Tectonophysics 510 (2011) 195–206

Contents lists available at ScienceDirect

Tectonophysics

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

Shape and origin of the East-Alpine slab constrained by the ALPASS teleseismic model

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ARTICLE INFO

Article history:
Received 22 March 2011
Received in revised form 30 June 2011
Accepted 3 July 2011
Available online 12 July 2011

Keywords:
Teleseismic tomography
Eastern Alps
Pannonian fragment
Upper mantle structure
Subduction
Extrusion

ABSTRACT

During the last two decades teleseismic studies yielded valuable information on the structure of the upper mantle below the Alpine–Mediterranean area. Subducted oceanic lithosphere forms a broad anomaly resting on but not penetrating the 670 km discontinuity. More shallow slabs imaged below the Alpine arc are interpreted as subducted continental lower lithosphere. Substantial advances in our understanding of past and active tectonic processes have been achieved due to these results. However, important issues like the polarity of subduction under the Eastern Alps and the slab geometry at the transition to the Pannonian realm are still under debate. The ALPASS teleseismic experiment was designed to address these open questions.

Teleseismic waveforms from 80 earthquakes recorded at 75 temporary and 79 permanent stations were collected during 2005 and 2006. From these data, a tomographic image of the upper mantle was generated between 60 km and 500 km depth. Crustal corrections, additional station terms, and ray bending caused by the velocity perturbations were considered. A steeply to vertically dipping "shallow slab" below the Eastern Alps is clearly resolved down to a depth of ~250 km. It is interpreted as European lower lithosphere detached from the crust and subducted during post-collision convergence between Adria and Europe. Below the Pannonian realm low velocities or high mantle temperatures prevail down to ~300 km depth, consistent with the concept of a Pannonian lithospheric fragment, which underwent strike–slip deformation relative to the European plate and extension during the post-collision phase of the Alpine orogeny. Between 350 km and 400 km depth, a "deep slab" extends from below the central Eastern Alps to under the Pannonian realm. It is interpreted as subducted lithosphere of the Alpine Tethys. At greater depth, there is a continuous transition to the high velocity anomaly above the 670 km discontinuity.

1. Introduction

Actual plate tectonic processes can be better understood by imaging the lithosphere and upper mantle using seismic tomography. Downgoing slabs of low temperature oceanic lithosphere and continental lithospheric mantle may be represented by bodies of relatively high seismic velocity, whereas low velocity areas may be related to areas of thinning crust and upwelling asthenosphere, mantle plumes or local mantle convection. In the Alpine–Mediterranean area, the complex history of tectonic movements between Africa and Europe (e.g., Dewey et al., 1973; Moores and Twiss, 1995) left its trace in the upper mantle. The spreading of the North and Central Atlantic Oceans and the closure of the PaleoTethys (~190 Ma) Ocean led to a sequence of rifting, break up of continental blocks, seafloor spreading, subduction of oceanic and continental lithosphere, and re-amalgamation and suturing of micro-plates (e.g., Le Pichon et al., 1988; Stampfli and Kozur, 2006).

In the area that is the target of this study (Fig. 1), the opening and closure of the Meliata and Vardar Oceans in the south and the Alpine Tethys (Piemont–Ligurian Ocean, Penninic Ocean) in the north strongly influenced the development of the Eastern Alps and the adjoining Carpathians, Dinarides and Southern Alps. An early orogenic phase, the Eo-Alpine orogeny, occurred after the subduction of the

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doi:10.1016/j.tecto.2011.07.001

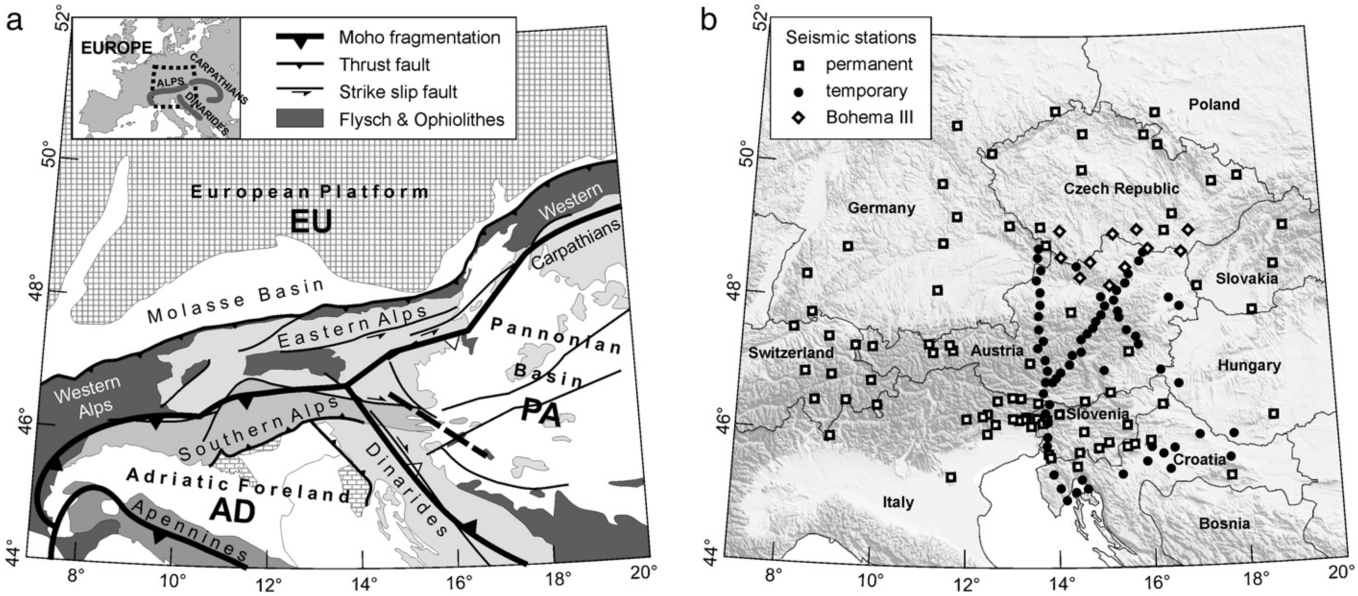

Fig. 1. Tectonic setting of the study area and locations of the seismic network. a) Geological map shows the main tectonic units and major faults; Flysch belts and ophiolites are mapped in dark gray; the Moho fragmentation (after Waldhauser et al., 1998 and Brückl et al., 2010) is plotted by bold lines; triangles indicate thrust polarity. b) Location of temporary ALPASS stations (spheres), seismic observatories (squares), and BOHEMA III stations (diamonds).

Meliata Ocean from 130 to 85 Ma. Seafloor spreading of the Alpine Tethys ended at about 130 Ma and subduction of this ocean was initiated ~80 Ma with Europe representing a passive margin. The Adriatic micro-plate or Adria started to move independently from Africa to the NW, and at ~35 Ma, it collided with Europe (e.g., Schmid et al., 2004). In the Oligocene (35–30 Ma), a slab break off occurred (Wortel and Spakman, 2000) in the central part of the Eastern Alps. During the Miocene, retreat of the remaining Alpine Tethys into the Carpathian embayment led to the development of the Pannonian basin and subsequently the Carpathians (e.g., Royden, 1993). The Apennines and Dinarides (e.g., Doglioni and Carminati, 2002; Horváth et al., 2006; Pamić et al., 2002) formed by subduction of Adriatic continental mantle to the west and the east. Major blocks of the East Alpine region (ALCAPA) extruded laterally to the east into the Carpathian embayment (Decker and Peresson, 1996; Linzer et al., 2002; Ratschbacher et al., 1991a,b) (Fig. 1). These units experienced significant extension, before their final collision with the Paleozoic European platform, which formed the Western Carpathians (Ustaszewski et al., 2008).

The Helenic arc represents the currently most active area related to the continued convergence between Africa and Europe. Global and large scale tomographic models (e.g., Bijwaard et al., 1998; Piromallo and Morelli, 2003; Wortel and Spakman, 2000) show a slab subducting into the upper mantle of the Alpine region and suggest penetration of the 670 km discontinuity. Between the 410 km and 670 km mantle discontinuities, an extensive region of relatively high seismic velocities exists underneath the Pannonian basin and the surrounding Alpine–Carpathian–Dinaric orogens. This zone is interpreted as the remnants of subducted oceanic plates (e.g., Vardar, Meliata, NeoTethys, Alpine Tethys or Piemont and Ligurian Ocean) and will be referred to as the "slab graveyard". Our use of this term should not be confused with cold subducted lithosphere, which is interpreted to have sunk to form a "slab graveyard" at the core–mantle boundary (e.g., Tackley, in press). Ps receiver functions derived from observatory data in central and eastern Europe yield high travel time differences between the 410 km and 670 km arrival and give additional support for the existence of the slab graveyard (Geissler et al., 2008). Shallower slabs are resolved for instance underneath the Alpine arc, the Apennines and the Dinarides. Paleogeographic reconstructions have shown that there is a balance between the volume of all these high velocity bodies and the volume of subducted dense and cold lithosphere (Handy et al., 2010).

A high-resolution tomographic image of the Alpine slab, extending from the Moho discontinuity to 400 km depth was provided by Lippitsch et al. (2003). The southward oriented dip of the slab in the Western Alps showed European lower lithosphere subducting underneath Adria. The lateral continuity of the slab appears reduced to the east, and further to the east, a pronounced north-dipping (~60°) slab was imaged. These results led to the interpretation of a subduction polarity change from west to east under the Eastern Alps. These findings have greatly influenced tectonic interpretations of the region (e.g., Horváth et al., 2006; Kissling et al., 2006; Schmid et al., 2004, 2008; Ustaszewski et al., 2008). However, more recent results are in conflict with these tectonic interpretations and favor the more "classical" interpretation of subduction of the European plate (EU) under the Adriatic plate (AD) along the whole Alpine arc and subduction of the Adriatic plate only under the Dinarides and Apennines (Doglioni and Carminati, 2002). Arguments for the more "classical" interpretation include the interpretation of the crustal structure along the TRANSALP transect by Lammerer and Weger (2008) and the Moho fragmentation and plate kinematics at the bifurcation of subduction via a triple junction between the European, Pannonian (PA), Adriatic lithospheric blocks (Brückl et al., 2010). The fragmentation of the Moho and the uppermost mantle into AD, EU, and PA blocks is superimposed on Fig. 1. The pattern of the fragmentation and the polarity of thrusting follow Brückl et al. (2010) in the Eastern Alps and northern Dinarides. In the Western Alps and Apennines, the boundaries between the European, Adriatic, and Ligurian plates follow the Moho map of Waldhauser et al. (1998). Šumanovac (2010) employed gravimetric modeling to delineate a significant Moho jump under the Dinarides. This result was implemented to extend the Moho fragmentation between EU and PA further to the south (Fig. 1a).

2. The ALPASS project

The ALPASS (Alpine Lithosphere and Upper Mantle PASsive Seismic Monitoring; http://info.tuwien.ac.at/geophysik/alpass.htm) project is an international effort to supply new data in the Eastern Alps and their neighboring tectonic provinces. This project has been a