Seismic profiling by the TRANSALP working group: Refraction and wide-angle reflection seismic traveltime tomography

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Keywords: Eastern Alps, deep seismic sounding, velocity structure, traveltime tomography

The objective of TRANSALP is the investigation of the deep structure and dynamic evolution of the Eastern Alps. The core of the project is formed by a 340 km long reflection and refraction seismic profile between Munich and Venice (TRANSALP Working Group 2001, 2002). This paper deals with the p-wave velocity distribution derived from the wide-angle observations and the implications on crustal structure.

PREVIOUS INVESTIGATIONS

So far, the state of knowledge was based essentially on refraction seismic measurements from the 1970s, which were characterized by large shot spacing and huge charges. This data provided low resolution but great depth penetration. Early models (Fig. 1) were dominated by layered structures – not least for the sake of simplicity – and interpreted in the context of isostatic concepts of crustal reequilibration. In the 1980s, reflection seismic data was gathered on a series of short profiles in the Central Alps by the Swiss NRP 20 project (Pfiffner, 1997). These non-contiguous sections were assembled to a pseudo cross-section in which, amongst other patterns, pronounced lower-crustal reflectors were observed dipping towards the Alpine root, implying a more geodynamic interpretation as images of syncollisional structures. These results inspired efforts to reinterpret the data from the Eastern Alps. New models were developed that reflect such structures but it was impossible to distinguish between these and the older models based on the data at that time. One of the targets of TRANSALP was the verification of these models.

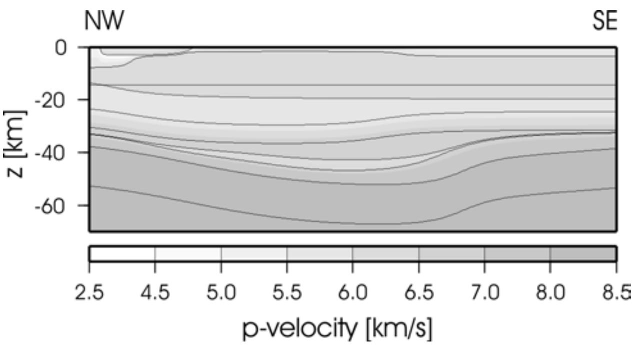

Fig. 1 –Velocity model for the Eastern Alps (Miller *et al.*, 1977)

DATA ACQUISITION

The acquisition of the wide-angle data was performed by a stationary network of 50 (40) seismological three-component stations in 1998 (1999) recording continuously with 200 (125) Hz. The seismic sources of TRANSALP 98 N were additionally observed by a mobile array of another 50 stations in (super-)critical Moho-distance (Fig. 2). All together, 1 TByte of data was acquired by four different recording systems comprising dynamite and vibroseis shots as well as natural events. After the standardization of the dataset and the correction of time errors, the vibroseis data was processed for 50 (32) stations in 1998 (1999). In the diversity stacked filtered sections, the seismic signal can be observed in distances of up to 30 (80) km. The reason for this difference is the doubling of the sweep energy in 1999. The signal from dynamite shots can be correlated in up to 170 km distance. Because rocks with high p-wave velocities (e.g. the Northern Calcareous Alps with 6 km/s) are exposed at the surface in many places in the Alps, the average vertical gradient is small and therefore the depth penetration for the direct wave is not greater than 10-12 km even for offsets of more than 100 km.

ANISOTROPY

Traveltime calculations show large discrepancies (up to 1 s for many phases) between the existing models and the new data. The largest differences between calculated and observed first break traveltimes are found near the central crest already at small offsets. This can be explained by anisotropy of the uppermost crust, because the majority of observations in the 1970s is oriented E-W, while TRANSALP crosses the Eastern Alps from N to S. Pronounced shear wave splitting observed in crossline recordings at the northern rim of the Tauern window and directional variations of offset dependent average velocities reveal an anisotropy in the upper 2 – 3 km of the Tauern window, where it amounts to 10% with the fast axis oriented E-W. This can be explained by the foliation directions, which are controlled by mechanisms of lateral extrusion. (For a discussion of escape tectonics in that region see Ratschbacher *et al.*, 1991.)

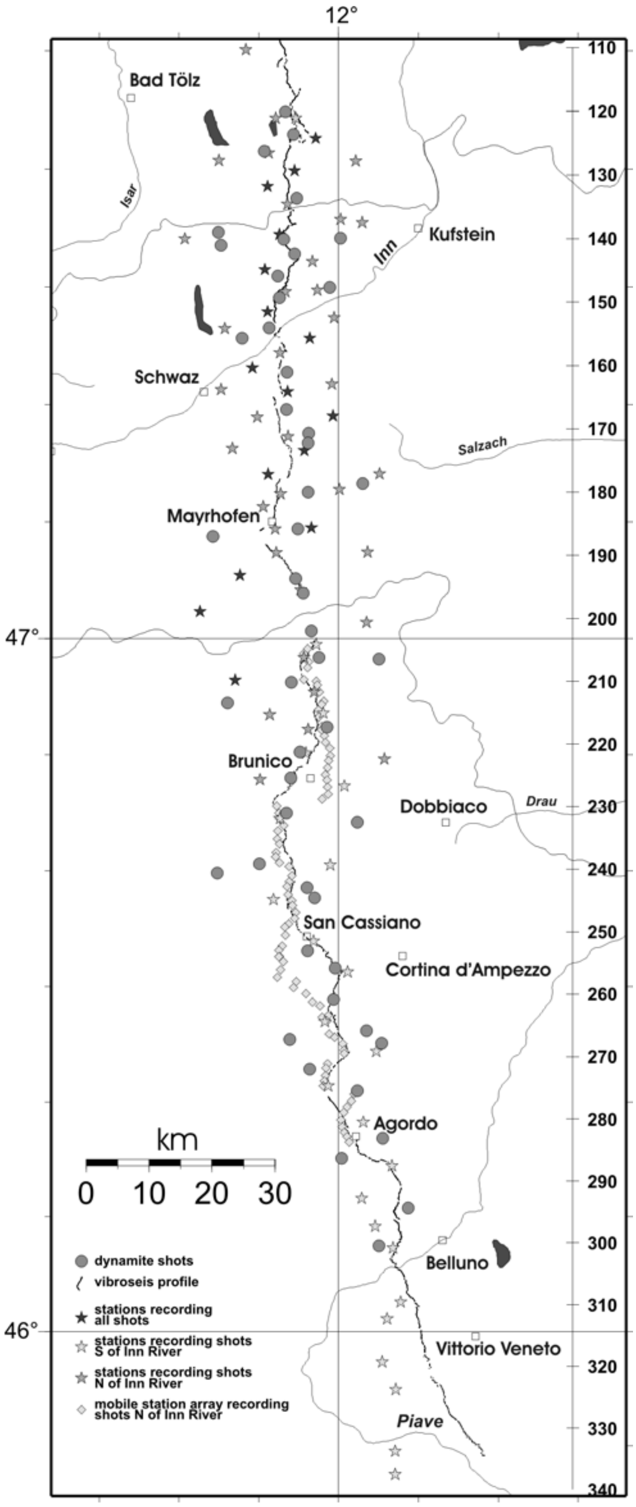

Fig. 2 – Seismic sources and network of seismological stations

A HIGH RESOLUTION MODEL

Apart from anisotropy there must be other reasons responsible for the remaining traveltime discrepancies between the older models and the new data. Further insights may be obtained by an independent modelling of the new data. A method of simultaneous 3D refraction and reflection seismic tomography has been developed on the basis of a damped least-squares matrix inversion from local earthquake tomography (Thurber, 1983) to invert the traveltime data. In a first step, traveltimes of the correlated phases were picked (Fig. 3). The dense vibroseis observations provide a basis for high resolution in the upper crust and will thus prevent a projection of velocity variations of the upper parts into the lower parts of a model. The velocity distribution in the middle and lower crust is constrained by explosion seismic Moho-reflections only. Two different starting models have been established by horizontally averaging the velocities of one of the existing refraction seismic models. One starting model is completely 1D while the other is 1D in the middle and lower crust despite an initial dip of the Moho towards the Alpine root and piecewise 1D in the upper crust with different v(z) functions for the foreland basins and the orogen. In the next step, the model parameterization was locally adjusted to the resolving power of the data. The resulting irregular inversion grid has an average node spacing of x/y/z approximately 2.5/10/0.5 [km] at the surface decreasing to 25/∞/8 (i.e. 2D) in the middle and lower crust.

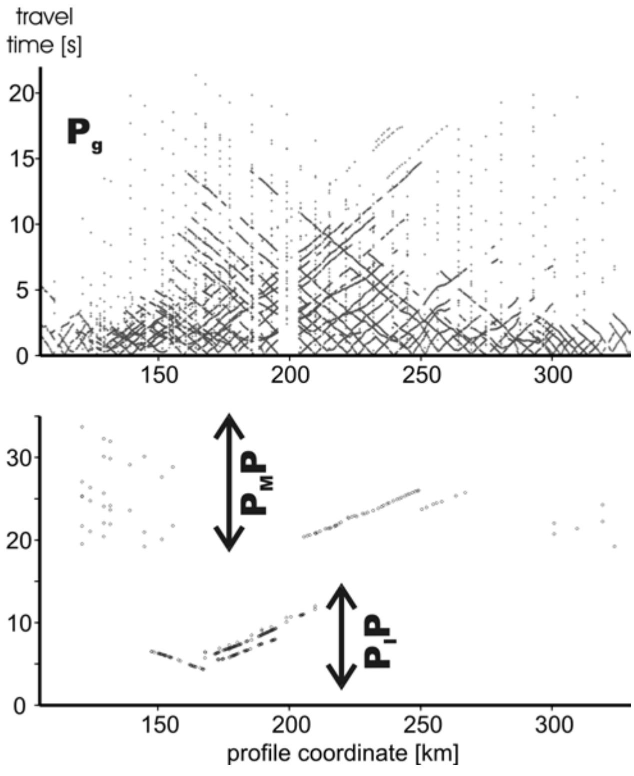

Fig. 3 – Traveltime picks used for the inversion

Fig. 4 shows the inversion course for both models. Although the parameterization is not identical they both end up with a similar model roughness and traveltime residuum of 0.05 s. But the result based on the 1D starting model overestimates the (well known) velocities in the Molasse Basin and underestimates its depth. Therefore, the result based on the pseudo 2.5D starting model (Fig. 5) is preferred, although all major features are qualitatively contained in both resulting models. The resolution diagonal elements corresponding to the inverted velocity and depth nodes are all greater than 0.2. In general, upper crustal velocities are significantly slower than in the older refraction seismic models, where they have been overestimated probably due to the low resolution. This fact is responsible for the main part of the traveltime differences.

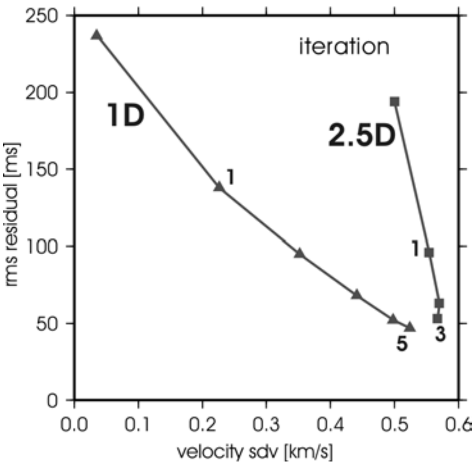

Fig. 4 – Inversion course for the 1D and the pseudo 2.5D starting models

INTERPRETATION

To the north and to the south, the foreland basins can be clearly identified by their low velocities. Very low velocities around the Passo Falzarego in the Dolomites (km 250) can be explained by diapirism. The base of the Tertiary in the Bavarian Molasse (see fig. 2 in Lueschen *et al.*, 2003, this volume) coincides with a change in velocity from 5.0 to 5.5 km/s. The Northern Calcareous Alps (NCA) are characterized by velocities greater than or equal to 6 km/s. Their reflective base at *ca.* 10 km depth corresponds roughly to the top of a LVZ. Further to the E a reflector below the Quartzphyllite Zone modelled from wide-angle reflections continues to form the top of the LVZ. This zone ends to the E, where it is bounded by the Sub-Tauern ramp. It is interpreted as European upper crust on which the Austro-Alpine units have been obducted. The depth of the Adriatic and European Moho coincides with the bottom of the lower crustal reflectors in the migrated reflection seismic section. The gap in the Moho between km 200 and 250 is reflected by a gap in the P_MP observations between km 250 and 300 (Fig. 3).

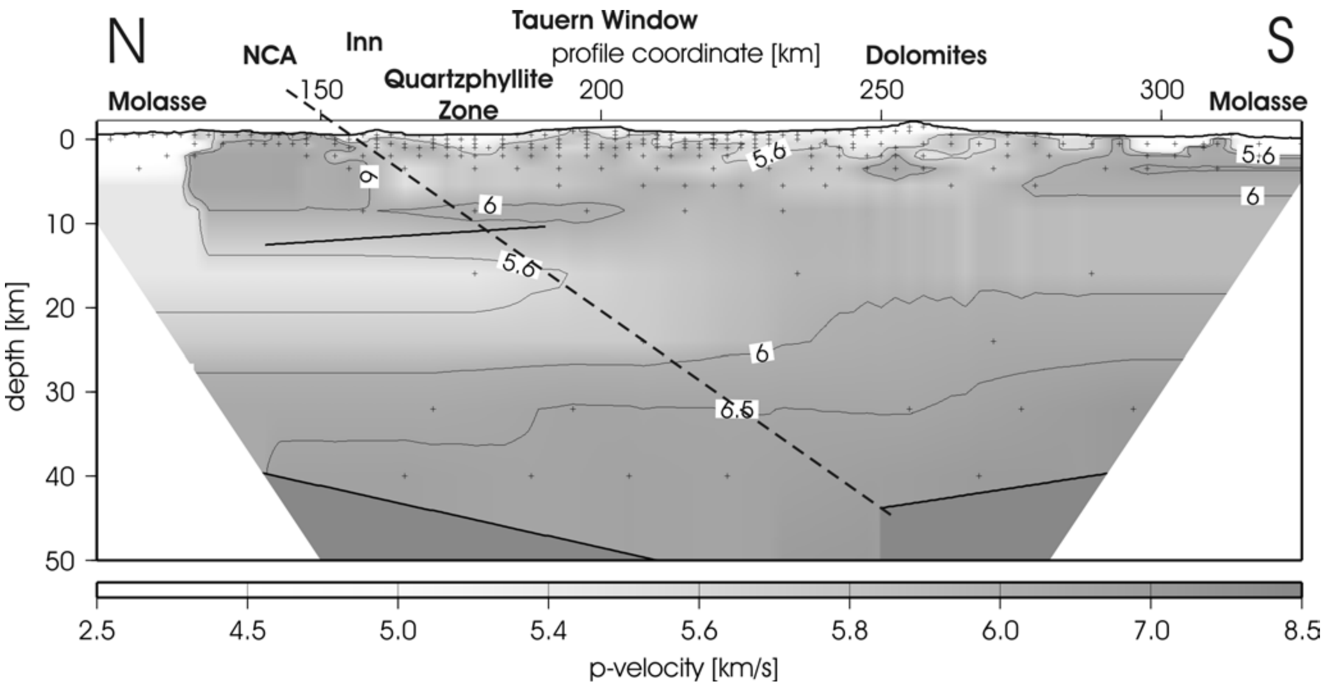

Fig. 5 – 2D section through the P-wave velocity model for the Eastern Alps along 12°E. Inversion nodes in this section are marked by a dot. The profile coordinate corresponds to Fig 2. A dashed line marks the position of the Sub-Tauern ramp.
Vertical exaggeration 1.5

ACKNOWLEDGEMENTS

The TRANSALP programme is jointly financed by the *Bundesministerium für Bildung und Forschung* (BMBF, Bonn), the *Bundesministerium für Wissenschaft und Verkehr* (BMWV, Vienna), the *Consiglio Nazionale dell Ricerche* (CNR, Roma) and the company ENI-AGIP (Milano). The TRANSALP group comprises partners from universities of Munich, Leoben, Salzburg, Zurich, Bologna, Milano, Roma and Trieste and from GFZ Potsdam and ENI-AGIP. The seismological recording systems were put at our disposal by the Geophysical Instrument Pool Potsdam. Their maintenance during the different campaigns by J. Kummerow, M. Bopp, T. Kraft and M. Tillmans is gratefully acknowledged.

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