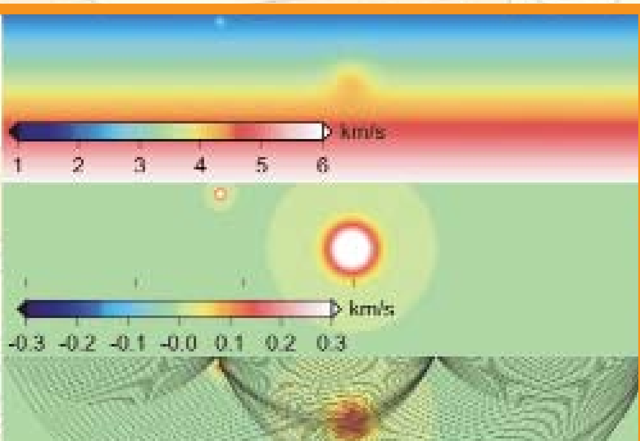
Warner Marzocchi and Aldo Zollo (Editors)

Conception, verification and application of innovative techniques to study active volcanoes

Istituto Nazionale di Geofisica e Vulcanologia

Dipartimento della Protezione Civile



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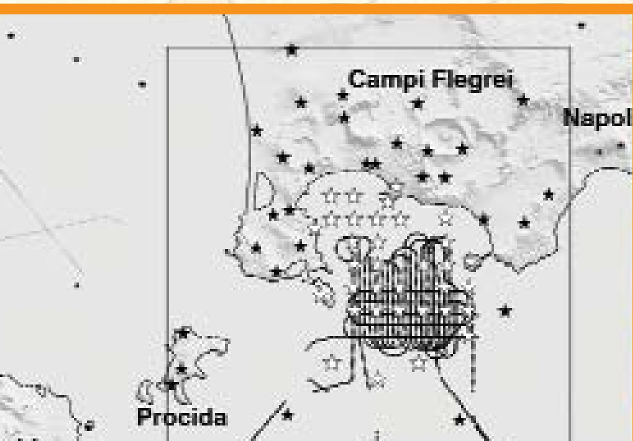

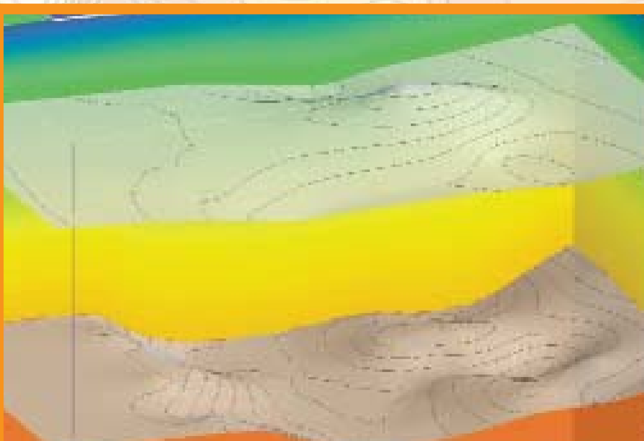

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A unified 3D velocity model for the Neapolitan volcanic areas

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Introduction

One of the main issues in seismic monitoring of active volcanic areas is the accurate location of earthquake hypocenters. Volcano-tectonic seismicity is often characterized by small magnitude swarms, recorded by few seismic stations with a high picking uncertainty. Sometimes events lacks clear S-wave arrivals, due to the nature of some volcanic sources. All these features, together with the complex crustal structure of volcanoes, makes the earthquake location problem critical in such areas.
One of the most important effort for improving the quality of hypocenter location is the use of realistic 3D velocity models. In the last 10 years, several scientific papers proposed 2D and 3D velocity models for Mt. Vesuvius, Campi Flegrei and the Gulf of Naples. They comes from both active seismic data (VESUVIO 94, TOMOVES 96, MAREVES 97 and SERAPIS 2001 experiments) and from local earthquake tomography.
In this report we propose a global unified velocity model spanning from Ischia island to Appennine Mts. that allows us to locate earthquakes in the Neapolitan volcanic areas and in the Gulf of Naples. This model comes from a weighted averaging of 5 tomographic velocity models and a background regional model. Most of the model provides only P-wave velocities, only 2 models, obtained through local earthquake tomography at Mt. Vesuvius and Campi Flegrei also gives a S-wave velocity estimate.
We show the difference between this new model and the previous 1D models adopted for routine locations at INGV-Osservatorio Vesuviano. We also relocate some events, using non-linear techniques showing differences in hypocenter position from previous locations and the improvement in final traveltime residuals and location uncertainties.

Starting velocity models

We selected 5 velocity model, from existing literature, choosing among the most recent papers the ones using the highest number of data. Numerical data have been kindly provided us by the authors. In the following we describe the characteristics of each model, ordered by date of publication.

The regional background (Improta et al., 2000)

The Neapolitan volcanic region lies close to the Appennine chain. This region is characterized by complex crustal structures due to the tectonic evolution of the area [Improta2000]. For this region a simple 1D model for the whole area is unrealistic. [Improta2000] proposed simplified 1D velocity models for the Sannio region (North of Naples) and the Irpinia region (South of Naples) (Figure 1). We interpolated these two models for obtaining a pseudo-2D velocity model for the eastern side of the considered area. No such detailed models exists for the western side of the Neapolitan region.

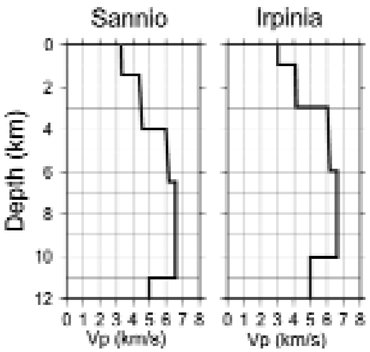

Fig. 1. 1D P-wave velocity models for Sannio and Irpinia regions. Redrawn from Improta et al., 2000.

The TOMOVES model (Lomax et al., 2001)

This model comes from the interpolation of 5 2D tomographic velocity models [Lomax2001] obtained through non-linear traveltime inversion of active seismic data [Zollo2002].
A first preliminary dataset was recorded in the "Vesuvio 94" experiment, when 3 shots where recorded by 80 seismographic stations deployed along a 30 km long profile. In 1996 a wider experiment: "TOMOVES 96" was performed. It consisted of 14 on-land shots recorded by 140 seismographic stations deployed along 4 profiles from 25 to 40 km long.
The 2D velocity models were obtained from the inversion of traveltimes observed along each profile, generated by shots located along the profile itself. P-wave velocity models have a spatial resolution of about 1 km and the maximum depth of the model is 5 km [Zollo2002]. [Lomax2001] performed a

radial interpolation of the 5 2D models of [Zollo2002]. The velocity model proposed in that paper consists of a grid having a volume of 24x24x10 km^3 and a spacing of 250 m. The model considers only P-wave velocities. The authors propose an average value of 1.9 for the Vp/Vs ratio.
The isosurface of about 5500 m/s velocity marks the depth of the carbonatic "basement" in the Vesuvius area. It shows a global decreasing trends toward the Gulf of Naples and a depression North of Vesuvius (Acerra depression). The central area of Vesuvius shows a high P-wave anomaly (Figure 2), interpreted by [Zollo2002] as a solified magma body.

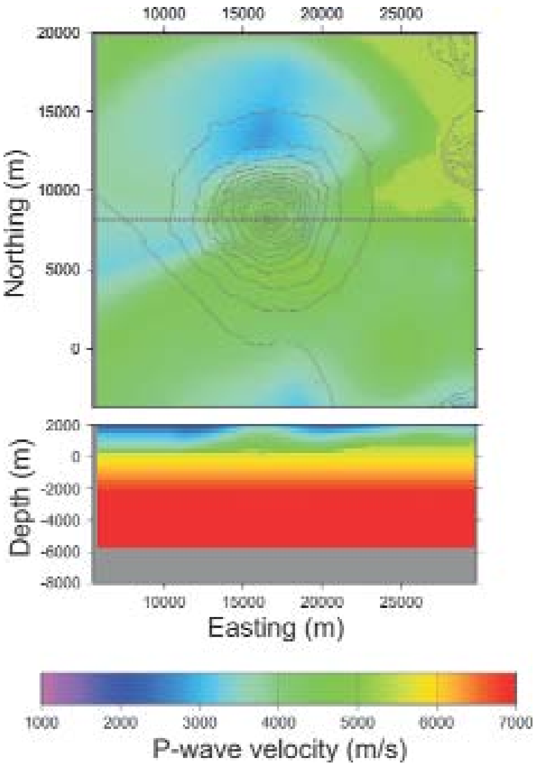

Fig. 2. P-wave velocity model of Lomax et al., 2001. The top map represents the velocity at a depth of 1 km. The dashed line is the projection of the EW cross section shown below.

The LET model of Mt. Vesuvius (Scarpa et al., 2002)

This model has been obtained though a linearized traveltime inversion of data from a set of 2139 earthquakes recorded at Vesuvius from 1987 to 2001 by at least 8 stations. The total number of phases used is 8600 P and 1900 S

[Scarpa2002]. The average resolution in the central part of the model is about 0.5 km.
A high-Vp anomaly at about the sea-level altitude, marks the separation between two clusters of hypocenters,located above and below it [Scarpa2002] (Figure 3). The Vp/Vs ratio shows anomalously high values at shallow depths.

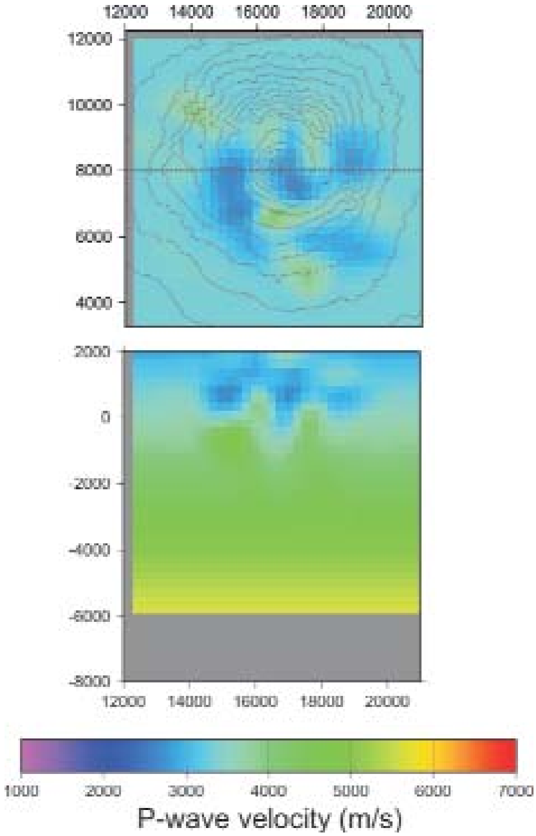

Fig. 3. P-wave velocity model of Scarpa et al., 2002. The top map represents the velocity at a depth of 1 km. The dashed line is the projection of the EW cross section shown below.

The SERAPIS models (Zollo et al., 2003) and (Judenherc and Zollo, 2004)

Following the results obtained with the TOMOVES experiment, a new active seismic survey was performed in September 2001. The aim of the experiment was to investigate the crustal structures of Campi Flegrei, Ischia and the Gulf

of Naples [Zollo2003]. The survey consisted of about 5000 airgun shots recorded by 62 OBS and 72 on-land stations [Zollo2003]. Two velocity models were obtained from the dataset using a linerized tomographic inversion technique [Judenherc2004]. The first model (NB) spans the whole Gulf of Naples, with a volume of 55x50x8 km^3 and spacing of 1 km. The second one (PB), with a higher resolution of 250 m, covers the Bay of Pozzuoli and the Campi Flegrei area with a volume of 20x15x5 km^3.
The NB model shows the main structural features of the Gulf of Naples, evidencing the depth of the carbonatic basement and a NE-SW fault system that dislocate it (Figure 4). The PB model shows details of the structure of the

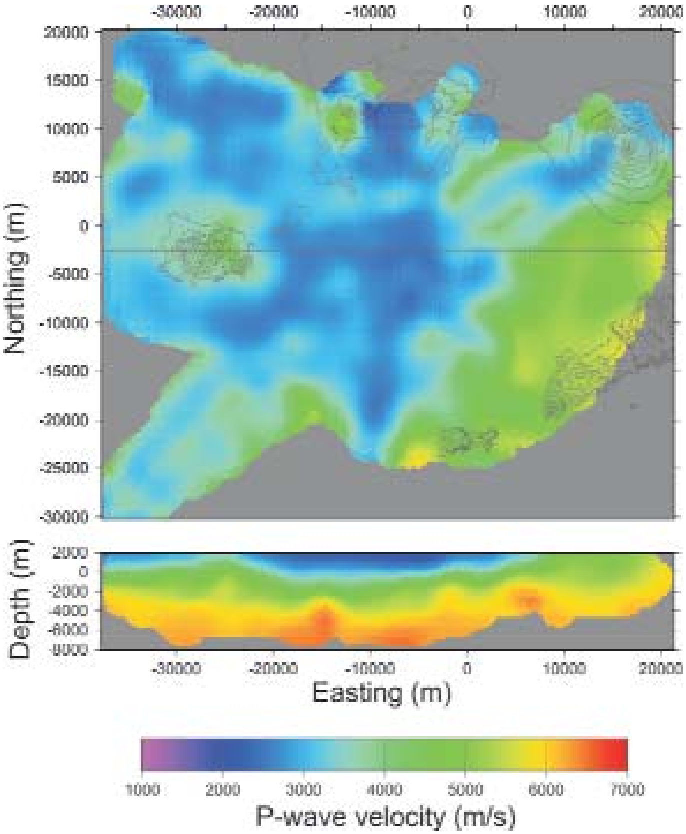

Fig. 4. P-wave velocity model (NB) of Judenherc and Zollo, 2004. The top map represents the velocity at a depth of 1 km. The dashed line is the projection of the EW cross section shown below.

Campi Flegrei caldera in the Pozzuoli Bay (Figure 5). An high velocity ring marks the caldera rim.

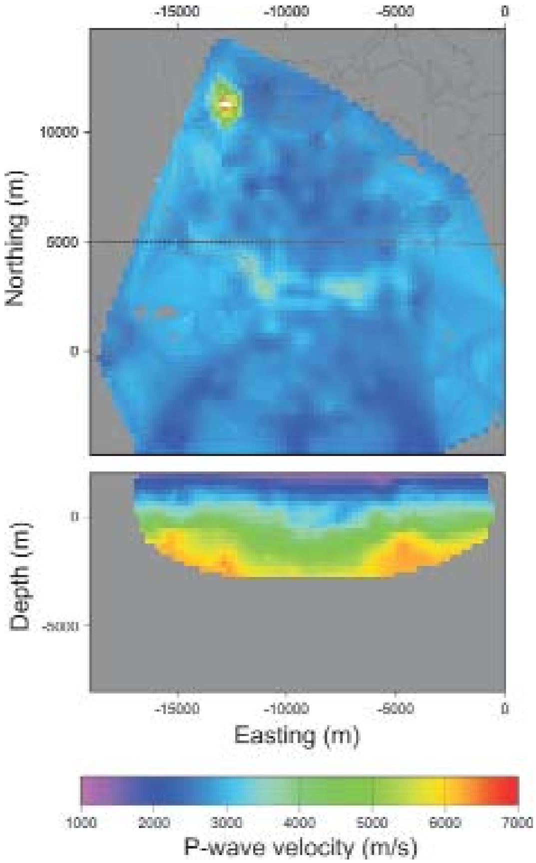

Fig. 5. P-wave velocity model (PB) of Judenherc and Zollo, 2004. The top map represents the velocity at a depth of 1 km. The dashed line is the projection of the EW cross section shown below.

The LET model of Campi Flegrei (Vanorio et al., 2005)

This tomographic model has been obtained from the inversion of traveltime data recorded by a digital network of 21 seismic stations. The dataset consists of 3447 P and 2289 S travel times from 462 local earthquakes at Campi Flegrei [Vanorio2005]. The events were recorded during the period from January 1st to April 15th 1984, when an unrest crisis was ongoing at Campi Flegrei. The main results of the tomographic inversion were a P and a S-wave velocity models. These models spans a volume of 14x14x5 km^3. The average resolution in the central part of the model is about 1 km.
This model gives a clear insight into the structure of the Campi Flegrei caldera (Figure 6). A huge low velocity anomaly marks the central depressed volume of the caldera. Small localized high Vp/Vs anomalies, below the town of Pozzuoli, probably marks a pressurized geothermal reservoir [Vanorio2005].

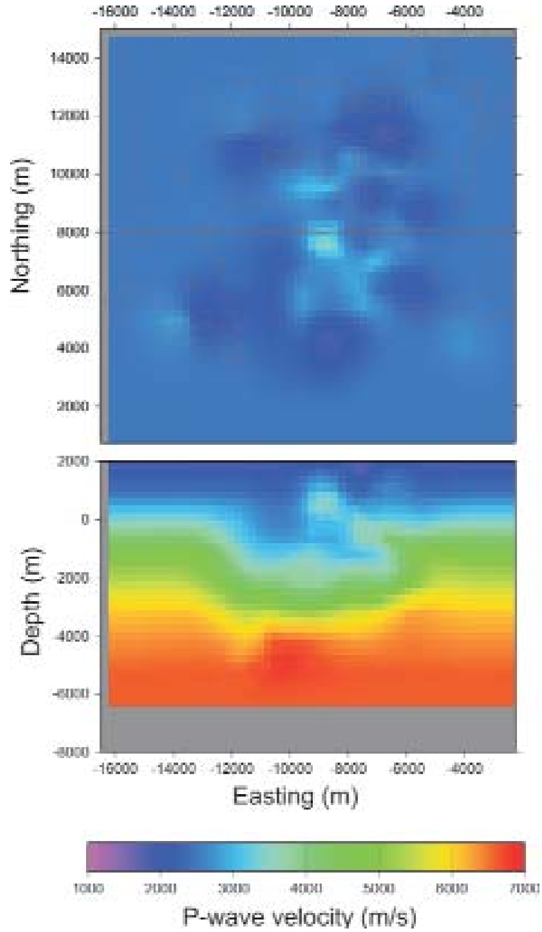

Fig. 6. P-wave velocity model of Vanorio et al., 2005. The top map represents the velocity at a depth of 1 km. The dashed line is the projection of the EW cross section shown below.

Unification of velocity models

Each velocity model spans a limited area of the considered region. Furthermore each model has a different spatial grid dimension and a variable resolution. For this reasons the unification of the models followed 6 steps. First individual models have been interpolated on the same spatial grid (250 m spacing) using a triangulation technique. Then for each model a spatial weighting function has been defined on the basis of its resolution. This function *w* has a range from 0 to 1. Usually tomographic models have a higher resolution in the central part, where there is a higher ray density and a good azimutal coverage of ray directions. An example of weight function for the SERAPIS NB and the Vanorio models is shown in Figure 7.

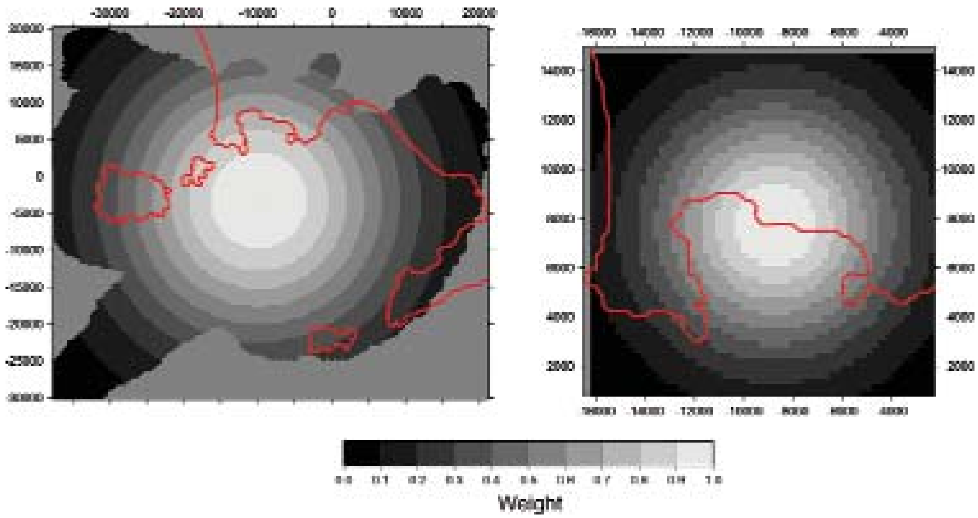

Fig. 7. Example of weighting scheme for the Serapis NB model (left) and for the Campi Flegrei model of Vanorio et al., 2005.

Then individual P wave models have been joined into a single one, using a weighter averaging as:

$$v\left(x_i, y_j, z_k\right) = \frac{\sum_{m=1}^{M} v_m\left(x_i, y_j, z_k\right) w_m\left(x_i, y_j, z_k\right)}{\sum_{m=1}^{M} w_m\left(x_i, y_j, z_k\right)} \quad (1)$$

where M is the number of models available at the point (x_i, y_j, z_k), $v_m(x_i, y_j, z_k)$ is the velocity (P or S) and $w_m(x_i, y_j, z_k)$ is the weight of the m-th model. Some portions of the model volume where not covered by any of the available tomographic models (Figure 8a). They were obtained by interpolation using a nerest-neighbour algorithm. The eastern border of the model has been defined following the two models of [Improta2000], while the western has been obtained by averaging the westernmost part of the Serapis PB model (Figure 8b). Then the resulting model has been smoothed with a gaussian filter with λ=1 km (Figure 8b).
The S wave model has been obtained in a similar way. Available tomographic models were only Scarpa et al., 2002 for Vesuvius and Vanorio et al, 2005 for Campi Flegrei. For the Lomax et al., 2001 model of Vesuvius it has been assumed V_P/V_S=1.9, while for the SERAPIS models it has been assumed V_P/V_S=1.8.
The resulting P and S models are shown in Figures 9 and 10.

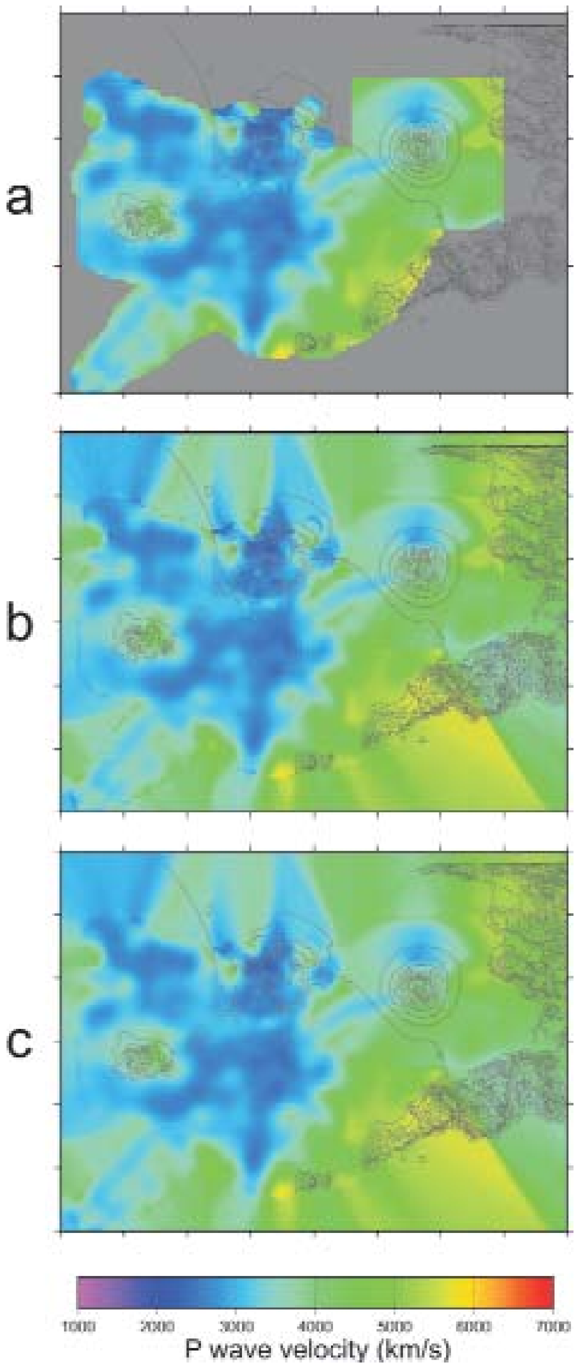

Fig. 8. Steps in the building of the global model. (a) represents the model after the weighted averaging of single models. (b) is the model after the extrapolation to undefined zones (gray areas in (a)). (c) is the final model after the smoothing. Each image represents the velocity model at 1:Km depth.

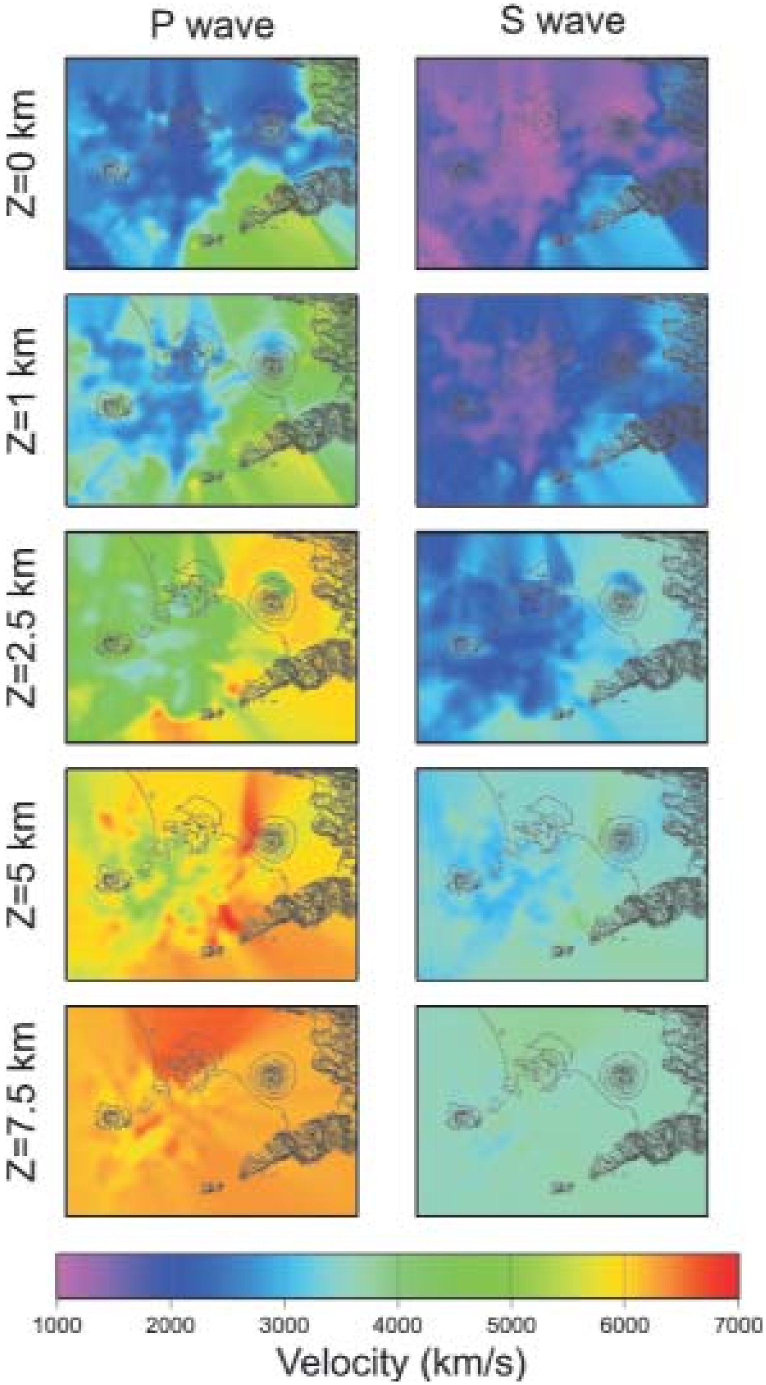

Fig. 9. P and S wave velocities at different depths.

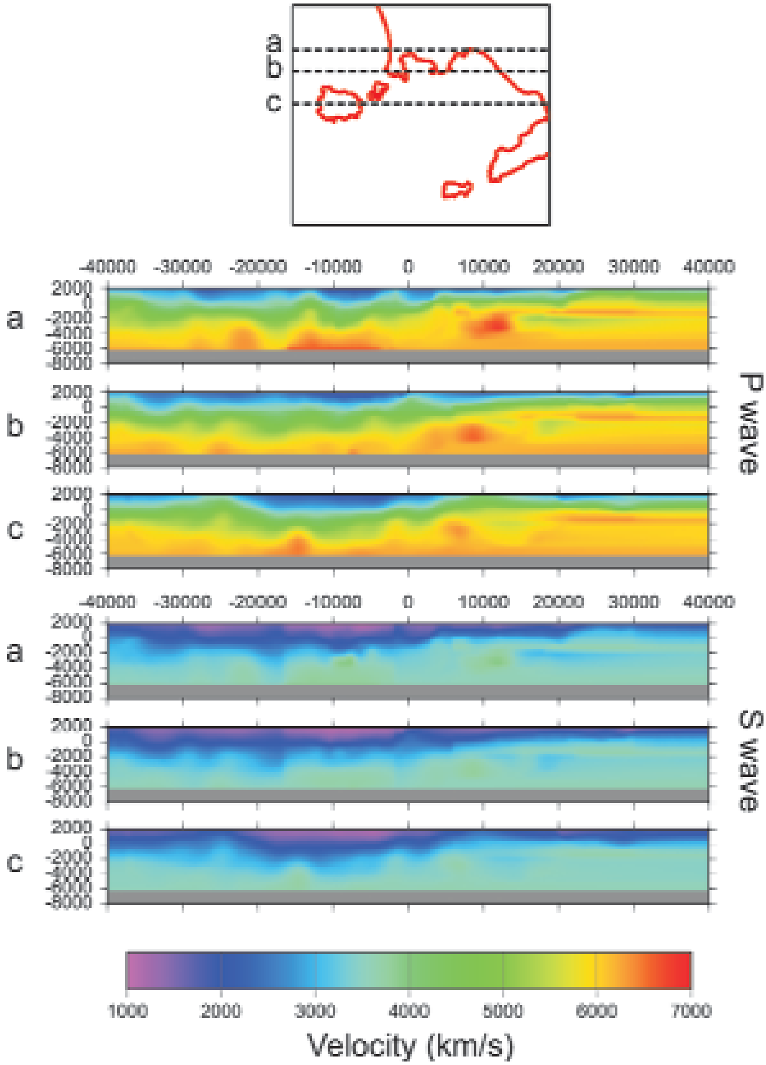

Fig. 10. EW cross-sections of the velocity model. Section traces are depicted in the top panel.

Relocation of seismic events

The routine location procedures at INGV "Osservatorio Vesuviano" are based on Hypo71-like 1D layered velocity models (Figures 11 and 12). We have relocated, part of the available dataset for checking changes in the hypocenters between the 1D and 3D locations. For 1D models the locations have been perfomed using HYPO71 software, while for the 3D model the software used is NonLinLoc (by Anthony Lomax).

Relocating events at Mt. Vesuvius

The current 1D velocity model of Vesuvius consists of only 2 layers (Figure 11). In Figure 12 we show the comparison of locations in the 1D and in the 3D model of about 800 events (with at least 6 pickings) recorded from 1999 to 2004 by the seismic monitoring network of INGV-OV. The most striking feature is the higher depth of hypocenters in the 3D model. While in 1D locations they are mostly located above 4 km depth, in 3D locations they are distributed until a depth of 6 km. The reason of this discrepancy can be understood from Figure 11. The 1D velocity model strongly underestimates the velocity above 2 km depth, making the hypocenters shallower than the 3D

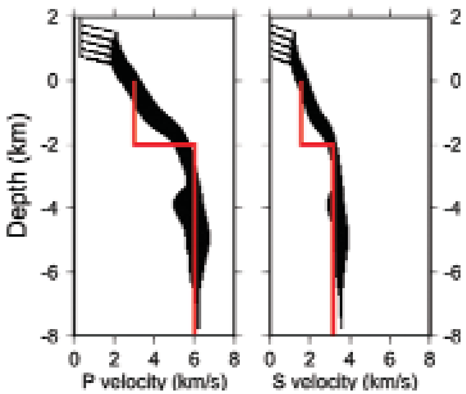

Fig. 11. Comparison between 1D velocity model (red line) and the velocity range of the 3D model (black area) in the Vesuvius area.

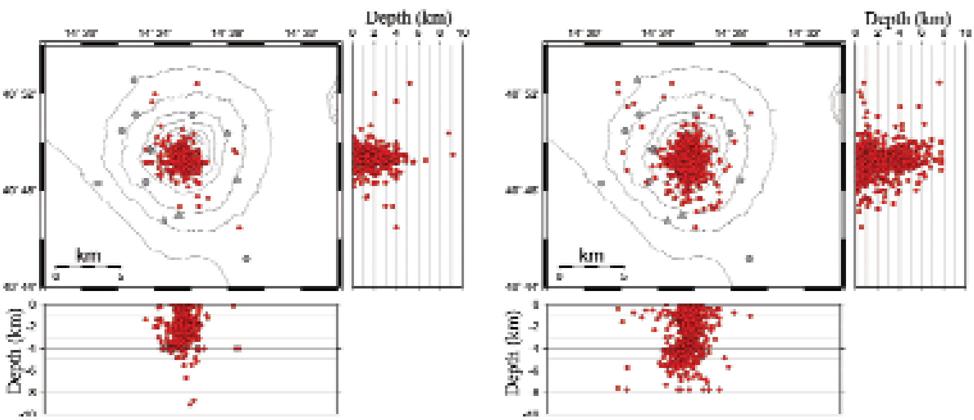

Fig. 12. Comparison between hypocenters located in the 1D (left) and the 3D model (right).

ones. From Figure 13 it is evident the improvement in the final RMS, that is known to be related to the quality of the velocity model [Klimes1996], but also in the location uncertainties (ERH and ERZ parameters).

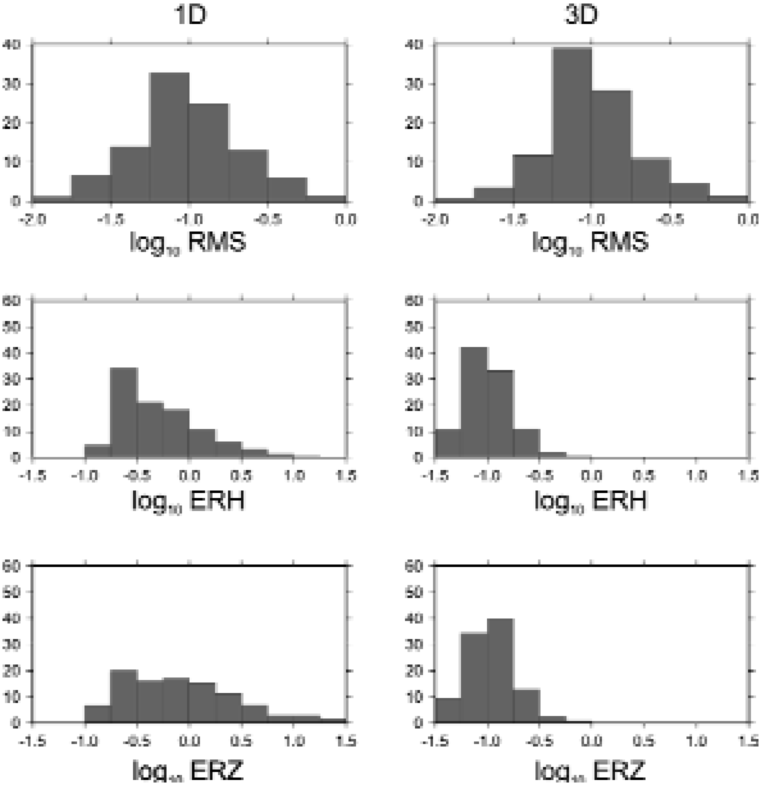

Fig. 13. Comparison between final residuals and location uncertainties in the 1D and 3D location for Vesuvius.

Relocating events at Campi Flegrei

The dataset of Campi Flegrei consists of about 100 events (with at least 6 pickings) recorded from 2000 to 2007. The comparison of 1D and 3D velocity models (Figure 14) shows a general underestimation of 1D model velocities but a rough agreements of the trend above 3 km depth. Also in this case, as for Vesuvius, hypocenters are slightly deeper in the 3D locations (Figure 15). Furthermore in the 3D model they shows a greater clustering of the epicenters. The improvement both in the RMS and on the location uncertainties is shown in Figure 16.

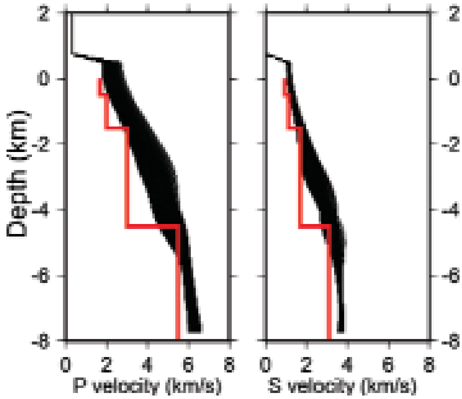

Fig. 14. Comparison between 1D velocity model (red line) and the velocity range of the 3D model (black area) in the Campi Flegrei area.

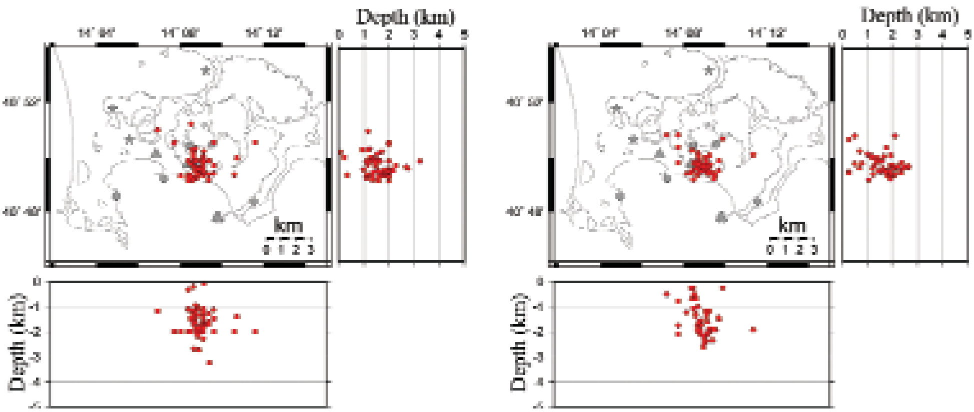

Fig. 15. Comparison between hypocenters located in the 1D (left) and the 3D model (right).

Conclusions

This new global 3D velocity model for the Neapolitan volcanic region, has shown to improve the quality of the locations both in Vesuvius and Campi Flegrei. The general shift in the hypocenter depths is significant and is due to the general underestimate of velocities in previous 1D models. The improvement in location quality will be useful both for monitoring as well as for scientific purposes.

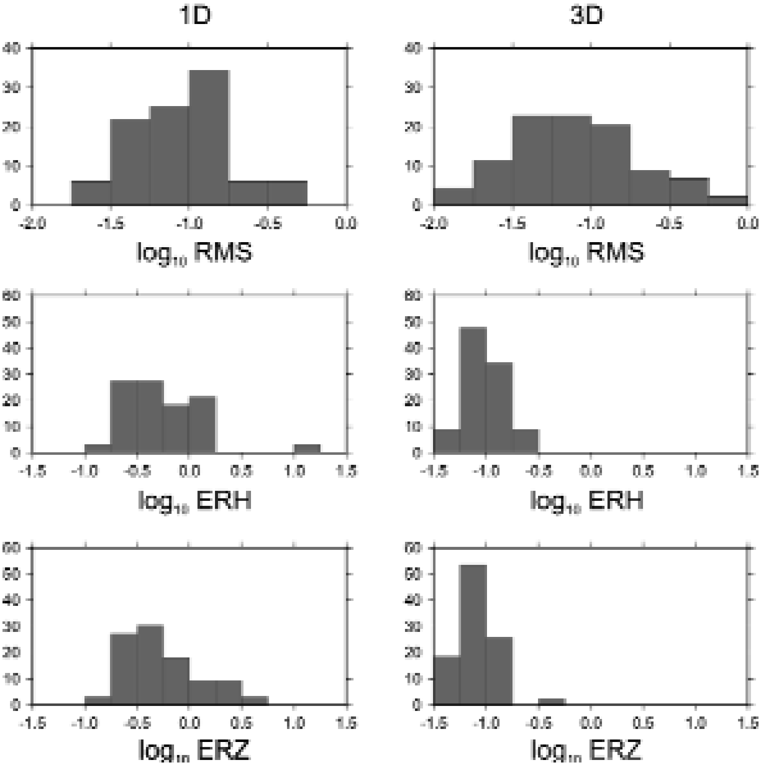

Fig. 16. Comparison between final residuals and location uncertainties in the 1D and 3D location for Campi Flegrei.

Acknowledgements

We wish to thank Dr. Anthony Lomax for providing us the NLLOC velocity model of Mt.Vesuvius, Prof. Aldo Zollo for the SERAPIS models, Dr. Tiziana Vanorio and Prof. Jean Virieux for the model of Campi Flegrei, Prof. Roberto Scarpa and Dr. Francesca Bianco for the velocity model of Mt. Vesuvius.

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