Tectonophysics 554–557 (2012) 63–73

Contents lists available at SciVerse ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Can local earthquake tomography settle the matter about subduction in the Northern and Central Apennines? Response from a new high resolution P velocity and Vp/Vs ratio 3-D model

D. Scafidi [a,*], S. Solarino [b]

[a] Dip.Te.Ris., Dipartimento per lo studio del Territorio e delle sue Risorse, Università degli Studi di Genova, Genova, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Genova, Italy

A R T I C L E I N F O

Article history:
Received 10 November 2011
Received in revised form 2 April 2012
Accepted 2 June 2012
Available online 13 June 2012

Keywords:
Seismic tomography
Apennines
Subduction
Asthenospheric upwelling

A B S T R A C T

According to the most common interpretation, the Apennines developed in Neogene and Quaternary times in the hanging wall of a west directed subduction zone. Seismic tomography is the most powerful tool to investigate large volume of Earth at depth, and it has been extensively applied to shed light on the geometry and shape of the subduction under the Italian peninsula. The various experiments were able to display the slab under the Southern Apennines, but even the most recent tomographic images were non-uniquely interpretable and left open questions about the characteristics of the subduction in the Northern-Central sector of the chain.

We here present the results of an improved inversion experiment focused on the Northern and Central Apennines. The results do not show any pronounced subduction slab and the most evident anomaly is a low velocity body extending down to 100 km depth, located in a relatively small area under the western Tuscany. On the basis of accurate synthetic tests, we assess that, if established, a subduction like geometry should be visible in our tomographic images. We then conclude that no subduction is imaged in the Northern and Central Apennines. We thus interpret this anomaly as an asthenospheric flow.

However, we cannot exclude that our result is due to intrinsic limitations of the methodology. In fact in response to the original question about the capability of local earthquake tomography to settle the matter about subduction, we underline that the absence of deep earthquakes to illuminate the model from below, the existence of seismic gaps in some sectors of the area under study even at shallow depth and the non uniqueness of interpretation of the tomographic images make local tomography unable to give alone definitive information on the deep structure of the Northern and Central Apennines.

1. Introduction

According to the most common interpretation, the Apennines developed in Neogene and Quaternary times in the hanging wall of a west directed subduction zone (Amato et al., 1993; Chiarabba et al., 2005; Lucente et al., 1999; Spakman, 1990). However there are alternative hypotheses that consider the Tyrrhenian area as a passive margin (Lavecchia et al., 2003a); or suppose that the Mediterranean lands are moving apart under expansion, with the Mediterranean on the way to becoming an ocean (Scalera, 2005). In this latter interpretation the high velocity bodies pointed out by some tomographic experiments (Cimini, 1999; Spakman and Wortel, 2004) are considered possible rising of anomalous mantle material, in turn responsible for the building up of the tectono-orogenic phenomena.

The many studies conducted on the Mediterranean area and the improvement in its knowledge that followed the seismic reflection and refraction experiments of the 1990s pointed out the complexity of the Tyrrhenian sector. The introduction of seismic tomography sensibly contributed to the explanation of this complexity introducing details and interpretations on the processes responsible for the current setting. In fact seismic tomography is the most powerful tool to investigate large volumes of Earth. 3-D images of Earth's interior have a large impact on the understanding of the structure and dynamics of the planet.

In this frame, the eastward retreat of the subduction was introduced as the most plausible explanation for the progressive eastward migration of the thrust fronts, the foreland flexure (and consequent shift of the foredeep basins) as well as the extensional processes along the internal Tyrrhenian back-arc basins (e.g., Doglioni et al., 1991, 1999; Faccenna et al., 2003; Malinverno and Ryan, 1986; Patacca et al., 1990; Royden et al., 1987). The absence of a continuous, high velocity body beneath the Apennines has been interpreted by some researchers (Lucente et al., 1999; Wortel and Spakman, 2000)

* Corresponding author.
E-mail address: scafidi@dipteris.unige.it (D. Scafidi).

0040-1951/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2012.06.007

as an evidence of the detachment of the Apenninic slab, started some 8 Ma in the Northern Apennines. According to this view the Apenninic slab is expected to be inactive whether the Ionian lithosphere subducting underneath Calabria is considered to be on the verge of detaching or just detached.

The 2003–2006 RETREAT project (Margheriti et al., 2006) deployed portable seismometers in the northern Apennines to detect the subducting slab and the anisotropy of the mantle deformation around the slab. Plomerova et al. (2006) and Salimbeni et al. (2008) found a pattern in SKS splitting that disagrees with either a simple corner-flow subduction model or active slab retreat. The SKS anisotropy is confirmed with surface-wave scattering by Levin et al. (2007).

In previous studies, our working group has conducted several seismic tomographies with either teleseismic and local data in the search of the geometry, size and extension with depth of the subduction under the Italian peninsula. However, the images resulting from teleseismic data (Solarino et al., 1996) were not conclusive for the Northern Apennines.

A series of attempts using local earthquake data have been then accomplished in the last decade by our working group to complement and possibly add details to the findings from the teleseismic tomography. The most recent study (Scafidi et al., 2009) has actually given details about the shallower sectors but still it has not been able to clearly display a subducting slab. A complete description of the results can be found in the original work, however some synthesis is given later in this study since it serves to distinguish between the limitations introduced by the data by the likely absence of a slab: both factors in fact may converge to the same result in a tomographic experiment.

The resolution power of the Scafidi et al. (2009) tomography, as expected for any local earthquakes 3-D inversion, was mainly limited to the depth of the events under the northern and central Apennines. Most of the seismicity there is in fact confined in the shallow 30 km depth; only very few earthquakes are located deeper (Solarino et al., 2002), however the reliability of results was not high enough to interpret the whole resulting tomographic image. Conversely, in the southern sector of the Italian peninsula, where a well pronounced slab has been displayed and acknowledged, the seismicity reaches 600 km (Chiarabba et al., 2005; Solarino and Cassinis, 2007) and the tomography provides information down to the entire depth of the inversion model (150 km).

Solarino and Cassinis (2007), by comparing DSS interpretation and recent seismic data, propose that the transition between European and Adriatic crusts is smooth and is accompanied by only few deep events which cannot be attributed to a slab geometry. However, the absence of deep seismicity in the northern and central sectors of the Apennines cannot alone be considered an evidence of non-subduction. In fact some authors (Carminati et al., 2002) showed that different rheological behaviors of the continental versus oceanic lithosphere can account for the shallower and subcrustal seismicity below the northern Apennines with respect to deeper and more intense seismicity below the Calabrian arc. In particular, the low seismicity or aseismic behavior of orogenic roots or slabs may in some cases be ascribed to a ductile deformation of quartz–feldspar rich subducting continental lithosphere rather than to the absence of active subduction. Some other authors (Chiarabba et al., 2009) attribute the shallow disappearance of seismicity to the low subduction rate, as inferred by both poor (if any) compressive deformation recorded by the Pleistocene strata from the external northern Apennines (Tozer et al., 2006) and recent GPS evidence (Devoti et al., 2008), and the subduction of only the lowest and hottest 10 km of the Adriatic crust. The subducting lower crust would reach temperatures of 600–700 °C; at such temperatures ductile creeping is expected to overcome friction, justifying the seismicity cutoff.

However, it must be remarked that GPS data have been interpreted in many diverse ways; Serpelloni et al. (2005) report the preponderance of extension at the orogen crest in the Northern Apennines, relative to weak convergence at the Apennines front. D'Agostino et al. (2008) propose a plate-tectonics model for the Apennines in which subduction plays a little role. Finally, Rosenbaum et al. (2008) discusses the possible relation of a disintegrating slab with Tyrrhenian volcanism.

Thus it is evident that it is necessary to determine whether the apparent absence of the slab in the northern Apennines is real or due to other methodological limitations. In order to analyze in more details this apparent discrepancy, a new seismic tomography is presented in this work. A very dense grid, the selection of a smaller area to be investigated (limited to northern and central Italy only) and the addition of new data partly improved the results. The actions undertaken cannot extend the maximum depth of the investigation, which is anyway limited to the deeper events, but at least ensure sufficient quality to the whole volume under study in order to really be able to interpret the model at depth.

The paper is organized in a description of the new experiment, the tests conducted to assess the reliability of results and an interpretation of the resulting model in the light of the geometry and shape of the likely subduction.

2. New local tomography refined in the search of subduction

In a recent study (Scafidi et al., 2009) we described the results of a tomography experiment carried out on a database selected from the International Seismological Center (2009, ISC hereinafter) and inverted using the methodology proposed by Thurber (1993). In that study the limitation imposed by the ray tracer originally included in Thurber's code has been overcome by the introduction of the accurate shooting ray-tracer algorithm proposed by Haslinger (1998), Haslinger et al. (1999) and Virieux and Farra (1991). Such ray-tracing algorithm permits to account for source–receiver distances much greater than the classical bending and pseudo-bending methodologies without introducing large errors. As a consequence, longer ray paths may provide information for deeper layers and ensure a better cross-firing throughout the inverted area. The Scafidi et al. (2009) study was able to show, somewhere with fair detail, many of the features, hypothesized or confirmed by other means, of the deep structure of the Italian peninsula. In particular, the subducting European plate under the Northwestern Alps, the change of vergence with a subducting Adriatic lithosphere in the Eastern Alps, the upwelling of the mantle in the Ligurian Sea and the well defined and deep subducting slab under the Calabrian arc were clearly outlined. These results were in a way validating both data and method and the capability of the approach to image the deeper structure, in particular a well established slab as under the Calabrian arc. However the image of the central-northern Apennines was not clear enough to permit a unique interpretation and remained open to either interpretations, subduction or thrust.

The ambiguous interpretation was the motivation for a new experiment, conducted on a smaller area, achieving in this way a denser inversion grid. The tomographic scheme and the methodology adopted in the present study is similar to that published in Scafidi et al. (2009) but it is based on a more accurate choice of the parameters for the inversion. Moreover, it uses an enhanced database of arrival times (Fig. 1). In particular, the addition of data recorded from 2005 to 2009 accounts for an increase of more than 40,000 P wave and 30,000 S wave arrival times comprised in an area smaller than the previous study. In fact, the complete database of 3698 earthquakes used in this study, now accounts for about 90,000 P wave and 42,000 S wave phases revised by the ISC from 2002 to 2009. On average there are about 35 phases for each event. Moreover, it has to be taken into account that the amount of the seismic stations operating in the Italian peninsula greatly improved in the last five years, as it can be seen in Fig. 2. So there has been an increase in the density and directions of rays crossing the area under study, in addition to