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Minimum 1D velocity models in Central and Southern Italy: a contribution to better constrain hypocentral determinations

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Abstract
We computed one-dimensional (1D) velocity models and station corrections for Central and Southern Italy, inverting re-picked *P*-wave arrival times recorded by the Istituto Nazionale di Geofisica seismic network. The re-picked data yield resolved *P*-wave velocity results and proved to be more suited than bulletin data for detailed tomographic studies. Using the improved velocity models, we relocated the most significant earthquakes which occurred in the Apennines in the past 7 years, achieving constrained hypocentral determinations for events within most of the Apenninic belt. The interpretation of the obtained 1D velocity models allows us to infer interesting features on the deep structure of the Apennines. Smooth velocity gradients with depth and low *P*-wave velocities are observed beneath the Apennines. We believe that our results are effective to constrain hypocentral locations in Italy and may represent a first step towards more detailed seismotectonic analyses.

Key words *earthquake location – 1D velocity model – Italian peninsula*

1. Introduction

The Italian seismic network operated by the Istituto Nazionale di Geofisica (ING) consists of 80 seismic stations that cover the entire peninsula. Seismic phases recorded by the network, integrated with data of local networks managed by other Italian Observatories and Universities, are used to prepare the ING seismic bulletin. Although earthquake hypocenters from the ING bulletin have location errors which are negligible for civil protection purposes and large scale seismotectonic analyses, more accurate hypocentral determinations are necessary for detailed seismotectonic and geodynamic studies. Figure 1 shows the seismicity located in the past 6 years, taken from the ING bulletin. A large number of seismic events of small and moderate magnitude (2.5 to 5.2) are located yearly (about 2000 every year) and may become very useful for detailed seismotectonic investigations. To better constrain the hypocentral determinations, in particular the hypocentral depths, more accurate reference velocity models are required. In this paper, we define reference velocity models for the Italian peninsula, considering the most relevant approaches to this problem (Kissling *et al.*, 1994 and references therein).

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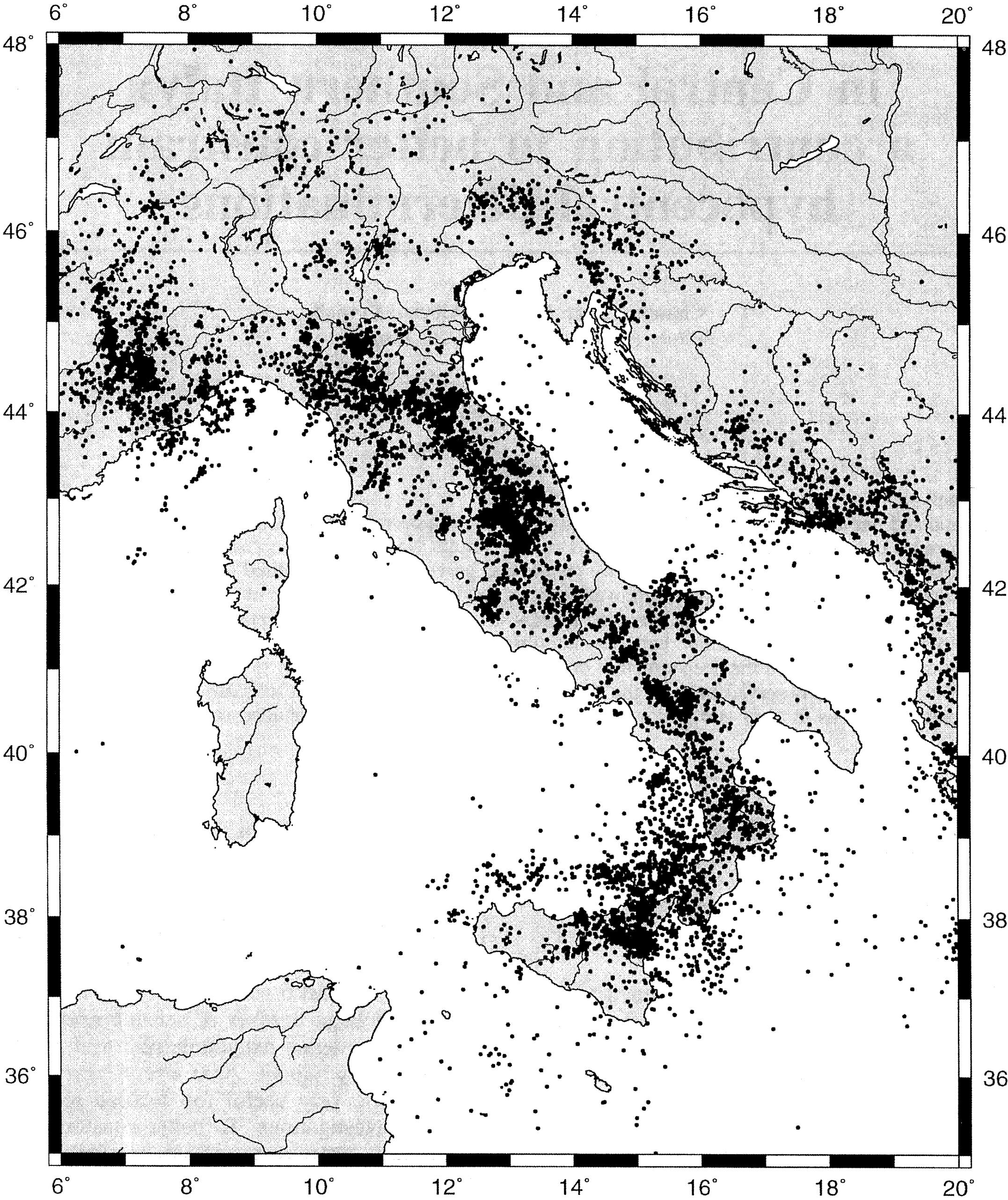

Fig. 1. Map of seismicity which occurred in the past 7 years. Hypocenters are from the ING bulletin (most of the focal depths are kept fixed). The gray circles indicate the sub-crustal seismicity, mainly located in the Calabrian arc.

The influence of 1D velocity models on earthquake location is severe and may result in a convergence toward a local minimum of the solution (Crosson, 1976; Lee and Stewart, 1981; Thurber, 1985, 1992; Lee and Shalev, 1992). Two different approaches exist to mitigate this problem: one consists of choosing the reference model considering all the independent available information existing for the area; the second is based on the inversion of seismic travel times to compute the best fitting 1D velocity model together with static station corrections (Kissling *et al.*, 1994).

Since the ING seismic network spans more than 1000 km with an average station spacing of about 40 km on the Apennines, seismic phases that traveled through the deep crust are used to locate hypocenters. In many cases, the information on the structure (and wave velocity) in the deep crust is poor. Particularly, in areas of recent and active subduction and collision, like the Apennines, the vertical structure of the chain is complex and still poorly defined (Amato *et al.*, 1997). At present, seismic profiling across the Apennines (CROP projects, AA.VV., 1991a,b) are developing and some results are available (AA.VV., 1996). Anyway, the lack of sufficient geological and geophysical information on seismic velocity within and beneath the Apenninic crust spurred us to define reference 1D models and station corrections inverting *P*-wave arrivals. In order to achieve reasonable results, we used re-picked data (taken from Frepoli and Amato, 1997; Montone *et al.*, 1997) that better resolve the fine details of the structure. The re-picked data set only includes seismic phases recorded at the ING seismic network.

2. Minimum 1D model

Earthquake location can be improved using a reference 1D model close to the true earth model and station corrections that mitigate the effects of the structure close to the receiver and deviations from the simple, laterally homogeneous model. Eberhart-Phillips (1990) and Kissling *et al.* (1994) proposed that the natural solution to this problem is the 1D model that itself represents the least square solution to the coupled hypocenter-velocity model parameter relation. They called this solution the minimum 1D model. Although Chiarabba *et al.* (1995) have shown that sufficient, independent, *a priori* information on the earth structure available for the modelling area may improve the solution to the problem, we applied the technique proposed by Kissling *et al.* (1994) in the Apennines, due to the scarce and poorly resolved information available to constrain the Apenninic crustal velocity structure. These reference 1D velocity models help the convergence to a stable hypocentral determination and may be used in subsequent three-dimensional tomographic studies.

Following this approach, we first established the starting 1D models considering the available information on the crustal structure (AA.VV, 1991a,b; 1996). Starting velocity values were selected considering available data and the results of Alessandrini *et al.* (1995) and Chiarabba and Amato (1996). Four layers have been used for the crust and one for the mantle beneath the Moho. The number of layers and their thickness were selected to optimize model parameterization and parameter resolution, *i.e.*, we invert for the maximum resolvable number of layers. The thickness of the first layer (12 km) accounts for the shallow thrust units building the Apennines. The sharp velocity discontinuity at 12 km corresponds to the average depth of the pre-Mesozoic basement. The Moho depth (35 km) is an average for the Apenninic belt from Amato *et al.* (1997).

Then, earthquakes are located using HYPOINVERSE (Klein, 1978) and selected for the inversion based on hypocentral errors, and number of phases. The selected events are inverted using VELEST (see Ellsworth, 1977; Roecker, 1981; Kradolfer, 1989; Kissling *et al.*, 1994 for details of the technique) to calculate the adjustments of *P*-wave velocities (layer depths are kept fixed) and station corrections. Finally, earthquakes are re-located with HYPOINVERSE using the computed models and the two different locations are compared.

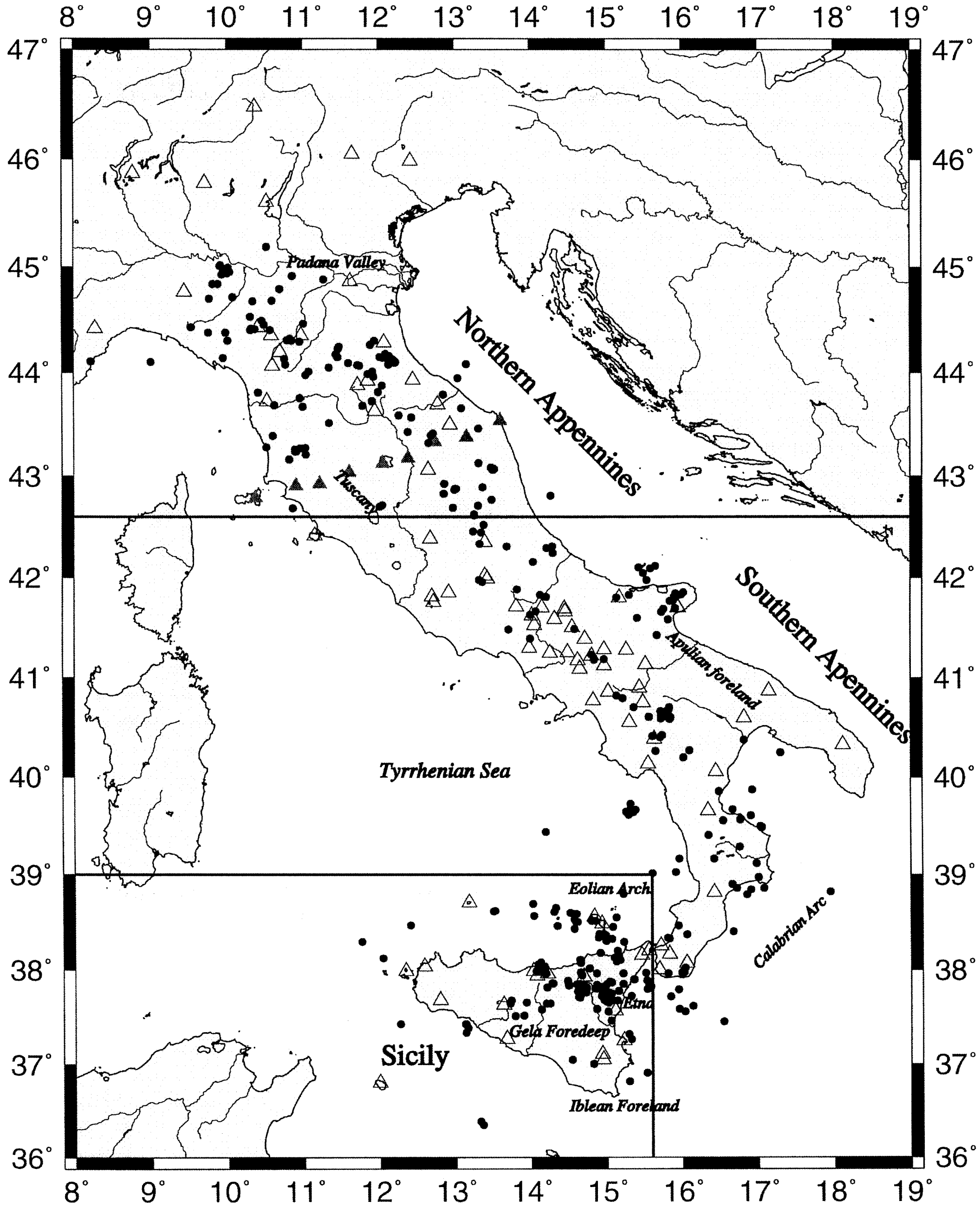

Fig. 2. Data set used in this study. The three sub-regions are shown. Open triangles are the seismic stations of the ING network. Gray triangles are stations of the 1994 temporary array that operated for 5 months (see Amato *et al.*, 1994) added to better constrain the structure of the Northern Apennines. Black dots are earthquakes used in the inversion.

3. Data selection and inversion procedure

P-wave arrivals from 422 earthquakes which occurred in the past 7 years within the Apenninic belt (fig. 2) have been accurately re-picked to obtain a high quality data set. Earthquakes in this data set have a magnitude ranging between 2.7 and 5.2, and represent most of the energy released by earthquakes in the Apennines in the analyzed period. We did not include events for which only few arrival times are available (earthquakes with magnitude less than 2.7). Reading accuracy is about 0.02-0.05 s for *P*-arrivals at epicentral distances less than 180 km, while reading errors of long-traveling phases can be large. In particular, very emergent P_n arrivals are generally observed at an epicentral distance between 180 and 300 km and they can be easily missed during the picking procedure. Such phase misidentification (the direct *P* is picked instead of the P_n) may result in an inappropriate modelling of the first arrival during the location. To avoid this problem producing artifacts in the solution, we used only *P*-wave arrivals within a distance of 180 km from the epicenter and *P*-wave residuals smaller than 0.8 s, excluding most of the P_n. We believe that this selection is important to constrain earthquake locations.

The Apennines were divided into three main regions, namely the Northern Apennines, the Southern Apennines, and Sicily, accounting for both difference in structural setting and data distribution (see fig. 2). The paucity of earthquakes occurred within the Southern Apenninic belt in the analyzed period (about 47 events with $M > 2.7$) compelled us to include Calabria within the same sub-region.

A total of 384 events located using HYPOINVERSE (Klein, 1978) with errors less than 6 km (both in horizontal and vertical) and with at least 14 first arrivals were selected for the inversions. The damped least squares best fitting 1D velocity model and station corrections were calculated for each sub-region using VELEST, a state of the art technique widely used for 1D model optimization (Ellsworth, 1977). Damping parameters for velocity variations and station corrections were selected optimizing the data misfit reduction and the parameter resolution.

4. Results

4.1. *The Northern Apennines*

A total of 1360 *P*-wave arrivals from 135 selected earthquakes were inverted. After 4 iterations, we obtained a variance improvement of about 86%, and a final rms of 0.29 s. The computed 1D model is shown in fig. 3 compared to the starting one. The errors in velocity model parameters are below 0.15 km/s (see fig. 3). We note an increase in the smoothness of the velocity variation with depth. A value of 5.7 km/s is found for the upper crust, and values around 6.2 km/s are computed for the lower crust, suggesting the absence of a strong velocity gradient with depth. At a depth of 35 km the *P*-wave velocity is 7.5 km/s.

Station corrections shown in fig. 4 present an interesting pattern. They reflect both the structure close to the receiver (the uppermost crust) and deviations from the computed 1D model due to lateral deep velocity heterogeneities. The correction values, ranging between +2 s and −2 s, are reasonably resolved – diagonal elements close to 0.9. Positive corrections are observed along the Apenninic chain. Since the uppermost crust here is composed of mainly limestone overthrust units, we believe that such strong corrections are related to low velocities in the lower crust. Stations along the Tyrrhenian coast, mainly belonging to the temporary array that cross the Apennines (Amato *et al.*, 1994), exhibit negative values reflecting higher velocities with respect to the computed 1D model in the deep crust. Stations in the Padana valley have strong positive delays, consistent with the presence of thick Quaternary deposits.

Earthquakes relocated by VELEST (fig. 5) present a consistent decrease of rms values, and location errors below 3 km. Average values of errors in origin time, *x*, *y* and *z* are 0.25 s, 1.68 km, 1.91 km, and 1.80 km respectively. The few and sparse events occurring close to the Tyrrhenian coast have larger errors, due to the poor station coverage (the temporary array operated for only five months, Amato *et al.* 1994). Since the ING seismic network is very sparse there, focal depths are difficult to obtain.

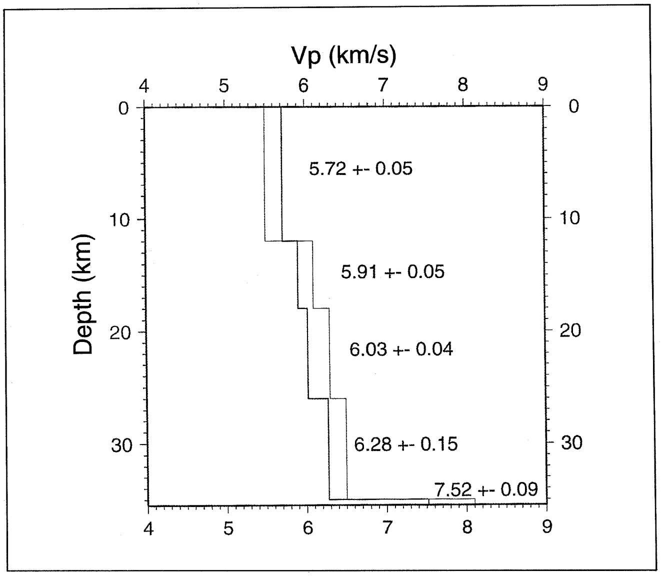

Fig. 3. Starting (light) and final (bold) *P*-wave 1D velocity models. Note the trend of increase in velocity in the upper layer and a decrease in the deeper ones.

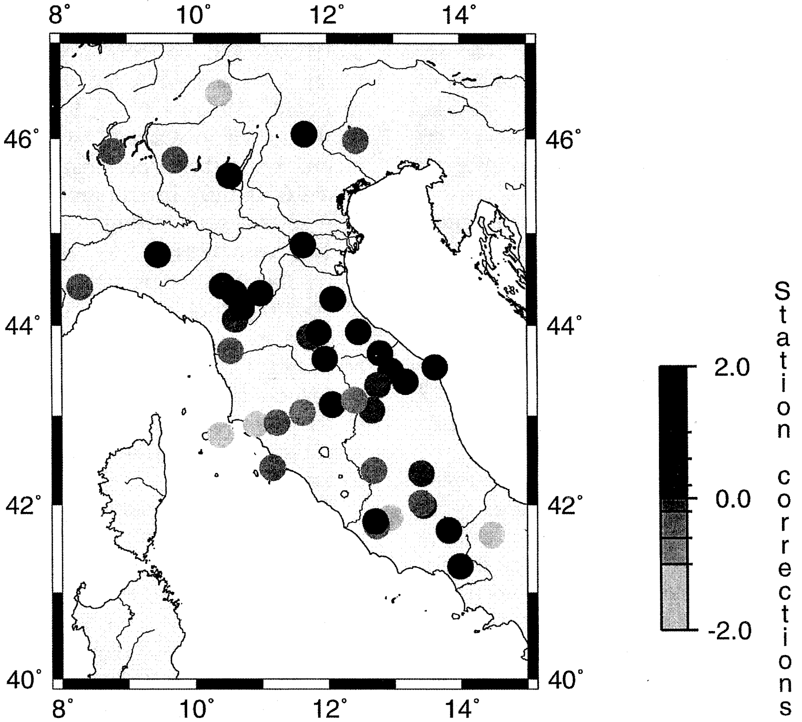

Fig. 4. Station corrections for the Northern Apennines. Positive values indicate low velocities for stations located along the belt while negative values observed in the Tyrrhenian area indicate high velocities.

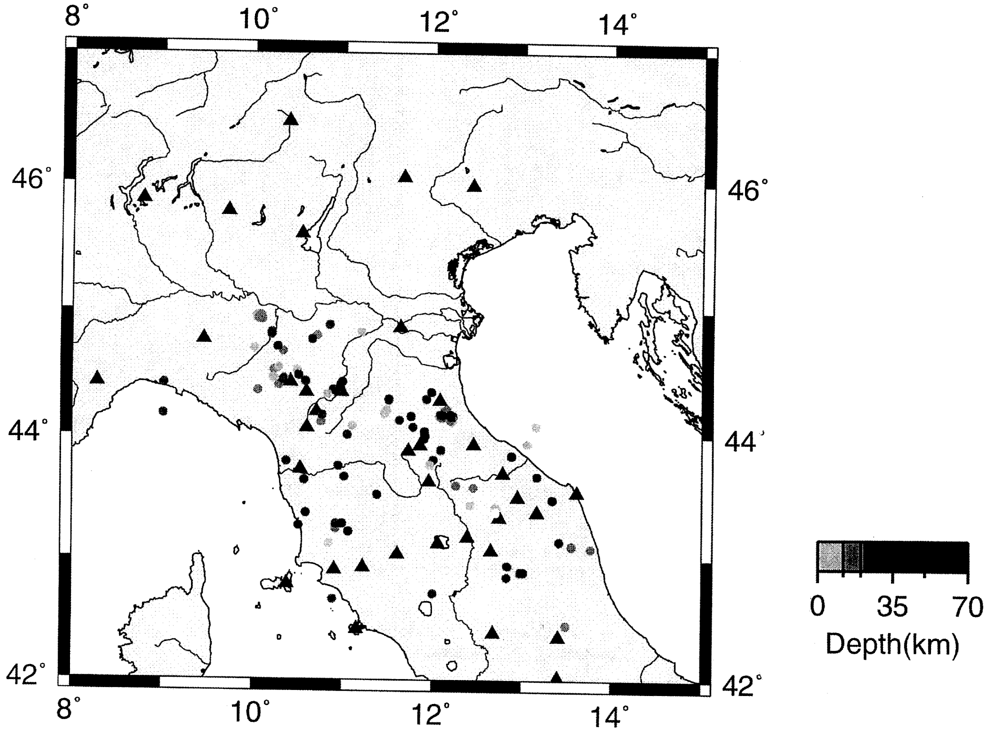

Fig. 5. Map of earthquakes relocated by VELEST, to be compared with fig. 2. The horizontal hypocentral variations are small between the two locations.

4.2. *The Southern Apennines*

A total of 1213 first arrivals from 114 earthquakes were inverted in this sub-region. The variance improvement after four iterations is 85%, the final rms is 0.37 s. Standard deviations of the modeled velocity values are less than 0.18 km/s. The computed model is shown in fig. 6 compared to the starting model. A trend of smoothing the solution is evident, as in the previous case. At the surface a value close to 5.9 km/s is observed. Velocities slightly increase with depth and values close to 6.3 km/s are modeled in the deeper crust. At 35 km the *P*-wave velocity is around 7.6 km/s.

Positive station corrections (fig. 7) are observed in the Southern Apenninic belt, suggesting the presence of low velocities in the crust. Slightly negative values are found both in the Adriatic and Iblean foreland, indicating high velocities in the crust and large lateral velocity anomalies across the Apennines. The corrections for stations located north of 42 degrees of latitude are less constrained, due to the low number of rays traveling there (rays traveling more than 180 km are not considered). Parameter resolution of corrections in the central part of the model is fairly good, with diagonal elements higher than 0.6.

Location errors and rms values decrease for the relocated earthquakes (shown in fig. 8). Average location errors are 0.19 s for the origin time, and 1.84 km, 1.11 km, and 2.1 km, for *x*, *y* and *z*, respectively. Hypocenters have small errors within the Southern Apenninic belt, but slightly larger ones on the Calabrian arc, due to the sparse station distribution.

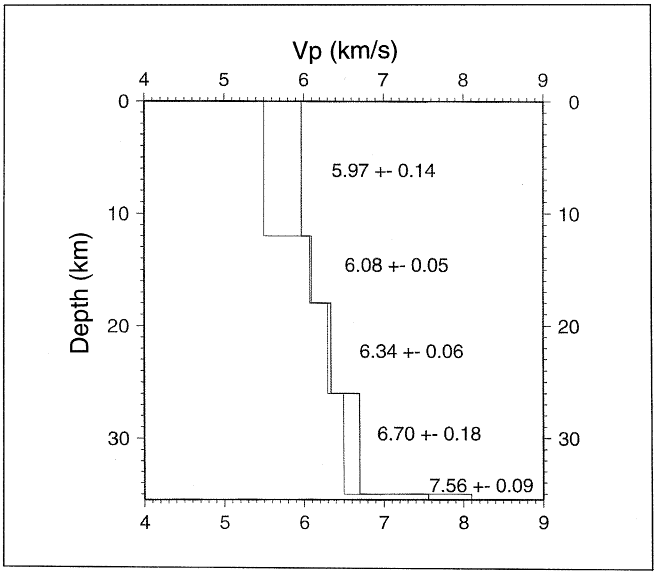

Fig. 6. Starting (light) and final (bold) *P*-wave 1D velocity models for the Southern Apennines. Note the trend of increase in velocity in the upper layer and the low velocity at the Moho (35 km depth).

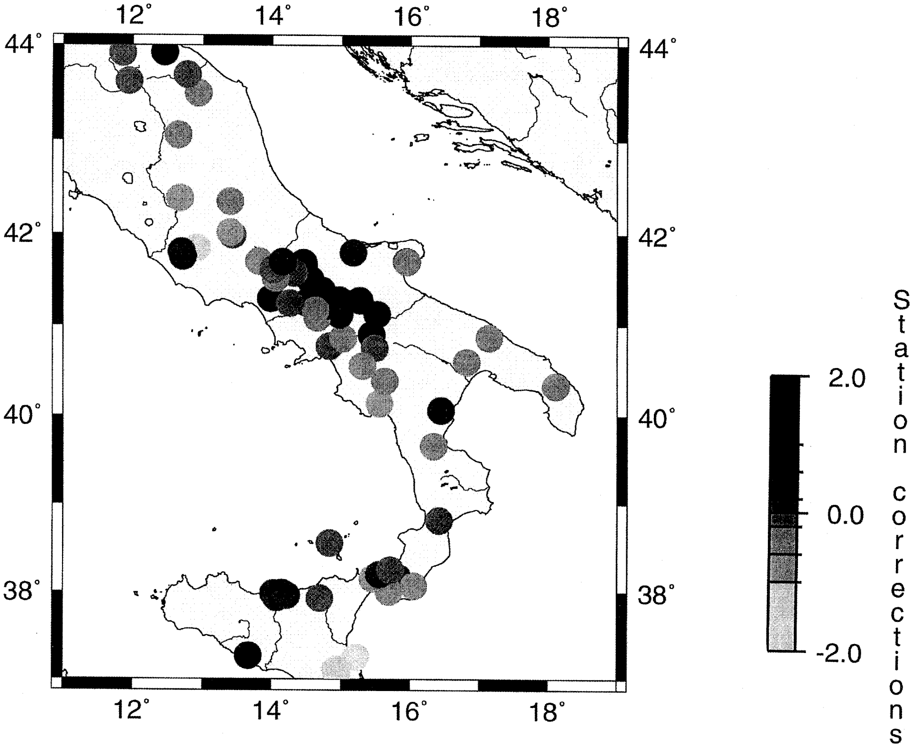

Fig. 7. Station corrections for the Southern Apennines. Positive values along the belt indicate low velocities while negative values in the Adriatic area reflect high velocities.

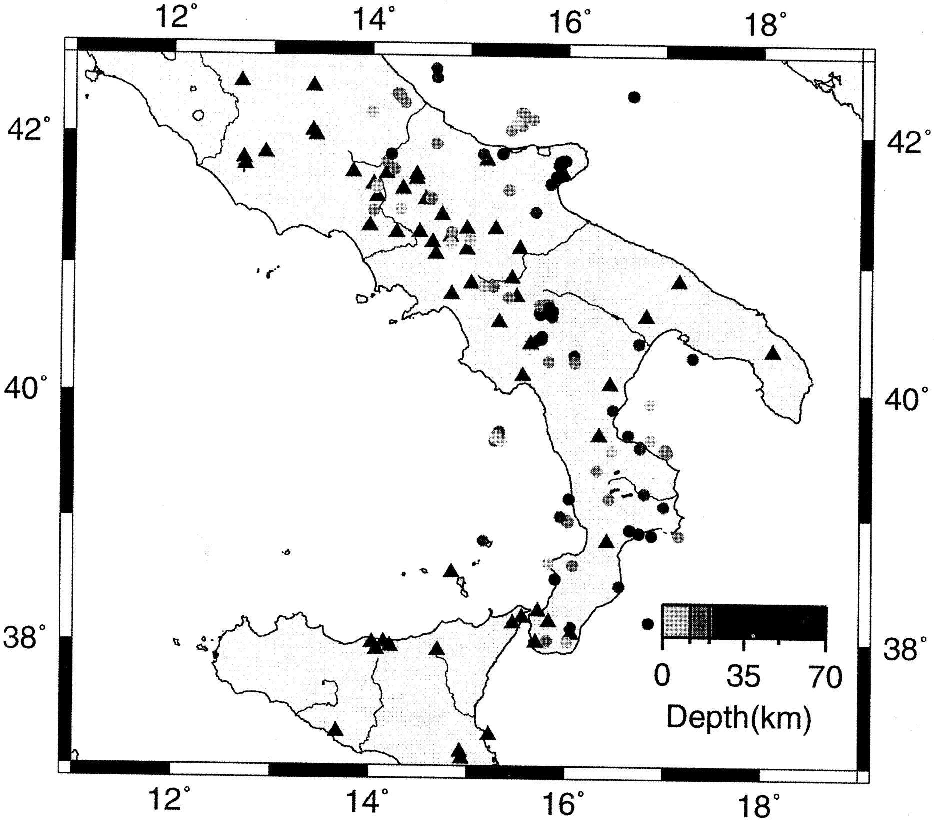

Fig. 8. Map of earthquakes relocated by VELEST, to be compared with fig. 2. The horizontal hypocentral variations between the two locations are small.

4.3. *Sicily*

A total of 1763 *P*-wave arrivals from 133 selected earthquakes were inverted achieving 83% variance reduction and a final rms of 0.42 s after 4 iterations. The obtained 1D model, compared with the starting one, is shown in fig. 9. We find a different pattern of velocity variations with respect to the Apennines. The velocity in the upper crust is reduced to 5.2 km/s, and sharp velocity discontinuities are recovered in the lower crust with values up to 6.8 km/s at 26 km depth. At 35 km depth, the *P*-wave velocity is around 7.3 km/s, much lower than expected values at the Moho. Standard deviations of velocity values are 0.11 km/s at 12 and 18 km depth, 0.05 km/s at 26, and 35 km depth.

Station corrections (fig. 10) are strongly positive in Southwestern/Central Sicily, consistently with the thick deposit of soft sediment of the Gela foredeep. Positive values are also found at the two stations surrounding the Etna volcano, while negative values are evident in the Calabrian arc and on the Tyrrhenian islands.

Location rms of the events decreases and final average location errors are 0.22 s for the origin time, 1.67, 1.59 and 2.64 km for the *x*, *y* and *z* coordinates. Relocated hypocenters are shown in fig. 11.

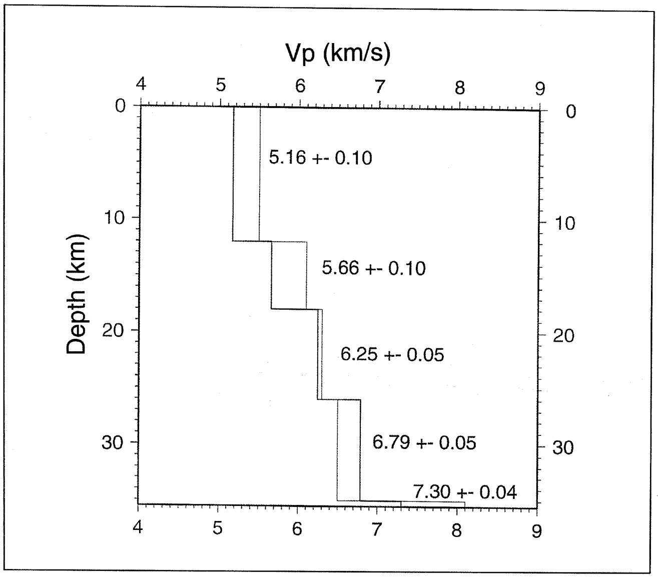

Fig. 9. Starting (light) and final (bold) *P*-wave 1D velocity models for Sicily. Note the decrease in velocity in the upper layer and the presence of velocity discontinuities in the lower crust.

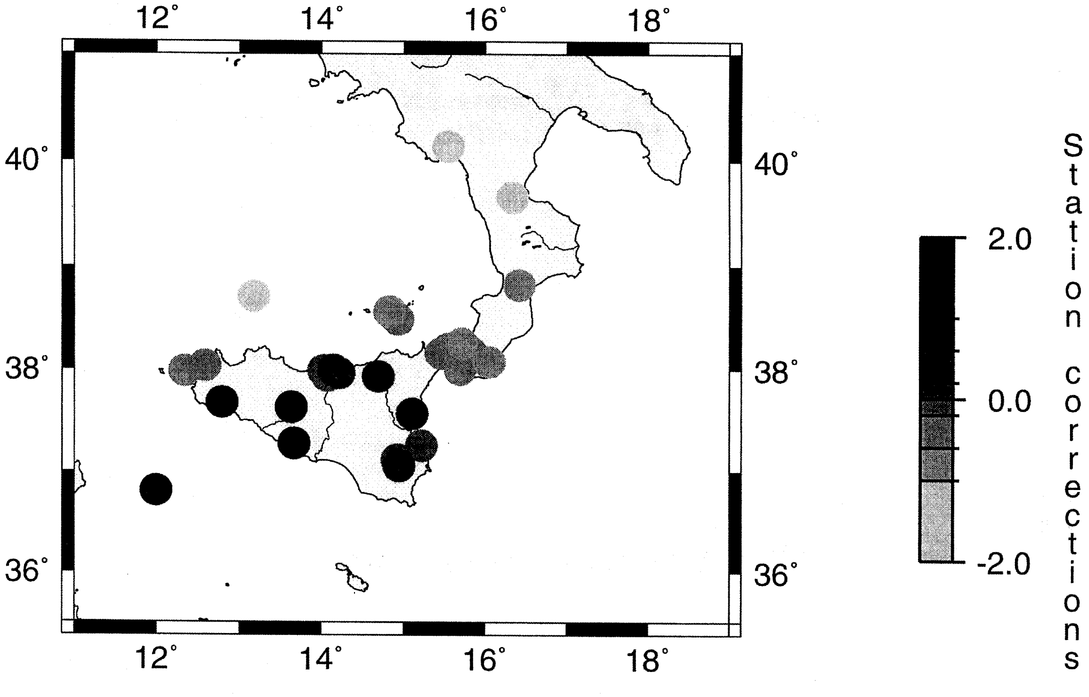

Fig. 10. Station corrections for Sicily. Positive values are found in the Gela foredeep and in the surrounding of Mt. Etna, while negative values are observed in the Tyrrhenian area, indicating high velocities.

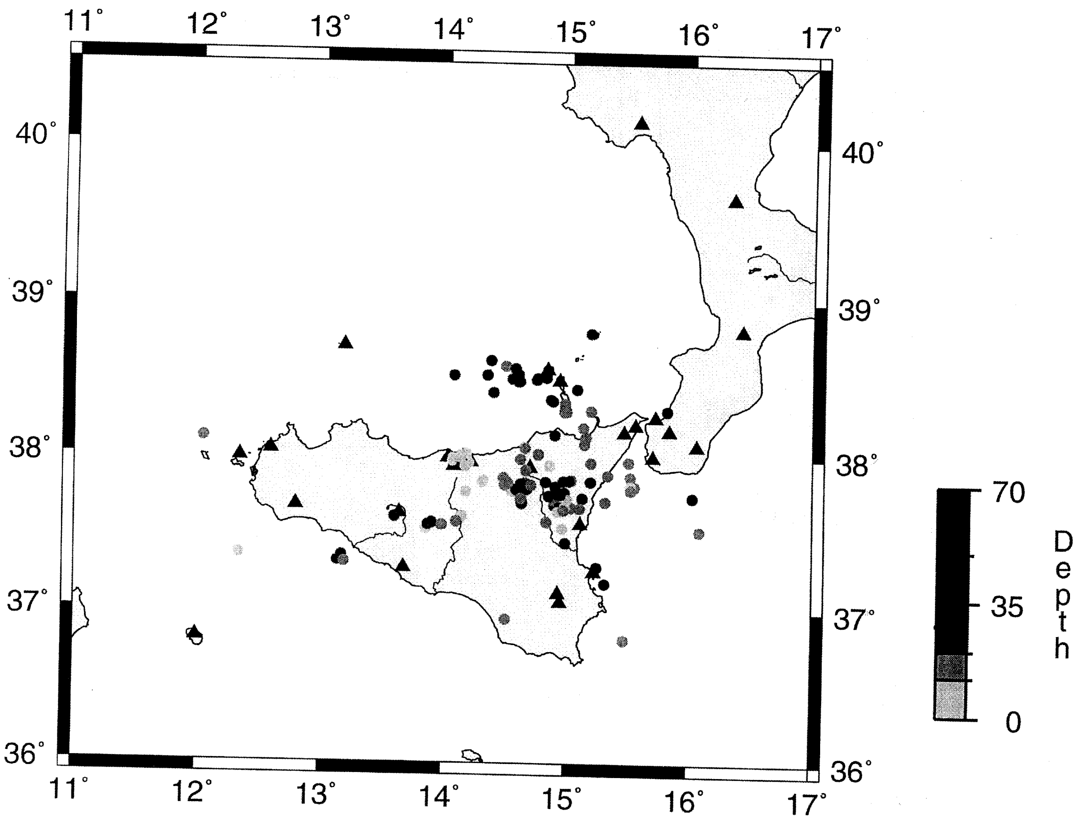

Fig. 11. Map of earthquakes relocated by VELEST, to be compared with fig. 2. The horizontal hypocentral variations are small between the two locations. Several earthquakes are located close together and beneath 30 km depth.

5. Results from bulletin data

We computed the minimum 1D model for the Northern Apennines using *P*-wave arrival times from the ING bulletin. This data set, obviously larger than the re-picked one, suffers for not negligible errors. Chiarabba and Amato (1996) showed that the difference in the two data sets can be large (fig. 12), with a trend of fictitious systematic delays in the bulletin data. 2426 *P*-wave observations from 200 selected events were inverted using similar parameters as the previous inversion of accurate data. We found a variance improvement of 52% and a final rms of 0.63 s after 4 iteration steps. We note that the rms obtained by this inversion is twice the rms obtained by the finely re-picked data (0.29 s). Thus, the data misfit reduction obtained inverting bulletin data is much lower than the reduction achieved using re-picked data. This suggests the presence of a significant noise in the bulletin data. Therefore, we favor the results obtained with the re-picked data due to their higher resolution.

Figure 13 shows the V_p model and fig. 14 the station corrections obtained by this inversion. Figure 15 shows the earthquakes relocated by VELEST. A first order similarity between the results of the inversions of the two data sets can be noted, at least in the lower crust.

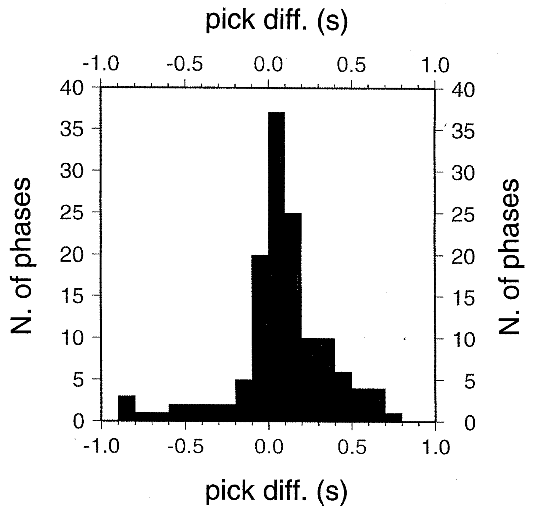

Fig. 12. Difference in *P*-wave arrival times between the bulletin and the re-picked data for 20 events.

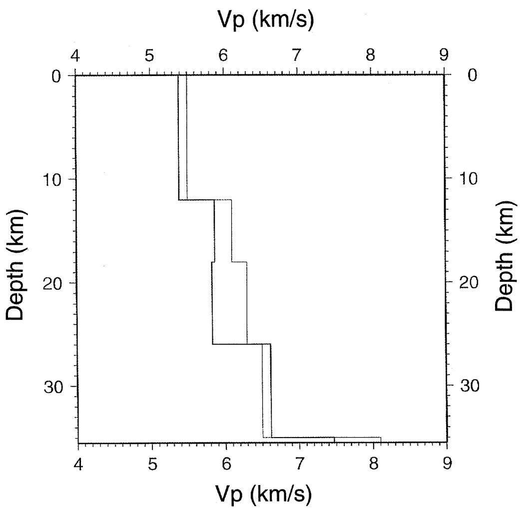

Fig. 13. Starting (light) and final (bold) *P*-wave 1D velocity models. Note the trend of decreasing the velocity in the lower crust.

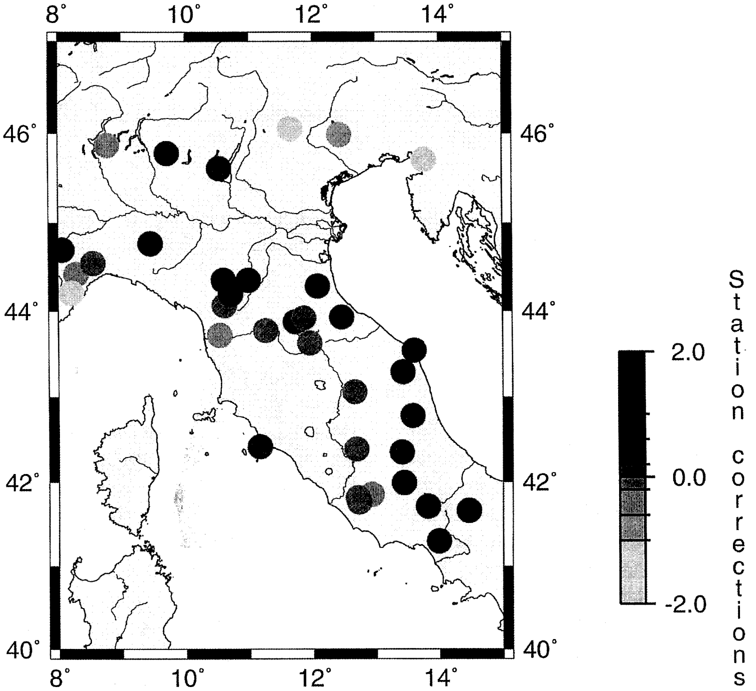

Fig. 14. Station corrections for the Northern Apennines. Positive values are observed along the belt, in agreement with results of the re-picked data inversion.

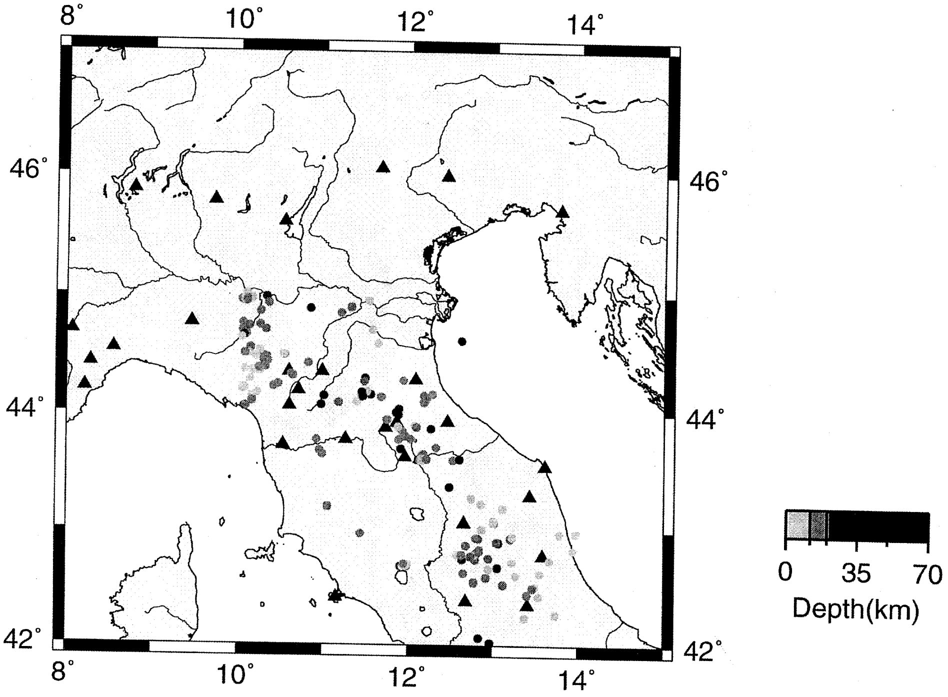

Fig. 15. Earthquakes relocated by VELEST (arrival times from the bulletin).

6. Earthquake relocation

In order to test if our computed models effectively improve the routine earthquake location, we relocated the whole re-picked data set using HYPOINVERSE with the computed minimum 1D models and station corrections. Damping parameters and data weighting functions were the same as the first HYPOINVERSE location (before the velocity inversion).

Figure 16 shows the difference in rms between the first locations and those obtained using the computed models. We note a consistent decrease of rms values for the relocated earthquakes. Moreover, residuals at the stations within 180 km of epicentral distance are strongly reduced. Although hypocentral errors are for some cases larger with the new model, we are satisfied with the relocations, because of the reduction of rms and the fit of *P*-wave arrivals at close distance from the epicenter.

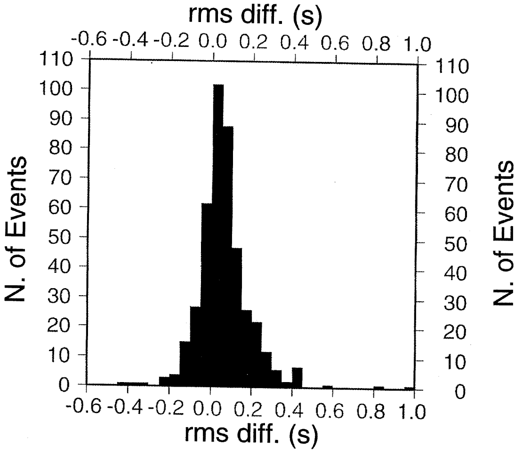

Fig. 16. Difference in rms of residuals between the first location and the HYPOINVERSE re-location with the computed models and station corrections. Note the consistent decrease in rms value obtained using the new models that indicate a good improvement of the solutions.

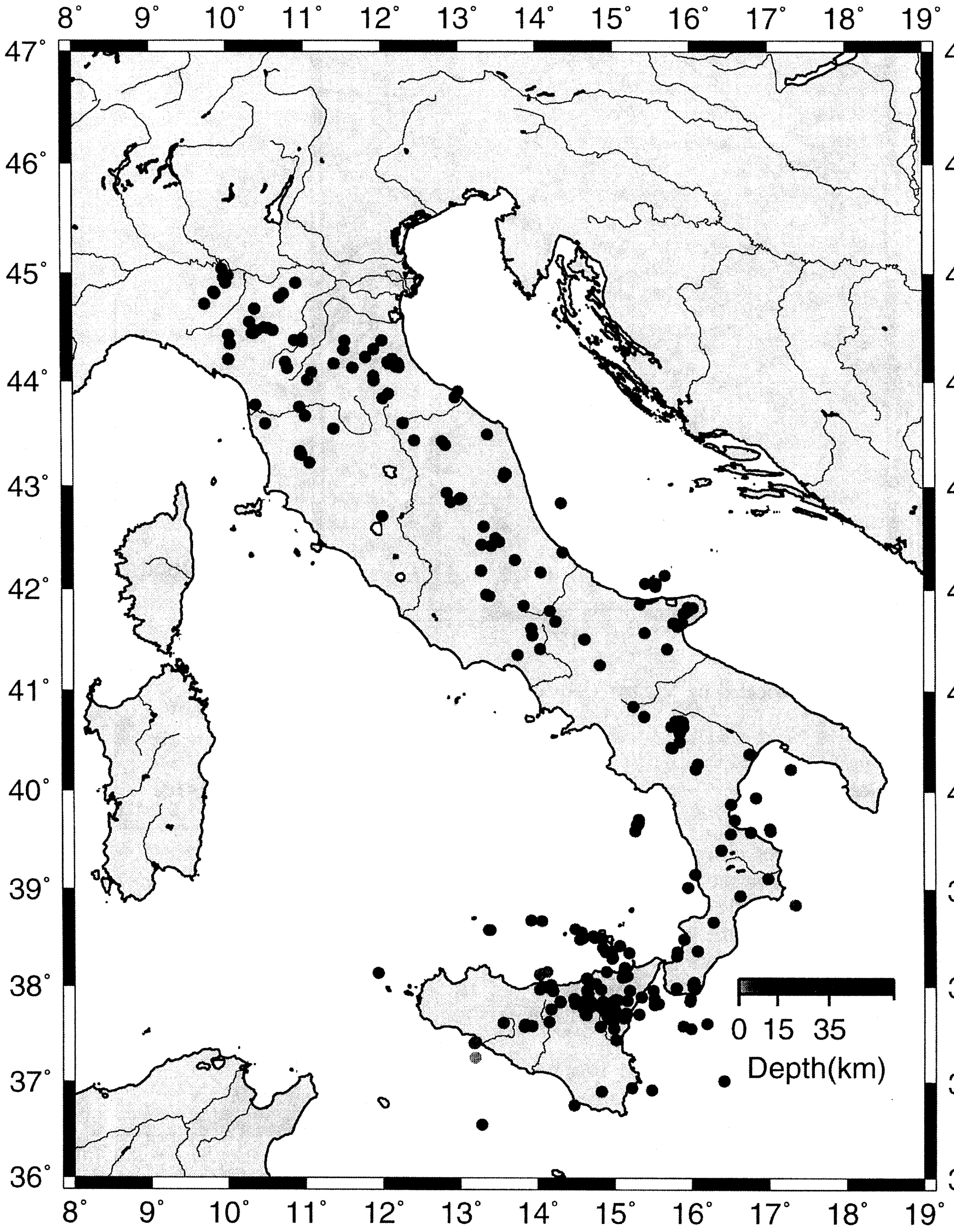

Fig. 17. Map of all the relocated events with hypocentral errors less than 4 km. Sub-crustal seismicity occurs underneath the Northern Apennines and in the Calabrian arc. Most of the events occur in the upper crust, while some earthquakes are located in the lower crust in the Apulian foreland, in the Potenza area and in Sicily.

Larger residuals observed at stations more than 180 km apart may be related to phase misidentification or to lateral variation of the velocity model, and suggests a very high heterogeneity and attenuation beneath the Apenninic belt.

Relocated earthquakes with hypocentral errors less than 4 km are plotted in fig. 17. The epicentral coordinates of the events are well resolved (diagonal elements of the resolution matrix larger than 0.6) with errors less than 2.0 km on average. Instead, earthquake depths have smaller resolution and larger errors, due to the sparse seismic network. Interestingly, the hypocentral depth of subcrustal earthquakes appears to be better constrained than that of shallow events, due to the average spacing between stations.

All along the belt, most of the events occur in the upper crust (hypocentral depths less than 15-20 km), defining the depth extent of the upper seismogenic layer. A significant number of events occur deeper in the crust and also beneath the Moho along the Northern Apennines. The occurrence of intermediate-depth earthquakes (down to 90 km depth) beneath the Northern Apenninic arc was already observed by Selvaggi and Amato (1992). Our results are in agreement with this previous study, and point out a complex seismotectonics in which sub-crustal seismicity exists and is related to the down-going Adriatic plate underneath the Apennines. In the Southern Apennines, earthquakes occur in the upper crust within a narrow seismic area elongated in the NW-SE direction beneath the belt. Large earthquakes ($M \sim 7$) originate within this upper brittle layer (Amato *et al.*, 1992). Eastward of the narrow seismic belt, two seismic zones, the Gargano promontory and the Potenza area, present focal depths between 20 and 30 km, in agreement with local earthquake studies (Azzara *et al.*, 1993). In the Calabrian arc and in the Eolian archipelago many earthquakes occur beneath 20 km depth, probably related to the subduction processes (Selvaggi and Chiarabba, 1995; Frepoli *et al.*, 1996). Seismicity occurs in the deep crust also beneath the Mt. Etna volcano.

7. Discussion

We propose reference 1D models and station corrections for Central and Southern Italy computed minimizing *P*-wave residuals via a damped least squares solution to the tomographic equation. These models are reasonably resolved and computed velocity parameters have small errors. Using the 1D models along with the finely re-picked data, earthquake locations are improved all along the Apenninic belt. Instead, bulletin data are affected by large errors that prevent the accurate location of earthquakes (with errors less than a few kilometers) and the recovering of structural details of the Earth.

The results obtained with the re-picked data can also be used for inference on the deep structure of the Apennines. We observe small velocity gradients with depth and low velocities in the lower crust of the Apenninic belt, consistently with the tomographic results of Alessandrini *et al.* (1995) and Chiarabba and Amato (1996). There is no evidence of pronounced velocity discontinuities or high velocities in the crust beneath the belt, in agreement with the receiver function analyses of Amato *et al.* (1997). Generally, a 1D model with V_p = 5.6-5.9 km/s in the upper crust and a slight increase to 6.2 km/s in the lower crust produces a good fit of the *P*-wave data. The *P*-wave velocity of about 7.6 km/s at 35 km depth is an intriguing feature that may be explained either by a Moho depth greater than 35 km or by a low-velocity anomaly at the Moho beneath the belt, consistently with results of P_n velocities (Mele *et al.*, 1995).

Figure 18 shows that P_n arrivals are better fitted by a velocity of 8.0 km/s (fig. 18b) with respect to a constant velocity along the belt of 7.6 km/s (fig. 18a). This suggests that velocity of ~ 7.6 km/s computed by VELEST may be an artifact due to the inversion of direct *P*-waves picked as first arrivals instead of emergent P_n at critical distance. Below 35 km depth, the *P*-wave velocity is around 8.0 km/s, while above this depth the structure is very complex with low-velocity zones that may extend to the lower crust. Figure 18b also shows that the first arrivals of earthquakes occurring in the upper mantle (solid circles) present a consis-

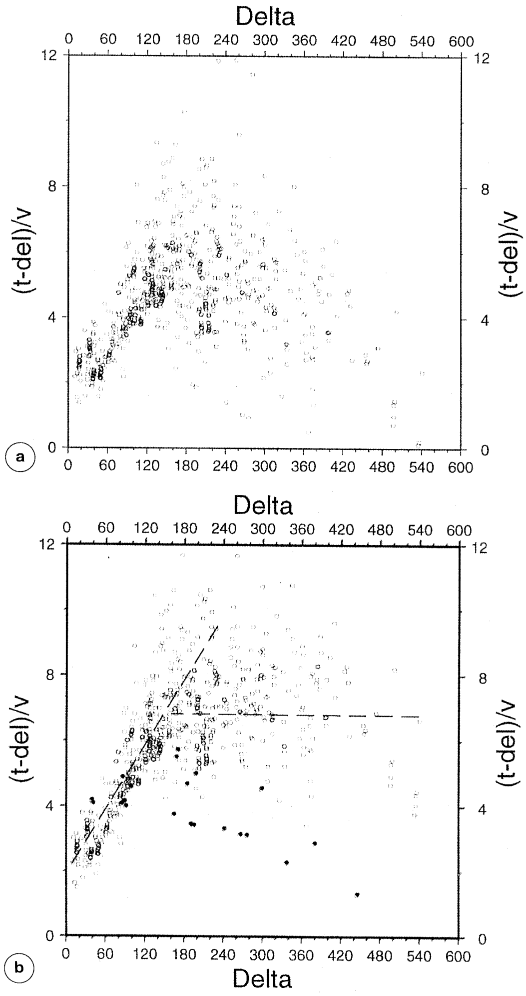

Fig. 18a,b. Dromochrone of re-picked data for the Northern Apennines. Travel times are reduced with $V_p = 7.6$ km/s (a) and $V_p = 8.0$ km/s (b). Data within an epicentral distance (Delta) of 180 km have been used in the inversion. Solid circles in (b) are data relative to the sub-crustal seismicity.

tent hyperbolic trend characteristic of deep events.

The large variation of station corrections reflects the presence of strong lateral velocity heterogeneities in the study area. Only for a few stations can these station corrections be explained by the shallow crust close to the receivers. For most of the stations, the upper crustal setting cannot be responsible for the observed corrections which, therefore, imply velocity anomalies at greater depth.

Figures 4 and 7 show that stations along the Tyrrhenian region present negative corrections that can probably be explained with a Moho depth less than 35 km, because the uppermost crust consists of Plio-Quaternary sediments and flysch sequences. This interpretation is consistent with recent results obtained by teleseismic receiver functions (Amato *et al.*, 1995) and CROP projects in the Northern Apennines (AA.VV., 1996) that indicate a Moho depth of about 24 km along the Tyrrhenian area. Beneath the belt, positive corrections indicate low *P*-wave velocities. Since the upper crust consists of limestone overthrust units and this slow region corresponds to long-scale remarkable negative Bouguer anomalies (Royden *et al.*, 1987), we favor a deep location of these low velocities in the lower crust (see Chiarabba and Amato, 1996) and/or around the Moho depth (see Mele *et al.*, 1995).

In the Southern Apennines, positive corrections extend to the whole stations along the belt, indicating low velocities in the lower crust as in the Northern Apennines. Stations on the Adriatic (Apulian) foreland and on the Tyrrhenian coast present negative values. The overall pattern consists of three alternate belts of negative and positive corrections, consistent with the *P*-wave residuals observed by Selvaggi and Chiarabba (1995) for deep earthquakes of the Calabrian arc, suggesting strong lateral heterogeneities in the lower crust.

In Sicily, the positive corrections of stations located in the Gela foredeep are consistent with the thick shallow deposits of soft sediments. The slightly positive corrections around Mt. Etna can be due to a slow region underneath the volcano. The negative corrections found for stations in Calabria may be related to high velocity zones beneath the arc.

The results of this paper can be straightforwardly used to locate earthquakes in the regions where each model is defined. Considering our results, the use of a greater number of layers seems to be unjustified. Because we computed these models selecting only the first arrivals at stations within 180 km of epicentral distance, such models are to be used with an analogue selection.

The definition of focal depths beneath the Apennines is fundamental to enhance the seismotectonics of the Central Mediterranean. The recognition of several seismogenic areas where the seismicity is concentrated in the lower crust or beneath the Moho makes the geodynamics of Italy very particular, and the role of on-going subductions not yet completely defined. In the future, an outstanding contribution would derive from detailed three-dimensional tomographic reconstruction to constrain lateral variations of velocity. Anyway future tomographic studies should use accurate re-picked data and a three-dimensional geometry of the Moho to finely resolve lateral heterogeneities within the crust.

8. Conclusions

We proposed reference 1D velocity models for the Northern and Southern Apennines and Sicily obtained inverting re-picked *P*-wave arrivals at the ING seismic network. These «minimum 1D models» ensure accurate earthquake location. The most representative seismicity which occurred within the Apennines in the past seven years have been re-located using these models and presents an interesting pattern. While most of the seismicity is confined within the upper crust, we note deep crustal and sub-crustal seismicity in the eastern side of the Apennines and in the Calabrian arc. The computed models allow us to make some inference on the deep structure of the Apennines, revealing the absence of sharp velocity discontinuities and the presence of diffuse low velocities in the lower crust beneath the belt and around the Moho depth.

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