Seismic profiling by the TRANSALP working group: deep crustal Vibroseis and explosive seismic profiling

Ewald LUESCHEN[1], Helmut GEBRANDE[1], Karl MILLAHN[2] and Rinaldo NICOLICH[3]

[1] University of Munich, Department of Earth and Environmental Sciences

[2] University of Leoben, Geophysical Institute

[3] University of Trieste, Dipartimento di Ingegneria Civile

Key words: *Eastern Alps, crustal structure, reflection profiling, Vibroseis, dynamite shooting*

The central project of the TRANSALP traverse is a 340 km long deep seismic reflection line crossing the Eastern Alps between Munich and Venice (Fig. 1). It has been acquired by partner institutions from Italy, Austria and Germany. Although the field campaign was split into four different parts between fall 1998 and summer 2001 because of financial and technical constraints, the project gathered for the first time continuous sections in the Alps using consistent field acquisition and data processing parameters. These sections include the orogen itself at its broadest width at a position where maximum continental compression is expected, as well as the two adjacent basins. The seismic sections, complementary in their depth penetration and resolution characteristics, were simultaneously obtained by Vibroseis, explosion and teleseismic techniques. They exhibit a bi-verging asymmetric structure of the maximum 55 km thick crust beneath the Alpine axis and 80-100 km long transcrustal ramps, the southward dipping 'Sub-Tauern-Ramp' and the northward dipping 'Sub-Dolomites-Ramp'. Strongly reflective patterns of these ramps can be traced to the Inn Valley in the North and to the Valsugana thrust belt in the South, both of which show enhanced seismicity in the brittle upper crust. The seismic sections do not reveal any direct evidence of the Periadriatic Fault system, the presumed equivalent to the Insubric Line in the Western Alps. According to our new evolutionary model, the Sub-Tauern-Ramp is linked at depth with remnants of the subducted Penninic Ocean. First structural and evolutionary models have been presented by the TRANSALP Working Group (2001; 2002).

Vibroseis near-vertical seismic profiling formed the core of the field data acquisition, complemented by explosive near-vertical seismic profiling, cross-line recording for three-dimensional control, wide-angle recording by a mobile 3-component receiver array for velocity control as well as a stationary network for passive tomography and seismicity studies. In this paper we concentrate on technical details and results of the Vibroseis and explosives seismic profiling. The Vibroseis survey was designed to accomplish high resolution and depth penetration for the upper and middle crust mainly. A vibratorpoint spacing of 100 m with 4 heavy vibrators, sweep signal 10-48 Hz of 28 s length, geophone group spacing 50 m, and a spread length of 18 km in split spread configuration with 360 recording channels resulted in nominal 90-fold common midpoint coverage. Please see webpage http://www.geophysik.uni-muenchen.de/TRANSALP for more detailed parameters.

Except the northernmost approximately 70 km of the transect in the Bavarian Molasse, the Vibroseis survey was accompanied by explosive seismic recording using shotpoints of 90 kg charge in 30 m deep boreholes and 5 km nominal spacing. The explosive seismic survey was designed to provide low-fold, but high-energy signals from the deeper parts of the crust. Shots were fired when the Vibroseis rolling spread arrived in both North and South off-end configuration including the spare spread with up to 1145 channels. In this way, both, Vibroseis and explosive data production was running simultaneously using the same recording unit. A daily progress of up to 5 km in Vibroseis production included recording of about 2-4 explosive shots. As expected, the depth penetration of the Vibroseis signal varies along the transect considerably. It turned out to be particularly low in such areas where high-impedance rocks are exposed at the surface, e.g. in the Northern Calcareous Alps. Here, the explosives provided a valuable and economic way to aid imaging of greater depth. This procedure was previously successful in the Western Alps (Pfiffner *et al.,* 1997) and in the Ural Mountains (Berzin *et al.,* 1996). Due to difficulties concerning the receiver line being located within the noise-contaminated Valle di Tures between S. Giovanni and Brunico and some bad shots in this area, this sector showed deficits in illuminating the deeper crust. This was reason for additional explosive measurements in this sector in July/August 2001. A stationary 20-km-long receiver spread was used at the eastern flank of the valley in a nearly complete noise-free environment to record 4 shotpoints. Thus, these final measurements were highly successful in recording deep crustal reflections even deeper than the crust-mantle boundary.

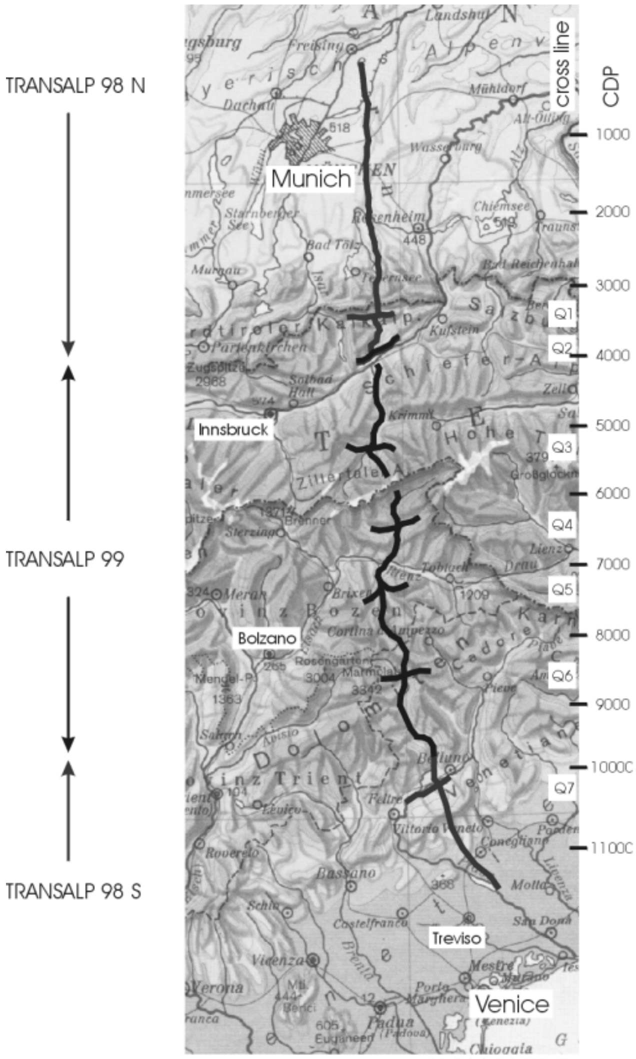

Fig. 1 – Location map of the TRANSALP transect. Length along main line is 300 km. Seven cross-lines are also marked.

The data processing was done at the universities of Munich and Leoben (connected via internet) and at the offices of ENI-AGIP at Milan on different hardware and software platforms. Here we report on processing results obtained at the universities at Munich and Leoben using the DISCO/FOCUS and ProMAX software. At the beginning of the processing all data of the main Vibroseis line (3841 field-correlated vibratorpoint records, 27 GByte) were combined to form one consistent dataset. The data of the southernmost 50 km, recorded by a SERCEL 368 system, were adjusted in amplitude level, because of a different instrument constant, to the other data, which were consistently obtained by a GEOX-ARAM24 system. All coordinates of sources and receivers, originally measured in local Gauss-Krueger systems, were transferred to the UTM-WGS84 standard. As a reference for tying seismic events to geological surface structures serve the common-midpoint (CMP) numbers (14 in the North to 11844 in the South) and their corresponding coordinates (in Meter) after binning the crooked-line midpoints between sources and receivers into 25-m intervals. The complete processing from geometry installation to Kirchhoff time and depth migration (poststack) has been documented step by step for a sample portion of the line. Strongly crooked geometry and varying recording conditions required iterative improvement of processing parameters, in particular with respect to amplitude scaling (geometrical spreading correction and, optionally, automatic gain control AGC and trace equalisation), static correction and velocity building. A short-window (400 ms) AGC proved to be most effective and robust one for increasing the signal-to-noise ratio during stacking. Static corrections to a datum level (500 m a.m.s.l.) turned out to be a crucial step. A combination of elevation statics, velocity statics based on a tomographic inversion of the first breaks and subsequent residual statics proved to be very efficient for stacking enhancement. This conventional common-midpoint (CMP) processing scheme was complemented for comparison by non-conventional schemes, such as dip-moveout (DMO) processing and pre-stack depth migration with subsequent stacking. The conventional CMP technique proved to be very robust despite of several strongly dipping reflection patterns. Thus, many different versions regarding processing schemes, parameters and plotting scales (1:50000 to 1:200000) have been produced, all having their specific advantages for interpretation. The velocity model required for depth and time migration was obtained by analysis of the stacking velocities in the layered structure of the Molasse areas and by tomographic inversion of the first arrivals of Vibroseis and explosive data recorded by the main-line Vibroseis and explosive data production and by the wide-aperture stationary network (offsets up to 80 km resulted in depth penetration to about 15 km, Bleibinhaus, this volume) in the Alpine areas. For the deeper part a macro velocity model from older, but still compatible deep seismic refraction measurements (Miller *et al.,* 1977) was used.

For the explosive seismic data a different way was chosen. Because of the large shotpoint interval of 5 km and the low-fold coverage, traces of best quality were selected to form a single-fold section, which was then normal-moveout corrected and (poststack) time- and depth-migrated using velocity models from the Vibroseis survey. After the additional experiment in 2001, these data were integrated into the complete explosive dataset.

Here we focus on a general overview and discuss then some crucial details of the main line. Figure 2 shows a manually driven line drawing obtained from both, the Vibroseis and the explosive depth sections, emphasising the most pronounced reflections. The Vibroseis sections are about 300 km long after the CMP-binning of the crooked-line geometry of originally 340 km length. The Vibroseis sections start in the North about 90 km north of the Alpine front, whereas the explosive section start directly at the Alpine front. As expected, the Vibroseis sections are superior in resolution in the upper and middle crust, but show deficits in the lower crust due to lack of signal energy. The explosive sections fill these gaps, having their resolution capabilities mainly in the lower crust due to the experimental design. Interestingly, with respect to the lower crust, both methods complement each other in a optimal way. A synoptic view on stack (zero-offset time), time and depth migrated sections is necessary to evaluate these sections because of well-known difficulties in migration of deep-crustal events. Despite of these problems which tend to produce 'smiles', both migration techniques were reasonably successfull. This is for instance documented in the predominant criss-cross reflection pattern at km 175-200 in the Vibroseis stack section. After depth migration (similarly after time migration) the elements focus well and migrate to their position, as expected from the ray-theoretical point of view, and produce a bi-verging pattern at km 150-220. Nevertheless, care has to be taken on lower crustal reflective spots and sectors, e.g. at km 130-140 and about 16 s in the Vibroseis section, which produce smiles because of their truncated character and smear out along the section. This effect is inherent of the migration principles, generally for deeper crustal targets in 2-D seismic surveys. This is a drawback particularly for the low-coverage explosive survey which exhibits several spurious signals at lower crustal levels. Ray-theoretical and Fresnel-zone principles as well as a retrospect to unprocessed field records help to distinguish real and spurious signals.

The northernmost and southernmost parts of the 300 km long Vibroseis section display the Molasse basins with the Tertiary base in the Bavarian Molasse as the most prominent reflection. Several former hydrocarbon exploration targets can be clearly identified at antithetic normal faults. These faults have been originated in an extensional upper crustal regime due to the downbending of the whole crust. Thin Mesozoic sediments and, particularly strong, the Tertiary base can be seen as subhorizontal reflections beneath the stratified Molasse sediments. The top of the crystalline basement, which from drilling further north is known to be located beneath up to 600 m thick Jurassic and Createaceous sediments, is less clearly visible.

The dashed line in the line drawing of Fig. 2 separates two obviously distinct crustal domains of the section, cutting through the core of the orogen from the surface at the Inn Valley (km 100) with an angle of 30 degree to the South over a length of about 100 km. This structure is interpreted to have acted as a tectonic ramp along which the southern block including the Tauern Window was upthrusted onto the northern block, thus being responsible for the exhumation of high-grade metamorphic rocks. It is referred as the 'Sub-Tauern-Ramp'. South-dipping sub-parallel reflections dominate in the middle crust of the southern block, particularly close to the Tauern Window. Further south, northward dipping elements in the middle crust, referred as the ‘Sub-Dolomites-Ramp’, may be related to the backthrust system of the Valsugana fault zone. The northern block, on the contrary, is characterised by an almost transparent middle crust. It is overlain by the highly reflective and stratified Molasse and by a 9-10 km thick package of the Northern Calcareous Alps which are characterised by south-dipping reflections and by an almost horizontal base reflection pattern. This base pattern shows two abrupt downward offsets at the Alpine front (km 70) and beneath the Inn Valley (km 100). The Northern Calcareous Alps, known to be part of the Adriatic-African domain like most of the southern block except the Tauern Window, seem to be overthrusted by its former basement along the Sub-Tauern-Ramp. The northern block, except the Northern Calcareous Alps, can be identified as European crust in collision with the Adriatic-African crust. The top of the European crystalline crust, identified by the base of Tertiary Molasse and Northern Calcareous Alps, and the bottom of the crust, identified with the base of the reflective lower crust, are almost sub-parallel and show a continuous downward flexure towards south.

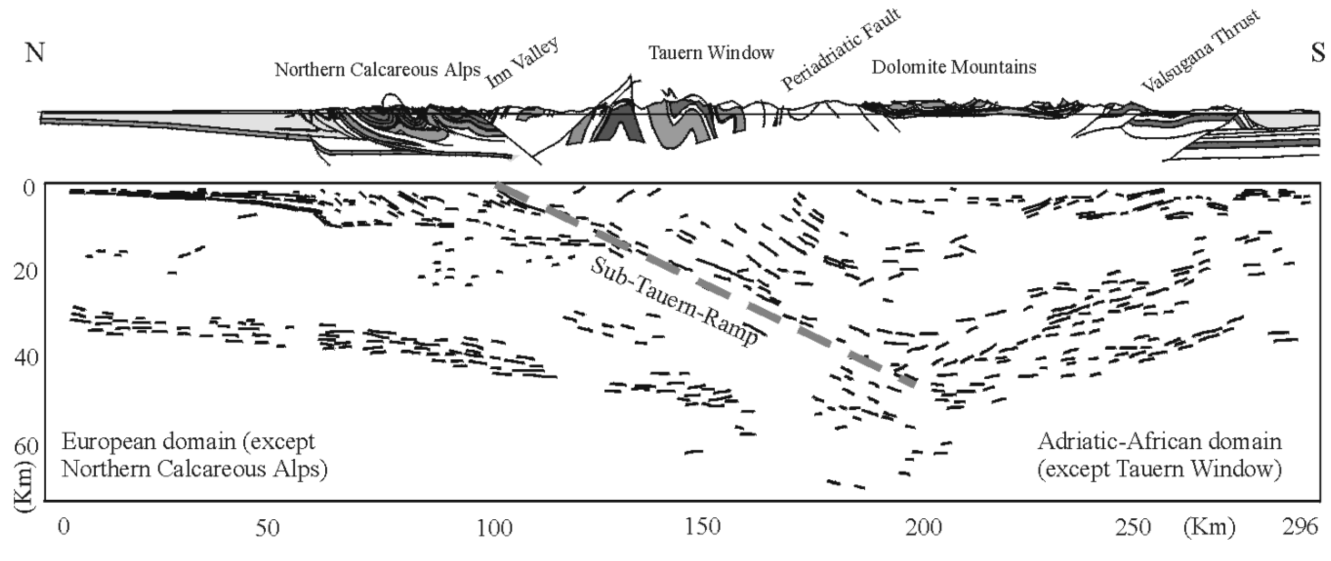

Fig. 2 – Compiled line drawing from Vibroseis and explosive seismic sections with geological units known from surface on top. Geological units from B. Lammerer and A. Castellarin (pers. communication).

The section displays some remarkable asymmetries in crustal structure. The Alpine root, if taken by the lowermost reflections, with a maximum depth of 55-60 km is shifted to the South with respect to the main Alpine crest within the Tauern Window. The reflective lower crust on the European side is remarkably thinner than on the Adriatic-African side in the south. Both seem to be separated by the Sub-Tauern-Ramp. The 5-6 km thick European lower crust is also much thinner than 50 km further north of TRANSALP where previous DEKORP seismic reflection data (Meissner and Bortfeld, 1990) detected a reflective interval between 15 and 30 km depth beneath a relatively transparent upper crystalline crust. The apparent thinning of the lower crust beneath the Bavarian Molasse, the Northern Calcareous Alps and the Tauern Window with respect to the adjacent northern regions remains enigmatic, although it is more natural that the generation of the reflective structures started long before the European crust began to bend down during the Alpine orogeny. The middle-lower crust on the Adriatic-African side reveals two distinct, almost sub-parallel, patterns of seismic reflections in the explosive sections. This 25-km thick (or doubled?) lower crust is confirmed by corresponding velocity peaks determined by previous seismic refraction profiling and seems to be restricted to the Southern Dolomites (Scarascia and Cassinis, 1997). The crustal root zone at 55-60 km depth (at line-km 160-170) is lacking reflectivity. This has been explicitly confirmed by the additional explosive experiment in 2001, which was characterised by an extremely high signal-to-noise ratio at the corresponding recording times of 15 to 20s.

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 delle Ricerche (CNR, Roma) and the company ENI-AGIP (Milan). The TRANSALP group comprises partners from universities of Munich, Leoben, Bologna, Salzburg, Milano, Roma, Trieste and Zurich and from GFZ Potsdam and company ENI-AGIP. We thank our contractors, THOR Geophysikalische Prospektion GmbH, Kiel, Germany, DMT, Essen, Germany, JOANNEUM Research, Leoben, Austria, GEOITALIA Sp.A., Milano, Italy, GEOTEC Sp.A., Campobasso, Italy, and O.G.S., Trieste, Italy, for their excellent and enthusiastic work under difficult terrain and logistic conditions, even during winter time. We appreciate administrative services by the GFZ Potsdam.

REFERENCES

BERZIN R., ONCKEN O., KNAPP J.H., PERÉZ-ESTAÚN A., HISMATULIN T., YUNUSOV N. and LIPILIN A., 1996 – *Orogenic evolution of the Ural Mountains: results from an integrated seismic experiment*. Nature, v. 274, pp. 220-221.

MEISSNER R. and BORTFELD R.K., 1990 – *DEKORP-Atlas, Results of Deutsches Kontinentales Reflexionsseismisches Programm*, Springer-Verlag, Berlin.

MILLER H., GEBRANDE H. and SCHMEDES E., 1977 – *Ein verbessertes Strukturmodell für die Ostalpen, abgeleitet aus refraktionsseismischen Daten unter Berücksichtigung des Alpen-Längsprofils.* Geol. Rundschau, v. 66, pp. 289-308.

PFIFFNER O.A., LEHNER P., HEITZMANN P., MUELLER St. and STECK A., 1997 – *Results of NRP20 - Deep Structure of the Alps*, Birkhäuser Verlag, 380 pp., Basel.

SCARASCIA S. and CASSINIS R., 1997 – *Crustal structures in the central-eastern Alpine sector: a revision of the available DSS data*. Tectonophysics, v. 271, pp. 157-188.

TRANSALP WORKING GROUP, 2001 – *European orogenic processes research transects the Eastern Alps*. EOS Trans, AGU, v. 82, pp. 453, 460-461.

TRANSALP WORKING GROUP, 2002 – *First deep seismic images of the Eastern Alps reveal giant crustal wedges and transcrustal ramps.* Geophys. Res. Lett., v. 29, 10.1029/2002GL014911.