Lithospheric Structure and Tectonics of the Eastern Alps – Evidence from New Seismic Data

Ewald Brückl

Vienna University of Technology
Austria

1. Introduction

During the last two decades, seismic campaigns carried out in the Eastern Alps and the surrounding geological units contributed substantially to our knowledge and understanding of the deep lithospheric structure and tectonics in this area. The main topics addressed by these efforts concern the collision between tectonic plates and fragments of the Adriatic realm with the European platform and the many geodynamic reactions induced by this large-scale process. The individual campaigns yielded valuable geophysical data in the form of cross-sections and 3D models of the lithosphere and upper mantle, as well as geologic and tectonic interpretations. However, the diversity of the geologic structures and tectonic processes in the wider Alpine area still pose many unanswered questions. This chapter provides an overview of the main results achieved by the seismic campaigns and presents a current image of the crust and upper mantle. Generalized geological interpretations will be given and tectonic processes inferred on the basis of the imaged structures. Most of the interpretational models will refer to collision and post-collision times and today's tectonics will be emphasized. Although this study considers information from several disciplines the author is aware that it is a limited projection of the comprehensive geology and tectonics in the area.

2. Geological overview

The study of the lithospheric structure and tectonics of the Eastern Alps calls for the consideration of the surrounding geological units. These units are the Western Alps, the European platform and the Molasse Basin in the North, the Carpathians and the Pannonian basin in the east, and the Dinarides and Adriatic foreland in the south. A geological map, generalized after Schmid et al. (2004), is shown in Fig. 1.

The European platform and its most southern promontory, the Bohemian Massif, comprise crystalline rocks which underwent the Caledonian or Variscian orogeny. The northern rim of the Alps and Carpathians is composed of a Flysch belt of Helvetic and Penninic provenance. The main body of the Eastern Alps consists of the Austro-Alpine units. Ocean-derived (Penninic Ocean, Alpine Tethys) metamorphic units and even European basement is exhumed in tectonic windows (Engadin, Tauern, Rechnitz window) (Oberhauser, 1980). The Southern Alps join the Eastern Alps at the Periadriatic or Insubric line (PAL). The

peninsula Istria resembles the main part of the tectonically little-disturbed Adriatic foreland (e.g., Poljak et al., 2000). The Dinarides are located south-east of the Southern Alps (e.g., Doglioni, 1987) and represent a bifurcation of the whole Alpine orogenic system. The Molasse basin in the north and the Adriatic and Venetian plain in the south are foreland basins of the Alpine orogen and are proof of the north-south oriented compression regime. The Styrian basin and especially the Pannonian basin resemble large extensional structures. The Vienna basin is a pull-apart basin within the north-east trending Vienna transfer fault system. The thickness of the Neogene sediments in the basins exceeds 5 km in some places according to the results of hydrocarbon exploration.

bf - Brenner fault, *bt* - Balaton fault, *ct* - Cicarija fault, *gl* - Giudicarie line, *id* - Idria fault, *in* - Inntal fault, *kf* - Katschberg fault, *lf* - Lavant fault, *mf* - Malta fault, *mhz* - Mid Hungarian fault system, *mm* - Muhr-Mürz fault, *nat* - Northern floor thrust of the Eastern Alps, *pal* - Periadriatic line, *sat* - South alpine thrust fault, *semp* - Salzach-Ennstal-Mariazell-Puchberg fault, *sf* - Sava fault, *smf* - southern marginal fault of the Pannonian basin, *tl* - Tonale line, *vf* - Vienna transfer fault, TW - Tauern window, EW - Engadin window, RW - Rechnitz window, TESZ - Transeuropean suture zone
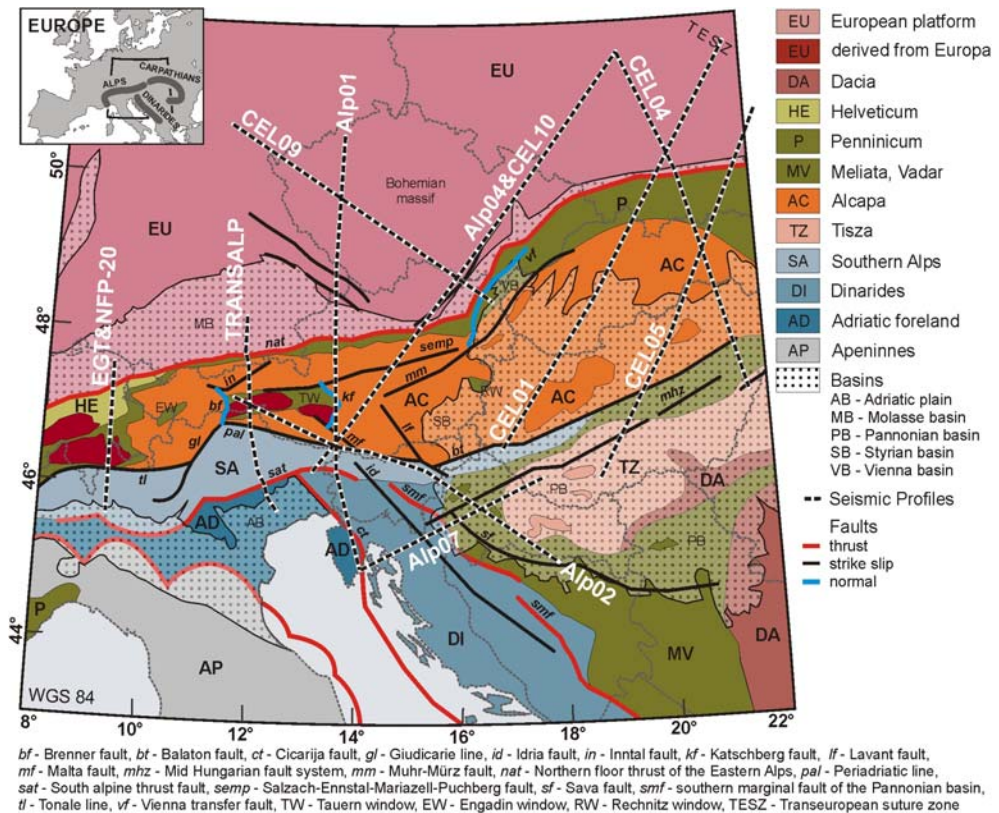
Fig. 1. Geological map

Main thrust faults are the Northern floor thrust of the Eastern Alps and the South Alpine thrust fault, as well as the Cicarija fault at the south-western front of the Dinarides (e.g., Oberhauser, 1980; Castellarin and Cantelli, 2000; Vrabec and Fodor, 2006). Major sinistral strike-slip faults within the Austro-Alpine units are the Inntal, SEMP (Salzach-Ennstal-Mariazell-Puchberg), and Mur-Mürz faults. Conjugate dextral strike-slip faults are the Möll and Lavant faults. These faults continue to the south-east into the Idria and Sava faults. The Brenner and Katschberg normal faults delimit the Tauern window in the west and east.

Right-lateral movements of about 100 km are reported for the PAL since the Oligocene (Mancktelow et al., 2001; Vrabec and Fodor, 2006). To the east, the PAL transits into the Mid Hungarian fault zone (MHZ), which separates the ALCAPA and TISZA units of the Pannonian basin (e.g., Tomljenović and Csontos, 2001; Horvath, 2006).

The main tectonic processes which built up the Alpine orogenic system started in Early and Mid-Jurassic times (~190 Ma) and are strongly related to the spreading history of the Northern and Central Atlantic. At that time, closure of the Paleotethys by subduction under the Eurasian megaunit was already completed and the Neotethys fully developed. Smaller ocean basins existed in the south-east of ALCAPA (e.g., Stampfli & Kozur, 2006; Le Pichon et al., 1988). In the north-west, rifting initiated the development of the Ligurian and Piemont branches of the Alpine Tethys. The displacement of Africa relative to the European platform led to a complex sequence of rifting, break-up of continental blocks, seafloor spreading, subduction of oceanic and continental lithosphere, and re-amalgamation and suturing of micro-plates. Considering the Eastern Alps and the adjoining Carpathians, Dinarides and Southern Alps, the opening and closure of the Meliata and Vardar oceans in the south and the Alpine Tethys in the north strongly influenced the development of these mountain chains. An early orogenic phase, the Eoalpine orogeny, occurred after the subduction of the Meliata ocean, about 130 – 85 Ma ago. Seafloor spreading of the Alpine Tethys ended about 130 Ma ago and subduction of this ocean initiated ~80 Ma with Europe as the passive margin. At the same time, the Adriatic micro-plate started to move more independently from Africa to the north-west (e.g., Handy et al., 2010).

After subduction of the Alpine Tethys and thrusting of the Penninic Flysch units during the Eocene, ~50 Ma ago (Decker and Peresson, 1996), the collision between Europe and Adria occurred ~35 Ma ago. This process induced far-reaching over-thrusting, north-vergent folding, and stacking of Austro-Alpine nappes to the north, the passive European continental margin. Slab break off (Davies and Blanckenburg, 1995; Wortel and Spakman, 2000) in the central part of the Eastern Alps was initiated in the Oligocene (35 – 30 Ma). Subduction of Adriatic continental mantle to the southwest formed the Apennines. Continued indentation of the Adriatic microplate to the north caused back-thrusting in the Southern Alps and the Dinarides (Castellarin and Cantelli, 2000; Pamić et al., 2002). Post-collision shortening of the orogeny lasted up to the late Miocene (Decker and Peresson, 1996, Ortner et al., 2006). Continuing convergence also left its traces in the central crystalline core including the Tauern Window (Lammerer et al., 2008) and the south-vergent thrust belt of the Southern Alps (Doglioni, 1987; Schönborn, 1999).

During the Miocene, the closure of the remaining ocean in the area of the Carpathian embayment led to the development of the Pannonian Basin and finally the Carpathians (e.g., Royden, 1993). Due to continued indentation of the Adriatic plate in combination with gravitational collapse directed to the unconstrained margin represented by the Pannonian basin, major blocks of the Eastern Alps extruded laterally to the east (Ratschbacher et al., 1991; Linzer et al., 2002). These processes enabled exhumation of ophiolites and even European crystalline basement below oceanic deposits in the Engadin, Tauern, and Rechnitz window (Fügenschuh et al., 1997; Rosenberg et al., 2004). Current tectonic activity due to continuing convergence between Africa and Europe has shifted southward to the subduction zones of the Calabrian and Hellenic arcs. However, the tectonic processes in the Eastern Alps that began in the Miocene are still at work, but diminishing.

3. Seismic profiles through the crust

The exploration of the lithosphere of the Eastern Alps and the surrounding area by WAR/R (wide angle reflection/refraction) experiments started around the Eschenlohe quarry, southern Germany, about 50 years ago (Giese and Prodehl, 1976). The Alpine longitudinal profile (ALP'75) extended along the axis of the Western and Eastern Alps to the Pannonian basin (e.g., Yan and Mechie, 1989; Scarascia and Cassinis, 1997). WAR/R as well as steep angle reflection profiles were also measured in the Bohemian Massif, the Pannonian Basin, and the Dinarides (e.g., Beránek and Zátopek, 1981; Posgay et al., 1981; Joksović and Andrić, 1983). The EGT& NFP-20 traverse provided a detailed crustal image along an approximately north-south oriented profile near the western border of the Eastern Alps. WAR/R data and near-vertical reflection data of the EGT and NFP-20 projects (Valasek et al., 1991; Ye et al., 1995; Pfiffner et al., 1997; Kissling et al., 2006) were combined. TRANSALP is a seismic traverse over the central part of the Eastern Alps from Munich to Venice (e.g., Gebrande et al., 2006 and references therein). The main activity concentrated on steep angle, high resolution reflection seismic profiling. Wide angle reflection and refraction tomography (Bleibinhaus et al., 2006), receiver functions (Kummerov et al., 2004), and teleseismic tomography (Lippitsch et al., 2003) were integrated into the transect. Gravimetric studies supplemented the seismic transect (Ebbing et al., 2006; Zanolla et al., 2006). In 2000 and 2002 the large WAR/R experiments CELEBRATION 2000 and ALP 2002 covered an area from the European Craton in the north-east to the Adriatic foreland in the south-west (Guterch et al., 2003a, 2003b; Brückl et al., 2003). During each deployment, about 1000 receivers were arranged on a network of seismic profiles and each shot was recorded on all profiles, thus realizing a 3D data acquisition. The reflection profiles T2 in the Western Carpathians (Tomek, 1993) and NESTMK (Graßl et al., 2004) near the eastern border of the Eastern Alps yielded valuable data about the crustal structures at the transition of the Bohemian Massif and the Eastern Alps to the Pannonian basin.

For this study 10 profiles were selected from the aforementioned projects and are presented in a generalized style (Fig. 2, for location see Fig. 1). The most important structures are the Moho discontinuity, suture zones within crust and upper mantle, accretion wedges, and decollements. The extent of major tectonic units and the tectonic style of collision, extension and transfer/transform zones are also of major interest.

The cross-section of the EGT&NFP-20 traverse is based on Valasek et al. (1991), Ye et al. (1995), Pfiffner et al. (1997), and Kissling et al. (2006). The WAR/R data reveal the P-wave velocity structure of the crust, Moho depth, and Pn-velocity below the Moho. The near-vertical reflection data allow for the delineation of the Helvetic and Penninic nappes and the basal decollement, a reflective European lower crust and the Moho boundary. Stacking of the wide angle PmP reflections gives further support for the Moho boundary. The geological/tectonic interpretation of Schmid et al. (2004) is adopted herein. Structures of particular interest for this study concern the distinct jump of the Moho boundary from Europe to Adria, the indenting Adriatic lower crust, the Helevetic and Penninic nappes overthrusted to the north, and the seismic signature of back-thrusting in the Southern Alps.

The TRANSALP profile is based on the seismic data of Lüschen et al. (2006), Kummerov et al. (2004), and the interpretations of Castellarin et al. (2006) and Lammerer et al. (2008). The East-Alpine nappes, which overthrusted Flysch and Molasse to the north, are well-imaged down to a depth of 15 km. In the Southern Alps, thrust faults and nappe decollements reach down to 20 km.
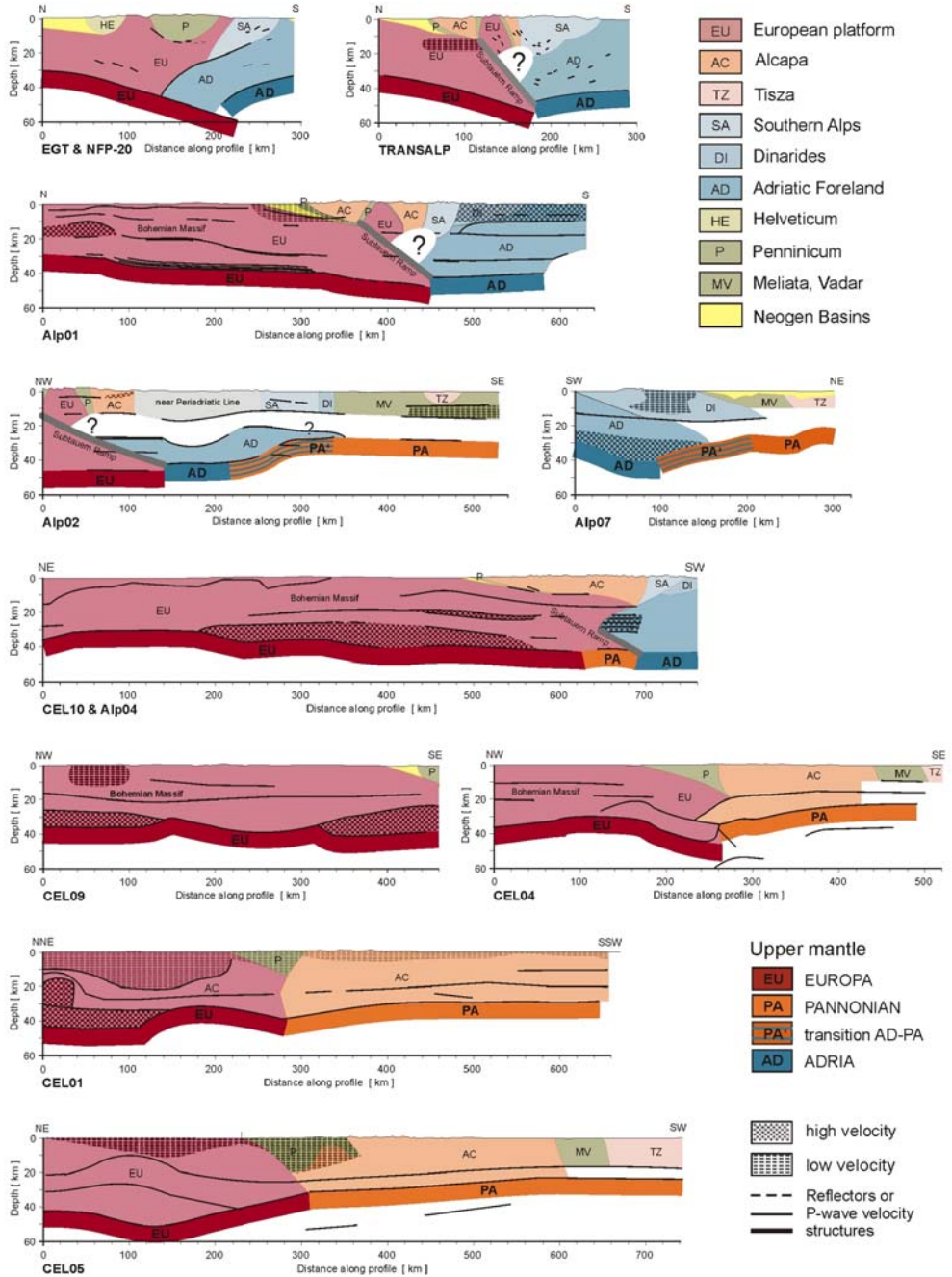
Fig. 2. Seismic profiles

The crystalline European basement below the East-Alpine nappes shows extensional structures which date back to the spreading of the Alpine Tethys. Tomography revealed a low-velocity zone below the Eastern Alps thrust belt (Bleibinhaus and Gebrande, 2006). The Periadriatic line is not uniquely imaged.

The Subtauern ramp is a crustal scale fault over which the Tauern window was exhumed by thrusting and folding. A reflective Adriatic lower crust indicates thickening. The Moho boundary is constrained by steep and wide angle reflections and by receiver functions (Kummerov et al., 2004) which indicate an upward jump from the European to the Adriatic Moho.

Alp01 (Brückl et al., 2007) extends from the Bohemian Massif to the Adriatic foreland (Istria). As a WAR/R profile, Alp01 cannot compete with TRANSALP with regard to resolution. However, the topography of the Moho and the velocity structure of the crust supplied sufficient constraints to transfer the tectonic style of the collision between Europe and Adria (especially the Subtauern ramp) from TRANSALP to Alp01. The shape of the gneiss core of the Tauern window is based on the "lateral extrusion model" proposed for the TRANSALP profile (TRANSALP Working Group, 2002; Castellarin et al., 2006). Clear evidence is also given for mid-, or lower Adriatic crustal thickening and a little-deformed Adriatic foreland.

Alp02 (Brückl et al., 2007) starts at the western end of the Tauern window and extends parallel to the Periadriatic line into the Pannonian basin and further south-east to the TISZA unit. Like Alp01, the interpretation in the area of the Tauern window follows TRANSALP. The Moho is fragmented into Europe (EU), Adria (AD) and the newly interpreted Pannonian fragment (PA), which corresponds to the thin Pannonian crust. Elastic plate modelling, but also the results from Alp07 indicate a transition zone between AD and PA, designated PA'. Most probably, lower Adriatic crust thrusts widely over PA' mantle. There are too few constraints to correlate mid-crustal layers with the geological units. Alp07 (Šumanovac et al., 2009; Šumanovac, 2010) crosses the transition from the Adriatic Sea over the Dinarides to the Pannonian basin at the latitude of Istria. Similar to Alp02, AD, PA', and PA mantle are discerned. Adriatic lower crust, identified by high velocities, thrusts over PA' mantle under the Dinarides. In the upper crust, an extended lower velocity zone exists above the AD-PA' boundary. Again, too few constraints exist for a geological correlation of the mid-crust.

CEL10&Alp04 (Hrubkova & Sroda, 2008; Grad et al., 2009) sample European crust under the Bohemian Massif. High velocity lower crust extends more than 300 km along this profile. This structure was also found on profile CEL09 (Hrubcova et al., 2005). On CEL10&Alp04 the thickness of the Austro-Alpine nappes overthrusting Flysch, Molasse und European basement is constrained by a distinct reflector at ~10 km depth. In the south, the profile just touches the PA fragment at Moho level and finally reaches Adriatic crust and mantle. A significant indenter of Adriatic middle crust into the European crust is marked by a stack of strong reflections.

The profiles CEL01, CEL04 (Sroda et al., 2006), and CEL05 (Grad et al., 2006) cross over the Western Carpathians from the European platform to the Pannonian basin. Near surface low velocity zones mark basins in the Paleozoikum of the European plate, the Flysch trough and the Pannonian basin. CEL04 allows for a clear location of the boundary between EU and PA Moho and upper mantle, approximately below the Pieniny clippen belt at the southern border of the Flysch belt (Outer Carpathians). On CEL01 and CEL05, a wide indentation of PA mantle under EU crust into the European domain was interpreted. In this study the

boundary between EU and PA is reinterpreted according to CEL04. The older reflection profile T2 (Tomek, 1993) gives further support for this interpretation. The thinning of EU crust on CEL05 from the EU platform to the contact with the thin PA crust may postdate to the time when EU was the passive margin of the ocean in the Carpathian embayment. ALCAPA lithosphere reached this margin after a considerable extensional phase. One could imagine that the collision was "soft", with little indentation.

4. Moho topography and plate boundaries

Several Moho maps have been generated which cover parts of the Alps (e.g. Waldhauser et al. 1998), continents (e.g., Desez and Ziegler, 2001) or even the whole globe (e.g., Mooney et al., 1998). The interpretation of the Moho structure and topography in a plate tectonic context is a promising task. Destructive plate boundaries can be identified by offsets of an otherwise smooth Moho boundary derived from controlled source seismic data (Waldhauser et al., 1998; Abramovitz and Thybo, 2000; Kissling et al., 2006; Brückl et al., 2007); natural source seismic methods like receiver functions and tomographic inversion also have the potential to clearly resolve destructive Moho boundaries (e.g., Kummerow et al., 2004; Di Stefano et al., 2009). Continental transform or transfer faults may exist without significant offsets of the Moho boundary (Weber et al., 2009; 2005; Thybo et al., 2003; Zhao et al., 2001).

Waldhauser et al., (1998) generated a Moho-map for the Western Alps on the basis of the available seismic data. They approximated the Moho boundary to the data values by smooth surfaces, considering data errors and inferred plate boundaries and allowed for Moho jumps, when otherwise only a rough surface could approximate the depth data. By this procedure, plate boundaries between Europe and Adria and Adria and Liguria were derived. The inferred Moho jumps indicate European upper mantle thrusting under Adriatic upper mantle and Adriatic upper mantle thrusting under Ligurian upper mantle.

Stacking of refracted and reflected P-waves, recorded during the CELEBRATION 2000 and ALP 2002 experiments, in combination with tomographic inversions were applied to generate a Moho-map and a P-wave velocity model of the East Alpine crust (Behm et al., 2007). These data on Moho depth were also integrated into the European Moho-map of Grad et al. (2008). For further considerations, the Moho-map by Grad et al. (2009) is used together with the original data of Behm et al. (2007). Depth and offset of the Moho at the plate boundaries determined by Waldhauser et al. (1998) were integrated. The Moho fragmentation between Adria and Liguria was extended to south east using tomographic data from Di Stefano et al. (2009). In the Eastern Alps, seismic profiles and the Moho-map indicate a fragmentation of the lithosphere into three blocks, the European plate, the Adriatic microplate, and a newly interpreted Pannonian fragment (Brückl et al., 2007; Behm et al., 2007). Brückl et al. (2010) applied 2D elastic plate modelling of the lithosphere to decide if a continuous plate is an appropriate model or if the introduction of a plate boundary yields a better fit. Plate boundaries (or broken plates) were inferred by the conditions that no bending moment is transferred and only vertical force couples act between the two plates at the boundary. The criteria imposed by elastic plate modelling to determine plate boundaries have some similarity to the curvature criteria Waldhauser et al. (1998) introduced. Both methods postulate the smoothness of the Moho discontinuity within one lithopsheric block or plate.
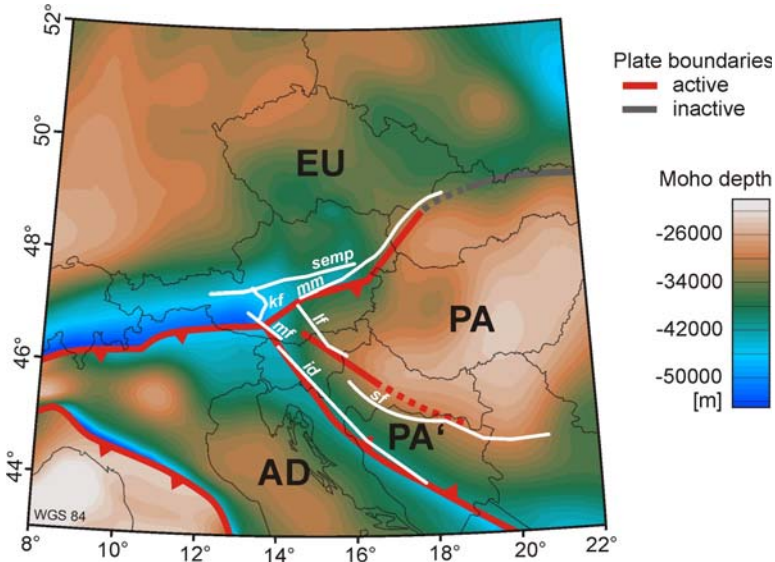
Fig. 3. Moho-map with Moho fragmentation and related fault system

The combined Moho-map of Grad et al. (2009) and Behm et al. (2007), together with the inferred Moho fragmentation is shown in Fig. 3. The Moho is fragmented into EU (European plate), AD (Adriatic microplate), Ligurian plate (LG), and PA (Pannonian fragment). As described before, the profiles Alp02 (Brückl et al., 2007) and Alp07 (Šumanovac, 2009), but also the elastic plate modelling (Brückl et al., 2010) indicate the existence of a transition zone from AD to PA, termed PA'. The general configuration of plates and the polarity of underthrusting almost correspond to the scheme by Doglioni and Carminati (2002). The difference is the plate boundary between EU and PA, which was beyond the scope of their paper. From the Western Alps to the triple junction (AD-EU-PA), a significant upward step from EU to AD is revealed by profiles EGT&NFP-20 and TRANSALP. On Alp01 a step with the same polarity but smaller extent was found. From the triple junction to the Rechnitz window in the east-north-east, a positive Moho step still exists from EU to PA and EU underthrusting PA is probable. The reflection profile NESTMK (Graßl, 2004) gives further support for this interpretation. Strike-slip or transpression may prevail. East of the Rechnitz window, in the area of the Vienna basin, transtension may dominate. The EU-PA boundary in the Western Carpathians does not exhibit a step and has the character of a "soft" collision between ALCAPA and the European platform (see profiles CEL01, CEL04, CEL05). The northern partition of AD-PA' represents a second order boundary with no significant jump, but a discontinuous change of inclination. In the southern partition, gravity modelling (Šumanovac et al., 2010) reveals a positive jump from AD to PA'. Force couples and the jump in the southern part indicate AD underthrusting PA'. PA'-PA may delimit a transition zone from the Dinaric orogen to the shallow PA crust.

5. 3D seismic models of the crust and implementation of gravity data

The CELEBRATION 2000 and ALP 2002 seismic experiments realized receiver deployments along a net of seismic lines and shots were simultaneously recorded at all receivers.

Therefore about 80% of the data were cross-line traces. Stacking techniques in combination with manually picked P- and S-wave phases and tomographic methods were used to generate 3D P- and S-wave velocity models of the crust and to calculate Poisson's ratio (Behm et al., 2007; Behm, 2009). Data from SUDETES 2003 (Grad et al., 2003) were also implemented for the generation of the S-wave model. These models have an almost complete coverage down to 10 km depth. The maximum penetration depth is about 30 km and is restricted mainly to the Bohemian Massif and the wider area of the Vienna basin.

Gravity studies have a long history within the scope of exploration of the deep crustal structure of the Eastern Alps (e.g., Meurers et al., 1987, Lillie et al., 1994). The seismologic explorations during the TRANSALP project were also accompanied by the compilation of latest gravity data in that region (Zanolla et al., 2006), gravimetric modelling and studies about isostasy (e.g., Ebbing et al., 2006). Studies on the integration of gravity data and the seismic models derived from the CELEBRATION 2000 and ALP 2002 data were carried out by Brückl et al. (2006) and Simeoni and Brückl (2009). Accurate Bouguer gravity data has been provided by Bielik et al. (2006) and Meurers and Ruess (2007) for the Alpine-Carpathian area. Areas not covered by this data have been supplemented by the regional Bouguer gravity data of the West-East Europe Project (http:/www.getech.com). A density model of the upper crust was derived from the seismic model of Behm et al. (2007) using the Vp – density relation of Christensen and Mooney (1995). For the sedimentary basins existing density-depth relations were used (for references see Simeoni and Brückl, 2009). The gravity effects of the upper crust (UC) and the Moho (M) were calculated and subtracted from the Bouguer anomaly (BA).

Depth slices through the 3D Vp-model of the crust (Behm, 2007) and gravity maps are compiled in Fig. 4. Fig. 4a,b,c show the deviation of the Vp-velocities from the average values for orogens according to Christensen and Mooney (1995) at depths of 5 km, 10 km, and 27.5 km. The original Bouguer gravity map (BA) is shown in Fig. 4d, using the same colour code as for the Moho depth map (Fig. 3). Fig. 4e shows BA-M, which is the Bouguer anomaly (BA) reduced by the gravity effect of the Moho. Fig. 4f shows a reduced Bouguer gravity BA-M-UC, where the gravity effect of the Moho (M) as well as the gravity effect of the upper crust (UC) has been subtracted. For Figs. 4e and 4f a similar colour code as for the Vp-depth slices (Fig 4a,b,c) was used in order to visually enhance spatial correlations between Vp velocities and the reduced gravity anomalies BA-M and BA-M-UC.

The Vp velocity at 5 km depth well reflects the tertiary basins (Molasse, Vienna, and western part of the Pannonian basin) as low velocity regions, even the depth of the basins is less than 5 km. The metamorphic eastern part of the Moldanubian, Bohemian Massif, and Adriatic foreland exposed at the peninsula Istria are high velocity zones. A new velocity structure correlates roughly with the west-east striking Greywacke zone, latitude ~ 47°. At their eastern end, these structures bend to the south. The high and low velocity regions at 5 km depth can again be identified at 10 km depth. The low Vp extend in the area of the PA'-PA Moho fragmentation. Vp south of the MHZ shows an increase, which is the only indication of a difference in geophysical data presented in this study between ALCAPA and TISZA. At the depth of 27.5 km the high velocity zone in the Bohemian Massif is still visible. However, while at the higher levels the velocity decreases significantly from the Bohemian Massif to the Vienna basin and further east, at the lower crust levels, the velocity increases toward the Pannonian basin with a maximum around the north-east striking Moho fragmentation between EU and PA. All velocity structures identified in the 3D model can also be seen in the 2D profiles (Fig. 2). An exception is the west-east striking high velocity zone along the Greywacke zone, which is not resolved by the Alp01 and CEL10&Alp04.
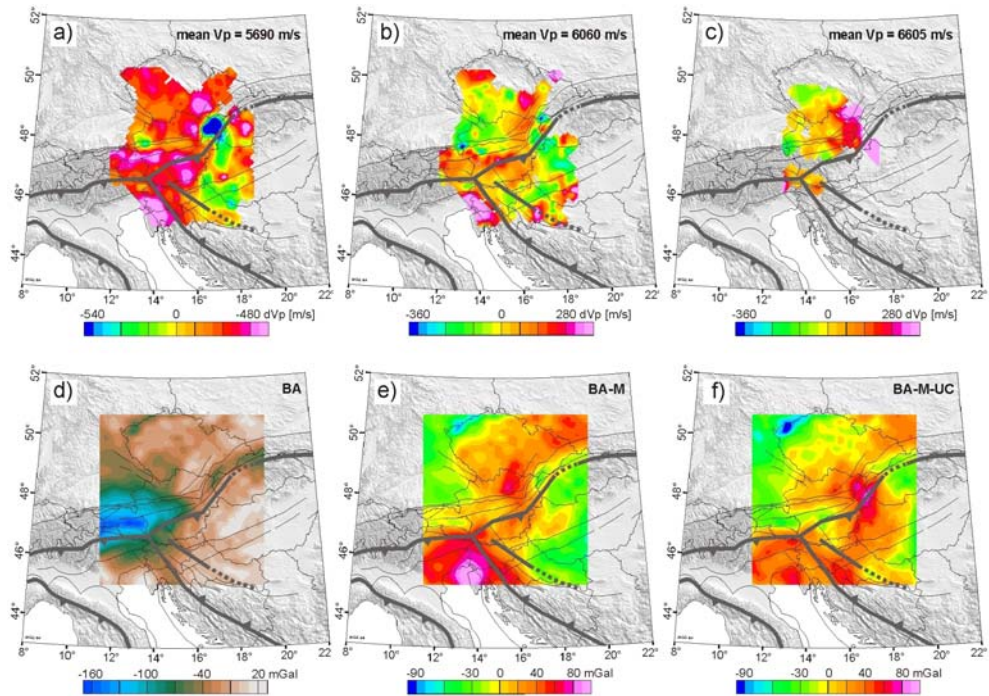
Fig. 4. Slices through the 3D P-wave velocity model of the crust at a) 5 km, b) 10 km, c) 27,5 km depth and gravity data (d, e, f)

The BA (Fig. 4d) reflects mainly the orogenic root and the relatively thin crust in the Pannonian Basin and the Venetian plain. The well-known, narrow gravity minimum of the Tauern window is superimposed on a wider gravity minimum caused by the East Alpine root. A relative gravity high correlates with the metamorphic eastern part of the Moldanubian, Bohemian Massif, and the corresponding high Vp velocity zones at all depth levels. The reduced anomaly BA-M shows again the gravity high in the Moldanubian and enhances the visibility of the gravity minimum at the Tauern window. The Molasse, Vienna, and Pannonian basins are clearly visible. The most prominent structure is an extended gravity high in the south which delineates the extent of the Adriatic indenter. The reduced anomaly BA-M-UC still shows the gravity high in the Moldanubian and the Adriatic indenter. The correlation with the basins is removed and the gravity minimum of the Tauern window is enlarged and now comprises the area around the Greywacke zone, similar to the high Vp zone at depth 5 km and 10 km. A gravity high not recognized on BA or BA-M neighbours the gravity high in the Moldanubian to the SE around the estimated trace of the Moho fragmentation between EU and PA. It coincides with the high velocity zone at 27.5 km depth (Fig. 4c). Most of the structures recognizable in the 3D Vp and gravity data need detailed modelling and analysis of uncertainties for further interpretation. However, there are two significant findings for this study. The first is the extent of the indenting Adriatic crust. It correlates well with the Moho fragmentation, but extends over the AD-EU and AD-PA' boundaries to the north and north-east. This could be interpreted as

an indenting Adriatic crustal wedge beyond the Moho fragmentation into European and Pannonian crust. The profiles TRANSALP, Alp01, CEL10&Alp04, and Alp07 support this interpretation. The second structure essential in the context of regional tectonics is the high velocity and gravity surplus in the lower crust below and slightly south-east of the Vienna basin. In case we assume the Moho fragmentation EU-PA between the triple junction and the Western Carpathians as transform or transfer, the section crossing the high velocity and gravity surplus zone would be trans-tensional. Magmatic intrusions into the lower crust could be an explanation for this anomaly. Additional information on the lithology of the crust comes from the 3D Vs and Poisson's ratio models generated by Behm (2009). This data indicates mafic intrusions in the upper crust of the Adriatic foreland. However, Poisson's ratios of the lower crustal high Vp region below and south-east of the Vienna basin are ~0.25. This value would be an indication that magmatic intrusions are not mafic.

6. Upper mantle tomography

Imaging the lithosphere and upper mantle by seismic tomography can substantially contribute to a better understanding of past and recent plate tectonic processes. Bodies of relatively high seismic velocity (mostly P-wave velocity) can represent down-going slabs of low temperature oceanic crust and lithospheric mantle. Low velocity areas may be related to areas of thinning lithosphere and upwelling astenosphere, mantle plumes or local mantle convections. Global and large-scale tomographic studies are mainly based on ISC travel time data from local, regional, and teleseismic earthquakes (e.g. Piromallo and Morelli, 2003; Wortel and Spakman, 2000; Bijwaard and Spakman, 1998; Koulakov et al. 2009). They may include crustal corrections and take advantage of traveltime reciprocity with respect to the locations of sources and receivers. Because these studies use absolute traveltimes, focal coordinates are relocated and deviations from a symmetric earth are considered for the whole ray paths from hypocentre to receiver. High resolution teleseismic investigations (e.g. Lippitsch et al., 2003; Rawlinson and Kennett, 2008; 2010; Dando, 2010; Mitterbauer et al. 2010) include data from temporary networks, implement crustal corrections based on the best available crustal models, and consider the velocity model by an accurate 3D ray tracing. Only traveltime differences are considered and the disturbance of teleseismic wave fronts by far distance inhomogeneities is neglected in the teleseismic range (~30° – 100°). Results from all these tomographic studies are presented as deviations of Vp or Vs velocities from a reference model, mostly a standard model like ak135.

A complete coverage of the wider Eastern Alps with relatively high resolution is provided by the P- and S-wave models of Koulakov et al. (2009). This P-wave model will be used and discussed together with the high-resolution teleseismic models of Lippitsch et al. (2003) and the latest local teleseismic model of Mitterbauer et al. (2010) derived from ALPASS data (http://info.tuwien.ac.at/geophysik/alpass.htm). The maximum depth extent of these models is 710 km, 400 km, and 600 km. Fig. 5 shows depth slices at 150, 180, 350, and 400 km through the models abbreviated K (Koulakov et al., 2009), L (Lippitsch et al., 2003), and M (Mitterbauer et al., 2010).

The Moho fragmentation is superimposed on the maps of P-wave velocity deviations from the reference values at the particular depths. Seismic stations, from where data were collected for the tomography, are also shown for the M- and the L-model within the frame of the map. The areas of no or low resolution are blank.
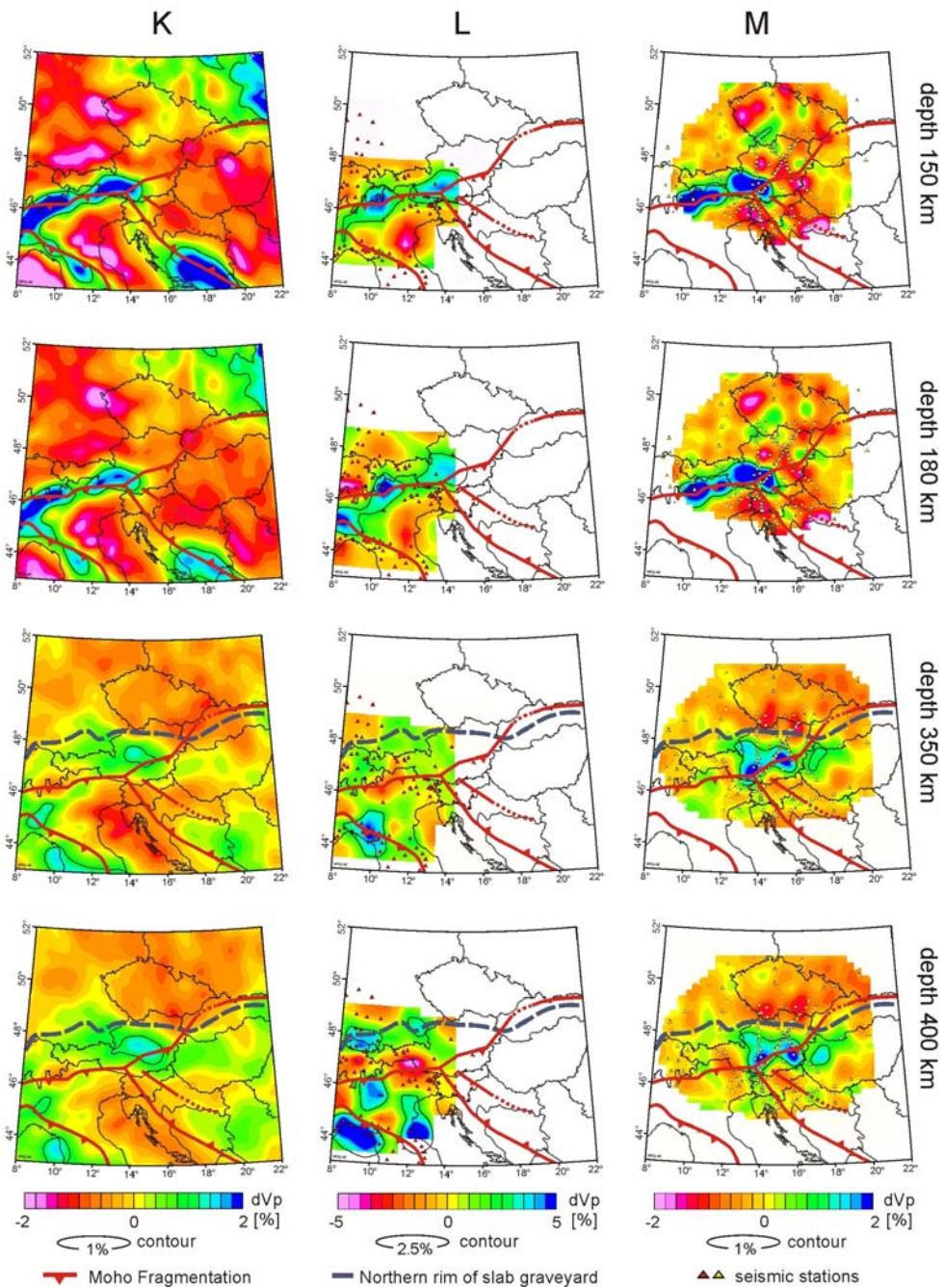
Fig. 5. Depth slices through the K-, L-, and M-models of the upper mantle

High velocity bodies below the Alps, Apennines, and Dinarides at 150 km and 180 km depth correspond to cold subducting slabs. Of main interest is the slab under the Eastern Alps and it will be referred to as "shallow slab". Contours of the shallow slab are superimposed on the depth slices. The axis of the shallow slab agrees well between all three models from 10°E to 14°E and approximately follows the Moho fragmentation. The assumption that the shallow slab was generated by a unique geodynamic process, in particular by subduction of (mainly) lithospheric mantle at the EU-AD boundary may be justified. Along the EU-PA Moho boundary, the K- and M-models do not show any structure which could be interpreted as a shallow slab. This finding is also in agreement with the global or large-scale models of Bijwaard et al. (1998) or Piromallo and Morelli (2003). The L-model does not extend so far to the east.

At 350 km and 400 km depth, the K- and M-models show an E-W striking high velocity body which terminates in the west between 12°E and 13°E. The L-model does not image this high velocity body. We refer to the high velocity body imaged by the K- and M-models as "deep slab". The teleseismic models derived from CBP-data (Dando, 2010) give further support for the existence and extent of this deep slab. Superimposed on these depth slices is also a contour which marks the northern rim of the so-called "slab graveyard" between 410 km and 670 km (e.g., Handy et al., 2010). The deep slab is located above the slab graveyard. The interpretation of the deep slab as subducted oceanic lithosphere of the Alpine Tethys on its way down to the slab graveyard is possible.

Fig. 6 shows 5 vertical profiles (P1 – P5) through the K- and M-teleseismic models down to a depth of 500 km. The corresponding profiles through the L-model are shown for the profiles P1, P2, P3, and P5 down to 400 km. Profiles 1 and 5 correspond to profile B and C after Lippitsch et al. (2003). Profiles 2 and 3 are along the TRANSALP transect and Alp01. Profile 4 crosses the Eastern Alps east of the Tauern window and the extent of the shallow slab. It is not covered by the L-model and the location map of the profiles is put in its place. The topography (enlarged in vertical direction) and the Moho according to the Moho-map (Fig. 3) are superimposed. The shallow slab is clearly imaged by all three models on profiles 1, 2, 3, and 5. The dip, as imaged by the K- and M-models, changes systematically from steeply south or vertical at the profiles P1 (near the boundary between Western and Eastern Alps) and P2 (central Tauern window) to steeply north at profiles P3 and P5 (at and beyond the eastern end of the Tauern window). P4 is located east of the shallow slab. The deep slab can clearly be identified on the K- and M-models at P3, P4 and P5. The high velocity zone widens with greater depth, indicating a continuous transition from the deep slab to the slab graveyard. This transition is better imaged by the K-model than by the M-model.

The L-model confirms the images of the shallow slab, supplied by the K- and M-models at P1, P2, and P3. On P5, the dip of the shallow slab resolved by the L-model deviates significantly from nearly vertical to ~ 60° north. In correspondence with the depth slices at 350 km and 400 km the deep slab cannot be identified on the profiles by the L-model.

As pointed out by Lippitsch et al. (2003), deep velocity anomalies may leak to higher levels in case these deep structures are not covered by the depth extent of the model, or considered by the embedding of the smaller regional model into a larger or global model. This may be the case for the L-model east of 14°-15°E. Therefore, from this latitude further to the east, the interpretations are based on the K- and M-models only.

The image of the L-model at P5 gave rise to the introduction of a subduction polarity change along the Alpine arc near 12°E, the longitude of the TRANSALP profile (e.g. Lippitsch et al.,
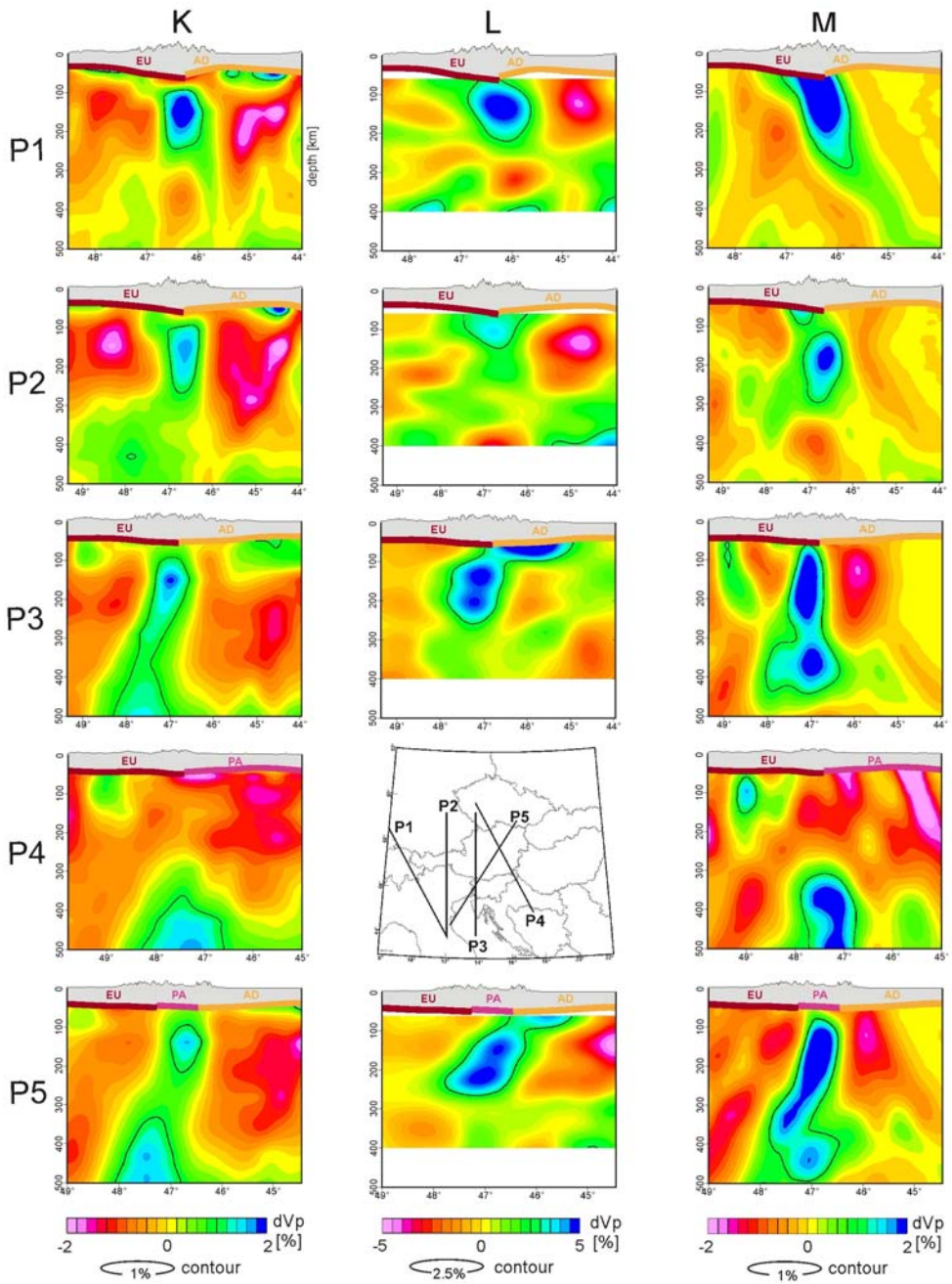
Fig. 6. Profiles through the K-, L-, and M-models of the upper mantle

2003; Schmid et al., 2004; Kissling et al., 2006). The idea is that parts of the Vardar or Meliata ocean, originally situated southeast of the Austro-Alpine, subducted to N and forced Adriatic continental lower lithosphere to subduct north-east beneath the Austro-Alpine. However, based on the arguments for a single shallow slab between 10°E and 14°E and the strong and unquestioned evidence for EU subducting AD at P1 (EGT&NFP-20), the whole shallow slab is interpreted as subducted EU lower continental lithosphere.

The K-model also provides well resolved images of slabs below the Apennines and Dinarides at 150 km and 180 km depth. Both slabs are subducted Adriatic continental lower lithosphere according to the plate tectonic scheme introduced by Doglioni and Carminati (2002). The axes of both slabs correlate well with the Moho fragmentations LG-AD and AD-PA(PA'). The Apennines slab dips to the SW. The Dinarides dip nearly vertically. It cannot be identified near the triple junction, but develops to a large body south of 45°N. Along the EU-PA Moho fragmentation, neither the K- nor the M-model shows any velocity structure comparable to the shallow slabs below the EU-AD, LG-AD, and AD-PA(PA') fragmentations.

7. Crustal thickening, post-collision convergence, lateral extrusion

Crustal thickening is closely related to post-collision convergence of an orogen and quantitative information can be derived from the balancing of these processes. Along the Alpine arc, the indentation of the Adriatic microplate has caused crustal thickening. Near the transition from the Western to the Eastern Alps at EGT&NFP-20, crustal thickening is the effect of a wide indentation of Adriatic lower crust, compression deformation of EU upper crust and Penninic thrusts, and backthrusting of AD upper crust according to seismic data (Valasek et al., 1991; Ye et al., 1995; Pfiffner et al., 1997) and their geologic interpretation (Schmid et al., 2004). In the area of the Tauern Window post-collision convergence and crustal thickening was considered along a cross section from the Molasse basin in the N to the Southern Alps and the Venetian plain (Brückl et al., 2010). Balancing was based on the assumption that no crustal material was subducted and three different regions were considered. North of the Subtauern ramp crustal thickening is mainly achieved by the overthrusting accretion wedge. The crystalline European crust north of the Subtauern ramp formed the Jurassic passive margin of the Penninic Ocean (Alpine Tethys) and experienced extension and crustal thinning before collision (Roeder, 1977). Geological data and reflection seismic profiles in the Molasse show that no or negligible thickening of the European passive margin occurred during collision (Wessely, 1987; Reiter et al., 2005). Ductile thickening of European basement below the Subtauern ramp cannot be excluded. However, an upper bound for crustal shortening of 20 km may be a reasonable assumption.

In the central part of the East Alpine orogen, crustal shortening is connected to the thrusting and folding of the Tauern window up the Subtauern ramp. Fügenschuh et al. (1997) derived a maximum exhumation of ~25 km for the central part of the window. As the southward dip of the Subtauern ramp is about 30° in the western part of the Tauern window (Lüschen et al, 2006) a vertical movement of 25 km corresponds to a horizontal northward directed displacement of about 55 km. This figure can be taken as a measure for the northward movement of the surrounding Adriatic crust over European crust.

S-directed thrusting of the Southern Alps is a relatively young process, most active during the Miocene (Doglioni, 1987, Schönborn, 1999; Schmid et al., 1996, Castellarin and Cantelli, 2000). The average thickness of the AD crust south of the Periadriatic line is 37 km. The

major part of the thickening took place either by thrusting in the crystalline upper crust and thrusting of AD lower crust over the Subtauern ramp (Castellarin et al., 2006), or by stacking of lower crust. Thickening of Adriatic crust south of the Periadriatic line corresponds to a crustal shortening of ~55 km assuming a thickness of 30 km for the pre-collision crust. This estimate of crustal shortening is very sensitive to the assumption of the thickness of the pre-collision crust. The estimates of the total north-south convergence since Oligocene derived from crustal thickening range from ~95 km to ~130 km.

Geological investigations and palinspastic reconstructions arrive at significantly larger figures (165 – 195 km) (e.g., Fügenschuh et al., 1997; Ustaszewski et al., 2008). The difference between crustal shortening derived by cross sectional balancing of the whole crust and by palinspastic reconstructions of the upper crust is not equally distributed over the whole profile. There is a fair agreement of N-S convergence derived by both methods in the Southern Alps (Schönborn, 1999; Castellarin and Cantelli, 2000; Castellarin et al., 2006). For the Eastern Alps the situation is significantly different. Frisch et al. (2000) derived 140 km crustal shortening at the western boundary of the Tauern window by a palinspastic reconstruction. The estimates of crustal shortening derived from crustal thickening and thrusting of the Tauern window over the Subtauern ramp range from 55 – 75 km. This discrepancy can be (at least partly) resolved by the assumption of eastward directed lateral extrusion of the central Eastern Alps and the Tauern window between the SEMP fault and the Periadriatic line (Ratschbacher et al. 1991). Linzer et al. (2002) estimated ~120 km of E-W extension between the Brenner and Katschberg normal faults. These faults form the western and eastern boundary of the Tauern window. Accounting for this significant E-directed movement of Tauern crust out of the collision zone by 3D balancing would significantly increase the amount of N-S-shortening across the Tauern window. Shortening is therefore underestimated by the restoration process applied above, which solely considers the amount of exhumation and the dip of the Subtauern ramp.

8. Active tectonics

Stable triple junctions impose constraints on the relative velocities between the plates constituting it. An analysis of relative plate velocities at triple junction between oceanic lithospheric blocks is well established, because the plate boundaries are narrow and clearly defined by topography, magnetic anomalies, and earthquake hypocentres (e.g., Moores & Twiss, 1995). Continental plate boundary processes at collision zones and transform or transfer faults find their expression in whole orogens or systems of strike-slip faults together with transtensional and transpressional structures, covering zones which may be several hundred kilometres wide (e.g., Gordon, 1995). A look at the geological map (Fig. 1) shows that this is also true for our investigation area and also the triple junction AD–EU–PA. One may hypothesize that continental active tectonics and kinematics can be more clearly described at the Moho level, comparable to boundaries between oceanic plates. On the basis of this idea, Brückl et al. (2010) analyzed the kinematics at the triple junction between AD – EU – PA, using the geodetic data of Grenerzcy and Kenyeres (2006), and Weber et al. (2006) to calibrate their model, and made predictions about the seismicity at the EU-PA and AD-PA(PA′) plate boundaries.

Fig. 7a shows the relative plate velocities, the extent of shallow slabs, and the velocity triangle at the AD-EU-PA triple junction according to the kinematic model of Brückl et al. (2010). To simplify the analysis the subdivision of the Pannonian fragment into PA and PA′
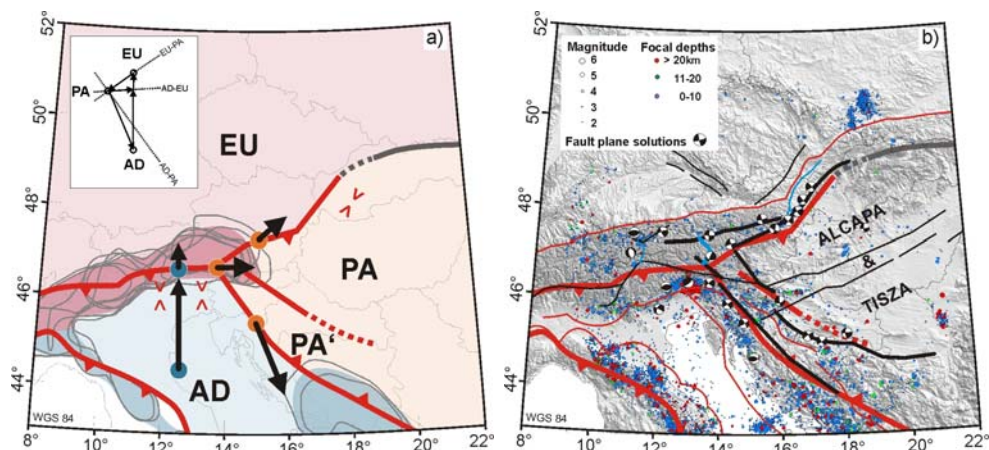
Fig. 7. Triple junction AD-EU-PA: a) kinematics and shallow slabs; b) faults and seismicity

was disregarded and only one Pannonian fragment (PA) considered. The following basic assumptions were made: stable triple junction and pure strike-slip at the EU-PA boundary near the triple junction. The geodetic constraints inferred were: 3 mm/yr N-S oriented convergence between AD and EU including the deformation zone in the Southern Alps and 1 mm/yr eastward escape of PA relative to AD. These assumptions and the geodetic constraints define the relative velocities at the triple junction. The total N-S convergence is partitioned into 0.6 mm/yr AD overthrusting EU and 2.4 mm/yr compression deformation of the Southern Alps. At the triple junction there is eastward spreading of PA relative to AD of 1 mm/yr. This extension is assumed to be compensated by the ongoing lateral extrusion of the Tauern window area as proposed by Ratschbacher et al. (1991) and derived by palinspastic reconstructions for Miocene times (e.g. Linzer et al., 2002). The mass deficit in this area derived by crustal balancing, which follows from lateral extrusion to the east, gives further support for this explanation. South of the compression area in the Southern Alps, the total AD-PA relative velocity is 2.5 mm/yr. The direction of the relative velocity indicates transpression and AD underthrusting PA. The EU-PA boundary near the triple junction has an azimuth of 55°. Further to the east this azimuth increases slightly at the Mur-Mürz fault and a transpressional regime prevails, similar to the situation at AD-PA south of the compression deformation zone in the SA. However, the absolute value of the relative velocity is only 50% at EU-PA in comparison with AD-PA. Seismicity should reflect this ratio. From the Rechnitz window, over the Vienna basin the assumed azimuth of the EU-PA plate boundary is about 35°, generating transtension.

The amount of 0.6 mm/yr AD overthrusting EU may lead to a continued folding and thrusting up the Subtauern ramp. The slope of this ramp is about 30° and a horizontal displacement of 0.6 mm/yr along this ramp would produce about 0.35 mm/yr uplift rate. According to geodetic data (GPS and levelling) the Tauern window still shows an uplift rate of ~1 mm/yr (Höggerl, 2001; Haslinger et al., 2007), which is significantly more than the amount estimated from convergence at the EU-AD plate boundary and the continued folding and thrusting of the Tauern window up the Subtauern ramp. It is a matter of debate how much of the uplift and subsidence rates is related to tectonic activity, especially the ongoing exhumation of the Tauern window, and what may be explained by post glacial

rebound. The ice streams in the central Eastern Alps advanced widely into the EU and AD forelands during the last ice age (van Husen, 1987). To the east the maximum extent of glaciation reached into the Styrian basin. But also present day glacier shrinkage should be considered as a possible cause of uplift (Barletta et al., 2006).

Together with geodetically observed crustal deformations, the seismicity proves active tectonic processes. Fig. 7b shows the terrain model, major faults, seismicity (NEIC 1973-2010), and representative focal plane solutions (Reinecker and Lenhardt, 1999; further references in Brückl et al. 2010). The pattern of the Moho fragmentation, also superimposed on this map, is strongly related to seismicity. The area of highest seismicity in the wider EA area are the Southern Alps south of the AD-EU boundary, the Friuli district. The upper crust hypocenter locations and focal mechanisms correspond to back-thrusting of the Southern Alps and strike slip movements. Another area of relatively high seismicity is the Mur-Mürz fault and the southern Vienna basin along the EU-PA Moho fragmentation. Focal plane solutions indicate mostly SW-NE oriented left-lateral strike slip with little dip slip components. Stripes of high seismicity follow the Dinaric thrust belt, southwest of the AD-PA' and PA'-PA Moho fragmentations. Irregular orientations of the principal stress axis at the transition from the Southern Alps to the northern Dinarides are an expression of the complex stress system in this area. Further to the south-east, especially in the costal part of Croatia, reverse or strike-slip faulting with sub-horizontal P-axis in south-west to south directions dominate the active tectonics along these faults. The Periadriatic line shows relatively little seismicity with the exception at its transition to the Mid-Hungarian fault zone. Gutdeutsch and Aric (1987) derived tectonic block models from seismic data alone for the wider Pannonian area. In addition to the European and Adriatic plate they introduced a Dinaric and a Pannonian fragment. The latter correspond approximately to PA' and to PA.

The pattern of the Moho fragmentation correlates well with major active faults (Fig. 7b; see also Fig. 3). The wider area of the newly interpreted Pannonian fragment is bounded by the Katschberg fault in the west, the SEMP fault in the north, the Malta and Idria faults, and probably the Dinaric thrust faults in the southwest. The Mur-Mürz, Lavant and Sava faults are other strike-slip faults, which are related to the Moho fragmentation and which enclose the thin Pannonian crust. Along the Periadriatic line and its prolongation to the Mid-Hungarian fault zone, no significant corresponding features in the deeper crustal structure can be identified. The northern part the Pannonian fragment is composed of ALCAPA units, and to the south, it extends over the Mid-Hungarian fault zone into the TISZA block. The kinematics at the triple junction and the lack of seismic data indicating significantly a boundary between ALCAPA and TISZA give rise to the hypothesis that ALCAPA east of the Tauern Window and TISZA merged to one "soft" plate. The low seismic activity at the EU-PA border in the Western Carpathians may be regarded as a further indication for a "soft" collision between ALCAPA and Europe in this area.

9. Conclusion

Wide angle reflection and refraction profiling supplied information about the seismic velocity structure (mainly Vp) of the crust and resolved the Moho boundary. Steep angle reflection profiles additionally provided detailed images of intra-crustal structures. The most comprehensive information were gained by integrated transects like TRANSALP or EGT&NPF-20. On the basis of this data, suture zones between plates or fragments were delineated and structures, mainly related to compression, were resolved. The topography of

the Moho discontinuity was determined and significant steps indicating plate boundaries were recognized. Moho-maps were compiled on the basis of 2D and 3D data. In this study a Moho-map based on the European Moho-map of Grad et al. (2009) and the higher resolution map of Behm et al. (2007) was used. On the basis of this data and additional criteria derived from curvature (Waldhauser et al., 1998) and elastic plate modelling (Brückl et al., 2010), a fragmentation of the Moho and upper mantle into EU, AD, PA (including PA') and the Ligurian plate (LG) was introduced (Fig. 3). The polarity of the Moho steps, the changes of Moho dip, and force couples derived by the elastic plate modelling were considered to identify plate boundary processes. Following this interpretation, the EU underthrusts AD and PA. AD underthrusts LG and PA (PA'). This scheme was also proposed earlier by Doglioni and Carminati, (2002).

3D Vp- and Vs-velocity models of the crust (Behm et al., 2007; Behm, 2009) and gravity data (e.g., Simeoni and Brückl, 2009) support interpolation of velocity structures between profiles and extrapolation to areas not covered by profiles. Important contributions of these models to the general understanding of the geodynamic and tectonic setting were, for instance, outlining the northern and north-eastern boundary of the Adriatic indenter at mid- and lower crustal level and the identification of a high velocity and high density lower crust in the transtensional area in and southeast of the Vienna basin.

Global and large-scale tomographic models of the upper mantle show a wide zone of high Vp-velocity bodies between the 410 km and 670 km discontinuity in the Alpine-Mediterranean region (e.g., Bijwaard and Spakman, 1998; Piromallo and Morelli, 2003). These structures are known as "slab graveyard" and generally interpreted as subducted oceanic lithosphere and continental lower lithosphere. In this study the large scale model of Koulakov at al. (2009) (K-model), the teleseismic model of Lippitsch et al. (2003) (L-model) and the new model of Mitterbauer et al. (2010) (M-model) are compared and used for tectonic interpretation. At the depth levels 350 km and 400 km, the K- and M-model image a west-east striking high velocity body east of 12°E and between 47° - 48°, the so-called "deep slab". It is not imaged by the L-model because it is mostly east of the high resolution area of the L-model. Another point is that the L-model is restricted in depth to 400 km. The deep slab is well imaged along vertical profiles (Fig. 6) by the K- and M-models. Its existence has also been confirmed by a teleseismic model based on data from the CBP-project (Dando, 2010). The deep slab is interpreted as oceanic lithosphere of the Alpine Tethys, which detached from the Alpine orogenic root after collision about 35 Ma ago (Davis and Blanckenburg, 1995) and did not arrive completely at the slab graveyard. A matter of ongoing discussion is the mechanism, how oceanic lithosphere in the Carpathian embayment found its way down to the slab graveyard. The classical model is roll-back as proposed by Royden (1993). However, this process is difficult to explain because of the shape of the deep slab and its relation to the European continental margin. Other mechanisms like delamination (Bird, 1979) or a Rayleigh-Taylor instability (Houseman and Molnar, 1997) should also be taken into consideration.

A "shallow slab" is well resolved on depth slices at 150 km and 180 km by all three models from ~10°E to about 14°-15°E (Fig. 7a-f). The axis of the shallow slab approximately follows the Moho fragmentation EU-AD and the eastern end of the shallow slab coincides roughly with the triple junction between AD-EU-PA. The profiles which cover the Eastern Alps from their western border to ~14°E show the shallow slab down to depths of ~180 km to ~250 km. The dip changes continuously from steeply south in the west to steeply north in the east. The ~60° north dipping slab, imaged by the L-model along a NE-SW oriented profile east of the Tauern

window could not be confirmed by the K- and M-models. The EGT&NFP-20 profile (e.g. Valasek et al., 1998), the TRANSALP transect (Lüschen et al., 2006) and the analysis of Moho steps by Waldhauser et al., (1998) and Brückl et al. (2010) support the interpretation that EU continental lower lithosphere (exclusively or mainly upper mantle) was subducted below AD along the whole EU-AD boundary. EU has been the passive margin during the subduction of the Alpine Tethys before collision. After collision, lower continental lithosphere of EU origin was detached from the crust and transported to greater depth forming the shallow slab. This mechanism supports ongoing convergence in the region of the orogenic core from the Western Alps to the eastern border of the Tauern window.

Before collision with EU, ALCAPA underwent an orogenic phase, the Eo-Alpine orogeny. Compression tectonics revived west of the triple junction after collision. East of the triple junction, tectonic escape to the north-east and gravitational collapse were the dominating processes. From the triple junction to the Western Carpathians, the movement of ALCAPA relative to EU has been mainly transfer, with change from pure strike slip to transpression (Mur-Mürz fault near the Rechnitz window) and transtension (Vienna basin, high velocity and density area in the lower crust). During tectonic escape ALCAPA extended significantly (e.g., Ustaszewski et al. 2008). The collision with the EU margin at the Western Carpathians was "soft", because of the weakening of the Pannonian lithosphere during extension into the Carpathian embayment. The crustal cross-sections through the Western Carpathians (Fig. 2) show no clear root below this orogen, but rather a continuous transition from the shallow Pannonian crust to the thick Paleozoic, and further to the north-east, Precambrian crust of the East European craton. This suggests that no shallow slab by subduction of continental lithosphere was generated along EU-PA from the triple junction to and along the Western Carpathians.

The interpretation of profile Alp07 and elastic plate modelling suggest that Adriatic mantle thrusts under the Dinaric crust. However, no clear indication for a subducting slab can be found from the triple junction to the south-east at about 45°N along the AD-PA', or PA'-PA Moho fragmentation. The kinematic analysis of current relative velocities at the triple junction (Fig. 7) revealed extension between AD and PA(PA') at the triple junction and transpression in the SE. In case this plate boundary process was active in roughly the same way since the beginning of lateral extrusion, a major slab must not necessarily have developed by subduction of AD lower lithosphere. This situation gradually changes to the south-east and a pronounced shallow slab is imaged by the K-model below the AD-PA(PA') Moho fragmentation in this area. This is plausible because the Euler pole of the relative movement of AD versus EU is located at 46-47° N and 8-10° E and the relative movement of AD versus PA(PA') changes from transpression to compression south of ~45°N.

In the area of the Tauern window and west of it, the ALCAPA units overthrusted European crust and lack their own lithospheric mantle. East of the Tauern window and the Katschberg normal fault at surface and the triple junction AD-EU-PA at Moho level, the ALCAPA units rest on their own lithospheric mantle. The mid-Hungarian fault zone (MHZ) has been a zone of repeated tectonic inversions (Csontos and Nagymarosy, 1998) since Eocene times. Periods of thrust faulting were followed by phases of extension and transtension. However, no significant geophysical boundary could be found between the ALCAPA and TISZA units by the data presented in this study. Seismicity at the Periadriatic line east of the triple junction and at the MHZ is relatively low. The kinematic model derived from geodetic data and the Moho fragmentation does not consider current deformation between ALCAPA and TISZA. One may speculate that ALCAPA and TISZA merged to one plate.

10. Acknowledgements

11. References

Abramovitz, T. & Thybo, H. (2000). Seismic images of Caledonian, lithosphere scale collision structures in the southeastern North Sea along Mona Lisa profile 2, *Tectonophysics*, 317(1-2), 27-54, doi:10.1016/S0040-1951(99)00266-8.

Barletta, V. R. (2006). Glacier shrinkage and modeled uplift of the Alps, *Geophys. Res. Lett.*, 33, L14307, doi:10.1029/2006GL026490.

Beránek, B. & Zátopek, A. (1981). Earth`s crust structure in Czechoslovakia and central Europe by methods of explosion seismology, In: *Geophysical Synthesis in Czechoslovakia*, A. Zátopek (Ed.), Veda, Bratislava, Slovakia, 253-264.

Behm, M. et al. (2007). Application of stacking and inversion techniques to 3D wide-angle reflection and refraction seismic data of the Eastern Alps, *Geophys. J. Int.*, 170, 1, 275-298.

Behm, M. (2009). 3-D modelling of the crustal S-wave velocity structure from active source data: application to the Eastern Alps and the Bohemian Massif, *Geophys. J. Int.*, 179, 1, 265-278, doi:10.1111/j.1365-246X.2009.04259.x.

Bielik, M. et al. (2006). Gravity anomaly map of the CELEBRATION 2000 region, *Geol. Carpathica*, 57(3), 145-156.

Bijwaard, H.; Spakman, W. & Engdahl, E.R. (1998). Closing the gap between regional and global travel time tomography, *J. geophys. Res.,* 103, 30 055–30 078.

Bird, P. (1979). Continental delamination and the Colorado Plateau, *JGR*, 84, 7561-7571.

Bleibinhaus, F. & Gebrande, H. (2006). Crustal structure of the Eastern Alps along the TRANSALP profile from wide-angle seismic tomography, *Tectonophysics*, 414 (1-4), 51-69, doi:10.1016/j.tecto.2005.10.028.

Brückl, E. et al. (2003). ALP2002 Seismic Experiment, *Studia geophysica geodaetica*, 47. ISSN 0039-3169, 671-679.

Brückl, E. et al. (2006). Studies on Crustal Structure and Gravity in the Eastern Alps, In: *Geodetic Deformation Monitoring: From Geophysical to Engineering Roles. IAG Symposium 131*, F. Sanso and A.J. Gil (Ed.), Springer, ISBN 3-540-38595-9, 181-192.

Brückl, E. et al. (2007). Crustal structure due to collisional and escape tectonics in the Eastern Alps region based on profiles Alp01 and Alp02 from the ALP 2002 seismic experiment, *J. Geophys. Res,* 112, B06308, doi:10.1029/2006JB004687, 1-25.

Brückl, E. et al. (2010). Crustal structure and active tectonics in the Eastern Alps, *Tectonics*, 29, TC2011, doi:10.1029/2009TC002491.

Castellarin, A. & Cantelli, L. (2000). Neo-Alpine evolution of the Sothern Alps, *Journal of Geodynamics*, 30, Pergamon Press, 251-274.

Castellarin, A. et al. (2006). Structure of the lithosphere beneath the Eastern Alps (southern sector of the TRANSALP transect), *Tectonophysics*, 414, 259-282.

Christensen, N.I. & Mooney, W.D. (1995). Seismic velocity structure and composition of the continental crust: a global view, *J. Geophys. Res.,* 100, 9761-9788.

Csontos, L. & Nagymarosy, A. (1998). The Mid-Hungarian line: a zone of repeated tectonic inversions, *Tectonophysics*, 297, 51-71.

Dando, B. (2010). Seismological structure of the Carpathian –Pannonian region in central Europe, *Ph.D. Thesis*, School of Earth and Environment, University of Leeds.

Davies, J. & von Brandenburg, F. (1995). Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens*, Earth and Planetary Science Letters*, 129, 85-102.

Decker, K. & Peresson, H. (1996). Tertiary kinematics in the Alpine-Carpathian-Pannonian system: links between thrusting, transform faulting and crustal extension, In: *Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe*, G. Wessely and W. Liebl (Ed.), EAGE, Spec. Publ., 5, 69-77.

Dezes, P. & Ziegler, P.A. (2001). European Map of the Mohorovicic discontinuity. 2nd EUCOR-URGENT Workshop (Upper Rhine Graben Evolution and Neotectonics), Mt. St. Odile, France.

Di Stefano, R. et al. (2009). Shallow subduction beneath Italy: Three-dimensional images of the Adriatic-European-Tyrrhenian lithosphere system based on high-quality P wave arrival times*, J. Geophys. Res*, 114, B05305, doi:10.1029/2008JB005641.

Doglioni, C. (1987). Tectonics of the Dolomites (Southern Alps Northern Dolomites), *Struct. Geology*, 9, 181-193.

Doglioni, C. & Carminati, E. (2002). The effects of four subductions in NE Italy, *Mem. Sci. Geol.*, 54, 1-4.

Ebbing, J; Braitenberg, C. & Götze, H.-J. (2006). The lithospheric density structure of the Eastern Alps, *Tectonophysics*, 414, 145-155.

Frisch, W.; Dunkl, I. & Kuhlemann, J. (2000). Postcollisional orogen parallel large scale extension in the Eastern Alps, *Tectonophysics*, 327(3-4), 239- 265, doi:10.1016/S0040-1951(00)00204-3.

Fügenschuh, B.; Seward, D. & Mancktelow, N. (1997). Exhumation in a convergent orogen: the western Tauern window, *Terra Nova*, 9, 213-217.

Gebrande, H. et al. (2006). TRANSALP - A transect through a young collisional orogen: Introduction, *Tectonophys*, 414(1-4), 1-7, doi:10.1016/j.tecto.2005.10.030.

Giese, P. & Prodehl, C. (1976). Main features of crustal structure in the Alps, In: *Explosion seismology in Central Europe*, P. Giese and C. Prodehl (Ed.), Springer, 347-375.

Gordon, R.G. (1995). *Present plate motions and plate boundaries, in Global Earth Physics*, A Handbook of Physical Constants, T. J. Ahrens (Ed.), AGU Ref. Shelf, vol. 1, 66-87, AGU, Washington, D. C.

Grad, M. et al. (2003). SUDETES 2003 Seismic Experiment, *Stud. Geophys. Geod*, 47, 681-689.

Grad, M. et al. (2006). Lithospheric structure beneath trans-Carpathian transect from Precambrian platform to Pannonian basin—CELEBRATION 2000 seismic profile CEL05, *J. Geophys. Res*, 111, B03301, doi: 10.1029/2005JB003647.

Grad, M.; Tiira, T. & Group, E.W. (2009). The moho depth map of the european plate, *Geophys. J. Int.*, 176, 279-292.

Graßl, H. et al. (2004). Seismic image of the deep crust at the eastern margin of the Alps (Austria): indications for crustal extension in a convergent origin, *Tectonophysics*, 380, 105-122.

Grenerczy, G. & Kenyeres, A. (2006). Crustal deformation between Adria and the European platform from space geodesy, In: *The Adria Microplate: GPS Geodesy, Tectonics and Hazards*, N. Pinter et al (Ed.), NATO Sci. Ser. IV, vol. 61, 321-334, Springer, Dordrecht, Netherlands, doi:10.1007/1-4020-4235-3_22.

Gutdeutsch, R. & Aric, K. (1987). Tectonic block models based on the seismicity in the East Alpine Carpathian and Pannonian area, In: *Geodynamics of the Eastern Alps*, H. W. Flügl and P. Faupl (Ed.), F. Deuticke, Vienna, 309-324.

Guterch, A. et al. (2003a). An overview of recent seismic refraction experiments in Central Europe, *Stud. Geophys. Geod.*, 47, 651- 657.

Guterch, A. et al. (2003b). CELEBRATION 2000 Seismic Experiment, *Stud. Geophys. Geod.*, 47, 659-669.

Handy, M. et al. (2010). Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps, *Science Reviews*, doi: 10.1016/j.earscirev.2010.06.002.

Haslinger, C.; Kraus, S. & Stangl, G. (2006). The intraplate velocities of GPS permanent stations of the Eastern Alps, *Vermessung Geoinf.*, 95(2), 66-72.

Höggerl, N. (1989). Rezente Höhenänderungen in Österreich abgeleitet aus Präzisionsnivellement-Messungen, *Österr. Beiträge zu Met. und Geophys.*, 2, 161- 173.

Horváth, F. et al. (2006). Formation and deformation of the Pannonian basin: constraints from observational data, In: *European Lithosphere Dynamics*, D.G. Gee and R.A. Stephenson (Ed.), Geological Society London Memoir, 32, 129-145.

Hrubcova, P. et al. (2005). Crustal and uppermost mantle structure of the Bohemian Massif based on CELEBRATION 2000 data, *J. Geophys. Res*, 110(B11305), doi: 10.1029/2004JB003080.

Hrubcova, P. et al. (2008). Crustal structure at the easternmost termination of the Variscan belt based on CELEBRATION 2000 and ALP 2002 data, *Tectonophysics*, 460, 55-75.

Houseman, G.A. & Molnar, P. (1997). Gravitational (Rayleigh-Taylor) instability of a layer with non-linear viscosity and convective thinning of continental lithosphere, *Geophys. J. Int.*, 128, 125-150.

Joksović, P. & Andrić, B. (1983). Report on examination of earth crust composition by deep seismic sounding on the profile of Pula – Maribor, Expert Document Fund, *Geofizika*, Zagreb.

Kissling, E. et al. (2006). Lithosphere structure and tectonic evolution of the Alpine arc: new evidence from high-resolution teleseismic tomography, In: *European Lithosphere Dynamics*, D.G. Gee and R. A. Stephenson, Mem. Geol. Soc., 32, 129-145.

Koulakov, I. et al. (2009). P- and S-velocity anomalies in the upper mantle beneath Europe from tomographic inversion of ISC data, *Geophys. J. Int.*, 179, 345-366.

Kummerow, J. et al. (2004). A natural and controlled source seismic profile through the Eastern Alps: TRANSALP, *Earth and Planetary Science Letters*, 225, 115-129.

Lammerer, B. et al. (2008). A crustal-scale cross section through the Tauern Window (eastern Alps) from geophysical and geological data, In: *Tectonic Aspects of the Alpine-Dinaride-Carpathian System*, Siegesmund, S. et al. (Ed.), Geological Society, London, Special Publications 298, pp. 219-229.

Le Pichon, X.; Bergerat, F. & Roulet, M.-J. (1988). Plate kinematics and tectonics leading to the Alpine belt formation: A new analysis, In: *Processes in Continental Lithospheric Deformation,* (S.P. Clark, B.C. Burchfiel, J. Suppe, (Ed.), GSA, Special Paper, 111-131.

Linzer, H.-G. et al. (2002). Balancing lateral orogenic float of the Eastern Alps, *Tectonophysics*, 354, 211-237.

Lillie, R.J. et al. (1994). Gravity modelling of the lithosphere in the Eastern Alpine–Western Carpathian–Pannonian basin region, *Tectonophysics*, 231(4), 215-235, doi:10.1016/0040-1951(94)90036-1.

Lippitsch, R.; Kissling, E. & Ansorge, J. (2003). Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography, *J. Geophys. Res,* 108 (B8), 2376, doi:10.1029/2002JB002016.

Lüschen, E. et. al. (2006). TRANSALP-deep crustal Vibroseis and explosive seismic profiling in the Eastern Alps, *Tectonophysics*, 414 (1-4), 9-38.

Mancktelow, N. et al. (2001). The DAV line and Periadriatic fault system in the Eastern Alps south of the Tauern window, *Int. J. Earth Sci.* , 90, 593- 622.

Meurers, B.; Ruess, D. & Steinhauser, P. (1987). The Gravimetric Alpine Traverse, In: *Geodynamics of the Eastern Alps*, H.W. Flügel & P. Faupl (Ed.), Verlag Deuticke, Wien, 334-344.

Meurers, B. & Ruess, D. (2007). Compilation of a new Bouguer gravity data base in Austria., *Österr. Zeitschr. f. Vermessung & Geoinformation*, 95, Heft 2.

Mitterbauer, U. et al. (2010). ALPASS- Neue Erkenntnisse über die seismische Struktur des oberen Erdmantels in den Ostalpen, *Pangeo 2010*, 15.9.-19.9.2010, Leoben.

Mooney, W.D.; Laske, G. & Masters, G. (1998). CRUST5. I: A global crustal model at 5' x 5', *J. Geophys. Res*, 103, 727-747.

Moores, E.M. & Twiss, R.J. (1995). *Tectonics*, W. H. Freeman (Ed.), New York, pp. 415.

Oberhauser, R. (1980). *Der Geologische Aufbau Österreichs*, Springer, New York. pp. 699.

Ortner, H.; Reiter, F. & Brandner, R. (2006). Kinematics of the Inntal shear zone-sub-Tauern ramp fault system section, Eastern Alps, Austria, *Tectonophysics*, 414, 241-258.

Pamić, J. et al. (2002). Geodynamic and petrogenetic evolution of Alpine ophiolites from the central and NW Dinarides: an overview, *Lithos*, 65, 113-142.

Peresson, H. & Decker, K. (1997). Far-filed effect of Late Miocene subduction in the Eastern Carpathians: E-W compression and inversion of structures in the Alpine-Carpathian-Pannonian region, *Tectonics*, 16, 38-56.

Pfiffner, O.A. et al. (1997). *Deep Structure of the Swiss Alps: Results of NRP 20*, Birkhäuser, Basel, pp. 380.

Piromallo, C. & Morelli, A. (2003). P wave tomography of the mantle under the Alpine-Mediterranean area, *J. geophys. Res.,* 108(B2), doi:10.1029/2002JB001757.

Poljak, M. et al. (2000). The seismotectonic characteristics of Slovenia, *Pure Appl. Geophys.*, 157, 37-55, doi:10.1007/PL00001099.

Posgay, K. et al. (1981). Character of the Earth's crust and upper mantle on the basis of seismic reflection measurements in Hungary, *Earth Evolut. Sci.*, 1 3/4, 272-279.

Ratschbacher, L. et al. (1991). Lateral extrusion in the Eastern Alps, Part 2.: Structural analysis, *Tectonics*, 10, 2, 257-271.

Rawlinson, N. & Kennett, B.L.N. (2008). Teleseismic tomography of the upper mantle beneath the southern Lachlan Orogen, Australia, *Physics of the Earth and Planetary Interiors*, 167 (2008) 84-97.

Reinecker, J. & Lenhardt, W. (1999). Present - day stress field and deformation in eastern Austria, *Int. J. Earth Sci.*, 88, 532-550, doi:10.1007/s005310050283.

Reiter, F.; Lenhardt, W. & Brandner, R. (2005). Indications for activity of the Brenner normal fault zone (Tyrol, Austria) from seismological and GPS data, *AJES*, 97, 16-23.

Roeder, D. (1977). Continental convergence in the Alps, *Tectonophysics*, 40(3-4), 339-350, doi:10.1016/0040-1951(77)90072-5.

Rosenberg, C.L. et al. (2004). Indentation model of the Eastern Alps and the origin of the Tauern Window, *Geology*, 32, 997-1000.

Royden, L.H. (1993). Evolution of retreating subduction boundaries formed during continental collision, *Tectonics*, 12 (3), 629-638.

Scarascia, S. & Cassinis R. (1997). Crustal structures in the central-eastern Alpine sector: a revision of available DSS data, *Tectonophysics*, 271, 157-188.

Schmid, S.M. et al. (2004). Tectonic map and overall architecture of the Alpine orogen, Eclogae Geologicae Helvetiae, 97, 93-117.

Schmid, S.M. et al. (1996). Geophysical geological transect and tectonic evolution of the Swiss Italian Alps, *Tectonics*, 15, 1036-1064, doi:10.1029/96TC00433.

Schönborn, G. (1999). Balancing cross sections with kinematic constraints: The Dolomites (northern Italy), *Tectonics*, 18, 527-545.

Simeoni, O. & Brückl, E. (2009). The effect of gravity stripping on the resolution of deep crustal structures in the Eastern Alps and surroundings Regions, *Austrian Journal of Earth Sciences*, 102/2, 157-169.

Sroda, P. (2006). Seismic anisotropy of the upper crust in southeastern Poland—effect of the compressional deformation at the EEC margin: results of CELEBRATION 2000 seismic data inversion, *Geophys. Res. Lett.*, 33, L22302, doi: 10.1029/2006GL027701.

Stampfli, G.M. & Kozur, H.W. (2006). Europe from the Variscan to the Alpine cycles. in European Lithosphere dynamics, In: *European Lithosphere Dynamics*, D.G., Gee, R.A. Stephenson, (Ed.), Geolog. Soc. London Memoirs, 32, London, pp. 129-145.

Šumanovac, F. et al. (2009). Crustal structure at the contact of the Dinarides and Pannonian basin based on 2-D seismic and gravity interpretation of the Alp07 profile in the ALP2002 experiment, *Geophys. J. Int.*, 179, 615-633. doi:10.1111/j.l365-246X.2009.04288.x.

Šumanovac, F. (2010). Lithosphere structure at the contact of the Adriatic microplate and the Pannonian segment based on the gravity modelling, *Tectonophysics*, 485, 94-106.

TRANSALP Working Group (2002). First deep seismic reflection images of the Eastern Alps reveal giant crustal wedges and transcrustal ramps, *Geophys. Res. Let.*, 29, doi:10.1029/2002GL014911.

Thybo, H. et al. (2003). Upper lithospheric seismic velocity structure across the Pripyat Trough and the Ukrainian Shield along the EUROBRIDGE'97 profile, *Tectonophysics*, 371(1-4), 41-79, doi:10.1016/S0040-1951(03)00200-2.

Tomek, C. (1993). Deep crustal structure beneath the Central and Inner West Carpathians, *Tectonophysics*, 226, 417-431.

Tomljenović, B. & Csontos, L. (2001). Neogene-Quaternary structures in the border zone between Alps, Dinarides and Pannonian basin (Hrvatsko Zagorje and Karlovac basins, Croatia), *Int. J. Earth Sciences*, 90, 560-578.

Ustaszewski, K. et al. (2008). A map view restoration of the Alpine Carpathian Dinaridic system for the early Miocene, *Swiss, J. Geosci.*, 101, Suppl. 1, 273-294.

Valasek, P. et al. (1991). Results of NFP 20 seismic reflection profiling along the Alpine section of the European Geotraverse (EGT), *Geophys. J. Int.,* 105, 85-102.

van Husen, D. (1987). *Die Ostalpen in den Eiszeiten*, Geol. Bundesanstalt, Vienna.

Vrabec, M. & Fodor, L. (2006). Late Cenozoic tectonics of Slovenia: Structural styles at the northeastern corner of the Adriatic microplate, In: *The Adria microplates*, N. Pinter. et al. (Ed.), Springer, 151-168.

Waldhauser, F.R. et al. (1998). Three-dimensional interface modelling with two-dimensional seismic data: The Alpine crust – mantle boundary, *Geophys. J. Int.,* 135, 264-278, doi:10.1046/j.1365-246X.1998.00647.x.

Weber, J. et al. (2006). The PIVO-2003 Experiment: A GPS Study of Istria Peninsula and Adria Microplate Motion, and Active Tectonics in Slovenia, In: *The Adria Microplate*, Pinter, N. et al. (Ed.), Springer, 305-320.

Weber, M. et al. (2009). Anatomy of the Dead Sea Transform from lithospheric to microscopic scale, *Rev. Geophys.*, 47, RG2002, doi:10.1029/2008RG000264.

Wessely, G. (1987). Mesozoic and Tertiary evolution of the Alpine Carpathian foreland in eastern Austria, *Tectonophysics*, 137(1-4), 45-59, doi:10.1016/0040-1951(87)90313-1.

Wortel, M.J.R. & Spakman, W. (2000). Subduction and Slab Detachment in the Mediterranean-Carpathian Region, *Science*, 290, no. 5498, 1910 - 1917.

Yan, Q.Z. & Mechie, J. (1989). A fine structural section through the crust and lower lithosphere of the Alps, *Geophys. J.*, 98, 465-488.

Ye, S.; Ansorge, J. & Cloetingh, S. (1995). Crustal structure beneath the Swiss Alps derived from seismic refraction data, *Tectonophysics*, 242, 199-221.

Zanolla, C. (2006). New gravity maps of the Eastern Alps and significance for the crustal structures, *Tectonophysics*, 414, 127-143.

Zhao, W. et al. (2001). Crustal structure of central Tibet as derived from project INDEPTH wide angle seismic data, *Geophys. J. Int.,* 145(2), 486-498, doi:10.1046/j.0956-540x.2001.01402.x.