GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 19, 2002, doi:10.1029/2003GL018173, 2003

Evidence for the buried rim of Campi Flegrei caldera from 3-d active seismic imaging

A. Zollo,[1] S. Judenherc,[1] E. Auger,[1] L. D'Auria,[1] J. Virieux,[2] P. Capuano,[3]
C. Chiarabba,[4] R. de Franco,[5] J. Makris,[6] A. Michelini,[7] and G. Musacchio[8]

Received 14 July 2003; accepted 14 August 2003; published 10 October 2003.

[1] An extended marine, active seismic survey has been performed on September, 2001 in the gulfs of Naples and Pozzuoli by recording about 5000 shots at a network of 62 sea bottom and 72 on shore seismographs. 3-D images of the shallow caldera structure are obtained from the tomographic inversion of about 77000 first P arrival times using the *Benz et al.* [1996] tomographic technique. 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. According to stratigraphic and sonic log data from deep boreholes and tomographic P velocities, the rim is likely formed by solidified lavas and/or tuffs with interbedded lava. This study confirms the existence for a depressed limestone basement beneath the caldera at less than 4 km depth, while no evidence are found for shallower magmatic bodies. *INDEX TERMS:* 3025 Marine Geology and Geophysics: Marine seismics (0935); 7280 Seismology: Volcano seismology (8419); 8180 Tectonophysics: Tomography. **Citation:** Zollo, A., S. Judenherc, E. Auger, L. D'Auria, J. Virieux, P. Capuano, C. Chiarabba, R. de Franco, J. Makris, A. Michelini, and G. Musacchio, Evidence for the buried rim of Campi Flegrei caldera from 3-d active seismic imaging, *Geophys. Res. Lett.*, *30*(19), 2002, doi:10.1029/2003GL018173, 2003.

1. Introduction

[2] Campi Flegrei is a resurgent caldera located 15 km west of Naples, Southern Italy, inside the Campanian Plain, a graben-like structure at the eastern margin of the Tyrrhenian Sea. The caldera formation is believed to be related to two main explosive eruptions that occurred 37–39 kyears and about 12 kyears ago [*Civetta et al.*, 1997]. In the last ten thousand years, the volcanic activity has been characterized by the occurrence of explosive eruptions with a return period of thousands of years. The most recent eruption occured in 1538, giving rise to an about 130 m, spatter cone.

[3] The caldera floor has been continously sinking with an average speed of about 1 cm per year, from 1538 till 1970. Two resurgency episodes occurred in 1970–1972 and 1982–1984 with a nearly symmetrical, up-lift with a maximum of about 2.5 m at the town of Pozzuoli in the center of the caldera. The ground has subsequently slowly subsided although it remains approximately 1.6 m above pre-1970 levels.

[4] In the recent past the structure of the caldera has been investigated by several 1-to-3 km deep boreholes, local earthquake seismic tomography, gravity and magnetic surveys, as well as sporadic observations of teleseismic and wide angle seismic data [*Rosi and Sbrana*, 1987; *Aster and Meyer*, 1988; *Cassano and La Torre*, 1987; *Ferrucci et al.*, 1992].

[5] Strong temperature gradients have been measured at rather shallow depths (450 degrees at 3 km depth [*Agip*, 1987]. The caldera appears to be filled by a few km thick layer of volcanic deposits, forming an inner basin characterized by low V_p, high V_p/V_s and high P-wave attenuation whose geometry is consistent with the gravity low anomaly [*de Lorenzo et al.*, 2001]. More than 10000 microeartquakes occurred during the 1982–84 ground uplift episode. The relocated seismicity shows that most of events are confined in the low velocity layer with maximum depths of 3–4 km [*Aster and Meyer*, 1988]. The possible occurrence of a magmatic reservoir at about 4–5 km depth is based mainly on extrapolation at depth of temperature data and teleseismic observations [*de Lorenzo et al.*, 2001; *Ferrucci et al.*, 1992].

[6] With the aim to provide new insights on the caldera structure and to investigate its feeding system, a dense and extended active seismic survey was performed during September 2001, in the gulfs of Naples and Pozzuoli in the framework of the SERAPIS project.

[7] The present article describes the results obtained from the 3D tomographic inversion of first P-arrival time data collected during this experiment.

2. Acquisition Lay-out and Data Modeling

[8] During the SERAPIS experiment, seismic signals produced by a battery of 12, 16-liters air-guns mounted on the oceanographic vessel NADIR (IFREMER) were recorded at a dense array of three-component, sea bottom (OBS) and on land seismographs installed in the bays of Naples and Pozzuoli (Figure 1).

[9] Seventy-two, three-component stations were installed on-land in the areas of Campi Flegrei, Mt.Vesuvius and on the islands of Ischia and Procida. Sixty, sea bottom seismographs (OBS) were installed in the gulfs of Naples and Pozzuoli by the University of Hamburg, with the logistic support of private companies Geopro (Germany) and Geolab (Italy). A total number of 5000 shots were fired during

---

[1] Univ. di Napoli "Federico II", Napoli, Italy.
[2] Institut GeoAzur, CNRS, Nice, France.
[3] OV, INGV, Univ. Molise, Isernia, Italy.
[4] CNT, INGV, Roma, Italy.
[5] IDPA, CNR, Milano, Isernia, Italy.
[6] Univ. of Hamburg, Hamburg, Germany.
[7] INOGS, Trieste, Italy.
[8] Sez. PRS, INGV, Milano, Italy.

0094-8276/03/2003GL018173$05.00

the experiment, with an average spacing of 125 m. All of the seismic lines were re-sampled at least twice, using a staggered configuration, which results in a smaller source spacing (less than 65 m).

[10] The picking of about 77000, first P arrivals were performed manually on the pre-processed traces, arranged as common receiver gathers (CRG). The records were band-pass filtered (5–15 Hz), amplitude equalized (AGC window of 1 sec) and plotted in a time reduced scale, using a reduction velocity of 6 km/sec. An automatic, normalized weighting factor was assigned to P-readings, depending on the distance from the source.

[11] The tomographic technique used in this study is described in detail by *Hole* [1992] and *Benz et al.* [1996]. Theoretical travel times are computed by finite difference solution of the eikonal equation [*Podvin and Lecomte*, 1991]. The inversion technique is based on a linearized, perturbative approach, with the use of smoothness constraint equations to regularize the solution and make stable the inversion procedure. This method was previously applied to investigate the Redoubt volcano structure [*Benz et al.*, 1996], Mt.Etna, Italy [*Villaseñor et al.*, 1998], the Kilauea caldera [*Dawson et al.*, 1999] and Mt.Vesuvius [*Scarpa et al.*, 2002].

[12] The observed P-travel times are plotted in Figure 2 (top-left) as a function of distance from the source. The 1-D starting model for the tomographic inversion was determined by the inversion of first P-arrival times using the same code for 3D inversion. The resulting 1-D model shows a sharp velocity gradient with depth in the shallow layer (from about 2 to 6 km/s between 0 and 4 km depth), and nearly constant velocity of 6 km/s at greater depths. The travel time residuals vs distance computed for the 1-D reference model show a scattered distribution around zero, associated with a RMS value of 0.14 sec. The final 3D model provides a variance reduction of 63% with a final RMS of 0.08 sec.

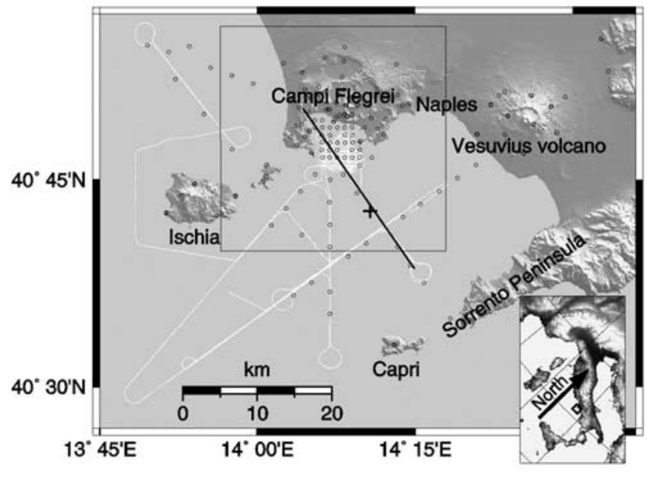

Figure 1. Map of the area investigated during the Serapis exeriment. The square delimitates the region studied in the present article. The white line traces the path of the vessel during the campaign. The open circles display the position of OBS and stations deployed during the experiment. The black segment crossing the Campi Flegrei bay area indicates the length and orientation of the section in Figure 4. The cross is the location of OBS48.

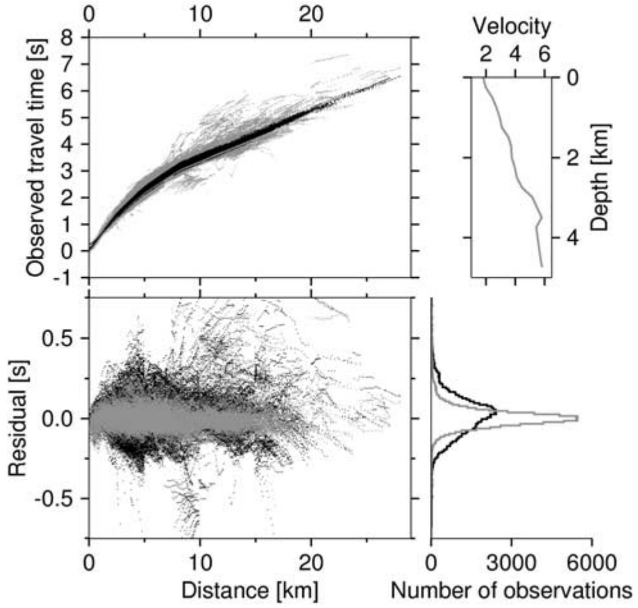

Figure 2. P-travel time data and residuals. *Top-left*. Observed P-arrival times plotted vs distance from the source (gray dots). The theoretical P-arrival times in the retrieved 1-D reference velocity model are shown (black dots). The latter do not align along a single line (as expected for a flat-layered model) due to the lateral variation of the sea bottom depth in the source area. *Top-right*. The reference 1-D P-velocity model used for the 3-D tomographic inversion. *Bottom-left*. P-arrival time residuals vs distance computed for the initial 1D model (black dots) and for the final 3D model (gray dots). *Bottom-right*. Residual histograms for the 1-D (gray line) and 3-D model (black line).

[13] The investigated volume covers a region of about 30×30 km^2 around the bay of Pozzuoli (see Figure 1) and extends to a depth of 5 km. The medium was parametrized using an uniform grid of constant-slowness cells. Several travel time inversion runs were performed using different cell sizes (250 m, 500 m and 1000 m), because the model resolution is expected to be spatially variable due to the acquisition lay-out and the heterogeneities of the 3D velocity structure. With the aim of investigating the spatial resolution of the inferred 3-D model, a number of synthetic tests (checker-board) were performed *a posteriori* using different resolution lengths (e.g., supplemental material[1]). These tests indicate that we are able to accurately retrieve the shape, amplitude, and location of anomalous bodies (1–2 km dominant wavelength) within the upper 2 km. At greater depths, down to 3.5 km, the resolution decreases but we are still able to retrieve 4–6 km wavelength anomalies.

3. 3-D Images of the Caldera Structure

[14] The tomographic images of the Campi Flegrei caldera structure are shown in Figure 3a, b, c at different depths and in the depth section view of Figure 4. The most prominent feature is the presence of an arc-like, high P-velocity anomaly (V_P = 3.5–4.0 km/s) delineating the

---

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL018173.

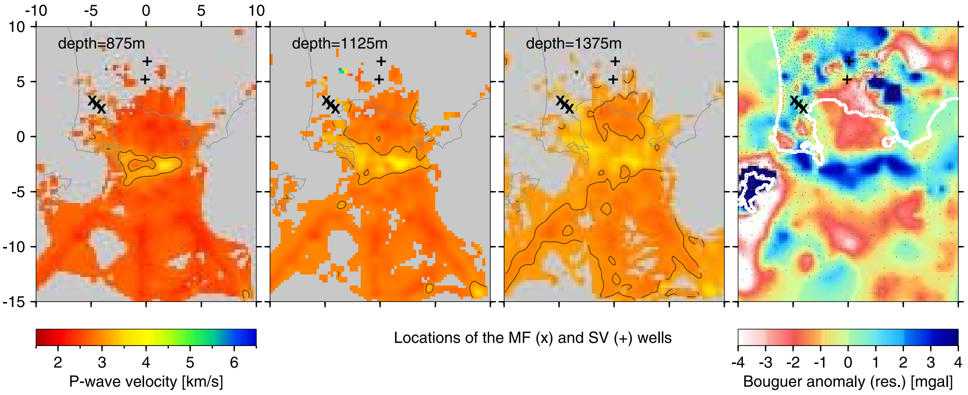

Figure 3. P-velocity and Bouguer gravity anomaly images. The tomographic P-velocity images are displayed from the left to the right at three different depths (875 m, 1125 m and 1375 m). Symbols "+" and "×" indicate the location of S.Vito and Mofete wells respectively, drilled by AGIP on late seventies for geothermal exploration purposes. The low-pass filtered map of Bouguer gravity anomaly (reduction density: 2.4 g/cm^3) is shown at left.

southern border of the gulf of Pozzuoli. It follows a pattern nearly concentric to the coastal line. The top of this body is at about 800 m depth and extends down to about 2000 m depth.

[15] Recently *Berrino et al.* [1998] extended at sea the gravity measurements in the Campi Flegrei area, perfomed by AGIP in early eighties. Gravity data have been re-processed and integrated to the existing data set by *Capuano and Achauer* [2003] who provided an updated Bouguer anomaly map (reduction density: 2400 Kg/m^3). The high pass (λ_{min} = 10 km) filtered map of Bouguer anomalies shows a positive, nearly circular anomaly delimiting the inner caldera (Figure 3d). The shape of the positive gravity anomaly closely matches the high P-velocity anomaly inferred from 3D seismic tomography. Its location and anular shape indicate it represents the image of the buried caldera rim.

[16] Litho-stratigrafic and sonic log data from five, 2–3 km deep boreholes drilled for geothermal exploration purposes on the land side of caldera (Figure 3) indicate that the caldera rim is formed by a sequence of compacted tuffs, tuffs with interbedded lavas and thermometamorphic rocks, the latter of which are encountered at about 2–2.5 km depth. P-wave, log velocities show a variation with depth (2.7–3 km/s at 0.8–1 km depth, 3.6–4.2 km/s at 2–2.2 km depth) [*Agip*, 1987] which is consistent with tomographic velocities in the same depth range.

[17] Figure 4 illustrates the effect of the high velocity anomaly on the recorded seismic waveforms. The time reduced CRG section for OBS 48 located at a distance of 20 km on Figure 4) clearly shows the anticipation of the first-P arrival times (green arrow) moving toward Campi Flegrei bay area (from 13 to 8 km distance in Figure 4). At offsets greater than 4–5 km the first arriving phases on almost all the seismic sections are wide-angle head waves. According to previous active seismic studies in this area, these phases propagate along the top of the Mesozoic limestone basement, underlying the volcanic and alluvium sedimentary sequences filling the whole Campanian Plain [*Finetti and Morelli*, 1974; *Fusi*, 1996; *Bruno et al.*, 1998; *Zollo et al.*, 2002]. The head wave travel times decrease linearly with offset approaching the bay area, along the SE-NW direction (Figure 4). Wide-angle refracted arrivals constrain the basement top discontinuity inside the bay area, detected on tomographic images at about 4 km depth. This evidence is also confirmed by the systematic observation inside the bay area of a prominent secondary arrival on different azimuth seismic sections, whose trend with distance matches the wide-angle, head wave arrival time pattern outside the Campi Flegrei bay area (e.g., blue arrow phase in Figure 4b).

4. Conclusions

[18] Campi Flegrei is an active resurgent caldera which has experienced repeated collapse and resurgent phenomena associated with large size eruptions in the last 40000 years. Surface geological observations led to its identification as a nested caldera, formed by subsequent collapse episodes [*Rosi and Sbrana*, 1987; *Orsi et al.*, 1996]. The present tomographic study reveals the existence of a single, buried caldera rim which is characterized by high P-velocity, high density rocks and it has an anular shape, nearly concentric

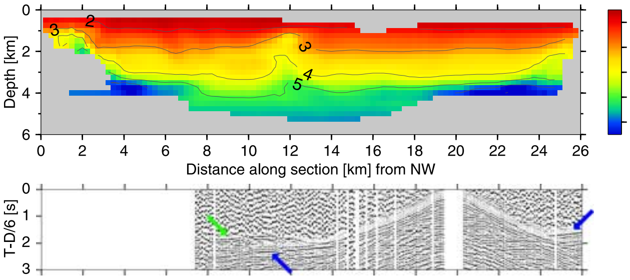

Figure 4. P-velocity depth section in the Campi Flegrei bay area. *Top*. Depth section of the P-velocity model along the direction indicated in Figure 1. *Bottom*. Common receiver seismic section for receiver OBS48, whose location in reported on Figure 1. In correspondance of the bay' entry, the early arrival of first P-waves (green arrow) can be related to the presence of the high velocity caldera rim, which acts like a diffracting body by deflecting upward the turning waves propagating in the surficial sedimentary layer. The blue arrow points to the head wave arrival generated at the limestone top discontinuity.

to the bay coast line. Borehole data indicate that the relatively high P velocities (3.5–4.5 km/s) of the caldera rim can be attributed to the presence of consolidated lava and/or tuffs with interbedded lava sequences and, at greater depth, to the occurrence of thermometamorphic rock formations. High temperature gradients have been measured in boreholes, which have been drilled along the positive gravity anomaly zone on land [*Agip*, 1987]. In addition, *de Lorenzo et al.* [2001] found evidence for a low Qp - high temperature anomaly between 2 and 3 km depth, occurring along the eastern, land side sector, of the found caldera rim. All these observations consistently suggest that the imaged caldera rim can be the site where intense fracturing phenomena occurred during caldera collapses and resurgencies, thus representing a preferential path for magma to intrude toward the surface during past eruptions. The evidence for the more recent (10000 y.b.p.) eruptive vents, occurring along or nearby the land rim sector strongly supports this hypothesis.

[19] No evidence for magma bodies with volume larger than 1 km^3 underneath the Campi Flegrei caldera is found by 3D seismic imaging down to 4–5 km depth. The tomographic images and the analysis of secondary head wave arrivals on seismograms reveal the existence of the Mesozoic limestone top discontinuity at about 4 km depth, beneath the caldera. This result confirm and corroborates the sparse observations obtained by previous seismic reflection soundings in the area [*Finetti and Morelli*, 1974]. This implies that the magma reservoir, feeding the Campi Flegrei volcanic system, has to be located deeper, well within the carbonate basement formation.

[20] **Acknowledgments.** We thank Paolo Gasparini for his comments and suggestions on the early version of the ms. L. Boschi and C. Satriano contributed to the data processing and picking. The french company Ifremer made available the vessel Nadir and its crew for the Serapis experiment. M. Noble assumed the ungrateful but essential charge of head of mission on board. Reviews by D. Hill and an anonymous reviewer helped to improve the clarity of the ms. This work has been funded by GNV-INGV (FP2000-2003) and Department of Civil Protection.

References

Agip, *Geologia e Geofisica Del Sistema Geotermico Dei Campi Flegrei.*, Servizi Centrali per l'Esplorazione, SERG-MMESG, San Donato, 1987.

Aster, R., and R. P. Meyer, Three-dimensional velocity structure and hypocenter distribution in the Campi Flegrei caldera, Italy, *Tectonophysics*, *149*, 195–218, 1988.

Benz, H. M., B. Chouet, P. B. Dawson, J. C. Lahr, R. A. Page, and J. A. Hole, Three-dimensional P and S wave velocity structure of Redoubt volcano, Alaska, *J. Geophys. Res.*, *101*, 8111–8182, 1996.

Berrino, G., G. Corrado, and U. Riccardi, Sea gravity data in the Gulf of Naples: A contribution to delineating the structural pattern of the Vesuvian area, *J. Geophys. Res.*, *82*, 139–150, 1998.

Bruno, P. G., G. Cippitelli, and A. Rapolla, Seismic study of the mesozoic carbonate basement around Mt. Somma-Vesuvius, Italy, *J. Geotherm. Volc. Res.*, *84*, 311–322, 1998.

Capuano, P., and U. Achauer, Gravity field modeling in the vesuvius and campanian area, in *The TomoVes Seismic Project: Looking Inside Mt. Vesuvius*, edited by A. Zollo et al., Cuen, Napoli, 2003.

Cassano, E., and P. La Torre, Geophysics, in *Somma-Vesuvius*, *CNR Editions*, Vol. 114, edited by R. Santacroce, pp. 175–196, Rome, 1987.

Civetta, L., G. Orsi, L. Pappalardo, R. V. Fisher, G. Heiken, and M. Ort, Geochemical zoning, mingling, eruptive dynamics and depositional processes-the campanian ignimbrite, Campi Flegrei caldera, *J. Volcanol. Geoth. Res.*, *75*, 183–219, 1997.

Dawson, P. B., B. A. Chouet, P. G. Okubo, A. Villaseñor, and H. M. Benz, Three-dimensional velocity structure of the Kilauea caldera, Hawaii, *Geophys. Res. Lett.*, *26*(18), 2805–2808, 1999.

De Lorenzo, S., A. Zollo, and F. Mongelli, Source parameters and three-dimensional attenuation structure from the inversion of microearthquakes pulse width data: Qp imaging and inferences on the thermal state of the Campi Flegrei caldera (Southern Italy), *J. Geophys. Res.*, *106*(B8), 16,265–16,286, 2001.

Ferrucci, F., A. Hirn, J. Virieux, G. De Natale, and L. Mirabile, P-sv conversions at a shallow boundary beneath Campi Flegrei caldera (Naples, Italy): Evidence for the magma chamber, *J. Geophys. Res.*, *97*(B11), 351–359, 1992.

Finetti, I., and C. Morelli, Esplorazione sismica a riflessione dei golfi di napoli e pozzuoli, *Boll. Geofis. Teor. Appl.*, *16*, 122–175, 1974.

Fusi, N., Structural settings of the carbonate 'basement' and its relationship with the magma uprising in the Gulf of Naples (Southern Italy), *Ann. Geofis.*, *39*, 493–509, 1996.

Hole, J. A., Nonlinear high-resolution three-dimensional seismic wave travel time Tomography, *J. Geophys. Res.*, *97*, 6553–6562, 1992.

Orsi, G., S. De Vita, and M. Di Vito, The restless, resurgent Campi Flegrei nested caldera (Italy): Constraints on its evolution and configuration, *J. Volc. Geotherm. Res.*, *74*, 179–214, 1996.

Podvin, P., and I. Lecomte, Finite difference computation of traveltimes in very contrasted velocity models: A massively parallel approach and its associated tools, *Geophys. J. Int.*, *105*, 271–284, 1991.

Rosi, M., and A. Sbrana, Phlegraean Fields, in *Somma-Vesuvius*, *CNR Editions*, Vol. 114, edited by R. Santacroce, pp. 1–175, Rome, 1987.

Scarpa, R., F. Tronca, F. Bianco, and E. Del Pezzo, High resolution velocity structure beneath Mount Vesuvius from seismic array data, *Geophys. Res. Lett.*, *29*(21), 2040, doi:10.1029/2002GL015576, 2002.

Villaseñor, A., H. M. Benz, L. Filippi, G. De Luca, R. Scarpa, G. Patané, and S. Vinciguerra, Three-dimensional P wave velocity structure of Mt. Etna, Italy, *Geophys. Res. Lett.*, *25*(11), 1975–1978, 1998.

Zollo, A., L. D'Auria, R. De Matteis, A. Herrero, J. Virieux, and P. Gasparini, Bayesian estimation of 2-D P-velocity models from active seismic arrival time data: Imaging of the shallow structure of Mt. Vesuvius (Southern Italy), *Geophys. J. Int.*, *151*, 566–582, 2002.

Zollo, A., J. Virieux, and J. Makris, et al., High resolution seismic imaging of the Campi Flegrei caldera, Southern Italy, *Eos Trans. AGU*, *83*(47), 2002.

E. Auger, L. D'Auria, S. Judenherc, and A. Zollo, Dipartimento di Scienze Fisiche, Università di Napoli "Federico II", Napoli, Italy. (aldo.zorro@na.infn.it)

P. Capuano, Univ. Molise, Isernia, Italy.

C. Chiarabba, CNT, INGV, Roma, Italy.

R. de Franco, IDPA, CNR, Milano, Isernia, Italy.

J. Makris, Univ. of Hamburg, Hamburg, Germany.

A. Michelini, INOGS, Trieste, Italy.

G. Musacchio, Sez. PRS, INGV, Milano, Italy.

J. Virieux, Institut GeoAzur, CNRS, Nice, France.