# Crustal structures and tectonic processes in the Eastern Alps revealed by recent controlled source seismic experiments

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## INTRODUCTION

The Eastern Alps are part of the Alpine-Himalayan orogeny formed by the collision between Africa and Europe. The Eastern Alps and surrounding tectonic provinces attract geoscientific interest since the 19th century. Seismological research and findings of global relevance date back to the early 20th century [Conrad 1925, Mohorovicic 1910]. Investigations by controlled source seismic experiments started around 1960 [Giese et al. 1976]. Further insight into the Alpine lithosphere brought the ALP 75 longitudinal profile [Alpine Explosion Seismology Group 1976, Aric & Gutdeutsch 1987, Yan & Mechie 1989]. A major effort was TRANSALP, a steep angle reflection profile crossing the central part of the Eastern Alps from Munich in the north to Venice in the south [Transalp Working Group 2002, Lüschen et al 2004]. The steep angle reflection profile was supplemented by wide angle observations [Bleibinhaus & Gebrande 2006], receiver function studies [Kummerov et al. 2004(?)], and gravimetric modelling [Ebbing et al. 2006,]. Short steep angle profiles were measured in NE Styria, near the Penninic Rechnitz window [Grasl et al. 2004].

Despite these efforts data was not sufficient to generate a 3D model of the crust and the Moho discontinuity at the same standard as in the Western Alps [e.g. Waldhauser et al. 1998]. A new chance to improve this situation has been the CELEBRATION 2000 and the ALP 2002 seismic experiments. These two experiments cover Europe from Poland to North Italy and Croatia, crossing the eastern part of the Eastern Alps. In this paper we report about results derived from this data in the Eastern Alps and their surrounding geologic provinces. We further introduce current investigations within the ALPASS – Alpine Lithosphere and Upper Mantle Passive Seismic Monitoring experiment.

## TECTONIC SETTING

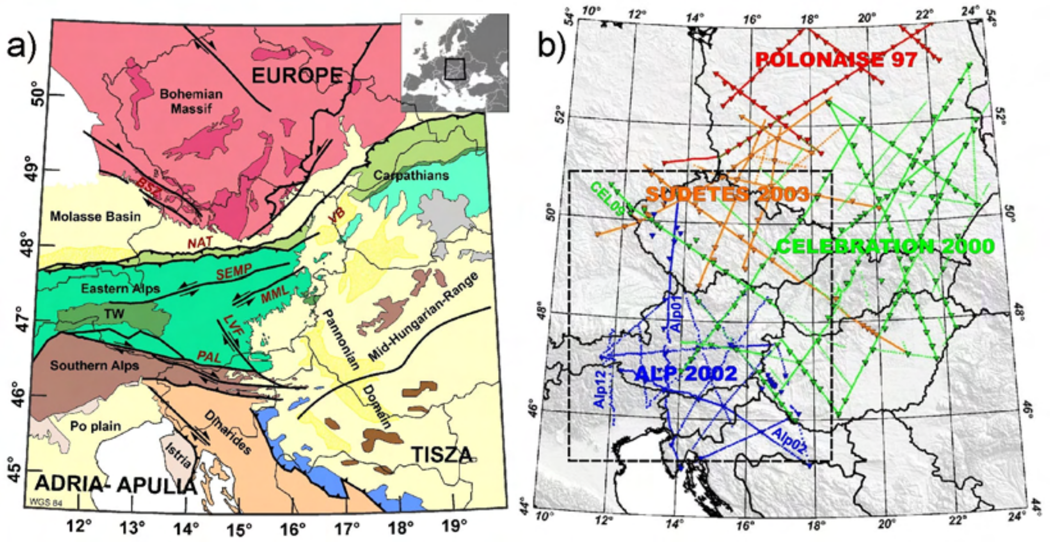


**Figure 1**: **(a)** Tectonic Setting (Eg.L. – Eger Line, NAF – North Alpine front, SEMP – Salzach-Ennstal-Mariazell-Puchberg fault; MML – Mur-Mürz Line, PAL – Periadriatic Lineament, LVF – Lavanttal fault, VB – Vienna Basin); **(b)** Field layout of recent large WAR/R experiments in Central Europe (POLONAISE'97, CELEBRATION 2000, ALP 2002, SUDETES 2003); CEL10, Alp01, Alp02, and Alp12 are profiles referred to in the text.

Most imprinting tectonic development of the Alps reach back to the opening of the Atlantic and Indian Ocean in Jurassic times, anticlockwise rotation of Africa and the closure of the Tethys Ocean [e.g. Le Pichon et al. 1988]. The Adriatic-Apulian micro-plate, which belongs to the African domain, collided with Europe in Late Cretaceous to Early Tertiary forming the Eastern Alps (**Figure 1a**). The nappe stack of the Eastern Alps overthrusted Flysch and Molasse to the north and builds the accretionary wedge. The Molasse basin represents the foreland and the Bohemian Massif, dipping to the south under Molasse, Flysch and the East Alpine nappes is part of the European platform. The Southern Alps, which continue into the Dinarides, follow south of the Peri-Adriatic Lineament (PAL). The Po plain represents the hinterland of the Alps, Istria the "rigid" Adriatic indenter. To the east the Eastern Alps transit to the Pannonian basin, to the north-east they continue over the Vienna basin into the Carpathians.

Tectonic structures related to convergence are the North Alpine thrust, the front of the Northern Calcareous Alp, and the South Alpine thrust. Crustal thickening took place due to the overthrusting of the accretionary wedge and fold-thrusting. The Penninic Windows were exhumed during these processes. Lateral extrusion and post-collisional crustal thinning took place by gravitationally induced extension to the Pannonian basin. A system of conjugate left and right lateral strike slip faults (SEMP, MML, LVF, PAL] has been activated or generated by this process [Aric and Gutdeutsch 1987, Ratschbacher et al. 1991]. The Vienna Basin (VB) was deepened in this tectonic regime by the pull-apart mechanism.

## NEW DATA

Huge amount of new seismic data was supplied by the Wide Angle Reflection / Refraction (WAR/R) experiments between 1997 and 2003 in Central Europe (**Figure 1b;** Guterch et al. 2003**)**. During these campaigns up to ~1000 single channel recorders were deployed along several profiles with a typical in-line spacing of 3 – 6 km. Shots were recorded not only along one profile, but simultaneously by all instruments. Thus a 3D coverage of the subsurface was achieved, offering the opportunity to apply innovative processing and interpretation techniques.

The data we used for our processing and interpretation comprise ~ 79,000 seismic traces acquired by the 3rd deployment of CELEBRATION 2000 (55 shots, 844 recorders) and the ALP 2002 experiment (39 shots, 947 recorders).

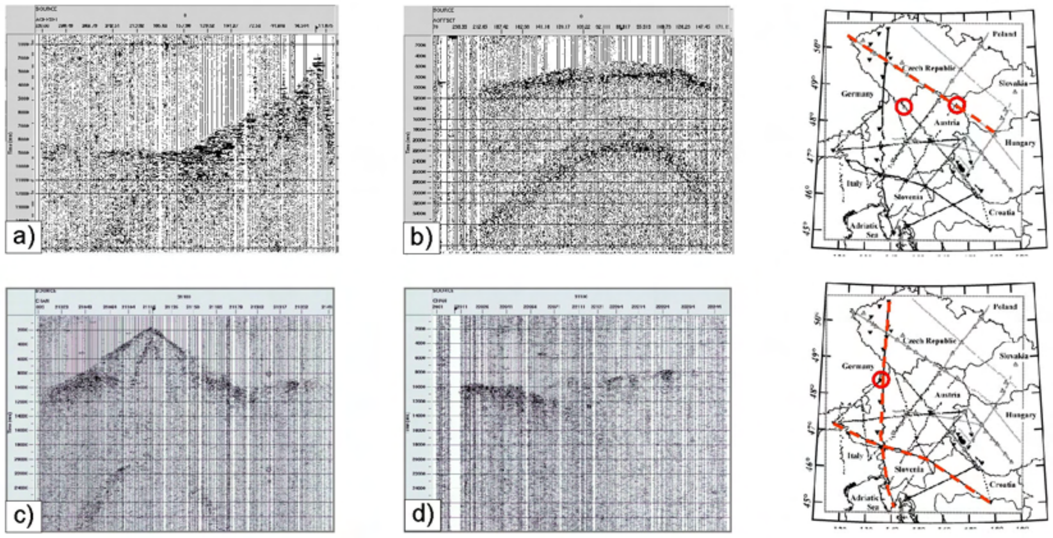


**Figure 2**: Examples of records from of CELEBRATION 2000, 3rd deployment and ALP 2002; **(a)** inline record, Bohemian Massif; **(b)** cross-line record, Bohemian Massif; **(c)** inline record, Alpine area; **(d)** cross-line record, Alpine area.

**Figure 2** shows examples of records from the Bohemian Massif (CELEBRATION 2000 data) and the Eastern Alpine area (ALP 2002). All these records have good signal to noise ratio. Inline shots (**Figures 2 a, c**) are easy to interpret in terms of the main crustal phases. Interpretation of cross-line shots is not so easy (**Figures 2 b, d).** The examples shown in **Figure 2** represent high data quality, which was not achieved by all of the recordings. Interpretation difficulty of cross-line shots and low signal to noise ratio, especially in parts of the Eastern Alpine area lead to application of stacking techniques. A model of the 3D P-wave velocity structure of the crust and a new Moho map have been generated by these techniques in combination with travel time tomography [Behm 2006, Behm et al. 2007]. Furthermore, 2D modelling of recordings along profiles has been carried out by classical interactive ray-tracing [e.g. Brückl et al. 2007].

## 3D VELOCITY STRUCTURE OF THE CRUST

**Figure 3** shows P-wave velocity slices through the upper (5 and 7 km depth), middle (10 and 14 km depth), and lower crust (21 and 29 km depth). Penetration depth of diving Pg-waves differed considerably over the investigation area, as can be seen from sparse coverage at greater depth.

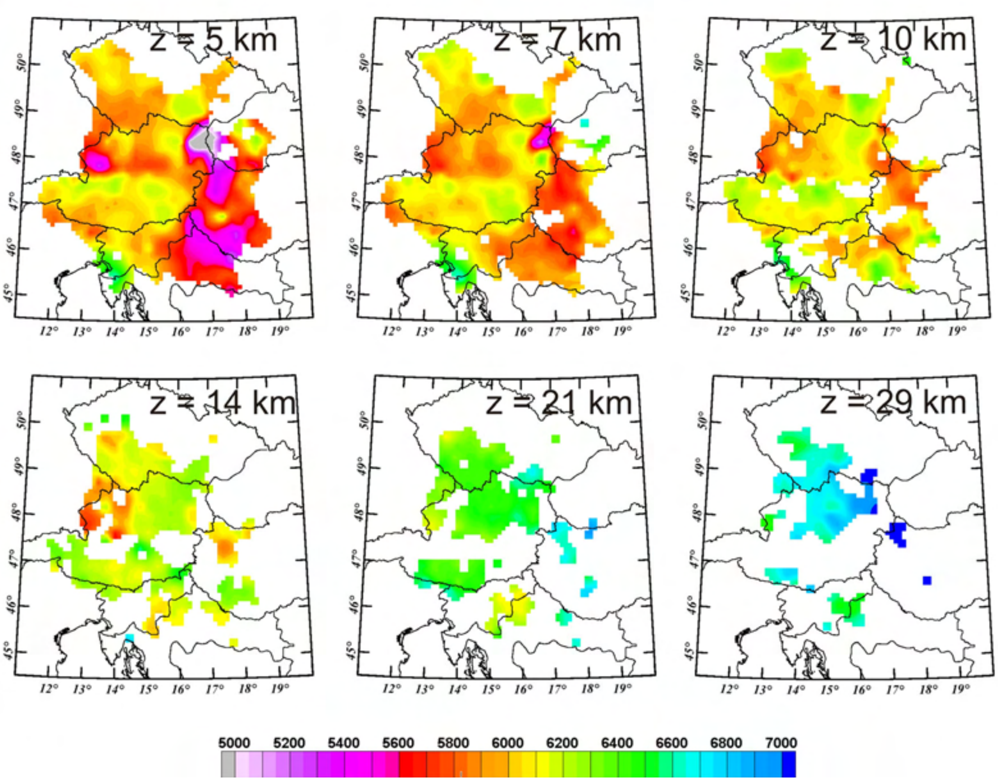


**Figure 3**: P-wave velocity slices through the crust at 5 – 29 km depth; scale of colour bar is m/s; redrawn after Behm [2006]

Velocities lower than 5 km/s correlate with tertiary basin fillings and are found down to 7 km depth in the Pannonian and Vienna Basins. At depths of 7 -14 km the Bohemian Massif is clearly differentiated into a central part (Moldanubian) with moderate velocities (5.5 - 6.1 km/s) and higher velocity areas (6.2 - 6.4 km/s) in northwest (Saxothuringian) and south-east (transition from Moldanubian to Moravian units). The peninsula Istria, a part of the unfolded Adriatic foreland, shows exceptionally high velocities in the uppermost crust (6.3 - 6.5 km/s). Relatively high velocities in the upper and middle crust are found in a belt north and north-east of the central Eastern Alps. The highest velocities (6.8 - 7.2 km/s) are found in the lower crust in an area extending from the south-eastern Bohemian Massif over the Vienna Basin to the north-western Pannonian Basin.

## NEW MOHO MAP

The application of stacking techniques to Pn- and PmP-phases, as well as the 3D delay time decomposition of Pn travel times (refraction tomography) indicate a fragmentation of the Moho in the investigated area into three parts: "Europe" (EU), "Adria" (AD) and the newly interpreted fragment "Pannonia" (PAN) (**Figure 4a**). The boundaries of these parts correlate with the strike of the Eastern Alps and the Dinarides. The Moho depths vary between 51 km in the Alpine region and 24 km in the Pannonian Basin. The European Moho dips to the south and the Adriatic Moho dips to the north-east. Both are interpreted to underthrust the Pannonian fragment. The vertical offset and fragmentation between Pannonian and the European Moho vanishes at the transition of the Eastern Alps to the Pannonian basin.

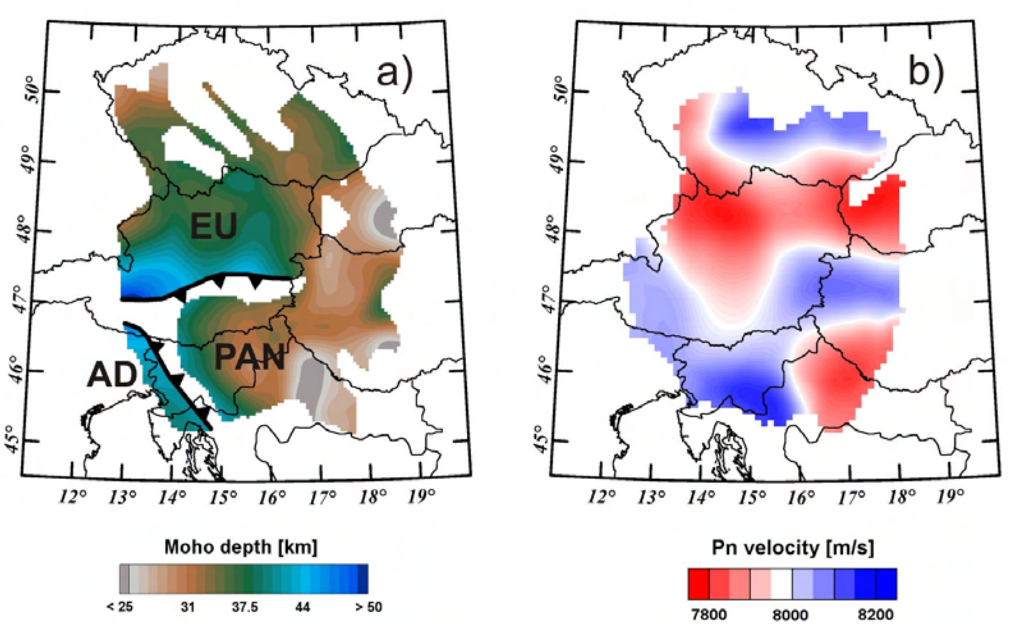


**Figure 4**: **(a)** Moho depth, **(b)** Pn velocity; redrawn after Behm [2006]

## 2D CROSS-SECTIONS

2D forward modelling using interactive ray-tracing techniques was applied to profiles of the investigation area. The longest profiles comprising the Eastern Alpine area are the north-south directed Alp01 and the WNW-ESE directed Alp02 [Brückl et al. 2007]. An important profile in the southern Bohemian Massif is CEL09 [Hrubcová et al. 2005]. Bleibinhaus et al. [2006] modelled in-line and cross-line data recorded at Alp12, where receivers were deployed along the former TRANSALP line. Further interpretations and publications of other profiles by interactive ray-tracing technique are in progress [e.g. Grad et al., submitted to GJI].

The P-wave velocity – depth section of profile Alp02 is shown as an example in **Figure 5.** This profile starts in the central part of the Eastern Alps and crosses the Tauern Window (TW) and takes its course sub-parallel to PAL, until it enters the Southern Alps, the Internal Dinarides, and by its last part the Tisza unit. P-wave velocities in the crust vary from 5.7 – 6.0 km/s near surface to 6.0 – 6.8 km/s in the lower crust. Moho-depth varies considerably from the Eastern Alpine region (~ 46 km) over the Southern Alps to the Internal Dinarides and the Tisza Unit (~ 28 km). A significant jump of ~ 10 km in under the Southern Alps has been interpreted as a crocodile structure.

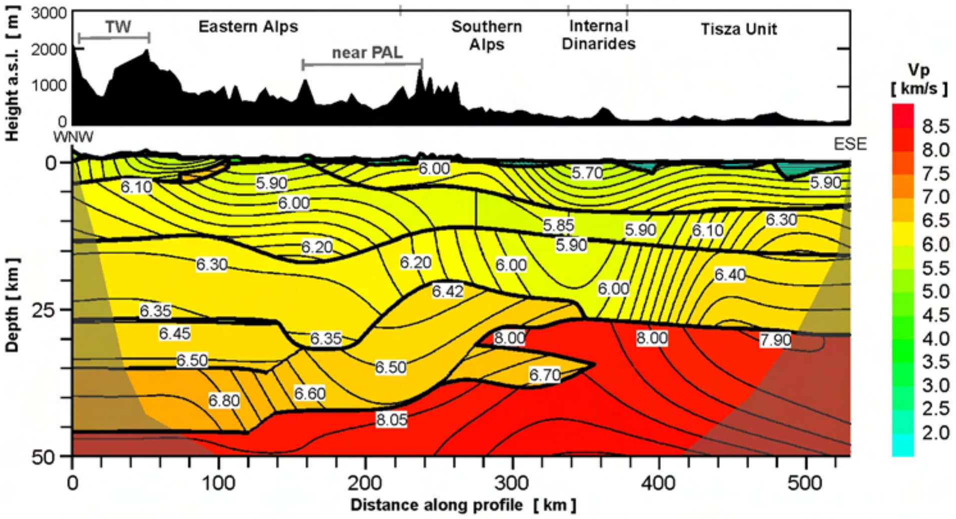


**Figure 5:** Alp02 P-wave velocity depth section (vertical exaggeration 4:1) with velocity bar; surface topography (vertical exaggeration 25:1) and major tectonic units are shown on top; redrawn after Brückl et al. [2007].

## INSIGHTS INTO TECTONIC PROCESSES

Collision between the European plate and the Adriatic micro-plate left its tectonic imprint on the crustal structure of the Eastern Alps in the western part of our investigation area. Tectonic interpretation of the NS directed Alp01 profile is an attempt to resolve these processes (**Figure 6**; for location see **Figure 1b**) [Brückl et al. 2007].

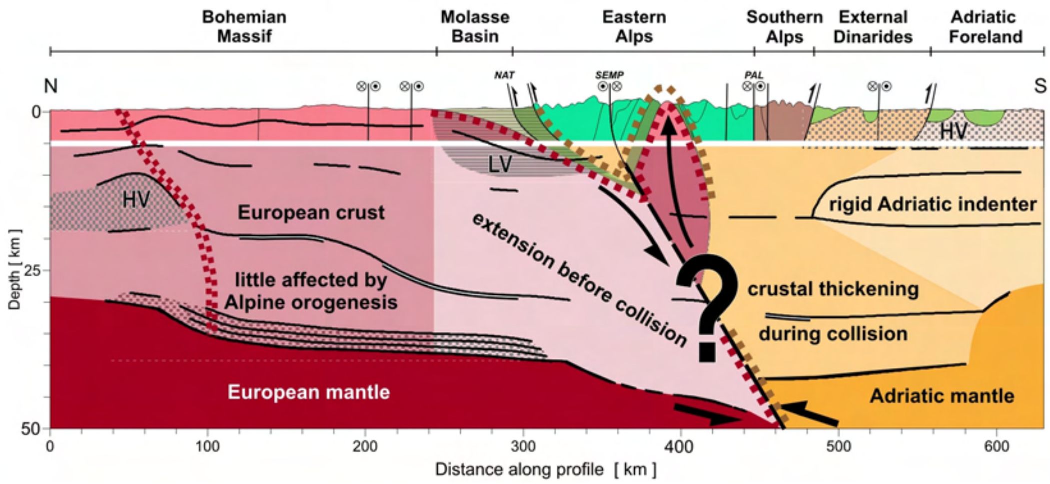


**Figure 6:** Alp01 tectonic model based on P-wave velocity depth section derived by forward modelling using ray-tracing techniques; for description see text; redrawn after Brückl et al. [2007].

The European Moho dips to the south below the Bohemian Massif and crystalline crust thickens. High velocity zones (HV in **Figure 6**), crustal reflectors and a reflective zone above the Moho distinguish the crust. However, we assume that the Bohemian Massif was little affected by the Alpine orogenesis in this part. To the south the European plate dips below the Molasse basin. The Flysch belt and the East Alpine accretion wedge overthrust the European plate. Extension prior to collision is indicated by thinning of the crystalline crust in this area. A low velocity zone (LV) below the Molasse Basin may be a consequence of this extension or the bending of the crust. We introduced the Sub-Tauern ramp, revealed by the TRANSALP transect [TRANSALP Working Group 2002] into our interpretation. Its location is constrained at depth by the jump of the Moho from the European to the Adriatic plate, and near surface by the SEMP. Exhumation of the Tauern Window (TW) was supported by fold-thrusting along this ramp. The northern part of the Adriatic crust thickened during collision. The "rigid" Adriatic indenter corresponds with the Istria high velocity zone (HV) and a higher Moho. The question mark over the Sub-Tauern ramp shows the zone where interpretation is most tentative.

The existence of a Pannonian fragment was derived from the Moho topography shown by the new Moho map (**Figure 4a**). The pronounced jump of the Moho at Alp02 (**Figure 5**) and a similar jump at the ALP'75 profile [e.g. Yan and Mechie, 1989] support this interpretation. **Figure 7a** is a schematic sketch of plate kinematics and interactions between Europe, the Adriatic micro-plate, and the Pannonian fragment. We assume that the crust of the Pannonian fragment belonged before and during collision to the Adriatic micro-plate. Lateral extrusion [Ratschbacher et al. 1991] accompanied by crustal thinning due to gravitationally induced extension forced isostatic Moho uplift and lead to the fragmentation. The interpretation of the Pn-phase stack, imaging the Moho along profile A-A' (**Figure 7b**) supports this idea. Subsidence of surface topography corresponds to Moho uplift at depth (indicated by arrows in **Figure 7b**). Ongoing NS compression is facilitated by underthrusting of the European as well as the Adriatic mantle below the Pannonian fragment.

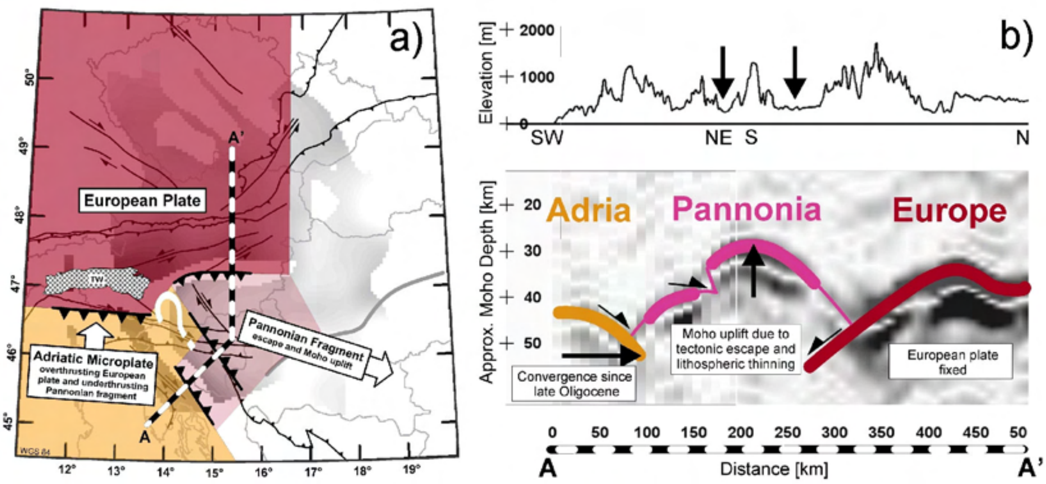


**Figure 7:** Generation of the Pannonian fragment – geodynamic model; **(a)** plate kinematics and interactions between Europe, the Adriatic micro-plate, and the Pannonian fragment; **(b)** interpretation of Pn-phase stack, imaging the Moho along profile A-A'.

## ALPASS – WORK IN PROGRESS

ALPASS is a passive seismic monitoring project aiming to reveal lower lithosphere and upper mantle beneath the wider Eastern Alpine region, and to contribute to a better understanding of the geodynamic processes at work [Mitterbauer et al. 2007]. By cooperation of Austria, Croatia, Finland, Hungary, Poland, and the USA 57 temporary seismic recording stations were deployed from May 2005 until May 2006. The layout (**Figure 8a**) was designed to extend the efforts of earlier experiments (e.g. TRANSALP) and to support two other passive seismic experiments (BOHEMA, CBP-Carpathian Basin Project) [Plomerova et al. 2003, Stuart et al. 2007], which are overlapping in the investigation area. Additionally, data from permanent networks was collected to improve coverage of the investigation area. 144 events (50% with M > 5.6) from epicentre distances between 30° and 100° were selected for teleseismic inversion. Travel time picking of P-wave arrivals has been done by a semi-automatic correlation technique. Crustal corrections benefit from the high resolution velocity model of the crust and the new Moho map derived from CELEBRATION 2000 and ALP 2002 data. Work on travel time picking, crustal corrections and inversion is in progress. An example of residual travel times calculated by subtracting IASPEI 91 travel times, applying the crustal corrections, and subtracting the mean is shown in **Figure 7b**. This data is one of more than 100 events, which are used for inversion.

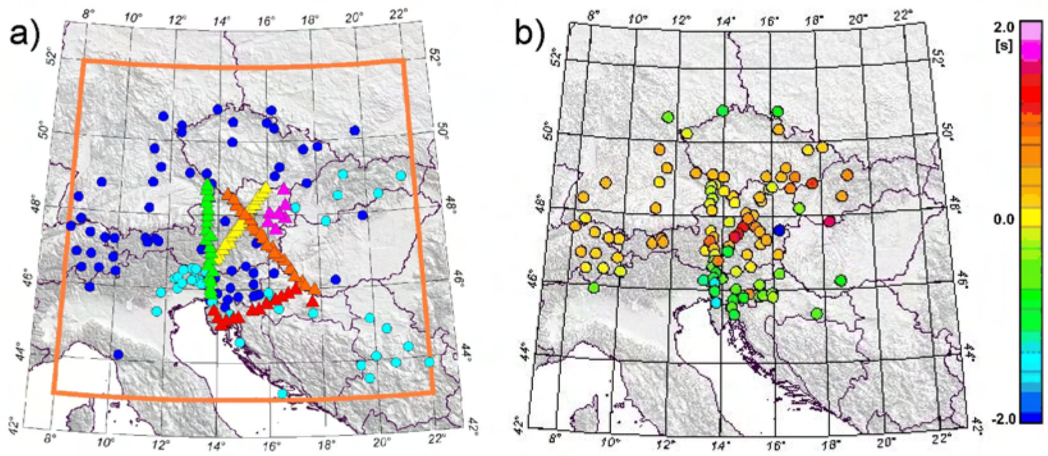


**Figure 8:** ALPASS – teleseismic tomography; **(a)** locations of temporary seismic stations (triangles) and permanent observatories (circles); **(b)** travel time residuals of the 05 10 05 Kuril Islands earthquake.

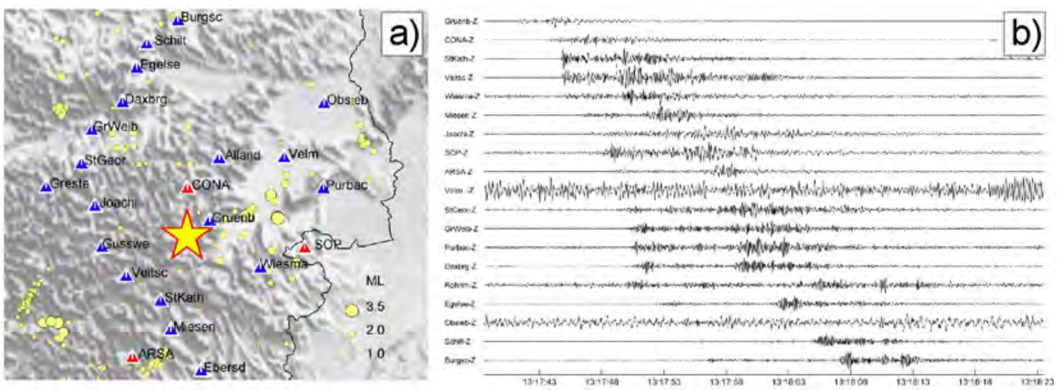


**Figure 9:** ALPASS – Relocation of local earthquakes; **(a)** location of temporal (blue triangles) and permanent (red triangles) seismic stations, epicentres of earthquakes during observation period (yellow circles, diameter represents local magnitude), **(b)** recordings of the 2006 04 15 13:17, Ml 2.2 earthquake (location marked by yellow star in 9a) by the temporal ALPASS stations.

Another goal of ALPASS is relocation of local earthquakes. We first concentrate on the Vienna Basin and the upper Mürz valley. ALPASS and permanent seismic stations used for this investigation, and earthquakes occurring in this area during the observation period are shown in **Figure 9a**. Recordings of the 2006 04 15 13:17, Ml 2.2 event (location marked by yellow star in 9a) is shown in **Figure 9b**. Relocation will benefit from the seismic velocity model of the crust and the uppermost mantle . By accurate locations and - in case of sufficient data quality - source mechanisms derived by waveform modelling, we expect new information on seismogenic faults and their relation to known tectonic structures.

We expect both aspects of the ALPASS project will support and extend the results achieved by the recent controlled source seismic experiments. The teleseismic tomography will bring more light into the mantle structure and general plate tectonic regime, especially the existence and orientation of subducting slabs. Relocation of local earthquakes will image active faults. These structures were not resolved directly by the WAR/R type controlled source seismic experiments presented in this paper.


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