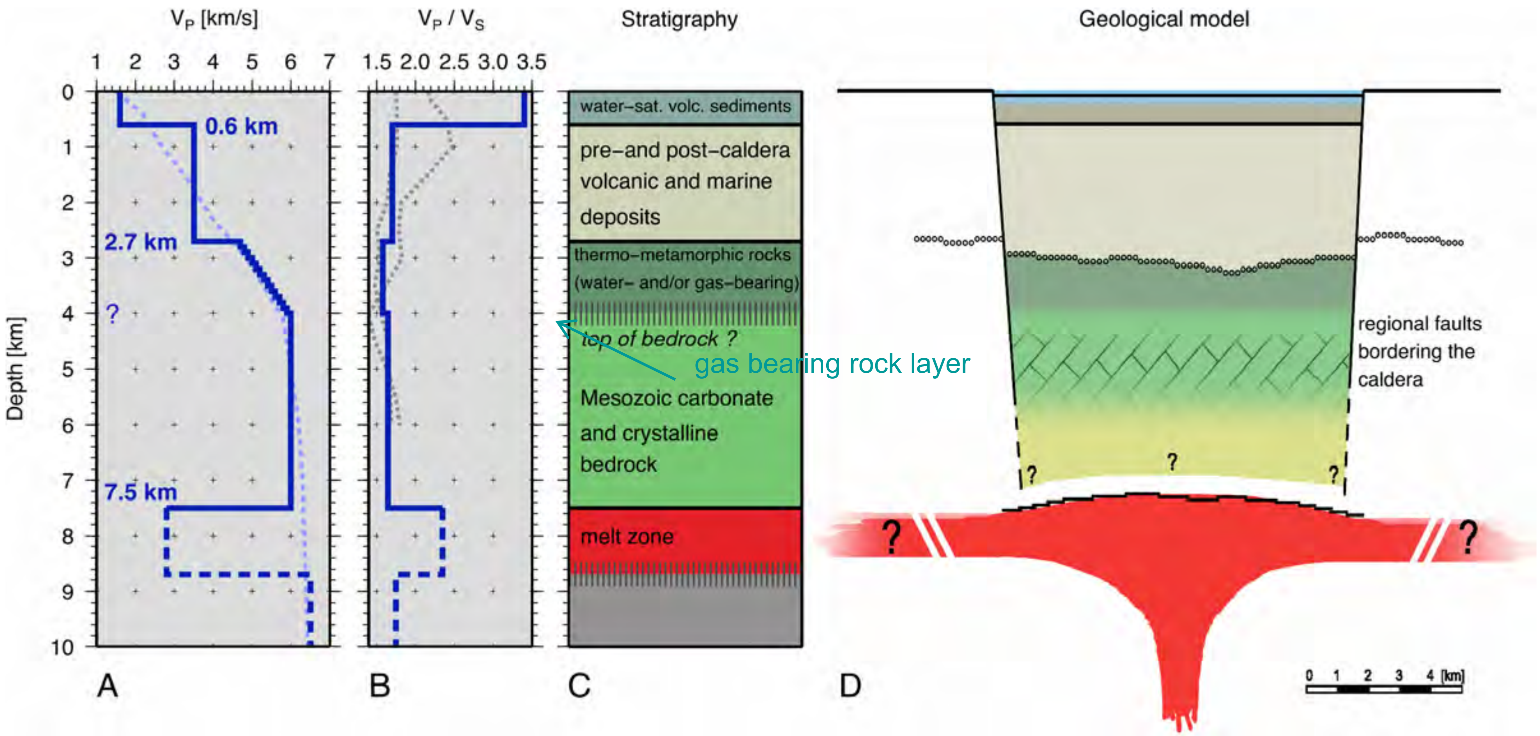


- Clear evidence for P-to-P and P-to-S seismic reflections from the top of an extended supercritical fluid-bearing rock formation at about 3,000 m and of an about 7,500 m deep, 1,000 m thick, low velocity layer, which is associated with a mid-crust, partial melting zone beneath the caldera
- The modeling of magma properties based on measured seismic velocities indicates a relatively high melt percentage (in the range 80–90%).

Zollo, A., Maercklin, N., Vassallo, M., Dello Iacono, D., Virieux, J., and Gasparini, P. (2008), Seismic reflections reveal a massive melt layer feeding Campi Flegrei caldera, *Geophys. Res. Lett.*, 35, L12306, doi:10.1029/2008GL034242.

Geophysical and Structural Model of Campi Flegrei caldera

- No evidence for large magma batch at superficial depths
- Gas reservoir at a depth of about 3 km depth (CF)
- Reservoir of partially melted magma at a depth around 8 km under CF, similar depth for Vesuvius → common reservoir ??
- The magma depth is consistent with geochemical investigations of phenocryst-hosted melt inclusions

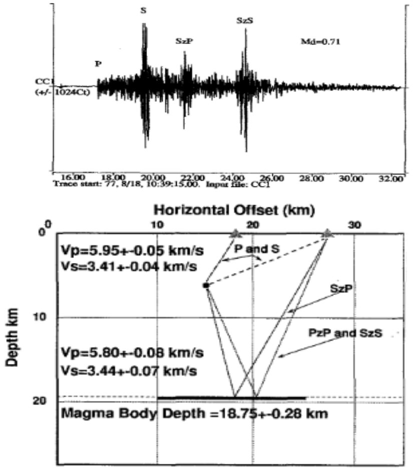


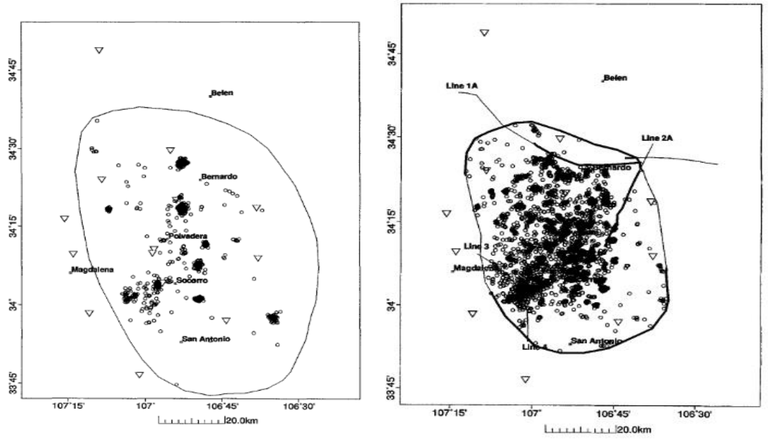
A. Average 1-D P-velocity model based on PP and PS travel times, and on PS-to-PP amplitude ratios. The dashed line is the average of the 3-D Vp model
B. *Vp/Vs* ratio vs depth. The dotted lines are two *Vp/Vs* depth profiles that were estimated from the local earthquake tomography (Vanorio et al. 2005)
C. Stratigraphic model
D. Geological sketch model of the Campi Flegrei caldera.

Other evidences for mid-crustal sill-like magmatic reservoirs

- ❑ Socorro magma body at Rio Grande rift, New Mexico, USA
  - Sill-depth: 18 km
  - Area: 3400 km^2 (appr.radius 32 km)
- ❑ Yellowstone caldera, USA
  - The imaged magma body is 90 km long, 5–17 km deep, and 2.5 times larger than previously imaged.
- ❑ Nikko-Shirane Volcano, Japan
  - Magma chamber (high attenuating body) bw 3 and 10 km depth
  - Oblique sill-like seismic reflector feeding the magma chamber
- ❑ Mid-crustal sub-Axial Magma Lens (SAML) at the East Pacific Rise
  - AML oceanic Mid-crustal depths (4-6 km)
  - SAML oceanic low-crustal depths (10-12 km)

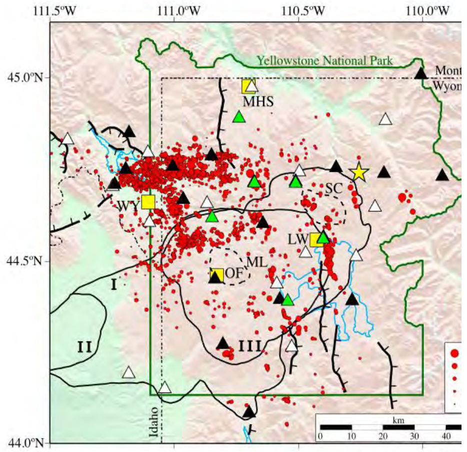
Balch et al 1997 Bull.Seism.Soc.Am

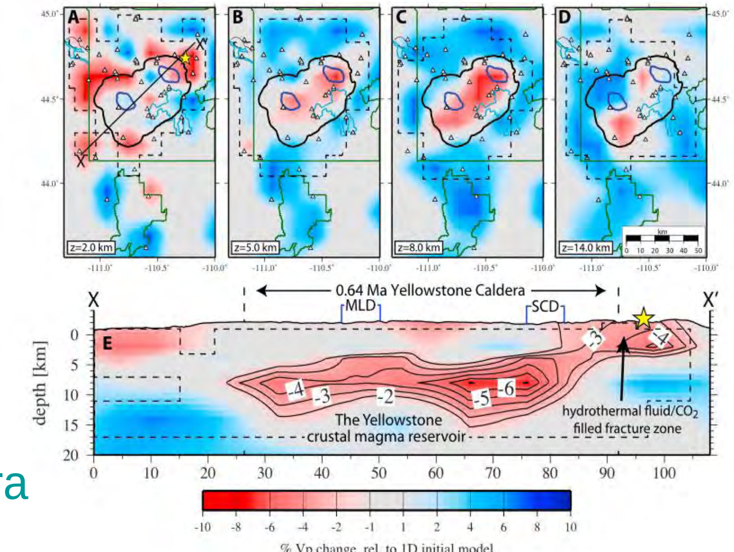




Socorro magma body

Farrell, et al, 2014, Geophys. Res. Lett.





Yellowstone caldera

The changed vision of the magmatic feeding system of volcanoes

Not a single but several magma chambers !

- Recent studies on crustal magma stability conditions changed the vision has changed of what is commonly called a "magma chamber": a single, large pocket, perennial in time, of liquid magma located under the volcano
- Petrological, geochemical and geophysical studies → the feeding system of a volcano is an interconnected network of magma lenses that communicate in a variable way (open system) and that can be destabilized from time to time, causing an eruption.

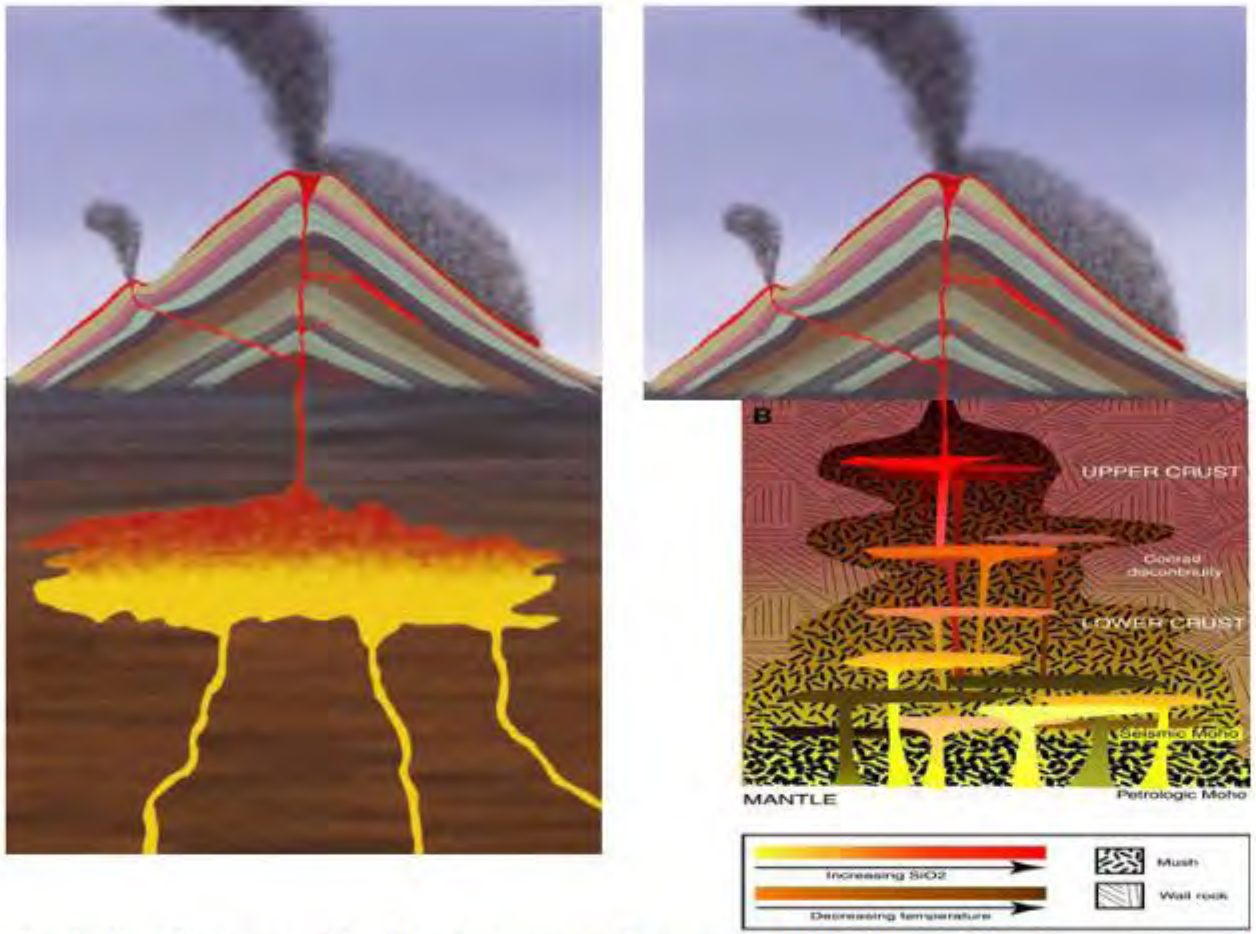


*Figure 33 : **Evolution du concept de chambre magmatique vers un système polybarique transcrustal.** Modifié d'après Caricchi et al. (2015) et Cashman et al. (2017).*

Balcone-Boissard, H., 2018. Dynamiques des magmas, du réservoir magmatique à la surface. Sorbonne Université UPMC, Paris.

A complex hierarchy of inter-connected magma sills

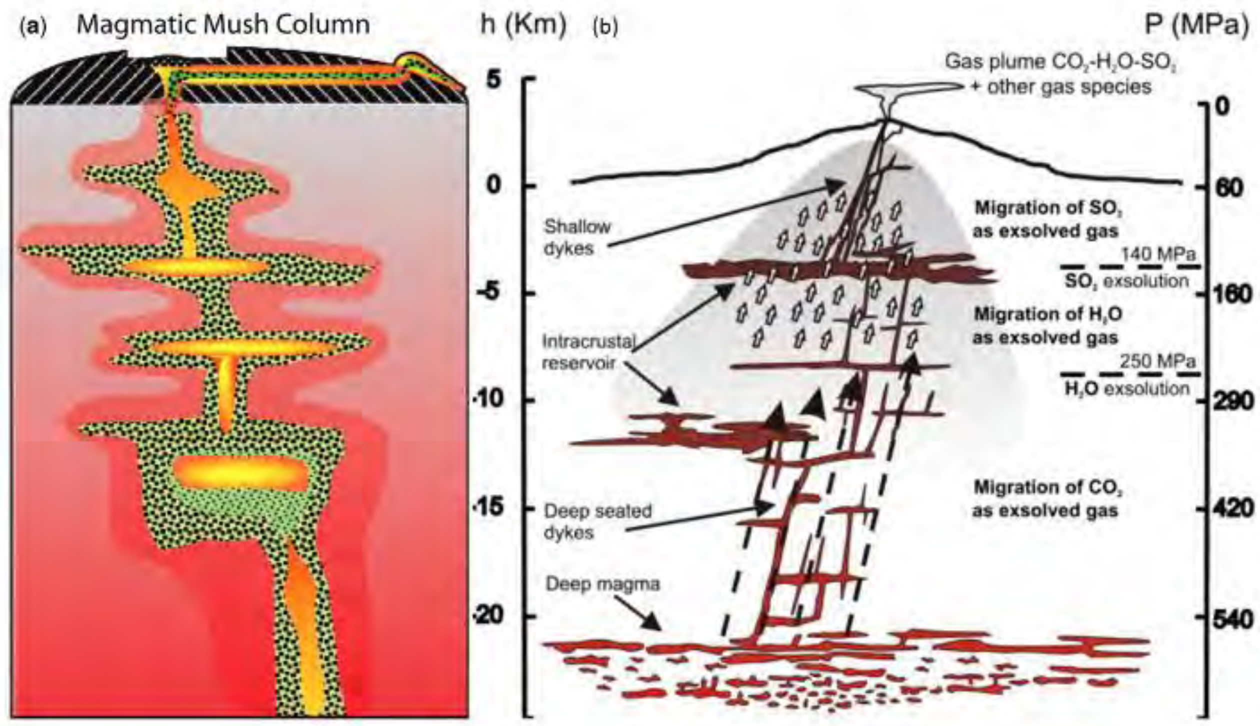


*Figure 34 : **Le mush, un système magmatique transcrustal** connecté par un réseau de dyke et parcouru par une migration de fluides dont la composition dépend des solubilités respectives des gaz impliqués. La figure (a) est tirée de Zellmer et Annen (2008) et la figure (b) de Ferlito et al. (2014).*

- Sub-volcanic plumbing systems are dominated by hot zones comprising relatively liquid-poor (<50%) crystal rock volumes → Mushes
- Within “Mushes” a potentially eruptible amount of magmatic liquid is present. Mush is thus by definition at or just above solidus → partially molten rock.
- The mush is a dynamic magmatic system with a complex geometry. It extends vertically within the upper but also intermediate and lower crust. It can be traversed by flows of volatile elements (CO2, H2O, SO2)

Balcone-Boissard, H., 2018. Dynamiques des magmas, du réservoir magmatique à la surface. Sorbonne Université UPMC, Paris.

A common deep plumbing system of Neapolitan volcanoes?

Fedi, M.,et al.,, 2018. Sci Rep

Moretti, R.et al., 2013. Journal of Petrology

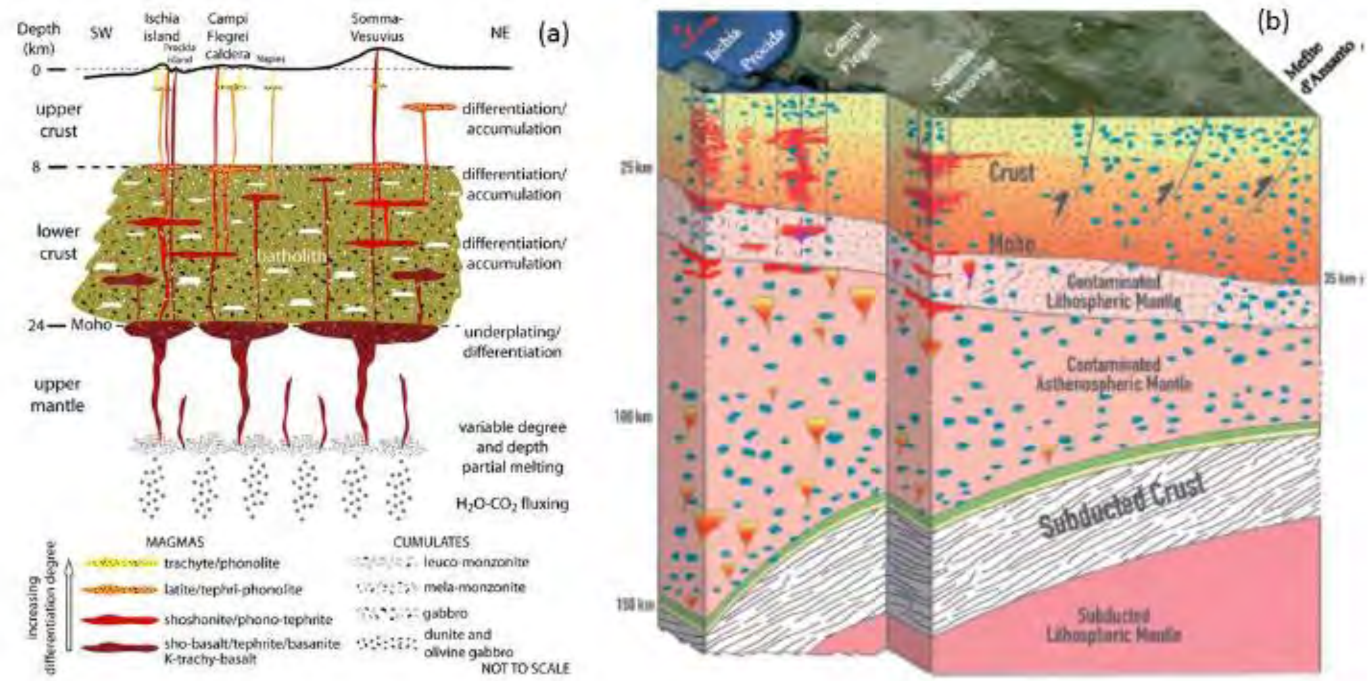


*Figure 12: **Modèle de réservoir magmatique sous les systèmes Monte Somma – Vésuve, Campi Flegrei et Ischia**, vu par la gravimétrie (a ; Fedi et al., 2018) et les éléments volatils (b ; Moretti et al., 2012).*

- Evidence for a major region of crustal magma stagnation and gas fluxing similar among Campi Flegrei, Mt.Vesuvius and Ischia volcanoes.
- The occurrence of such an extended, mid-crustal magma layer below the active Neapolitan volcanoes suggests a causal link common to the entire Neapolitan volcanic region.
- Hypothesis (Moretti et al.,2013): interplay between regional structures (NW-SE normal and NE-SW transfer faults) and a widespread, common deep volatile source (dominant CO2), derived from subducting metasediments.

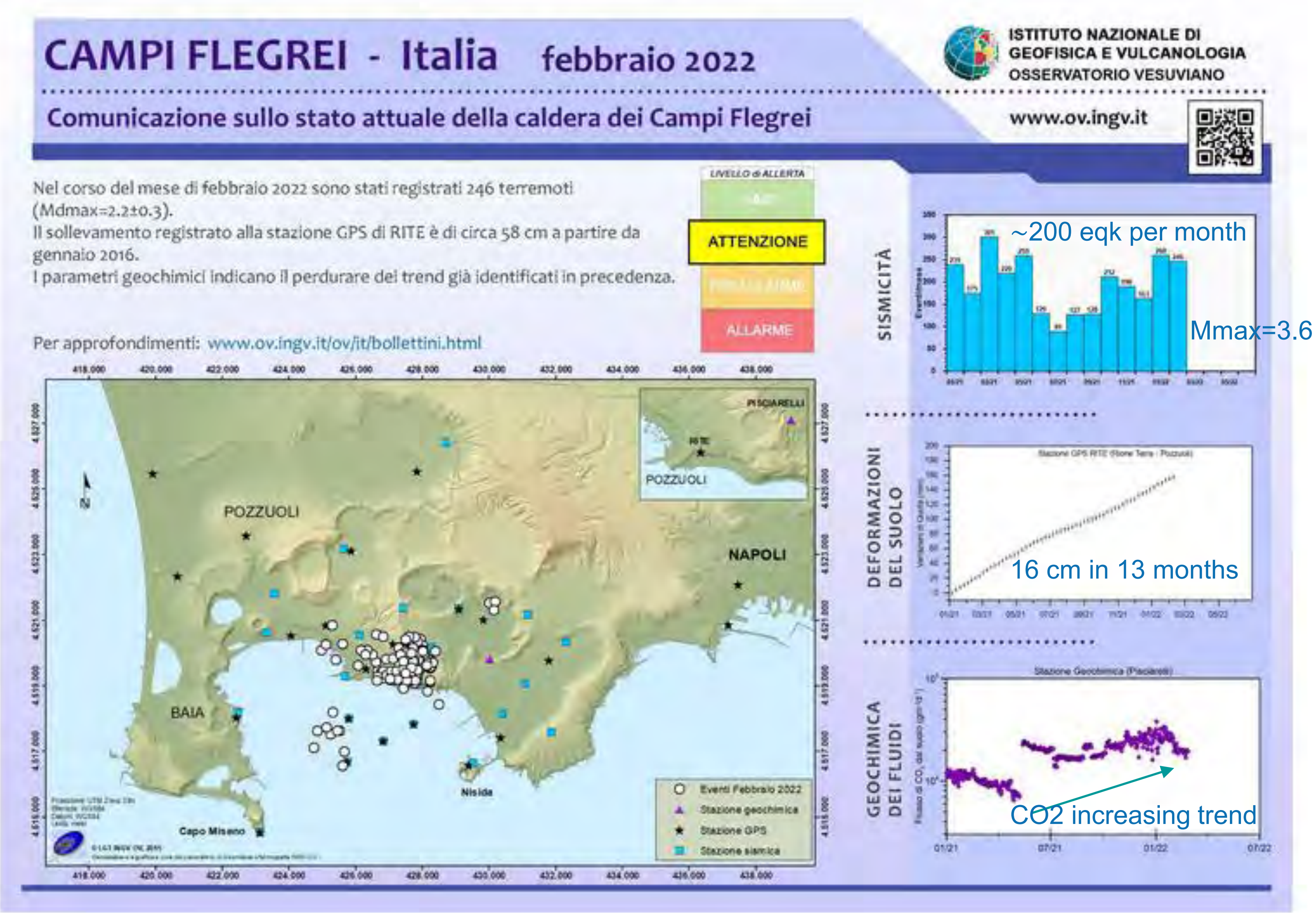
Balcone-Boissard, H., 2018. Dynamiques des magmas, du réservoir magmatique à la surface. Sorbonne Université UPMC, Paris.

Open questions & (next) future challenges in volcano monitoring

Open questions

- Are there other, smaller size, shallower magma reservoirs at Mt. Vesuvius and Campi Flegrei from which the next eruption could originate? To now, Geophysics could not detect them.
- Is there an open connecting network between the different magma layers in the hypothesis of a complex crustal «mush» system?
- How to gain new, high-resolution experimental evidence for this complex magma structure within the crust?

Present Alert Level of Campi Flegrei: «Yellow»



Since 2011, at the center of the caldera, the ground is continuously uprising at a rate of abou 8 cm/year, 85 cm in 11 years.

How to intepret the ongoing unrest at Campi Flegrei caldera?

The sporadic occurrence of (aborted) shallow magmatic intrusions?

The poro-elastic deformation of the shallow hydrothermal system as a response to changes in fluid content and pore pressure ?
The latter mechanism seems plausible from the thermal-poro-elastic modelling of the hydrothermal system (Todesco,2021)

Imaging and monitoring volcanoes: **What's** ongoing ?

Densify the surface/borehole/sea-bottom seismic networks

- To Detect and track seismic signals «below the noise level» associated with fluid mouvements

Track changes of elastic/anelastic medium properties

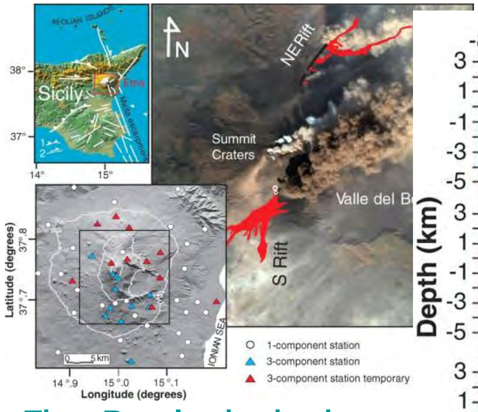
- 4D transmission/reflection tomography
- ambient noise/coda wave continuous monitoring

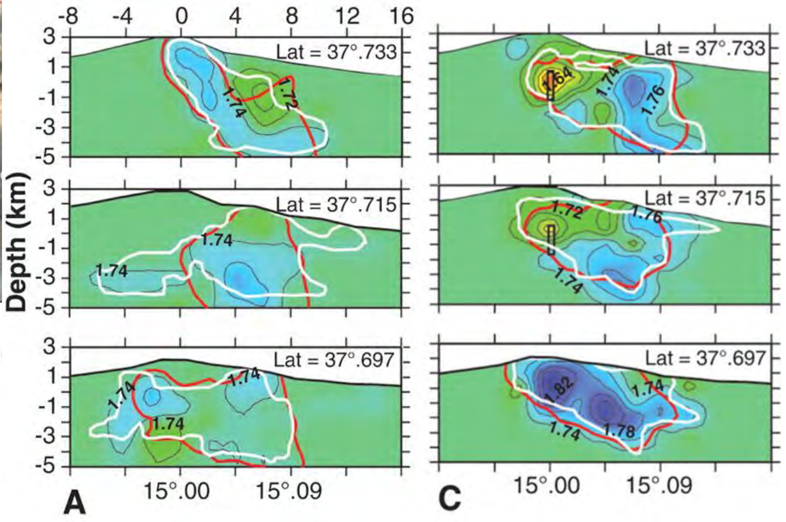
From tomography images to rock physical properties:

- Detect and track the fluid-driven pore-pressure changes vs time

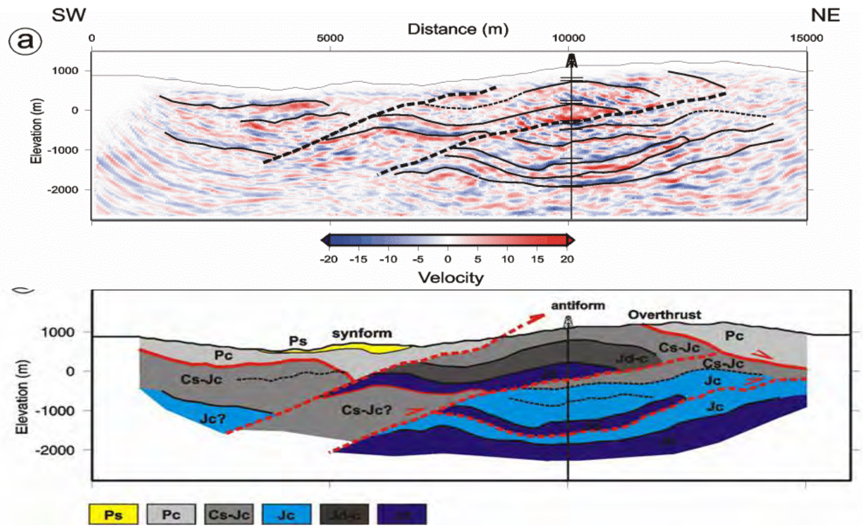
Multiparametric medium imaging

- Joint inversion of different physical observables (velocity, density, resistivity, attenuation ..)





Time-Resolved seismic tomography detects magma intrusions at Mount Etna (Patanè et al., 2003)



Quantitative seismic imaging of complex structures for seismic hazard estimation and for reservoir characterisation: a key strategy (Virieux et al., 2004)

Le puzzle des volcans napolitains

Jean Virieux, professeur à l'université de Nice Sophia-Antipolis, et **Aldo Zollo**, professeur de sismologie à l'université de Naples Federico II, sont les responsables français et italien des programmes de tomographie du Vésuve et des champs Phlégréens.

LA BAIE DE NAPLES, au sud-ouest de l'Italie, dominée par le Vésuve, s'ouvre sur la mer Tyrrhénienne. Le volcan et la zone éruptive des champs Phlégréens, de l'autre côté de la ville, menacent plusieurs centaines de milliers de personnes.

Jean Virieux, Aldo Zollo, 2004. Le puzzle des volcan napoltains. La recherche.

The End

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Arienzo, I., Moretti, R., Civetta, L., Orsi, G., Papale, P., 2010. The feeding system of Agnano–Monte Spina eruption (Campi Flegrei, Italy): Dragging the past into present activity and future scenarios. Chemical Geology 270, 135–147. https://doi.org/10.1016/j.chemgeo.2009.11.012

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Tomoves 1996

EU project '99
from left: A. Zollo, J. Virieux, U. Achauer, R. de Franco, O. Coutent, M. Mango Furnari
S. Singh, P. Gasparini, A. Corsi, G. De Natale, C. Chiarabba, G. De Luca.

At the base camp in Terzigno during the 1996 TomoVes experiment (courtesy of C. Campanella).

Imaging and monitoring volcanoes: **What's** ongoing ?

Densify the surface/borehole/sea-bottom seismic networks

- Detect and track seismic signals «below the noise level» associated with fluid mouvements
- Improve the accuracy of eqk location and src parameter determination → seismicity tracking

4D Tomography, elastic/anelastic:

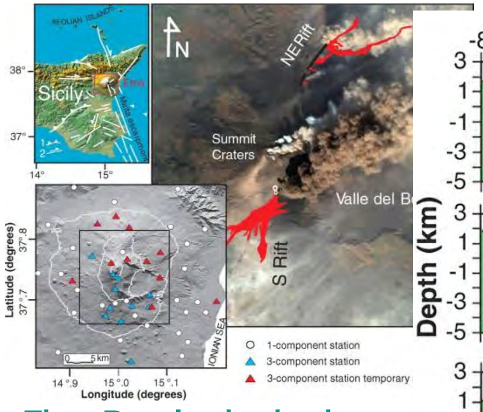
- detect and monitor space-time medium changes (noise, body waves and coda waves)
- Repeated active/passive seismic reflection

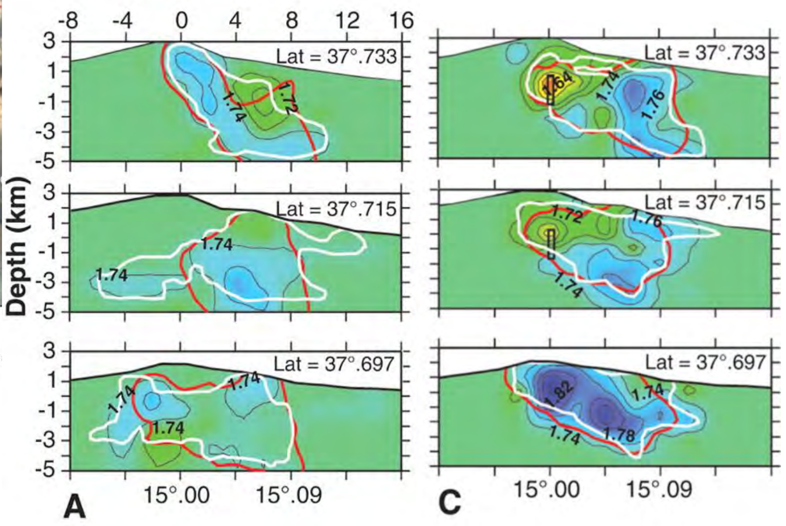
From tomography images to rock lithology:

- link elastic/anelastic properties to rock lithologies and physical properties (porosity, fluid saturation)
- Map the fluid-driven pore-pressure changes vs time

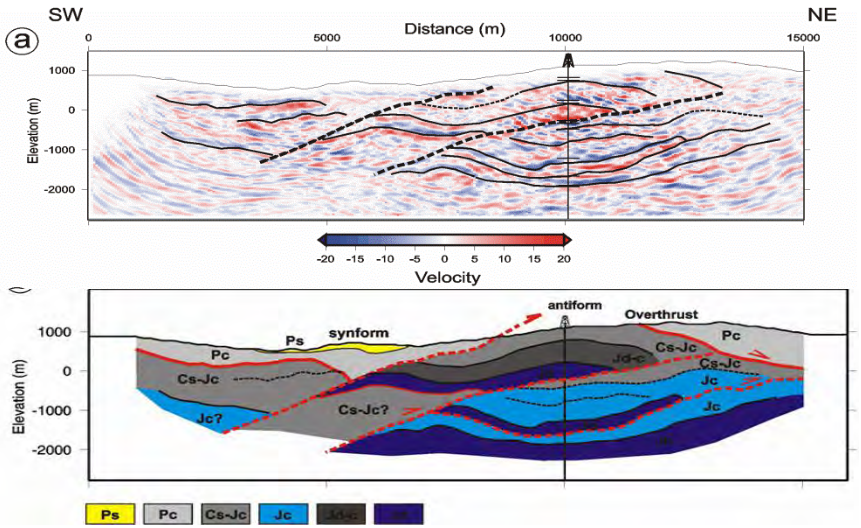
Multiparametric medium imaging

- Joint inversion of different physical observables (velocity, density, resistivity, attenuation ..)





Time-Resolved seismic tomography detects magma intrusions at Mount Etna (Patanè et al., 2003)



Quantitative seismic imaging of complex structures for seismic hazard estimation and for reservoir characterisation: a key strategy (Virieux et al., 2004)

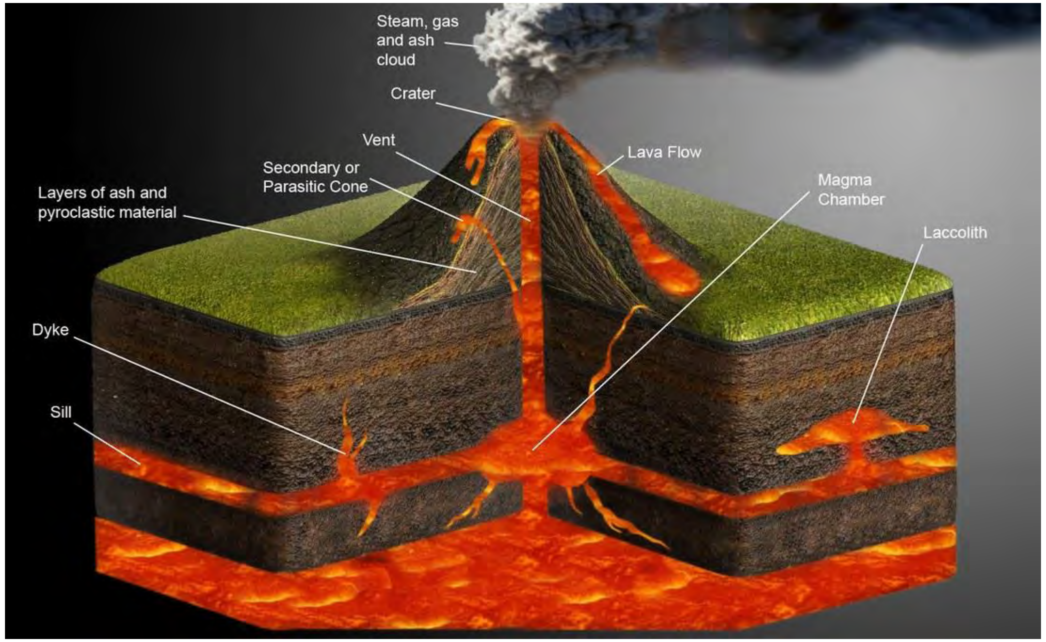
Basic ideas: transfer of knowledge, new approaches and technologies

- Know-how Transfer:
  - From the geophysical exploration of oil and gas reservoirs to the internal volcano srtucture imaging
- Big Challenges:
  - Densely populated area around the volcanoes: high urban noise, difficult logistic and many constraints on source and receiver deployment
  - Strongly heterogeneous structure, possibly high-attenuating medium: the strongly diffracting shallow layers could reprsent a screen to downward propagating seismic waves
  - Active experiments use explosive charges: limitations on the usable charge size
- Expected Gain
  - Locate at depth the magma reservoir feeding the past and potentially the future eruptive activity
  - Reconstruct a reliable 3D model that would have improved the accuracy of location, magnitude determination, source mechanism of earthquakes
  - S&T: test and apply innovative technologies and methodologie to be exported on other italian and worldwide volcanoes

Immagine da satellite dell’area napoletano-flegrea in cui è evidenziata l’urbanizzazione.(Telespazio) (G. Orsi et sl., website OV-INGV)

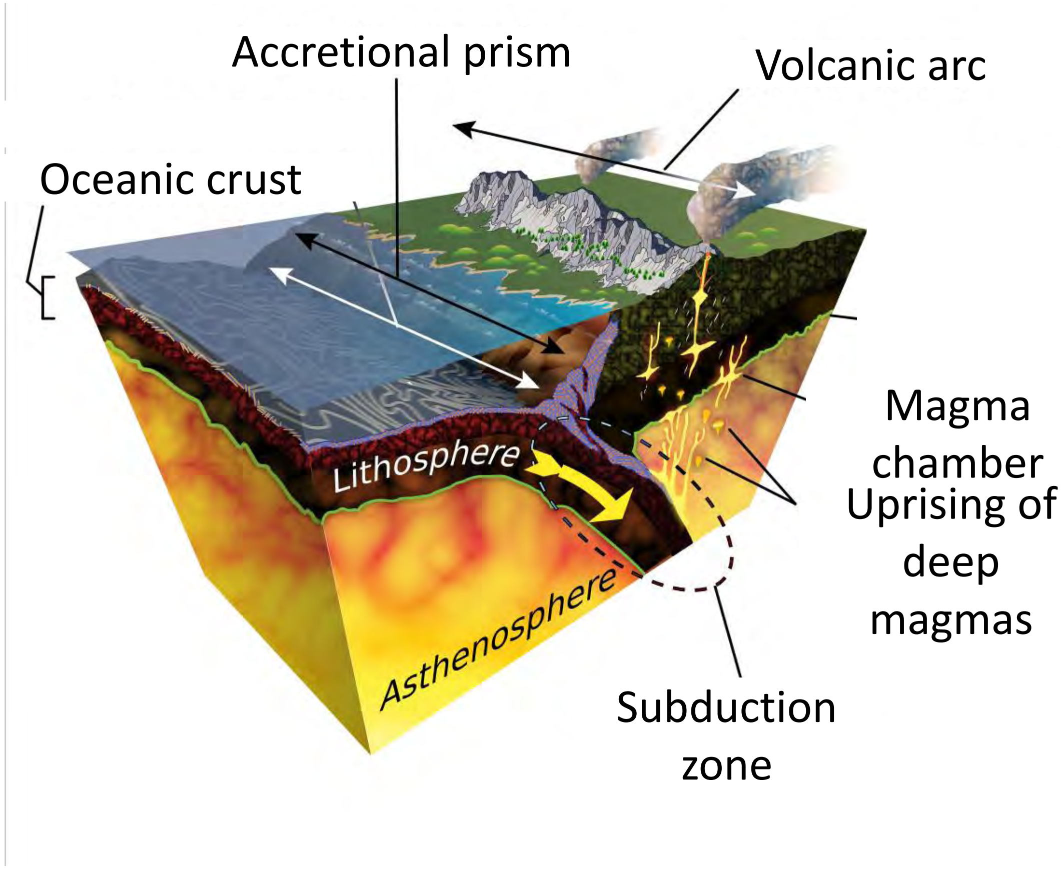
What is the magma chamber of a volcano?

What is a magma chamber



A magma chamber is an internal reservoir of molten or partially molten rocks that accumulates below the Earth's surface.

What is a magma chamber



The magma is at such pressure and temperature that, and also because of the presence of a volatile component (gas) , it gradually fractures the surrounding rock volume, creating a pathway to the surface favored by the contrast in density with the surrounding denser rocks.

What is a magma chamber

Many volcanoes are located above magma chambers. These are difficult to detect. The known ones are located between 3 and 20 km deep.

The magma that migrates up to the surface gives rise to a volcanic eruption with different degrees of explosiveness in relation to the gas content, its viscosity and possible interactions with shallow aquifers.

What is the depth, shape and size of the magma chamber feeding Mt Vesuvius and Campi Flegrei volcanoes?

- In 1993 the idea of conducting a series of active/passive seismic experiments for the detailed reconstruction of the seismic image of Neapolitan volcano internal structures

- It was motivated by the need expressed by the then director of the National Civil Protection, the volcanologist Franco Barberi, to obtain accurate, quantitative models of the volcanic structure and magma chamber allowing to develop realistic future eruptive scenarios.

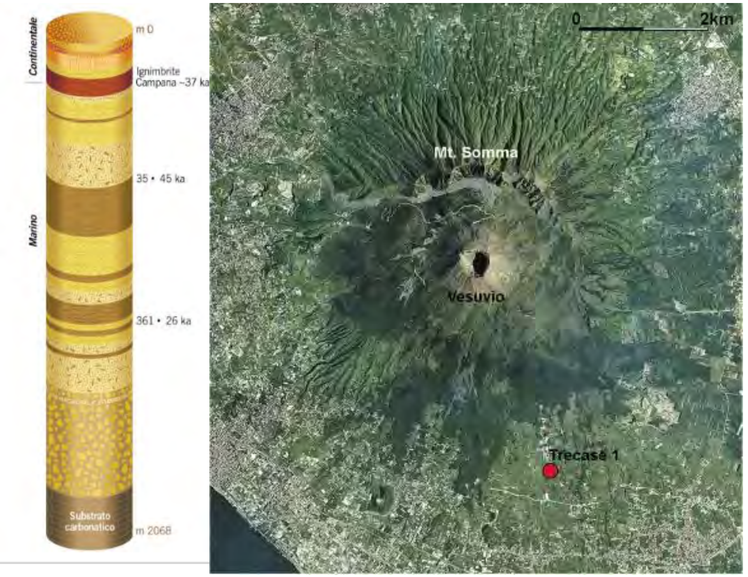
- To foster a close cooperation and interaction in Italy btw geophysical groups (lead by University of Naples) at volcano physical modelling (lead by University of Pisa)

Previous information on the volcano internal structure

- High resolution off-shore seismic reflection survey (1977)
- AGIP-ENEL joint venture to explore the feasibility of exploiting geothermal energy at Mt Vesuvius and Campi Flegrei (late 70s and early 80s)
    - Boreholes down to about 3 km depth

Agip
DES/MESG

Mt. Vesuvius: Trecase borehole



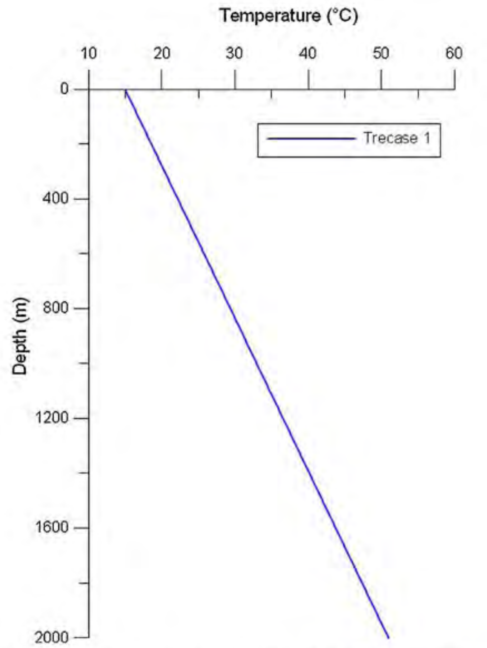


Fig. 16. Temperature versus depth measured during the drilling at Vesuvius (Trecase well).
After AGIP (1987).

De Natale et al, Campi Flegrei Deep Drilling Project, 2012; Carlino et al., 2011

Previous information on the volcano internal structure

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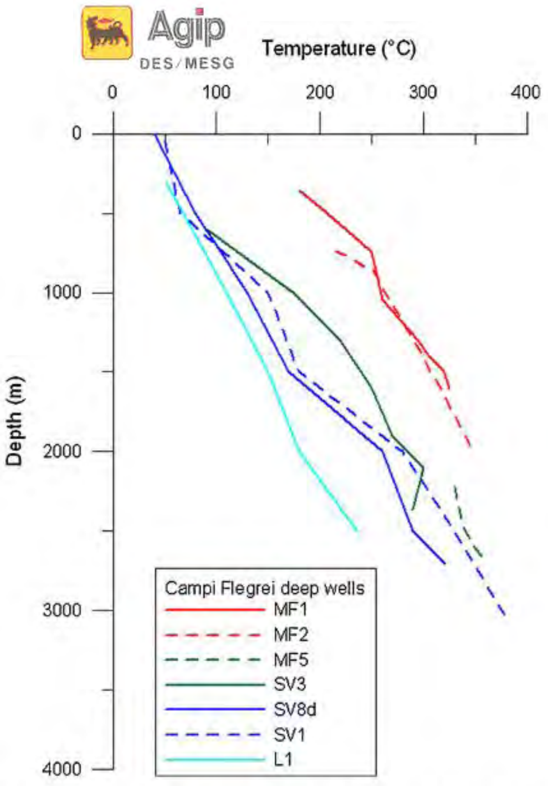
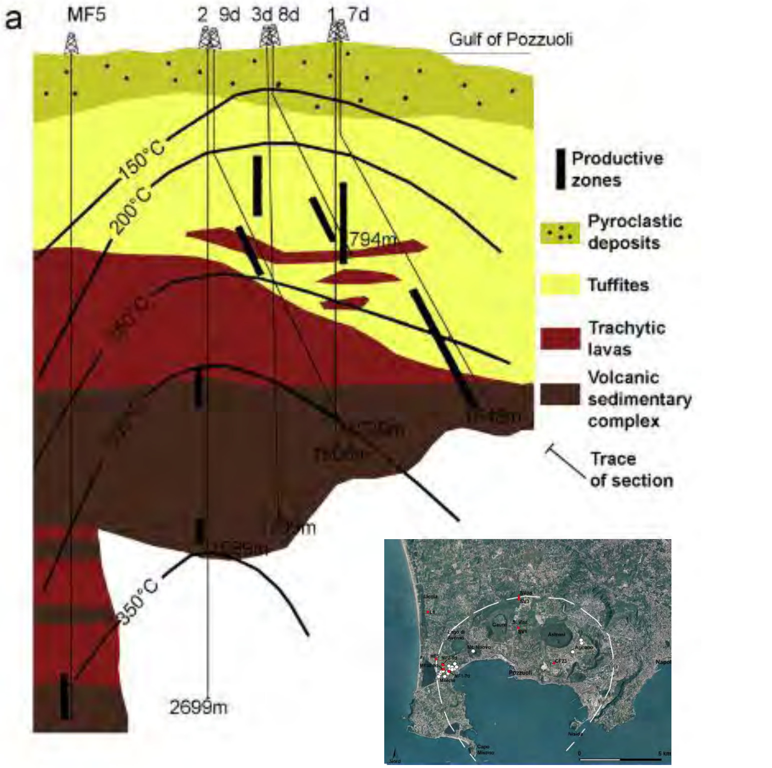


Fig. 12. Temperature profiles measured during the drilling of the deepest wells at Campi Flegrei.
After AGIP (1987).

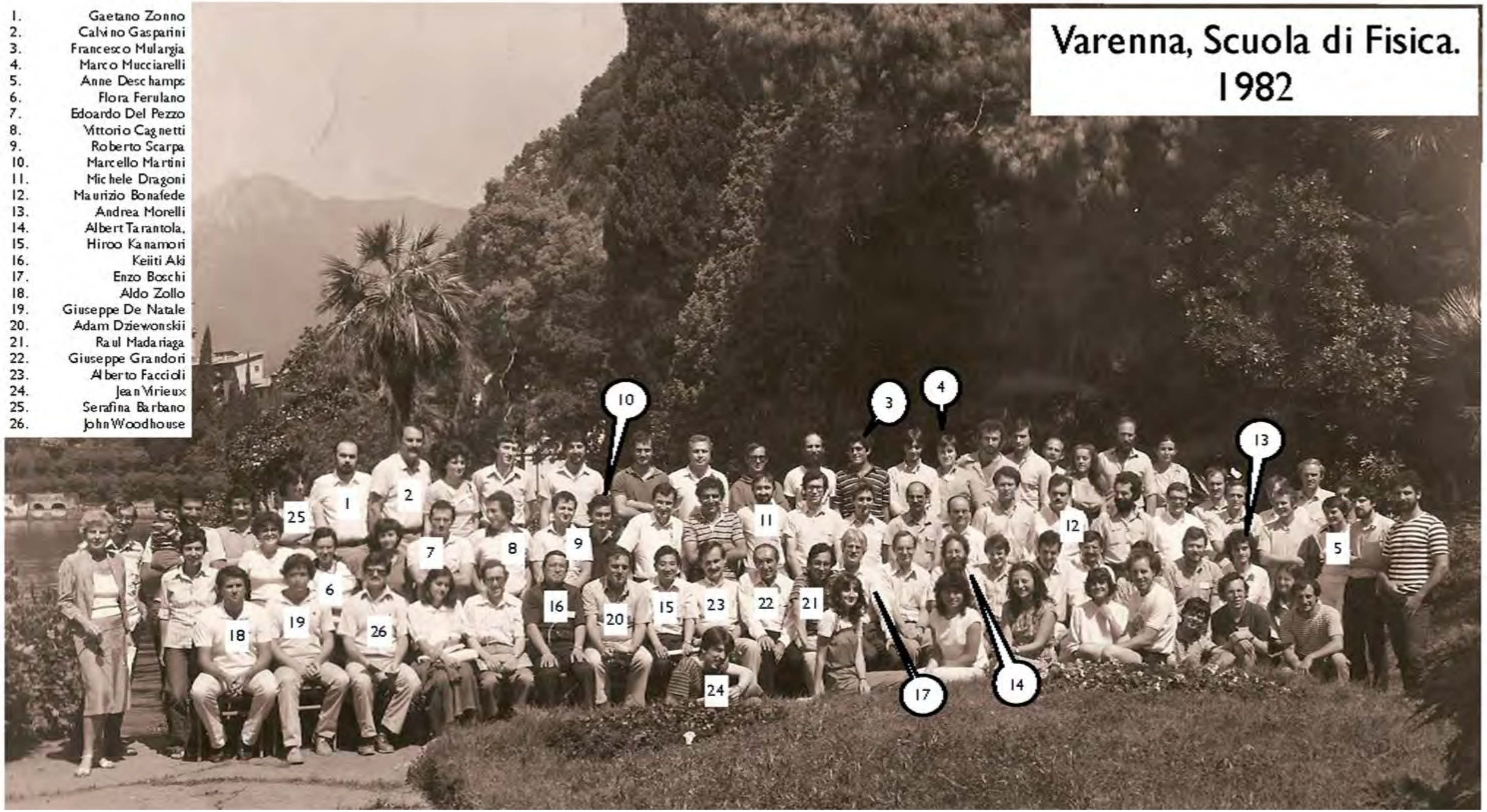
Carlino et al., 2011

Campi Flegrei : Mofete boreholes

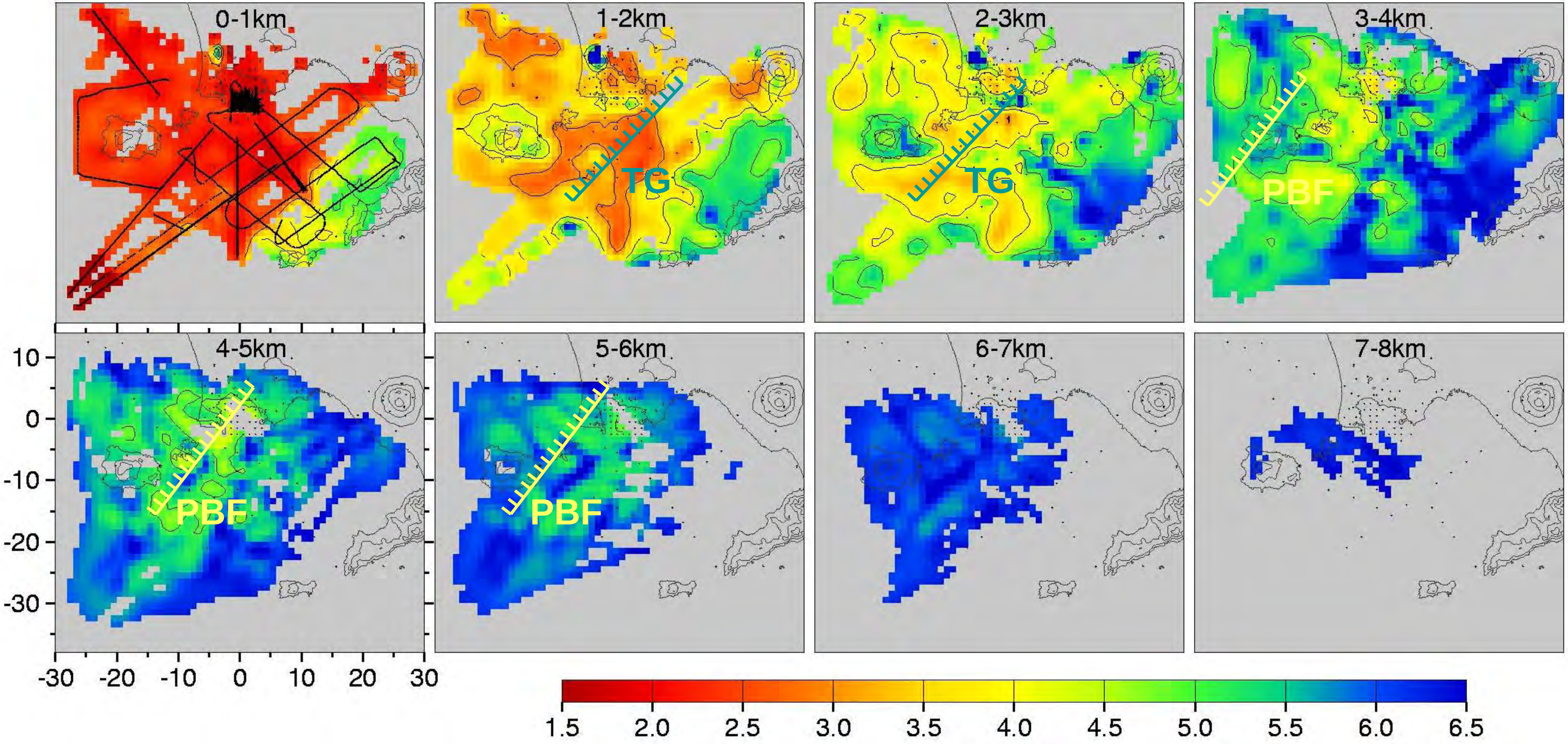


Rosi and Sbrana,1987; Carlino et al., 2011

La premiere rencontre
Varenna, 1982

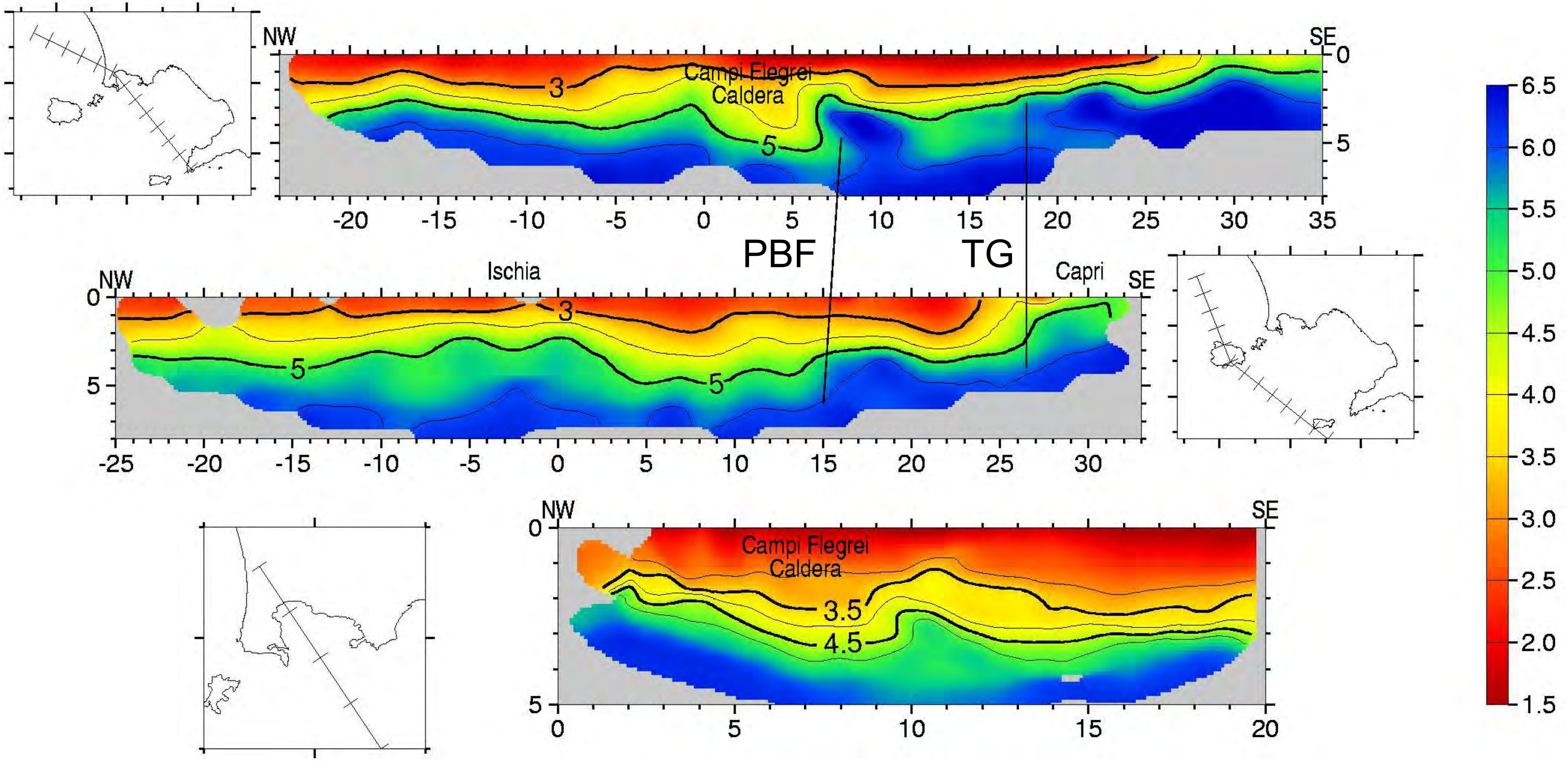


Regional P-velocity model from the 3D travel time tomography



Judenherc, S., Zollo, A., 2004. The Bay of Naples (southern Italy): Constraints on the volcanic structures inferred from a dense seismic survey. JOURNAL OF GEOPHYSICAL RESEARCH-SOLID EARTH 109

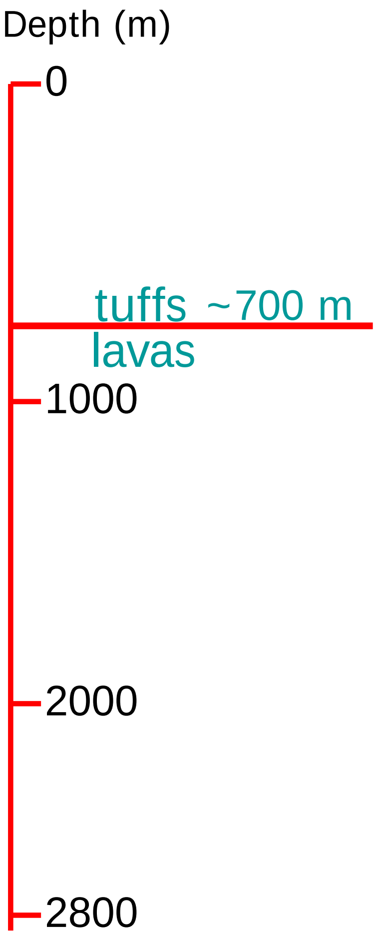
Depth Sections

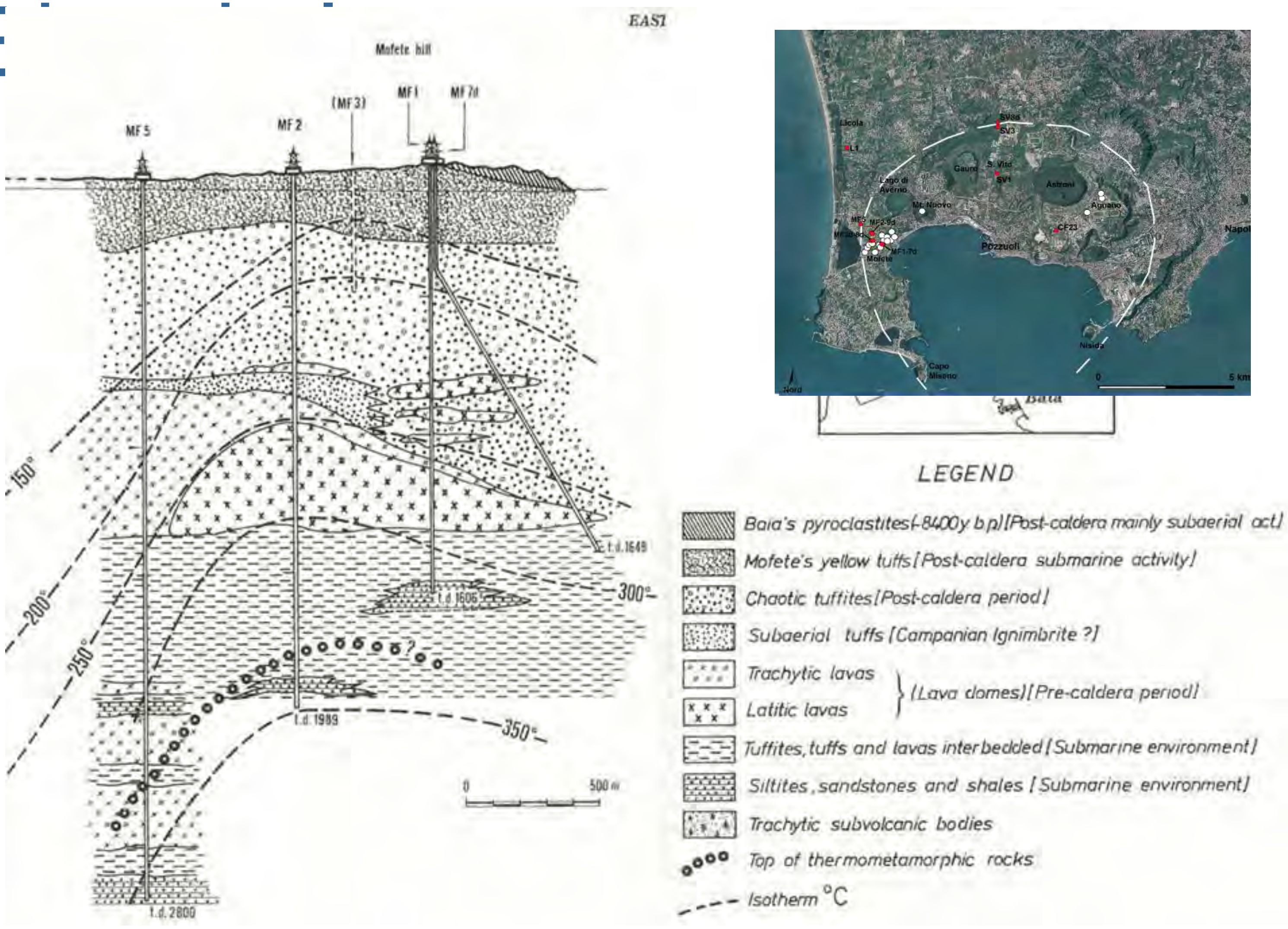


Judenherc, S., Zollo, A., 2004. The Bay of Naples (southern Italy): Constraints on the volcanic structures inferred from a dense seismic survey. JOURNAL OF GEOPHYSICAL RESEARCH-SOLID EARTH 109

Rosi & Sbrana 1987

MOFETE





S. VITO boreholes

Rosi & Sbrana 1987

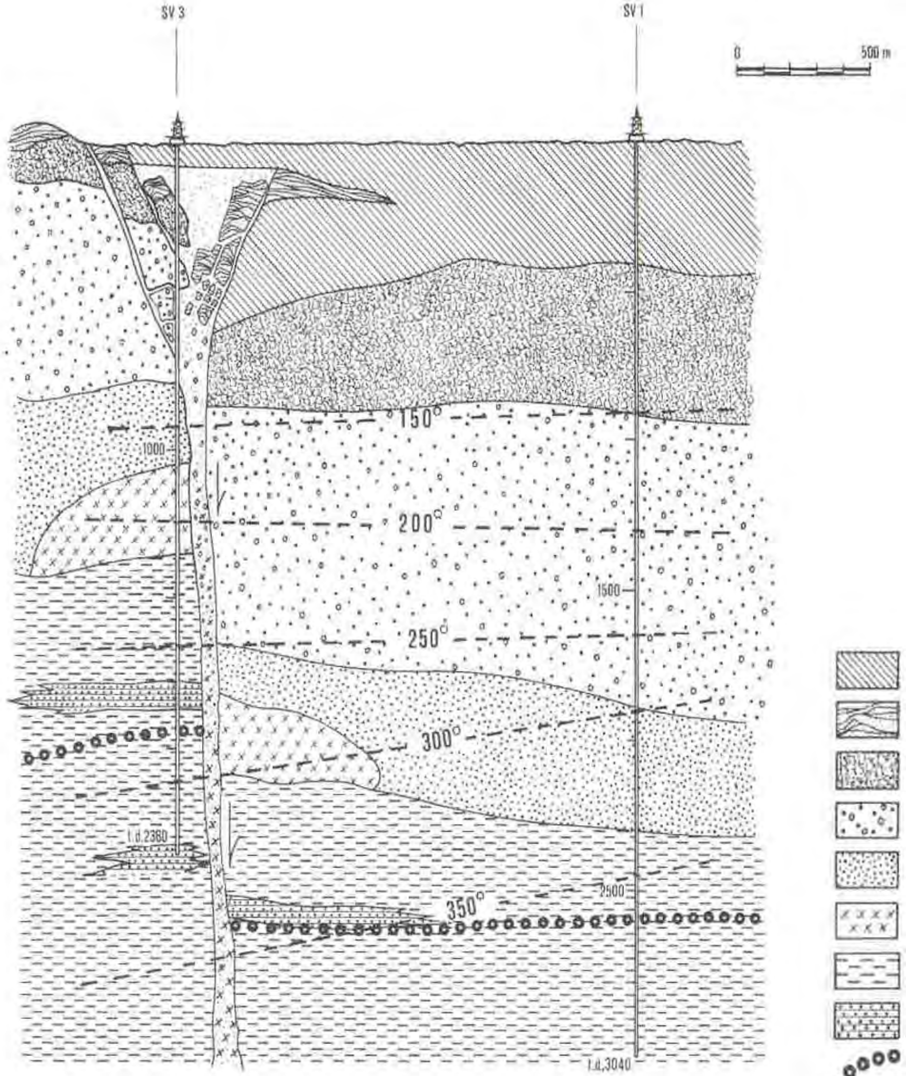
Depth (m)

0

1000

2000

3000

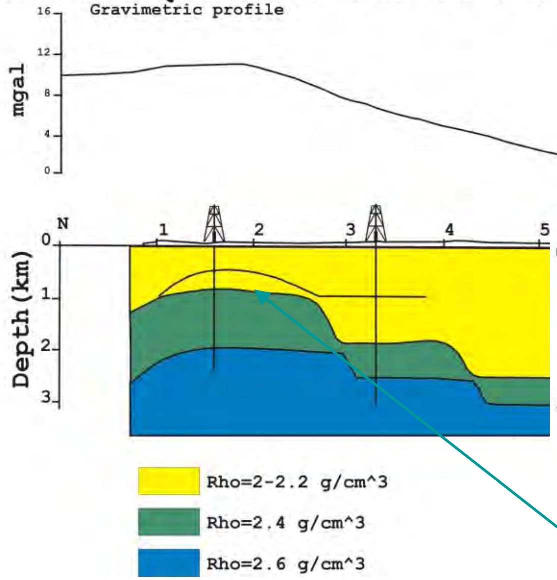


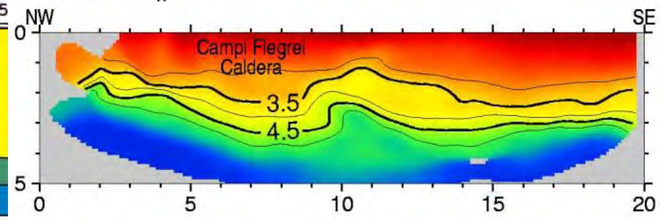
LEGEND

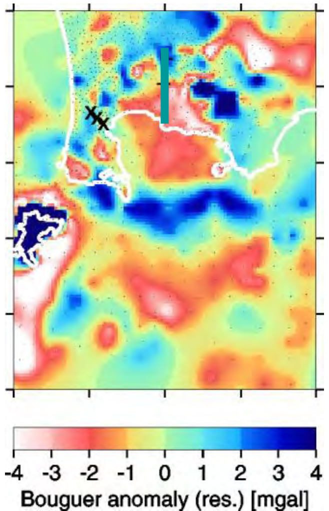
- Incoherent pyroclastic rocks [Post-caldera mainly subaerial act.]
- Latitic scoriae and pumices (M. Spaccata)
- Gauro's yellow tuffs [Post-caldera submarine activity]
- Chaotic tuffites [Post-caldera period]
- Chaotic tuffs [Subaerial environment]
- Trachytic lavas (Lava domes) [Pre-caldera period]
- Tuffites, tuffs and lavas interbedded [Submarine environment]
- Silts and sandstones interbedded [Submarine environment]
- Top of thermometamorphic rocks
- Isotherm °C

S.Vito borehole data

2D gravity modeling in the S.Vito well area(Cassano and La Torre,1987)







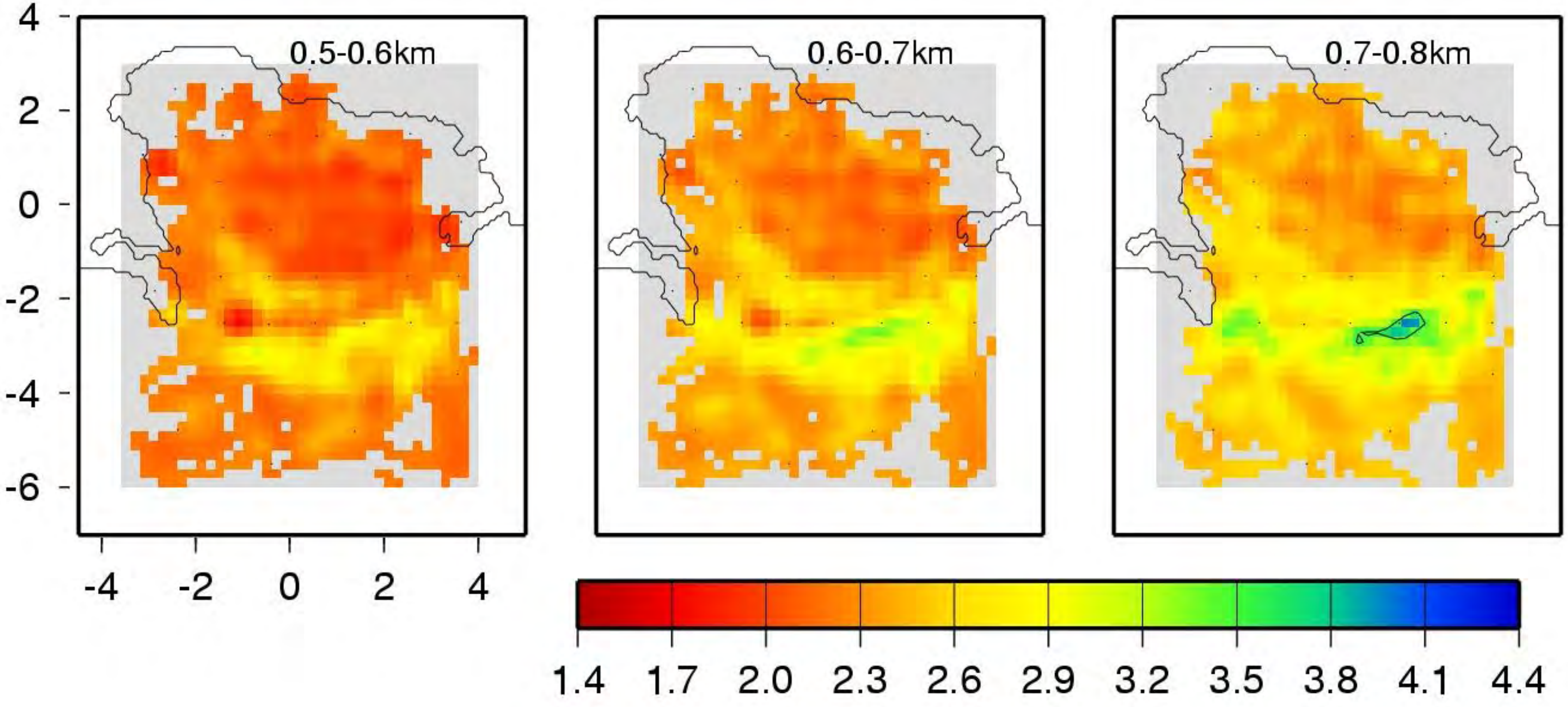
Log stratigraphy

clastic rocks and

nd lava interbedded

P-wave tomography

Complexity at very shallow depths

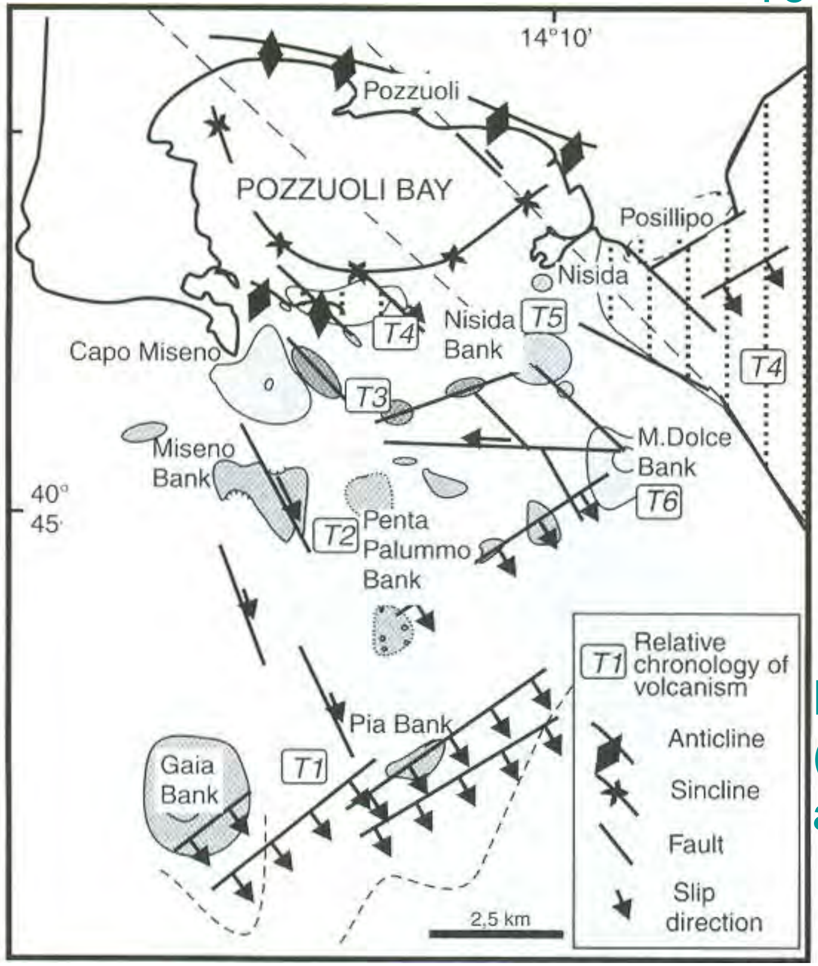


Cell size: 100 x 100 x 100 m^3

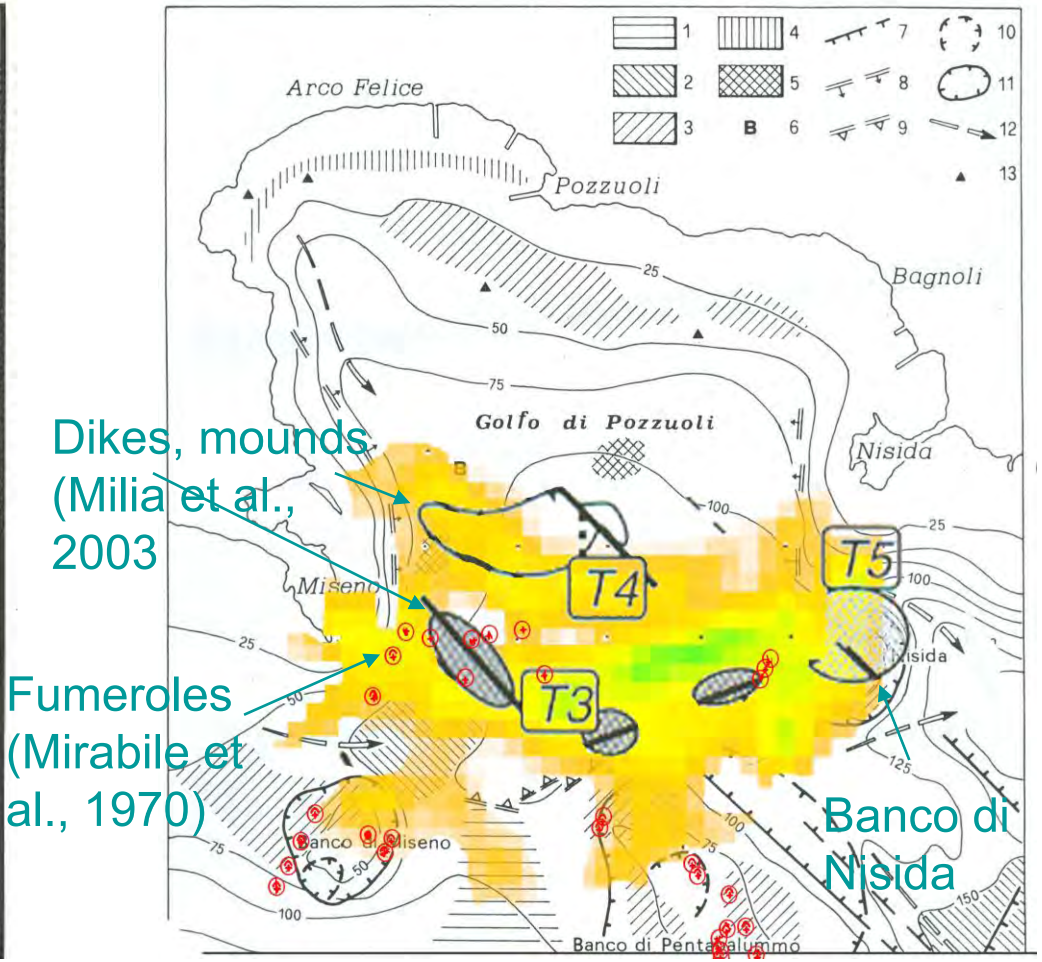
Zollo, Dello Iacono, Judenherc,in preparazione

VHRTomo & shallow seismics

T3= volcanic dikes
T4= mounds (Neap.Grey Tuff erupt.)
T5= Banco di Nisida

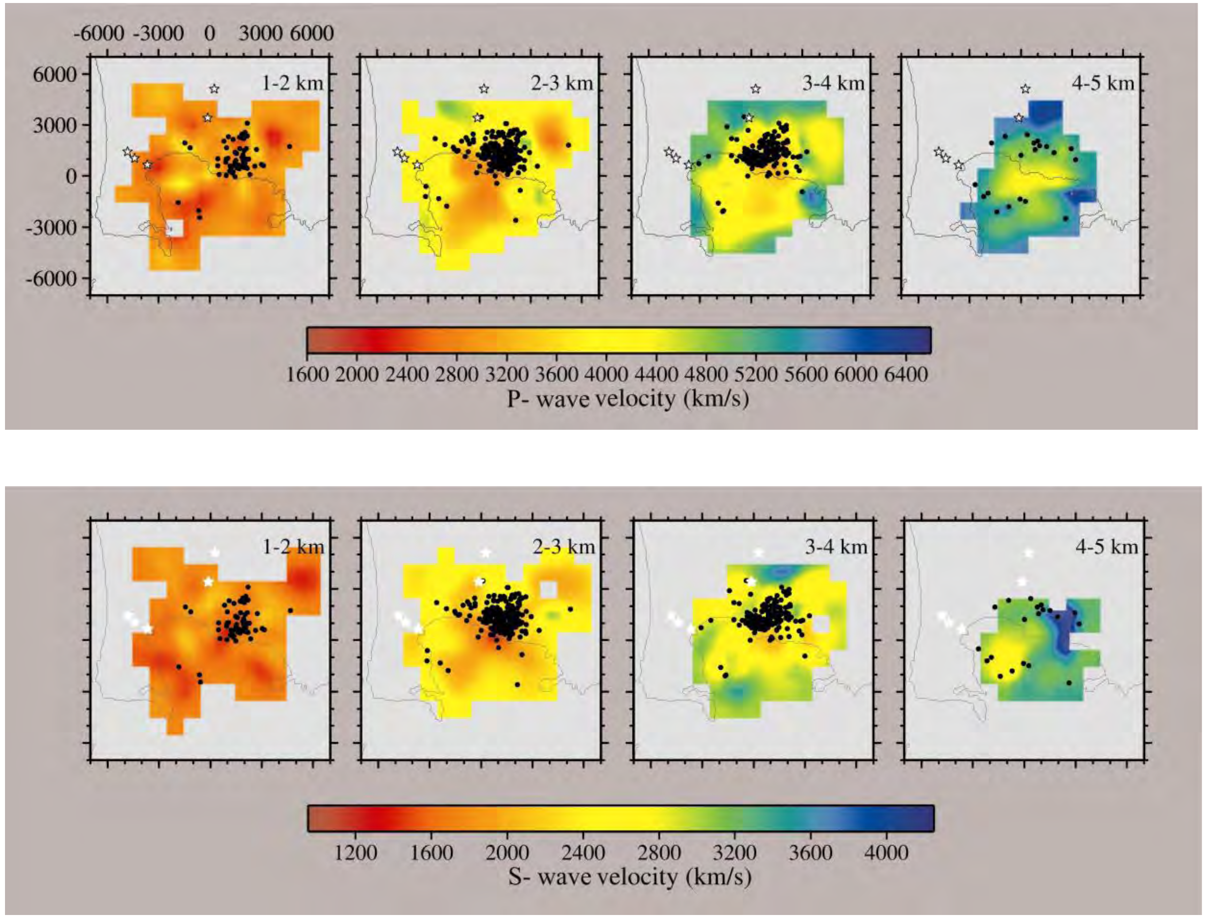


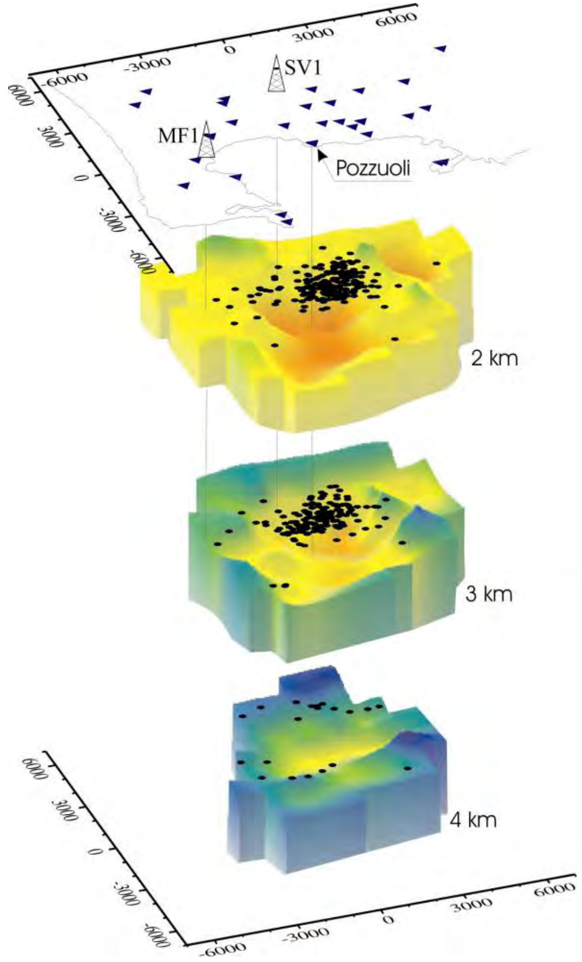
Milia et al. 2003



Modified after De Pippo et al. 1984

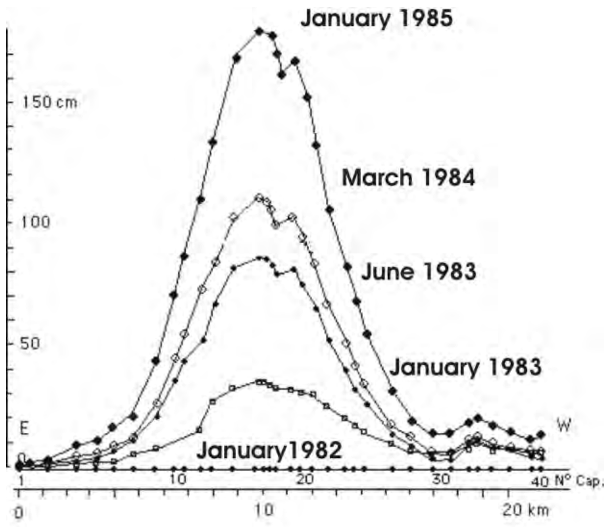
Results: P- and S- velocity Images

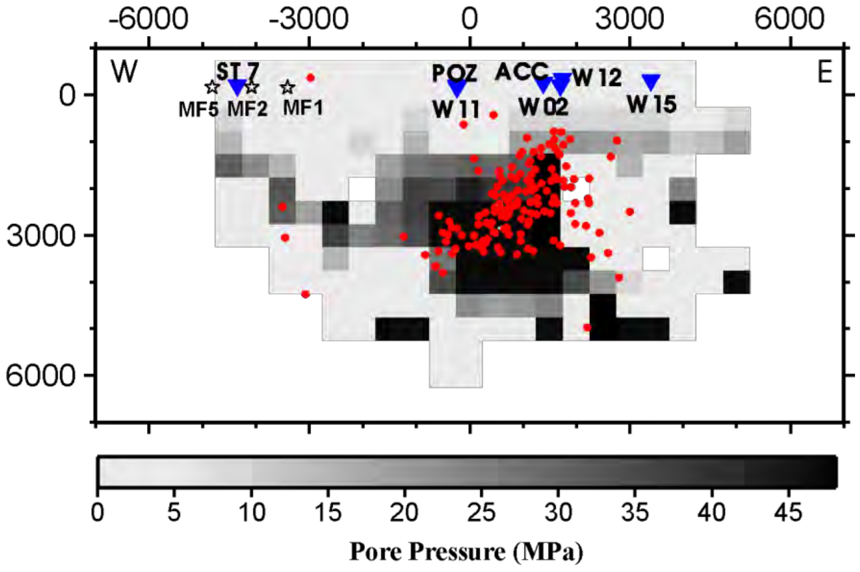




Vanorio et al., JGR, 2004

Inversion of Rock Physics Parameters from Velocity Models





Translation of velocity images into lithology, porosity and pore filling phase images through rock physics effective-medium modeling (Dvorkin et al 1999).

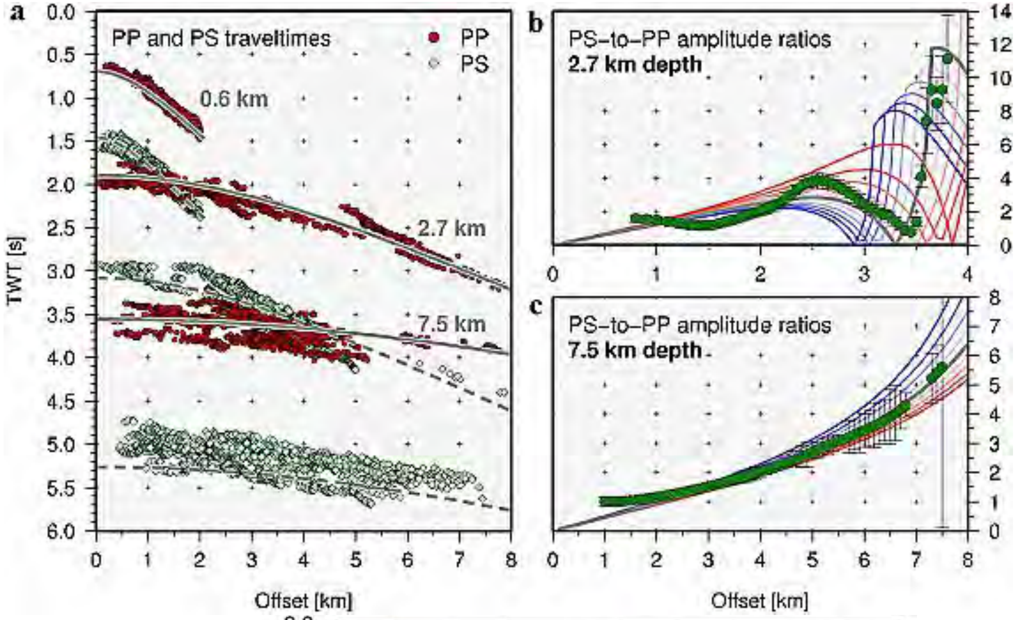
Models require knowledge of both the shear, bulk moduli, and density of the matrix (Hill's formula) and those of fluid phases (pressure and temperature based equations)

The effect of the pore fluid is calculated at different reservoir conditions in the low-frequency domain through the Gassmann's poroelastic theory.

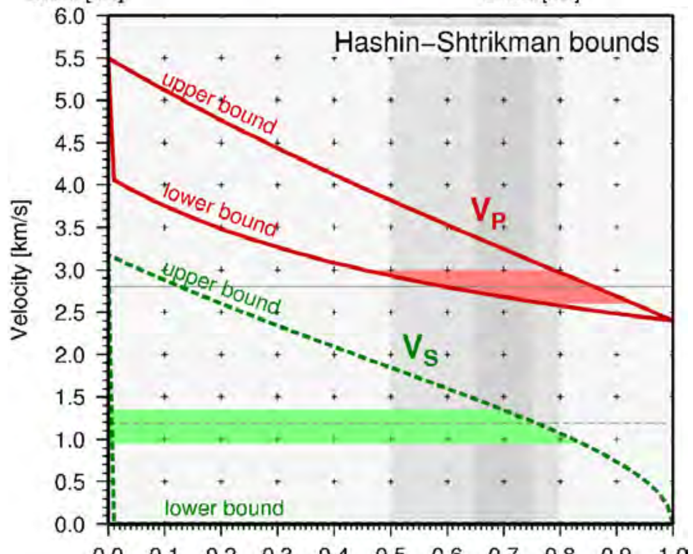
Rock property images are finally determined by minimizing the difference between the tomographic and the modeled velocities through the use of local and semi-global inversion scheme.

Vanorio, Virieux, Latorre 2004, Fall AGU Meeting

Estimated magma velocities and melt fraction



- P-to-S amplitude ratios increase monotonically with offset, as expected for a reflection at a moderate to strong negative P-velocity contrast across the interface
- The theoretical modeling: Vp below the 7,500-m discontinuity around 2,800 m/s i.e., a strong negative Vp contrast with an estimated Vp/Vs increase from 1.65 to 2.35, or to higher values
- These values indicate that the 7,500-m interface is the top of a low velocity layer, whose seismic velocities are consistent with values expected for a magma body set in a densely fractured volume of rock
- Similar values of P- and S-velocities for mid-crustal melts were estimated seismically at the Katla and Grímsvötn volcanoes in Iceland and at the East Pacific Rise

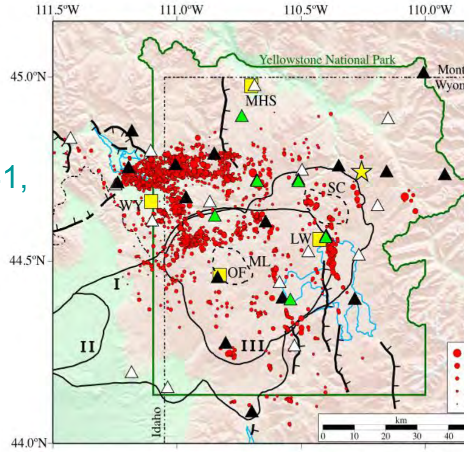


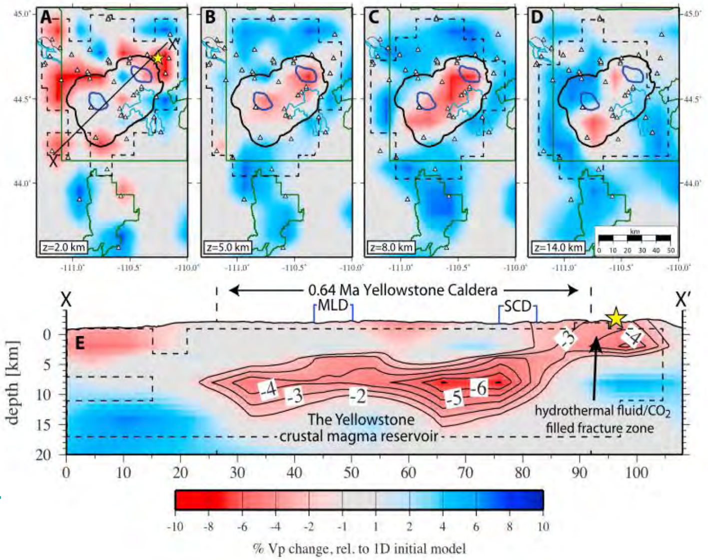
- The melt fraction can be estimated from the measured seismic velocities by computing the Hashin-Shtrikman bounds generalized for a two-phase medium [*Mavko et al.*, 1998],
- We used *Vp* = 5,500 m/s and *Vs* = 3,175 m/s for the solid phase, and *Vp* = 2,400 m/s and *Vs* = 0 m/s for the pure melt, while the density was held constant at ρ = 2,600 kg/m^3. The results indicate the presence of 65%–75% melt directly beneath the reflector.
- However it has been proposed that magmas at depth could glassify in cooler regions generating significant Vs and changing Vp to an unrelaxed value [*Dingwell and Webb*, 1989, 1990].
- The Hashin-Strikman bounds, recalculated with nonzero Vs for the melt, generally leads to a higher percentage of partial melt in the Campi Flegrei melt zone. For instance, using Vp = 2,400–2,600 m/s and Vs = 800–1,000 m/s for the melt, our model suggests the presence of around 80%–90% partial melt (up to 100% possible).

Other evidences for mid-crustal sill-like magmatic reservoirs

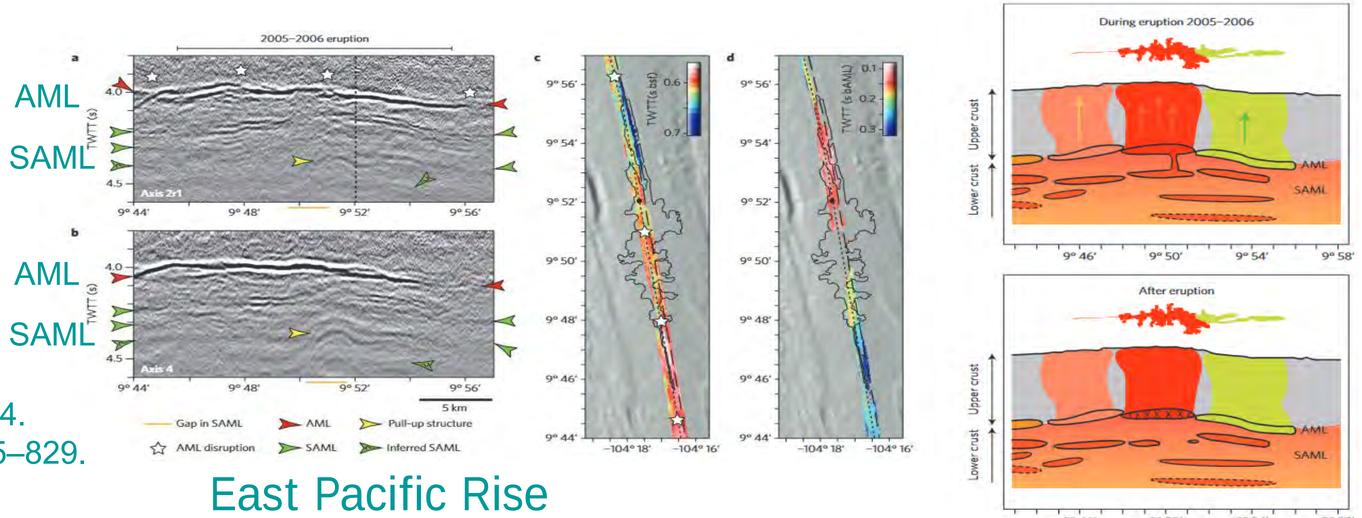
- Socorro magma body at Rio Grande rift, New Mexico, USA
- Yellowstone caldera, USA
- Nikko-Shirane Volcano, Japan
- Mid-crustal sub-Axial Magma Lens (SAML) at the East Pacific Rise

Farrell, et al, 2014, Geophys. Res. Lett. 41, 3068–3073





Yellowstone caldera

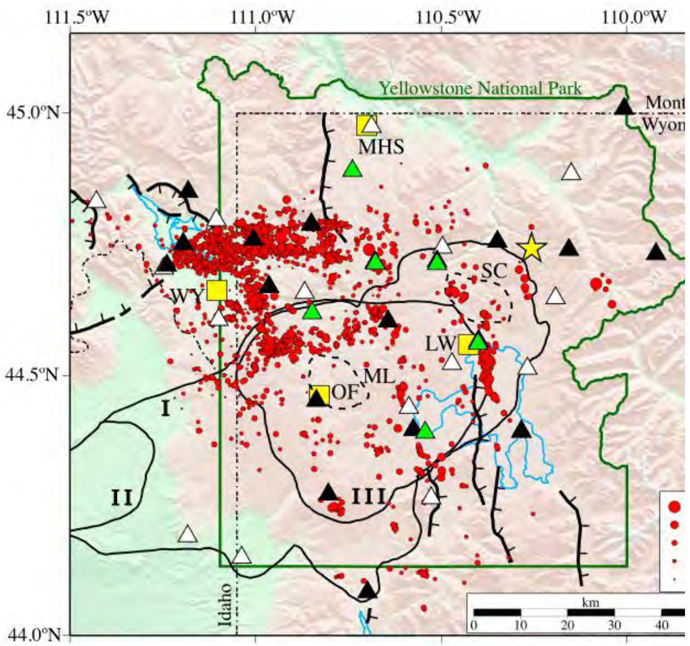


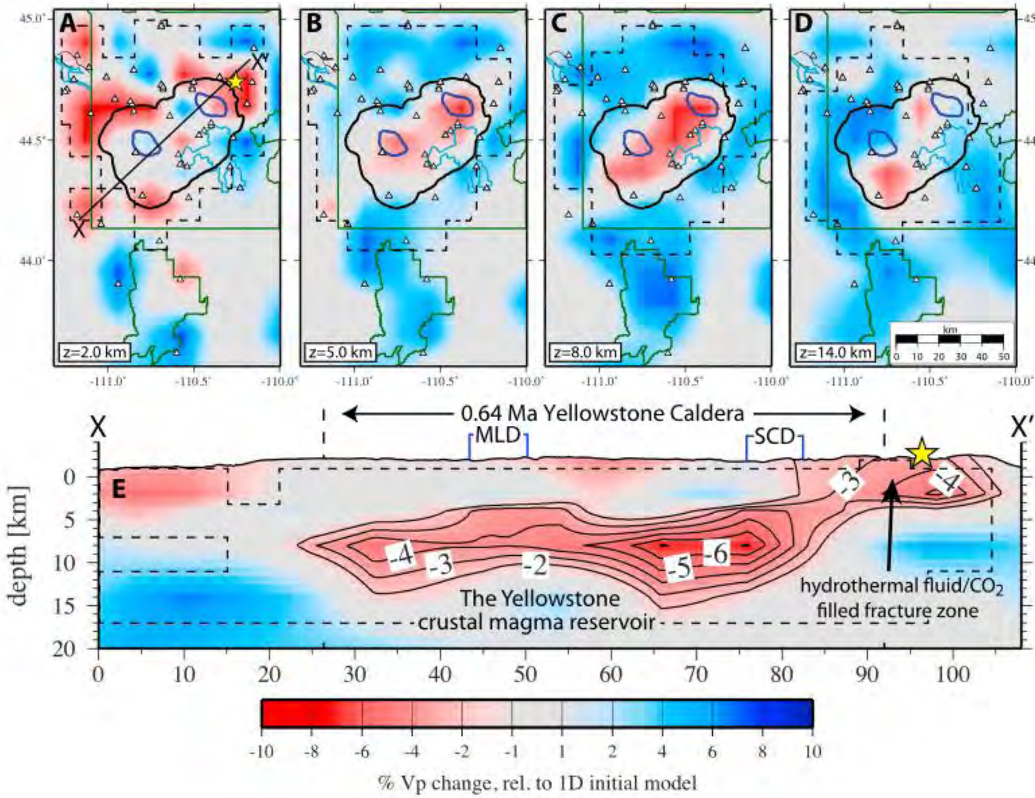
Marjanović, et al,2014. Nature Geosci 7, 825–829.

East Pacific Rise

Yellowstone caldera

- Data from the Yellowstone Seismic Network from 1984 to 2011
- 3-D tomography, P-wave velocity
- A large, low Vp body, interpreted to be the crustal magma reservoir
- The imaged magma body is 90 km long, 5–17 km deep, and 2.5 times larger than previously imaged.

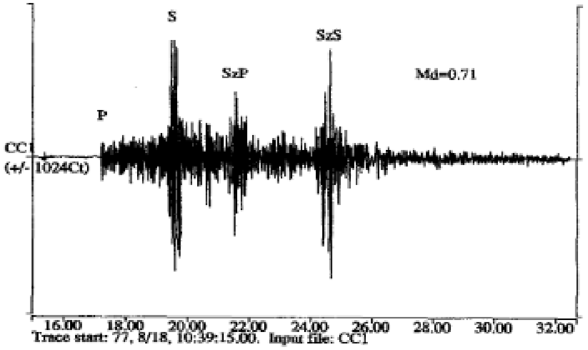


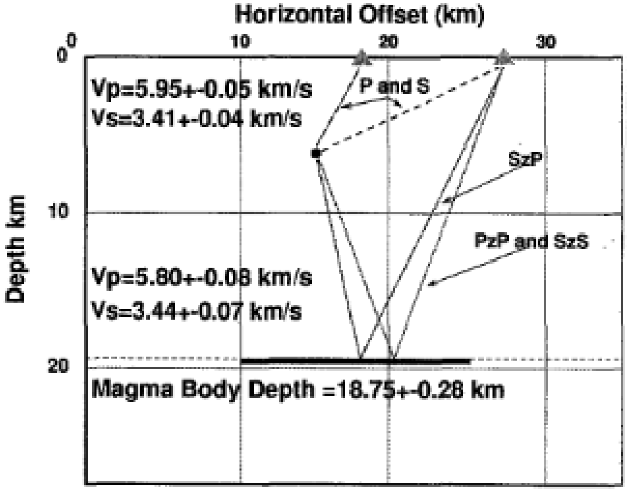


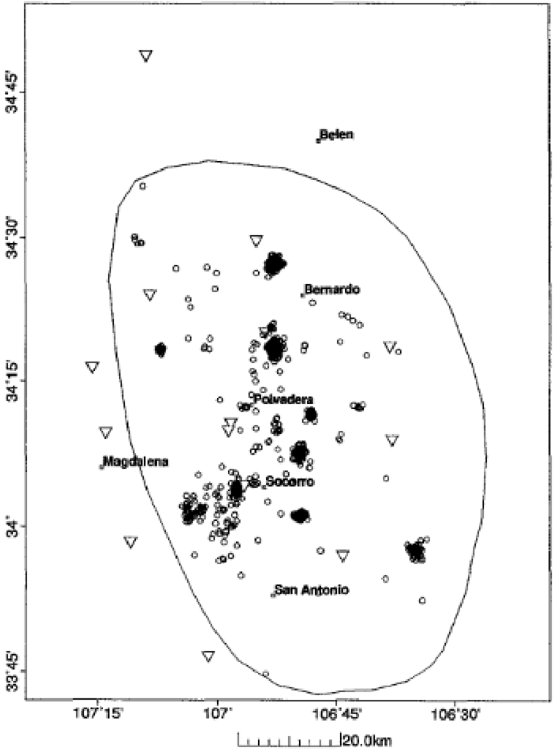
Farrell, J., Smith, R.B., Husen, S., Diehl, T., 2014. Tomography from 26 years of seismicity revealing that the spatial extent of the Yellowstone crustal magma reservoir extends well beyond the Yellowstone caldera. Geophys. Res. Lett. 41, 3068–3073. https://doi.org/10.1002/2014GL059588

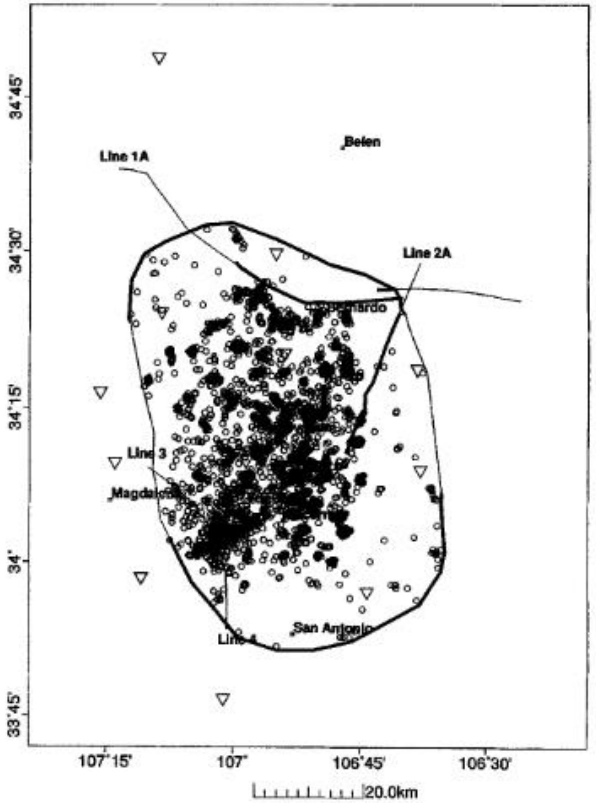
Socorro magma body at Rio Grande rift, New Mexico

- Remapped magma body using PP, SP, and SS reflections on LE record 1975-1995)
- Sill-depth: 18 km
- Area: 3400 km^2 (appr.radius 32 km)



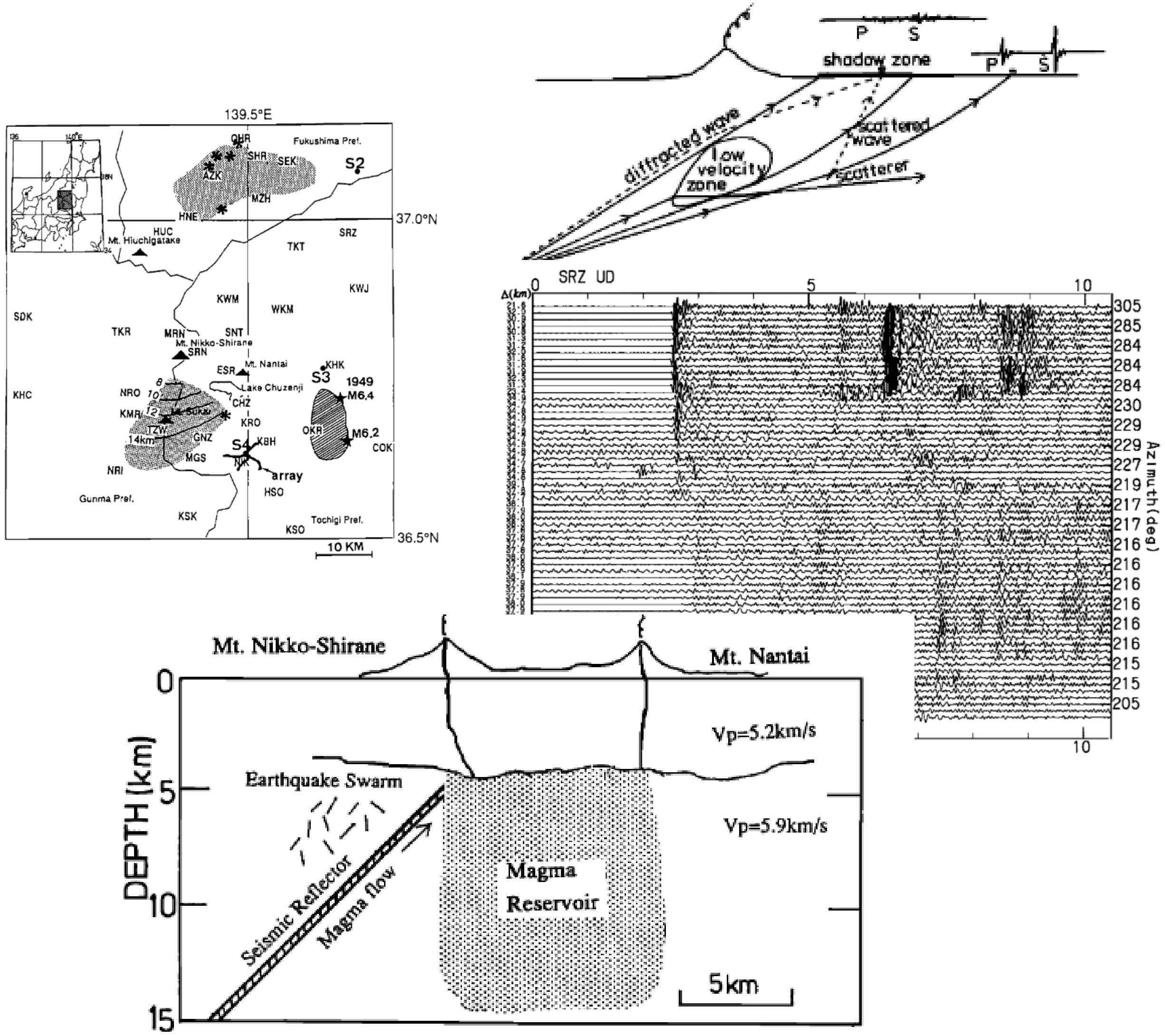






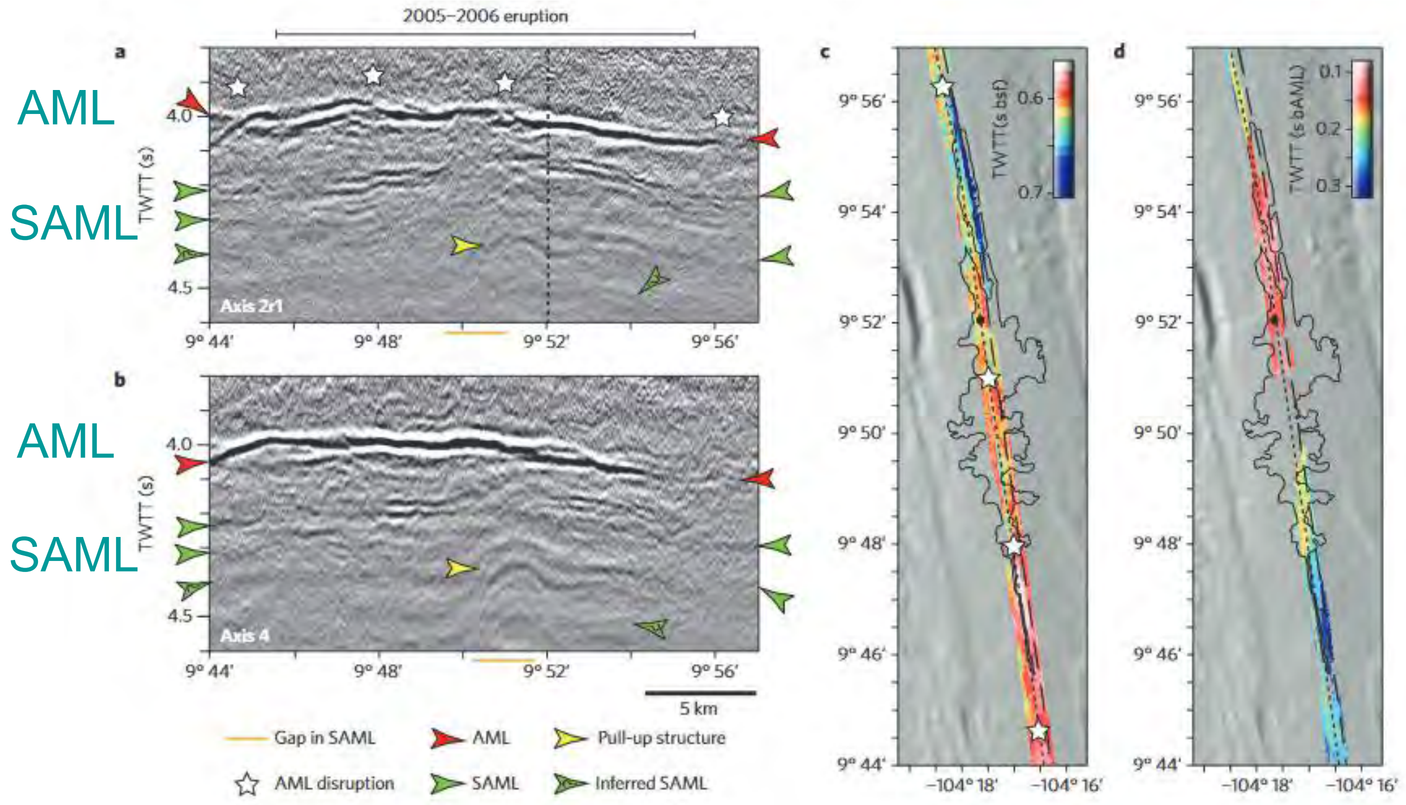
Balch, R.S., Hartse, H.E., Sanford, A.R., Lin, K., 1997. A New Map of the Geographic Extent of the Socorro Mid-Crustal Magma Body. BULLETIN OF THE SEISMOLOGICAL SOCIETY OF AMERICA 87, 174–182.

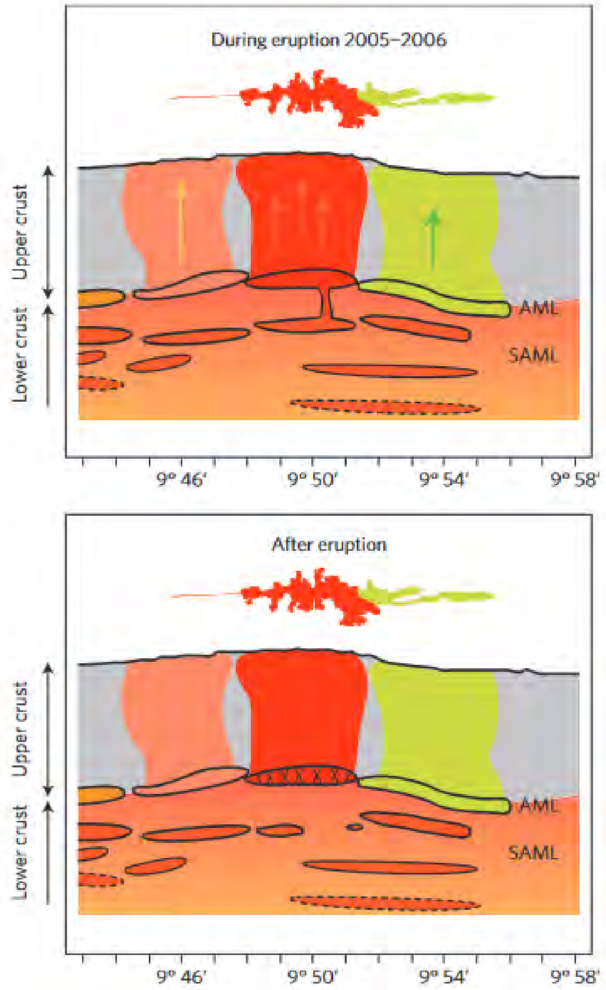
Nikko-Shirane Volcano, Japan



- The magma body beneath Mount Nikko-Shirane volcano causes strong reflections and a wide seismic shadow zone
- The P-to-coda and S-to-coda energy is used to map the location of the attenuating magma body
- the result shows the existence of an anomalous attenuation zone in the area east of Nikko-Shirane volcano with a diameter of about 10 km at depths greater than3 km.

Mid-crustal sub-Axial Magma Lens (SAML) at the East Pacific Rise





Marjanović, M., Carbotte, S.M., Carton, H., Nedimović, M.R., Mutter, J.C., Canales, J.P., 2014. A multi-sill magma plumbing system beneath the axis of the East Pacific Rise. Nature Geosci 7, 825–829. https://doi.org/10.1038/ngeo2272

Prologue

- La premiere rencontre
  - Varenna, 1982
- La vie de laboratorie à l'IPGP
  - Les idees, le collaborations peuvent naitre autor d'une table dans la salle à cafè
- la collaboration scientifique par les article co-authored
  - List of co-authored articles : 22 in 27 years (about 1 article per year, since 1995 to now)
- The cloud-of-words from titles of co-authored papers
  - Seismic, of course
  - Mt Vesuvius, Campi Flegrei Caldera
  - Fluid, fault image, tomography
- Educational Seismology
  - Not publishable
  - EduSeis

The long story of search for the magma chamber beneath Mt Vesuvius and Campi Flegrei volcanoes

- The risk of Neapolitan volcanoes
- The basic question: What is the magma chamber depth, shape and size ?
- Previous knowledge
- Seismic imaging of volcanoes: S&T research developments during the past 40 years

Seismic investigation of the internal structure of Mt. Vesuvius and Campi Flegrei

- A 7-year project of repeated seismic probing of neapolitain volcanoes
- Basic ideas: transfer of knowledge, new approaches and technologies
- Previous information on the volcano structure
- Results from the experiments in 1994,1996 and 1997
  - The shallow structure
  - The mid-crustal magma sill

Seismic exploration of the Campi Flegrei caldera structure

- 2001, Experiment SERAPIS
- Change of the experimental setup: sources airguns at sea, recording at offshore OBS and onshore stations
- Objectives : the shallow structure, the caldera rim at sea, the deep magma chamber
- Results of Serapis:
  - the buried rim of the caldera
  - the gas (CO_2?) reservoir at 3 km depth
  - the magma sill at 8 km depth