

Special Issue: Vesuvius monitoring and knowledge

Inside Mt. Vesuvius: a new method to look at the seismic (velocity and attenuation) tomographic imagingEdoardo Del Pezzo^{1,2,*}, Francesca Bianco¹¹ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli, Osservatorio Vesuviano, Naples, Italy² Instituto Andaluz de Geofísica, Universidad de Granada, Granada, Spain**Article history**

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ABSTRACT

New velocity and attenuation images of the geological structures below Mt. Vesuvius have been obtained using the programming facilities as well as the enhanced graphical power of Mathematica^{8TM}. The velocity and attenuation space distributions, already calculated inverting respectively P-wave travel times and amplitude spectra of local VT quakes, are first optimally interpolated and then graphically represented in a new Mathematica^{8TM} code notebook (a powerful computational document with more facilities than a simple code) developed by the present authors. The notebook aims at interactively and friendly representing 3D volume distributions of velocity and attenuation parameters. The user can easily obtain vertical sections (N-S, E-W, NE-SW and NW-SE oriented) and define color scales to represent velocity or attenuation variations or prefer iso-surface plots to represent the pattern of peculiar geological structures. The use of dynamic graphical representation, allowing the sliding of any (horizontal and/or vertical) slice through the volume under study, gives an unusual and powerful vision of any small velocity or attenuation anomaly. The (open source) code, coupled with the friendly use of internal routines of Mathematica, allows to adapt the graphical representation to any user necessity. The method appears to be particularly adapt to represent attenuation images, where the space variations of the parameters are strong with respect to their average. The 3-D plots of the interpolated velocity and attenuation fields enhance the image of Mt. Vesuvius structure, evidencing low-velocity associated with high attenuation anomalies which appeared unfocused in the plots reported by Scarpa et al. [2002] and De Siena et al. [2009].

1. Introduction

The interpretation of seismic tomography images is based on the visual association of earth volumes marked by a peculiar space distributions of velocity, attenuation or scattering with a characteristic compatible rock lithology. Consequently, the 3-D representation of the spatial distribution of velocity and attenuation influences the geological interpretation, conditioning the final results. In the case of Mt. Vesuvius, a correct

interpretation of the results from seismic tomography (in attenuation and velocity) may be crucially influenced by the visual representation of the results, being the geological structure of this volcano highly heterogeneous, with drastic lateral or vertical changes of lithology in small distance ranges [Scarpa et al. 2002, De Siena et al. 2009]. Our main goal is to facilitate the revision of the geological interpretation based on the joint tomography results described in the two papers above (velocity and attenuation); hence we developed a new Mathematica^{8TM} notebook, i.e. a powerful computational documents with more facilities than a simple code, aimed at an easy and personalized visualization of the 3D velocity and attenuation patterns. We called this notebook *SeeVes*. In the present note we will describe the structure of *SeeVes* and we will show an application producing new tomography images of Mt. Vesuvius (attenuation and velocity). The notebook may be easily used for the visualization of any other result from 3D tomography in other areas.

2. The Mathematica^{8TM} code

To describe the mathematics underlying the code we use the same algebraic notation of Mathematica^{8TM}. The commented notebook *SeeVes* is temporarily enclosed in a separate file.pdf (but will be soon freely downloadable). It is structured into three parts. The first deals with data import in a suitable format. We use the important facility of importing topographical maps contained in Surfer Binary files (Golden Software Surfer-8, at www.goldensoftware.com/) into Mathematica^{8TM}. Then we import velocity tomography and attenuation tomography files like those described in Scarpa et al. [2002] and De Siena et al. [2009] provided as ASCII 3-columns.

The second part of the notebook performs the process of data interpolation. In the case of Mt. Vesu-

vius, we interpolate both the velocity and the attenuation distribution with a Spline interpolator (internal in *Mathematica*^{8TM}). In this way for Mt. Vesuvius we build three functions of the space coordinates $V_p[x, y, z]$, $\Delta Q_p^{-1}[x, y, z]$ and $\Delta Q_s^{-1}[x, y, z]$ describing for any space position inside the volume under study the P-wave velocity, the differential P-wave total attenuation and the differential S-wave total attenuation (differences from the volume averages) respectively.

The third part of notebook deals with graphical procedures. We use the graphical routines “Contour-Plot” of *Mathematica*^{8TM} to represent the interpolated

velocity and attenuation fields in the space (in 2D horizontal or vertical sections). Color scales are user-defined. We use blue tonalities (from light cyan to intense dark-blue) to represent both high velocity and low attenuation volumes. Red tonalities (from light-yellow toward intense-red) represents low velocity and high attenuation volumes. We finally combine these 2-D plots into 3-D plots using the powerful routine “Graphics3D” which projects any 2-D plot into a 3-D frame, using an user defined space orientation. In this way we obtain the Plots represented in Figure 1. These plots can be mouse-copied from the notebook and pasted into any representation software to obtain .pdf files (or equivalent interchange formats) for preparing publication figures. *SeeVes* use a cartesian (UTM coordinates) topographical frame.

It is often useful to accompany the representation of tomography images with the corresponding hypocentral distribution image. To perform this task we prepared an associated *Mathematica*^{8TM} notebook to plot the 3-D hypocentral distribution. This notebook contains also a routine which calculates the numerical density of the earthquakes for a unit volume; this quantity, in the assumption of a stationary seismic energy release process, describes the probability $P[x, y, z, \Delta l, m_1, m_2]$ that an earthquake with magnitude between m_1 and m_2 occurs

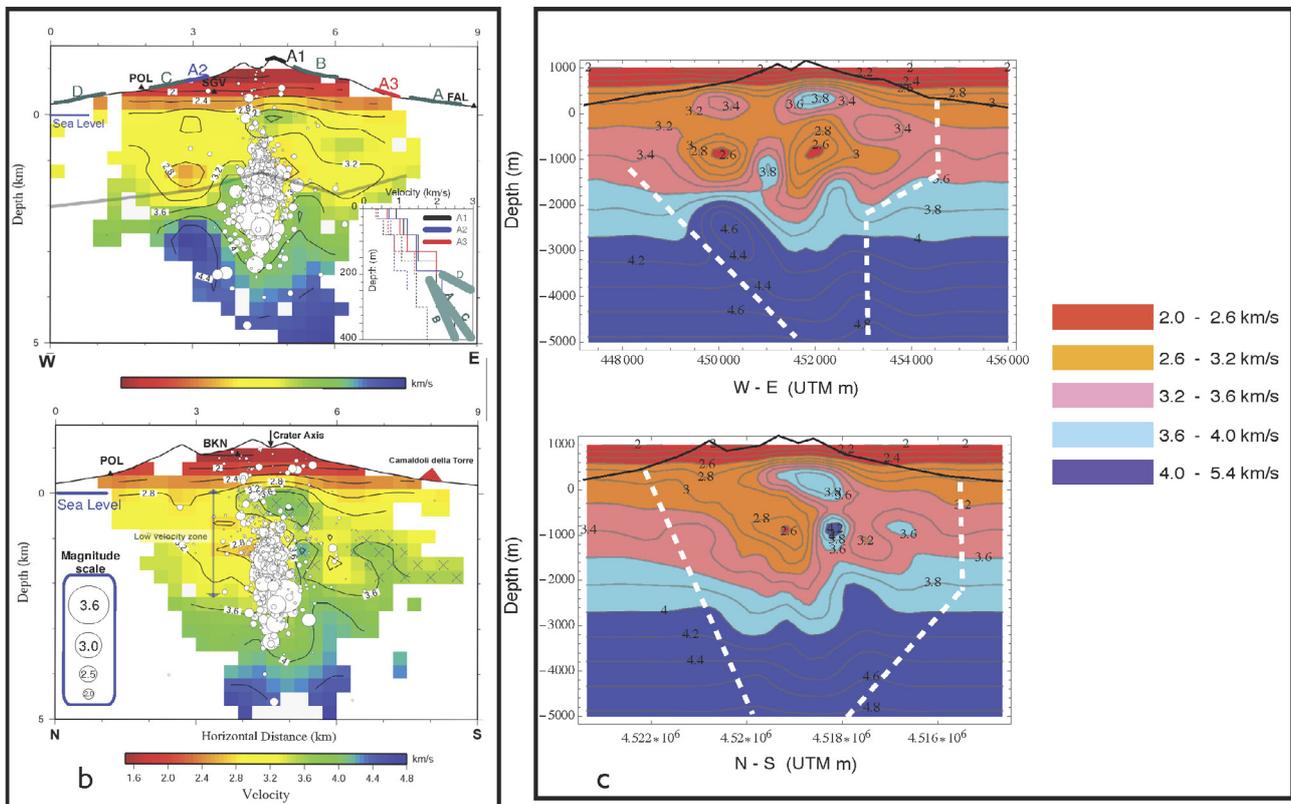


Figure 1. (a) 3D plot of interpolated V_p distribution in the earth volume below Mt. Vesuvius, centered at the crater axis. Easting and Northing is in UTM (meters). Depth is negative below the sea level. Mt. Vesuvius map is plotted in transparency at 800 m a.s.l.; (b) W-E and N-S velocity sections redrawn from Scarpa et al. [2002]; (c) W-E and N-S velocity sections represented using *SeeVes*. Dashed line borders the resolved area.

inside a volume with linear dimension Δl , centered at space coordinates x, y, z . It is given by

$$P[x, y, z, \Delta l, m_1, m_2] = \frac{N[x, y, z, \Delta l] N[x, y, z, \Delta l, m_1, m_2]}{N_T N[x, y, z, \Delta l]} \quad (1)$$

where $N[x, y, z, \Delta l]$ is the number of earthquakes in the volume with linear dimension Δl centered at position (x, y, z) , N_T is the total number of earthquakes in that area and $N[x, y, z, \Delta l, m_1, m_2]$ is the number of quakes with magnitude inside the interval (m_1, m_2) . The routine interpolates the quantity given in Equation (1) between the grid points (x, y, z) in which it is calculated, allowing an easy visualization when using contour lines of equal probability. The plot of Mt. Vesuvius seismicity occurred between 1987 and today with magnitude greater than 2.5 (between 2.5 and 3.6; 3.6 is the maximum magnitude ever recorded in this time interval) is reported in Figure 2. The 3-D plots are made using the same frame (UTM coordinates, depth in meters) both for tomography and for hypocentral probability-distributions.

3. Tomography representation for Mt. Vesuvius

3.1. Velocity tomography

As previously discussed, we use the results described in Scarpa et al. [2002] and De Siena et al. [2009] for P-wave velocity and S- and P-wave total-Q tomography of Mt. Vesuvius respectively. In the present note we briefly report the main elements of these two papers, which are also discussed in other papers in this special volume. Scarpa et al. [2002] use passive travel time data from a set of 2139 local Volcano-Tectonic (VT) quakes occurred in the time period 1987-2001, recorded by local and temporary networks operating on Mt. Vesuvius, for a total of 8600 P-wave recordings and 1600 S-wave recordings. The tomography is carried out using the approach described by Benz et al. [1996], with additional constraints in the uppermost crust P-velocity (upper 400 meters below the ground level) determined by small array data using the SPAC method [De Luca et al. 1997]. Volume investigated in Scarpa et al. [2002] is centered around Mt. Vesuvius crater axis, horizontally extended about 10 km with an extension in depth from the crater top until 5 km below the sea level. Results from this study are reproduced using the present *Mathematica*^{8TM} routines in Figure 1. In the sections of Figure 1 the color scale represents the spline interpolated P-velocity values. In the paper by Scarpa et al. [2002] the sections were instead averaged among three adjacent blocks, the central

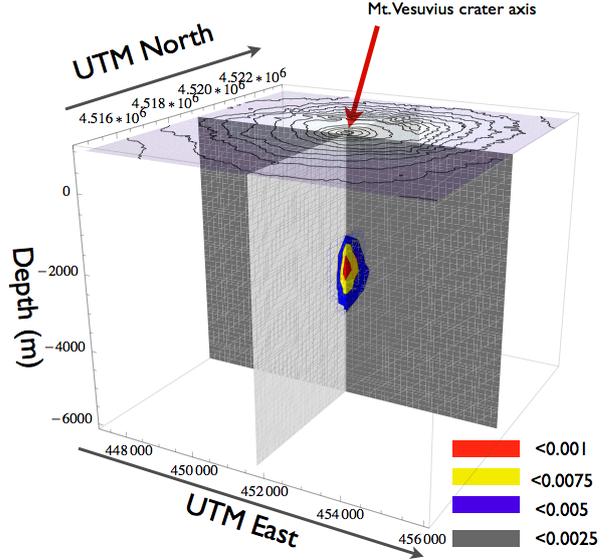


Figure 2. 3-D plot of the location probability (Equation 1) for earthquakes with magnitude between 2.5 and 3.6 occurred between 1987 and today. Color scale represents the quantity $P[x, y, z, 2.5, 3.6]$. Relevant energy emission corresponds to the red zone, which is strictly confined in a very narrow (500 m) and thin (1000 m) volume centered at -2500 m below the sea level.

being cut by the section plane. S-velocity structure for Mt. Vesuvius resulted much less resolved, due to the high signal to noise ratio around the S-wave onsets, due to the presence of high level P-coda waves, and thus was not plotted in the paper by Scarpa et al. [2002]. It is self-evident that the visualization in Figure 1a-c is much more informative than that in Figure 1b, redrawn by Scarpa et al. [2002]. For instance, the geometry of the shallow high velocity body (light blue 3.6-4.0 km/s) around the crater axis, appears much more visible and constrained, favouring its interpretation as an old intrusive body, cooled and solidified. The location of the VT quakes used as input data is not reported in this plot to avoid superpositions with the velocity image. Earthquake distribution probability, for earthquakes with magnitude between 2.5 and 3.6, occurred from 1987 up today, is depicted in Figure 2. As clearly shown in this figure, the higher probability is clearly confined in a very narrow volume, centered at -2500 m below the sea level.

3.2. Total attenuation tomography

P- and S-wave attenuation tomography of Mt. Vesuvius has been obtained by De Siena et al. [2009] using the ordinary spectral slope method for P-waves and a technique based on the estimation of coda normalized S-wave spectra for S-waves. These authors analysed a subset of the earthquake set used for velocity tomography by Scarpa et al. [2002] consisting of 826 local VT quakes for a total of 6609 waveforms

recorded at 3-component stations. S- and P-wave attenuation tomography images were achieved in a multi-resolution approach, which allowed to reach up to 300 meters resolution in the volume centred around the crater with an average linear dimension of 2-3 km and 900 meters resolution outside. All details are reported in De Siena et al. [2009]. We used *SeeVes* to redraw both P and S waves attenuation images using the results by De Siena et al. [2009]. In Figure 3a,c we show the *SeeVes* 3-D S-wave attenuation image and the WE and SN sections, respectively, compared to the WE and SN sections by De Siena et al. [2009] in Figure 3b. In Figure 3b,c a white continuous line borders the zone where maximum resolution of 300 m was achieved, and a dashed white line the zone with a resolution of 900 m. Outside these borders the color scale is not interpretable. As previously discussed for the case of the velocity images, also for the attenuation ones we are able to discriminate much more details in the new representation (Figure 3a,c) than in the old plots (Figure 3b).

For instance, the spatial location of the shallow low attenuation zone in the first 2 km appears much more constrained, as well as the smaller high attenuation areas in the first kilometer. Moreover, the limits of the attenuation contrasts are clearly delineated and not smoothed as in Figure 3b. In this way *SeeVes* enhances the possibility of better interpreting the images till to the maximum resolution (300 m) available in the smaller zone bordered by the white segmented line, and in the same way avoids false interpretations when attenuation anomalies result to be smaller than the minimum cell dimensions. The representation method used in *SeeVes* seems thus to be particularly suitable in case of attenuation tomography, typically showing a space distribution of values with strong variations with respect to their average.

4. Discussion and conclusions

The approach described in this note is largely based on the use of internal *Mathematica*^{8TM} routines. The interpolation of the velocity, attenuation and location probability resulted to be particularly fast and accurate, due to internal optimization of the Spline routines present in *Mathematica*^{8TM}. Figure 4 shows the

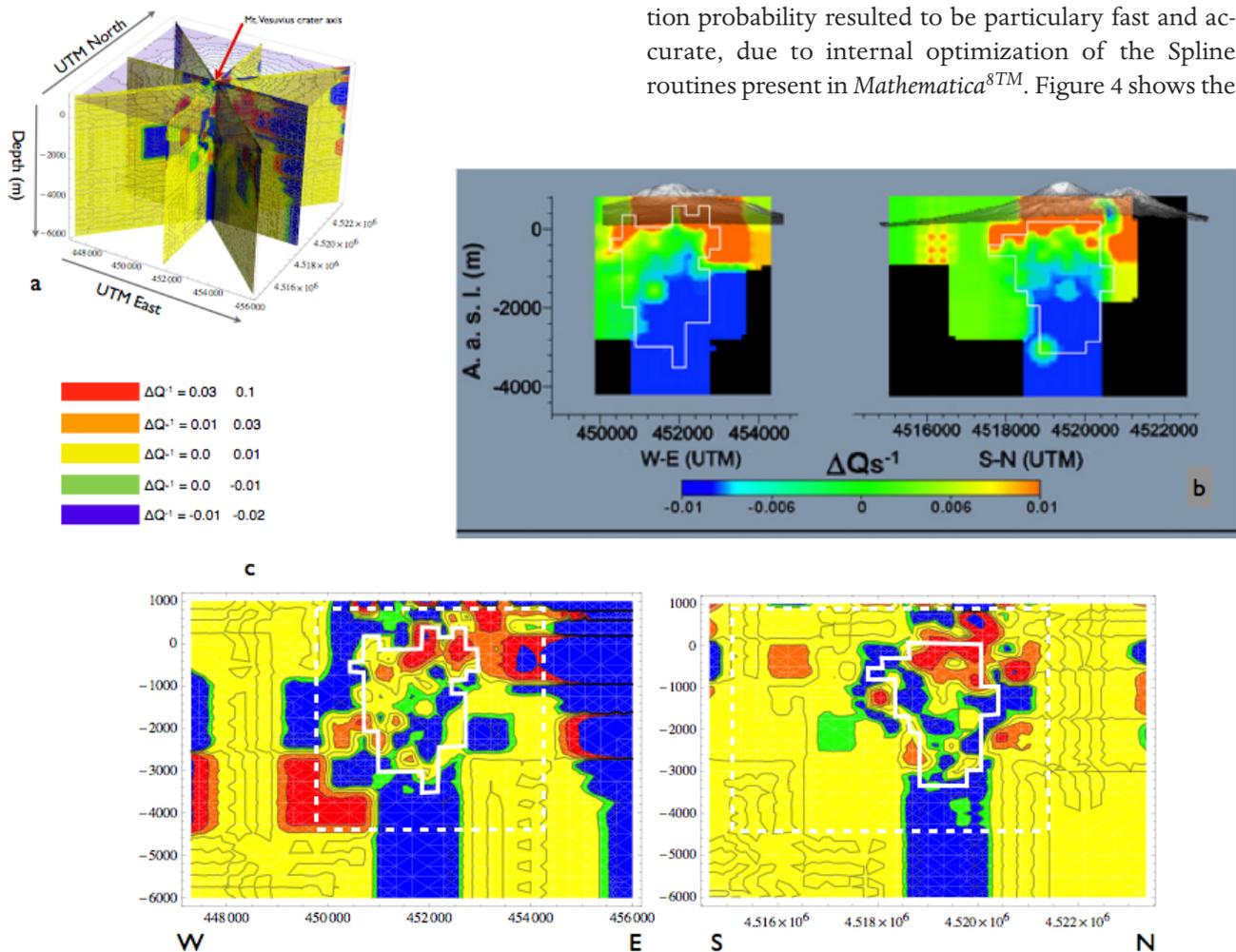


Figure 3. (a) 3D S-wave differential total-attenuation obtained through *SeeVes*. The values inside a 2-km wide strip along the borders of the box are artifacts due to the process of interpolation; (b) W-E and S-N sections of the differential attenuation redrawn by De Siena et al. [2009]; (c) W-E and S-N sections of the differential attenuation obtained using *SeeVes*. To these last images we have reported the borders of the volume with the resolution of 300 m (white lines) and the borders of the volume with 900 m resolution (dashed white lines).

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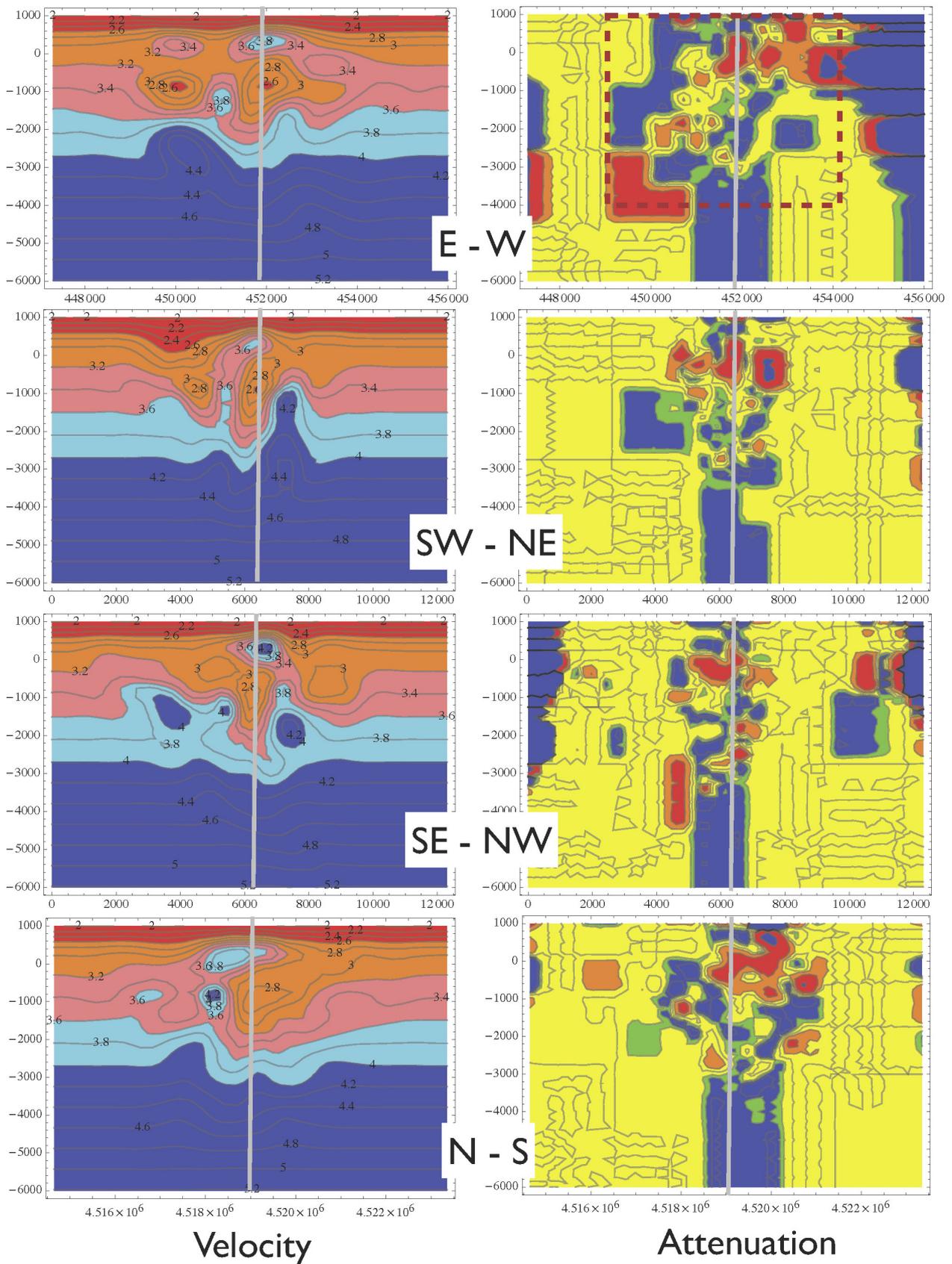


Figure 4. N-S, E-W, NE-SE, NW-SE sections in velocity (left panels) and differential attenuation. Color scale is the same as in Figures 1a and 3a. Isoline values for velocity (km/s) are reported in the left panels. Grey vertical lines indicate the intersection among the section 3-D planes depicted in Figures 1 and 3, which roughly corresponds with the crater axis. The shaded rectangle in the first upper-right panel shows the volume effectively resolved by attenuation tomography.

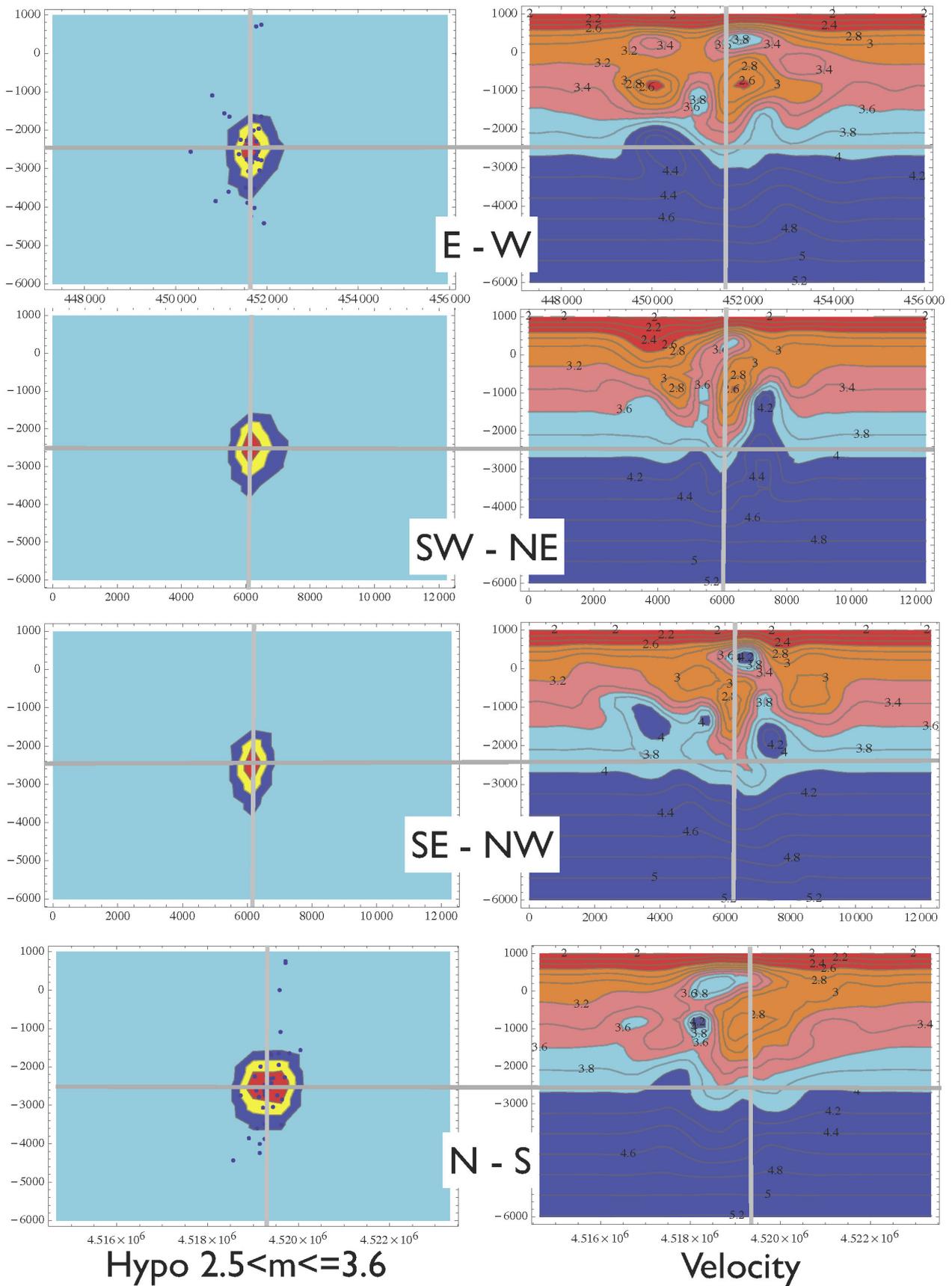


Figure 5. Left panels shows the location probability in the sections EW, NS, SW-NE and SE-NW respectively. The probability is calculated along the sections, and is not integrated along the third coordinate axis. Points in sections N-S and E-W represent all the hypocenter of earthquakes with magnitudes greater than 2.5, projected onto the section plane.

vertical sections (velocity and attenuation) which form the 3-D plots in Figures 1a and 3a, as an additional example of the possible outputs of *SeeVes* that, hence, allows a straightforward comparison between velocity and attenuation images and greatly helps in their interpretation. Figure 5 shows the location probability plotted aside velocity. It is noteworthy that the earthquakes at Mt. Vesuvius have the higher probability to occur in a narrow stripe centered at a depth of 2500 m b.s.l., in a zone characterized by velocity contrasts. In particular, looking at the SE-NW sections in Figure 5 it may appear that the maximum of the location probability is on a fault-shape structure, however in an area with high velocity contrasts.

We believe that the graphical representation of an interpolated field may help in the interpretation more than the representation of raw quantities as the smoothing associated with the interpolation procedure optimally renders the space variation of the field quantity. The possibility to rotate the images in 3D simply using the mouse inside the *Mathematica*^{8TM} notebook is of further help for an optimal visualization. In another paper of this special volume we will show how this new representation has helped in the joint interpretation of geochemical and seismological data in terms of presence of aquifers below the crater zone of Mt. Vesuvius.

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