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Key Points:
- The combination of passive and active seismic data provides a robust image of the deep structure of crust and lithosphere
- Beneath the N. Apennines, the mantle wedge is located beneath the topography divide, 40 km eastward with respect to previous estimate
- Only one third of the Adriatic crust is accreted in the orogenic wedge, while the rest descend down to deeper depth

Supporting Information:
- Supporting Information S1

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Deep Structure of Northern Apennines Subduction Orogen (Italy) as Revealed by a Joint Interpretation of Passive and Active Seismic Data

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Abstract The Apennines is a well-studied orogeny formed by the accretion of continental slivers during the subduction of the Adriatic plate, but its deep structure is still a topic of controversy. Here we illuminated the deep structure of the Northern Apennines belt by combining results from the analysis of active seismic (CROP03) and receiver function data. The result from combining these two approaches provides a new robust view of the structure of the deep crust/upper mantle, from the back-arc region to the Adriatic subduction zone. Our analysis confirms the shallow Moho depth beneath the back-arc region and defines the top of the downgoing plate, showing that the two plates separate at depth about 40 km closer to the trench than reported in previous reconstructions. This spatial relationship has profound implications for the geometry of the shallow subduction zone and of the mantle wedge, by the amount of crustal material consumed at trench.

Plain Language Summary Depicting the structure of the Earth is a goal for all Earth scientists. Knowledge of the Earth's properties is fundamental for a number of societal challenges, from locating georesources to the mitigation of seismic risk. We investigate the structure of the Earth's crust beneath a well-studied subduction orogeny, the Apennines (Italy), analyzing together different seismic data sets. The Apennines mountain chain were the locus of a number of middle- to high-magnitude seismic sequences in the last few years. Our findings will be a necessary step forward in defining the active processes in the Earth's interior and in defining the seismic risk of the area.

1. Introduction

Subduction of continental lithosphere produces orogenic wedge, scraping off slices of crustal material from the downgoing plate and transferring them to the upper plate (Dewey & Burke, 1973; Royden, 1993). The structure of the subduction orogeny differs from Cordillera-type orogeny as they are constituted by material coming from the downgoing plate and they may actually represent an immature phase of a collisional orogeny. Active or extinct subduction orogenies are well described worldwide along the Tethyan belt, but probably the best examples are in the Mediterranean, where the Africa and Adriatic plates are converging toward Eurasia at an extremely slow rate providing a snapshot of an incomplete collisional process.

Several models illustrate the way subduction orogeny forms and the way material is transferred from the downgoing plate and accreted to the overriding one (e.g., Brun & Faccenna, 2008). This implies that the crustal growth of the orogenic wedge occurred directly on top of the asthenosphere, with extreme consequences in terms of rheology. From a geometrical point of view, the subducting plate and the upper plate are in contact along a line at depth, which is defined in cross section as the S point (Willett et al., 1993), which migrates backward during accretion. A number of fundamental parameters affecting the way subduction orogens grow are left unconstrained. For example, we have poor constraints on the depth of decollement of the crustal slices within the downgoing plate and on the way they are transferred and accreted to the upper plate. Other relevant but poorly understood processes include the fluid budget released by the continental crust during dehydration and metamorphism.

The Northern Apennines (NA) probably represents one of the best studied examples of subduction orogeny having been explored by intensive campaigns of both shallow deep active and passive seismic experiments

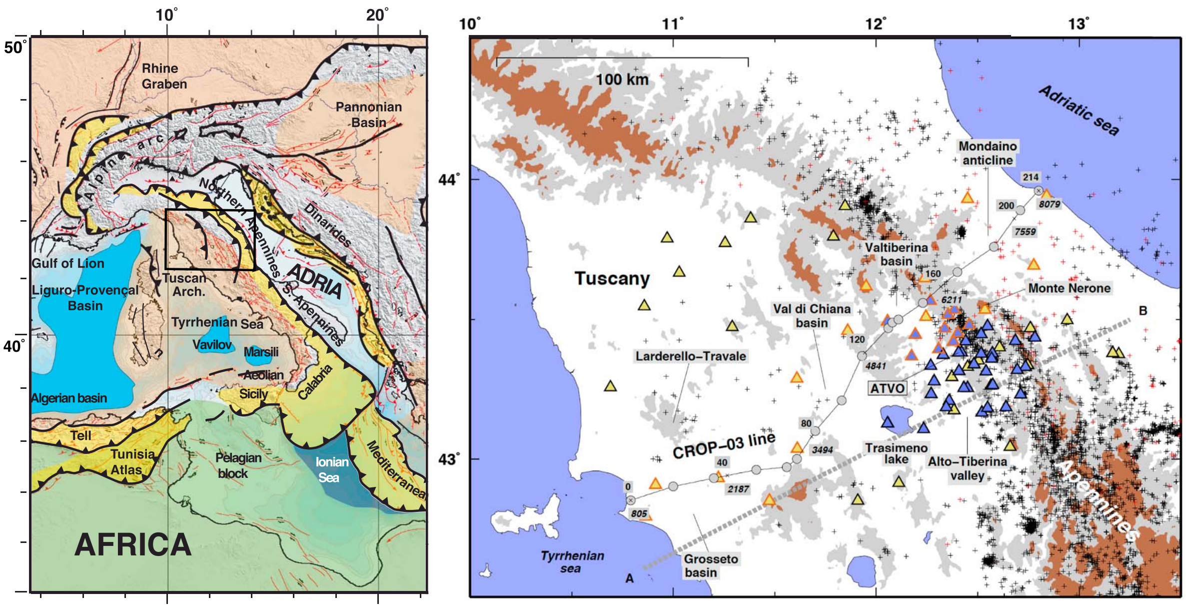

Figure 1. Map of the study area. The gray line indicates the CROP03 active seismic line (numbers refer to kilometers along the line, italics number refers to CDF along the line). Triangles show the positions of seismic stations in the area. Yellow-filled triangles refer to previous temporary experiment (Piana Agostinetti et al., 2011, and references therein). Blue-filled triangles indicate the new stations analyzed for the present study (see Table S1 for the details of the results). Triangles with a red outline highlight the seismic stations used in Figures 2 and 3. Gray and brown colors indicate the topography higher than 500 m and 1,000 m, respectively. A dashed gray line depicts the trace of the teleseismic tomographic image presented in Figure 3. Crosses show epicenters of local seismicity (red crosses for events with a focal depth greater than 25 km (De Luca et al., 2009).

along with decades of geological studies (Barchi et al., 1998; Finetti et al., 2001; Liotta et al., 1998). It formed during the subduction of the continental Adriatic plate beneath Eurasia after the complete closure of the Jurassic Ligurian Ocean (Figure 1). The onset of continental subduction, around 30 Ma, remarkably coincides also with the onset of back-arc extension related to rollback and/or delamination of the subducting slab (Chiarabba et al., 2014; Faccenna et al., 2001; Malinverno & Ryan, 1986). This produced extension, intense crustal thinning, and back-arc spreading that migrated eastward following the retreat of the Adriatic slab and the northeastern propagation of the compressional structure. The velocity of subduction since the onset of continental subduction has decreased to the present-day rate of a few millimeters per year, with the position of active extension located along the divide of the orogenic belt and flanked by compression in the Po Plain-Adriatic Sea (Picotti & Pazzaglia, 2008).

The deep structure of the Adriatic slab, as imaged in teleseismic tomography (Faccenna et al., 2001; Giacomuzzi et al., 2011) and regional tomography (Koulakov et al., 2009; Piromallo & Morelli, 2003) shows a subvertical fast velocity body down to the bottom of the upper mantle, variously interpreted as the relict of the subducted Tethyan ocean or the delamination of the Adriatic lithosphere (Koulakov et al., 2015). Subcrustal seismicity is however limited to 90 km depth (Selvaggi & Amato, 1992). Tomographic images and aereomagnetic data (Di Stefano et al., 2009; Speranza & Chiappini, 2002) also indicate an elevated Moho temperature and, thus, a very thin or absent mantle lithosphere beneath the NA. The shallow structure in this region has been investigated using active seismic data (Pauselli et al., 2006), regional earthquake data (Di Stefano et al., 2009), and teleseismic converted phases (receiver function, RF; Piana Agostinetti et al., 2008, Piana Agostinetti et al., 2011). In the internal and external domains, the analyses of active and passive seismic data broadly agree on the Moho topography. On the other hand, differences are noted in the interpretations of the two different seismic data sets in the central portion of the belt, where a more complex structure is expected and the seismic observations can be biased by the presence of strong anisotropy within the mantle wedge corner (Piana Agostinetti et al., 2011). The interpretation of deep crustal seismic profiles shows a shallow Moho beneath Tuscany merging with the top of the Adriatic plate, that is, S point, as west as the Trasimeno lake (Figure 1), that is, beneath the internal domain of the NA orogeny (Pauselli et al., 2006). Conversely, passive seismic data suggest that the S point is positioned about 30–50 km east of the Trasimeno lake, close to easternmost extensional basins (Di Stefano et al., 2009; Piana Agostinetti, 2015; Roselli et al., 2008). This difference has profound implications not only on the structure and rheology of the orogeny but also on models that explain the connection between thermal structure, deformation, and topography (Pauselli et al., 2010; Willett et al., 2001).

In addition, different interpretations have been proposed based on the Crosta Profonda project (CROP03) deep seismic profile (e.g., Barchi et al., 1998; Decandia et al., 1998; De Franco et al., 1998; Pauselli et al., 2006). There is general agreement on the position of the main crustal interfaces beneath Tuscany, where active seismic data seem to indicate a shallow interface within the Larderello-Travale geothermal field (k-horizon), and a deeper interface at about 20 km depth, widely interpreted as the Tyrrhenian Moho. However, the different models differ in the interpretation of a sharp reflector beneath the Valtiberina basin: (a) the Easternmost continuation of the k-horizon (Decandia et al., 1998); (b) the top of the lower-crust of the Adriatic plate (Barchi et al., 1998); or (c) the Tyrrhenian Moho (De Franco et al., 1998). At the eastern end of the line, research groups agree on the interpretation of the deeper reflector as the Adriatic Moho, at about 35 km depth (Pauselli et al., 2006).

Here we compute a new RF data set for the central portion of the NA orogeny for broadband seismic stations deployed in the middle of the NA orogen, and we reinterpret the CROP03 active seismic line. We select new and previously published RF data set for stations strictly close (<20 km) to the CROP03 line to avoid misinterpretation given by the 3-D structure of the orogen. The joint interpretation of the active and passive seismic data helps to shed light on the position of the crust-mantle interface along the entire profile, allowing us to precisely locate the S point and the mantle wedge geometry.

2. Data and Methods

Images of the active seismic data for the CROP03 line are freely available at ViDEPI website (http://unmig.sviluppoeconomico.gov.it/videpi/videpi.asp). We download the raw, unmigrated images to avoid any bias introduced by too intense postprocessing activities and potential artifacts from data migration processing. We interpret the deep portion of the profile, pointing the main reflections deeper than 2 s. Profile distances are converted from acquisition (CDF) position to kilometer and depth are migrated from two-way time to kilometer using a homogeneous crustal model (mean P wave velocity, $V_P = 6.5$ km/s). While this simple migration can bias the depth position for the shallow interfaces ($\leq$10 km depth), the deeper structure is not significantly affected in terms of relative positions. Given our approximations, errors associated to interfaces positions obtained from reflection data can be of the same magnitude as uncertainties associated to estimates based on passive seismic measurements.

Teleseismic waveforms recorded across the NA have been used to estimate the depth of the most prominent seismic interfaces, through the analysis of teleseismic P-to-S converted phases (so-called RF). Such velocity contrast generally corresponds to the Moho interface, with relevant exceptions across subduction zones (Piana Agostinetti et al., 2009; Piana Agostinetti & Miller, 2014). We computed 42 RF data sets recorded along the central portion of the CROP03 line (Figure 1 and Figure S2 in the supporting information), in an area where few RF data sets have been analyzed in the past. Our RF data sets allow a direct comparison of active and passive seismic data in this portion of the CROP03 profile. Broadband seismic stations belong to the Alto-Tiberina seismic network (Chiaraluce, 2014). Teleseismic RFs are computed using the procedure described in Di Bona (1998). We obtain an average of 56 high signal-to-noise ratio RFs per station, with a minimum of 25 and a maximum of 123. The depth of the most relevant seismic contrast beneath each single station is estimated using the approach described in Zhu and Kanamori (2000), with details provided in Piana Agostinetti and Amato (2009) and Licciardi et al. (2014). The results are shown in Table S1 with an example of the RFs for one station provided in Figure S1.

We complement our RF data sets with results from previous RF studies focused on the NA (Piana Agostinetti et al., 2008; Piana Agostinetti & Amato, 2009; Piana Agostinetti, 2015). We select only RFs recorded within a distance of 20 km from the CROP03 line. While this selection reduces the number of available RF data sets to 28 (11 new RF data sets belonging to the Alto-Tiberina seismic network), it avoids influence of structural heterogeneities not present along the profiles.

3. Results

Figure 2a reports the uninterpreted active source seismic profile, for reference. Figure 2b shows the major reflectors in yellow and the less prominent ones in orange. For consistency and readability, we use the same

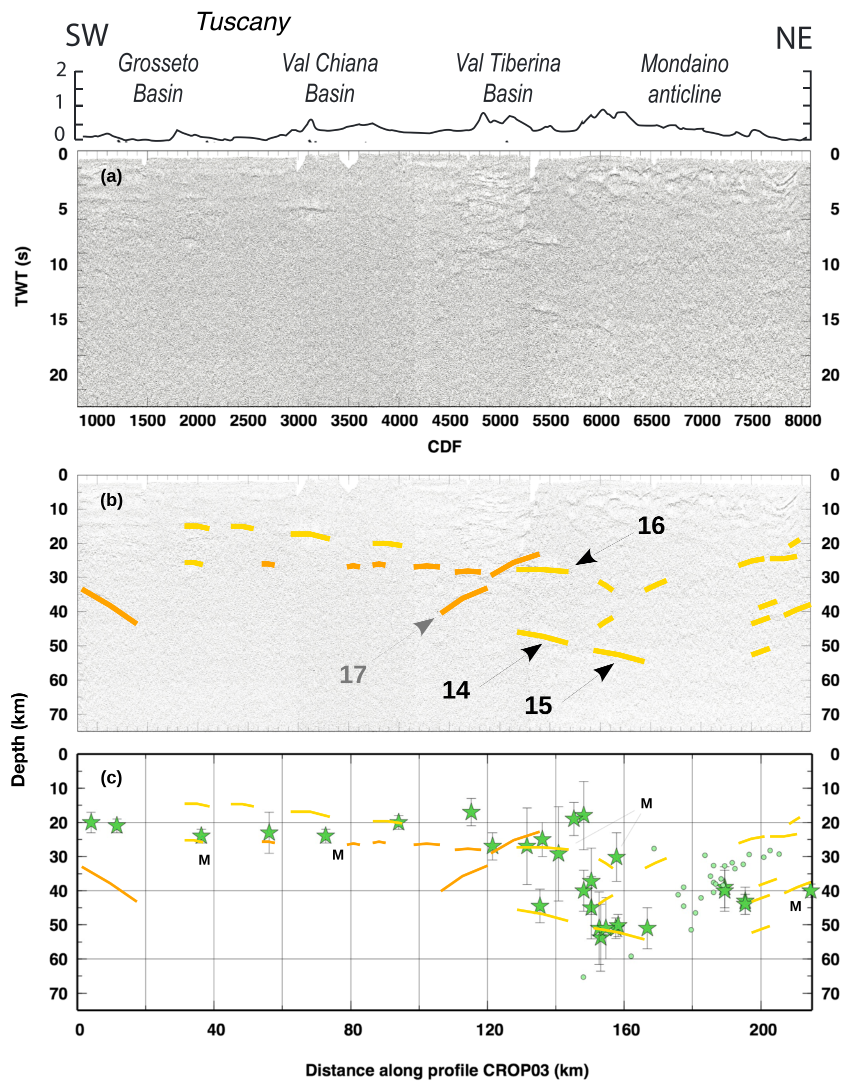

Figure 2. (a) CROP03 seismic line (from Videpi website: http://unmig.sviluppoeconomico.gov.it/videpi/videpi.asp). TWT means "two-way time"; (b) our interpretation of the seismic line. Yellow lines represent prominent reflectors, while we mark with orange lines less pronounced and/or coherent reflections. Far the sake of clarity, numbers refer to main interface labels in Pauselli et al. (2006). (c) Main reflectors from panel (b) together with Moho depth estimates from RF analysis. Yellow stars indicate *S* wave velocity constrast estimates, together with their error bars. Green circles report intermediate-depth seismicity (>25 km focal depth). An "M" marks the spot where clear Moho signals have been found.

labels as in Pauselli et al. (2006) for some of the reflectors we found that are close to those found therein. However, those reflectors do not reproduce Pauselli et al., (2006)'s results and represent our own new contribution. On the western side, reflectors gently dip eastward, while on the eastside they dip westward. On both sides, two sets of reflectors are evident at different depth. At a distance of 140–160 km (beneath the Alto-Tiberina valley, Figure 1), three eastward dipping, sharp reflectors can be traced at 50-km depth ("14" and "15") and at about 30-km depth ("16"). Differently from Pauselli et al. (2006), reflector "16" is found to be the westward continuation of the deeper reflector beneath Tuscany. Two additional west dipping reflectors, number "17," are pointed out. The interpretation of reflectors labeled "17" is still debated (Pauselli et al., 2006), and RF data will provide additional independent constraints. In particular, reflector "16" has been interpreted as the Tyrrhenian Moho (De Franco et al., 1998) or as a shallower k-horizon that is usually restricted to the western portion of the belt (Liotta et al., 1998) and related to the emplacement of an intrusive body and fluid overpressure (Liotta & Ranalli, 1999; Piana Agostinetti, Licciardi, et al., 2017).

Figure 2c shows the combined analysis. On the western side, beneath Tuscany (between 0 and 120 km), results agree and define two subhorizontal common interfaces, the bottom of which at about 20–25-km depth and the shallower at 15–20-km depth, traced from reflection data between 30 and 90 km along the profile. In the central part of the profile, the structure beneath the wedge is more complex. At profile distances between 120 and 160 km, the velocity contrast at about 30-km depth is well defined by RF data, which approximately follows the reflector "16." Along the same portion of the profile, RF estimates align defining two deeper velocity contrasts. The first interface dips westward from 30-km depth (at 160-km distance) to about 45-km depth (at 135-km distance). The second interface is deeper (50–55-km depth) and dips westward as well (between 150 and 170 km), but with a slightly smaller dip angle ($\leq$10°). Finally, along the Adriatic coast, results from the RF analysis are clustered at about 40–45-km depth, matching the deeper reflector found in the area from active seismic studies.

Figure 2c, also shows the intermediate-depth (focal depth $\geq$ 25 km) seismicity with epicenters located within 20 km from the CROP03 line. Subcrustal events depict a west dipping elongated cluster (De Luca et al., 2009) in the external domain descending down to 60–70-km depth and confined mostly between the two sets of west dipping reflectors.

4. Interpretation

Figure 3 shows a synoptic view of the deep structure of the NA based on the available data. Both sets of data combine to define a Tyrrhenian Moho that can be traced from the west coast eastward to a distance of 160 km, possibly gently dipping eastward from 20- to 30-km depth. The Tyrrhenian Moho can be then extended to the reflector "16," as previously suggested by De Franco et al. (1998). Thus, in our model, Tyrrhenian Moho can be traced as far East as the Monte Nerone (Figure 1, half way between the Valtiberina basin and the Mondaino anticline). New gravity measurements are in agreement with our model (Girolami et al., 2014). We find to be less likely the idea that reflectors "16" may represent the inboard continuation of the k-horizon, which in our analysis is restricted between 30 and 100 km in distance. The interpretation of reflector "17", from 120 to 150 km, is less straightforward. We cannot rule out that here crustal-scale thrusts may slightly offset the Tyrrhenian Moho (Barchi et al., 1998) even though we would expect to not have a single structure but a wider shear zone. The other possible hypothesis is that those signal are due to lateral effect (as suggessted in Pauselli et al., 2006).

In the central portion of the belt, the upper west dipping interface marks the top of the slab, indicating partial eclotigization of the lower Adriatic crust. The emergence of such reflector is associated to the release of fluids from the subducted lower crust to the mantle wedge. Such fluids are responsible for the lowering of the *S* wave velocity in the mantle wedge, so that the velocity constrast across the top of the subducted lower crust becomes the local most prominent *S* wave velocity interface. This is a common observation throughout subduction zones (see, e.g., for Northern Japan, Kawakatsu & Watada, 2007). Our model supports the hypothesis that, across subduction zones, the most relevant seismic interface is not always the crust mantle boundary (e.g., Piana Agostinetti & Miller, 2014). The deeper west dipping interface is associated/interpreted as the Adriatic Moho and can be followed to the eastern end of the CROP03 line. Remarkably, the intermediate-depth seismicity seems to occur mainly in between the two west dipping interfaces described above and approaches the bottom interface from east to west. Thus, the seismic cluster dips steeper than the interfaces, as observed in other subduction zones (e.g., Ferris et al., 2003) and may be interpreted as crustal duplexes formed during underthrusting and related metamorphic reactions. From the distance of the two reflectors at the eastward end of our cross section, we can estimate that about 20 km of the Adriatic crust is subducted to shallow depths. This amount of crustal materials corresponds to about 2/3 of the original crustal section of the undeformed 30k-thick Adriatic crust as measured along the Apulia foreland (Amato et al., 2014). The remaining shallower one third of the crust is accreted at the toe of the wedge. This differs from previous interpretations that proposed that only Adriatic lower crust is subducted (Chiarabba et al., 2009; Pauselli et al., 2006), and it potentially affects the estimated amount of shortening across the orogen. The subducted materials likely release fluids as they undergo metamorphic phase changes. Such fluids are both released at shallow depths, migrating upward along the shallow fault system (e.g., the Alto-Tiberifan fault system, ATf; Piana Agostinetti, Giacomuzzi, et al., 2017), and mantle depths, where they can contribute to hydrate the Tuscan upper mantle (Minissale et al., 2000). Following Pauselli et al. (2006), we do not interpret reflectors "14" and "15." Those signals could be generated from 3-D structure or multiple phases. In fact, their position at depth corresponds to the volume of the mantle wedge where the strongest anisotropy has been found

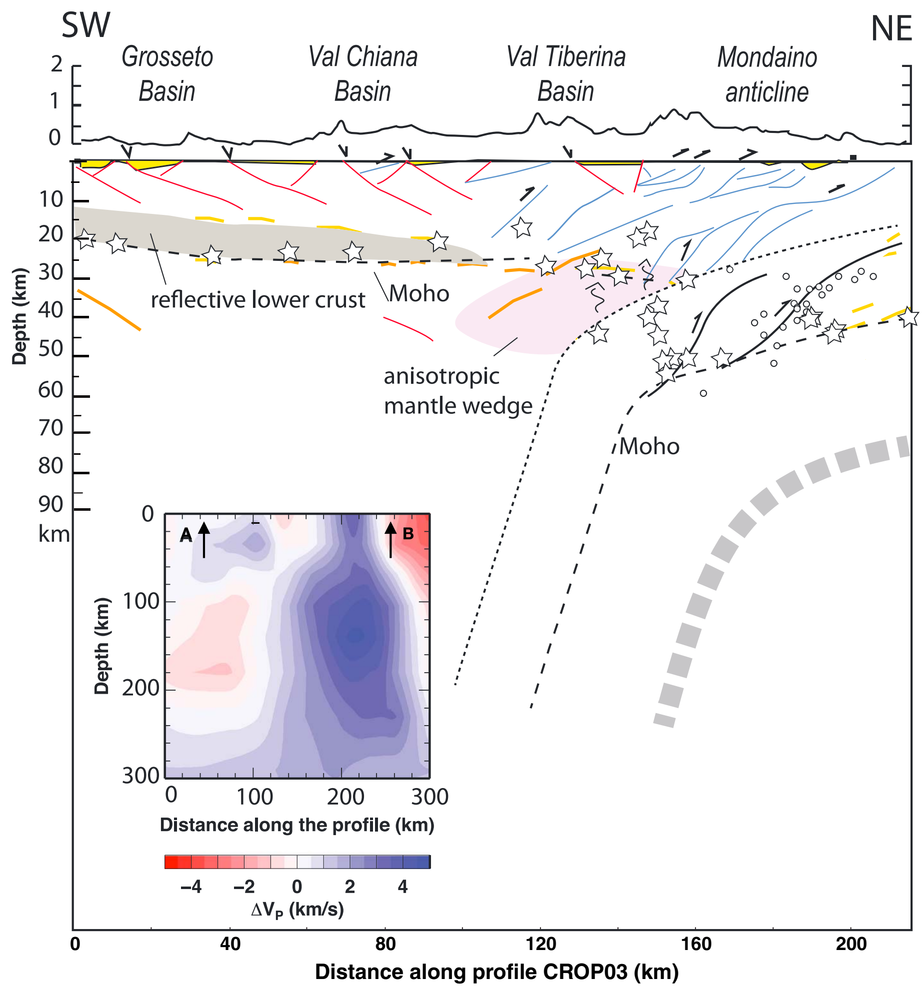

Figure 3. Geological interpretation. Red and blue thin lines indicate normal and thrust faults, respectively. Dashed and dotted black lines display the interpreted Moho and the top of the subducted portion of the Adriatic crust, respectively. A thick gray dashed line shows the Lithosphere-Asthenosphere boundary from Miller and Piana Agostinetti (2012). Fault traces are from Faccenna et al. (2001). Circles, stars, and yellow/orange lines as in Figure 2c. Inset: *P* wave velocity of the upper mantle from teleseismic tomography (Giacomuzzi et al., 2011) beneath Northern Apennines. Profile AB in Figure 1 is indicated with the two arrows.

(Piana Agostinetti et al., 2011). Such anisotropic behavior of the mantle wedge materials could have generated laterally scattered waves.

Summing up, the mantle wedge associated with the NA subduction zone extends close to the axis of the orogeny, where we observe the transition from extensional (internal) to compression (external) stress regime (Frepoli & Amato, 1997). Therefore the lateral migration of the S point during crustal accretion drives the migration of the extensional front at the surface. Our cross section also implies a reduced crustal root but an asymmetric doubling of the crust beneath the topographic axis of the belt, where the crustal column reaches more than 50 km. We do not have constraints on the presence of mantle lithosphere beneath the belt. However, estimates of elevated Moho temperature from aeromagnetic data (Speranza & Chiappini, 2002) and tomography (Di Stefano et al., 2009) indicate that the mantle lithosphere, if any, is reduced to a thin layer ($\leq$20 km). The absence of mantle lithosphere beneath the Apennines is also in agreement with the idea that the subduction orogen formed by accretion and transfer of crustal slices scraped from the downgoing plate (Brun & Faccenna, 2008). The potential lack of a mantle lithosphere and the presence of a subducting slab has also a strong impact on the way the topography is supported. Overall, the topography is lower than expected by about a few hundreds of meters and this dynamic depression may well be explained by the pull of the active subducting slab (Faccenna et al., 2014).

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5. Conclusions

We provide a new interpretation of the structure of the NA subduction orogeny, based on deep crustal seismic profile and RF data. Our results indicate that

1. the combination of passive and active seismic data provides a robust image of the deep crustal and lithospheric structure;
2. only one third of the Adriatic crust has been accreted in the orogenic wedge, while the rest descends down to deeper depths. This estimate should be considered in the balance of the shortening and crustal thickening over time and is important for understanding the fluid budget, composition of the mantle and arc volcanism;
3. the mantle wedge is located beneath the topographic divide and in correspondence of the youngest extensional intrachain basin, much eastward with respect to previous estimate. This finding has implications for the modeling of gravity anomalies, heat flow, and crustal rheology, across the orogeny.

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