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Fluid migration in continental subduction: The Northern Apennines case study

Nicola Piana Agostinetti *, Irene Bianchi, Alessandro Amato, Claudio Chiarabba

Istituto Nazionale di Geofisica e Vulcanologia, Centro Nazionale Terremoti, Via Vigna Murata 605, 00143, Rome, Italy

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ABSTRACT

Subduction zones are the place in the world where fluids are transported from the foredeep to the mantle and back-to-the-surface in the back-arc. The subduction of an oceanic plate implies the transportation of the oceanic crust to depth and its methamorphization. Oceanic sediments release water in the (relatively) shallower part of the subduction zone, while dehydration of the subducted basaltic crust allows fluid circulation at larger depths. While the water budget in oceanic subduction has been deeply investigated, less attention has been given to the fluids implied in the subduction of a continental margin (i.e. in continental subduction). In this study, we use teleseismic receiver function (RF) analysis to image the process of water migration at depth, from the subducting plate to the mantle wedge, under the Northern Apennines (NAP, Italy). Harmonic decomposition of the RF data-set is used to constrain both isotropic and anisotropic structures. Isotropic structures highlight the subduction of the Adriatic lower crust under the NAP orogens, from 35–40 km to 65 km depth, as a dipping low *S*-velocity layer. Anisotropic structures indicate the presence of a broad anisotropic zone (anisotropy as high as 7%). This zone develops in the subducted Adriatic lower crust and mantle wedge, between 45 and 65 km depth, directly beneath the orogens and the more recent back-arc extensional basin. The anisotropy is related to the metamorphism of the Adriatic lower crust (gabbro to blueschists) and its consequent eclogitization (blueschists to eclogite). The second metamorphic phase releases water directly in the mantle wedge, hydrating the back-arc upper mantle. The fluid migration process imaged in this study below the northern Apennines could be a proxy for understanding other regions of ongoing continental subduction.

1. Introduction

Water and hydrous minerals are key components of many geodynamic processes in subduction zones, from the genesis of earthquakes and episodic tremors at shallow depth (Abers et al., 2009) to the generation of melts and upwelling diapirs under the magmatic arcs (Stern, 2002). At greater depth, topography of the mantle transition zone has been linked to the water flow induced by the subduction of oceanic crust (Tonegawa et al., 2008). A widely accepted model for water transportation into the mantle, due to the subduction of oceanic lithosphere, considers: (1) fluids released from sediments, at shallow depth; and (2) the dehydration of subducting oceanic crust at 70–100 km depth (Hacker et al., 2003). Deeper water transportation implies the presence of a supra-slab serpentinized mantle dragged down within the descending slab (Iwamori, 1998). Continental subduction is likely to show a different behaviour, due to the intrinsic differences in the subducted materials and their response to subduction process. Due to its buoyancy, the continental lithosphere does not easily sink in the upper mantle, generating gravitational instability which does not evolve as in oceanic subduction. Moreover, slices of continental crust can be dragged down coupled to the continental lithosphere inducing peculiar metamorphism (Whitney et al., 2010).

Many seismological observations have been used to catch the presence of water and hydrous minerals at depth, as well as the process of dehydration and water release. Anomalous high V_p/V_s ratio has been associated to water confined in the subducted, overpressured oceanic crust where the interface between the two plates is sealed at shallow depth (Audet et al., 2009). A seismological signature of water transportation in the fore-arc mantle is the presence of low *S*-wave velocity anomalies at depth, sub-parallel to the descending oceanic lithosphere, indicating the serpentinization of the supra-slab mantle (Kawakatsu and Watada, 2007) and water released from the dehydration of the oceanic mantle lithosphere. The upper planes of double Benioff Zones have been associated to dehydration reactions within the subducting oceanic crust (Brudzinski et al., 2007). Tomographic studies image rock mineral transformation into the descending crust as a variation of its seismic velocities with depth (Reyners et al., 2006). Seismic anisotropy is a less used marker for the presence of hydrated materials and fluids at depth, even if anisotropic materials are likely in a subduction zone. Serpentinization of the mantle wedge produces a zone of negative anisotropy (i.e. where the seismic velocity along the symmetry axis is lower than along the normal plane) on top of the slab (Park et al., 2004).

* Corresponding author.
E-mail addresses: nicola.piana@ingv.it (N.P. Agostinetti), irene.bianchi@ingv.it (I. Bianchi), alessandro.amato@ingv.it (A. Amato), claudio.chiarabba@ingv.it (C. Chiarabba).

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Water released from the slab can induce partial melting of the mantle wedge peridotite, which displays strong anisotropic pattern (Takei, 2010). Finally, high pressure, hydrous metamorphic faces are intrinsic anisotropic, i.e. amphiboles (Christensen and Mooney, 1995).

1.1. Tectonic setting

Geodynamics of the Mediterranean area is mainly driven by the convergence between the Nubia and Eurasia plates, occurred in the last 100 million years (Faccenna et al., 2001). Due to this ongoing process, from the Upper Cretaceous the central Mediterranean was re-organised as micro-plates which accommodate the convergence in peculiar ways. One example is represented by the Apennines orogen, which strikes almost parallel to the convergence direction between the main Africa and Eurasia plates (Dewey et al., 1989). Furthermore, tomographic images of the upper mantle beneath the Apennines reveal the presence of a cold dipping body and its clear segmentation (Lucente et al., 1999), pointing out the complexity of this re-organisation process. A widely accepted hypothesis suggests that the oceanic domain which separated the two continents was progressively subducted under the Iberian–European margin due to slab pull, inducing trench retreat (Faccenna et al., 2001). Trench retreat has been observed elsewhere in the central Mediterranean region, and indicate a “path” of counterclockwise rotation of the subduction zone (Carminati et al., 1998). The process of slab retreat has been also invoked to explain the synchronous presence of coupled extension and compression along the subduction zone (Malinverno and Ryan, 1986; Mariucci et al., 1999), which is a long-standing observation in central Mediterranean (Frepoli and Amato, 1997). In the Apennines, starting 30 My ago, continental materials were incorporated in the orogenic wedge, following the entrance of the continental margin of the Adria microplate at the trench, and leading to subduction of the continental lithosphere (Di Stefano et al., 2009; Faccenna et al., 2001). According to some authors (e.g. Channell and Mareschall, 1989) the Apennines continental subduction has evolved to a stage of “delamination” in which the continental lithosphere is detached by (part of) the crust and sinks in the upper mantle dragged by the oceanic lithosphere negative buoyancy (also called “post-subduction” delamination).

The Northern Apennines (NAP) is the portion of the belt comprised between 43° and 45° latitude (Fig. 1). In this region the strike of the chain rotate from WNW–ESE to N–S, giving to the orogens its arcuate shape. The NAP separates the Tuscan (West) from the Adriatic (East) regions. The two regions display very different characteristics: local seismicity (De Luca et al., 2009), rheology (Pauselli et al., 2010), crustal structure (Finetti, 2005), heat flux (Pauselli and Federico, 2002), geothermal fluids (Minissale et al., 2000) and stress field (Montone et al., 2004; Pondrelli et al., 2006). Tomographic studies highlighted the presence of a cold dipping body beneath the NAP chain and the Tuscan domain (Lucente et al., 1999). Such body has been interpreted as the cold oceanic lithosphere subducted under the Eurasia plate. Subcrustal seismicity is present beneath the Tuscan side of the orogens (De Luca et al., 2009), revealing the presence of a dehydrating body sinking into the upper mantle (Chiarabba et al., 2009) and confirming the subduction hypothesis.

1.2. Previous RF studies across Northern Apennines

Receiver functions (RF) are time-series which emphasise the *P*-to-*s* (*Ps*) converted waves in the P coda of teleseismic records. RF are computed through the deconvolution of the vertical from the horizontal

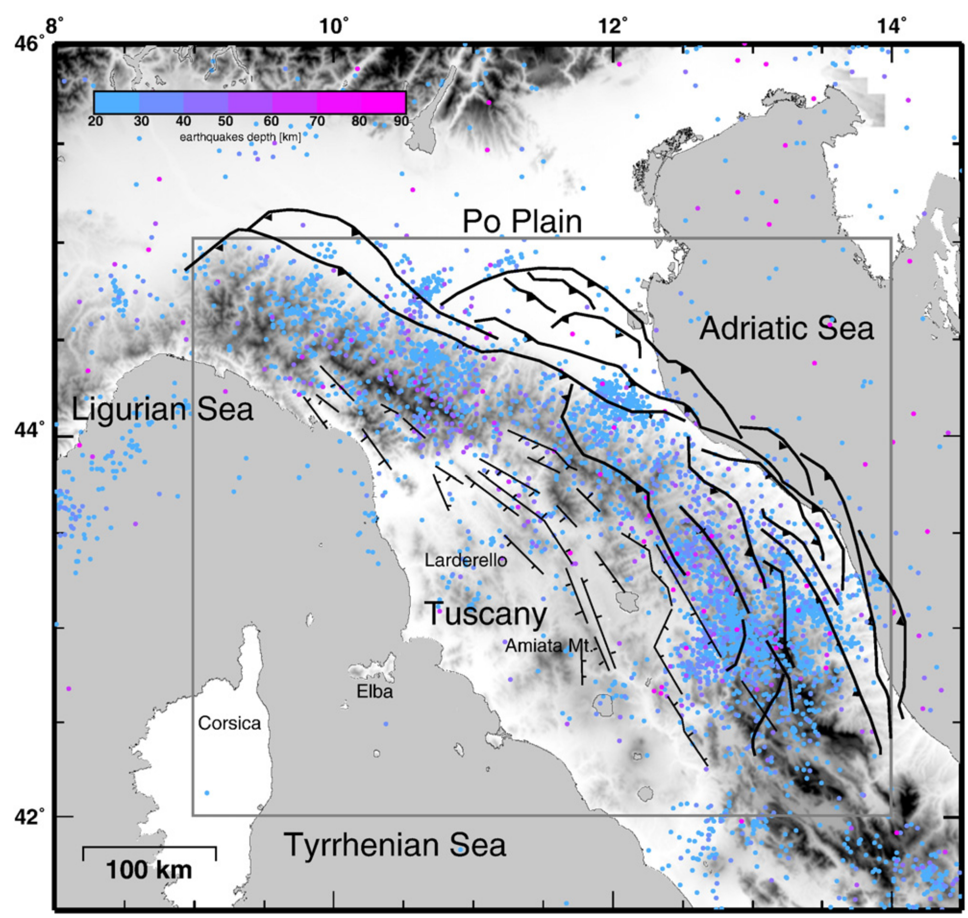

Fig. 1. Tectonic sketch of the study area. The curved black lines toward the Adraitic Sea are the traces of the more external thrust fronts. The thin black lines in the Apennines are the normal faults. Circles are epicenters of Z>35 km seismicity. The rectangle depicts the area of the next figure.