A 3D velocity model for earthquake location in Campi Flegrei area: application to the 1982-84 uplift event

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Abstract: The uplift crisis of the 1982-1984 in the Campi Flegrei area underlined the importance of seismic surveillance for this volcanic caldera. One of the key elements for an effective seismic network is to make use of a reliable velocity model for earthquake location.
In the present work we will discuss criteria for the construction and validation of a new 3D P-wave velocity model for earthquake location in the Campi Flegrei area built from the integration of two high-resolution 3D tomographic images of the region.
The model is used for locating a group of earthquakes from the uplift event of the 1982-1984.

Introduction

The Campi Flegrei (CF) caldera is an active volcanic system located at the west of the city of Naples. Like other calderas, CF periodically experiences significant unrest episodes which include ground deformations and seismic swarms. Nevertheless ground deformations in CF may reach values without equal in the world. Two marked ground uplift took place in the area in the periods 1970-1972 and 1982-1984. The last one, began in the second half of 1982 and was characterized by a total vertical displacement of 1.8 m (Barberi et al., 1984), together with a seismic swarm of more that 15,000 shallow microearthquakes with a maximum duration magnitude of 4.0 (Zollo and De Natale, 1986).

Aster and Mayer (1988) first made a joint tomographic and earthquake location study, using 228 events occurred during the 1982-1984 crisis. Recently (Capuano et al., this issue) a database of 3C waveforms containing several hundreds microearthquakes have been reconstructed and the whole waveform data base have been re-picked.
Vanorio et al. (2005) upgraded the original dataset by using 1209 earthquakes and performed a new joint inversion of earthquake location and P and S velocity model. They interpreted the resulting velocity model by using experimental measurements of rock physical properties.
The SERAPIS experiment (Zollo et al., 2002) has given a new insight into the structure of the CF area. Zollo et al. (2003) and Judenherc and Zollo (2004) obtained high-resolution 3D P wave velocity images from the inversion of the active seismic data (~90,000 P wave first arrival times), evidencing several volcanic structures like the buried rim of the Campi Flegrei caldera.
One of the most important components of volcanic surveillance is the recording and analysis of seismic activity. Due to the strong 3D structural variations generally characterizing the volcanic areas, in order to obtain reliable earthquake locations it is important not only to have a dense network with a good azimuthal coverage deployed on the area but also a valid velocity model.
In this paper, starting from the results of tomographic studies, we have developed and validated a 3D P-wave velocity model for earthquake location in CF area. This model have been used to locate the seismicity of the 1982-1984 uplift episode.

Construction of the model

We constructed a 16 x 20 x 8 km 3D P-wave model for the CF area and surroundings, centered on the Bay of Pozzuoli, starting from two 3D tomographic images. The first is a 250m-cell P wave tomography of the Bay of Pozzuoli obtained by Zollo et al. (2003); the second is a 1000m-cell image of the Gulf of Naples obtained by Judenherc and Zollo (2004).
Due to the resolution of the tomographic procedure, both the starting models have cells where the velocity value is not defined. However, for event location, the velocity model must be defined everywhere in the search volume so that the location algorithm can look for all the possible ray paths.
In order to define a complete velocity model for the CF area we proceed as follows.
First we select the interested area, then the large scale model (1000m) is re-sampled at 250m, finally the two model are merged together using the values of the large scale model where the 250m values were not defined. Then, for the cells which still remained undefined, we use a mean value for that particular depth.
The resulting model was filtered using a cosine filter with one cell width (250m), in order to avoid abrupt changes in velocity from a cell to another and,

therefore, unrealistic reflections in ray paths, especially for those areas where different kind of information were combined.
Finally, the model was extended above the sea level, using the mean velocity value of the shallowest layer.
The resulting model is shown in Figure 1. P-wave velocity values go from 1.12 km/s at the surface to about 7 km/s for the deepest layers.
As already evidenced by Zollo et al. (2003), the most important feature of the model is the presence of an arc-like, high P-velocity anomaly (Vp = 3.5-4.0 km/s) delineating the southern border of the gulf of Pozzuoli, presenting a pattern almost concentric to the coastal line. The top of this body is at about 800m depth and it extends down to about 2000m depth. Its location and annular shape indicate that it represents the image of the buried rim of the CF caldera.

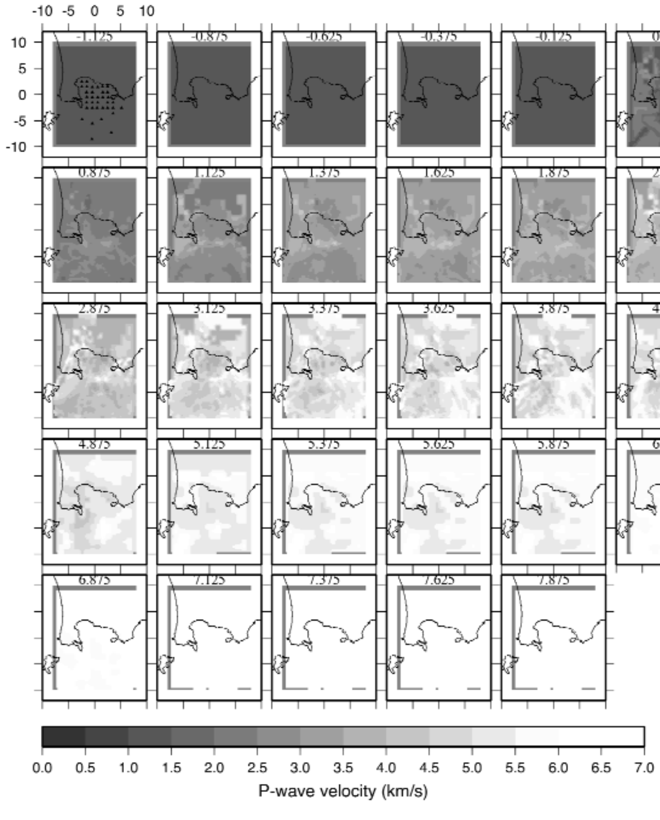

Fig. 1. 3D P-wave velocity filtered model resulting from the integration of two tomographic images of the CF area from the SERAPIS experiment (Zollo et al., 2003; Judenherc and Zollo, 2004). The first slice also shows the position of the OBS used for the location of the SERAPIS shots in the Pozzuoli bay.
You can see this figure in color on page 207.

The Italian Oil Agency (AGIP) drilled five 2-3 km deep boreholes on the landside of the caldera for geothermal exploration purposes (AGIP, 1987). Lithostratigrafic and sonic log data indicate that the caldera rim is formed by a sequence of compacted tuffs, tuffs with interbedded lavas and thermo metamorphic 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) which is consistent with our velocity model in the same depth range.

Verification of the 3D velocity model

We evaluated the quality of the constructed velocity model looking at the differences between observed and calculated travel times for the shots in the Pozzuoli bay from the SERAPIS experiment (Zollo et al., 2002); then we tried to locate the shots using the proposed model.
The travel times are calculated using a method based on the finite difference solution of the eikonal equation (Podvin and Lecomte, 1991), which is valid for a 3D heterogeneous medium.
Figure 2 shows the distribution of the differences between observed and calculated travel times using different models. We make a comparison between a 1D model, obtained calculating the mean value of each layer, the 3D velocity model obtained by Vanorio et al. (2005), our proposed 3D unfiltered model and the 3D filtered model.
Both the 1D model and the Vanorio model present a highly spread distribution of time residuals and a very large mean value (-0.37s and 0.23s, respectively). The 3D unfiltered model still present a bias (-0.05s), but the distribution of residual is very narrow, which indicates that actual travel times are better reproduced. The 3D filtered model presents a worse bias (-0.11s), but a similar distribution.
We verify the consistency of our model also by comparing the location of the SERAPIS shots using these four models computed by NonLinLoc program (Lomax et al., 2000) to obtain probabilistic location using a non-linear global search methods. The results of location are shown in Figure 3. The black stars are the located events; the grey dots show the actual position of the shots.
Figure 3a shows the location obtained using the 1D model. The shots path is quite well reproduced but there is a shift in horizontal position that becomes larger moving inward the Pozzuoli bay. All the events are located around 1 km depth with a little dispersion. Nevertheless we are locating very shallow events (in Figure 3 we show the mean event depth which is around 10 meters).
Figure 3b shows the location obtained with the 3D Vanorio model. The shots path is only vaguely reproduced. Events are very scattered in depth without showing an evident mean value. A great quantity of events (21%) is located above the sea level.

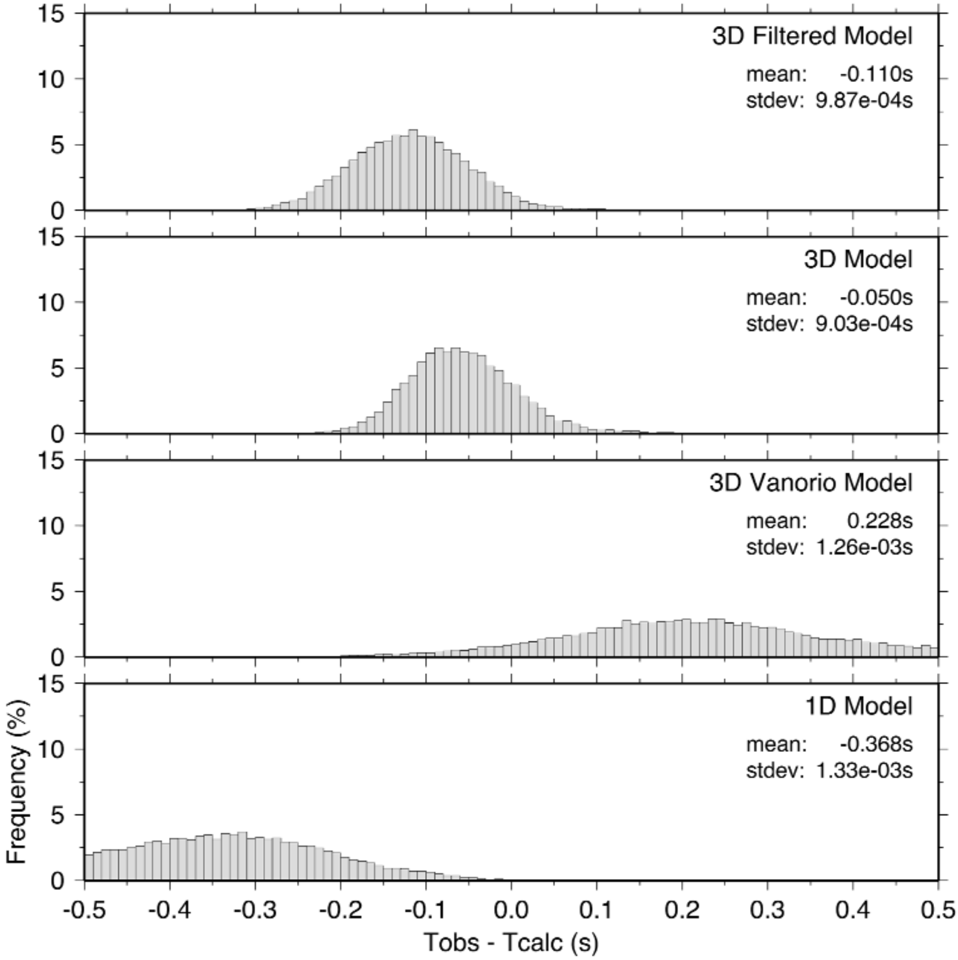

Fig. 2. Distribution of the differences between observed and calculated travel times at the Pozzuoli OBS for different velocity models: (a) 1D velocity model obtained using a mean velocity value for each layer, (b) 3D velocity model from Vanorio et al. (2005), (c) proposed 3D unfiltered model and (d) proposed 3D filtered model.

The third location is obtained using our 3D unfiltered model (Figure 3c). The horizontal view shows a good agreement between observed and actual shots position, even if there is still a little shift. The events are distributed in depth mainly along three levels, as one can clearly see from WE projection, and become deeper moving outside the bay. The events located in the northern part of the figure have a mean depth which is closer to the actual one, but with a dispersion which makes a number of events to lie above the sea level. The events in the central and southern part of the figure are placed at an unrealistic depth (the maximum depth of the bay in that area is

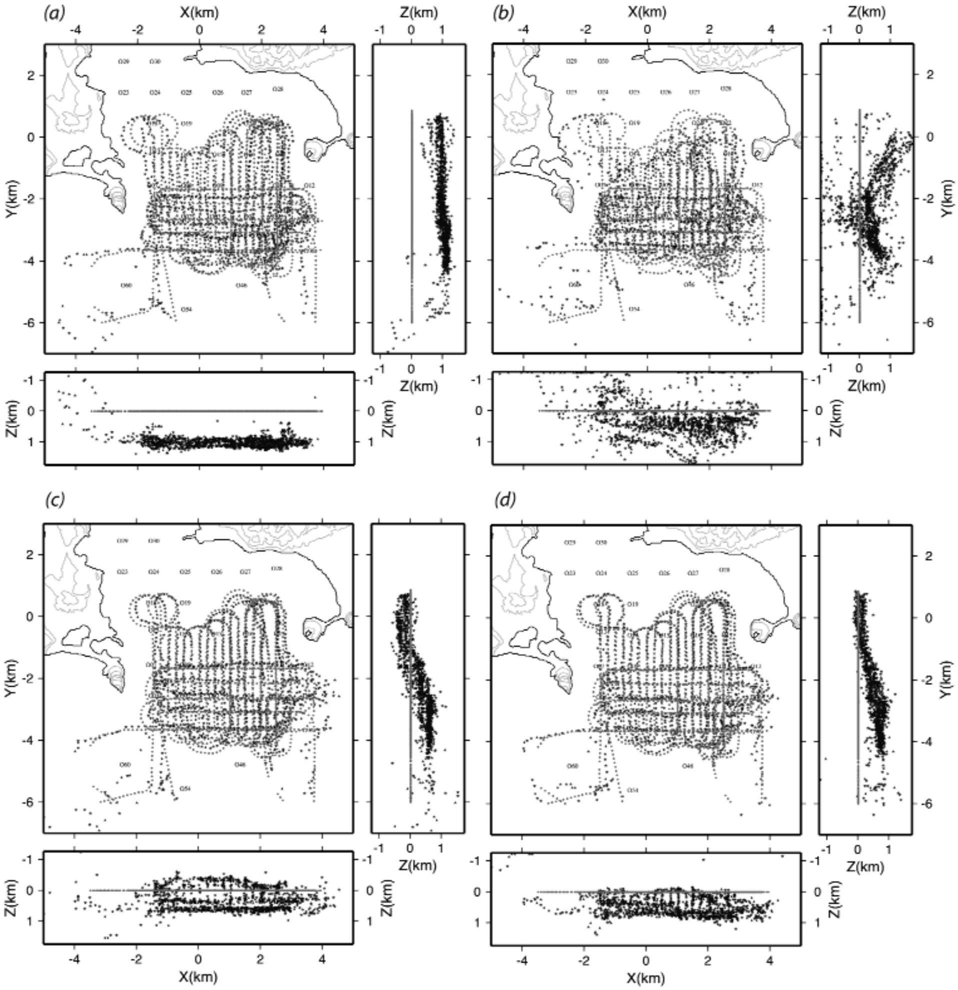

Fig. 3. SERAPIS shots locations using the four models described in Figure 2: 1D (a), Vanorio (b), 3D unfiltered (c), 3D filtered (d). The grey dots show the actual shot positions in the plane view, while they indicate a mean depth in the vertical views. The black stars are the located shots.

around 300m). This is probably due to the lower density of OBS in this area (as one can see from Figure 1), which implies a bad quality of the location in terms of the 68% confidence ellipsoid major semi-axis length (Lomax et al., 2001).

Figure 3d shows the location results using the 3D filtered model. The horizontal pattern is accurately reproduced; the dispersion in depth is strongly reduced with many events around the actual mean depth in the area where the location is more accurate. Again, as we move outward the bay, the quality of the location decreases and the depth estimate gets worse.

Figure 4 shows the distribution of the values of the 68% confidence ellipsoid major semi-axis length as a function of the position along the N-S direction. One can see how, for both the unfiltered and the filtered model, the quality of the location improves moving inward the bay (highest values of Y).

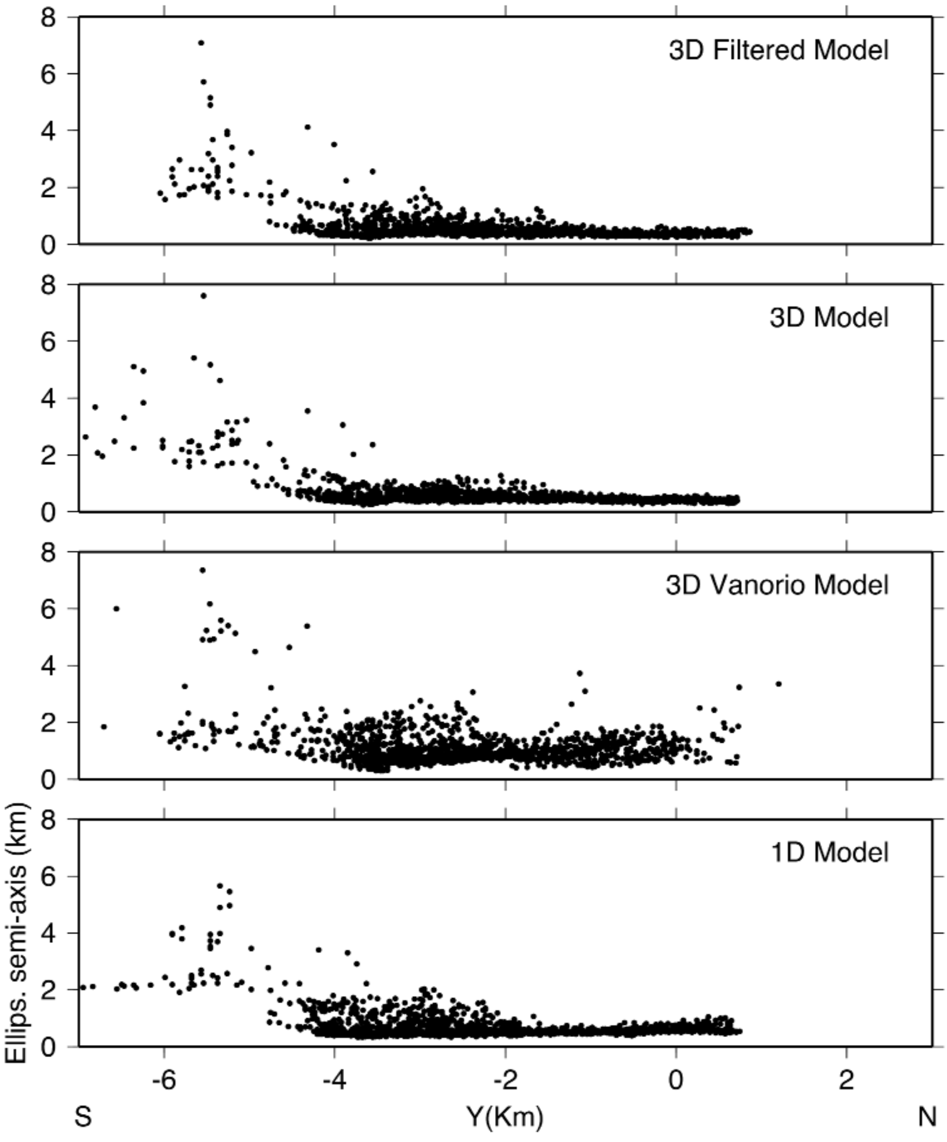

Fig. 4. Length of the major semi-axis of the 68% confidence ellipsoid as a function of the Y (N-S) position for the four models described in Figure 2.

Figure 5 shows the final residuals after the shots location. The filtered model gives better residuals than the unfiltered one, confirming the above discussion. After the analysis of the results of the described comparison, we may conclude that the 3D filtered velocity is highly consistent with the shots location and the observed P-wave arrival times, thus it may represent a more detailed P velocity model for locating earthquakes. We use this model to locate microearthquakes from the 1982-84 uplift event.

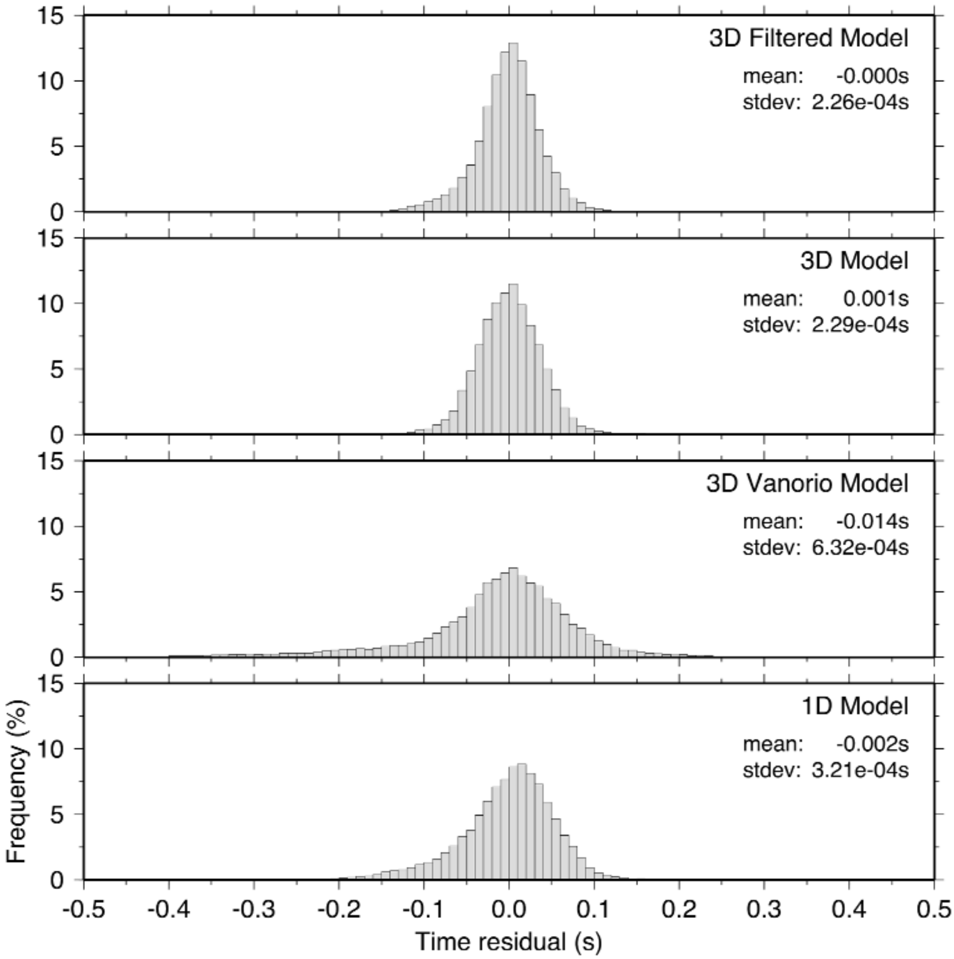

Fig. 5. Distribution of time residuals after the location of Pozzuoli shots for the four models described in Figure 2.

Location of the earthquakes from the 1982-84 uplift event

As a contribute to monitor the seismic activity accompanying the 1982-1984 crisis, the University of Wisconsin began a field experiment deploying a temporary network consisting of 21 three-component digital short-period seismometers. Data were recorded at 100 or 200 Hz sampling rates and 1 Hz geophones were used (Aster and Meyer, 1988). The seismic monitoring network recorded more than 15,000 events. Events were clustered in time, mainly concentrated in the Pozzuoli-Solfatara area and had maximum duration magnitudes of 4.0 (De Natale and Zollo, 1986).
After the reconstruction of waveforms database and phase pickings (Capuano et al., this issue), Vanorio et al. (2005) used these database joint with the seismicity occurred in the previous period, recorded by the Osservatorio Vesuviano seismic network, to produce tomographic maps.
We started from a dataset of 726 events from January 1st trough April 15th 1984, with a total number of 4237 P and 2837 S readings. For the location we used a fixed Vp/Vs ratio of 1.68; this is a reasonably good mean value for the inferred Vp/Vs ratio distribution in the area (Vanorio et al, 2005). A more consistent investigation of Vp/Vs ratio will be dealt in an upcoming study.
After the first location, we calculated the station corrections as the mean residual value for each station. We iterated this process two times. Figure 6 shows station residuals for P and S readings before applying station corrections (a) and after the last iteration (b). It is evident that the station residuals are highly reduced, except for two stations (W06, W08) for which, anyway, there are very few readings (13 and 8, respectively).
Figure 7 shows the final location result. We selected for plotting only the events with a maximum 68 per cent confidence ellipsoid semi-axis length of 1.5 km (319 earthquakes). The events are located within a small area in the Solfatara zone. Most of the hypocenters are clustered around a depth between 2 and 3 km. These results are in good accordance with the localization obtained by Vanorio et al. (2005) but events appear less scattered, especially in the W-E direction.

Discussion

We have constructed a 3D velocity model (Figure 1) for earthquake location in CF area and surroundings starting from two high-resolution tomographic images obtained after the SERAPIS seismic experiment.
We confirm that the 3D velocity model reproduce P waves travel times and location for the SERAPIS shots, also comparing with results obtained using a 1D mean model and the 3D tomographic model proposed by Vanorio et al. (2005).
This new 3D velocity model has been used to obtain non-linear global search earthquakes locations selecting 726 earthquakes from the 1982-1984 CF uplift

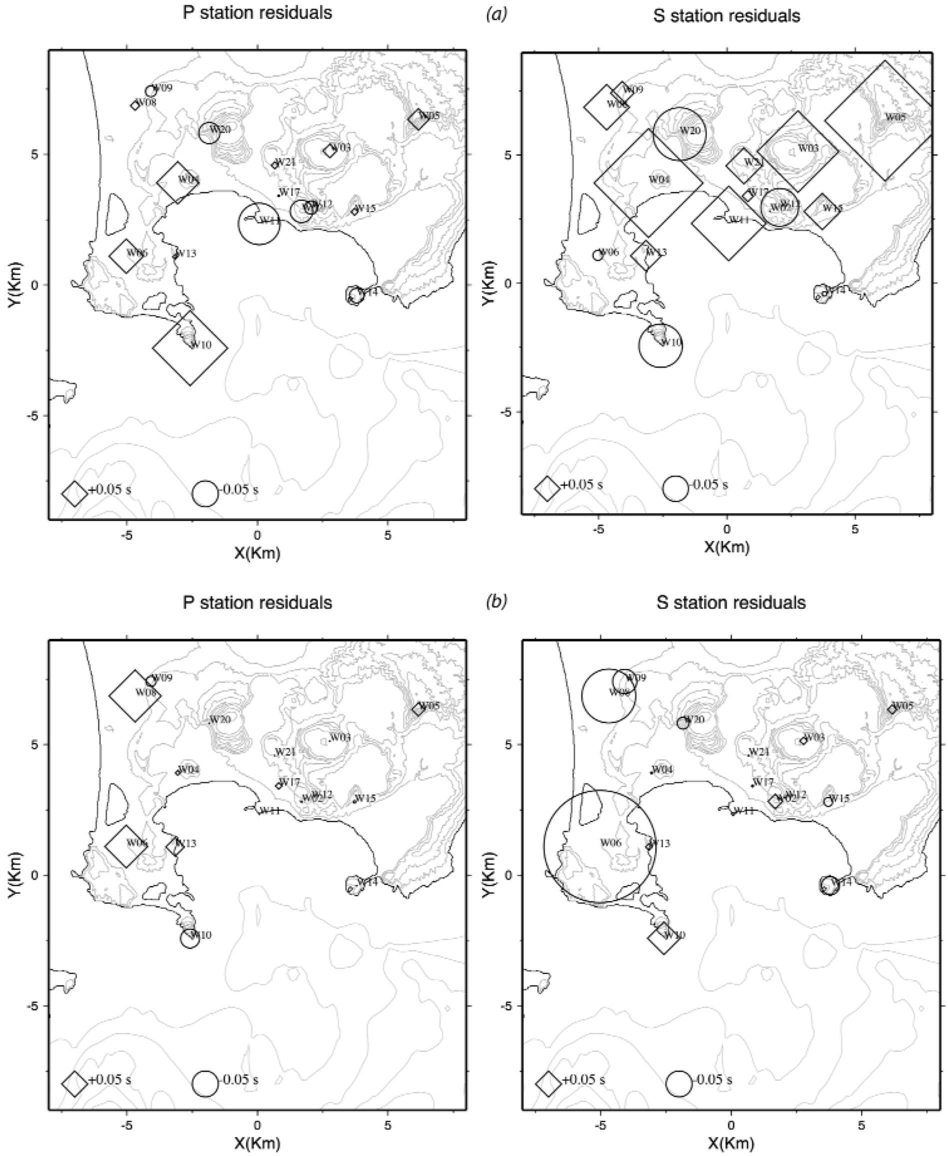

Fig. 6. P and S residuals for the Wisconsin stations (Aster and Meyer, 1988) before (a) and after (b) applying station corrections.

event obtaining locations in good accordance with previous studies (Aster and Mayer, 1988; Vanorio et al., 2005), but based on a larger and more robust database.

The earthquake locations obtained with the new 3D model are probably most representative of the true locations since this model is derived from shot data

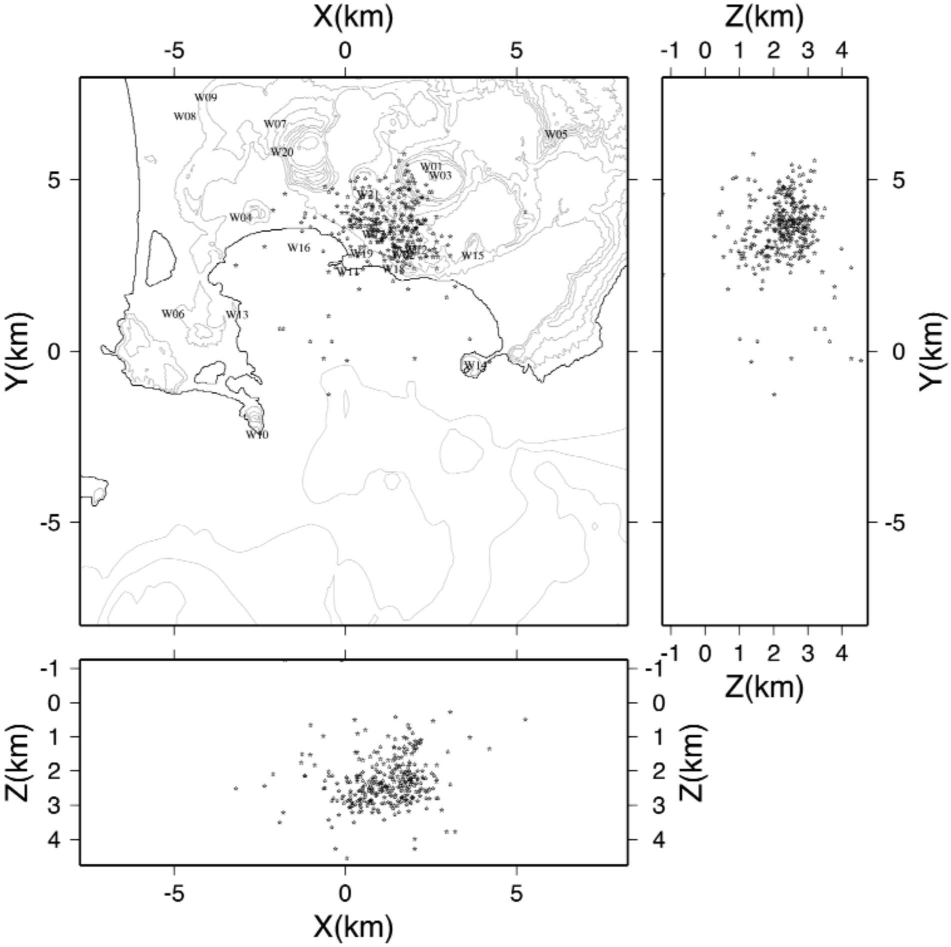

Fig. 7. Final location of 726 earthquakes from the 1982-84 uplift event. We selected for plotting only the events with a maximum 68% confidence ellipsoid semi-axis length of 1.5 km (319 earthquakes). The events are located within a small area in the Solfatara zone. Most of the hypocenters are clustered around a depth between 2 and 3 km.

with known source locations and origin times. Finally, we believe that the new 3D model can give more realistic images of earthquake distribution than a 1D model because of the high heterogeneity of the area (Judenherc and Zollo, 2004) and it will improve the accuracy of earthquake location and depth estimate in the volcano monitoring.

A successive study to verify Vp/Vs ratio and compute more reliable focal mechanism, will contribute to a better understanding of shallow structure at CF caldera.

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