# A New Seismic Model of the Eastern Alps and its Relevance for Geodesy and Geodynamics



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**Abstract**

Between 1997 and 2003, Central Europe was the target of large international seismic programs to investigate the upper lithosphere. So far, new results concerning the Eastern Alpine region include a 3D model of the P-wave velocity in the crust and a map of the Mohorovicic discontinuity (Moho) and interpretations of two representative profiles.. Taking gravity data into account, these models provide also insights into the density distribution of the lithosphere and isostatic compensation. The lateral distribution of the crustal velocities and the new Moho map enable to determine a significant fragmentation of the lithosphere. The inferred kinematics of the crustal blocks is closely related to Neogene tectonics and displacements observed by GPS.

**Kurzfassung**

In den Jahren 1997–2003 wurden in Zentraleuropa unter Beteiligung von 17 Nationen ausgedehnte seismische Experimente durchgeführt, welche der Untersuchung der oberen Lithosphäre dienen. Die bisherigen Ergebnisse für den Bereich der Ostalpen und umliegender Gebiete umfassen die 3-dimensionale Verteilung der P-Wellengeschwindigkeit in der Erdkruste und eine neue Tiefen- und Strukturkarte der Mohorovicic-Diskontinuität. In Verbindung mit Schweredaten ermöglicht dieses Modell Rückschlüsse auf die Dichteverteilung in der Lithosphäre und die Isostasie. Die Struktur der Mohorovicic-Diskontinuität und die laterale Verteilung der P-Wellengeschwindigkeiten innerhalb der Erdkruste ergibt eine Fragmentierung der Lithosphäre. Die daraus ableitbare Kinematik der tektonischen Blöcke steht mit neogenen geologischen Vorgängen und aktuellen, geodätisch beobachteten Verschiebungen in engem Zusammenhang.

## Geology and tectonic setting of the Eastern Alps and their surrounding provinces

The major geologic units of the Eastern Alps and their surrounding tectonic provinces are shown in Figure 1 [Schmid et al. 2004, Oberhauser 1980, Franke and Żelaźniewicz 2000]. The Bohemian massif in the north represents the European platform. To the south, European crust dips below the Molasse basin, the foreland of the Alpine orogen. The Molasse basin is overthrusted to the north by the accretionary wedge of the Eastern Alps, which comprises of the Flysch belt and the Austro-Alpine nappes. European crust has been exhumed in the Tauern Window. The Periadriatic lineament (PAL) separates the Eastern Alps from the Southern Alps. The Southern Alps share similar lithologies with the Eastern Alps, but exhibit a southward directed vergency. They are bounded to the south by the External Dinarides and the Adriatic foreland (Po plain and peninsula Istria). To the north-east, the Eastern Alps continue into the Carpathians, while the Pannonian domain, which comprises parts of the Internal Dinarides and the Tisza unit, marks the south-eastern border of the Eastern Alps. The Pannonian domain is interrupted by the Mid Hungarian Line (MHL), an important SW-NE trending fault zone.

The tectonic structure of the Alps results from a long and ongoing evolution, initiated contemporary with the opening of the Atlantic Ocean in the early Jurassic, approximately 180 Million years ago. Major geodynamic processes of the Eastern Alps include a first orogenic cycle in the Cretaceous (Eoalpine phase), resulting from the subduction of the Triassic Meliata Ocean, the subduction of the Alpine Tethys in the Tertiary, and the subsequent continent-continent collision between the European and Adriatic-Apulian plates. Crustal shortening of the Eastern Alps in north-south direction followed. The maximum extent of shortening is assumed to be 100 km, which corresponds to 50% of the original width. Since the Late Oligocene and Early Miocene, the ongoing north-south oriented compression of the Eastern Alps has been accompanied by vertical and lateral extrusion and tectonic escape of large crustal wedges to the unconstrained margin represented by the Pannonian basin in the east.

Major normal (e.g., Brenner, Tauern East) and strike-slip fault systems (Periadriatic line, Salzach-Enns-Mariazell-Puchberg line, Mur-Mürz line) were formed or reactivated by this tectonic process [Ratschbacher et al. 1991]. Within this tectonic regime, the Vienna basin and several intra-alpine basins were generated by the pull-apart mechanism.

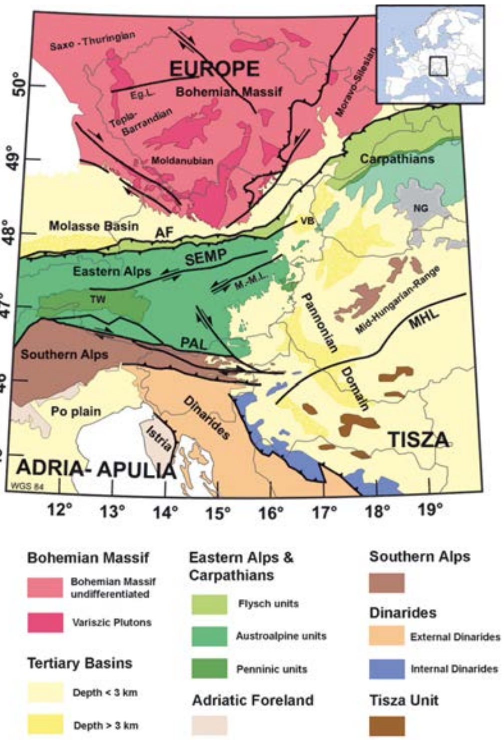


*Figure 1: Tectonic setting of the investigated area [Schmid et al. 2004, Oberhauser 1980, Franke and Żelaźniewicz 2000]. SEMP: Salzach-Enns-Mariazell-Puchberg line; M.-M.L: Mur-Mürz line; Eg.L: Eger line; AF: Alpine Front; PAL: Perdiadriatic lineament; MHL: Mid-Hungarian Line; TW: Tauern Window; VB: Vienna Basin; NG: Neogene Volcanics*

Key questions concerning the geodynamic evolution of the Eastern Alpine lithosphere are the direction of subduction, the significance of major fault systems and their imprints in the deep crust, the continuation of large tectonic units into depth and the composition of the lower crust. Seismic models are of great importance for addressing these subjects.

### Seismic experiments

Seismic investigations in the Eastern Alps started in the early 1960's with refraction lines around the quarry Eschenlohe [Giese and Prodehl 1976]. Among further important refraction lines are ALP75, ALP77, and ALP78, which cover large parts of Austria and north-eastern Italy. Several 2D interpretations derive from these experiments [Miller et al. 1977; Aric et al. 1987; Yan and Mechie 1989; Scarascia and Cassinis 1997]. TRANSALP was a large interdisciplinary project targeting the crustal structure of the Eastern Alps along transect from Munich to Venice [Lüschen et al. 2004; Bleibinhaus and Gebrande 2006]. Its core formed a 300 km long NS oriented reflection line. Three short reflections lines (altogether ~100 km length) were shot between 1992 and 2001 at the eastern edge of the Eastern Alps [Weber et al. 1996; Grassl et al. 2004], focussing on Penninic units and their relation to deeper structures.

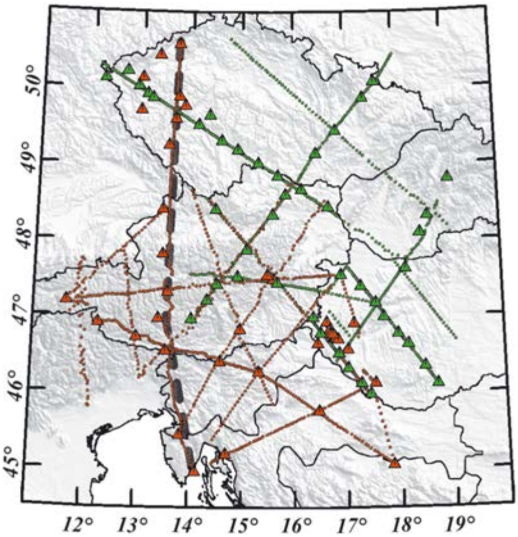


*Figure 2: Layout of the experiments CELEBRATION 2000 (green; $3^{rd}$ deployment) and ALP 2002 (red). Triangles indicate shot locations, and small circles represent recorders. The dotted grey line shows the orientation of the profile Alp01.*

CELEBRATION 2000 and ALP 2002 were among an unprecedented series of large international 3D wide-angle refraction and reflection (WAR/R) experiments to investigate the lithosphere of Central Europe [Guterch et al. 2003]. Both projects comprised the combined efforts of 15 nations. ALP 2002 was initiated and led by the Institute of Geodesy and Geophysics at the Vienna University of Technology [Brückl et al. 2003]. The layout of the projects is shown in Figure 2. In this study we use data from the $3^{rd}$ deployment of CELEBRATION 2000, which included 55 shots and 844 receivers deployed along 7 profiles (total length of approximately 2800 km). Furthermore all 39 shots and 947 receivers (4300 km profile length) along 13 profiles from the ALP 2002 experiment were integrated. Shot charges were 300 kg on average and were distributed to 5 boreholes of 50 m depth. The receivers were mainly single channel recorders with pre-programmed recording time windows. The average receiver distance was 2.9 km on high density profiles and 5.8 km on low density profiles. Approximately 900 record sections and a total of about 79,000 traces were obtained.

## Interpretation of seismic data

The wave field reflects the complex tectonic setting (Figure 3). Our interpretation aims at modelling the P-wave velocity distribution in the crust and the uppermost mantle. Thus we utilise compressional waves that dive through the crust (Pg), which are reflected from the Moho (PmP), and which travel through the uppermost mantle (Pn). The velocity distribution is described in terms of smooth variations and/or first-order discontinuities (e.g., Moho).

The traditional interpretation method of WAR/R data is 2D interactive modelling based on ray tracing. This method provides detailed information on the velocity distribution within the crust and the uppermost mantle, in particular when intracrustal reflections (Pc) are additionally considered. However, this kind of interpretation is restricted to inline data where shots and receivers are aligned along one profile. Inline data amount to only ~20% of the whole data set. The remaining ~80% are crossline data, which represent recordings of shots with a lateral offset to receivers arranged along a profile.

Besides interactive modelling, other common methods are 2D and 3D travel time tomography that require high signal-to-noise (S/N) ratio of the data [e.g., Hole 1992]. In particular young orogens, such as the Eastern Alps, are characterized by complicated structures that lead to scattering of seismic energy and therefore a low

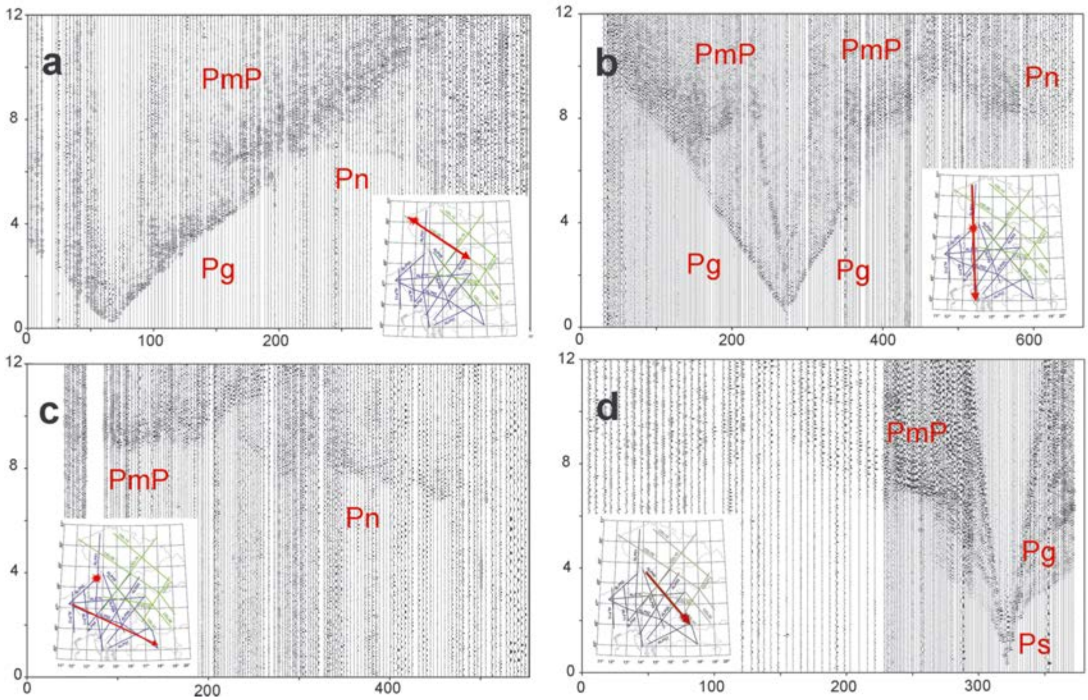


*Figure 3: Examples of record sections, reduction velocity (linear move-out correction) is 8 km/s. Horizontal axis: profile coordinate [km]; Vertical axis: Reduced arrival time* (a) *inline recording along 400 km of profile CEL09;* (b) *inline recording along 650 km of profile Alp01;* (c) *crossline recording along 550 km of profile Alp02;* (d) *inline recording along 370 km of profile CEL07. Note the varying quality of diving waves through sediments (Ps) and crust (Pg), of waves reflected from the Moho (PmP), and of waves travelling through the uppermost mantle (Pn).*

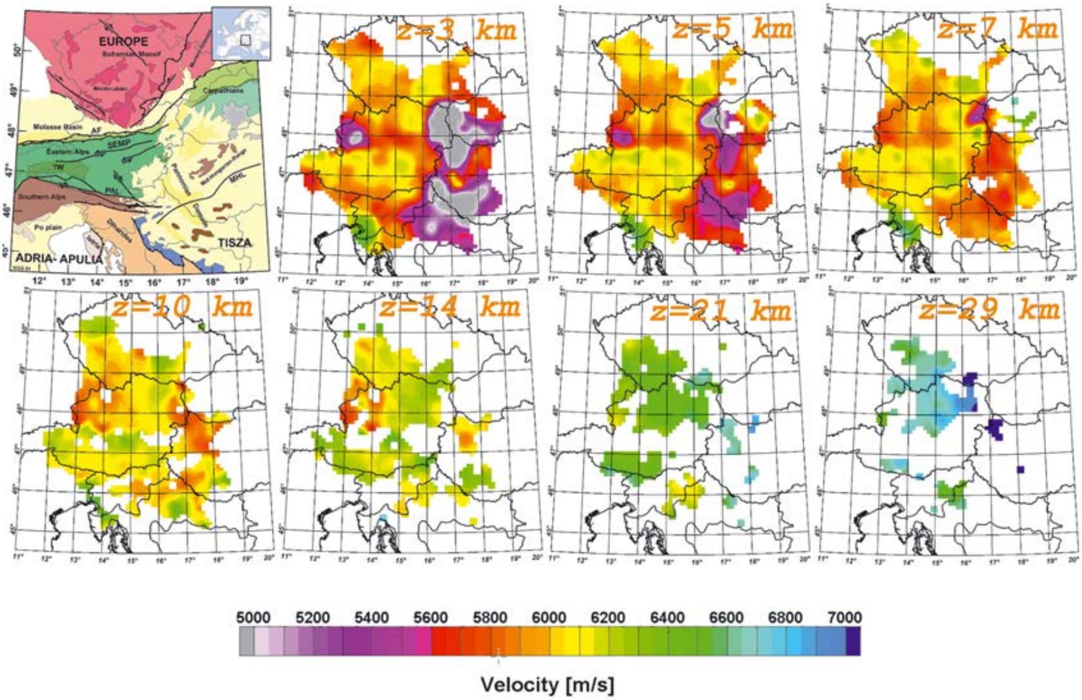


*Figure 4: 7 selected horizontal slices at different depths through the 3D P-wave velocity model of the crust.*

S/N ratio. In case of 3D tomography, it has to be taken into account that travel times from crossline recordings are much more difficult to interpret than from inline recordings.

For these reasons we further developed and applied 3D methods, which increase the S/N ratio and simplify the wave field. This ensures the use of the full data, regardless wether they represent crossline or inline recordings. The approach is based on a signal detection algorithm [Astiz et al. 1996] and stacking and inversion techniques especially designed for 3D WAR/R data [Behm et al. 2007]. The outcome of the methods are robust 3D models, which are not restricted to vertical sections along the individual recording profiles, but provide real 3D coverage.

In case of the crust, we stack Pg waves. Travel times are picked from stacked data and are inverted for P-wave velocities. Stacked data are supplemented by travel times from the original single-fold record sections (Figure 3) wherever the S/N ratio is high. Finally, a smooth 3D P-wave velocity model of the crust is obtained. Horizontal slices through this model are shown in Figure 4. In the uppermost crust (0–3 km), the velocities correlate well with the tectonic setting. Low velocities represent Neogene basin fillings. Very high velocities are found in the unfolded Adriatic foreland. The most remarkable features down to depths of 10 km are pronounced velocity contrasts between segments that are related to different terrains of the Bohemian massif (Saxothuringian, Moldanubian, Moravo-Silesian) and Austro-Alpine units. These contrasts are also partially identified in the middle crust (10–20 km). Furthermore, in this depth range the Mid-Hungarian line correlates with a separation of low from high velocities. In the lower crust (> 20 km), the coverage of the model allows to interpret "normal" velocities in the Alps and the north-western part of the Bohemian Massif, compared to "anomalous" high velocities at the transition from the Bohemian Massif to the Alps and Pannonian Domain.

The Moho topography has been evaluated by a delay time approach based on stacked Pn waves. Delay times are proxy of Moho depths and are converted to depths with the velocity model of the crust. Again, the model provided by stacked data is supplemented by travel times of single fold

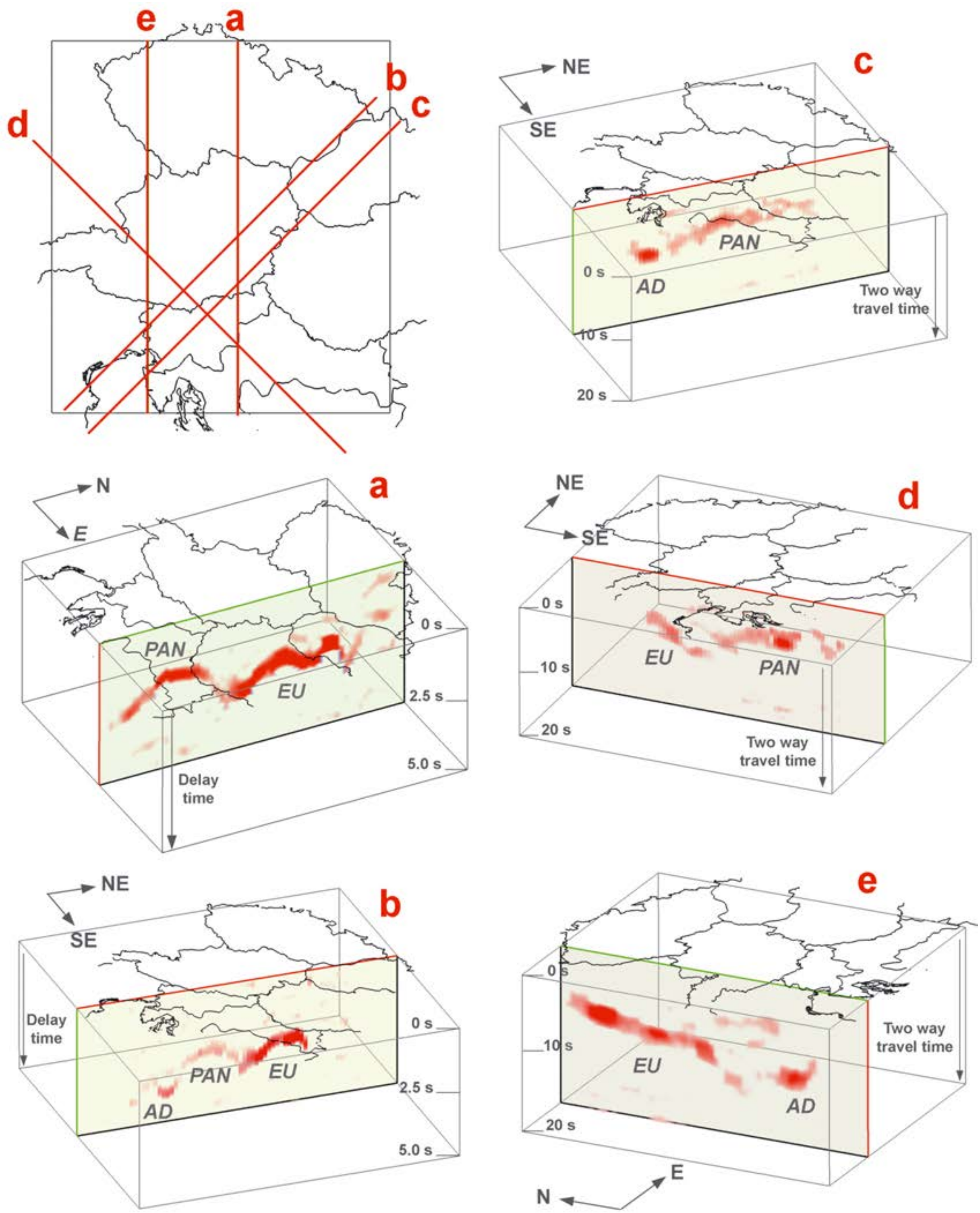


*Figure 5:* Slices through the 3D volume of Pn (a, b) and PmP stacks (c–e), highlighting the observed Moho fragmentation. EU: European Moho; AD: Adriatic Moho; PAN: Pannonian Moho. The "red bands" are stacked waves associated with the Moho, and the intensity of the red colour is equivalent to the amplitude of the stacked waves. The stacks are shown in the time domain and the reference level (zero time) is the depth of 10 km. For PmP stacks, the range of the time axis (two way zero offset travel time) is 20 s. For Pn stacks, the range of the time axis (delay time) is 5 s.

traces. Further, reflections from the Moho (PmP) are stacked to gain additional information on the Moho topography. The procedures yield 3D volumes of stacked Pn and PmP waves such that the coverage is not restricted to the profiles.

The stacked Pn and PmP data further enable to identify vertical offsets at the Moho. We interpret a pronounced fragmentation of the Moho (Figures 5a–5e) and identify the new plate fragment "Pannonia" located between the European platform in the North and the Adriatic microplate in the South-West. The Pannonian Moho is underthrusted by both the European and Adriatic Moho. The regions of underthrusting correlate well with the Alpidic and Dinaric orogens. The Moho depths vary between 24 km in the Pannonian Domain and 51 km at the central part of the Eastern Alps where the three plates collide (Figure 6). Previous 2D investigations [Yan and Mechie 1989, Scarascia and Cassinis 1993] are in agreement with the introduction of the Pannonian fragment.

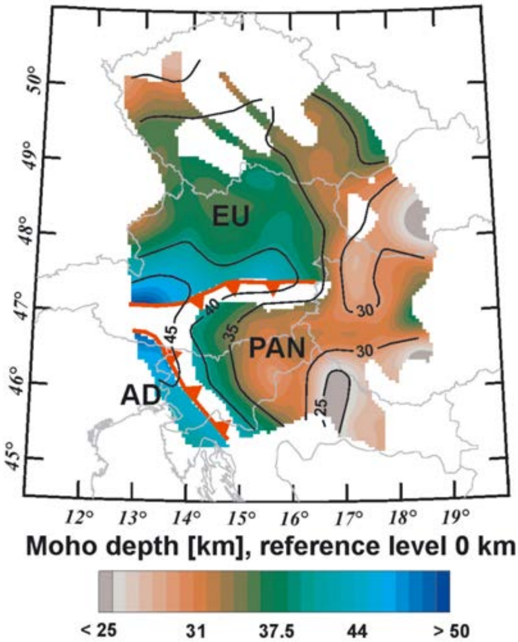


*Figure 6: Moho depth map, colour coded with superimposed continuous isolines. The fragmentation into European plate (EU), Adriatic microplate (AD) and the Pannonian fragment (PAN), as derived from the 3D volume of stacked Pn and PmP waves, is visualized by thrust symbols. Gaps result from lack of data.*

The analysis of Pn waves leads also to a map of the velocity distribution in the uppermost mantle (Figure 7). Although the uppermost mantle velocities are not as well constrained as the crustal velocities, we can separate relatively low velocities in the Pannonian domain from higher velocities in the Adriatic part. Lower upper mantle velocities are also found at the transition from the Bohemian Massif to the Alpine area.

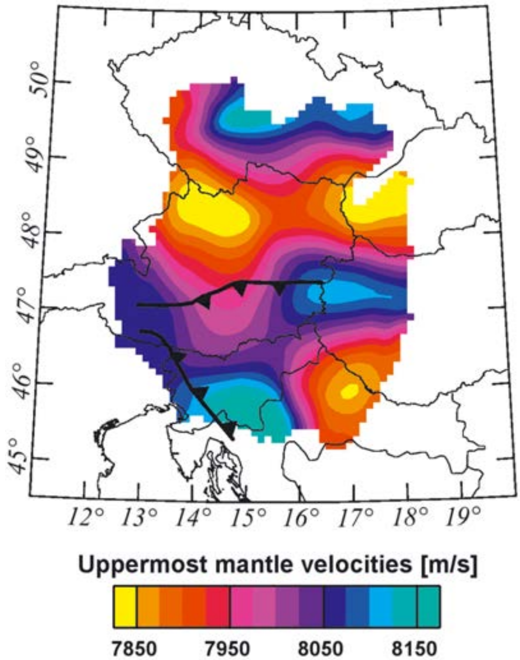


*Figure 7: Map of the uppermost mantle velocity (Pn velocity). The interpreted fragmentation of the Moho is indicated by thrust symbols.*

Additionally to 3D modelling, interactive 2D modelling based on ray tracing has been used to interpret profiles with high density receiver layout and a high number of shots. By interactive modelling, the velocity model along the profile is optimized by trial and error until a satisfying fit between observed and modelled seismic phases is achieved. Travel times, rays and synthetic seismograms were calculated with the ray tracing package SEIS83 [Červený and Pšenčík 1983]. The initial model is generated by tomographic inversions of first arrival travel time data [Hole 1992] and a priori information on near surface structures like Neogene basins [Brix and Schultz 1993; Saftić et al. 2003].

The main profiles of the ALP 2002 experiment are Alp01 (650 km, N-S, 212 receivers, 13 shots) and Alp02 (550 km, WNW-ESE, 151 receivers, 8 shots). In Figure 8 we show a preliminary interpretation of Alp01 [Behm et al. 2006], the final interpretation will be presented by Brückl et al. [in print]. The most important findings from these profiles are a down-dipping European Moho below the Adriatic mantle (Alp01) and a sudden Moho uprise at the transition from the Alpine area to Pannonian domain (Alp02). In general, the results confirm the main findings of the 3D model as the fragmentation into three plate fragments and certain high and low velocity regions in the crust. By careful evaluation of crustal and Moho reflections (Pc and PmP phases) the 2D modelling based on ray tracing yields also velocity information in parts of the lower crust where the 3D-velocity model lacks coverage.

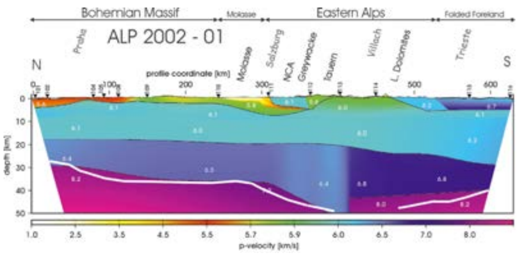


*Figure 8: 2D model along the profile Alp01 derived by interactive ray tracing. Numbers show the velocity in km/s. The Moho is located at the transition from the blue to the violet coloured region. The white line shows the Moho depth obtained from 3D modelling. Inverted triangles and numbers at the surface indicate shot points. Vertical exaggeration is 5:1.*

Analysis of sensitivity and accuracy [Behm 2006] provide estimations of errors of the velocity models and the Moho depth map. On average, the accuracy of velocities ranges from ±60 m/s in the upper crust to ±100 m/s in the middle and lower crust. Depending on the coverage, the accuracy of Moho depths varies between ±1 km and ±3 km.

## Implementation of gravity data

Senftl (1965) derived a Bouguer gravity map of Austria from data acquired for hydrocarbon exploration and geodetic purpose along the benchmarks of levelling lines based on approximately 2000 stations. The gravimetic net has been densified since the Gravimetric Alpine Traverse [Meurers et al. 1987, Meurers 1993]. Use of this data was made in the eastern part of our investigation area by Lillie et al. [1994], who focused on regional studies extending from the Eastern Alps to the Carpahtians and Pannonian Basin. In the western part of our investigation area the Eschenlohe seismic profiles [Braitenberg et al. 1997, Dal Moro et al. 1998] and the TRANSALP transect served as constraints for gravimetric inversions and investigations of isostasy [Ebbing et al. 2001, Ebbing 2002, Braitenberg et al. 2002, Ebbing 2004]. A gravimetric study, using the seismic 3D-model of the Eastern Alps and their surroundings derived from CELELEBRATION 2000 and ALP 2002 data, as described above, was made by Brückl et al. [2006a]. The main purpose of this study was to supply additional constraints for P-wave velocities in the lower crust derived from gravity, since the seismic 3D model does not cover these depths sufficiently. Methods and results of this study will be described briefly in the following paragraphs.

The used gravity data (Figure 9) are compiled from "New Austrian Bouguer Map" [Kraiger and Kühtreiber 1992] and the Bouguer gravity map of the West East European Gravity Project (http://www.getech.com). The density for reduction of masses is d = 2670 kg/m$^3$. The authors use the orthometric height system in such a way that rather masses above the geoid are reduced than those above the ellipsoid. This leads to the geophysical indirect effect that in Austria is widely negligible at the accuracy level of the Bouguer gravity.

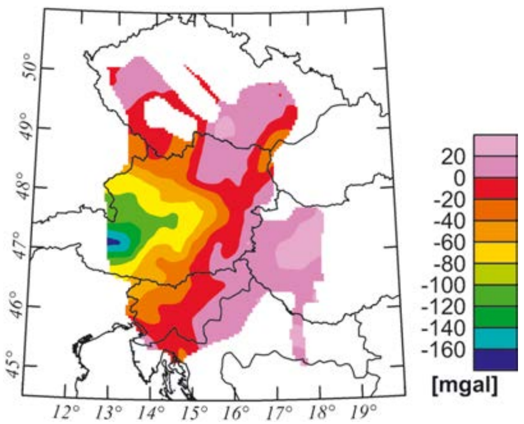


*Figure 9: Bouguer gravity map of the investigation area compiled from data of the West East European Gravity Project and the Ldquo;New Austrian Bouguer Map" (for references see text).*

Densities can be estimated from correlations with seismic P-wave velocities. Sobolev and Babeyko [1994] derived a relation between P-wave velocity and density that considers the thermal gradient and the mineral transformations within the crust with changing PT conditions. As only few observations on the geothermal gradient are available within the Eastern Alps [Sachsenhofer 2001], we chose the Christensen and Mooney [1995] velocity-density relationship. This relationship requires only P-wave velocity data to estimate crustal densities. The Moho depth map (Figure 6) is a further constraint to the gravimetric modelling. However, as pointed out before, the seismic velocities of the lower crust are the most uncertain parameters, and these errors are also propagated to the Moho depths. For this reason we convert the Moho depth map to the time domain. The Moho depth in the time domain (Tm) is the travel time of a P-wave from surface to Moho along a vertical straight ray. This quantity is much less sensitive to errors of crustal velocities than the Moho depth itself. Therefore, Tm has been used as constraint for our gravimetric modelling.

The 3D seismic model covers the upper crust down to 10 km depth almost entirely. Thus we decide to generate a density model from this data by the Christensen and Mooney velocity-density relationship and subtract its gravity effect from the Bouguer anomaly. The next step is to calculate the gravity effect of the middle and lower crust between $Z = -10$ km and the Moho. For this purpose we select a series of reasonable linear velocity-depth functions, convert them to density-depth functions by the Christensen-Mooney relationship, and calculate Moho depths from Tm for each velocity-depth function. We assume that an optimum velocity-depth function and the corresponding density-depth function removes the correlation between Tm and the residual of the Bouguer gravity after subtraction of the effect of the whole crust. The velocity function with 6102 m/s at 10 km depth and 7174 m/s at 50 km depth fulfills this condition. Corresponding densities are 2758 $kg/m^3$ (10 km) and 3210 $kg/m^3$ (50 km). The mantle density is assumed to be 3270 $kg/m^3$. Our approach to determine an optimum average density-depth function for the middle and lower crust is similar to Nettleton's method to derive the density of topographic masses. In Nettleton's method the optimum topographic density corresponds to a zero correlation between Bouguer anomaly and terrain elevation.

The residual Bouguer gravity after subtraction of the gravity effect of the whole crust is shown in Figure 10. The reference density model of the upper lithosphere is 2670 $kg/m^3$ for the uppermost 10km, 2900 $kg/m^3$ from 10 km to Moho and 3270 $kg/m^3$ for the upper mantle. The residual Bouguer gravity shows significant correlations with tectonic structures (compare Figures 10 and 1). Gravity lows correlate with the South Bohemian Pluton, which has significantly lower densities than the metamorphic part of the Bohemian Massif [Meurers 1993], and with the Tauern Window [see also Ebbing 2002]. Evidence for an Adriatic-Apulian plate dipping below the assumed tectonic block "Pannonia" and the Dinarides is indicated by positive anomalies. Strong positive anomalies are also found in the transition from the Northern Pannonian domain (Vienna Basin) to the European platform, where the seismic models show high velocities in the lower crust.

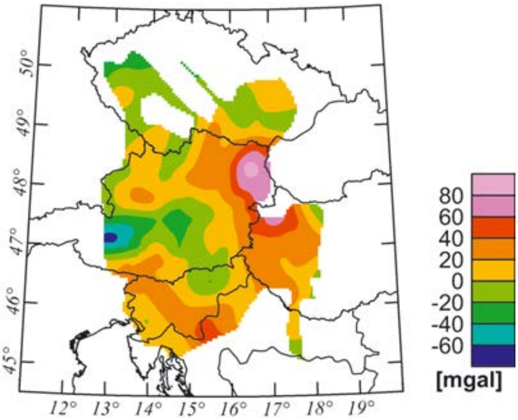


*Figure 10: Residual Bouguer gravity, the effect of the whole crust subtracted.*

The sources of the residual Bouguer gravity are most probably located within the crust, as could be demonstrated by tests with sources at different depth levels. Finally, we model the residual Bouguer gravity by superimposing density variations on the average density below 10 km depth. Back transformation of the densities to velocities yields average P-wave velocities for the crust below 10 km depth, which are mainly gravimetrically derived (Figure 11a). For comparison the average P-wave velocities derived only from seismic data (3D and 2D models) are shown in Figure 11b. The differences between the seismically and gravimetrically determined velocities vary between $-381$ m/s and 362 m/s with a mean and standard deviation of $-7 \pm 147$ m/s. Corresponding values for the Moho depths are $-3.8$ km, $+2.7$ km, and $+0.1 \pm 1.2$ km. These figures are in accordance with the Moho depth errors we estimated for the seismic model. However, only few structural features in the two velocity maps (Figures 11a, b) show similarity, which should be the topic of further investigations

Finally, density models from seismic and gravimetric modelling are combined. The vertical loading stress at $Z = 50$ km (a level below the orogen root), derived from the loads of this model is shown in Figure 12. The base area of the vertical colums is 20 km times 20 km and only local compensation is considered. The standard

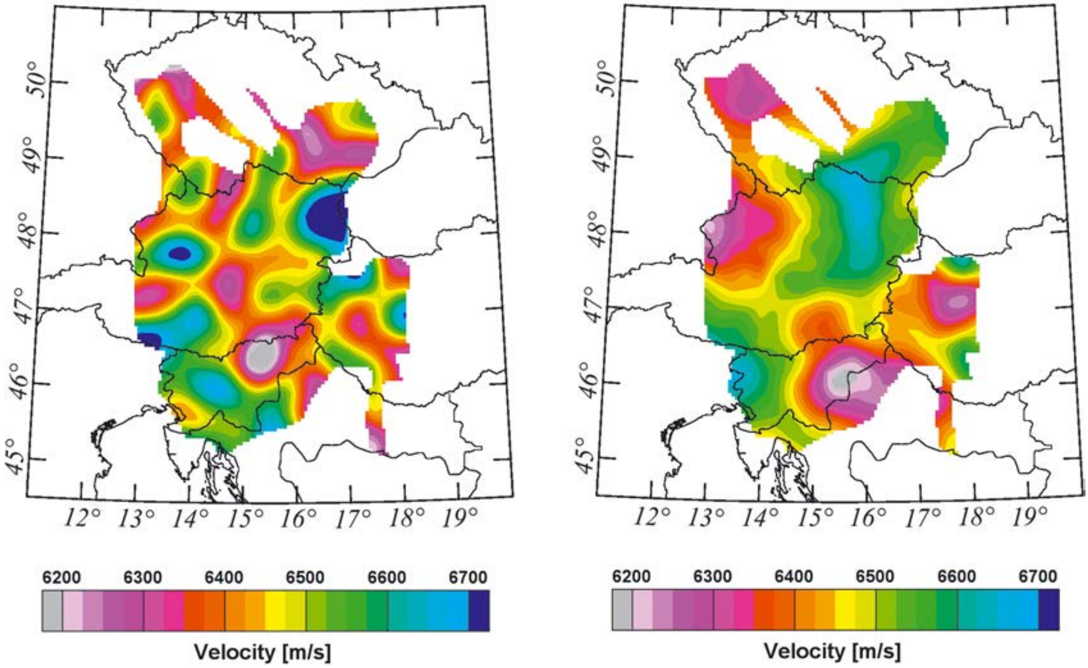


*Figure 11: Average P-wave velocity of the middle and lower crust from 10 km to Moho depth;* (a) *from gravimetric data;* (b) *from seismic data.*

deviation from Airy isostatic equilibrium at $Z = 50$ km is $\pm 6$ MPa. The corresponding value at $Z = 0$ km is $\pm 11$ MPa. These figures and the corresponding variances demonstrate that the major part of the surface loads is compensated by Airy isostasy. Ebbing et al. [2006] derived deviations from isostatic equilibrium in the same order of magnitude in the central part of the Eastern Alps (TRANSALP) at depth levels between 60 and 300 km.

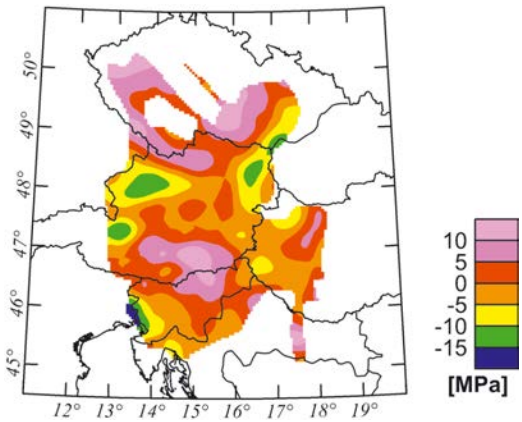


*Figure 12: Vertical loading stress at $Z = 50$ km, derived from the loads given by our density model. The values are relative to the reference lithosphere.*

**Geodynamic interpretation**

The outcome of the CELEBRATION 2000 and ALP 2002 projects concerning the Eastern Alpine region can be related to geodynamic processes. Some structures in the geophysical models, like the seismic velocity distribution in the Bohemian massif, or the low velocity European basement below the Molasse basin, find their explanation in processes that took place during pre-Alpidic orogenetic cycles, or the development of the Penninic Ocean. The high upper crust velocities at the peninsula Istria suit the concept of an Adriatic indenter. The high lower crust densities below the Vienna basin and the north-western Pannonian basin are relevant for isostatic compensation and may be explained by magmatic underplating during the generation of these basins by the pull-apart mechanism.

The most prominent tectonic structure revealed by the CELEBRATION 2000 and ALP 2002 projects is the Pannonian fragment. According to our interpretation [Brückl et al. in print] the Adriatic microplate and the Pannonian fragment formed one single unit during the collision process (Late Cretaceous until Early Oligocene). Since the onset of extrusion and tectonic escape in Late Oligocene / Early Miocene, significant upper crustal tension took place. The corresponding flattening of surface topography in the eastern part of the Eastern and Southern Alps has been compensated by a pronounced thinning of the whole crust and an upward jump of the Moho discontinuity of ~10 km. This interpretation is further supported by low seismic velocities in the upper and middle crust in this area. Furthermore the Moho jump could also facilitate continuing convergence between Europe and the Adriatic microplate by underthrusting of Adriatic mantle below Pannonian mantle. The uppermost mantle velocities (Figure 7) may support this interpretation, if we assume a rigid Adriatic indenter with high velocities. The lower velocities in the eastern part of the Pannonian fragment (former Adriatic plate) are possibly related to the increased heat flow below the Pannonian basin.

A sketch of the geodynamic situation in key area of tectonic processes shows the main Neogene tectonic movements, which are related to the geophysical structures of our models (Figure 13). This scheme of approximately N-S directed convergence between European plate and Adriatic microplate, uplift of the Tauern Window due to vertical extrusion, and lateral escape of the Pannonian fragment approximately to the SSE corresponds well with geologic estimates of continuing convergence and tectonic escape [Linzer et al. 2002], actual seismicity [Reinecker and Lenhardt 1999] and crustal movements in lateral [Grenerczy and Kenyeres 2006] and vertical [Höggerl 1989] directions.

## Conclusion

The application of stacking, travel time tomography, and delay time methods to 3D seismic data resulted in a detailed image of the P-wave velocity distribution in the crust and a new map of the Moho discontinuity. Complementary interpretations of selected profiles with dense receiver spacing and sufficient number of inline shots revealed crustal reflectors, supplied additional information on the velocity of the middle and lower crust, and refined the image of the Moho discontinuity. Furthermore, the seismic model of the upper crust (down to 10 km depth) and the Moho depth information in time domain (travel time of the normal incidence PmP reflection) were used to constrain gravimetric modelling of Bouguer gravity. P-wave velocities were converted to densities by the use of a well-established relation [Christensen and Mooney 1995] and the gravimetrically determined densities of the middle and lower crust were back transformed to P-wave velocities using the inverse relation. On average these velocities agree well with the seismic model. However, only few features on the maps of both velocities (Figure 11 a, b) correlate well. Therefore, the density model should be refined by using the latest Bouguer anomaly map [Bielik et al. 2006] and implementing detailed information on upper

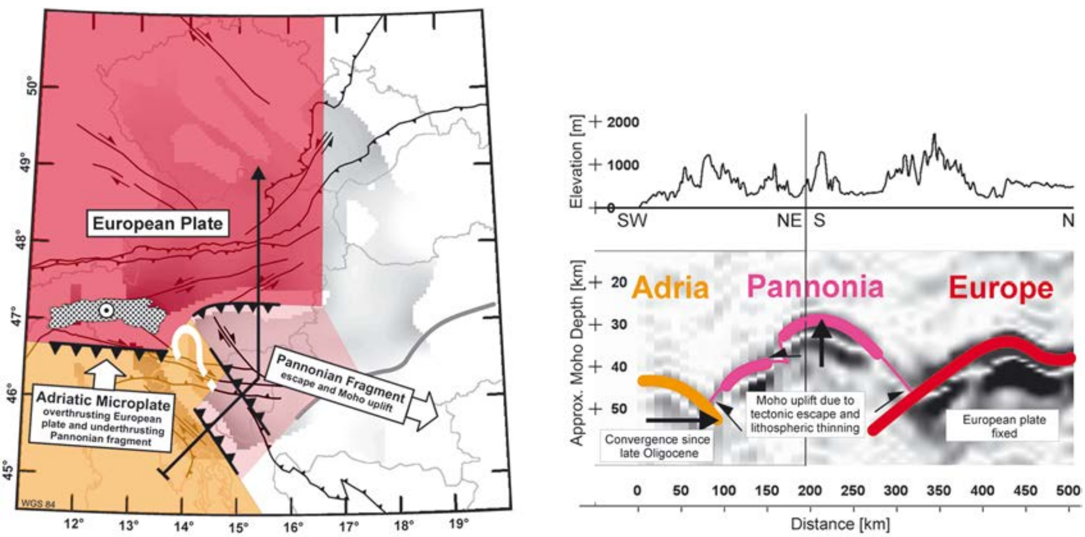


*Figure 13: Geodynamic Model:* (a) *kinematics of European plate, Adriatic microplate and Pannonian fragment; arrows and other symbols indicate direction of underthrusting of upper mantle, vertical extrusion of Tauern Window, and relative horizontal displacement due to collision and tectonic escape;* (b) *cross section through PmP stack and its tectonic interpretation along profile shown in (a).*

crustal densities [e.g., Steinhauser et al. 1984]. The seismic data contain also S-wave phases (Sg). This additional information has currently been exploited, and may help to refine the relations between density and seismic velocities. Finally, the density model should reach an accuracy that makes it useful for geoid determinations.

The seismic model, in particular the topography of the Moho discontinuity can be closely related to inter-plate collision and to tectonic extrusion and escape processes since the Tertiary. Seismicity and geodetically observed deformations indicate that these processes are still active. The development of a geodynamic model combining geological data, geophysical determined structures, and observed actual processes is a challenge for future work. So far, our geophysical investigations comprise the crust and uppermost mantle. The ongoing ALPASS project [Brückl et al. 2006b] is a passive seismic monitoring program based on a temporary network. It targets the upper mantle including the asthenophere by teleseismic tomography and the activity of large scale fault systems (e.g., Mur-Mürztal). The additional information on deep structures will increase our knowledge of the large scale plate tectonic processes, and will also improve gravimetric modelling (influence of asthenosphere topography on Bouguer anomaly). The high resolution image and quantification (magnitude, moment tensor, slip vector) of seismic activity at fault systems together with long term GPS observations will provide a sound basis for an improved understanding of present tectonic processes.

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