1D versus 3D velocity models for earthquake locations: a case study in Campania-Lucania region (Southern Italy)

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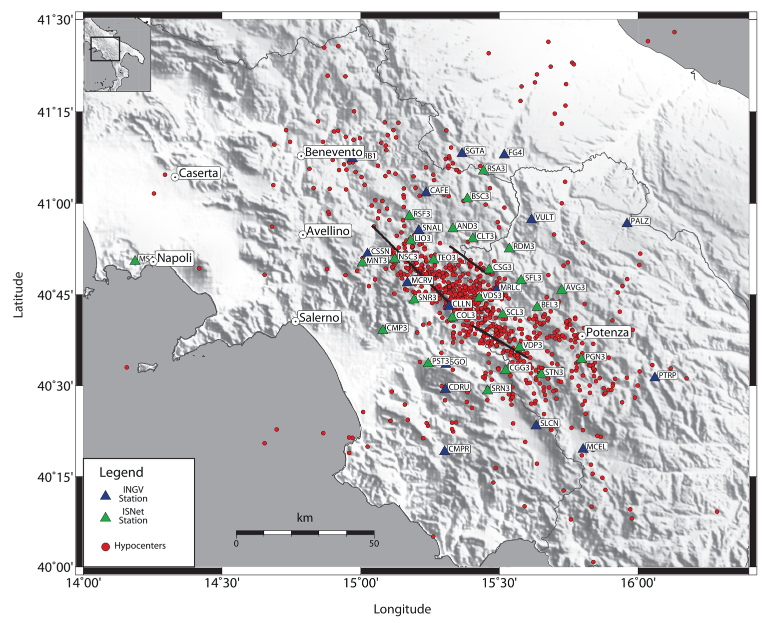
Introduction

Simplified one-dimensional velocity models are generally used both for monitoring and for research purposes in geologically complex seismogenic areas. In these situations the use of 1D models to represent the true three-dimensional velocity distribution can lead to systematic errors in the estimated earthquake locations. This is the case of Campania-Lucania Region (Southern Italy) where the geological and geophysical knowledge reveal a significant lateral variation of the elastic properties of the medium.

The aim of this work is to determine the 1D P-wave velocity model of the study area and compare it with a 3D model in order to investigate possible systematic effects on earthquake locations obtained using 1D model.

Following the approach of Kissling et al. (1995), a P-wave "**minimum 1-D velocity model**" is computed by a joint inversion of **layered velocity model, station corrections** and **hypocenter locations**, using high quality P first-arrival travel times.

In order to interpret the pattern of station corrections, a **three-dimensional crustal velocity** model has been obtained from the inversion of P first-arrival travel times, using a linearized, iterative tomographic algorithm (La Torre et al., 2004; Vanorio et al., 2005). **The final locations computed in the 1D model are compared with the locations obtained in the 3D model.** In particular we studied the role of static corrections in the use of 1D velocity models in complex areas.

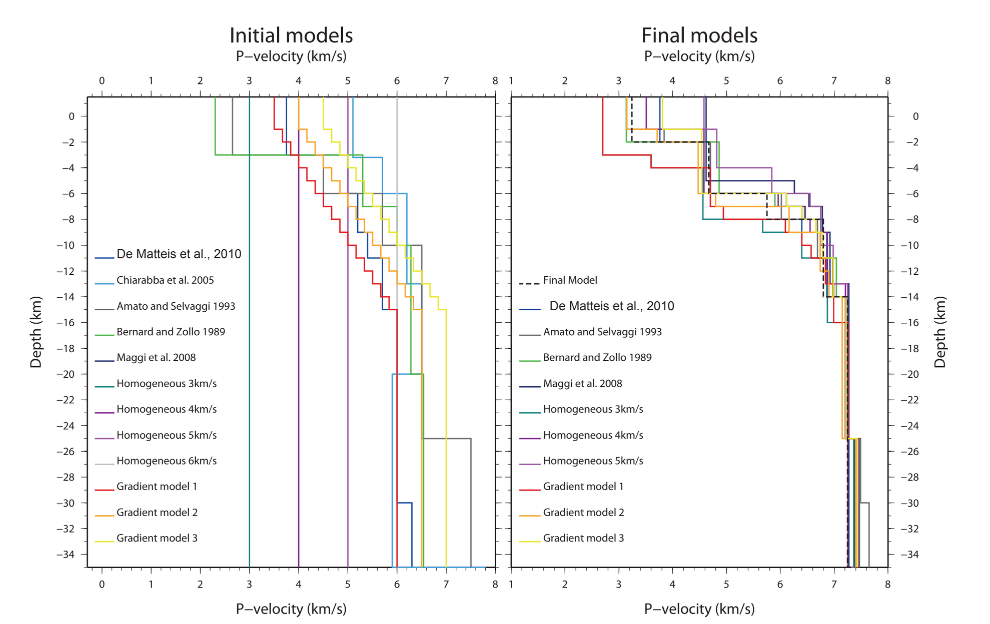


Data

We analyzed the last five years (August 2005 - April 2010) of the instrumental seismicity recorded by AMRA (**ISNet** - Irpinia Seismic Network) and **INGV** (Istituto Nazionale di Geofisica e Vulcanologia) networks deployed in Southern Italy in the area where the Irpinia earthquake on 23 November 1980 (M 6.9) occurred.

We manually picked P- and S- wave arrival times for a total of **8663 P- and 4358 S- phases** on an high-quality waveform dataset from **980 earthquakes** with a local magnitude range of **0.1 ≤ ML≤ 3.2**. A weighting factor was assigned to the reading of the first P- and S-wave arrival times according to the estimated uncertainties. A first evaluation of picking consistency has been performed analyzing the modified Wadati diagram (Chatelain, 1978), which also provides an estimate of an average Vp/Vs ratio. Then, the picking quality has been assessed by performing a preliminary location and looking, for each station, for outliers in the histograms of residuals. We used the code NonLinLoc (Lomax, et al., 2000) for the hypocentral locations.

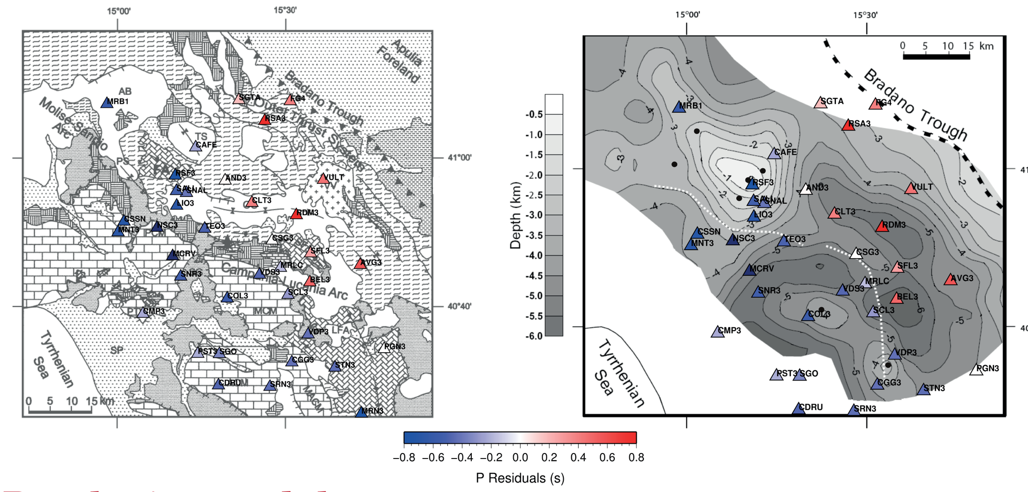
Velocity models



In order to investigate the velocity model for the area we selected the events with a **maximum gap of 200°**, a **minimum of 5 P-arrival time readings**, **maximum location error of 10 km** and maximum **RMS of 0.6 s**. This selection consists of **390 events** for a total of **4620 P-arrival times**.

1D Velocity model

We performed an analysis for the **best P-wave 1D velocity model**, using **VELEST code** (Kissling et al., 1995) using several starting 1D velocity models (in figure on the left). The final models with RMS ranging between 0.135 and 0.139 s. To select the velocity models with the same RMS from a statistical point of view we applied the statistical Test F. These models show a very broad range of P-wave velocities in the first kilometers that decreases with depth (on the right side of the figure). The average velocity models has been used as starting model for a further inversion whose solution represents the best "**Minimum 1D model**" (dotted line in figure on the right). We obtained a **RMS reduction** of about **61%** with a final value of **0.135 s**.



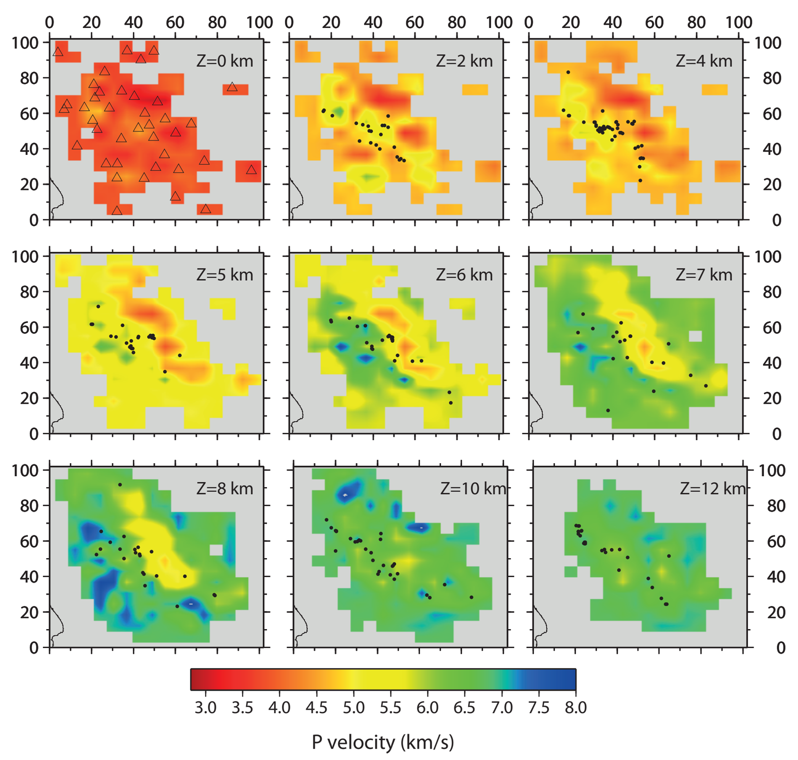
Station corrections are part of the 1D velocity model since they should partly account for the three-dimensionality of the velocity field that can not be adequately represented by the 1D model. The distribution of station corrections shows a **strong lateral variation in a direction orthogonal to the Apenninic chain**, which is consistent with the transition between the carbonatic platform outcrops at South-West and the Miocene sedimentary basins at North-East. We also observe a strong correlation of the larger negative values with lower depth of the Apula carbonate platform top (for more details on the geology see Improta et al., 2003).

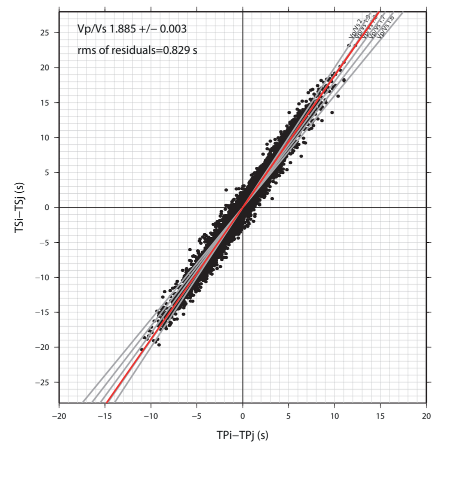
3D velocity model

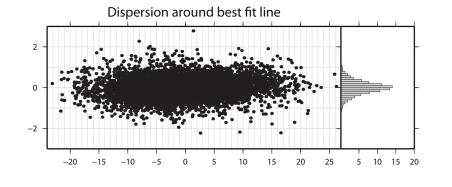
The observation of a **very coherent spatial pattern of station corrections** with the expected velocity variation due to the geological features of the area calls in question the adequacy of a 1D velocity model to represent such strong crustal heterogeneities.

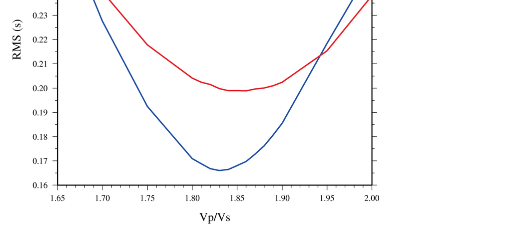
Delay P arrival times are inverted for both earthquake locations and velocity distribution. First arrival travel times of wave fronts are computed through a finite difference solution of the eikonal equation (Podvin et al., 1991) in a fine grid of 0.5 x 0.5 x 0.5 km^3. For each event-receiver pair, travel times are recalculated by numerical integration of the slowness field along the previously traced rays. The parameters are inverted using the **LSQR method** of Paige et al., (1982). For the velocity field we used a nodal representation. Different grid spacing are tested, and we chose the optimal model parametrization according to the minimum of the **Akaike Information Criteria (AIC)** (Akaike, 1974). We performed the inversion starting from the best '1D Minimum velocity model'. The obtained model, with the associated static delay time for each station, are re-inverted to find the final model. We obtained a **RMS reduction** of about **68%** with a final value of **0.1 s**

The tomographic image clearly indicates the **presence of a strong velocity variation along the direction orthogonal to the Appenninic chain**, from 5 to 8-9 km of the crust, defining two domains characterized by relatively low (3.5 - 4.8 km/s) and high (5.2 - 6.5 km/s) velocity respectively. The comparison of retrieved Vp anomalies with the spatial distribution of 1D derived station corrections confirms that the latter reflects the large-scale geological changes.

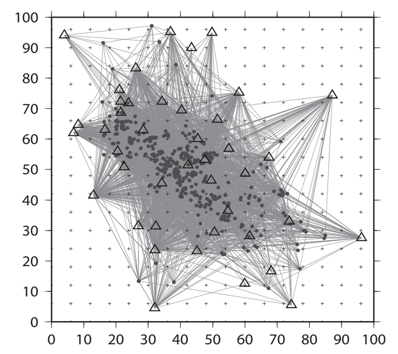








Grid spacing (km^3)	RMS (s)	AIC
24x24x8	0.165	-13386
12x12x4	0.135	-14900
6x6x2	0.105	-15398
3x3x1	0.086	-8759
1.5x1.5x0.5	0.075	19063



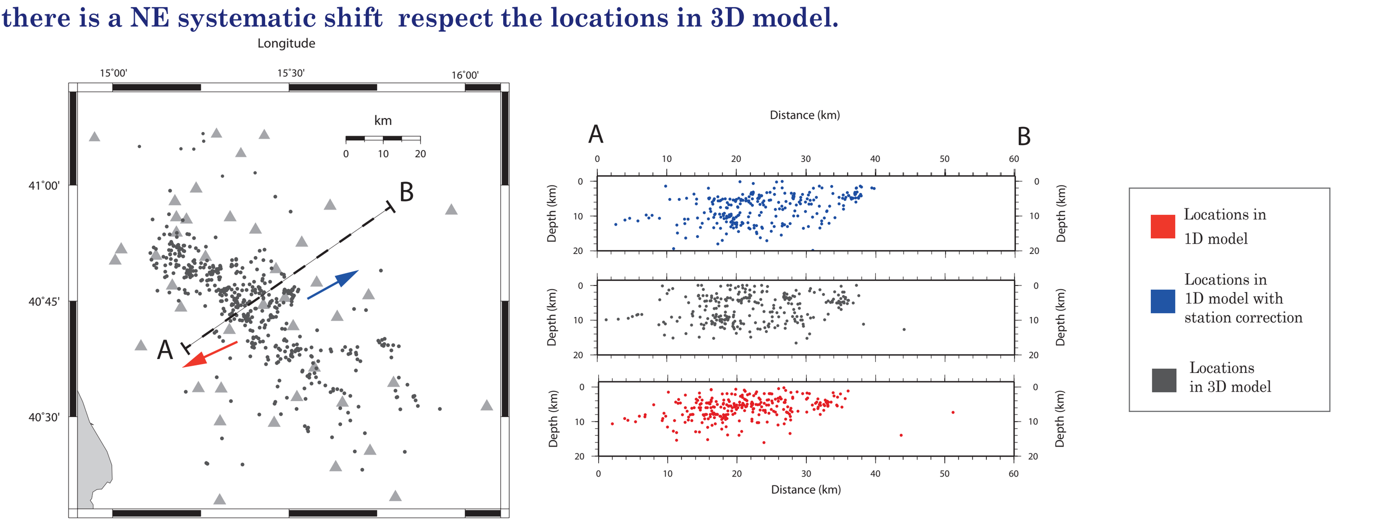
Vp/Vs determination

To improve the hypocentral location also with the use of the S-wave arrival times, an average **Vp/Vs** ratio is computed.

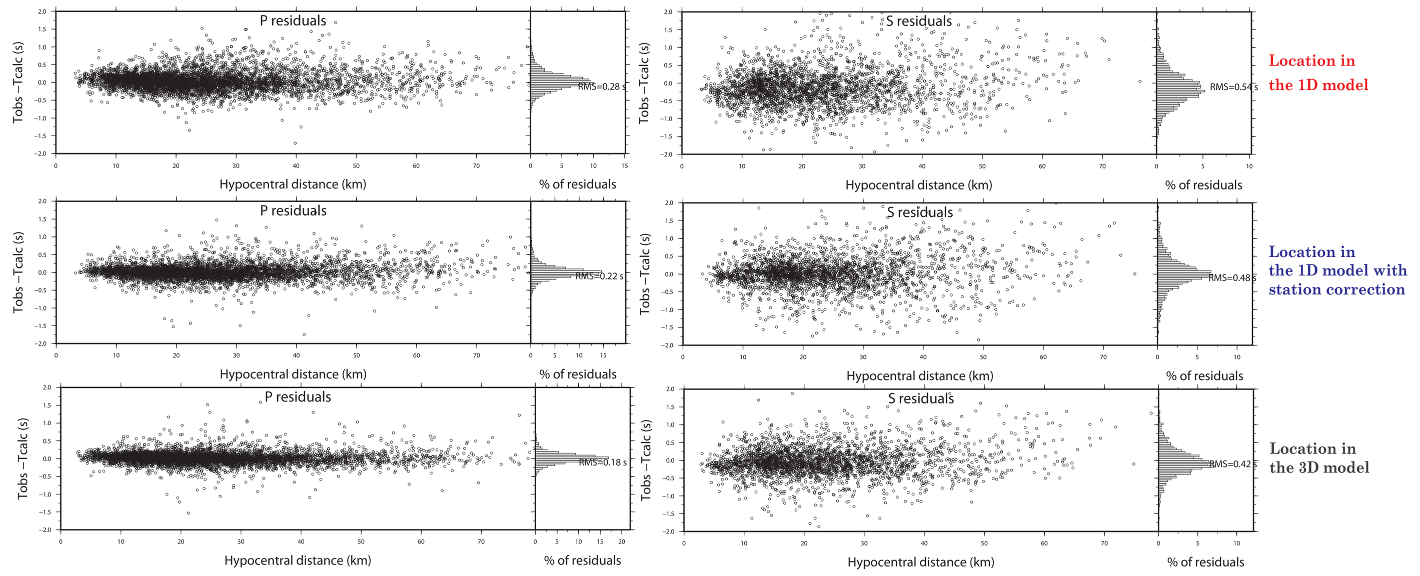
The "**modified Wadati diagram**" provides an estimate of Vp/Vs between 1.8 and 1.9. We also analyzed the **RMS of location** (NonLinLoc code) for different values of Vp/Vs ratio for a selected data-set of events in the 1D and 3D velocity models. We chose an average Vp/Vs ratio of **1.85**. This value is quite similar to that obtained by other studies in the same region (Maggi et al., 2008; De Matteis et al., 2010).

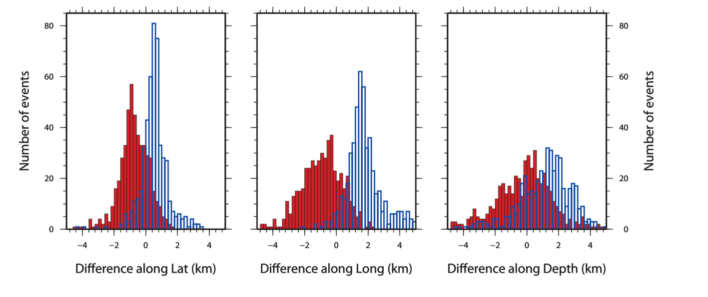
Earthquake locations: 1D vs 3D

We compared the final locations computed using the 3D model (gray), the 1D model (red) and the1D model taking into account the station corrections (blue) of a selected data-set (487 earthquakes with minimum 5P and 2S and gap<200°).
We observed a **SW systematic shift of the locations in 1D model respect the locations in 3D model**. This is due to a northeast low-velocity anomaly not considered in the 1D medium. **When the station corrections were considered there is a NE systematic shift respect the locations in 3D model.**

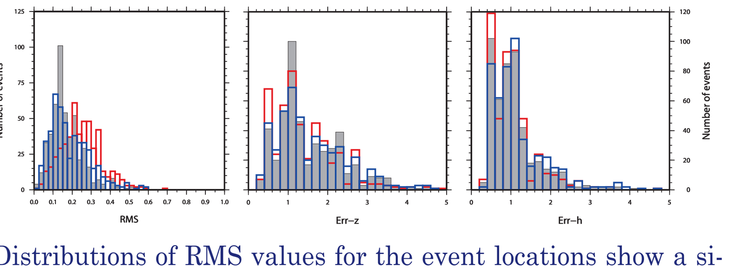


Analyzing the difference between the observed and computed travel times for the different velocity models we generally observed **a better distribution of P-residuals respect to the S-residuals**.
Moreover there is a **gradual improvement in terms of RMS** when we considered the location in 1D model, the 1D model with the station corrections and finally the 3D located earthquakes.

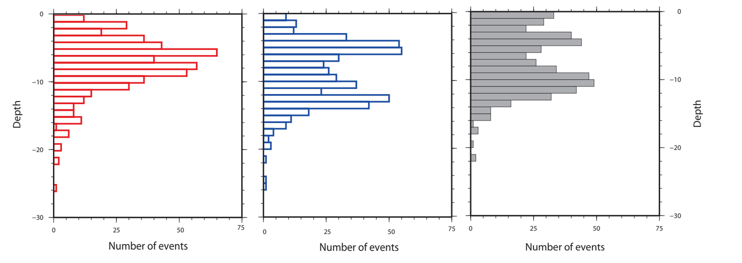




The histograms of the differences between the 1D and 3D locations along latitude, longitude and depth quantifies the shift respect to the 3D location (red: 1D model; blue: 1D model considering the station corrections). It appears to be more important along the Longitude.



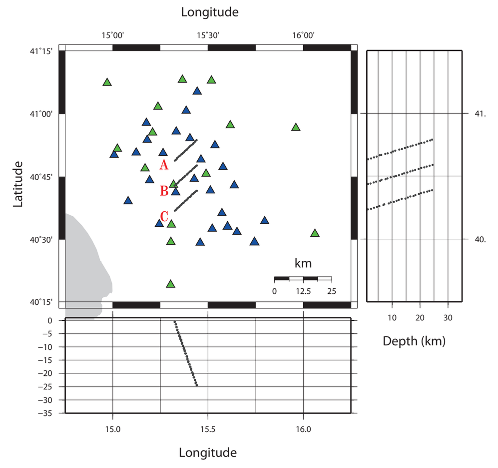
Distributions of RMS values for the event locations show a significant variation for 1D locations (average RMS=0.25 s) , 1D locations with static corrections (RMS=0.19 s) and 3D locations (RMS=0.17 s).
There is no significative difference for the three models on the distributions of vertical (Err-z) and horizontal error (Err-h).



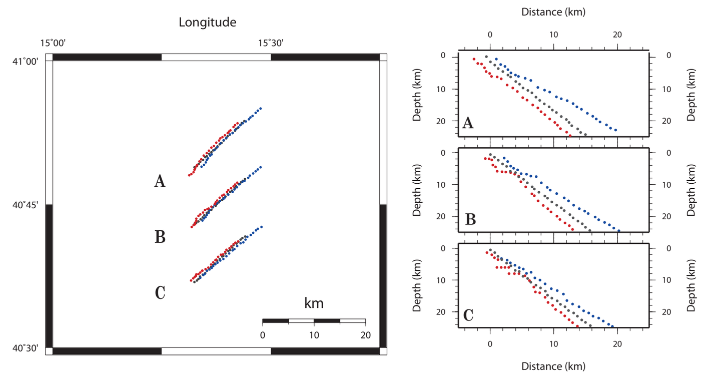
We analysed the distributions of the events with the depth for the the three velocity models. The seismicity appears more concentrated in the first 10 km depth in the1D velocity model.
The distributions became bimodal in the 1D model with station corrections and the 3D model and very similar to each other.

Synthetic case

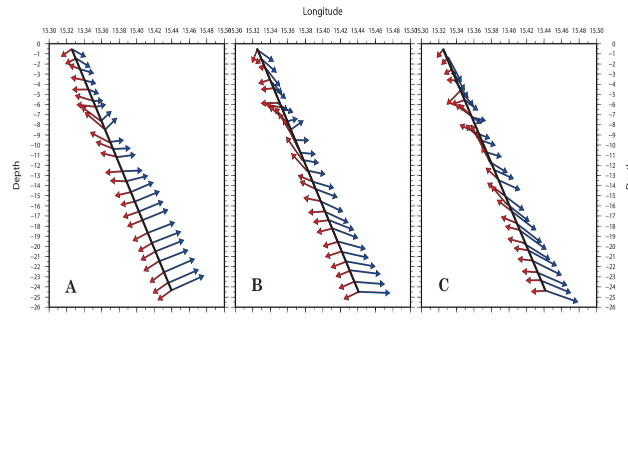
We supposed 75 sources disposed along three lines A, B, C (on the left).
With NLLoc code we computed the theorical travel time (P and S) at 42 station of the ISNet and INGV network in the 3D model.
After we relocated in the 3D velocity model (gray) and in 1D velocity model (with and without the station correction computed for this synthetic test).



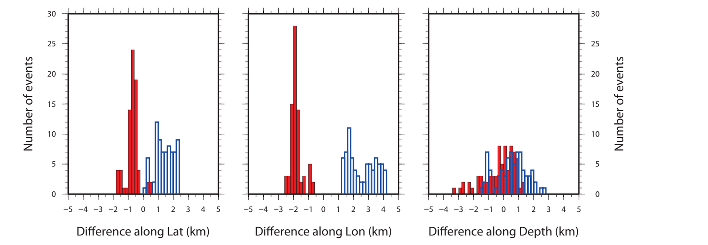
The synthetic test confirms the shift observed in the real case.
In particular we remarked in the section along the lines of sources, a **shift of the source positions which changes the slope of sources lines**.



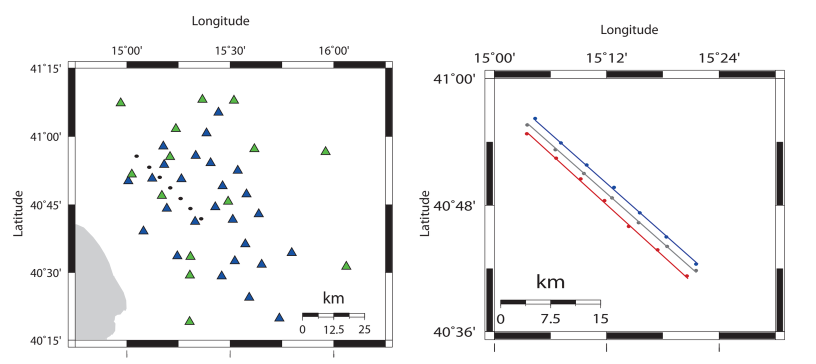
The vector from the position of the sources located in the 3D model to the position of the sources located in the 1D velocity model along the longitude is shown for each lines of sources.
We can observe the strong effect on the depth due to the presence of interfaces on the locations performed with the 1D velocity model not considering the station correction.



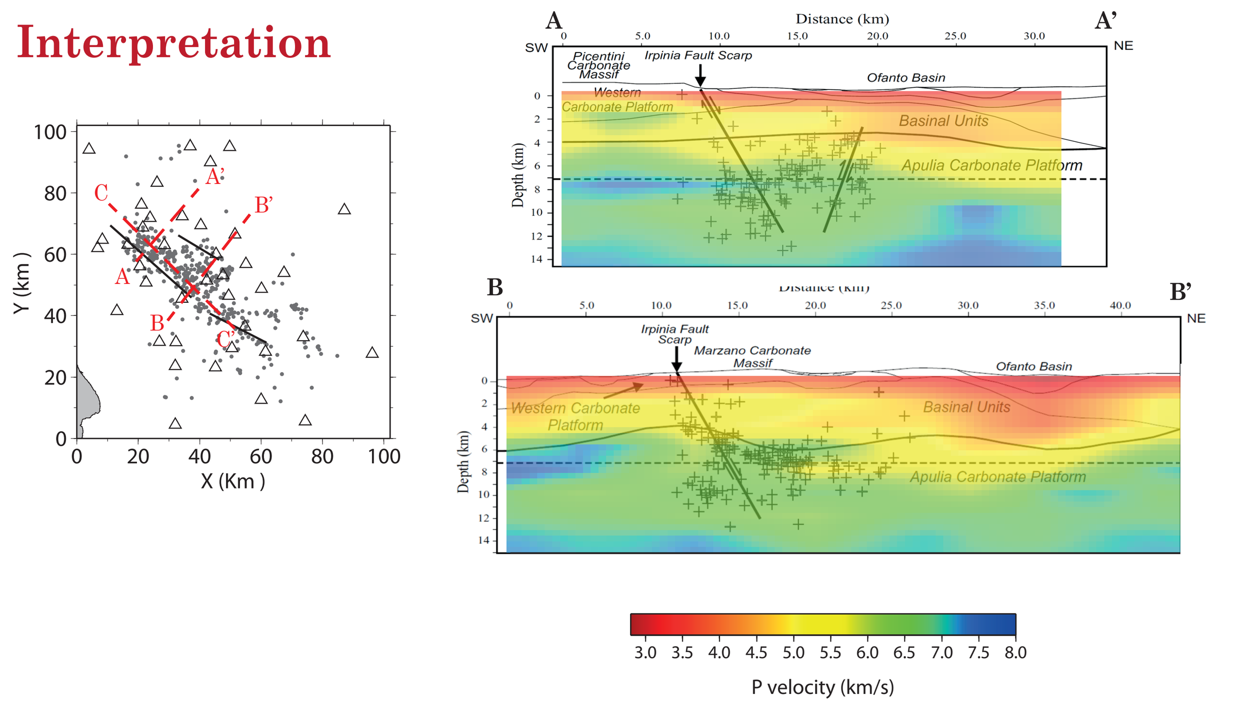
This shift is shown in the histograms of the differences between the 1D locations (with and without station corrections) and 3D locations along latitude, longitude and depth.



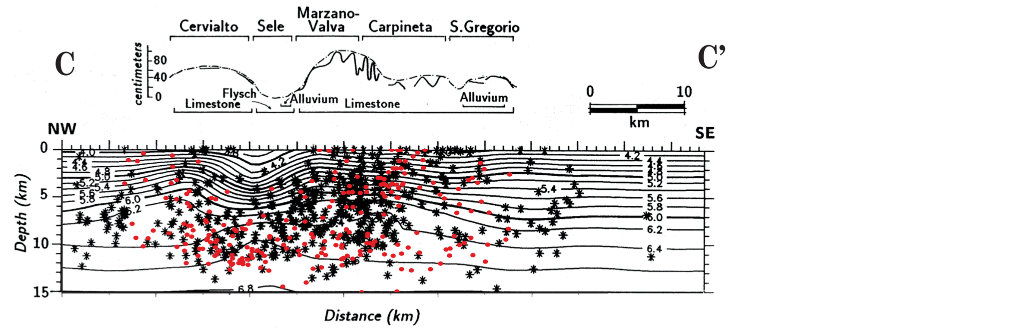
The **epicentral shift** is better highlighted performing another synthetic test in which we considered seven sources at fixed depth (7.5 km) along a tipical Appenninic alignment.



Interpretation



The retreived 3D velocity model is superimposed on two schematic geological sections (A-A' and B-B') proposed by Improta et al. (2003). Aftershocks are redrawn from Amato and Selvaggi (1993). The fault segments are deduced from the model proposed by Pantosti and Valensise (1990).
Note the general **good agreement of the Apulian Carbonate Platform** top with the region of the model caractherized by high velocity values (6.0-6.5 km/s).
In the section A-A' we see a **good corrispondence of the Western Carbonate Platform** with an high velocity anomaly of about 6 km/s (SW) and a shallow **low velocity (3.5 - 4.5 km/s) anomaly in corrispondence of the sedimentary basins (NE)**. This feature is more clear in section B-B' in corrispondence of the Ofanto Basin.



We compared the final locations in the 3D model (red dots) with the distribution of the 23 november 1980 aftershocks (black stars; Amato and Selvaggi, 1993) and with the surface slip profile of the 1980 earthquake (Pantosti and Valensise, 1990). This profile is longitudinal to the Appenninic Chain. **Most of seismicity is concentrated beneath the Marzano-Valva carbonate massif** where a greater surface deformation (about 1 meter) was observed. The **region of the Sele valley**, where no surface slip is observed, is caracterized by a **seismicity gap in the upper 7 km** due to the presence of alluvional sediments.

Conclusion

- We retreive the best 1D P-wave velocity model with station corrections for the Campania-Lucania Region.

- The spatial pattern of station corrections is coherent with the expected velocity variation due to the geological features.

- The 3D P-wave velocity model provides a physical explanation of the station corrections distribution: the tomographic result clearly indicates the presence of a strong velocity variation along the direction orthogonal to the Apenninic chain.

- The relocated seismicity in the different velocity models exibits a systematic shift in the hypocentral distribution. The synthetic tests confirm this observation.

- The recent low magnitude seismicity reproduces the distribution of 23 november 1980 aftershocks.

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