



Mapping the Moho Across the Northern and Central Apennine Chain and Eastern Sicily

The Teleseismic Receiver Functions Method

Giuliana Mele

INGV – Istituto Nazionale di Geofisica e Vulcanologia, via Vigna Murata 605, 00143 Roma,
Italy (giuliana.mele@ingv.it)

Abstract. Waveforms of seismic events occurred at epicentral distances ranging from 30° to 90°, and recorded by 3-component stations installed in peninsular Italy and in eastern Sicily, were analyzed using the receiver function technique. Receiver functions are time series where the arrivals of P-to-S waves converted at marked velocity contrasts beneath a seismometer are enhanced. Teleseismic receiver functions are frequently used to identify waves converted at the Moho discontinuity to infer crustal thickness. Across the northern Apennines, receiver functions show that west of this chain (i.e. beneath the Elba island and Tuscany) the Moho is flat and shallow, while it deepens from the eastern coast of the peninsula toward the chain. Two Ps conversions are observed at a station located in the Tiberina valley, indicating the presence of the Moho at depths of about 20 and 52 km. More to the south, across the central Apennines, the Moho is shallower beneath the Tyrrhenian margin of the peninsula than beneath the Adriatic margin, and deepens from both sides toward the Apennines. The largest crustal thickness is inferred in the area of highest topography. The Moho depths estimated with the receiver function technique are in agreement with the interpretation of active seismic data in the western margin of peninsular Italy and along the Adriatic coast, while they are significantly larger beneath the Apennines. Results of an ongoing study in eastern Sicily show that Moho depth increases from north to south. In this area, the northernmost stations show also a later Ps converted by a lower interface.

Key words. Moho discontinuity – Seismology – Teleseismic receiver functions

1. Introduction

This paper summarizes the results of recent studies aimed at reconstructing the trend of the crust-mantle boundary across peninsular Italy, using earthquakes data (Mele and Sandvol, 2003; Mele et al., 2006; Di Luzio et al., 2009). These studies have shown that crustal thickness is larger than 40 km beneath the core of the Apennine chain, in contrast with the interpretation of active seismic data (Cassinis et al., 2003, and references therein). Preliminary results obtained in

eastern Sicily with the same technique are also presented and briefly discussed.

Figure 1 shows the map of Moho isobaths of Italy redrawn after Cassinis et al. (2003). These authors synthetized the results of seismic explorations carried out in the 1956-1987 period, distinguishing several crustal domains:

- i) the European continental crust in the Alps and Corsica and Sardinia islands;
- ii) African/Adriatic crust in the southern Alps, Po plain, eastern margin of peninsular Italy and southern Sicily;

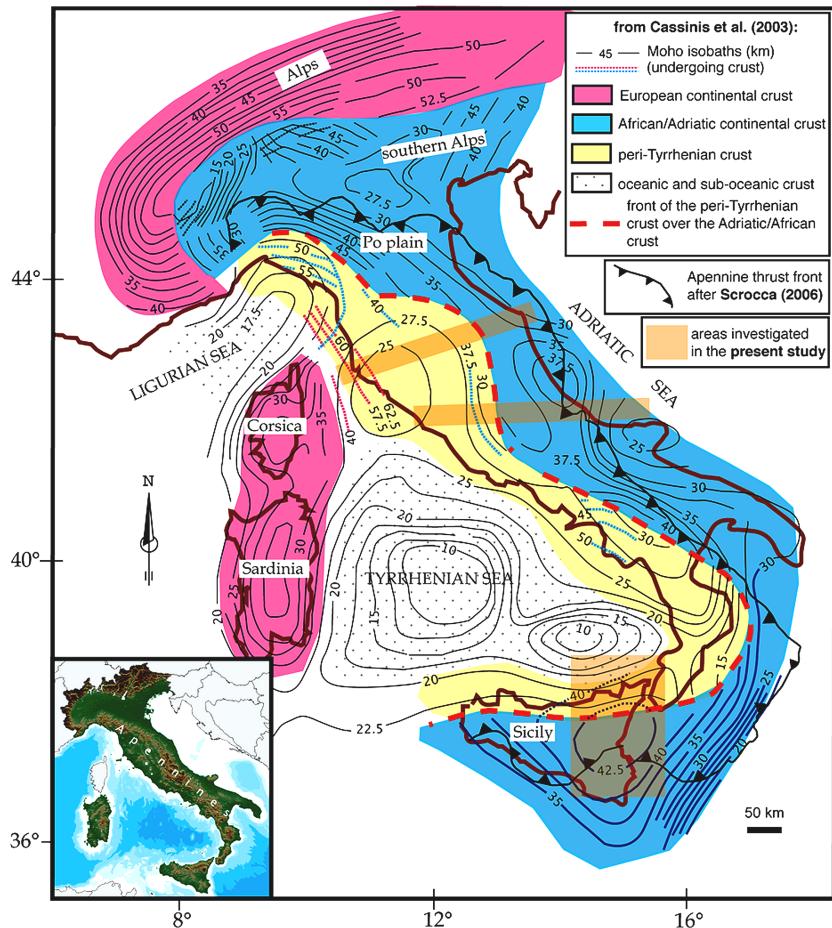


Fig. 1. Map of Moho isobaths derived from the interpretation of DSS (Deep Seismic Soundings) data, redrawn after Cassinis et al. (2003). Following these authors, the peri-Tyrrhenian Moho overthrusts the Adriatic Moho along the dashed red line.

- iii) a stretched transitional crust in the peri-Tyrrhenian margin of peninsular Italy and Sicily;
- iv) oceanic and sub-oceanic crust in the Tyrrhenian and Ligurian Seas.

2. Teleseismic receiver functions

Earthquakes are classified in terms of distance from the recording site as local, regional, upper mantle, and teleseismic (Table 1).

Three-component recordings of teleseismic events are used to infer the first-order structure of the lithosphere and upper mantle (e.g. Langston, 1979; Sandvol

et al., 1998; Zhu and Kanamori, 2000; Niu et al., 2004).

In fact, in the presence of a marked velocity contrast (i.e. a seismic discontinuity) the incoming compressional (P) wave is converted into shear wave (S) (Fig. 2a). The resulting Ps wave has larger amplitude on the horizontal, radial direction, i.e. the direction along the great circle connecting source and receiver.

By deconvolving the vertical component of the seismogram from the horizontal component rotated into the radial direction, most of the unwanted source (rupture kinematics, near-source structure) and propagation path effects are removed and

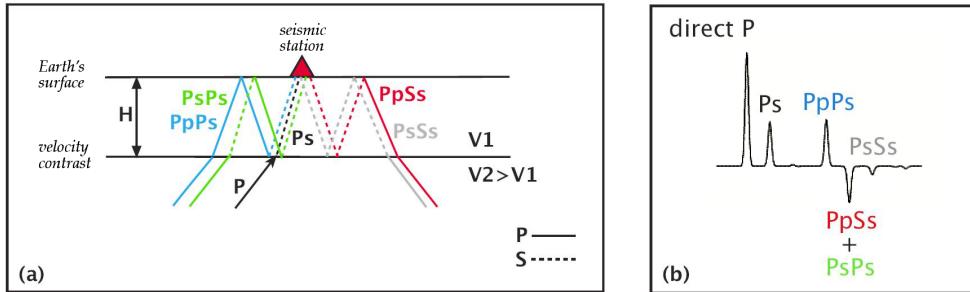


Fig. 2. (a)– Geometry of raypaths of Ps waves and later reverberations generated by a teleseismic wave interacting with a velocity discontinuity; each portion of a raypath is called leg and is identified by a letter indicating the mode of propagation as P or S wave. The name of a phase is given by the sequence of legs. (b)– corresponding receiver function.

Earthquake	Epicentral Distance	Direct P wave propagates through:
local	< 1° (~100 km)	shallow crust
regional	1°-13°	whole crust
upper mantle	13°-30°	upper mantle
teleseismic	> 30°	lower mantle and core

Table 1. Classification of earthquakes/seismograms in terms of epicentral distance. The direct P wave travels the minimum-time path between source and receiver, and corresponds to the first arrival on the seismogram.

near-receiver effects are enhanced (e.g., Langston, 1979; Ammon, 1991; Zhao and Frohlich, 1996). The resulting signal, called receiver function, is a simpler waveform displaying the direct P wave followed by a composite of Ps waves that reverberate in the structure beneath the seismometer (Fig. 2b).

The time separation between the P and Ps arrivals depends on:

- i) the depth of the velocity contrast (H);
- ii) the velocity structure in the layer between the velocity contrast and the Earth's surface (V_p , V_s), and
- iii) the incidence angle of the P wave (expressed through the ray parameter p):

$$H = \frac{t_{Ps-P}}{\sqrt{(1/V_s^2 - p^2)} - \sqrt{(1/V_p^2 - p^2)}}. \quad (1)$$

The most significant Ps conversions observed in teleseismic receiver functions are those generated at the Moho and at the

410- and 660-km boundaries, where the velocity contrast is larger. With respect to the first P arrival, these phases are approximately delayed 4, 40 and 65 s, respectively. Teleseismic receiver functions are most frequently used to identify the Ps wave converted at the Moho discontinuity (called Ps_{Moho} hereinafter) to infer crustal thickness.

3. Data

To determine Moho depths, receiver functions are computed using teleseisms occurred at any depth and limited to a maximum distance of 90°. The reason is that seismograms of earthquakes occurring beyond this distance are complicated by the interaction with the Earth's outer core; instead, between 30° and 90° seismograms are characterized by relatively simple P arrivals (seismic waves sample the lower mantle where velocity distribution is smooth), which is an advantage for

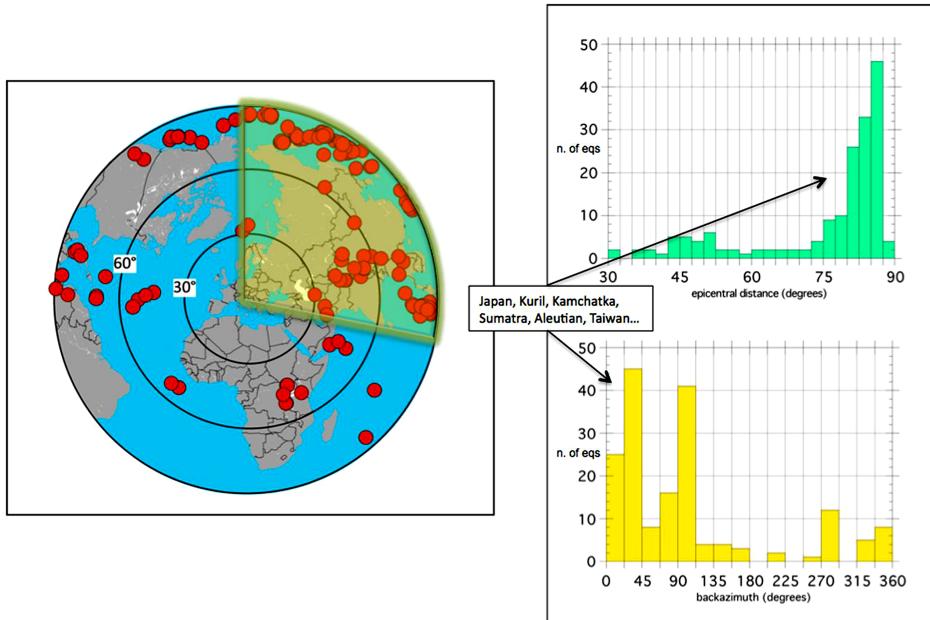


Fig. 3. Azimuthal projection, centered on Italy, and histograms of distance and backazimuth of the teleseisms used to compute receiver functions. Most of the teleseismic events recorded in Italy occur in the sector shaded in green.

the identification of the shortly following Ps_{Moho} phase.

With respect to Italy, most teleseismic events occur between 70° and 90° and in the NE quadrant, where particularly active seismogenic areas are present (e.g., Sumatra and eastern Indonesia, Kamchatka, Kuril Islands, Japan, Aleutian arc) (Fig. 3). Nevertheless, azimuthal gaps are common in these studies because the natural distribution of seismic areas prevents acquisition of teleseisms from a wide range of azimuth.

The first regional arrays of 3-component, broadband seismic stations were installed in Italy in the 1990s during temporary experiments that lasted a few months each. The arrays extended from the Tyrrhenian to the Adriatic coastlines of peninsular Italy crossing the Apennine chain. The present work focuses on the results obtained by Mele and coauthors in the northern and central Apennines.

4. Observations

– 4.1. – Northern Apennines (array 1). Fig. 4 shows the results obtained along the array 1 (highlighted in yellow in Fig. 4a). At the westernmost stations installed in the Elba island and across the Tuscany region, Ps_{Moho} arrivals are earlier than those recorded in the eastern part of the array, where $P_{S_{\text{Moho}}}$ are also progressively more delayed from the Adriatic coast toward west (Fig. 4b). In the receiver functions of a station installed in the Tiberina valley are observed two converted waves with a time separation of about 3 s (Fig. 4b).

In the absence of independent determination of a bulk crustal velocity, Moho depth was computed from equation (1) assuming $Vp = 6.2 \pm 0.2$ km/s and a Poisson's ratio of 0.25 (Zandt & Ammon, 1995). The results show that the Moho is 20 to 24 km beneath the Elba island and Tuscany, while it deepens from 28 km in the Adriatic coast to 52 km

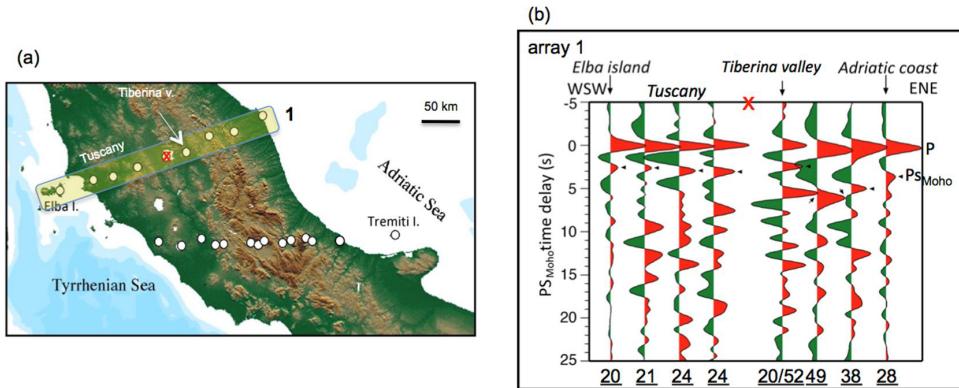


Fig. 4. (a)–Relief map of the study area showing the seismic stations used in this work (circles); (b)–profile of receiver function stacks computed along the array 1 using events with similar backazimuth and epicentral distance. A red cross marks a station discarded for the low quality of the recordings. Waveforms are aligned with the P wave (first positive pulse) at 0 s. Black underlined numbers are the Moho depths computed by Mele and Sandvol (2003).

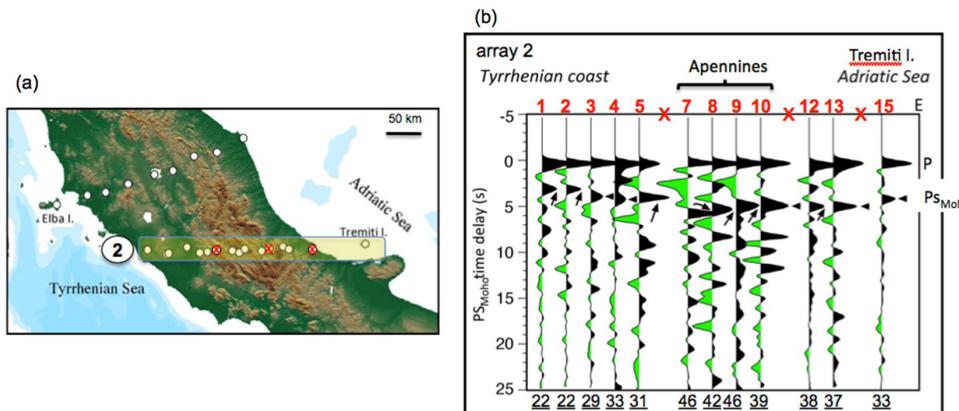


Fig. 5. (a)–Relief map of the study area showing the seismic stations used in this work (circles); (b)–profile of receiver function stacks computed along the array 2 using events with similar backazimuth and epicentral distance. Red crosses mark stations discarded for the low quality/numbers of the recordings. Waveforms are aligned with the P wave (first positive pulse) at 0 s. Black underlined numbers are Moho depths computed by Mele et al. (2006) at stations 1–5, 8, and 15 and by Di Luzio et al. (2009) at stations 7, 9, 10, 12, 13.

in the Tiberina valley. Even though the time delay is shorter at this station than at the adjacent eastern station, the depth estimated beneath the Tiberina valley is larger because Mele and Sandvol (2003) assumed the presence of mantle material between the two converting interfaces, using $V_p=7.9$ km/s that is the velocity estimated in the Tyrrhenian uppermost mantle by Mele et al. (1998).

– 4.2. – *Central Apennines (array 2)*. As for the array 1, the PS_{Moho} arrivals are earlier in the western part than in the eastern part of the array 2 (highlighted in yellow in Fig. 5a). From both sides of the array, the PS_{Moho} –P delay increases toward the Apennine chain (Fig. 5b), the largest crustal thickness corresponding to the highest topography (Mele et al., 2006; Di Luzio et al., 2009); in the Adriatic fore-

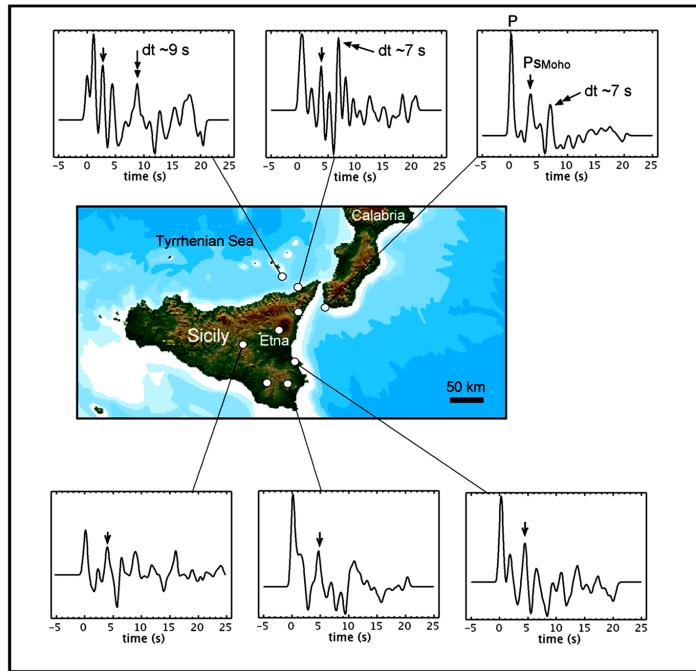


Fig. 6. Topography map of Sicily and southern Calabria showing stations location and example receiver functions. Arrows indicate the Ps_{Moho} phase. At the northernmost stations (upper panels), a later conversion (marked by a double arrow) is observed 7 to 9 s after the direct P arrival.

land crustal thickness is 33 km (Mele et al., 2006).

— 4.3. — *Eastern Sicily.* In eastern Sicily and surrounding areas, teleseismic receiver functions were computed at several permanent stations of the Italian Seismic Network (RSNC) and Mediterranean Network (MedNet), both operated by the Istituto Nazionale di Geofisica e Vulcanologia (Fig. 6).

Preliminary results show that the $Ps-P$ delay increases regularly from north to south; the northernmost stations show a second Ps conversion (double arrowhead in the upper panels of Fig. 6) that is delayed by 3–6 s with respect to the first Ps_{Moho} , produced by a deeper interface.

5. Summary and conclusion

The regional seismic arrays 1 and 2 cross a region where the peri-Tyrrhenian and Adriatic Mohos adjoin; therefore, each station can be tentatively assigned to either

crustal domains on the basis of the estimated Moho depth – the shallower Moho belonging to the peri-Tyrrhenian crust, the westward deepening Moho belonging to the Adriatic crust – and compared with the results of Cassinini et al. (2003) (Fig. 7a).

The results of Mele and Sandvol (2003) showed that the eastern border of the peri-Tyrrhenian Moho runs somewhere between the station installed in the Tiberina valley, where a double Ps conversion indicates the presence of both the peri-Tyrrhenian and Adriatic Mohos at different depths, and the nearest eastern station, where receiver functions display a single Ps phase converted at a depth that is consistent with the trend of the Adriatic Moho.

The vertical offset between the peri-Tyrrhenian and Adriatic Mohos beneath the Tiberina valley is about 30 km (left upper panel of Fig. 7a).

Along the array 2, the Moho depths estimated by Mele et al. (2006), partly re-

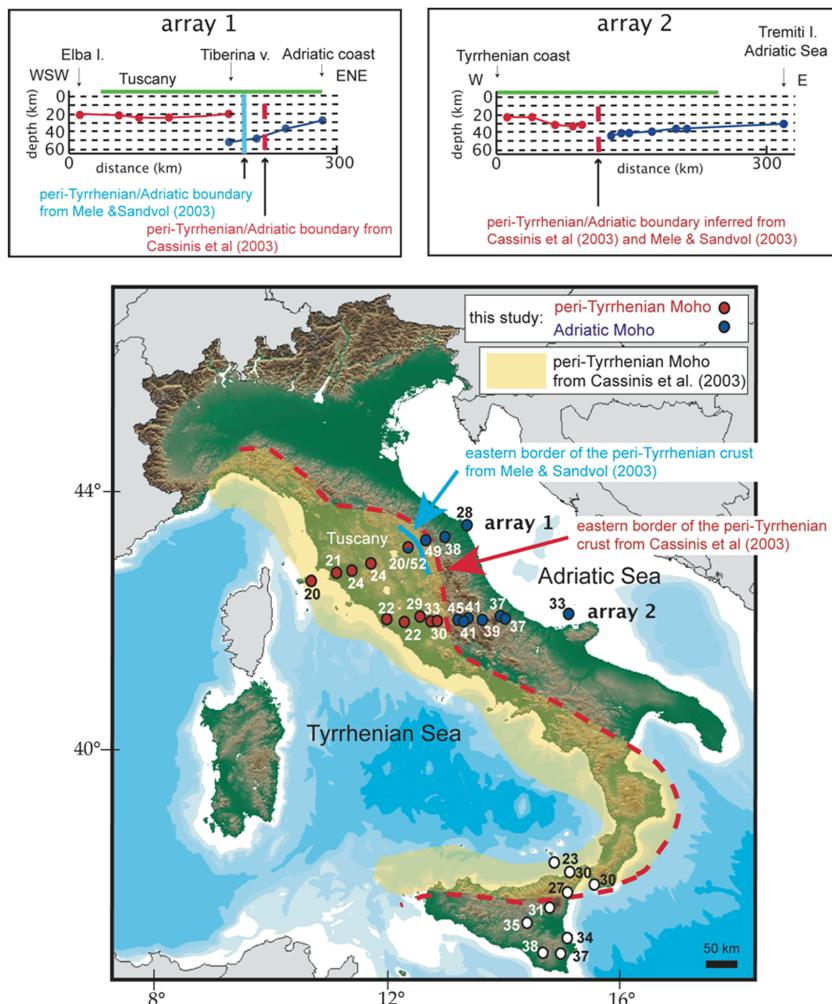


Fig. 7. Topography map of Italy showing the Moho depths estimated from the $\text{Ps}_{\text{Moho}} - \text{P}$ delays by Mele and co-authors. Across the Apennines (Mele and Sandvol, 2003; Mele et al., 2006; Di Luzio et al., 2009), red and blue circles indicate stations with depths consistent with the trend of the peri-Tyrrhenian and Adriatic crustal domains, respectively. Results are compared with those obtained from the interpretation of DSS data (Cassinis et al., 2003): the red dashed line indicates the eastern border of the peri-Tyrrhenian Moho following Cassinis et al. (2003), the azure line indicates the same feature inferred along the array 1 from the results of Mele and Sandvol (2003). Results overlap along the array 2. The upper panels show cross-sections of the arrays 1 and 2; the vertical offset between the peri-Tyrrhenian (red solid line) and the Adriatic (blue solid line) Moho is ~ 30 km along the array 1 and ~ 15 km along the array 2. In eastern Sicily and southernmost Calabria, Moho depths increase regularly from north to south, which makes the transition between the two Mohos less obvious (Mele, in preparation). Moho depths include the elevation of the recording sites.

vised by Di Luzio et al. (2009), are consistent with the extent of the peri-Tyrrhenian and Adriatic crusts proposed by Cassinis et al. (2003), even though the Adriatic Moho is significantly deeper than imaged with DSS data.

The depths of the crust-mantle boundary estimated by Mele and co-authors match the interpretation of active seismic data in the peri-Tyrrhenian and Adriatic margins of peninsular Italy. On the contrary, results are not in agreement beneath

the Apennine chain where receiver functions point out a much thicker crust. The results obtained with the receiver function technique suggest a revision of the interpretation of active seismic data in the Apennine region.

An ongoing receiver function study in eastern Sicily (Mele, in preparation) shows that Moho depth increases from north to south quite regularly, which makes the border between the peri-Tyrrhenian and Adriatic crust not clearly distinguishable in this area. The Moho is 23 km deep beneath the Vulcano island, in the southern Tyrrhenian Sea, 28 to 30 km beneath northeastern Sicily and southern Calabria, 33 km beneath the Mt. Etna volcano, 37 to 39 km beneath the Iblei Mts. (Fig. 7). The isobath 42.5 km of Cassinis et al. (2003) is not confirmed by this study.

At the northernmost stations, a late conversion arriving 3 to 6 s after the first Ps_{Moho} phase is observed, corresponding to a seismic discontinuity lying 35 to 70 km below the peri-Tyrrhenian Moho.

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Author's Biographical Notes: Giuliana Mele was born in Foggia, Italy, in 1964. She studied Geology at the University of Rome «La Sapienza», where she graduated in 1989. She has been working at the Istituto Nazionale di Geofisica (now Istituto Nazionale di Geofisica e Vulcanologia) of Rome since the academic degree (Laurea), mainly focusing her research activity on Seismology.