Journal of Geodynamics 82 (2014) 69–77

Contents lists available at ScienceDirect

Journal of Geodynamics

journal homepage: http://www.elsevier.com/locate/jog

Seismic signature of the Alpine indentation, evidence from the Eastern Alps

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ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form 11 July 2014
Accepted 21 July 2014
Available online 1 August 2014

Keywords:
Eastern Alps
Receiver functions
Moho
Anisotropy
Lower crust
Upper mantle

ABSTRACT

The type of collision between the European and the Adriatic plates in the easternmost Alps is one of the most interesting questions regarding the Alpine evolution. Tectonic processes such as compression, escape and uplift are interconnected and shape this area. We can understand these ongoing processes better, if we look for signs of the deformation within the Earth's deep crust of the region. By collecting records from permanent and temporary seismic networks, we assemble a receiver function dataset, and analyze it with the aim of giving new insights on the structure of the lower crust and of the shallow portion of the upper mantle, which are inaccessible to direct observation. Imaging is accomplished by performing common conversion depth stacks along three profiles that crosscut the Eastern Alpine orogen, and allow isolating features consistently persistent in the area. The study shows a moderately flat Moho underlying a seismically anisotropic middle-lower crust from the Southern Alps to the Austroalpine nappes. The spatial progression of anisotropic axes reflects the orientation of the relative motion and of the stress field detected at the surface. These observations suggest that distributed deformation is due to the effect of the Alpine indentation. In the shallow upper mantle right below the Moho interface, a further anisotropic layer is recognized, extended from the Bohemian Massif to the Northern Calcareous Alps.

1. Introduction

The boundary between the African and Eurasian plates in the Mediterranean area consists of a broad zone of deformation, due to the convergence between the two plates (DeMets et al., 1990, 1994) (Fig. 1, inset).

Since late Cretaceous the Adriatic microplate, acting as a promontory of Africa, has deeply indented Europe, resulting in yielding the Alpine orogeny (Platt et al., 1989). Within the convergence of the large (Europe and Africa) plates, the Adriatic microplate moves independently, and rotates counterclockwise with respect to stable Europe, controlling the strain pattern along its boundaries (Nocquet and Calais, 2004). The CCW rotation of Adria leads to different deformation regimes along the Alpine arc, such as: compression in the Eastern Alps, dextral shear in the Central Alps and transtension or very slow deformation in the western Alps. The shape of the eastern Alpine chain is considered to be the consequence of the tectonic activity in the Tertiary, during which contemporaneous shortening perpendicular to, and extension parallel to the orogen occurred (e.g., Ratschbacher et al., 1989).

At the surface, post-collisional shortening between the Adriatic and European plates was compensated by frontal thrusting along the frontal Alpine thrust (AF) onto the Molasse foreland basin and by contemporaneous lateral wedging of the upper plate. The main structures that bound the eastward escaping wedges are to the North the sinistral Salzach–Ennstal–Mariazell–Puchberg (SEMP) fault system, and to the South the dextral Periadriatic line (PAL) (Ratschbacher et al., 1991a,b). The SEMP line has been recognized as a single continuous major strike-slip zone (Linzer et al., 2002), separating the North Calcareous Alps (NCA) from the eastward escaping Australpine units.

Most of the knowledge on the actual structure of the Alpine lithosphere comes from traditional body and surface wave seismic imaging which has shown high seismic velocities in the crust and upper mantle below the Alps (e.g. Lippitsch et al., 2003; Piromallo and Morelli, 2003; Diehl et al., 2009; Mitterbauer et al., 2011; Giacomuzzi et al., 2011). Deep high-velocity anomalies have been interpreted as evidence for subducted slabs, and shallower anomalies as thickened lower crust (e.g. Wortel and Spakman, 1993; Waldhauser et al., 1998; Lippitsch et al., 2003; Wagner et al., 2012). Tomographic images of the Alps have been limited to inversions for

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http://dx.doi.org/10.1016/j.jog.2014.07.005

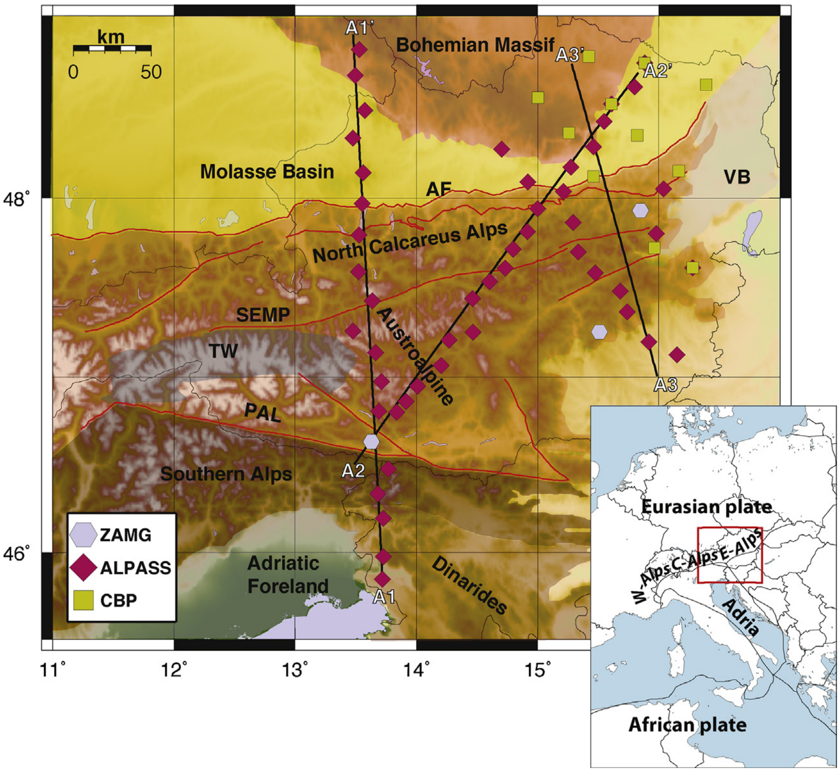

Fig. 1. Map of the Eastern Alps with station locations. Colors are related to different networks. Red lines draw the path of major tectonic lines in the vicinity of the stations (AF = frontal Alpine thrust, PAL = Periadriatic Line, SEMP = Salzach–Ennstal–Mariazell–Puchberg fault system). Names for the different tectonic domains are written on shaded areas (TW = Tauern Window, VB = Vienna Basin). Inset shows the location of the study area in the Eastern Alps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

isotropic velocity structure. Anisotropic properties of the media are complementary to isotropic velocities, and provide constraints on the geodynamics of the region. Studies on seismic anisotropy in the Alps have been focusing on the larger-scale features attributed to mantle deformation of the entire Alpine region (Barruol et al., 2011; Bokelmann et al., 2013), while seismic anisotropy in the upper layers of the lithosphere has been less explored. Besides the study of Fry et al. (2010) who mapped seismic anisotropy using surface waves for the Western and Central Alps, no other study on anisotropy in the Alpine crust has been carried out so far. Zhu and Tromp (2013) describe the anisotropic properties of the lithosphere beneath Europe, and retrieve two crucial layers in which anisotropy concentrates, i.e. the lower crust and the upper mantle. The anisotropy has been interpreted as resulting from both frozen (e.g. Deschamps et al., 2008) and present sources, related to past tectonics or active crustal deformation and stress field (e.g. Crampin and Lovell, 1991). In response to strain, crustal (e.g., amphibole) and mantle (e.g., olivine) minerals can develop some specific fabrics that result in seismic anisotropy.

In the mantle, anisotropy is generally attributed to lattice-preferred orientation (LPO) of olivine minerals, and is interpreted as an indicator of strain resulting from mantle flow (e.g., Savage, 1999; Mainprice et al., 2005).

In the middle and lower crust anisotropy is a particularly important parameter for metamorphic rocks such as gneiss, amphibolite, and mica schist, in which anisotropic grade (8.3%, 9.3%, and 13.0%, respectively) is even higher than the average anisotropy in mantle dunite (8%) (Christensen and Mooney, 1995).

Tectonic processes can cause mechanical shearing, crystal reorientation, and/or re-crystallization during metamorphism that might produce textural fabrics, which are seismically anisotropic. Therefore orientation and amount of anisotropy may serve as proxies for crustal deformation (e.g. Okaya et al., 2004). Besides LPO, seismic anisotropy can be mimicked by heterogeneities at length scales smaller than the seismic waves wavelength (e.g. Hake, 1993; Fichtner et al., 2013); shape-preferred orientation (SPO) of fluid inclusions or cracks (Babuška and Cara, 1991) cause shear-wave birefringence. Finely-stratified media of different stiffness (Backus, 1962), or subhorizontal thin layers most probably have their primary origin in lithologic and metamorphic layering, including that caused by igneous intrusions and shear zones (Mooney and Meissner, 1992). These layers may often have varying amount of seismic anisotropy resulting from ductile strain.

In order to unravel the anisotropic properties of the Alpine crust and shallow upper mantle, the teleseismic receiver functions (RFs) methodology, able to detect the effect of anisotropic material at the desired scale, has been applied. The interpretation includes both radial (R) and transverse (T) components. The effects of anisotropy on the RFs dataset were illustrated in more than one theoretical study (e.g. Eckhardt and Rabbel, 2011; Nagaya et al., 2008; Levin and Park, 1998), showing the strong backazimuthal dependence of RFs on the 3D characteristics of the traversed media. This technique was applied in several places around the world with the aim of creating realistic velocity models beneath single stations or wide areas (e.g. Savage, 1998, 1999; Ozacar and Zandt, 2004; Liu and Niu, 2012; Porter et al., 2011). The use of teleseismic RFs has the advantage of not being affected by heterogeneous depth distribution of local earthquakes (as e.g. Piccinini et al., 2006; Pastori et al., 2009), since teleseismic rays sample the entire crust beneath the stations. This technique is applied for the first time in this area with the aim of defining the depth of anisotropic layers and the spatial orientation of the anisotropy symmetry axes.