Deep structure of the crust in the area of the 2016-2017 Central Italy seismic sequence from receiver function analysis

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Key Points:

- We compute a high-resolution model of Moho topography across the area of the 2016-2017 Central Italy seismic sequence.
- Large Moho depth values (¿50 km) are aligned NNE-SSW suggesting a vertical crustal discontinuity, associated to the Ancona-Anzio Line (AAL)
- Shallow structures as the Olevano-Antrodoco-Sibillini thrust front (OAS) also display vertical discontinuity in correspondence of the AAL

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Abstract

We compute a high-resolution topographic model of the Moho beneath the faulting system activated during the 2016-2017 Central Italy seismic sequence, using Receiver Function (RF) analysis. We document that Ps conversions recorded in RF data-set varies abruptly at very short distance across the crustal lineament called Ancona-Anzio Line (AAL). Moho depth varies from about 25-30 km in the Tyrrhenian domain on the West to 35-40 km in the Adriatic domain in the East. Where the two domains are juxtaposed along the AAL, Moho depth values cluster around 50 km depth, in a stripe-like area 20 km wide. Such unique features marks the deformation zone in the lithosphere and testifies the abrupt change in delamination style in the two sectors of the Apennines. Intermittent large normal faulting earthquakes driven by across-belt extension break through such inherited strong structural changes although conditioned by localized barriers to fluids migration and overpressuring.

Plain Language Summary

The physical process that leads to the genesis of Earthquakes is likely to be rooted in the deep Earth. Here we document how short-scale heterogenities in the geometry of the crust-mantle interface correlate to complex fault geometry at shallow depth. Such link, if confirmed, indicates that the seismogenetic process is more complex than generally expected and it is strongly influenced by inherited structures in the deeper portion of the crust.

1 Introduction

The evolution of long seismic sequences with multiple mainshocks is often guided by a complexity that is intrinsic in the heterogeneity of stress or structural properties of crust. The 2016-2017 series of large earthquakes of central Apennines is an exemplary case of such complex behavior (Chiaraluce et al., 2017). As an overall, the area is ideal to explore how nested tectonics events interact and influence the evolution of natural systems, since extension and compression co-existed during the eastward propagation of the orogenesis, driven by the slab retreat (Malinverno & Ryan, 1986), and they still play an important role in the geodynamics of the Apennines (Montone & Mariucci, 2016).

The slab retreat has been the main driving process along the Apennines-Calabria system (Royden et al., 1987), where the Ionian and Adriatic plates have been slowly subducted beneath the European plate. Its evolution in time promoted different geophysical processes in different portions of the montain chain (Chiarabba et al., 2014) and segmentation of the subducted materials (Rosenbaum et al., 2008; Rosenbaum & Piana Agostinetti, 2015; Piana Agostinetti, 2015; Chiarabba et al., 2016). The area of the 2016-2017 Central Italy seismic sequence encompasses the transition at mantle depth between two of these scenarios: to the Northwest, the Adriatic subduction/delamination is still on going (Piana Agostinetti et al., 2011), while to the Southeast a slab windows has been imaged (Giacomuzzi et al., 2011). A slab tear fault has been proposed to separate at depth the two regions along the 42° parallel, in the Tyrrhenian sea, which might join the so called Ancona-Anzio Line (AAL) at shallow depth (Rosenbaum et al., 2008). The crustal response to the formation of such tear has not been fully unraveled yet, even associated geofluids have been found (Vannoli et al., 2021).

A striking relation between deep fluid degassing and seismicity (Chiodini et al., 2004) and multi-scale interference between active extension and inherited structural complexity (Chiarabba, De Gori, et al., 2020) have been inferred by geochemical and seismological data. Pulsed episodic deep fluid release could be promoted from deeper process occuring in the lower-crust and upper-mantle (Piana Agostinetti et al., 2017) and it affect the crumbling of seismic release into multiple failures on adjoining fault segments, as documented by recent large earthquakes (Malagnini et al., 2012; Chiarabba, Buttinelli, et al., 2020).

In this study, we analyzed a wide set of broad band data to provide inferences on the structure of the crust and the topography of the crust/mantle interface, in a key sector where previous studies reported results with a rather poor spatial resolution (see Moho depth estimates in Piana Agostinetti & Amato, 2009, Figure 1). We use available data from temporary stations installed during the 2016-2017 Central Italy seismic sequence by a joint BGS and INGV effort (Dr Margarita Segou, Dr John McCloskey, Dr Brian Baptie, Dr David Hawthorn, 2016), together with recently deployed permanent stations, to get a very dense mapping of the Moho depth and profiles of crustal structures (Figure 1). Moho depth estimates and crustal profiles are retrieved through the analysis of teleseismic P-to-s converted waves (so called Receiver Function, RF Langston, 1979) stacked following widely used procedures (Zhu & Kanamori, 2000; Bianchi et al., 2010) The obtained Moho topography is compared to first-order crustal geological lineament supposed to have a direct impact on the current seismogenesis (i.e. the AAL, Falcucci et al., 2018) and other geological and geophysical observations (i.e. the deep expression of the Olevano antrodoco-Sibillini -OAS- thrust front, Buttinelli et al., n.d.). Stacked RFs are migrated along a profile that run parallel to the fault system to understand if and how deep is the influence of crustal heterogeneity in the propagation of seismicity and coseismic ruptures along the system.

1.1 Geophysical and geological background

The Apennines belt evolved along the subduction of the former Thetys ocean beneath the Eurasia plate (Faccenna et al., 2004) during the last 30 Ma. Due to the change in trench geometry and heterogenities in the incoming plate, the Apennines developed in different sections (Rosenbaum et al., 2008), driven by different geophysical processes (Chiarabba et al., 2014). Delamination/subduction of the continetal margin has been suggested ot the North of our investigated area (Piana Agostinetti & Faccenna, 2018), while the lack of a subduction process has been identified to the South (e.g Scrocca et al., 2007). Heterogeneity of the entire crust along the belt is strong as well as the Moho topography (e.g. Piana Agostinetti & Amato, 2009), especially in such a key sector marking the passage between a "Tyrrhenian style" thinned crust to the West and an "Adriatic style" thickened crust. The 2016-2017 sequence cuts across the boundary between two distinct domains of the Apennines that evolved independently since Jurassic times as distinct portions of the Tethys realm, potentially separated by a major lithospheric discontinuity, already identified in the so-called AAL (Castellarin et al., 1978).

In the Apennines, repeated tectonic inversions episodes followed the migration of paired compressional and extensional deformation (Buttinelli et al., 2018; Pizzi et al., 2017). At present the mountain belt, edified by compression mostly during Miocene e minorily in Pliocene, is extending at a 2-3 mm/yr rate (Carafa et al., 2020), balanced by compression on the Adriatic side (Figure 1). During the last decades, repeated series of extensional earthquakes developed on a 200 km long sector, namely the Colfiorito 1997, L'Aquila 2009 and the 2016-2017 sequences (Valoroso et al., 2013; Chiarabba, Buttinelli, et al., 2020; Michele et al., 2020). A complex interaction between newly formed normal faults and reactivated inherited thrusts and normal faults, legacy of previous extensional and compressional tectonic phases, was invoked to justify complexity in seismicity patterns and the intermittent rupturing of the system. Evidences from geological and geophysical surveys (e.g. Buttinelli et al., n.d.) and large historical earthquakes (e.g. Rovida et al., 2020), extended such intermittent mechanism back in the past. An intimate connection between the first order crustal setting of the central Apennines (still referable to the compressional phase), tectonic inversions and fluid assisted processes has

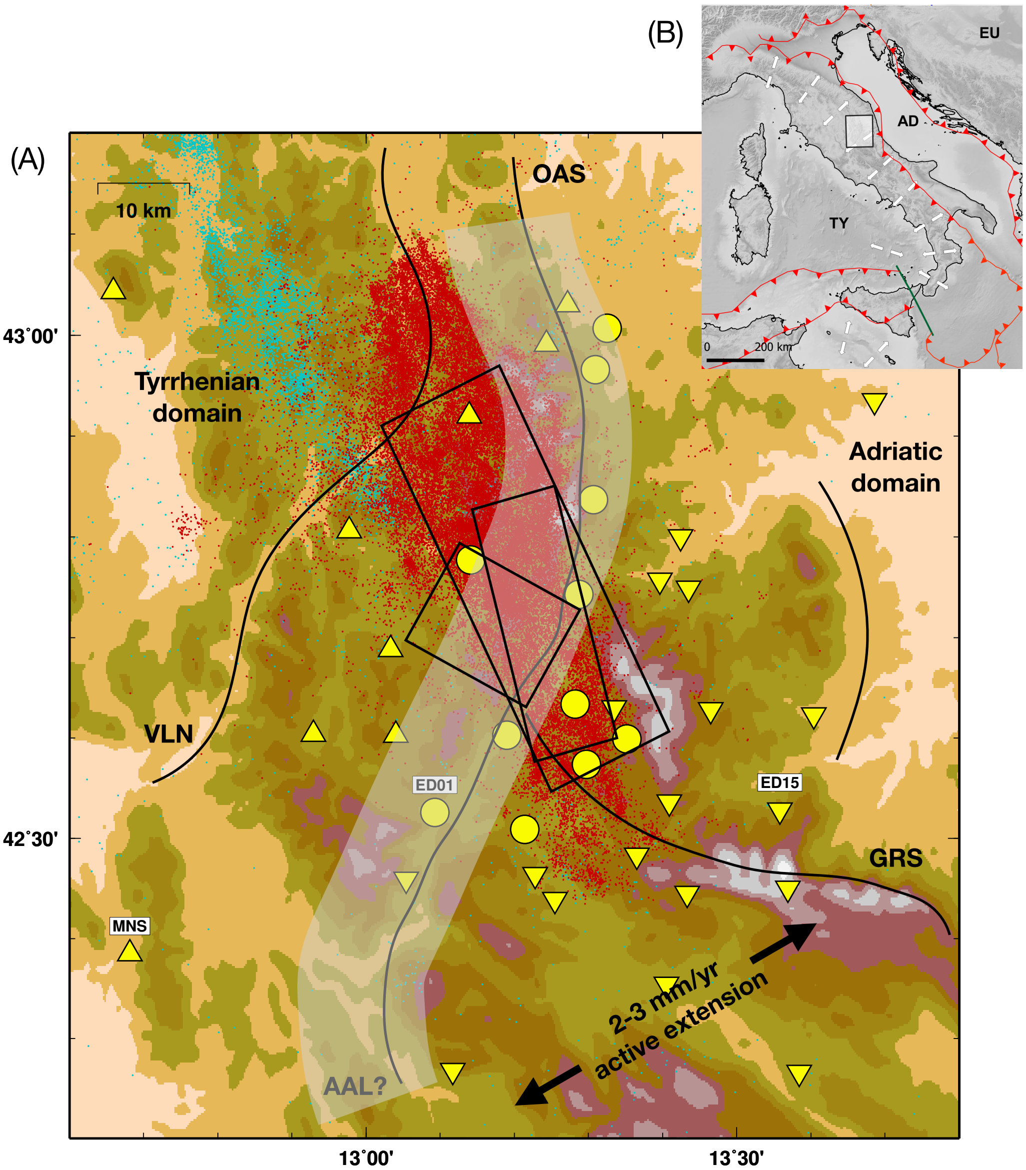

Figure 1. Map of the study area. (A) Details of the seismic network and local geological structures. Yellow symbols indicate seismic stations: triangles - TYR group; inverted triangles - ADR group; Circles - AAL group (see text for group definitions). Red and blue dots show seismicity related to the 2016-2017 Central Italy seismic sequence and previous sesimicity, respectively. Black lines display main thrust: VAN - Val Nerina, OAS - Olevano-Androdoco-Sibillini, GRS - Gran Sasso, ACQ - Acquasanta. The whitish area corresponds to the suggested location at depth of the AAL. Extension direction is shown as black arrows. Black boxes indicate major fault planes activated deruing the 2016-2017 Central Italy seismic sequence (Scognamiglio et al., 2018; Cirella et al., 2018). (B) Location of the study area in the Italian peninsula.TY inidcate Tyrrhenian domain; AD, Adriatic; EU, Eurasia plate

been invoked (e.g. Chiarabba, De Gori, et al., 2020), while how broad is the impact of the inherited crustal-scale heterogeneities on seimotectonic is still a matter of debate.

2 Data and methods

Teleseismic RF is a widely used method for mapping first-order seismic discontinuity at depth, based on the analysis of P-to-s converted phases. A teleseismic P-wave crossing a seismic discontinuity is partially converted to S-wave (Langston, 1979), and stacking of converted and multiples phases allows to estimate the depth of the discontinuity that generate them, as well as the average seismic velocity above it (Zhu & Kanamori, 2000). Teleseismic events recorded at 40 broadband stations (23 temporary and 17 permanent) have been used to compute single station RF data-sets using a frequency-domain deconvolution (Di Bona, 1998), with a Gaussian filter of A=2, limiting frequency content lower than about 1Hz. After visual inspection, we retain an average of 30 and 120 high S/N ratio RF for each temporary and permanent station, respectively. The quality of each RF data-set is separately evaluated following Piana Agostinetti and Amato (2009)'s approach (see Table S1).

To help in the interpretation of Ps conversions produced by seismic discontinuities, RF data-sets have been decomposed in angular harmonics, to extract the isotropic component, k=0 harmonics (Piana Agostinetti & Miller, 2014), which is representative of the bulk elastic properties of the rocks traversed by teleseismic rays. Afterward, RF data-sets have been stacked for mapping the depth of the main S-wave velocity discontinuity and average crustal V_P/V_S ratio (i.e. the Moho Zhu & Kanamori, 2000). Here we followed the implementation of Piana Agostinetti and Amato (2009) and we refer to such study for the details on the technique and the values adopted for the different parameters. We test three different average crustal V_P values: 6.0, 6.5 and 7.0 km/s, and we adopt the original weigthing scheme: 0.7, 0.2 and 0.1, for Moho Ps and its multiple phases.

Finally, we make use of migrated RF data to focus on the shear-wave velocity contrasts in the shallow crust along the Apennines normal faulting system. Following the approach used in Chiarabba et al. (2016), we select teleseismic ray traversing the rock volume around a N165E profile that cross the AAL, from which we compute a k=0 harmonics of the RF every 5 km along the profile. The k=0 harmonics are used to compose a picture of the subsurface, where positive/negative Ps phases (i.e. positive/negative S-wave velocity jumps) at depth can be traced all along the profile.

3 Results

The analysis of the RF data-set allows us to define three groups of seismic stations, based on the peculiar features of their data-set and their geographic location: TYR, ADR and AAL (see Table S1). Their characteristic RF data-sets are shown in Figure 2ace as a function of the back-azimuth of the incoming P-wave: MNS for TYR group, ED01 for AAL, and ED15 for ADR. Stations deployed eastward (ADR) and westward (TYR) of the Apennines watershed display a clear Ps converted phase at about 3-4s and 4-5s, respectively, for almost all back-azimuthal directions (green stripes in Figure 2ae), which is a strong candidate as Moho Ps conversion. Associated multiples phases can also be seen even if lateral scattering reduced their energy (light green in Figure 2bf). At the contrary, stations installed along the AAL present Ps arrivals with a strong back-azimuthal dependence in the 3-5s time-window (Figure 2c). For those stations, k=0 harmonics highlights coherent arrivals at about 6-7s, 25s and 31s, indicating a substantial delay for Ps and multiple phases, potentially originated from the Moho (Figure 2d).

The resulting stacking functions for those stations confirm the anomaly in the RF data-set for the stations deployed along the AAL (Figure 3). In fact, a clear Moho depth is estimated for station MNS (TYR, Moho depth of 30.0 ± 0.6 km) and ED15 (ADR,

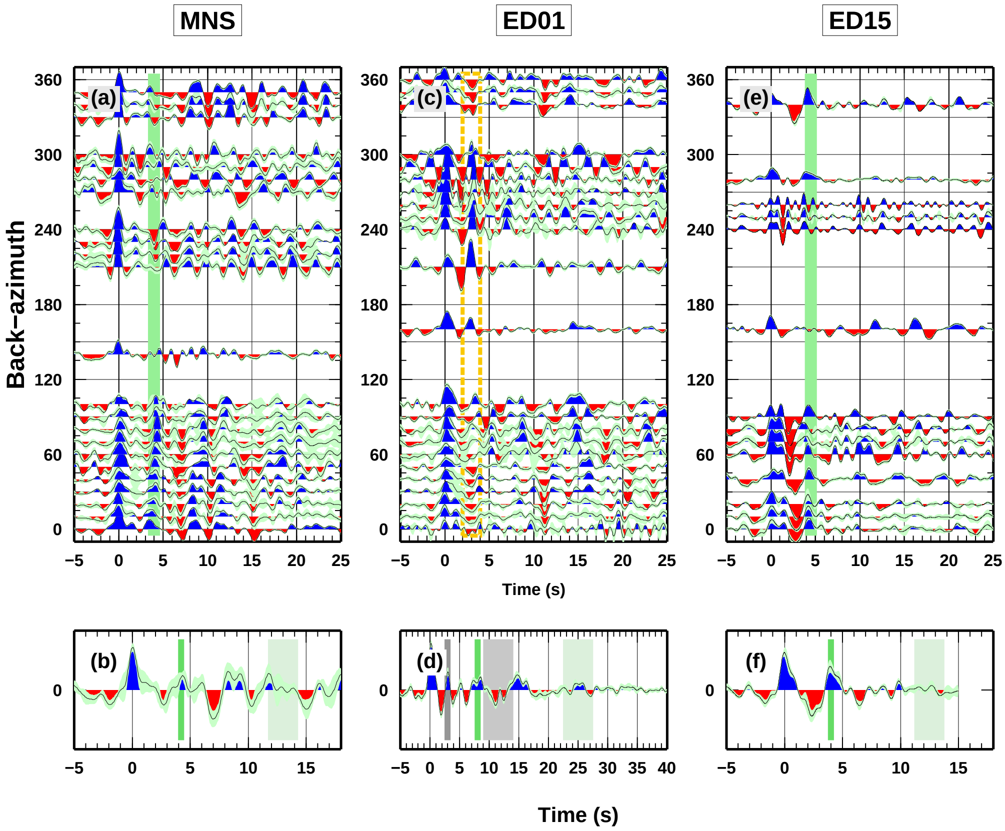

Figure 2. Examples of RF data-sets for the three domains: (a-b) TYR; (c-d) AAL; (e-f) ADR. In (a-c-e) Radial RF data-sets are shown as a function of back-azimuth. Positive (negative) amplitudes are expressed as blue (red) wiggles. A light-green band indicates the uncertainties. In (b-d-e), the k=0 harmonics of the RF data-sets are shown. Coloured vertical stripes and the dashed-box indicate the features commented in the analysis.

36.5 ± 3.3 km), where a single well-resolved maximum in the stacking function is found, with slightly larger value eastward of AAL (Figure 3ae). Station ED01, directly located in the area of the AAL, shows a more complex stacking function with multiple minima, where the most coherent one display a Moho depth as larger as 62.5 ± 9.6 km (Figure 3c). This is a consistent pattern throughout all stations deployed along the AAL (circles in Figure 1). Multiple minima in the stacking function have been attributed to Moho doubling and crustal complexities in the area (Piana Agostinetti & Amato, 2009; Piana Agostinetti, 2015; Licciardi et al., n.d.). High Vp/Vs ratio are inferred over the entire area as expected (Licciardi et al., n.d.), with large uncertainties for station ED15 (Figure 3e).

Our analysis permits to get a very detailed reconstruction of the Moho depth and geometry in a key sector of the Apennines with unprecedented details largely improving the resolution achieved by previous studies where only nine punctual estimates are present (Piana Agostinetti & Amato, 2009). A striking deepening of the Moho, correlated with the assumed location of the AAL, emerges from the interpolated map of the crust-mantle topography over the study area (Figure 4ab). All punctual measurements reporting Moho depth larger than 50 km sits within 10 km from the AAL trace. Our analysis confirms previous estimates of Moho depth across the central Apennines (Di Bona et al., 2008), with slightly shallower values westward of the AAL (average Moho depth of 32 km) with respect to the Adriatic side of the AAL (average Moho depth of 37 km).

The same overall picture is shown in the stacked and 10km-depth migrated RF dataset along a N165E profile (Figure 4e) that cross the AAL. Intriguingly, the AAL evidence at depth mimic the surface espression of the OAS, a large thrust features which conditioned the overall evolution of the central Apennnines, currently marking at surface the passage between the two distinct domains of mostly carbonatic units overthrusted onto foredeep domains of the Laga Basin (e.g. Bigi et al., 2013). The crustal features change abruptly across the AAL. A broad sharp Vs reduction in the mid-crust is visible to the south section of the profile, while positive intra-crustal discontinuities are found in the north at the same depth level. In the deeper part of the migrated RF section, the Ps converted phase at the Moho can be traced at about 30 km depth (limit of our RF migration) only in the northern seciont of the profile. Such features robustly correlate with the local tomography Vp models of the shallow crust (Figure 4d, Chiarabba, De Gori, et al., 2020).

4 Discussions

Complexity in seismic sequence evolution, coseismic ruptures propagation and seismicity migration is exemplary documented by extensional earthquakes in the Apennines. Part of itthe complexity is due to the eastward surfing of extension over a strongly heterogeneous edifice previously formed by diachronous delamination and under-thrusting of the Adria lithosphere. Therefore, young normal faults cut across the formerly edified compressional system, originally formed by stacks of sedimentary piles from distinct domains of the Tethys continental margin. The large earthquakes of 2016 developed on and across distinct segments located on the two sides of a major lihtospheric discontinuity (AAL) that separated the contiguous basin-vs-platform-evolving sectors of the margin (Figure 4a). The crustal structure of the two sectors is remarkably different (Figure 4e) and consistent with anomalies in velocity tomography (Figure 4d). The major crustal discotinuity of AAL conditioned the development of major large thrust as the OAS during the compressional phase, while its legacy still impact on the overall reactivation and kinematic inversion of major tectonic structures within the active extensional stress regime.

Our main result is a sharp deepening of the Moho across the AAL (Figure 4b) with a geometry oblique to the main sense of the belt motion, generally assumed and proposed in many reconstructions. The large crustal thickness observed all along the AAL sug-

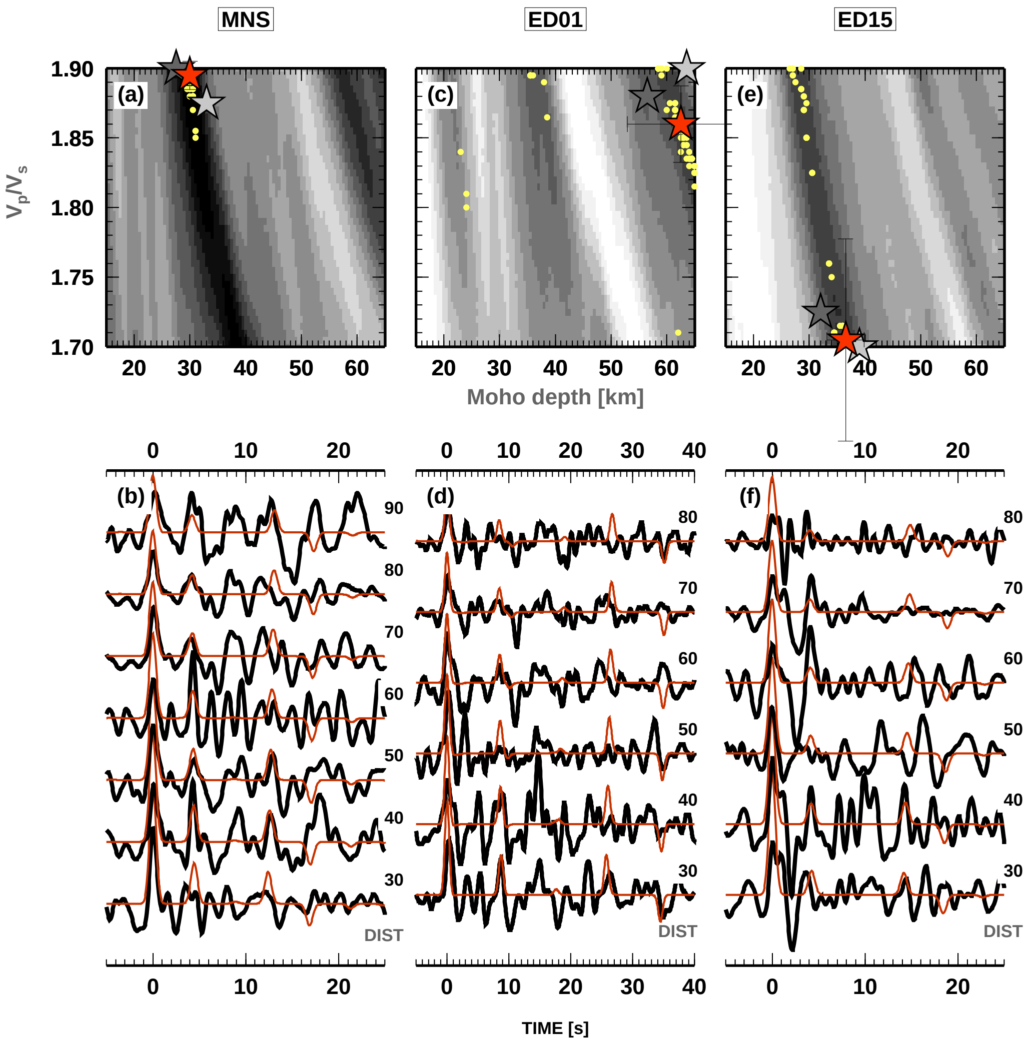

Figure 3. Examples of Zhu and Kanamori (2000)'s analysis for the three stations presented in Figure 2. In (a-c-e) the map of the stacking function is presented, for a V_P vlue of 6.5 km/s. Grey-scale indicates function value, from withe (minimum) to black (maximum). The coloured stars represent the best-solution for V_P: 6.0 (light grey), 6.5 (red) and 7.0 (dark grey) km/s. The yellow dots show the solution found during bootstrap evaluation of Moho and V_P/V_S uncertainties. In (b-d-f), fit between observed RF (black lines) as a function of epicentral distance and synthetic RF (red lines) generated by the best-fit model (red stars in panel (a-c-e).

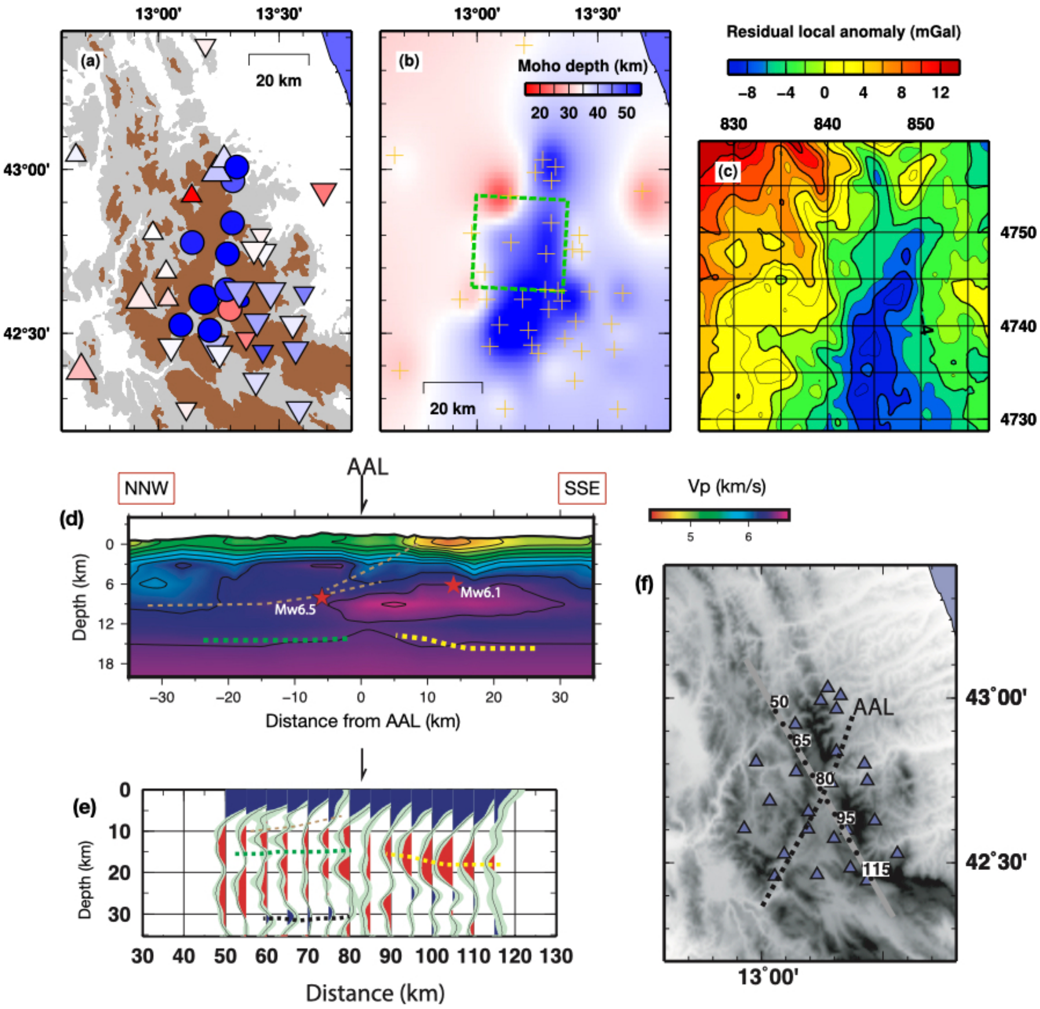

Figure 4. (a) Moho depth estimated for the seismic station used in this study. Symbols encode domains: triangles - TYR; circles - AAL; inverted triangles - ADR. Symbol colors show Moho depth value. Symbol dimensions indicate Moho depth uncertainties: less than 2km - 0.6 cm; between 2 and 5 km - 0.5 cm; between 5 and 15 km - 0.4 cm; larger than 15 km - 0.2 cm. Brown color depicts topography higher than 1000m. (b) Interpolated Moho depth map using the data-points presented in panel (a). (c) Residual gravity anomaly from Mancinelli et al. (2020); RETRACE-3D (2021) after removing the regional trend. (d) P-wave Velocity tomogram along the fault system (modifed from Chiarabba et al., 2018). The two 2016 main shocks are reported along with elements derived from the RFs profile. (e) RF profile along the fault system with the main features interpreted (black dashed lines= Moho; brown dashed lines=OAS; green dashed line=mid-crustal high velocity ascribed to multi-stack layering; yellow dashed line=mid-crustal low velocity). (f) Trace of the RF profile and used stations.

gests that the primary structuring of this nodal area since late Miocene is related to processes at the entire crust-scale. Although the not obvious tectonic meaning of the observed pattern, it changes scenarios and paradigms on the Apennines subduction, where a southwestern Moho deepening of the Adria Moho is always assumed, and possibly the current seismotectonics. The parallelism between the Moho pattern from RF and the residual Bouguer anomalies, stripped assuming the standard Moho flexure (Figure 4c), supports our conclusion.

Our results might indicate that the delamination of the Adria microplate, still ongoing to the Northwest of the AAL, has been suddenly halted to the South of the AAL. In such scenario, to the South of the AAL, the nose of the mantle wedge close to the locus where the two plates (Eurasia and Adriatic plates) originally separated, the so called S-point, did not retreat anymore toward Northeast as expected. The internal layering in the nose (e.g. found in Piana Agostinetti & Faccenna, 2018), generated and sustained by the fluids migration from the subducted crust (Piana Agostinetti et al., 2011), probably disappeared after the end of the retreat process leaving a thickened crust. The mentioned internal layering could be still seen in the Ps phases at 3-5 s in ED01 data-set, which show striking back-azimuthal variations.

These strong crustal changes occur right in the area where the two 2016 main-shocks developed (Figure 4a), suggesting that inherited structures control fault segmentation (e.g. Buttinelli et al., n.d.) and dynamic splitting of coseismic ruptures (Cirella et al., 2018).

Our results indicate that the structural change across the AAL is strong and interest the entire lithosphere (Figure 4). Although the strong lateral heterogeneity, the 2017 ruptures propagated across the AAL, locally interferring with the inherited structure and reverting rheological attitudes of fault portions. We are attracted to explain such complexity as due to a different attitude to create and sustain fluid overpressure in the mid-crust along the normal faulting system. The larger difference along the system is explicit across the AAL.

A final remark comes from the lateral heterogeneity of the crust across the AAL. Intra-crustal high Vs discontinuities are present to the north (green line in Figure 4e) suggesting a more developed stacking of sedimentary units that incorporates slices of high velocity basement units (e.g. anhydrites, dolostones and possibly low-grade metasedimentary rocks). The present day role of such structuring is to favor shallower rooting of normal faults on both deep and relatively flat thrust surfaces and east-dipping decollement and shallower fluid over-pressured volumes. These features are consistent with the observation that the largest magnitude of historical earthquakes is smaller to the north, despite a similar across-belt extension.

5 Conclusions

We have produced a new high resolution map of the crust/mantle interface and crustal structure in a key sector of the central Apennines normal faulting system along which the most recent and dramatic sequence developed in 2016-2017. We observe a strickly Moho discontinuity along the AAL, where local values of Moho depth reach more than 50 km along a 20km wide stripe that follows the (segguested) position of the AAL at depth. The strong lateral heterogeneity of the crust and varying Moho geometry influenced the segmentation of seismic release into different multiple mainshocks conditioning the evolution of coseismic ruptures. The lateral heterogeneity accounts for local conditions in the crust to create and sustain over-pressurized fluid volumes distinctly along the fault system. We argue that the mutual behavior of fault portions as barrier or asperity observed during the sequence could be related to this different aptitude of the fault system.

In the future, a more refined definition of the Tyrrhenian and Adriatic crust, and their justaposition could be investigated in terms of a full 3D Vs crustal model, to give more insights into the connection with recent generation of east-dipping decollements and the formation (and preservation) of crustal barriers for fluid movements and rock volumes pressurization. Such elements could help in the revaluation of the seismogenesis of the central Apennines considering the impact of such major structures in the genesis of the shallower ones.

6 Acknowledgements

Data from BGS temporary stations can be found in Dr Margarita Segou, Dr John McCloskey, Dr Brian Baptie, Dr David Hawthorn (2016) at link: http://www.fdsn.org/networks/detail/YR_2016/ . INGV data can be downloaded from EIDA web server: https://www.orfeus-eu.org/data/eida/ . NPA publications are printed with the financial support of the Austrian Science Fund (FWF), project number: M2218-N29. The Generic Mapping Tools software was used for plotting the figures of this manuscript (Wessel & Smith, 1998).

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SUPPLEMENTARY MATERIALS

TABLE S1. Moho depth estimates used in this study. NRF indicates the number of high quality RF used. Qu represents the Quality of the RF-dataset, following Piana Agostinetti and Amato (2009). GROUP is defined in the main text.