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Imaging the velocity structure of the Calabrian Arc region (southern Italy) through the integration of different seismological data

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ABSTRACT We present a new 3D, P-wave velocity model of the crust and upper lithosphere for the Calabrian Arc region. The model results from integration of different types of seismic velocity data available in the literature, following a method conceptually similar to one that has been successfully applied in the Alpine region. The model obtained, clearly shows the first-order structural features of the area, in agreement with the complex puzzle of lithospheric units. It also has the advantage of representing the simplest velocity structure that is consistent with all published data. We then employed this “a-priori” velocity model as starting model for a local earthquake tomography. The velocity pattern obtained furnishes new information on the relationships between deep dynamics related to the Ionian subduction system and processes occurring at crustal depths. In addition, also the low RMS values coming from hypocenter locations indicate an improvement with respect to 3D models already available and to tomographic results obtained by testing different starting velocity models.

Key words: tomography, Calabrian Arc.

1. Introduction

The aim of this work is to furnish a more complete picture of the lithospheric structure of the Calabrian Arc region (Fig. 1) integrating all the “a-priori” information available in the literature. Several studies have been performed in the past to improve the structural knowledge of the Calabrian Arc region, mainly based on active seismic surveys and local earthquake or teleseismic tomographies (Chironi *et al*., 2000; Barberi *et al*., 2004; Montuori *et al*., 2007; Steckler *et al*., 2008; among others), but few efforts have been spent on comparing or integrating the information coming from these different analyses. We tried to verify the consistency of the above-mentioned data and to use them for the definition of an integrated velocity model including the first-order heterogeneities. A similar approach has been carried out in the Alpine region by Waldhauser *et al*. (1998, 2002). These authors developed an integrated 3D, crustal P-wave velocity model encompassing the western and central Alps and the northern Apennines by combining published controlled-source seismic and local earthquake tomographic data. The model obtained includes first-order structures such as the Moho topography, sedimentary basins and the known, strong intracrustal velocity anomalies. The employment of the obtained model as starting velocity model for a teleseismic tomography showed a meaningful improvement of the resolution of results (Waldhauser *et al*., 1998, 2002).

In order to use a similar approach also in the Calabrian Arc region, we collected all types of seismic velocity data available, mainly derived from active seismic surveys (Chironi *et al*., 2000; Nicolich *et al*., 2000; Cassinis *et al*., 2005; among others) and seismic tomographies (Barberi *et al*., 2004; Chiarabba *et al*., 2008; Monna and Dahm, 2009). Moreover, we also considered the Moho depth reported by the European Moho Map (Dèzes and Ziegler, 2001) and by Pontevivo and Panza (2006). The data so collected have been integrated in order to build an "a-priori" velocity model that has been successively employed as a starting model for a local earthquake tomography. The importance of a quite reliable starting model in tomographic inversions is widely known in the literature (see e.g., Eberhart-Phillips, 1993; Kissling *et al*., 1994, 1995) and it assumes a more relevant role in a highly heterogeneous region like the Calabrian Arc characterized by different lithospheric domains and strong Moho topography (see e.g., Catalano *et al*., 2001; Finetti, 2005a; Pontevivo and Panza, 2006).

2. Structural and geodynamic settings

The Calabrian Arc is a major tectonic structure of southern Italy, characterized by strong lithospheric heterogeneity (see e.g., Catalano *et al*., 2001; Finetti, 2005a; Pontevivo and Panza, 2006). Many investigators (see, among others, Malinverno and Ryan, 1986; Faccenna *et al*., 1996) have suggested that geological and geophysical data in the whole southern Tyrrhenian region can be interpreted in the framework of a geodynamic model assuming the coexistence of NW-SE convergence of the Nubia and Europe plates and gravity-induced south-eastward rollback of an Ionian lithospheric slab subducting north-westward beneath the Tyrrhenian lithosphere (Fig. 1). Rollback is believed to have been the primary tectonic source for (i) the Tyrrhenian basin opening, (ii) the south-eastward migration of the southern Tyrrhenian lithosphere and (iii) its (i.e., the southern Tyrrhenian lithosphere) thinning and overthrusting onto the Ionian lithosphere [Barberi *et al*. (2004) and references therein].

The space-time evolution of the rollback process (characterized by reduced intensity and greater concentration in the Calabrian Arc area since the Upper Pliocene) can be referred to as a clear structural differentiation between the Calabrian Arc and the marginal tectonic units of Sicily and the southern Apennines, as crustal and lithospheric differences of the downgoing foreland that is oceanic under southern Calabria and in the Ionian basin, while it is continental in the southern Apennines and Sicily (Catalano *et al*., 2001). Looking at a greater depth, Neri *et al*. (2009) have shown that the Ionian subducting slab is in-depth continuous only beneath the central part of the arc (southern Calabria), while it has already undergone detachment at the edges of the Arc beneath northern Calabria and north-eastern Sicily, respectively. The same authors also put in evidenced two transitional zones separating the different domains (Fig. 1).

3. Data and the "a-priori" velocity model

We first collected all types of seismic velocity data available for the study region, and, from among them, we selected the published analyses reported in Table 1. Our selection followed a few

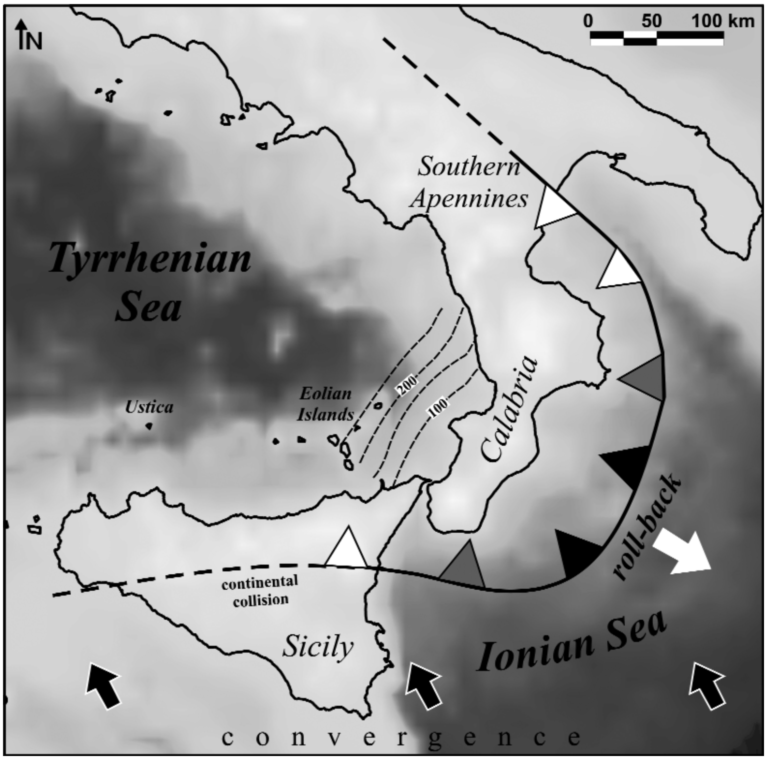

Fig. 1 - Map of the portion of the Apennines-Maghrebides subduction system of southern Italy. The solid curve with the sawtooth pattern indicates the present location of the Calabrian Arc subducting system. The sawtooth points in the direction of subduction. According to the local earthquake tomography by Neri *et al*. (2009), black sawteeth indicate continuous subducting slab, white sawteeth the plate boundary segments where slab detachment has already occurred while gray sawteeth are the present transition ranges between continuous and detached slab. The white arrow shows the sense of rollback of the subducting slabs. The black arrows indicate the present motion of Africa relative to Europe (Calais *et al*., 2003; Nocquet and Calais, 2004). Thick dashed lines are depth contour lines of the Wadati-Benioff zone.

basic criteria: (i) in order not to influence the results with the author's interpretations (still debated in some cases) we retained only the data directly reported as P-wave velocity values and (ii) because we are mainly interested in the crust and upper mantle heterogeneities (up to ca. 50

Table 1 - List of seismic velocity data collected for the "a-priori" velocity model construction divided by covered depth range and geographic region investigated.

Depth range	**Investigation area**	**Reference**
Crust and upper mantle	Sicily	Chironi *et al*., 2000
Crust	Ionian margin of Sicily:Mount Etna	Nicolich *et al*., 2000
Lithosphere-Astenosphere transition	Europe	Dèzes and Ziegler, 2001
Lithosphere-Astenosphere transition	Italy	Pontevivo and Panza, 2002
Crust	south Italy	Barberi *et al*., 2004
Crust and upper mantle	Italy	Cassinis *et al*., 2005
Lithosphere-Astenosphere transition	south Italy	Pontevivo and Panza, 2006
Lower crust and mantle	south Italy	Chiarabba *et al*., 2008
Crust and upper mantle	south Italy	Monna and Dahm, 2009
Upper mantle	Calabrian Arc	Neri *et al*., 2009

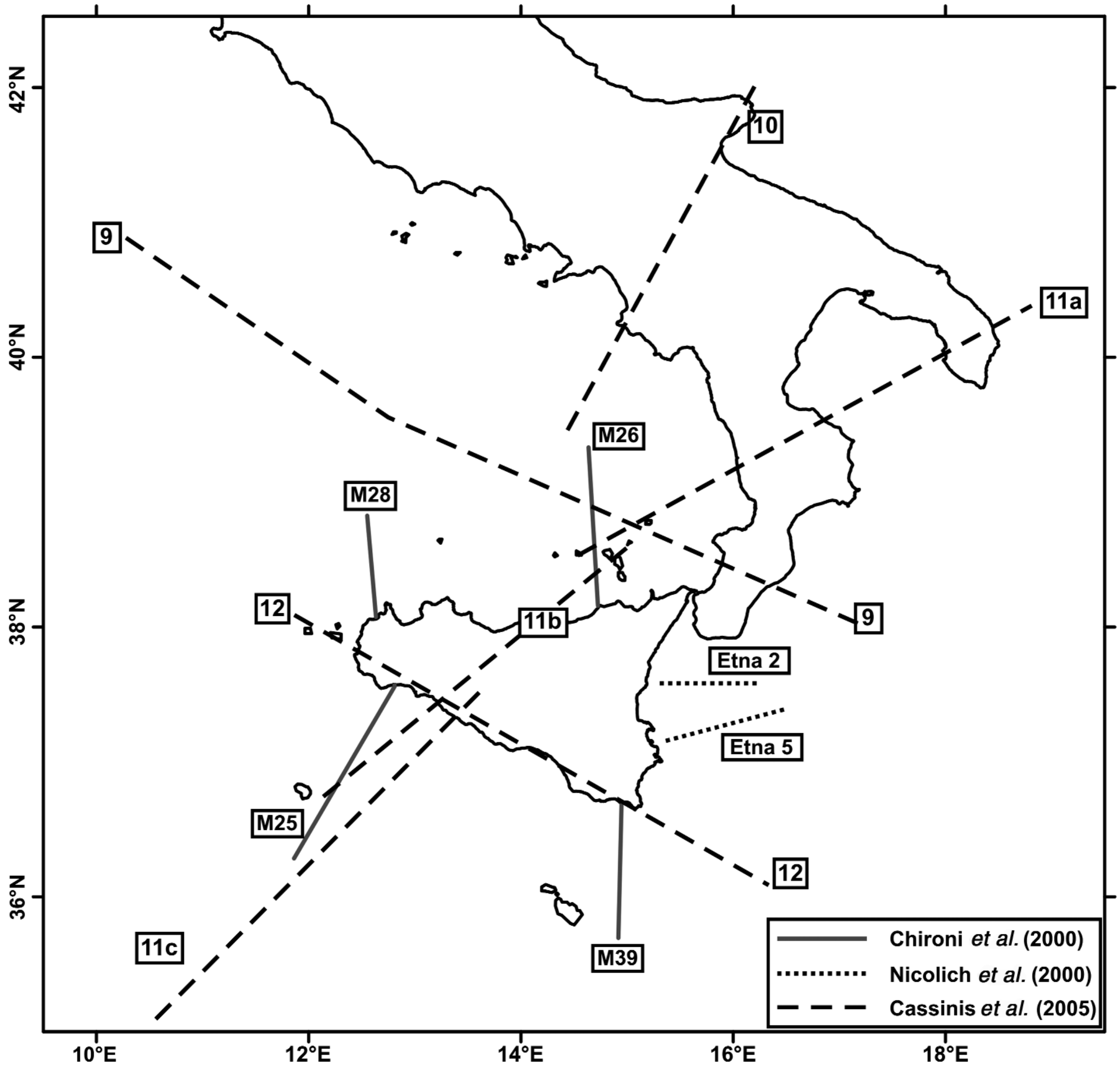

Fig. 2 - Wide-angle reflection - refraction (WARR) profiles used in the present work taken from Chironi *et al*. (2000) (gray lines), Nicolich *et al*. (2000) (black dotted lines), Cassinis *et al*. (2005) (black dashed lines).

km of depth), we discarded the studies for which these sectors are marginal (i.e., lower mantle tomographies). The selected data set mainly derives from active seismic surveys as Wide-Angle Reflection-Refraction (WARR) profiles [Chironi *et al*. (2000), Nicolich *et al*. (2000), Cassinis *et al*. (2005); see Fig. 2], and seismic tomographies (Barberi *et al*., 2004; Chiarabba *et al*., 2008; Monna and Dham, 2009). Moreover, we considered the Moho depth reported by the European Moho Map (Dèzes and Ziegler, 2001) and Pontevivo and Panza (2006) as a further constraint (Table 1). All the collected velocity-depth couples of data have been referred to the nodes of a grid with a 40 km horizontal spacing, covering the region of our interest (Fig. 4a) and for each node, we reported these couples of data in a Vp versus depth graph (black dots in Fig. 3).

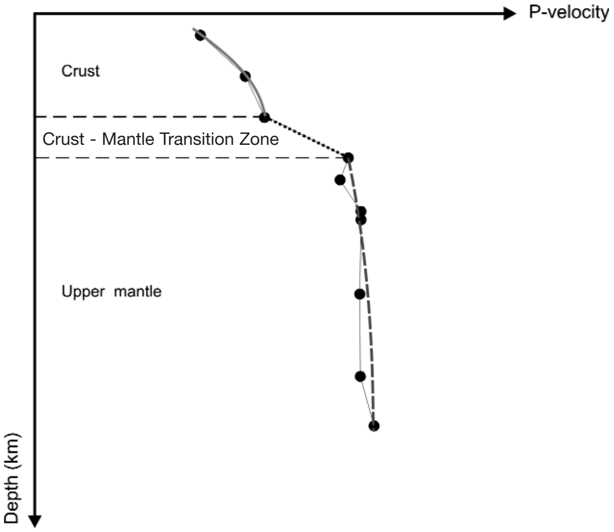

Fig. 3 - Example of a velocity-depth function reported in the three-layer basic model. This kind of graph was constructed for each grid node. Solid dots represent velocity-depth data obtained from seismic “a-priori” information. The fit of the data was performed considering three different intervals: the first covers the crustal depth range (gray line); the second indentifies the crust-mantle transition zone (black dotted line); the last encloses the upper mantle (gray dashed line).

The seismic profiles reach depths ranging from 30 to 50 km, Barberi *et al*. (2004) primarily sample the upper 30 km of depth while Chiarabba *et al*. (2008) and Monna and Dahm (2009) allow us to investigate the velocity model also at greater depths. Tomographic data provide a pretty good coverage of on-shore areas and of sectors of the Tyrrhenian and Ionian Seas close to the coastlines. As put in evidence by Fig. 2, the data coming from active seismic surveys allow us to improve the horizontal coverage, in particular in the off-shore areas. In order to furnish an overall view of the spatial coverage of the selected data, in Fig. 4a we also distinguish the well constrained nodes (black crosses) sampled by seismic profiles and/or tomographic results relative to the more reliable regions (according to the quality criteria reported by the respective authors) by nodes (gray crosses) characterized by lower quality constraints (i.e., tomographic peripheral sectors). We used the Moho depth obtained from WARR profiles, the European Moho Map and the results obtained by Pontevivo and Panza (2006) as primary constraints to detect, also through the comparisons with all the other data, the depth ranges characterized by marked velocity variations (i.e., the crust-mantle transition zone, see Fig. 3).

Due to the different typologies of data, the velocity trend in depth was different for each node. To obtain a regular vertical step of the data comparable for all the nodes, we had to convert such point-like data in velocity-depth functions searching for the best fit curves. Differently from Waldhauser’s approach, we preferred to minimize the influence of subjective considerations by avoiding geological constraints and as reference we used a very simple model. It is a three-layer basic model where the first layer covers the crustal depth range, the second identifies the crust-mantle transition zone, the last encloses the sub-moho mantle interval (Fig. 3). Visual inspection of the velocity-depth plots allowed us to verify the good agreement of the different data that is further supported by the analysis of the R^2 parameter of the best fit curves. R^2 values greater than 0.7 for 80% of nodes, put in evidence a very small degree of dispersion and thus a high consistency in our data set. The fit furnished a homogeneous vertical distribution of the P-velocity values at each node and allowed us to build the “a-priori” velocity model by applying a horizontal spatial smoothing. In Fig. 4, we report this model with a vertical step of 10 km, starting from a 0 to 50 km depth.

The “a-priori” velocity model (Fig. 4) clearly shows the first-order structural features of the area. In particular, in agreement with the complex puzzle of lithospheric units of the region, our model allows us to identify five macro-zones characterized by different velocity settings (Sicily, Tyrrhenian Sea, Ionian Sea, Calabria and southern Apennines, see also Fig. 1). These structural setting of the investigated region and the main features of each lithospheric unit are quite widespread in the literature (Catalano *et al*., 2001; Barberi *et al*., 2004; Pontevivo and Panza, 2006; Chiarabba *et al*., 2008; Monna and Dahm, 2009). The model of Fig. 4 has therefore the advantage of including the main heterogeneities related to structural differentiations in a simple averaged velocity structure of the Calabrian Arc region. In the next section, we will use the velocity model obtained as starting model for a local earthquake tomography and we will show how it may improve the resolution of such kind of analysis.

4. Seismic data set and tomographic inversion

Data and recordings relative to earthquakes shallower than 60 km that occurred in southern Italy between January 1981 and December 2008 have been collected from the Italian national catalogs and databases (http://www.ingv.it) and from the databases of the local seismic networks operating in Calabria and Sicily (Bottari *et al*., 1981; Guerra *et al*., 1991; Chiodo *et al*., 1994; Barberi *et al*., 2004). From the collected data set, we selected events with a minimum of 7 P and 8 P+S readings, the quality of which was in the majority of cases checked directly on the recordings. We obtained a final inversion data set of 58,450 P and 35,149 S arrival times from 5,691 earthquakes recorded at a total of 373 stations (Fig. 5) and we used a grid with horizontal spacing of 40 km (Fig. 4a) and vertical spacing of 10 km. The standard Simulps code (Evans *et al*., 1994) has been used to invert the arrival time data for the P-wave velocity structure at the depth levels of 10, 20, 30, 40 and 50 km. The damping parameter was chosen by evaluating the trade-off curve of data variance and Vp variance, and selecting the damping value that greatly reduces data variance with only a moderate increase in solution variance [Eberhart-Phillips (1986); inset of Fig. 5]. In order to avoid the possibility of poorly constrained nodes biasing velocity estimates at the potentially well constrained ones, we performed the inversion only in the sectors with large ray density.

The final inversion nodes were characterized by derivative weight sum values (Toomey and Foulger, 1989) greater than 2000. The inversion full-resolution matrix has been used to evaluate the reliability of the final tomographic model, making a combined use of the spread function SF (Toomey and Foulger, 1989; Michelini and McEvilly, 1991) and the resolution smearing contours (Reyners *et al*., 1999). To properly address the choice of the SF upper bound in the present study, we estimated the 70% smearing contours at the individual nodes with the procedure of Reyners *et al*. (1999) and compared these contours with the SF values, as was done by previous investigators (Eberhart-Phillips and Reyners, 2001; Husen *et al*., 2003; Reyners *et al*., 2006; Sherburn *et al*., 2006). In our case. we found that SF values no larger than 3.0 always correspond to nodes without smearing from beyond the adjacent nodes, e.g., to well-resolved nodes. Therefore, we assumed the SF value of 3.0 as a conservative upper bound to contour the well-resolved zones of the tomographic

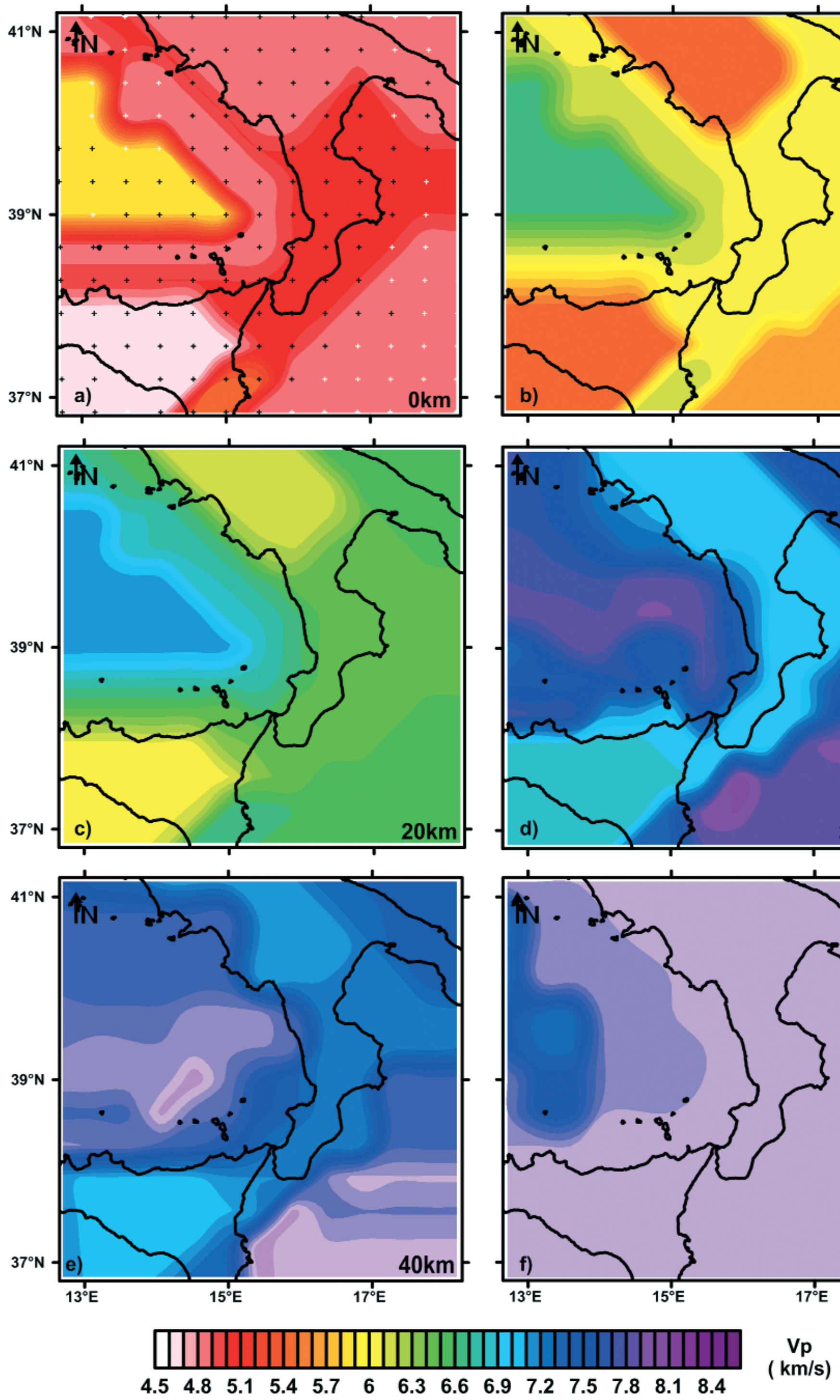

Fig. 4 - The “a-priori” P-wave velocity model of the study area obtained in the present work and used as starting model for the tomographic inversion. The number in the lower-right hand corner indicates the b.s.l. depth in kilometers. In panel (a) the planimetric view of the inversion grid is displayed. Black crosses represent the well constrained nodes sampled by seismic profiles and/or tomographic results relative to the more reliable regions; gray crosses represent the nodes characterized by lower quality constraints (see text for further details).

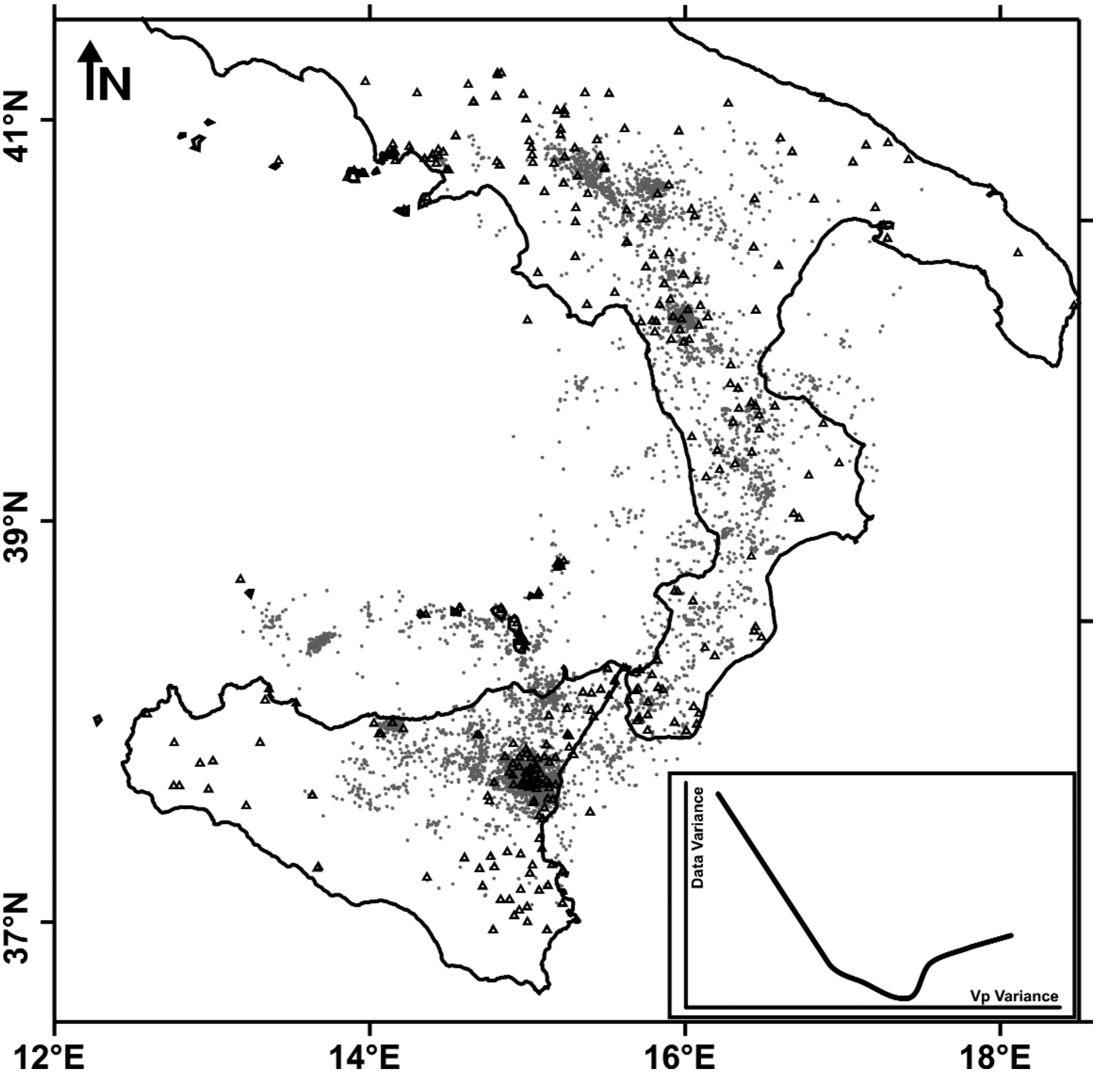

Fig. 5 - Earthquakes shallower than 60 km that occurred in southern Italy between January 1981 and December 2008 with a minimun of 7 P and 8 P+S recordings and available from national and local networks (http://www.ingv.it). The inversion data set consisted of 5,691 earthquakes (gray dots) recorded at a total of 373 seismic stations (black triangles). The inset in the lower right-hand corner shows the trade-off curve computed to select the damping value that greatly reduces the data variance with a moderate increase in the solution variance.

model (Fig. 6). Finally, we checked the model reliability in the SF 3.0 zones by standard synthetic tests like checkerboard tests [see, e.g., Zhao *et al*. (1992); Fig. 7], which gave additional evidence of the stability of the model and suitability of the inversion grid.

5. Discussion of results

Tomography results preserve the main structural features already displayed in our "a-priori" velocity model (Fig. 4), showing first-order heterogeneities related to the five different units

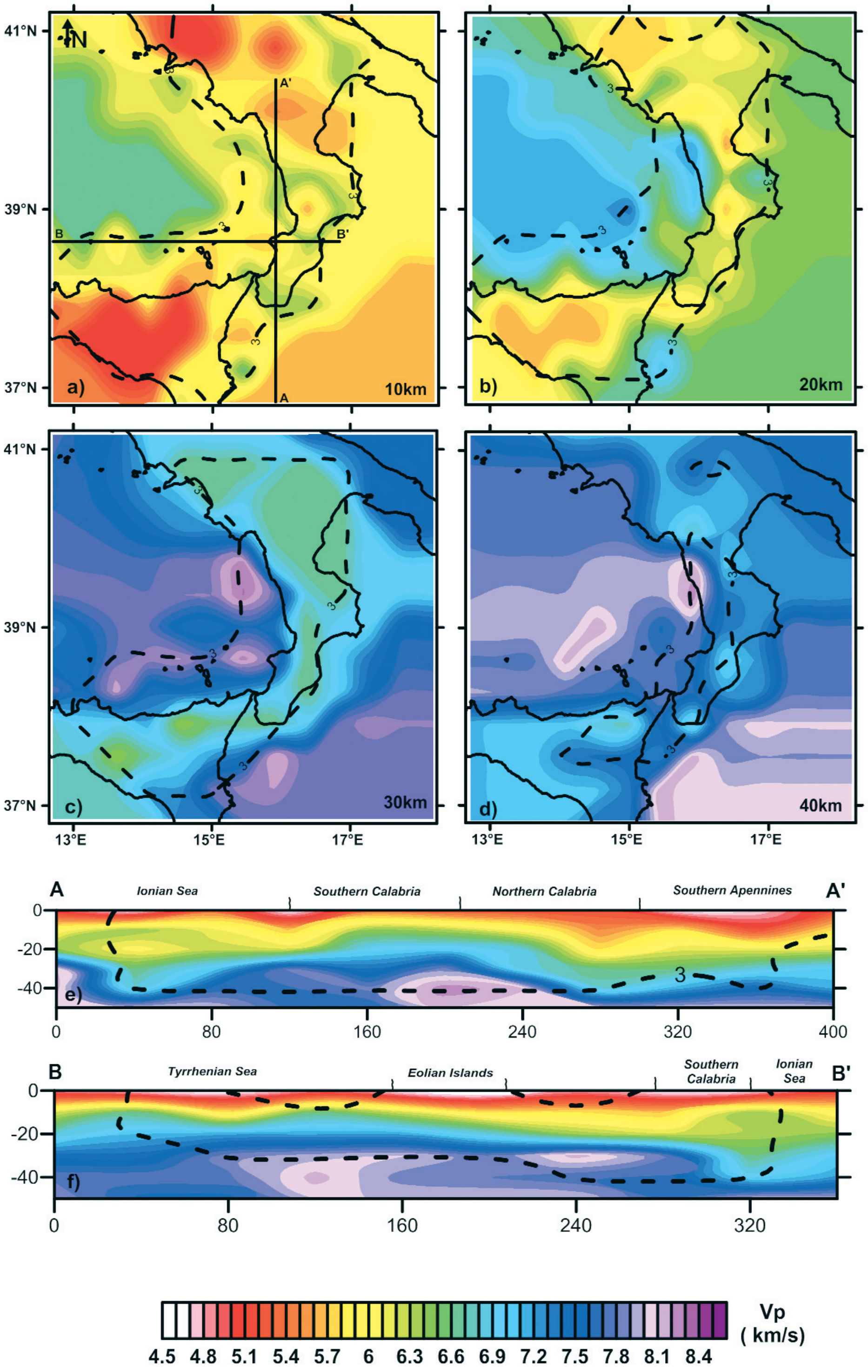

Fig. 6 - P-wave velocity model obtained by tomographic inversion in the present study. The number in the lower right-hand corner indicates the b.s.l. depth in kilometers. The black dashed curves contour the good resolution zones where the Spread Function values are no larger than 3.0. Panels (e) and (f) represent the vertical sections of the tomographic model along the profiles indicated in panel (a).

identified in the Calabrian Arc region (see e.g., the well-known crustal thickening of Sicily with respect to the Tyrrhenian Sea). In addition to these main features already revealed by several studies (see e.g., Barberi *et al*., 2004; Chiarabba *et al*., 2008; Monna and Dahm, 2009), our results also highlight local heterogeneities in the well-resolved sectors.

A striking feature in Fig. 6a (10 km depth), not present in the starting model, is represented by relatively high velocity values found in most of Calabria and in the north-eastern corner of Sicily, coherent with the values available in the southern Tyrrhenian area. In agreement with previously published models (Chiarabba *et al*., 2008; Seeber *et al*., 2008; Monna and Dahm, 2009; Neri *et al*., 2009), this feature may be related to the process of south-eastward migration of the southern Tyrrhenian lithosphere induced by rollback of the Ionian subducting lithosphere, that was progressively constrained between the continental margins of Sicily to the SW and the southern Apennines to the NE. The relevance of our result at a 10 km depth is that the crustal boundaries between these domains (i.e., Calabro-Tyrrhenian, Sicily and southern Apennines) can be clearly distinguished in the tomographic view of Fig. 6a for their different velocity patterns. This finding may be interpreted as a shallow signature of the subduction process. Slighter evidence of the same features may also be found at the depth of 20 km of the tomographic structure (Fig. 6b). More uniform velocity can be detected at a 30 km depth (Fig 6c) across the arc from southern Apennines to northern Sicily. This finding does not necessarily imply structural and geodynamic continuity below the chain. P-wave velocities of the order of 6.5-7 km/s estimated at a 30 km depth below the chain may correspond both to lower-crust layers of continental crust beneath Sicily and to crustal rocks of the Ionian slab subducting underneath the thinner Tyrrhenian crust in the Calabrian area [see, among others, Catalano *et al*. (2001), Barberi *et al*. (2004), Finetti (2005a, 2005b)]. The reliability domain of the tomographic model becomes small at a 40 km depth (Fig. 6d).

The cross-section AA' (Fig. 6e) well reflects the structural differences among Calabrian and southern Apennines domains showing a gradual change in the velocity patterns. Fig. 6f (section BB') reveals the thin Tyrrhenian crust and a thick zone with velocities of about 6.5-7 km/s beneath southern Calabria. The latter can be due to crustal doubling beneath southern Calabria and therefore it can be interpreted as possible evidence of the deep contact zone between the overthrusting (Tyrrhenian) and underthrusting (Ionian) units [see also Barberi *et al*. (2004), Neri *et al*. (2011)].

Finally, we want to remark that the use of our "a-priori" model as a starting velocity model in the P-wave tomographic inversion of shallow earthquakes led to a meaningful improvement of hypocenter locations (mean RMS=0.48 s) with respect to the crustal 3D model already available for the region (Barberi *et al*., 2004) and to the tomographic results obtained by testing different starting velocity models.

6. Summary and conclusions

The main result of this study is the average P-wave velocity model of the Calabrian Arc lithosphere obtained by integrating all the "a-priori" information available for the study region. A similar approach has been carried out in the Alpine region by Waldhauser *et al*. (1998, 2002), showing how the employment of such a kind of model as reference crustal model in teleseismic tomographies may significantly improve the result with respect to the standard 1D model.

To build the "a-priori" velocity model we first collected the structural information available

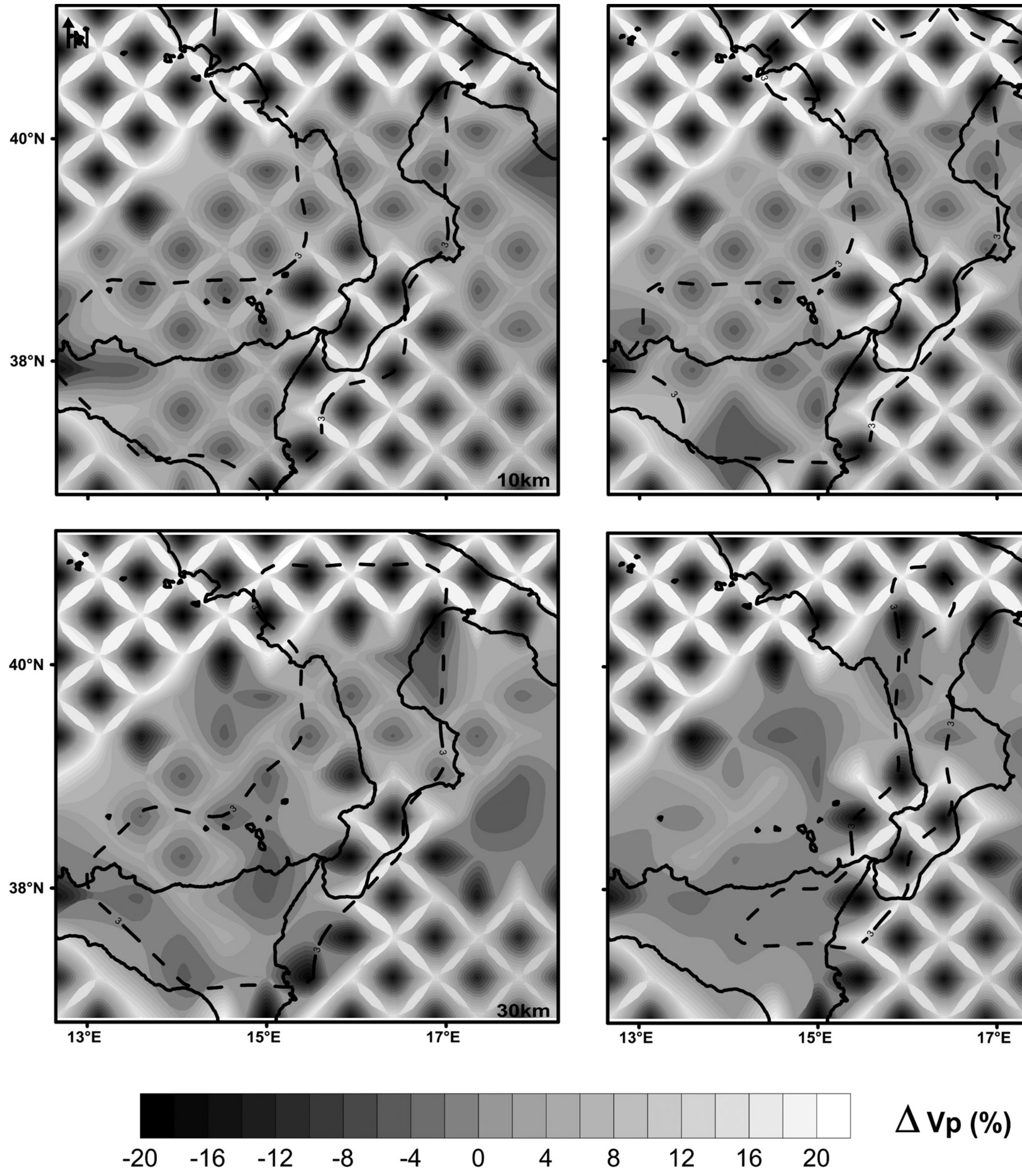

Fig. 7 - Vp distribution obtained from the checkerboard test discussed in the text. The black dashed curves contour the zones where Spread Function values are less than 3.0.

for the region in terms of P-wave velocities and then we reported the relative couples of Vp-depth data on the nodes of a 40-km spaced horizontal grid. For each grid node we built the Vp versus depth plot and, using additional data to constrain the Moho depth range, we estimated the best fit curves for a three-layer basic model (i.e. the first layer covers the crustal depth range, the second identifies the Moho transition zone, the last encloses the sub-moho mantle interval). Finally, we built the "a-priori" velocity model applying a horizontal, spatial smoothing to the P-velocity values of the grid nodes. The procedure of integration allowed us to verify the consistency of the different data available for the Calabrian Arc region, confirmed by the high values of the R^2 parameter of the best fit curves ($R^2 > 0.7$ for 80% of nodes).

The “a-priori” velocity model thus obtained has the advantage of clearly reflecting the first-order structural features of the area in an overall picture of the velocity structure of the Calabrian Arc region that also represents the simplest velocity structure consistent with all published data. Moreover, with the procedure here proposed, the “a-priori” velocity model may be improved as new useful measurements will be achieved so representing a basic knowledge that can be easily extended and updated.

Finally, the use of this “a-priori” model as a starting velocity model in a new P-wave tomographic inversion of shallow earthquakes led to a significant improvement of hypocenter location and highlighted the relationships between the deep dynamics and the processes occurring at crustal depths. In particular, the tomographic model permitted us to better locate structural heterogeneities that may be intended as a shallow signature of the subduction process, marking the area where rollback and trench retreat have been confined in recent geological times. The well constrained results of this tomography, furnishing a more detailed view of the crustal structures, have been also used to perform a multidisciplinary structural analysis of the Calabrian Arc region (Neri *et al*., 2011). In conclusion, the model obtained by integration of all the P-velocity data available for the Calabrian Arc region contributes to providing a more complete picture of the lithospheric structure of the area and represents a basic knowledge useful for further investigation.

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