

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Nature and origin of an undetected seismic phase in waveforms from Southern Tyrrhenian (Italy) intermediate-depth and deep earthquakes: first evidence for the phase-A in the subducted uppermost lithospheric mantle?

This is a pre print version of the following article:

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1922171> since 2023-07-22T13:32:24Z

Published version:

DOI:10.1016/j.tecto.2023.229919

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

1 **Nature and Origin of an Undetected Seismic Phase in Waveforms from Southern Tyrrhenian (Italy)**
2 **Intermediate-Depth and Deep Earthquakes: first evidence for the Phase-A in the Subducted**
3 **Uppermost Lithospheric Mantle?**

4 T. Ninivaggi¹, G. Selvaggi¹, S. Mazza¹, M. Filippucci², F. Tursi³, & W. Czuba⁴

5
6 ¹ Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy.

7 ² Università degli Studi di Bari “Aldo Moro”, Dipartimento di Scienze della Terra e Geo-
8 ambientali, Bari, Italy.

9 ³Università degli studi di Padova, Dipartimento di Geoscienze, Padua, Italy.

10 ⁴ Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland.

11 Corresponding author:

12 Teresa Ninivaggi

13 E-mail Address: teresaninivaggi@gmail.com

14 Postal Address: Via E. De Amicis, 12 – Altamura (Bari) 70022

15 **Abstract**

16 We have found a previously unreported seismic phase in seismograms of European seismic
17 stations from intermediate-depth and deep earthquakes of the Southern Tyrrhenian subduction
18 zone. We observe this phase at stations from 6 to 9 degrees from the epicentre, towards north. Only
19 seismograms of earthquakes located in a well-defined region of the slab, in the depth range of 215–
20 320 km, show this secondary phase. In this work, we describe the nature and possible origin of
21 this phase and we provide a simple 2D model to explain the observed arrival times. Our analyses
22 reveal that this secondary phase propagates downward in a narrow, high velocity layer, possibly

23 located within the deepest part of the slab. We suggest that this layer reveals the presence of the
24 dense hydrous magnesium silicate *phase A*, introduced from petrological laboratory experiments,
25 inferred to carry water in the upper mantle and predicted to be found in cold subduction zones.

26 **Key Words:**

27 Later seismic arrival/phase

28 Waveforms analyses

29 Intermediate and deep seismicity

30 Southern Tyrrhenian Subduction Zone

31 Mineral phase A

32 **1 Introduction**

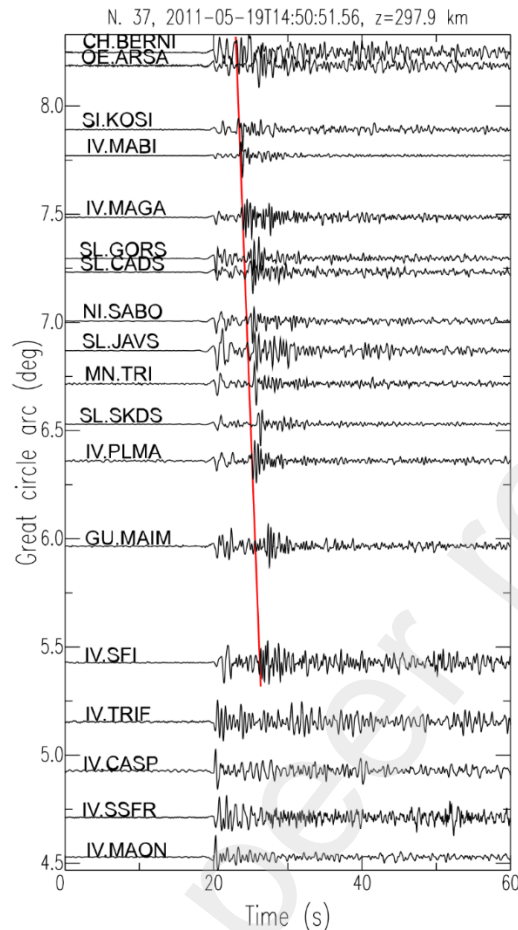
33 Seismograms of deep earthquakes from many subduction zones show later phases. Most of these
34 observations come from the Pacific subduction zones and they have been widely used to get useful
35 indication on the geometric characteristics of subducting slabs (Hasegawa et al., 1978; Matsuzawa
36 et al., 1986; Ohmi & Hori, 2000; Zhao et al., 1997). These phases, beside the depth phases, are
37 generally associated to *P* (*S*) waves converted or reflected at the upper slab interface from the
38 direct *S* (*P*) waves (Ohmi & Hori, 2000; Zhao, 2019; Zhao et al., 1997, Fukao et al., 1978; Obara
39 & Sato, 1988). Observations of dispersive and complicated wave trains are also relevant in
40 seismograms of deep earthquakes as they provide important implications for the petrological
41 properties of subducted lithosphere. For example, dispersive high frequency trains of *P*- and *S*-
42 waves observed at the fore-arc seismic stations of the Hellenic Trench from intermediate depth
43 earthquakes reveal the presence of a low velocity channel in the upper part of the slab (Abers,

44 2000, 2005; Essen et al., 2009; Hori, 1990; Martin et al., 2003; Martin & Rietbrock, 2006). The
45 low velocity channel is an important finding to trace water path within the subduction process.
46 Similar characteristics were also found in seismograms of Calabria stations, recorded from deep
47 earthquakes of the Southern Tyrrhenian subduction zone and interpreted as generated by small
48 scale heterogeneities within the slab (Sun et al., 2014).

49 Working on seismograms of a deep earthquake from the Southern Tyrrhenian subduction zone
50 occurred in 2011, we noticed a clear secondary phase, few seconds after the direct *P*-wave, at
51 stations located some hundreds of km away from the epicenter towards north (Figure 1).

52

53



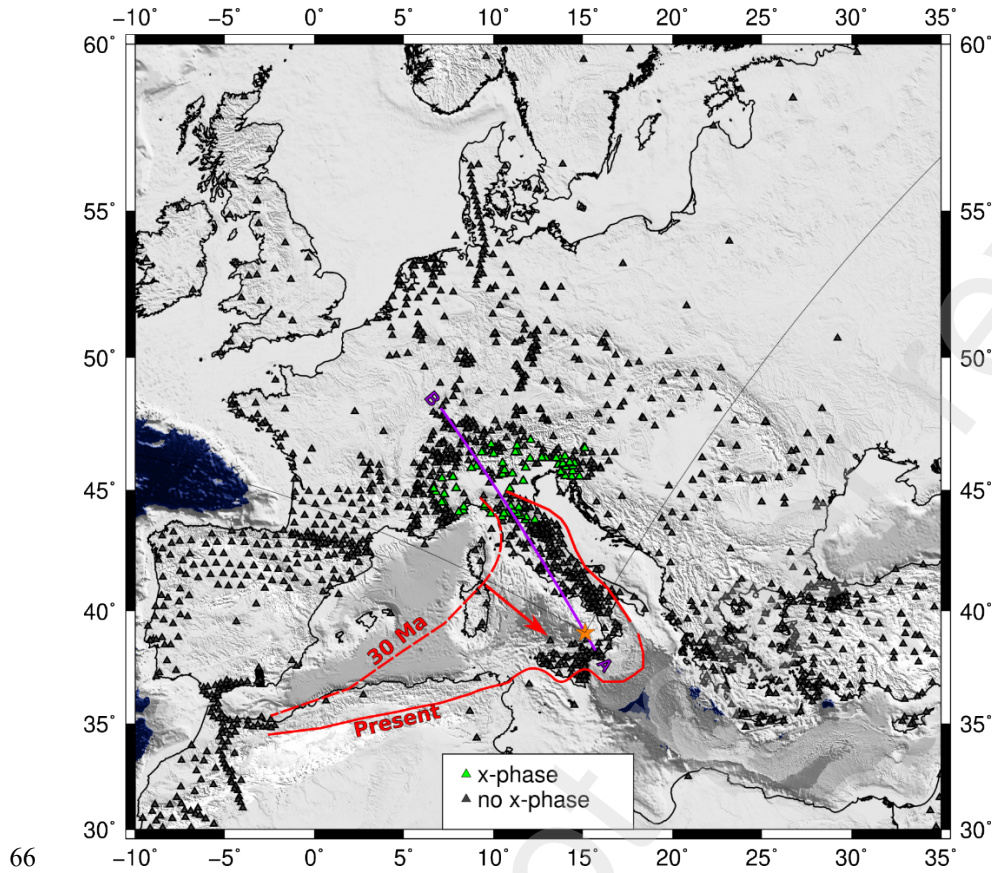
54

55 **Figure 1.** Time-distance vertical seismograms of the 2011 event aligned with P arrival time at 20
 56 s. The red line marks the secondary phase arrivals.

57

58 This phase, that we have called *x-phase*, disappears at stations located in Central and northern
 59 Europe (Figure 2). In a first stage of the work, we accepted the same lines of interpretation of the
 60 quoted literature, but we soon understood that the arrival times of the phase we were looking at
 61 were not consistent neither with a sP (pS) converted phase, nor with a guided wave. This because
 62 the lag times after direct arrivals are constant or increase with distances for converted or guided
 63 waves, respectively (Hori, 1990; Zhao et al., 1997). The difference in arrival times between our

64 phase and the direct P -wave decreases with the epicentral distance and it does it in a way that
65 excludes such interpretations.



67 **Figure 2** – Stations which recorded the x -phase (green triangles). Seismograms of stations in black
68 do not show the later arrival. Section trace AB of the Figure 9, passing from the 2011 earthquake
69 (n. 37). The red lines delineate the old (30 Ma) and the present subduction signature. The two
70 thin black lines delineate the azimuths 300° and 30° clockwise with respect to the epicentre.

71

72 We decided, then, to investigate a wider dataset composed of the 43 deep and largest earthquakes
73 of the Southern Tyrrhenian subduction zone and to perform classical waveforms analyses to derive
74 the main seismological features of the unreported phase. We, finally, made a 2D ray path modelling

75 to infer the origin of the *x-phase*. In this paper, we first describe the dataset and the observations
76 related to the seismic phase then we use the results to constrain a 2D model of the slab to explain
77 the observations. One major point we discuss in this work is the possible identification in the
78 subducting slab of a dense magnesium silicate mineral phase carrying water in the upper mantle
79 and the petrological implication of this finding.

80

81 **2. Tectonic setting**

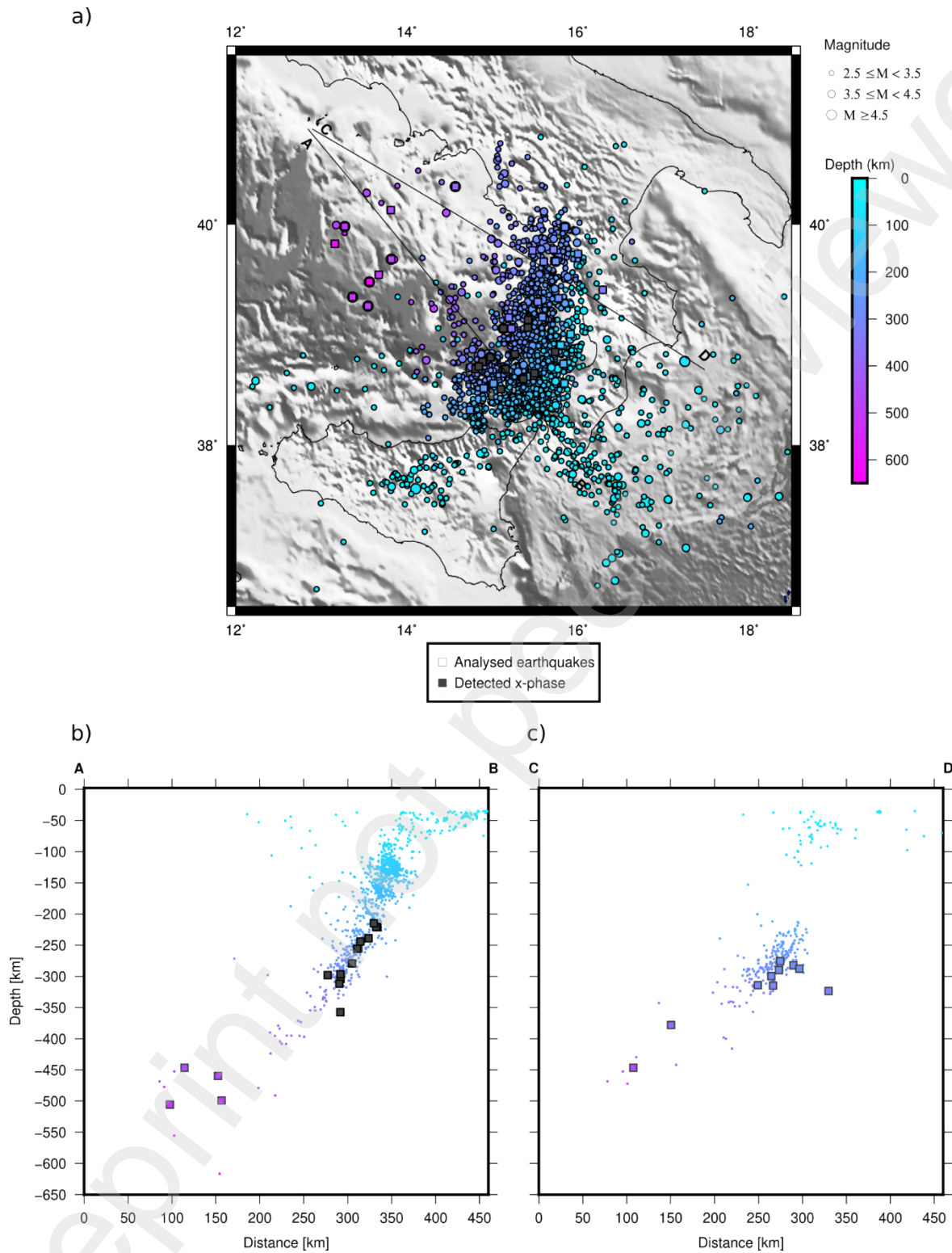
82 The Southern Tyrrhenian basin is the result of the Ionian lithosphere rollback and associated
83 opening of the back arc basin that lasted for 80 Myr (Faccenna et al., 2001). Based on tomographic
84 images, plate tectonics reconstructions and geological data, Faccenna et al., (2001) recognized
85 multiple evolutionary stages of the subduction process characterized by different back-arc opening
86 rates, sometimes as fast as 30-40 mm/yr (Figure 2). The slab should have reached the 660 km
87 transition zone after about 60-70 Myr of subduction process (Faccenna et al., 2001). GNSS
88 velocity field (D'Agostino et al., 2011) shows that the present day roll back, if any, of the Ionian
89 lithosphere could be at the level of 1 mm/yr, much slower than in the past. The subduction of the
90 Ionian lithosphere beneath the Calabrian arc and the Tyrrhenian Sea is nowadays marked by an
91 intense intermediate and deep seismicity. The occurrence of deep earthquakes beneath the
92 Southern Tyrrhenian Sea is well known since the seventies, and reported in a wide literature
93 (Ritsema, 1972; see also Chiarabba et al., 2008; Scarfi et al., 2018; Selvaggi & Chiarabba, 1995).
94 The seismicity distribution clearly defines a NW-dipping Wadati-Benioff plane from the Ionian
95 Sea towards the central Tyrrhenian Sea. Earthquakes can be as deep as 600 km (Figure 3).
96 Seismicity distribution and tomographic images show that the descending Ionian slab is very steep

97 (~70°) in the first 300-350 km and starts flattening below those depths (Chiarabba et al., 2008;
98 Cimini & Marchetti, 2006; Lucente et al., 1999; Scarfi et al., 2018; Spakman et al., 1993).

99 The slab is seismically continuous only in its southwestern part, beneath the Aeolian Islands
100 (Figure 3b) while, in the north-eastern portion, along the Calabrian coasts, the slab is mostly
101 aseismic between 100 km and 250 km depth (Figure 3c). The aseismic part of the slab has been
102 interpreted as an indication that the slab is dying out along a horizontal break-off that propagates
103 in a scissor-type mode (Amato et al., 1993; Scarfi et al., 2018; Spakman et al., 1993).

104 The Southern Tyrrhenian slab is in down dip shortening in a large part of it, from about
105 100 km down to 400 km depth, and the magnitude of earthquakes increases with depth (Frepoli
106 et al., 1996; Selvaggi, 2001). The largest earthquake occurred in 1938 and had a magnitude of
107 7.1 (Anderson & Jackson, 1987). The depth estimate was 290 km and it is one of the largest
108 earthquake ever recorded in Italy. The way the slab deforms suggests that the gravitational pull is
109 probably the main driving force of the subduction.

110



111

112 **Figure 3 - Seismicity map of the Southern Tyrrhenian Subduction Zone from 1990 to 2020. (a)**

113 *Squares are the 43 analysed earthquakes; grey filled squares are those earthquakes where we*

114 recognised the *x*-phase. **(b)** Vertical cross-sections perpendicular to the strike of the
115 southwestern part of the slab (AB) and **(c)** its north-eastern part (CD).

116

117 **3. Data and Methods**

118 We decided to make a systematic analysis of deep earthquakes from the Tyrrhenian subduction
119 zone to further investigate and constrain the previous observations on the *x*-phase. We selected the
120 43 largest earthquakes from 1990 to 2020 ($ML \geq 4.5$) located in Southern Tyrrhenian region from
121 the INGV Italian Seismological Instrumental and Parametric Database (<http://cnt.rm.ingv.it/iside>).
122 The depth range is between 100 km and 644 km. The earthquakes list and additional examples of
123 the computed analysis from the whole dataset are available in the supplementary material.

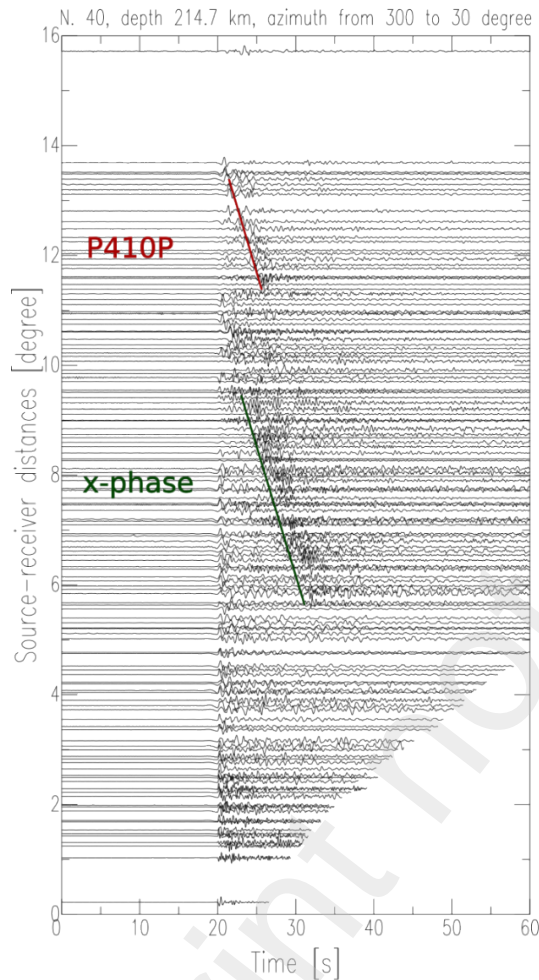
124 We extracted the digital waveforms of the earthquakes from the European Integrated Data Archive
125 (EIDA, <http://eida.ingv.it/>) and from Incorporated Research Institutions for Seismology Data
126 Management Centre (IRIS DMC, <https://ds.iris.edu/ds/nodes/dmc/data/types/waveform-data/>).
127 The selected seismic stations are from 10° up to 71° North in latitude (from Central Africa to north
128 Norway) and between 10° West and 50° East in longitude (from Portugal to eastern Turkey). We
129 used seismograms from broadband high gain seismometers (HH or BH streams) for each
130 earthquake, when available. If they were not, we used short period high gain seismometers (EH or
131 SH), especially for the oldest earthquakes. To analyse the whole dataset, i.e. more than 25,000
132 seismograms, we plot record sections normalising each waveform by its absolute maximum
133 amplitude, excluding the *S*-waves from the plot windows. We sorted seismograms by increasing
134 source-receiver distance and aligned by direct *P*-arrival time. Phase recognition in the selected
135 dataset was made through visual inspection on the record sections. Record sections for the whole

136 dataset were analysed dividing the large number of stations in angular sectors of about 45 to 60
137 degrees of azimuth. Figure 4 shows an example of a record section for two different azimuths (an
138 ample choice of record sections is available in the supplementary material). We generally observe
139 the x-phase along the direction perpendicular to the slab face (left in Figure 4) from 600 to about

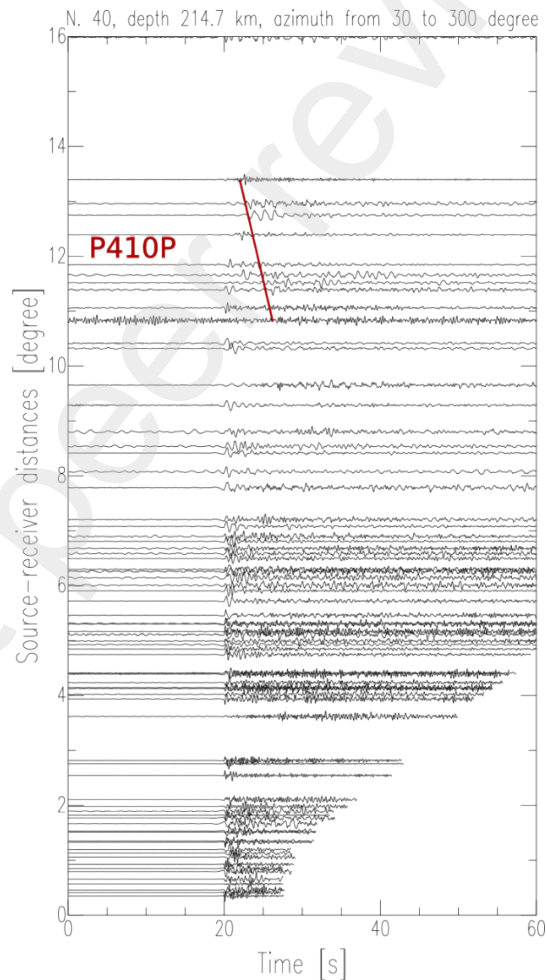
140 1000 km from the epicentre and in the range from 330 to 30 degrees. For the complementary
141 sector, from 30 to 300 clockwise, record sections never show the x-phase.

142

a)



b)

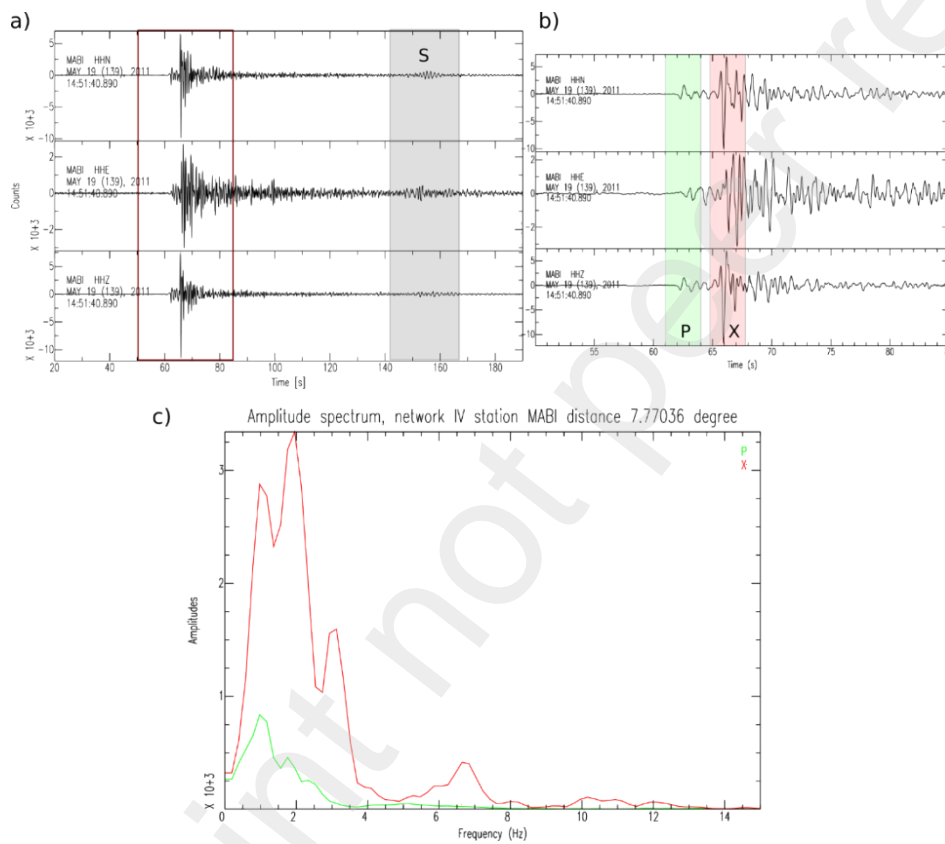


143

144 **Figure 4 – (a)** Record Section in the azimuth 300-30 for an intermediate depth earthquake of the
145 Southern Tyrrhenian Subduction Zone. **(b)** Record Section for the same earthquake but for the
146 complementary azimuth. The x-phase is visible only in the stations to the north of the epicentre at
147 a distance from 600 km to about 1000 km.

148 The *x-phase* is rather prominent and easy to recognise. It generally appears in the vertical
 149 component as an impulsive arrival with an amplitude about two times larger than the first *P*-arrival
 150 (Figure 5a). It is also clearly visible in the horizontal component and again it has a larger amplitude
 151 with respect to the direct *P* wave. The *x-phase* has similar amplitude on the vertical and NS
 152 component, and both are about the double with respect to the EW component (Figure 5b).

153



154

155 *Figure 5 - (a) Three component waveforms of station MABI located at 7.7 degrees from epicentre.*
 156 *The red box indicates the window of Figure b; (b) the green and the red boxes show the time*
 157 *window on which the amplitude spectra of the P and x-phase are computed. The arrival on the*
 158 *vertical and the NS component is impulsive while it is less clear in the EW component. The station*

159 *is located to the north of the epicentre; (c) Amplitude spectra of the direct P wave (green) and the*
160 *later arrival (red).*

161 At greater distances, from 11 degrees onwards, we found another arrival after the direct *P*-wave
162 that is well reproduced by the 410 km discontinuity. We also noticed that the *x-phase* has,
163 generally, a higher frequency content in comparison to the direct *P* wave. We have not done
164 systematic analyses on the frequency content as it is not the goal of this paper and it will be part
165 of a future work. We have seen, however, that the *x-phase* is characterised by a frequency of about
166 2 Hz while the direct *P*-wave of about 1 Hz (Figure 5c).

167

168 **4. Results**

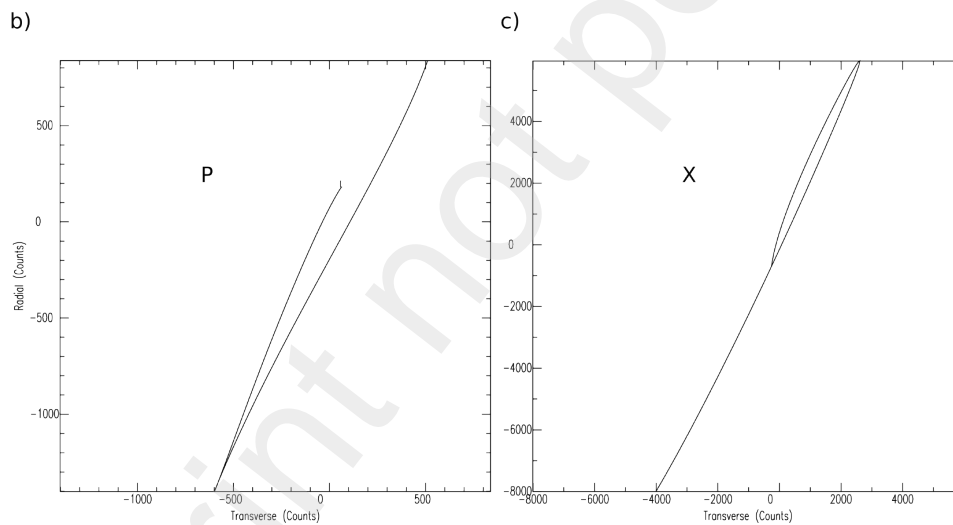
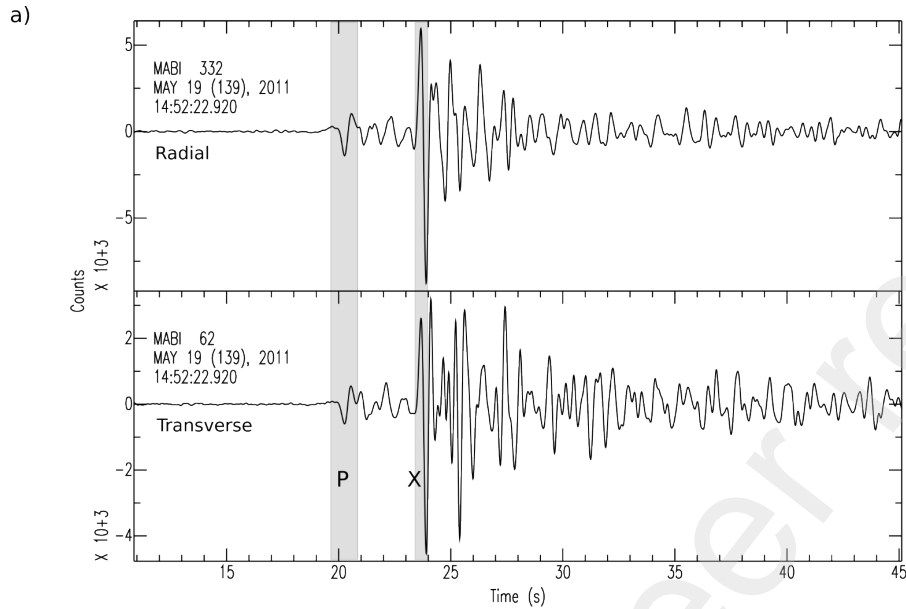
169

170 The diagrams in Figure 6 shows the particle motion of the first *P*-arrival and the secondary *x-phase*
171 at MABI station located 8.23° away from the epicentre. The selected earthquake occurred at a
172 depth of 298 km beneath the Aeolian Islands. The ray-path for both phases deviates of about 5°
173 from the theoretical source-receiver back-azimuth. The *x-phase* shows a typical *P*-wave particle
174 motion and we verified that this is a general observation for the *x-phase*. These characteristics
175 indicate that the *x-phase* is a compressional *P*-wave that travels in a less attenuating path than the
176 direct *P*-wave.

177 After analysing all the available record sections, we notice that the *x-phase* appears at about 6
178 degrees from the epicenter, it is not present in all the events, and it is dependent on the azimuth.

179 The time difference between direct *P* and the secondary wave, at the distance where the phase

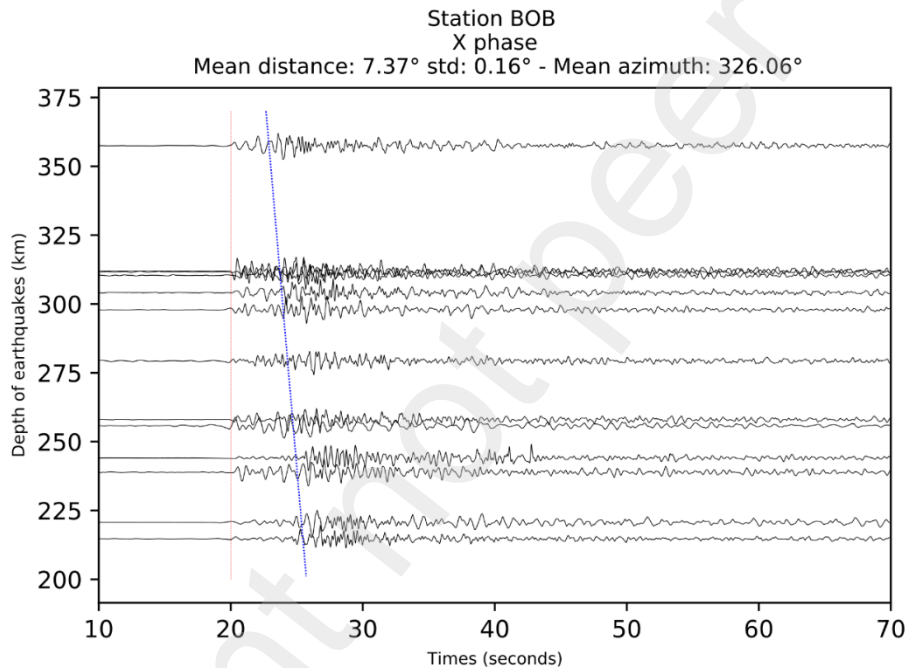
180 appears, is 10 seconds, as an average. The arrival time difference between the direct P and the x -
 181 phase decreases with epicentral distance and, at about 9 degrees, the x -phase reaches the first onset.



182

183 **Figure 6 - (a)** Radial and transverse waveforms of station MABI. The grey boxes highlight the
 184 time windows of which the particle motions are computed; **(b)** particle motion diagram of the
 185 direct P wave and **(c)** of the x -phase.

186 The x-phase has an apparent velocity of about 11 km/s. Record sections show that the apparent
 187 velocity after 9 degrees and after the x-phase reaches the first onset is equal to the direct P wave
 188 and not to that of the *x-phase*. This means that the *x-phase* reaches the surface only between 6 and
 189 9 degrees and not after or before these distances. This is a strong constrain in the x-phase
 190 interpretation. We then plot the seismograms in function of hypocenters for each station. The
 191 arrival time decreases with increasing depths at each station (Figure 7). This suggests that the x-
 192 *phase* is in some way related with a deeper interface, probably within the slab. The deeper the
 193 earthquake, the shorter the difference in the arrival time between the direct P wave and the x-phase.

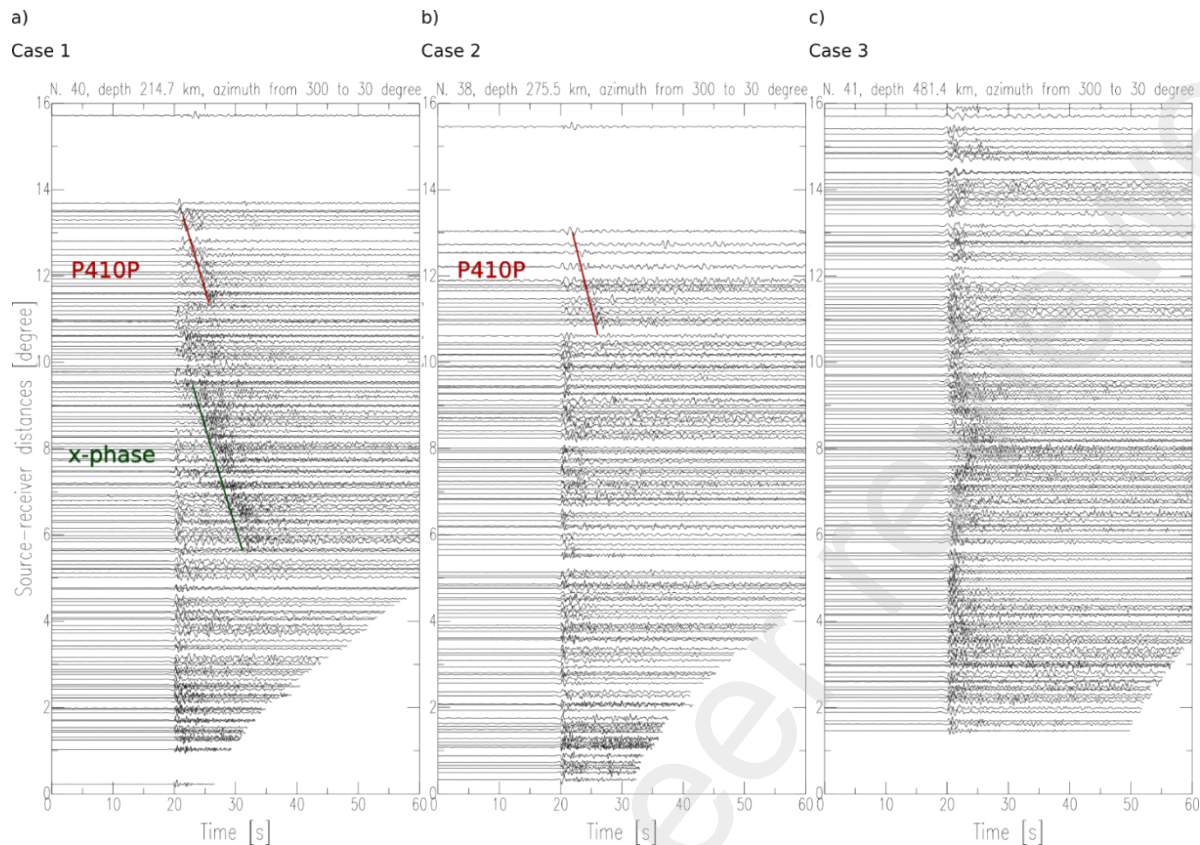


194
 195 **Figure 7** – Vertical waveforms recorded at the seismic station BOB for different earthquakes. They
 196 are sorted by earthquake depth and aligned by P first arrivals on the y-axis (the red vertical line).
 197 The blue line highlights the x-phase arrivals.

198 Only seismograms of stations located in the northerly quadrants with respect to the epicentre show
 199 the later P-arrival, as shown in Figures 2 and 4. Results can be generalised in the following way.

200 All the seismograms between 6 and 9 degrees from earthquakes with hypocentre below the Aeolian
201 Arc and in the depth range 220 to 312 km show the *x*-phase, a compressional P wave, as in the
202 example of Figure 8a. Earthquakes with hypocentre in the western side of Calabria's coasts never
203 show the secondary phase, but only the phase associated to the ~410 km discontinuity (Figure 8b).
204 Earthquakes beneath the coast of Calabria occur at the same depth range of the earthquakes beneath
205 the Aeolian Islands. Earthquakes with hypocentre deeper than 400 km do not show neither the
206 secondary phase nor a phase associated to the 410 km discontinuity (Figure 8c). Figure 9 shows
207 the spatial distribution of the three different cases. A further peculiar observation is from profile
208 A–B of Figure 3b. It shows that the hypocentres of the earthquake where we observed the *x*-phase,
209 below the Aeolian Islands, are concentrated in the bottom part of the seismic zone, near to the
210 interface between the lower edges of the slab with the surrounding mantle. We compared two
211 seismic catalogues (INGV Italian Seismological Instrumental and Parametric Database available
212 at <http://cnt.rm.ingv.it/iside> and D. La Torre personal communication) and the hypocentres,
213 although slightly different, show the same pattern.

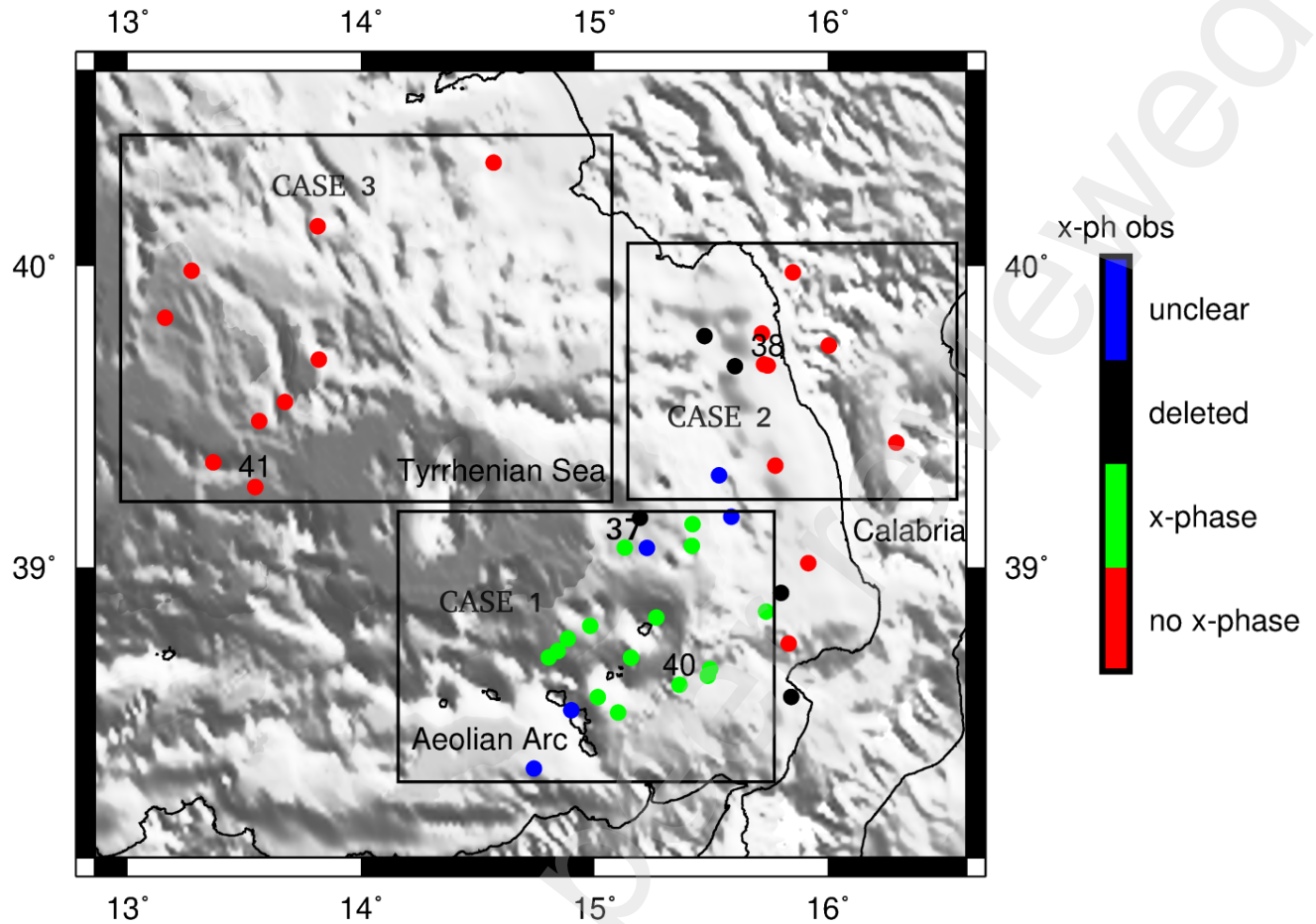
214



215

216 **Figure 8** - Examples of record sections of the three cases we discuss in the text. The “N.” in the
 217 title corresponds to number id in the map of the Figure 8 (N. 40, 38, 41).

218 The seismological constraints derived from the observations made in this work, allow us to design
 219 a simple 2D modelling by means of fitting the arrival times. The final goal is to understand the
 220 nature and origin of the x-phase. We are aware that a 2D approach is a first approximation of a
 221 complex 3D geometry as it is the Southern Tyrrhenian subduction zone and future work will
 222 include a full 3D model to take into account the complex three-dimensional geometry of the
 223 problem.



224

225 *Figure 9 – Map distribution of the earthquakes that show the secondary seismic phase (green*
 226 *dots), that do not show the x-phase (red dots) and those earthquakes where the presence of the x-*
 227 *phase is unclear (blue dots).*

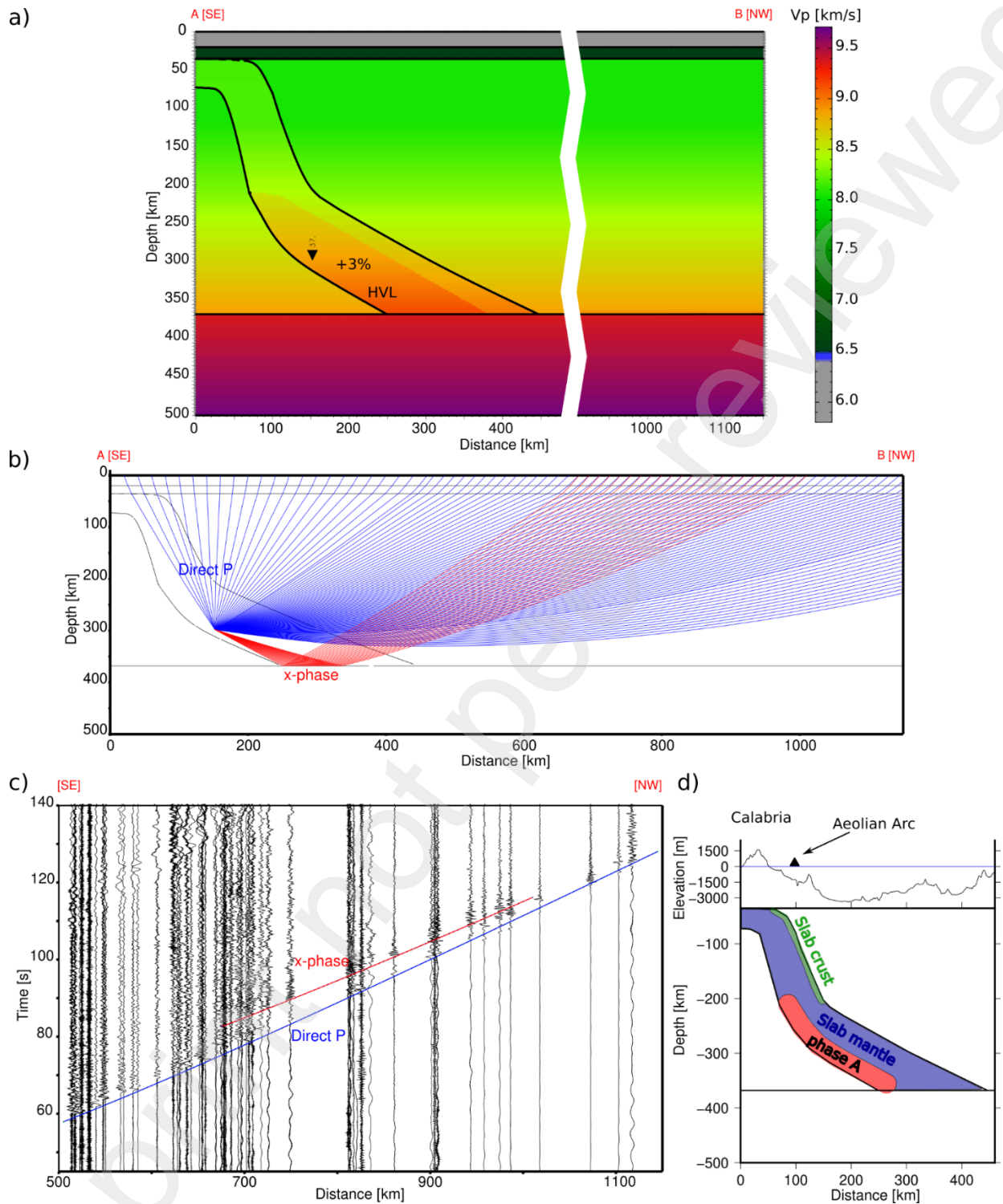
228 We calculated theoretical travel time curves with Seis83 software (Červený, V., & I. Pšenčík,
 229 1984) that makes use of ray-tracing technique (Červený et al., 1977) with the graphical interface
 230 model (Komminaho, 1998) and ZPLOT (Zelt, 1994).

231 Several models were tested to match the arrival times of the *x-phase*. We used IASP91 velocity
 232 model (Kennett and Engdahl, 1991) to represent the velocity structure outside the slab (Figure
 233 10a), whereas the slab boundaries were constrained by seismicity distribution (Figure 3b).

234 Following Pino and Helmberger, (1997), the 410-km discontinuity is raised up to a depth of 370
235 km, as generally observed in subduction zones (Collier et al., 2001). According to tomographic
236 studies (Amato et al., 1993; Scarfi et al., 2018; Spakman et al., 1993), the subducting lithosphere
237 is characterized by positive velocity anomalies. We increased the velocity inside the slab in
238 different run by a percentage between 1.5% and 5% to the IASP91 velocity values.

239 The arrivals of the direct P wave are well fitted by a subducting lithosphere with an average
240 increment of 1.5% of IASP91 velocity model, whereas the *x-phase* requires much faster velocities,
241 at least 3% higher than IASP91. Hence, we introduced a narrow high velocity layer, HVL, in the
242 lowermost subducted lithospheric mantle, in the region where we observe the hypocentre of the
243 earthquakes with the secondary phase with an average increase of the velocity up to 3% with
244 respect to IASP91. Compressional velocities in the HVL between 250 and 370 km depth are from
245 8.9 to 9.15 km/s. The model is able to fit the arrival times of the x-phase for all the deep earthquakes
246 below the Aeolian Island we have modelled (Figure 10c).

247



248

249 **Figure 10** – (a) 2D velocity model, section trace in the Figure 2 (n.b. the section orientation is
 250 opposite of those in Figure 3b-c to have increasing distances rightwards). The black triangle is
 251 the 2011 earthquake (N. 37) with x-phase; (b) Calculated ray paths for the earthquake N. 37; (c)

252 *calculated travel time curves on the observed record section of earthquake N. 37. The blue line*
253 *shows the calculated direct P wave arrivals, and the red line is for the x-phase; (d) Sketch of the*
254 *possible petrology and thickness of the HVL.*

255

256 The introduction of a HVL provides the explanation to most of the positive and negative
257 observations we have done in this work. It explains why the secondary phase is not observed in
258 very deep earthquakes, below the 410 km discontinuity. It may explain also the different frequency
259 content of the direct P wave if compared to that of the x-phase traveling along a different, probably
260 less attenuating, path. It also provides an explanation why we see the *x-phase* only at specific
261 epicentral distances (between 6 and 9 degrees).

262 Between the unresolved issues, the reasons why we do not observe the later arrival in the
263 earthquakes located below the Calabrian Arc slab is the most intriguing. There are clear geometric
264 differences between these two sectors of the slab and probably a combination of geometry of the
265 slab and its velocity structure is a necessary condition to generate the secondary phase. This is one
266 of the main goals of a future 3D model.

267

268 **5. Discussion and Conclusions**

269 We have described the nature and origin of a later arrival observed in intermediate-depth and deep
270 earthquakes of the Tyrrhenian subduction zone at stations from 6 to 9 degrees from epicentres,
271 towards north. Only earthquakes beneath the Aeolian Islands and in the depth range between 215–
272 320 km generate this later *P*-arrival. The 2D modelling shows that a combination of velocity

273 structure and geometric characteristics is able to reproduce rather well the positive and negative
274 observations of the whole dataset.

275 Travel times indicate that the phase is not a depth phase. The main characteristic of depth phases
276 is that the difference of time between a depth phase onset and the *P*-onset is an increasing function
277 of the epicentral distance (Murphy & Barker, 2006). For the same reason, it is not even a *SP*-wave,
278 which is a direct *S*-wave traveling upward and converted at the upper boundary of the slab, as
279 analysed in Zhao et al. (1997) for the Japan slab. The later arrival described in this work is a *P*-
280 wave that propagates downward in a high velocity layer located in the lowermost part of the
281 subducted lithospheric mantle.

282 As far as we know, a HVL, as the one we have introduced in this work, has not been previously
283 described from a seismological point of view. The dubitative question mark in our title reflects
284 some assumptions contained in the modelling and other considerations that should be verified.
285 These refer to three main questions. Why tomographic images available for the Tyrrhenian
286 subduction zone do not show such a narrow HVL? Why the fast and late *P*-arrival has not been
287 observed elsewhere, in other subduction systems? Are *P*-wave velocities as fast as 9.1 km/s
288 reasonable at 300-350 km depth within a slab?

289 There are plenty of tomography results published for the Tyrrhenian subduction zone that use
290 different datasets and inversion techniques (Amato et al., 1993; Chiarabba et al., 2008; Lucente et
291 al., 1999; Selvaggi & Chiarabba, 1995; Spakman et al, 1993). None of them shows a clear well
292 defined HVL, although all agree that at depths between 200 and 400 km, the *P*-velocity is higher
293 than the velocity of the surrounding mantle but not at the level of the HVL we have introduced.
294 An answer is that the thickness of the HVL could be as wide as 20–30 km and such layer is

295 probably too narrow to be detected by the course grid generally used to model the mantle at those
296 depths. The high velocities of the HVL could then be averaged within the general high *P*-velocity
297 at those depths, masking the real velocity anomaly of the HVL.

298 The fact that we see the later *P*-arrival only in the Southern Tyrrhenian Subduction Zone, then, is
299 probably due to the peculiar combination of the velocity structure, geometric conditions, as said
300 before, as well as the station distribution in front of the slab. Concerning the Tyrrhenian
301 subduction, we are particularly lucky as it has the whole Europe and its numerous seismological
302 stations in front of it, spanning distances evenly for thousands of km. Such network geometry is
303 not easy to find in other subduction zones. All the subductions along the Pacific have a less
304 favourable network geometry. The distance between 6 and 9 degrees from the epicentre for most
305 of the pacific subductions are either in the sea or in less monitored areas. That is probably why the
306 *x-phase* is not a common finding from other subduction zones, although it is not excluded that it
307 could be observed elsewhere. We also checked seismograms from Hellenic subduction and from
308 some Vrancea intermediate-depth earthquakes without any interesting result. We noticed, anyway,
309 that in Greece and in Romania there are no *x-phase*. Systematic research all around subduction
310 zones will be part of the extension of this research in the future.

311 Finally, a comparison with laboratory experiments on mineral transformations conducted at upper
312 mantle conditions, provides a nice, elegant and simple explanation for the nature of our
313 observations and allows us to make some important inferences on the origin of the *x-phase*.

314 We have shown that the earthquakes with the *x-phase* are located in the uppermost mantle
315 lithosphere of the subducted slab, near the lower boundary of the seismic plate, between 215 to
316 about 320 km of depth. The representing lithology that composes the lithospheric mantle at these
317 depths is generally lherzolite and harzburgite (e.g., Hacker et al., 2003a). These rocks commonly

318 enter into the subduction as locally hydrated, with water incorporated into OH-bearing minerals
319 like antigorite serpentine and chlorite (see Figure 5 in Hacker et al., 2003a). The slab deepening
320 during subduction causes devolatilization reactions (e.g., Hacker et al., 2003a, b) facilitating the
321 embrittlement of these minerals. This process gives rise to earthquakes. When antigorite serpentine
322 and chlorite react out at depth, not all the water escapes from the system and some can be still hold
323 into a meta-stable mineral phase in the upper-mantle deep slab (e.g., Sclar et al., 1965; Cai et al.,
324 2021). This mineral phase, which is a dense magnesium hydrated silicate, has been called in
325 literature *phase A* (Sclar et al., 1965). Phase A is stable at higher pressure and temperature
326 conditions and its importance is because carries water deep into the Earth (Wunder & Schreyer,
327 1992; Fumagalli et al., 2001). Recent ultrasonic measurements of compressional waves on *phase*
328 *A* in a cold subduction show an increase of P-velocities to the level introduced in the HVL model
329 (Cai et al., 2021) and at depths from about 200 km and down. In addition, these depths are
330 consistent with the range where we model the HVL in the Tyrrhenian subduction. Therefore, we
331 interpret the HVL as related to the presence of the dense hydrous magnesium silicate *phase A*,
332 formed after antigorite breakdown as inferred from laboratory experiments and predicted by phase
333 equilibria in cold subduction zones (van Keken et al., 2011; Cai et al., 2021), as the Tyrrhenian
334 subduction seems to be. This is the first direct seismological observation of the phase A in the
335 subduction process.

336

337

338 **Data availability**

339 For the creation of this manuscript the data were extracted from the following archives.
340 Earthquakes data are from the Italian Seismological Instrumental and Parametric Data-base (ISIDE

341 Working Group, 2007). Waveforms are extracted from the European Integrated Data Archive
342 (EIDA, <http://eida.ingv.it/>) infrastructure within the Observatories & Research Facilities for
343 European Seismology (ORFEUS) and Federation of Digital Seismograph Networks (FDSN) and
344 from the Incorporated Research Institutions for Seismology Data Management Centre. (IRIS
345 DMC, <https://ds.iris.edu/ds/nodes/dmc/data/types/waveform-data/>). Most of the data are from the
346 networks having the identifiers: IV, MN, NI, SI, SL, CH, GU, OE (INGV Seismological Data
347 Centre, 2006; MedNet Project Partner Institutions, 1990; OGS and University of Trieste, 2002;
348 Slovenian Environment Agency, 1990; Swiss Seismological Service at ETH Zurich, 1983;
349 University of Genoa, 1967; ZAMG - Zentralanstalt für Meteorologie und Geodynamik, 1987).

350 **Acknowledgments**

351 This work has been funded by INGV internal funding (Bando Ricerca Libera 2019) and supported
352 by a subsidy from the Polish Ministry of Education and Science for the Institute of Geophysics,
353 Polish Academy of Sciences.

354 Figures were made using the SAC software (Goldstein et al., 2003; Goldstein and Snoke, 2005)
355 the Generic Mapping Tools (GMT), version 5 (Wessel et al., 2013) available at
356 <https://www.genericmapping-tools.org> and the Obspy tool (Beyreuther et al., 2010).

357 We thank Prof. Johannes Schweitzer for its insightful comments and advice in the first stage of
358 the work.

359

360 **References**

361 Abers, G. A. (2000). Hydrated subducted crust at 100–250 km depth. Earth and Planetary
362 Science Letters, 176(3-4), 323-330. [https://doi.org/10.1016/S0012-821X\(00\)00007-8](https://doi.org/10.1016/S0012-821X(00)00007-8)

363 Abers, G. A. (2005). Seismic low-velocity layer at the top of subducting slabs: observations,
364 predictions, and systematics. Physics of the Earth and Planetary Interiors, 149(1-2), 7-29.
365 <https://doi.org/10.1016/j.pepi.2004.10.002>

366 Amato, A., Alessandrini, B., Cimini, G., Frepoli, A., & Selvaggi, G. (1993). Active and remnant
367 subducted slabs beneath Italy: evidence from seismic tomography and seismicity. Annals of
368 Geophysics, 36(2). <https://doi.org/10.4401/ag-4272>

369 Anderson, H., & J. Jackson (1987), Active tectonics of the Adriatic region, Geophys. J. R.
370 Astron. Soc., 91, 937 – 983.

371 Beyreuther, M., Barsch, R., Krischer, L., Megies, T., Behr, Y., Wassermann J., (2010) ObsPy: A
372 Python Toolbox for Seismology SRL, 81(3), 530-533. 10.1785/gssrl.81.3.530

373 Cai, N., Qi, X., Chen, T., Wang, S., Yu, T., Wang, Y., et al. (2021). Enhanced Visibility of
374 Subduction Slabs by the Formation of Dense Hydrous Phase A. Geophysical Research Letters,
375 48(19), 1–10. <https://doi.org/10.1029/2021GL095487>.

376 Červený, V., Molotkov, I. A., & Pšenčík, I. (1977). Ray method in seismology. Univerzita
377 Karlova, [https://doi.org/10.1016/S0065-2687\(06\)48001-8](https://doi.org/10.1016/S0065-2687(06)48001-8)

378 Červený, V. & Pšenčík, I., (1984). SEIS83 - Numerical modelling of seismic wave fields in 2-D
379 laterally varying layered structures by the ray method, in Documentation of Earthquake

380 Algorithms, Rep. SE-35, pp. 36–40, ed. Engdal, World Data Center (A) for Solid Earth
381 Geophysics.

382 Chiarabba, C., De Gori, P., & Speranza, F. (2008). The southern Tyrrhenian subduction zone:
383 deep geometry, magmatism and Plio-Pleistocene evolution. *Earth and Planetary Science Letters*,
384 268(3-4), 408-423., <https://doi.org/10.1016/j.epsl.2008.01.036>

385 Cimini, G. B., & Marchetti, A. (2006). Deep structure of peninsular Italy from seismic
386 tomography and subcrustal seismicity. *Annals of Geophysics*. <http://hdl.handle.net/2122/2000>

387 Collier, J. D., Helffrich, G. R., & Wood, B. J. (2001). Seismic discontinuities and subduction
388 zones. *Physics of the Earth and Planetary Interiors*, 127(1-4), 35-49.
389 [https://doi.org/10.1016/S0031-9201\(01\)00220-5](https://doi.org/10.1016/S0031-9201(01)00220-5)

390 D'Agostino, N., E. D'Anastasio, A. Gervasi, I. Guerra, M. R. Nedimović, L. Seeber, and M.
391 Steckler (2011), Forearc extension and slow rollback of the Calabrian Arc from GPS
392 measurements, *Geophys. Res. Lett.*, 38, L17304, doi:10.1029/2011GL048270.

393 Essen, K., Braatz, M., Ceranna, L., Friederich, W., & Meier, T. (2009). Numerical modelling of
394 seismic wave propagation along the plate contact of the Hellenic Subduction Zone-the influence
395 of a deep subduction channel. *Geophysical Journal International*, 179(3), 1737-1756,
396 <https://doi.org/10.1111/j.1365-246X.2009.04369.x>

397 Faccenna, C., Becker, T.W., Lucente, F.P., Jolivet, L., & Rossetti F., (2001) History of
398 subduction and back-arc extension in the Central Mediterranean, *Geophysical Journal*
399 *International*, 145, 809-820, <https://doi.org/10.1046/j.0956-540x.2001.01435.x>

400 Frepoli, A., Selvaggi, G., Chiarabba, C., & Amato, A. (1996). State of stress in the Southern
401 Tyrrhenian subduction zone from fault-plane solutions. *Geophysical Journal International*,
402 125(3), 879-891. <https://doi.org/10.1111/j.1365-246X.1996.tb06031.x>

403 Fukao, Y., Kanjo, K. & Nakamura, I. (1978), Deep seismic zone as an upper mantle reflector of
404 body waves. *Nature* 272, 606–608. <https://doi.org/10.1038/272606a0>

405 Fumagalli, P., Stixrude, L., Poli, S., & Snyder, D. (2001). The 10Å phase: A high-pressure
406 expandable sheet silicate stable during subduction of hydrated lithosphere. *Earth and Planetary
407 Science Letters*, 186(2), 125–141. [https://doi.org/10.1016/S0012-821X\(01\)002382](https://doi.org/10.1016/S0012-821X(01)002382)

408 Goldstein, P., D. Dodge, M. Firpo, Lee Minner (2003) “SAC2000: Signal processing and
409 analysis tools for seismologists and engineers, invited contribution to “The IASPEI International
410 Handbook of Earthquake and Engineering Seismology”, Edited by WHK Lee, H. Kanamori, P.C.
411 Jennings, and C. Kisslinger, Academic Press, London.

412 Goldstein, P. A. U. L., & Snoke, A. (2005). SAC availability for the IRIS
413 community. *Incorporated Research Institutions for Seismology Newsletter*, 7(UCRL-JRNL-
414 211140).

415 Hacker, B. R., Abers, G. A., & Peacock, S. M. (2003a). Subduction factory 1. Theoretical
416 mineralogy, densities, seismic wave speeds, and H₂O contents. *Journal of Geophysical Research:*
417 *Solid Earth*, 108(B1), 1–26. <https://doi.org/10.1029/2001jb001127>

418 Hacker, B. R., Peacock, S. M., Abers, G. A., & Holloway, S. D. (2003b). Subduction factory 2.
419 Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration

420 reactions? *Journal of Geophysical Research: Solid Earth*, 108(B1).
421 <https://doi.org/10.1029/2001jb001129>

422 Hasegawa, A., Umino, N., & Takagi, A. (1978). Double-planed structure of the deep seismic
423 zone in the northeastern Japan arc. *Tectonophysics*, 47(1-2), 43-58.

424 Hori, S. (1990). Seismic waves guided by untransformed oceanic crust subducting into the
425 mantle: the case of the Kanto district, central Japan. *Tectonophysics*, 176(3-4), 355-376.

426 INGV Seismological Data Centre, (2006). *Rete Sismica Nazionale (RSN)*. Istituto Nazionale di
427 Geofisica e Vulcanologia (INGV), Italy. <https://doi.org/10.13127/SD/X0FXNH7QFY>

428 ISIDE Working Group. (2007). Italian Seismological Instrumental and Parametric Database
429 (ISIDE). Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/ISIDE>

430 Kennett, B.L.N. and Engdahl, E.R. (1991), Traveletimes for global earthquake location and phase
431 identification. *Geophysical Journal International*, 105: 429-465. [https://doi.org/10.1111/j.1365-](https://doi.org/10.1111/j.1365-246X.1991.tb06724.x)
432 [246X.1991.tb06724.x](https://doi.org/10.1111/j.1365-246X.1991.tb06724.x)

433 Komminaho, K., (1998). Software Manual for Programs MODEL and XRAYs: A Graphical
434 interface for SEIS83 Program Package, University of Oulu, Dep. of Geophys., Rep. 20, 31 pp.

435 Lucente, F. P., Chiarabba, C., Cimini, G. B., & Giardini, D. (1999). Tomographic constraints on
436 the geodynamic evolution of the Italian region. *Journal of Geophysical Research: Solid Earth*,
437 104 (B9), 20307-20327. <https://doi.org/10.1029/1999JB900147>

438 Martin, S., Rietbrock, A., Haberland, C. & Asch, G., 2003. Guided waves propagating in
439 subducted oceanic crust, *J. geophys. Res.*, 108 (B11), 2536,
440 <https://doi.org/10.1029/2003JB002450> .

441 Martin, S. & Rietbrock, A., 2006. Guided waves at subduction zones: dependencies on slab
442 geometry, receiver locations and earthquake sources, *Geophys. J. Int.*, 167, 693–704,
443 <https://doi.org/10.1111/j.1365-246X.2006.02963.x>

444 Matsuzawa, T., Umino, N., Hasegawa, A., & Takagi, A. (1986). Upper mantle velocity structure
445 estimated from PS-converted wave beneath the north-eastern Japan Arc. *Geophysical Journal*
446 *International*, 86(3), 767-787, <https://doi.org/10.1111/j.1365-246X.1986.tb00659.x>

447 MedNet Project Partner Institutions. (1990, January 1). Mediterranean Very Broadband
448 Seismographic Network (MedNet). Istituto Nazionale di Geofisica e Vulcanologia (INGV).
449 <https://doi.org/10.13127/SD/FBBBTDTD6Q>

450 Murphy, J. R., & Barker, B. W. (2006). Improved focal-depth determination through automated
451 identification of the seismic depth phases pP and sP. *Bulletin of the Seismological Society of*
452 *America*, 96(4A), 1213-1229, <https://doi.org/10.1785/0120050259>

453 Obara, K., & Sato, H. (1988). Existence of an S wave reflector near the upper plane of the double
454 seismic zone beneath the Southern Kanto District, Japan, *J. Geophys. Res.*, 93(B12), 15037–
455 15045, <https://doi.org/10.1029/JB093iB12p15037>.

456 OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) and University of Trieste
457 (2002): North-East Italy Broadband Network. International Federation of Digital Seismograph
458 Networks. Dataset/Seismic Network. <https://doi.org/10.7914/SN/NI>

459 Ohmi, S., & Hori, S. (2000). Seismic wave conversion near the upper boundary of the Pacific
460 plate beneath the Kanto district, Japan. *Geophysical Journal International*, 141(1), 136-148,
461 <https://doi.org/10.1046/j.1365-246X.2000.00086.x>

462 Pino, N. A. and D. V. Helmberger (1997), Upper mantle compressional velocity structure
463 beneath the West Mediterranean Basin, *J. Geophys. Res.*, 102(B2), 2953–2967,
464 <https://doi.org/10.1029/96JB03461>

465 Ritsema A.R. (1972) Deep earthquakes of the Tyrrhenian Sea, *Geol. Mijnb.*, 51, 541 -545.

466 Scarfi, L., Barberi, G., Barreca, G., Cannavò, F., Koulakov, I., & Patanè, D. (2018). Slab
467 narrowing in the Central Mediterranean: the Calabro-Ionian subduction zone as imaged by high
468 resolution seismic tomography. *Scientific reports*, 8(1), 1-12,
469 <https://doi.org/10.1038/s41598.018-23543-8>

470 Sclar, C. B. (1965). High-pressure synthesis and stability of a new hydrogen-bearing layer
471 silicate in the system MgO-SiO₂-H₂O. *Am. Geophys. Union Trans.*, 46, 184.

472 Selvaggi, G. (2001). Strain pattern of the Southern Tyrrhenian slab from moment tensors of deep
473 earthquakes: implications on the down-dip velocity. *Annals of Geophysics*, 44(1).
474 <https://doi.org/10.4401/ag-3613>

475 Selvaggi, G., & Chiarabba, C. (1995). Seismicity and P-wave velocity image of the Southern
476 Tyrrhenian subduction zone. *Geophysical Journal International*, 121(3), 818-826.
477 <https://doi.org/10.1111/j.1365-246X.1995.tb06441.x>

478 Slovenian Environment Agency (1990): Seismic Network of the Republic of Slovenia.
479 International Federation of Digital Seismograph Networks. Dataset/Seismic
480 Network. <https://doi.org/10.7914/SN/SL>

481 Spakman, W., van der Lee, S., & van der Hilst, R. (1993). Travel-time tomography of the
482 European-Mediterranean mantle down to 1400 km. *Physics of the Earth and Planetary Interiors*,
483 79(1-2), 3-74. [https://doi.org/10.1016/0031-9201\(93\)90142-V](https://doi.org/10.1016/0031-9201(93)90142-V)

484 Sun, D., Miller, M. S., Agostinetti, N. P., Asimow, P. D., & Li, D. (2014). High frequency
485 seismic waves and slab structures beneath Italy. *Earth and Planetary Science Letters*, 391, 212-
486 223, <https://doi.org/10.1016/j.epsl.2014.01.034>.

487 Swiss Seismological Service (SED) at ETH Zurich; (1983): National Seismic Networks of
488 Switzerland; ETH Zürich. Other/Seismic Network. <https://doi.org/10.12686/sed/networks/ch>

489 University of Genoa (1967): Regional Seismic Network of North Western Italy. International
490 Federation of Digital Seismograph Networks. Dataset/Seismic
491 Network. <https://doi.org/10.7914/SN/GU>

492 van Keken, P. E., B. R. Hacker, E. M. Syracuse, and G. A. Abers (2011), Subduction factory: 4.
493 Depth-dependent flux of H₂O from subducting slabs worldwide, *J. Geophys. Res.*, 116, B01401,
494 doi:10.1029/2010JB007922.

495 Wessel, P., Smith, W. H., Scharroo, R., Luis, J., & Wobbe, F. (2013). Generic mapping tools:
496 improved version released. *Eos, Transactions American Geophysical Union*, 94(45), 409-410.
497 <https://doi.org/10.1002/2013EO45000>.

498 Wunder, B., & Schreyer, W. (1992). Metastability of the 10-Å phase in the system MgO-SiO₂-
499 H₂O (MSH). what about hydrous MSH phases in subduction zones? *Journal of Petrology*, 33(4),
500 877–889. <https://doi.org/10.1093/petrology/33.4.877>

501 ZAMG - Zentralanstalt für Meteorologie und Geodynamik (1987): Austrian Seismic Network.
502 International Federation of Digital Seismograph Networks. Dataset/Seismic
503 Network. <https://doi.org/10.7914/SN/OE>

504 Zelt, C.A., 1994. Software Package ZPLOT, Bullard Laboratories, University of Cambridge.

505 Zhao, D., Matsuzawa, T., & Hasegawa, A. (1997). Morphology of the subducting slab boundary
506 in the northeastern Japan arc. *Physics of the Earth and Planetary Interiors*, 102(1-2), 89-
507 104. [https://doi.org/10.1016/S0031-9201\(96\)03258-X](https://doi.org/10.1016/S0031-9201(96)03258-X)

508 Zhao, C.A., (2019). Importance of later phases in seismic tomography. *Physics of the Earth and*
509 *Planetary Interiors*, 296, 106314, <https://doi.org/10.1016/j.pepi.2019.106314>.

510