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High frequency seismic waves and slab structures beneath Italy

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ABSTRACT

Tomographic images indicate a complicated subducted slab structure beneath the central Mediterranean where gaps in fast velocity anomalies in the upper mantle are interpreted as slab tears. The detailed shape and location of these tears are important for kinematic reconstructions and understanding the evolution of the subduction system. However, tomographic images, which are produced by smoothed, damped inversions, will underestimate the sharpness of the structures. Here, we use the records from the Italian National Seismic Network (IV) to study the detailed slab structure. The waveform records for stations in Calabria show large amplitude, high frequency ($f > 5$ Hz) late arrivals with long coda after a relatively low-frequency onset for both P and S waves. In contrast, the stations in the southern and central Apennines lack such high frequency arrivals, which correlate spatially with the central Apennines slab window inferred from tomography and receiver function studies. Thus, studying the high frequency arrivals provides an effective way to investigate the structure of slab and detect possible slab tears. The observed high frequency arrivals in the southern Italy are the strongest for events from 300 km depth and greater whose hypocenters are located within the slab inferred from fast P-wave velocity perturbations. This characteristic behavior agrees with previous studies from other tectonic regions, suggesting the high frequency energy is generated by small scale heterogeneities within the slab which act as scatterers. Furthermore, using a 2-D finite difference (FD) code, we calculate synthetic seismograms to search for the scale, shape and velocity perturbations of the heterogeneities that may explain features observed in the data. Our preferred model of the slab heterogeneities beneath the Tyrrhenian Sea has laminar structure parallel to the slab dip and can be described by a von Kármán function with a down-dip correlation length of 10 km and 0.5 km in thickness with $\sim 2.5\%$ V_p fluctuations within the slab. This suggests that the heterogeneities are inherited from the melt shear bands formed during the original formation of the oceanic lithosphere near the mid-ocean ridge.

1. Introduction

Tomographic images show complex slab structures at depth, which are controlled by subduction dynamics, such as the episodic nature of subduction and the inhomogeneity of the subducted oceanic lithosphere (Giacomuzzi et al., 2012; Lucente et al., 1999; Miller et al., 2005, 2006; Obayashi et al., 2009; Sigloch et al., 2008; Widiyantoro and van der Hilst, 1996; Wortel and Spakman, 2000). Complexity in the slab morphology may include slab tears, which reveal acute phases in the tectonic history. However, only having tomographic images can lead to inconclusive or disputed existence of slab tearing due to the resolution and nature of the models. However, alternative methods have been used for imaging slabs and possible gaps in the slab structure. Obayashi et al. (2009) proposed that detections of converted phases from the side wall of the slab gaps and the detailed distribution of seismicity are needed. Other groups have also applied receiver function imaging to detect interfaces with the slab (e.g. Bostock, 2013; Kim et al., 2010; Piana Agostinetti et al., 2009; Bianchi et al., 2010; Miller and Piana Agostinetti, 2012; Sodoudi et al., 2011). The absence of such converted phases at a convergent margin provides additional geophysical evidence for the existence of the slab gap, especially when combined with the known location (or lack) of deep seismicity and inferred slab structure in tomographic images (Miller and Piana Agostinetti, 2012). The variations in the observed high frequency signals on broadband seismometers located near the convergent plate boundary from deep earthquakes provide another efficient way to detect slab structure. A continuous slab is needed to conserve the high frequency energy and allow it to

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propagate to the stations in the forearc. Therefore, if a slab gap is present these characteristic high frequency signals should not observed.

There are two types of high frequency phases associated with slab. The first type has high frequency phases as the first arrivals, such as in Tonga (Barazangi et al., 1972) and New Zealand (van der Hilst and Snieder, 1996), which are explained by a thin high velocity layer (van der Hilst and Snieder, 1996) in the slab. The second type has high frequency phases as coda arrivals. In many cases, the high frequency phases have large amplitude (James and Snoke, 1990; Kennett and Furumura, 2010). Studies have indicated that this type of high frequency signals may generate from wide-angle reflection from the upper boundary of the steeply dipping slab (James and Snoke, 1990; Mele, 1998) or as guided waves traveling in the low velocity layer on top of the downgoing plate (Abers et al., 2003). Recently, Furumura and Kennett (2005) proposed alternatively intriguing explanation. By introducing small-scale heterogeneities in the oceanic lithosphere, scattering of seismic waves satisfy three main observations (1) long duration coda type high frequency arrivals; (2) long period first arrivals; and (3) the high frequency singnals only presented on deep (>100 km) events (Furumura and Kennett, 2005). With recent advances in computational resources, quantitative studies on related high frequency wave propagation within slabs have been emerged (Furumura and Kennett, 2005; Kennett and Furumura, 2008, 2013; Martin et al., 2003; Shito et al., 2013). Most studies suggested that the high frequency guided waves are promoted by small-scale heterogeneities in the oceanic lithosphere. However, the detailed physical properties of these heterogeneities are not well constrained. What those heterogeneities represent physically and how they are formed are still puzzling. Thus, global samples of slabs in different geographic and tectonic regions, and with various physical properties (ages, dipping angle, subduction velocity) will be important to better understand those slab related high frequency seismic phases.

Here, we present observations of the high frequency seismic signals from deep earthquakes recorded by the National Seismic Network stations in Italy. The observed high-frequency signals are mainly found for the stations in southern Italy, which are linked to the Calabria slab. However, we also observe a region lacking high frequency arrivals that is localized above the proposed central Apennines slab window. By modeling the observed high frequency arrivals at southern Italy, we support the presence of the small-scale heterogeneities inside the slab and can also infer the location of the discontinuous slab beneath the Italian peninsula.

2. Observations

The high station density in Italian National Seismic Network (IV) makes detailed studies of the slab structure beneath the central Mediterranean feasible (Fig. 1A). Here we analyze deep, regional events that occurred between 2007 and 2012, using the event locations and origin times from Italian Seismological Instrumental and parametric DATA-BASE (ISIDe, http://iside.rm.ingv.it). The most useful earthquakes for this study have a depth greater than 200 km (Table 1), which were clustered in the deepest part of the Calabria subduction zone beneath the Tyrrhenian Sea (Fig. 1A). Seismograms were deconvolved from the instrument responses and then bandpass filtered (0.5–10 Hz). The tangential (SH) and radial (SV) components were rotated from the original horizontal components (N–S and E–W). Examples of vertical-component seismograms are shown in Fig. 1B–D.

The seismograms from the stations in the southern part of Italy show very prominent high frequency coda arrivals after the initial P arrivals. In contrast, the data from stations in the southern Apennines lack such high frequency signals (Fig. 1B–D and Fig. S1). Similar waveform characteristics were also seen in a previous study with fewer data by Mele (1998). There are clear boundaries between those stations that record the characteristic high frequency energy and those without, as indicated by the magenta dash lines in Fig. 1B–D. One division is between Calabria and the southern Apennines, the other is between the central Apennines and the northern Apennines. Seismic records and their power spectra for two representative stations (green triangles in Fig. 1D), PAOL in the southern Apennines and CEL in Calabria are displayed in Fig. 2. Station PAOL has a "normal" decaying high frequency spectrum and station CEL shows persistent high frequency energy up to 10 Hz.

Table 1
Earthquakes used in this study.

Date	Lon (°)	Lat (°)	Depth (km)
2011 05 19	15.18	39.05	292
2008 12 17	15.59	39.17	269
2010 11 03	13.27	39.98	506
2011 12 18	12.80	36.15	16
2007 07 04	15.26	38.83	279
2008 02 20	13.78	41.58	8
2008 05 30	14.88	40.57	309
2009 04 07	13.39	42.31	17
2009 04 25	26.71	45.59	106
2009 09 07	13.98	38.73	18
2009 11 23	15.28	39.66	294
2010 04 11	−3.69	37.10	616

To capture the lateral variations of the high frequency behavior within the whole array, the records were cut within 5 seconds before and 15 seconds after the initial P arrivals. Then we applied an adaptive multitaper method (Prieto et al., 2009) to the data to obtain a smoothed spectrum (Fig. 2). The amplitude ratio of the frequency of 7.5 Hz to 1 Hz in the smoothed spectrum was measured for every station after. Fig. 3A–C shows maps of the amplitude ratios for three deep events (2011 05 19, 2010 11 03, and 2008 12 17), where the stations in the southern to central Apennines lack high frequency energy (indicated in red). Those stations with null high frequency arrivals lie directly above, and may, therefore be a direct expression of the central Apennines slab window inferred from tomographic studies (Giacomuzzi et al., 2012; Lucente et al., 1999; Piromallo and Morelli, 2003; Wortel and Spakman, 2000). In contrast, the stations in Calabria display strong high frequency arrivals (indicated with green and blue colors in Fig. 3) and in the waveform data in Fig. 1, which indicates a possible link between the presence of the deep, continuous slab and the high frequency arrivals. The southern boundary, shown by a magenta dashed line drawn to separate the red and green colored amplitudes, between the southern Italian stations with high frequency arrivals and those without agree with the southern boundary of the central Apennines slab window (blue dashed lines) suggested by both tomographic images and S-receiver function studies (Lucente et al., 1999; Miller and Piana Agostinetti, 2012; Rosenbaum et al., 2008). The northern boundary of the null high frequency region deviates from suggested northern boundary of the central Apennines slab window, i.e. Anzio–Ancona Line, but overlaps with the Livorno–Sillaro line (black dashed lines in Fig. 3), which may indicate the location of subducted continental margin material. However, the seismic waves arriving in the central to northern Apennines sample the slab in a more oblique angle, which causes the northern Apennines slab to not be as well resolved as the Calabria slab in the south.

The observed high frequency energy has three possible sources: localized shallow structures beneath the stations, complex structures near the earthquake source, or anomalous structures along the ray path. The local structures beneath stations, such as basin structure (Scrivner and Helmberger, 1994), will produce similar