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Improvement in earthquake location accuracy from Minimum 1-D velocity model: an example from the Gioia Tauro Basin (southwestern Calabria, Italy)

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Abstract: We computed a 1-D velocity model in the Gioia Tauro Basin area (southwestern Calabria, Italy) by inverting P-wave arrival times recorded by local seismic network consisting of eleven stations. For this purpose we used a data set of 207 local earthquakes which were located with a minimum of 7 arrivals, a travel time residual (*rms*) ≤ 0.3 s and an azimuthal gap ≤ 180º. This "Minimum 1-D velocity model" is complemented by station corrections which are influenced by near-surface velocity heterogeneity. Using the new P-wave velocity model and the program HYPOELLIPSE, we relocated the 207 selected events. Tests were carried out to verify the robustness of inversion results in order to corroborate the conclusions drawn from our findings. The comparison between previous and present earthquake locations has shown a significant improvement. The obtained "Minimum 1-D velocity model" may strongly help in the future routine earthquake location in the area.

Key words: southern Calabria, Gioia Tauro Basin, earthquake location, minimum 1-D model.

Introduction

Southern Calabria is one of the most active seismic zones in Europe. The Calabrian arc is a part of the Mediterranean orogenic belt (Fig. 1) connecting the Southern Apennines with the Maghrebian thrust belts (Haccard et al. 1972; Alvarez 1976). In this tectonic arc the effects of Quaternary activity are well known (e.g. Tortorici et al. 1995).

In southwestern Calabria, the Aspromonte and Serre structures (Fig. 1) consist of a pile of thrust sheets, mainly composed by gneisses and granites, which belong to the uplifted metamorphic basement. To the east, the structures gently slope towards the Ionian Sea, whereas their western edge is steeper and is controlled by faulting (Amodio-Morelli et al. 1976).

The Gioia Tauro Basin (Fig. 1) consists of about 600 meters of marine sediments (from Upper Pliocene to Lower Pleistocene) mainly composed of several hundred meters of clay, and about 100 m of regressive sands and conglomerates (Middle Pleistocene). This sequence is overlain by alluvial fanglomerates and sands (from Middle to Upper Pleistocene).

Detailed seismic studies in the area are strictly linked to the accuracy of earthquake locations. From 1985 to 1994, a local seismic network was operated by ENEL (the Italian national electric company) with the main goal of monitoring the seismicity in the Gioia Tauro Basin. More than 3500 earthquakes were located during this period.

In this paper, to better constrain the hypocenter location for the Gioia Tauro Basin, we have defined a Minimum 1-D model, by considering the a-priori P-wave velocity model of Bottari et al. (1982) and following the most relevant approach to this problem (Kissling et al. 1994). The obtained model minimizes the average of *rms* (travel time residual) for a set of well-located events, by computing a solution for the coupled hypocenter and 1-D velocity model problem. Ignoring the coupling between hypocentral and velocity parameters, during the location process, can introduce errors in the hypocenter location, which depends also on the assumed velocity structure (Kissling et al. 1995).

This concept, which represents a first step towards more detailed seismic studies, can be considered universal as we can give examples not only from Gioia Tauro Basin and from southern Italy (Chiarabba & Frepoli 1997; Musumeci et al. 2003), but also from other areas of the world. In fact one of the first extensions of the Minimum 1-D was applied to northwestern Italy (Kissling et al. 1995), but this method was also used in areas such as northern Chile (Husen et al. 1999), Costa Rica (Quintero & Kissling 2001), Romania (Popa et al. 2001), New Zealand (Sherburn & White 2005), northern Egypt (El-Hadid et al. 2005).

The coupled hypocenter-velocity model problem

The travel-time of a seismic wave is a non-linear function of both hypocenter parameters and seismic velocities sampled along the ray paths between stations and hypocenter. This dependence on hypocenter parameters and seismic velocities is called the coupled hypocenter-veloc-

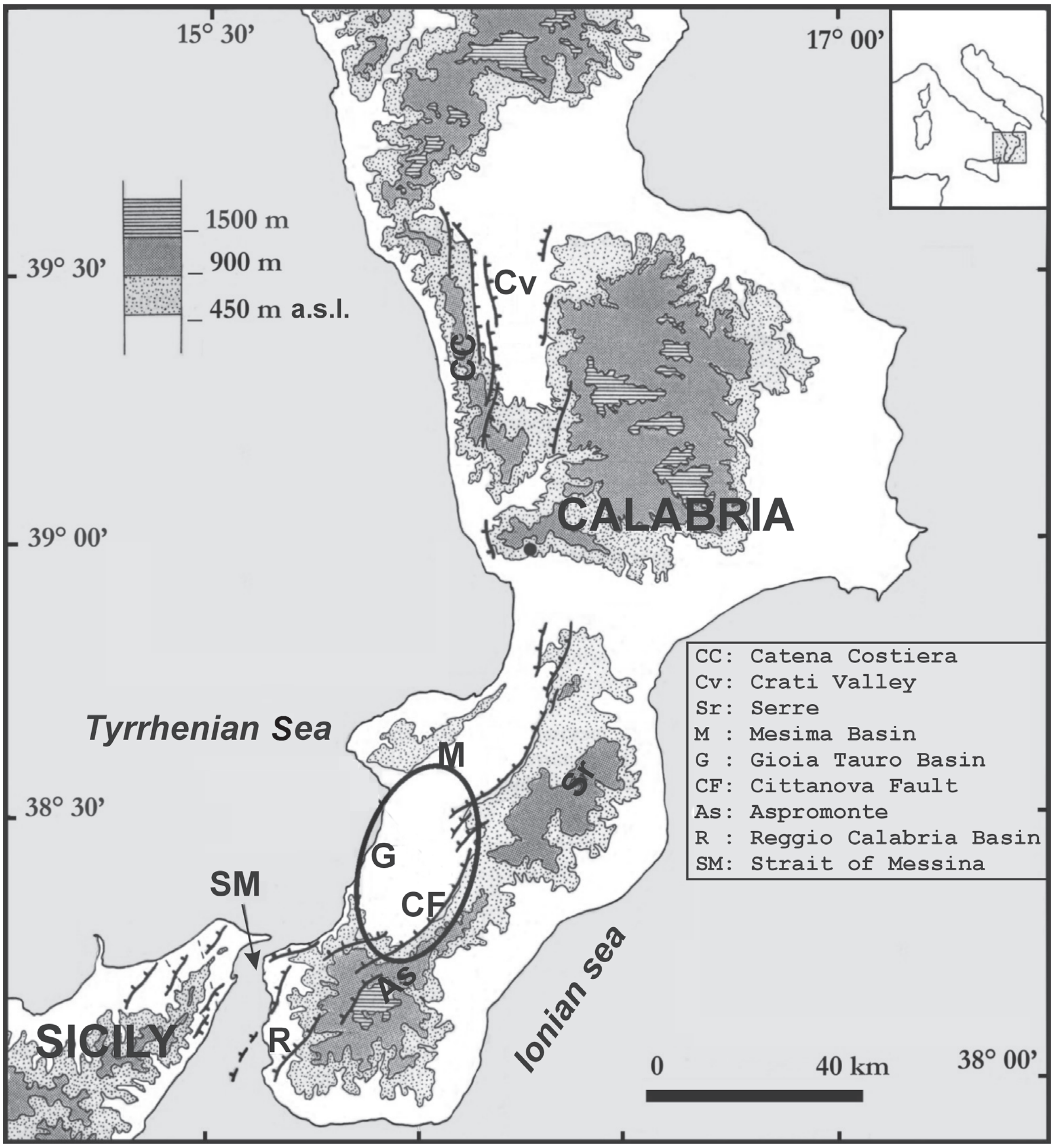

Fig. 1. Seismotectonic sketch of the Calabria arc. The location of the Gioia Tauro Basin is marked by the black ellipse.

ity model problem (Crosson 1976; Kissling 1988; Thurber 1992). It can be linearized and written in matrix notation (Kissling et al. 1994) as:

$$t = Hh + Mm + e = A d + e$$

where **t** = vector of travel time residuals; **H** = matrix of partial derivatives of travel time with respect to hypocentral parameters; **h** = vector of hypocentral parameter adjustments; **M** = matrix of partial derivatives of travel times with respect to model parameters; **m** = vector of velocity parameter adjustments; **e** = vector of travel time errors, including contributions from errors in measuring the observed travel times (t_{obs}), errors in calculated travel times (t_{calc}) due to errors in station locations, use of the wrong velocity model and hypocentral coordinates, and errors caused by the linear approximation; **A** = matrix of all partial derivatives; **d** = vector of hypocentral and model parameter adjustments.

In a standard earthquake location, the velocity parameters are fixed to a-priori values, and the observed travel times are minimized by perturbating the four hypocentral parameters.

Neglecting the coupling between hypocenter and velocity parameters during the location process, however, can introduce systematic errors. Precise hypocenter locations and error estimate, therefore, request the simultaneous solution of both velocity and hypocentral parameters. Then the correct hypocentral coordinates can be reliably achieved by solving the coupled hypocenter-velocity model problem, rather than alternating independent hypocenter and velocity adjustment steps (Thurber 1992; Kissling et al. 1994).

The obtained Minimum 1-D model represents a velocity model that reflects the a-priori information and that leads to a minimum average of *rms* values for the best selected earthquakes used in the inversion.

Each velocity layer of the Minimum 1-D model is the weighted area averaged over all rays in the data-set within that depth interval. To account for lateral variations in the shallow structure, station corrections are included in the 1-D inversion process.

The general applicability of the concept of the Minimum 1-D model and its performance for high-precision earthquake location have been tested and documented by relocating mine blasts and shots. In particular, no significant and systematic shift in hypocenter locations is observed after a 3-D inversion when using the Minimum 1-D model as the initial reference model (Kissling 1988). Thus, also in the Gioia Tauro Basin area, the Minimum 1-D model concept is the most appropriate for uniform high-precision earthquake location, outperforming any velocity model based on a-priori information.

Earthquake data and inversion procedure

In the Gioia Tauro region, a local seismic network covering an area of about 1200 km^2 (Fig. 2), was operated from April 1985 to April 1994. Three seismic stations (DLV, PDL and CST) had 3-component seismometers, while eight had only a vertical one. Each station was equipped with short period Mark L4C seismometers with a natural frequency of 1 Hz. The data were sampled with a sampling frequency of 153.8 Hz, and an anti-alias filter with a corner frequency of 30 Hz was applied. Data were transmitted continuously to the acquisition center, located near the CGT station, by UHF radio and stored in trigger mode on magnetic tape.

Since all instruments were operated in continuous mode, to detect possible events a simple software trigger using LTA/STA (Long Term Average/Short Term Average) ratio 8 was used. The records were grouped, converted in .EVE format and stored on CD-ROM. Identifying first arrival times of P- and S-waves on waveforms was done with the WINHYPO package (Raffaele 2004). It allows a comfortable data processing including earthquake location using the HYPOELLIPSE program (Lahr 1989).

During the operating period of the network 3539 events were located (Fig. 2) with a 1-D a-priori velocity model (Bottari et al. 1982). The weights of the time readings were assigned with respect to the estimated errors (Table 1). Most of the P-wave arrivals were assigned a weight of 0 as they could be read with a picking accuracy of a few tens of milliseconds. For S-waves the usual weight was 2, corresponding to a reading error of about 0.2 s. The number of observations per class of weight is shown in Table 2.

The approach used here for the simultaneous inversion of a 1-D velocity structure into two steps. During the first step, the code HYPOELLIPSE (Lahr 1989) routinely relo-

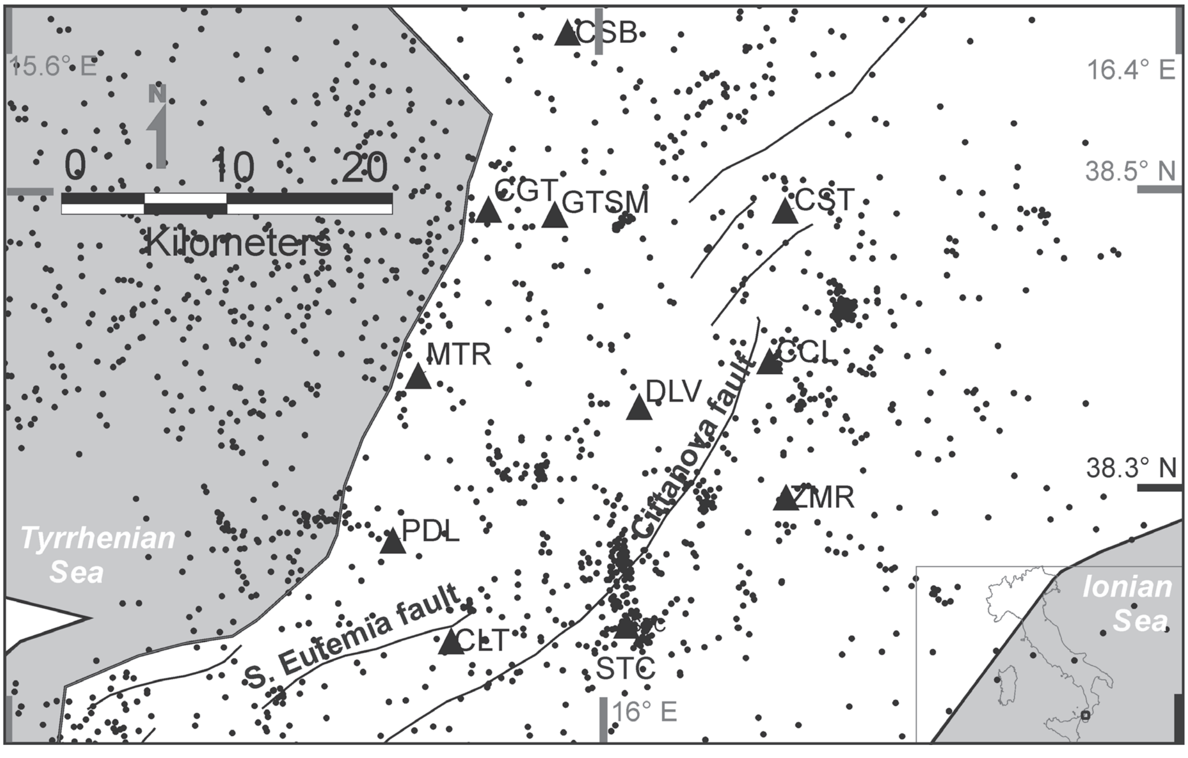

Fig. 2. Map of the study area. Epicenters are represented by circles for located 3539 events. Seismic stations are represented by triangles. The surface evidence of faults is reported with continuous lines.

Table 1: Weight of the arrival time readings with respect to the reading errors.

Weight	P onset time accuracy (s)	S onset time accuracy (s)
0	<0.05	<0.1
1	0.05..01	<0.1..0.175
2	0.1…0.15	0.175..0.25
3	0.15..0.2	0.25..0.3
4	> 0.2	> 0.3

Table 2: Number of observations per class for the 3539 events.

	P0	P1	P2	P3	P4	S0	S1	S2	S3	S4
N obs	21 039	275	1 360	845	1 365	53	106	3 036	101	234

cates the events using the a-priori 1-D model. Then, the relocalized events are selected following the criteria exposed in the section 4. In the second step, a 1-D inversion is performed to compute simultaneously hypocenter parameters, 1-D velocity model and station delays using the *best events*. The aim of this step is to constrain the 1-D Minimum model, this new velocity model should constrain hypocenter parameters that give the global minimum of the cost function (Kissling 1988).

An outline of the inversion procedure for the computation of the 1-D Minimum velocity model is presented in Fig. 3.

Minimum 1-D model and station delays

Because uncertainties in hypocenter locations introduce instabilities in the inversion process (Kissling et al. 1994), the computation of the Minimum 1-D model for the area under study was carried out after a careful filtering of data with respect to their quality. We considered solely events for which at least 7 arrival times were available, with a "gap" $\leq 180°$ and a *rms* ≤ 0.3 s. The resulting data-set consists of 207 well-locatable events with 1555 P- and 402 S-onset readings.

The selected events are then inverted by using the program Velest (Kissling 1995) to calculate the adjustments of P-wave velocities and station corrections. As the number of readable S-wave arrival onsets was restricted, we forsake inverting S-wave velocities. In particular, the steps that lead to the final model consist of twelve inversions, of one iteration, where the output files of the previous inversion, as regards to the P-wave model, the hypocenter locations and station corrections, become input files to the following one. For the S-wave model the input file was derived from the P-wave model assuming $V_p/V_s = 1.73$. Therefore S-wave readings were used only to better constrain the focal depths.

Following the method proposed by Kissling et al. (1994), as the layer depths are kept fixed, we have begun with a large number of 2 km thick layers and combined layers for which velocities converged to similar values during the inversion process. The inversion process was

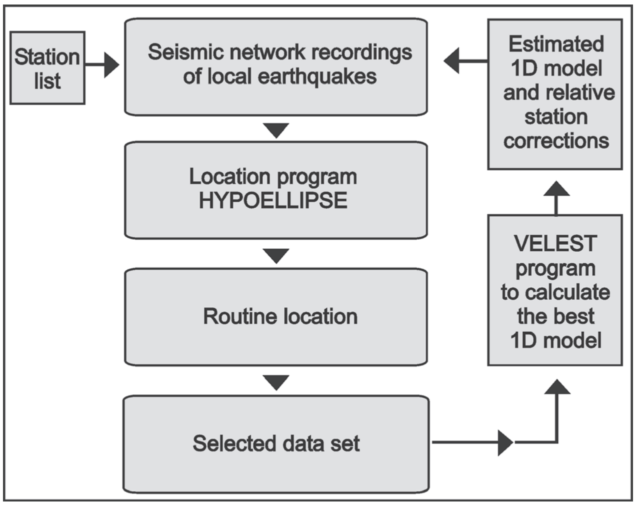

Fig. 3. Block diagram of the inversion procedure to compute the Minimum 1-D model.

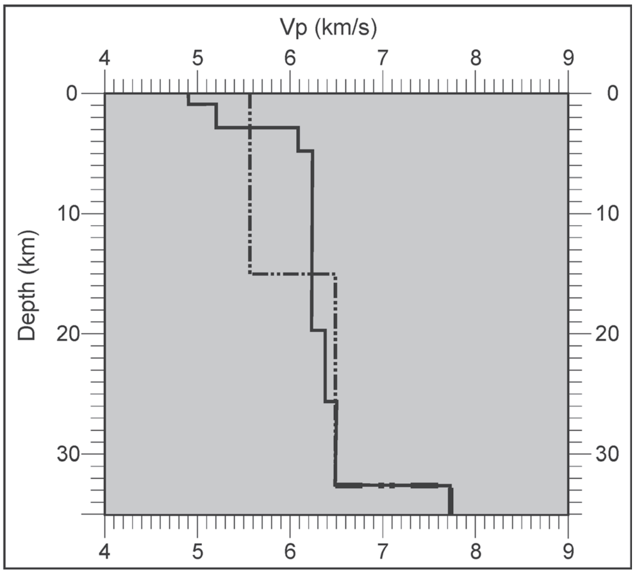

Fig. 4. Starting 1-D velocity model (dotted line) from Bottari et al. (1982) and computed Minimum 1-D velocity model (solid line).

stopped when the earthquake locations, stations delays and velocity values did not further vary significantly.

The Minimum 1-D velocity structure is shown in Fig. 4, together with the a-priori model of Bottari et al. (1982). P-wave velocity is 4.90 km/s in the upper layer, while in the deeper layers the P-wave velocity is respectively of 5.20, 6.05, 6.25 and 6.40 km/s up to 7.7 km/s below 33 km. Below 25 km the starting value of velocity remains unchanged, as few illuminating ray-paths were available.

Station corrections must be considered an integral part of the velocity model and reflect the heterogeneous near-surface structure (which may otherwise not be adequately represented by a 1-D model) (Haslinger 1998). The station delays are given as relative values with respect to the reference station DLV. They support the validity of the velocity model as it can be related clearly to the general

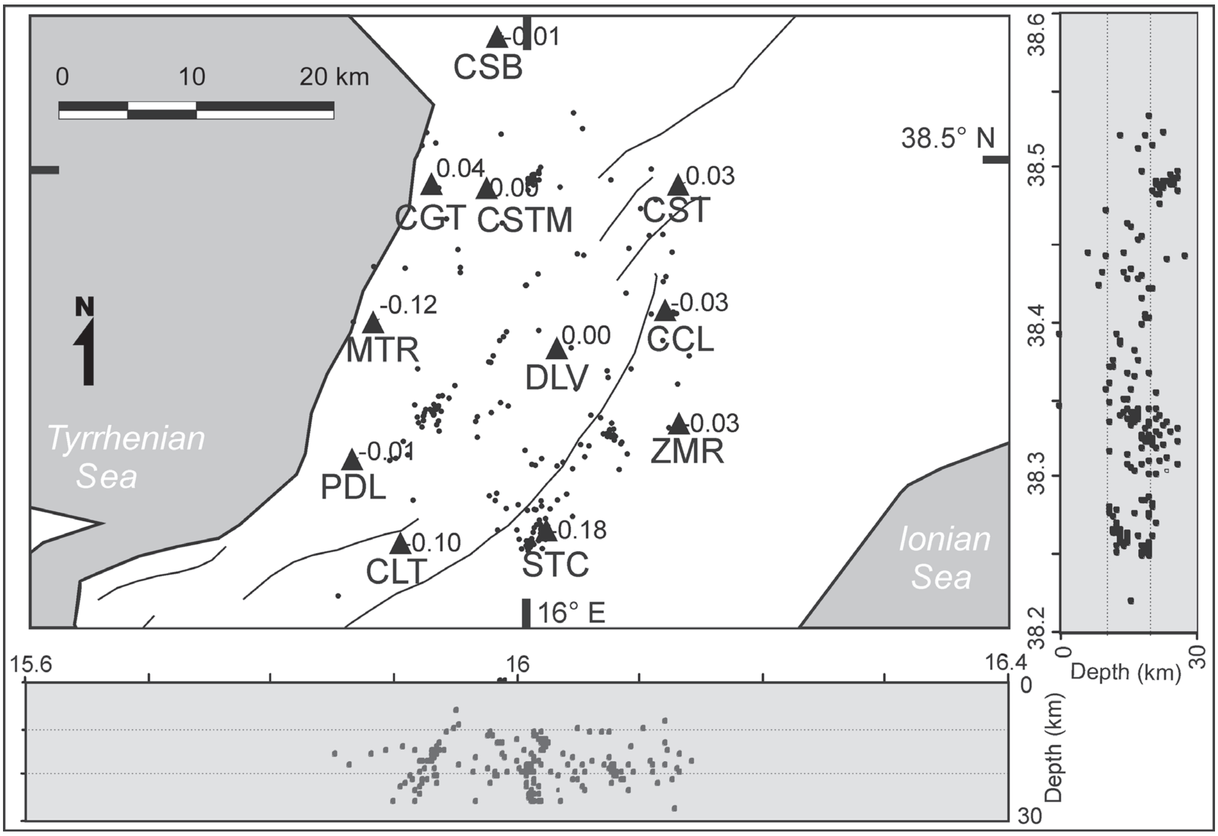

Fig. 5. Distribution of seismicity located by Velest after the 1-D inversion process and station corrections of the Minimum 1-D velocity model. Negative delays correspond to the true velocities faster than the model. E-W and N-S cross-sections show the focal depth for the 207 selected events. The surface evidence of faults is reported with continuous lines.

near-surface conditions inferred from geological evidence. They show a '0' or positive value in correspondence of thick sediments and negative values for the others stations outside the Gioia Tauro Basin, associated with outcropping metamorphic rocks of the Aspromonte and Serre structures (Figs. 1 and 5).

Results and discussion

In order to test whether the computed model improves the routine earthquake location, we relocated the selected data with the HYPOELLIPSE program, and using the computed Minimum 1-D model and the station corrections. Fig. 6 shows the *rms* differences between the location using the model of Bottari et al. (1982) and our optimum 1-D model. With the optimum 1-D model the *rms* travel time residuals were reduced to over 85 % compared to the starting model. The quality of relocated events significantly improves because of the considerable reduction of travel time residuals.

A map of relocated events by the program VELEST is shown in Fig. 5. The distribution of seismicity suggests that most of the seismic events are clustered in space and time. One large cluster of about fifty events occurred on September 11, 1992 at a depth of ca. 10 km, lying in the area of the station STC. Most of the earthquakes are confined in the upper 25 km of the crust. They occurred along

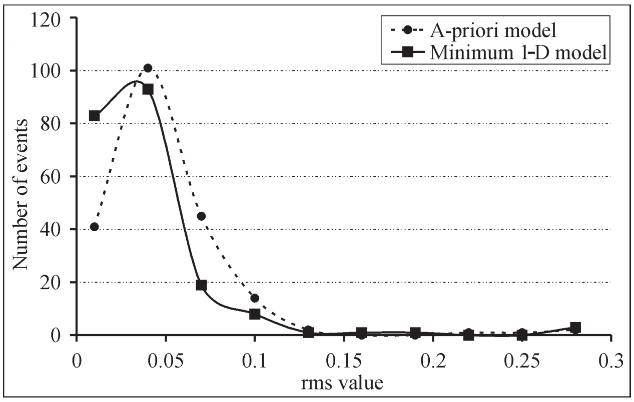

Fig. 6. Comparison in *rms* between the location with the routinely used model and re-location with the computed 1-D model, and station correction for the 207 selected events. Note the significant decrease in *rms* value obtained using the 1-D model.

existent weaknesses zones, such as the Cittanova fault (Figs. 1 and 5).

To verify if the results are robust performed a stability test on the selected events as proposed in the user's guide of the VELEST code (Kissling 1995).

For this purpose, before the inversion process, we randomly varied, the starting hypocenter locations by an amount of up to 8 km in E-W, N-S and Z directions. This

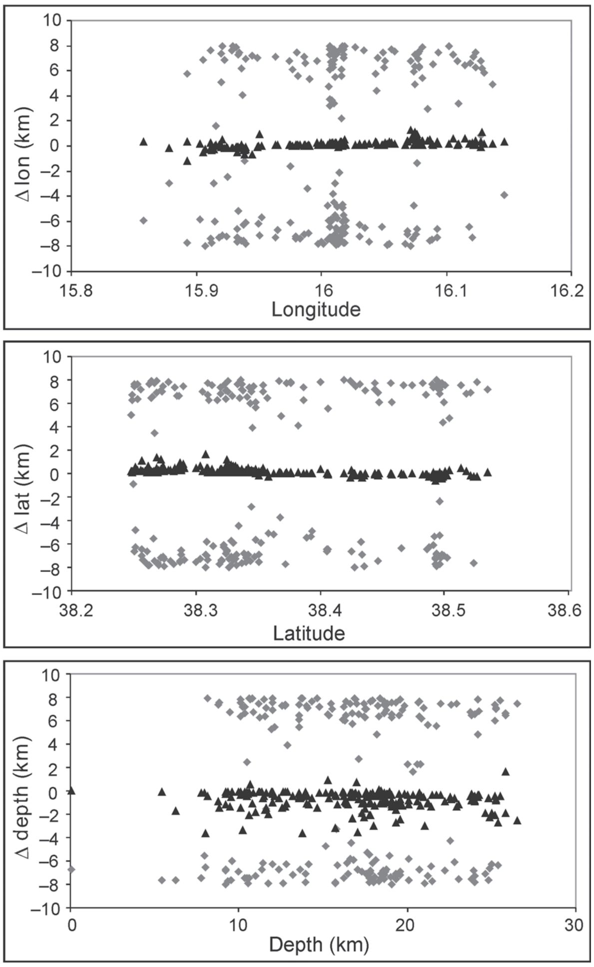

Fig. 7. Hypocenter stability test. Grey squares: coordinate difference between randomized input and Minimum 1-D locations. Black triangles: difference after inverting with the randomized input data. For more details, see text.

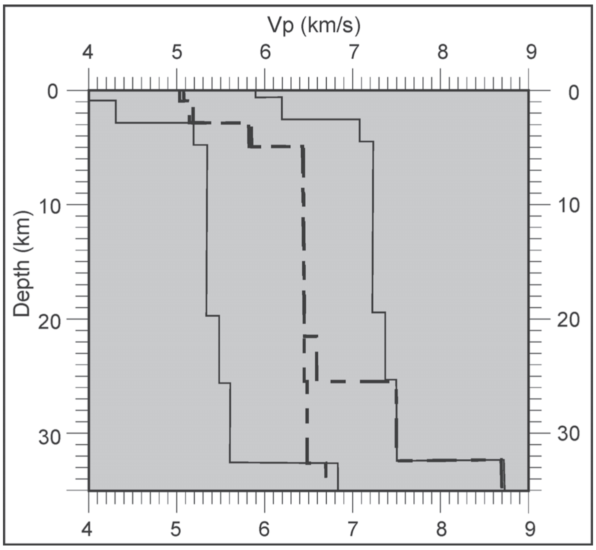

Fig. 8. Stability tests with high and low input velocity models. Input models and Minimum 1-D model shown as solid lines, output models shown as dashed lines.

process provides a check for a bias in the hypocenter locations and for the stability of the solution to the coupled problem. If the proposed Minimum 1-D velocity model denotes a robust minimum in the solution space, no significant changes in hypocenter locations are expected (Husen 1999). We used the disturbed starting locations in the joint 1-D inversion and examined the differences between the solutions found with the original data and the ones where disturbed starting locations were used. Five performances of this experiment were carried out and the maximum difference, between the solutions was taken as an evaluation of stability (Fig. 7). In fact, all events have been relocated close to their original position, indicating that the hypocenter locations were not systematically biased.

A second stability test was carried out, as suggested by Haslinger (1998), maintaining fixed the final hypocenter coordinates of the 207 inverted events, and repeating the inversion process using initial velocity models with higher or lower velocities with regard to the Minimum 1-D model. The stable convergence to the Minimum 1-D model indicates that the inferred velocity model is an adequate 1-D approximation of the upper 25 km of the crust (Fig. 8).

Concluding remarks

In the Gioia Tauro Basin, data from a 9-year running seismic network were used to compute the one dimensional P-wave velocity model (Fig. 4) and corresponding station delays corrections (Fig. 5), by minimizing P-wave residuals for a data-set of selected events.

Two tests have been performed to check both the hypocenter locations and the Minimum 1-D model repeating the inversion process, maintaining fixed either the obtained velocity model or the final earthquake locations. If the proposed Minimum 1-D velocity model denotes a robust minimum in the solution space, no significant changes in velocity and hypocenter locations are expected demonstrating the stability of the solution to the coupled problem. In the first test all hypocenters were more or less relocated back to their original positions, while in the second test the results indicate that the Minimum 1-D model is an adequate approximation of the crust above 25 km depth.

In general, the location of the epicentres suggests a relation of the seismicity to the main tectonic lines, such as the Cittanova fault, which have a NE-SW trend. Most of the earthquakes are confined to the upper 25 km of the crust and a significant earthquake cluster (ca. 50 events occurred on September 11, 1992) has been recorded, at a depth of ca. 10 km (Fig. 5).

Finally, we explained that the application of the method by Kissling et al. (1994) is able to calculate a new Minimum 1-D velocity model. This model represents an improvement for routine earthquake location with respect to other 1-D velocity models based on actual a-priori information of the basin area.

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