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Tectonophysics 414 (2006) 39–49
TECTONOPHYSICS
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TRANSALP—Cross-line recording during the seismic reflection transect in the Eastern Alps

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Received 15 February 2005; received in revised form 15 August 2005; accepted 4 October 2005
Available online 10 January 2006

Abstract

Cross-line recording formed a companion experiment of the TRANSALP seismic reflection transect through the Eastern Alps, conducted by partner institutions from Austria, Germany and Italy in three field campaigns in the period fall 1998 to fall 1999. Besides of the originally expected three-dimensional control for the north–south running main transect, additional information on seismic anisotropy and alternative images of crucial parts of the main transect could be gained.

Conventionally processed sections along N–S running common-midpoint (CMP) binning lines confirm and strengthen the predominance of midcrustal reflective structures of the 'Sub-Tauern-Ramp' beneath and south of the Tauern Window. Velocity analysis of the first arrivals exhibit about 10% higher velocities in east–west propagating P-waves, compatible with texture-dominated rock anisotropy, recorded on cross-lines at the Tauern Window. Pre-stack depth migration of cross-line recordings shows dominant south dip of the Sub-Tauern-Ramp with easterly dip components and a sub-horizontal root zone of the Sub-Dolomites-Ramp.

Keywords: Seismic profiling; Cross-line recording; Vibroseis; Explosive sources; Crustal structure; Eastern Alps

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1. Introduction

The mission objective of the TRANSALP traverse was a 340 km long deep seismic reflection line crossing the Eastern Alps between Munich and Venice (Lüschen et al., 2005-this volume; TRANSALP Working Group, 2001, 2002). Vibroseis near-vertical seismic profiling formed the core of the experiment, complemented by explosive near-vertical seismic profiling (Lüschen et al., 2005-this volume), cross-line recording for three-dimensional control, wide-angle recording by mobile arrays for velocity control (Bleibinhaus and Gebrande, 2005-this volume) and passive tomography and seismicity studies using a long-term stationary array (Kummerow et al., 2005-this volume; Lippitsch et al., 2003; Kummerow et al., 2004). Here we focus on details of the cross-line recordings.

The east–west running cross-lines were distributed systematically along the north–south main traverse.

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doi:10.1016/j.tecto.2005.10.029

Their field design was minimised (i.e. without vibrator sources along the cross-lines) in order to keep the additional costs of the project as low as possible. However, as we will show here, the additionally gained information has exceeded the initial expectations. A similar field design using cross-line receiver lines integrated with main source lines is known from the northwestern Canadian Arctic (Cook and Coflin, 1990) with one experimental cross-line, and in a more systematic manner along the whole transects from DEKORP-profiling in the Saxothuringicum of the East-German Hercynian Mountains (DEKORP Research Group, 1994) and in the URSEIS profiling of the Ural Mountains (Berzin et al., 1996). Economically, all these measurements were of little additional costs, but provided valuable three-dimensional control along the main 2-D transect.

2. Field data acquisition and data processing

Seven receiver cross-lines (Q1–Q7, Fig. 1) of approximately 20 km length each recorded off-end dynamite shot points and passively all those vibrator and dynamite sources of the main line, that were located between the two adjacent cross-lines. All these measurements were performed by contractor companies by connecting the cross-line recording spreads directly to the main-line spread at the tiepoints or by additional recording systems operated in slave mode via radio link. Recording parameters, which differ from those of the main north–south line, are listed in Table 1. The Vibroseis recordings exhibit a 10 km wide (nominally single fold), rectangular subsurface coverage (Fig. 1), that is continuous in north–south direction along the whole transect when all cross-line coverage is mounted

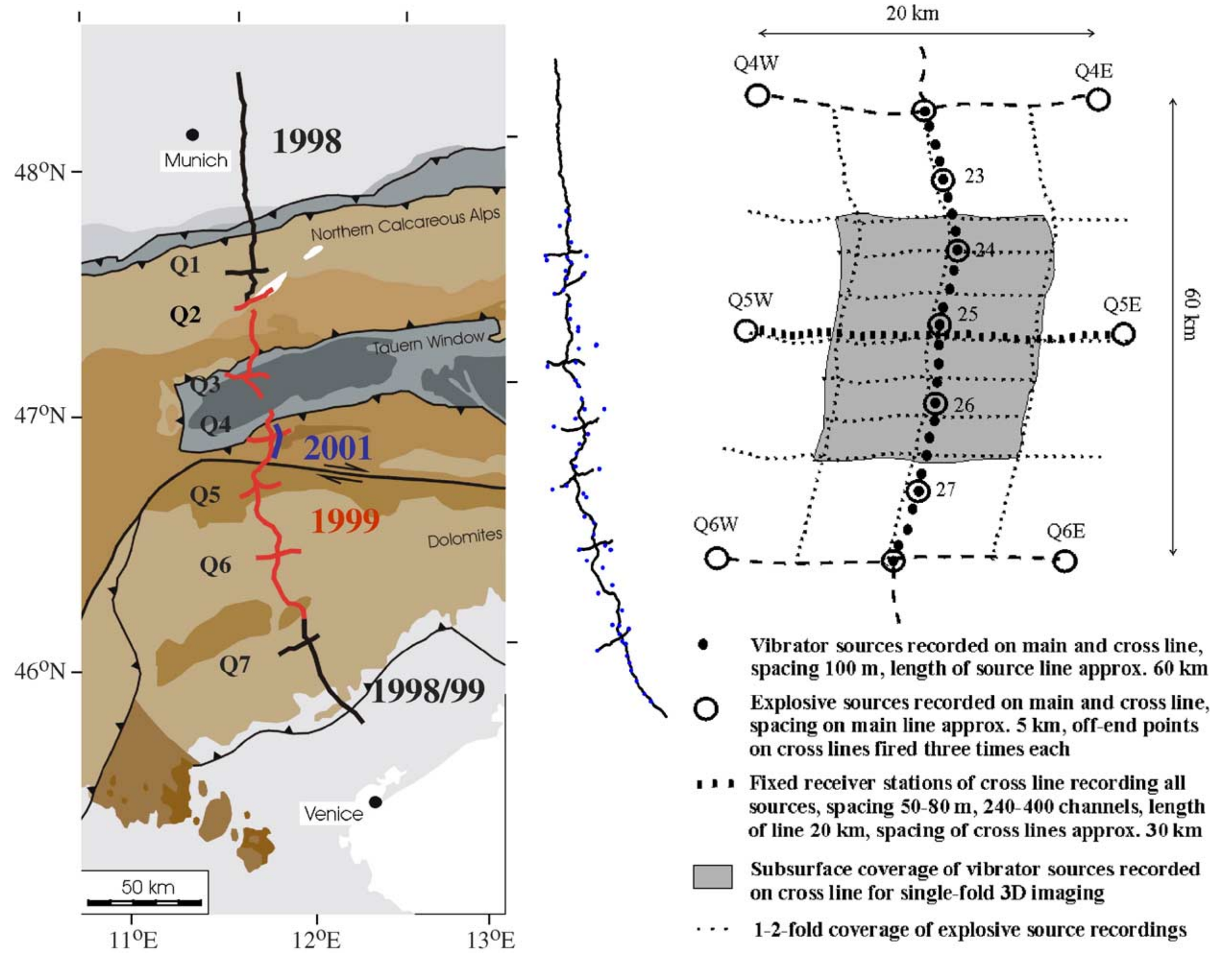

Fig. 1. Left: simplified tectonic map showing location of the TRANSALP transect across the Eastern Alps and of the seven cross-lines (Q1–Q7, from north to south). Numbers are years of field campaigns. Middle: location map of receiver lines and dynamite shot points of main line and cross-lines. Right: schematic configuration of receivers and sources of one particular cross-line and its respective subsurface coverage.

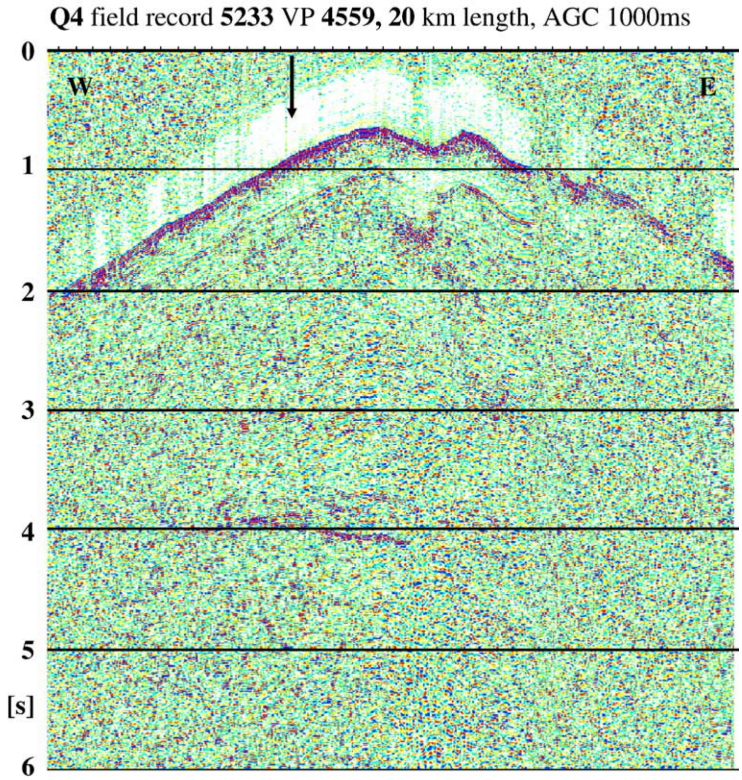

Fig. 2. Raw field record (6 s from 20 s recorded) of one particular vibrator source recorded on cross-line Q4 (common source gather). Source is offset to the north. Arrow marks receiver for common receiver gather shown in Fig. 3. Amplitudes are AGC (automatic gain control)-scaled and colour-coded.

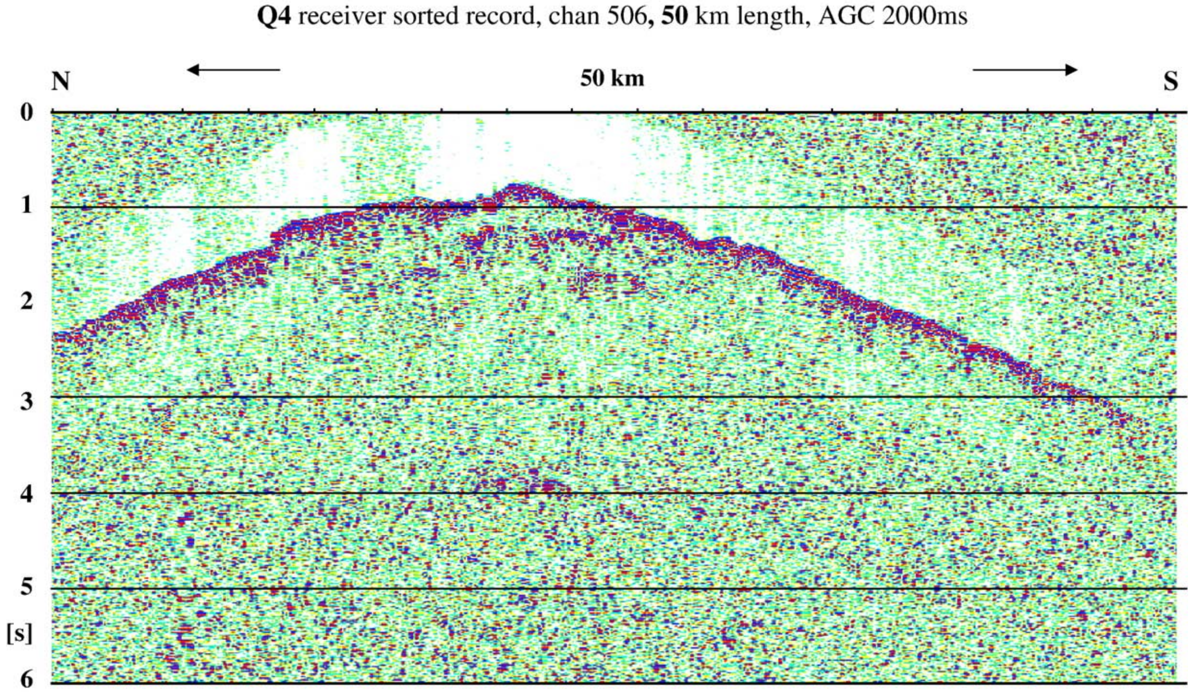

Fig. 3. Raw field record (6 s from 20 s recorded) of one particular receiver of cross-line Q4 recording all vibrator sources (common receiver gather). Location of receiver is marked in Fig. 2. Amplitudes are AGC (automatic gain control)-scaled and colour-coded.

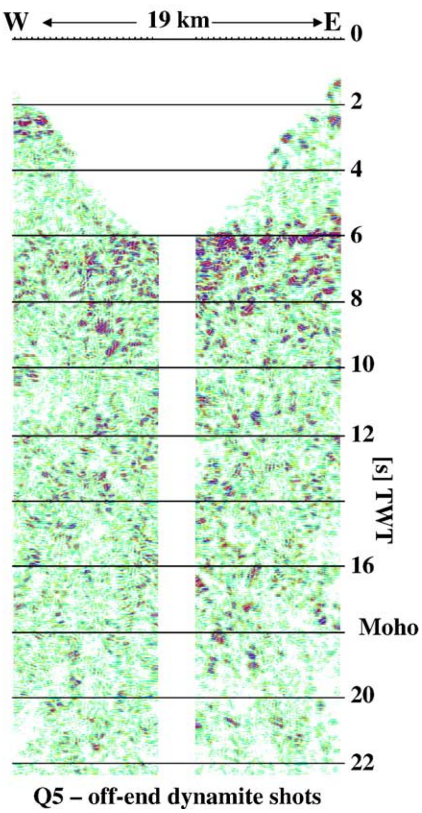

Fig. 4. Dynamite section of cross-line Q5 with two off-end shot points. Processing consists of CMP-binning, amplitude scaling with long AGC window, bandpass filtering, elevation statics, normal-moveout correction, coherency enhancement. For midcrustal reflections at 6–8 s two-way-traveltime (approx. 18–24 km depth) compare with Figs. 6 and 10. Moho reflections at about 18–19 s two-way traveltime.

together. The off-end dynamite shot points, including those on the adjacent lines, were recorded on the cross-lines, as well as on the main-line spread. Thus, the whole subsurface coverage system of the dynamite recordings consists of east–west running lines, spaced 2.5 km (nominally), and three parallel lines in north–south direction with two-fold coverage (Fig. 1).

Typical raw field recordings are shown in Fig. 2 in the common-shot domain (one particular vibrator point observed at all receivers) and Fig. 3 in the common-receiver domain (one particular receiver observing all vibrator points). Due to lower environmental noise in the east–west running sub-valleys, the signal-to-noise ratio is generally superior to that of major parts of the main line. Exceptionally, part of the record of Fig. 2 is of lower quality in this respect; see its eastern part, which is dominated by heavy traffic and water-falls. The signal spot at about 4 s in both figures may be subject to study its relation to the Periadriatic Fault at depth, if it dips subvertically or steeply to the north, as indicated by surface expressions and existing structure models (see discussion by Lüschen et al., 2005-this volume). However, the reflection is of relative short length (approx. 10 km in time section corresponding to 5 km at depth) in all directions and does not show a preferred dip in any direction.

The cross-line recordings were matter of a variety of different processing experiments. Following the original intention, the cross-line recordings were used for three-dimensional pre-stack depth migration (Hähle, 2003), as described below. However, conventional common midpoint stacking, as being used for the main line (see Lüschen et al., 2005-this volume) proved to be a valuable and robust tool for producing seismic sections, which could be directly compared or integrated with the main-line sections. Processing parameters were adopted from the main line. Most emphasis in both processing flows was concentrated on the cross-lines Q3 (at northern rim of the Tauern Window), Q4 (at southern rim of the Tauern Window) and Q5 (south of the Periadriatic Lineament), since these lines promised to illuminate the most interesting crustal features according to images of the main line.

3. Seismic sections and interpretations

The dynamite sections can be processed in a simple, but robust way (Fig. 4: Q5). The records of the two off-end shot points were CMP-binned, corrected for geometrical spreading, elevation statics and normal moveout. The dominant reflections at about 6 s (approx. 18 km depth) are part of the giant bi-vergent pattern in the axial region of the Eastern Alps known from the main line. Obviously, there is no dip in east–west direction and the length of the pattern extends over the full length of the line (approx. 20 km). This pattern is also matter of interest in Figs. 5 and 6. Not all of the off-end shot points were of sufficient quality to produce sections as in Fig. 4 due to reasons discussed by Lüschen et al. (2005-this volume). A systematic unified approach using most of the cross-line and main-line dynamite shots, recorded on the main line and on the cross-lines, is planned for the future, using three-dimensional pre-stack depth migration based on a new 3-D velocity model (compare Bleibinhaus et al., 2005-this volume).

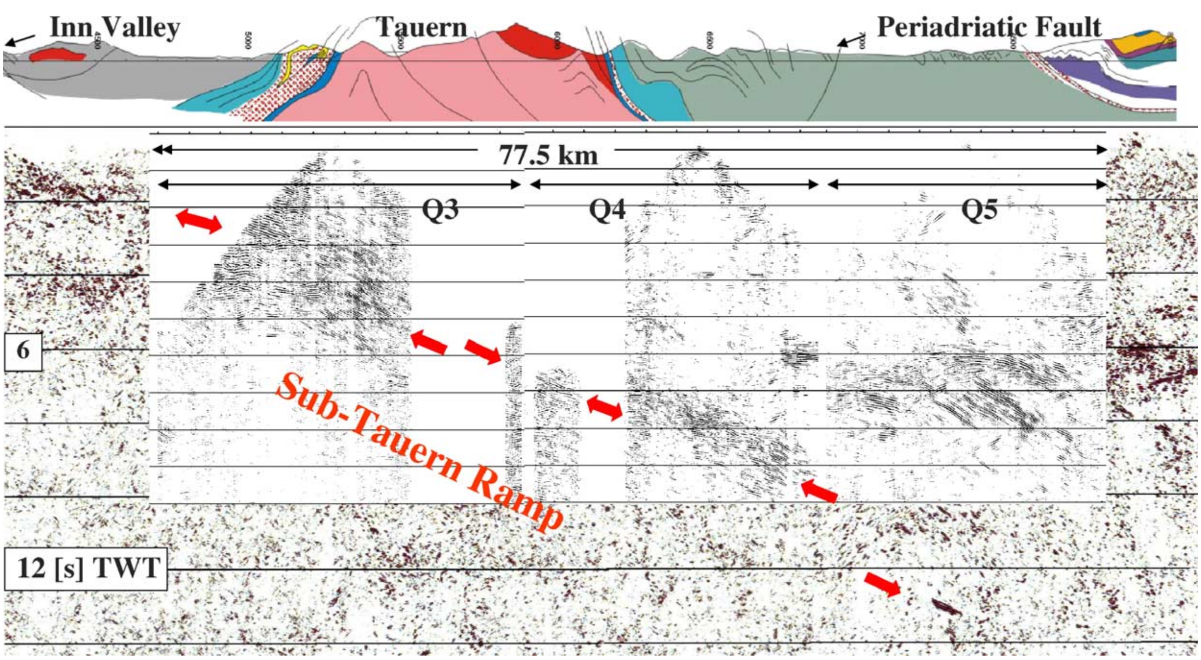

Fig. 5. North–south stack sections of cross-lines Q3, Q4 and Q5 superposed on main-line Vibroseis stack section between the Inn Valley and the Dolomite Mountains. Common-Midpoint (CMP-) processing adopted from the main line. Binning of the cross-line coverage in 5 km wide and 100 m long cells. Reflection patterns marked by arrows (unmigrated) are interpreted as 'Sub-Tauern-Ramp.'

A conventional processing approach is applied to the Vibroseis recordings of cross-lines Q3 (north of Tauern Window), Q4 (south of Tauern Window) and Q5 (above strong criss-cross reflection pattern). North–south running binning lines with a binning width of 5 km and length of 100 m have been used to select the traces and to construct CMP stack sections according to processing steps adopted from the main line. These sections, if mounted together, provide an alternative stack section (Fig. 5), complementary to the main-line stack section of an almost identical subsurface coverage. The dominant reflection pattern on these sections corresponds to the south-dipping 'Sub-Tauern-Ramp,' which here is even more pronounced than on the main line. Particularly the stack section of cross-line Q4 provides further evidence that the 'Sub-Tauern-Ramp' is actually the most dominant feature in the Alpine crust. The section of Q4 is also almost identical in its location with the complementary explosive section gathered in 2001 (Lüschen et al., 2005-this volume). A ramp-like thrust zone, however with different geometry, has been proposed already by Lammerer and Weger (1998) in order to explain the exhumation of the crystalline Tauern Window. The seismic images indicate that this crustal thrust zone consists of a 5–6 km thick pattern of slices or lenses instead of a single thrust plane. Slices of Penninic units of the subducted ocean might be included within this pattern according to the interpretation presented by the TRANSALP Working Group (2002). Its internal structure cannot be easily resolved because of interferences, scattering and varying reflectivity characteristics. In the section of Q4, it is even more evident that the zone above the ramp is actually void of significant reflections, located between the Tauern Window and the criss-cross reflection pattern south of the Periadriatic Lineament. Although also evident from the main line, there were doubts because of noisy recording conditions of the main line here in the Valle di Tures due to dense population and heavy traffic. The section of Q5 in Fig. 5 shows another proof of the criss-cross pattern.

Experiments with varying azimuths of the binning line and corresponding stacking of cross-line Q5 are shown in Fig. 6. All sections show a pronounced reflection at about 6 s TWT, which is of hyperbolic character in northerly directions. As in the main line, it would focus towards the position of its apex after migration. Its true length in N–S direction is, therefore, relatively short, that is of the order of few kilometers only, in contrast to its E–W extension, which is of the order of more than 20 km (compare Fig. 4). Images of northern and north–northeastern azimuths are almost identical with the corresponding sector of the main line (see Lüschen et al., 2005-this volume). Particularly, the criss-cross reflection pattern in the zero-offset time domain as the expression of the bi-vergent crustal structures shows up mainly in northern to north–northeast directions. Therefore, the main dip direction of these structures lies within the mentioned sections.

The cross-line recording also allows seismic velocity studies, which depend on azimuth between source and receiver (Fig. 7). Velocities are calculated from the source–receiver distance and the traveltime of first arrivals and correspond to diving waves travelling almost horizontally with maximum depth propagation of approximately 2–3 km. Although some scatter is visible because of near-surface and topography effects, a clear relationship of velocities with azimuth and offset is discernible. As expected, the velocities increase with offset according to the increasing depth of these diving waves (due to the positive velocity gradient), until they stay at an almost constant level at greater offset. This behaviour is also known from numerous velocity measurements in the laboratory, when the confining pressure of the rock samples is increased simulating greater depth by closing cracks and microcracks (e.g. Ullemeyer et al., 2005-this volume). In case of cross-line Q4, average velocities for wave propagation in E–W direction (azimuth 90° and 270°) are systematically more than 10% higher than velocities of waves travelling in N–S direction (azimuth 0° and 180°). This behaviour is compatible with microfabric observations in and around the Tauern Window (Lammerer and Weger, 1998) showing an E–W elongation of the rock texture caused by N–S compression and E–W stretch-

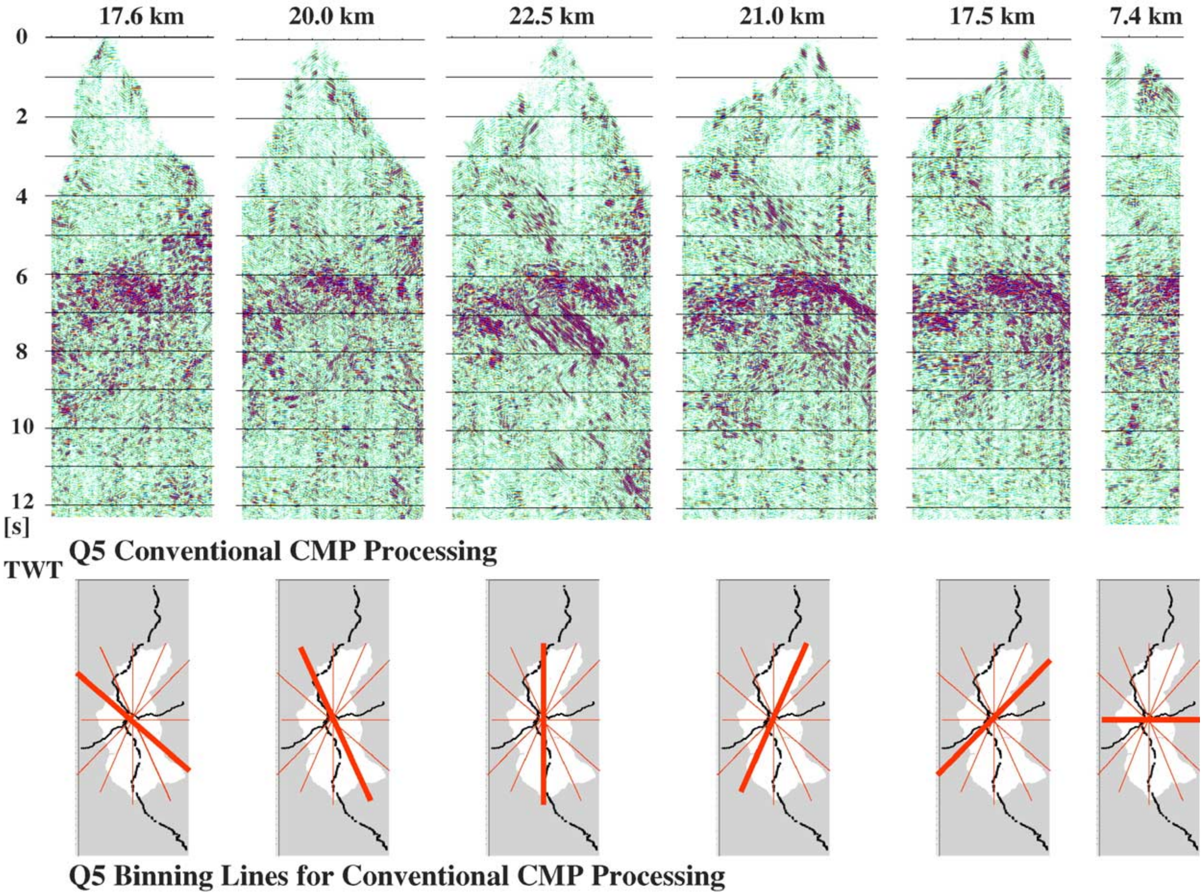

Fig. 6. Stack sections of cross-line Q5 (south of the Periadriatic Lineament) corresponding to binning lines at varying azimuths (top row). Bottom row: thick red line is binning line of stack section on top; 5 km × 100 m binning; source line in N−S direction; receiver line in WSW−ENE direction; source–receiver midpoint coverage shown as white area. Vertical exaggeration of stack sections approximately 1.5 to 1.

ing. A similar observation has been made by studying the azimuthal variations of cross-line Q3 at the northern rim of the Tauern Window. In the cross-line Q3, S-wave splitting as a direct diagnostic proof of seismic anisotropy has been observed in shot gathers recorded in E–W direction (Bleibinhaus and Gebrande, 2005-this volume). In contrast, all other cross-lines show some variation of the seismic velocities with azimuth; however, this cannot be distinguished from the effect of lateral inhomogeneities (e.g. cross-line Q5 in Fig. 7). There is clear evidence of seismic anisotropy caused by rock anisotropy due to tectonic paleo-strain constrained to the Tauern Window and their surroundings, at least for the upper few kilometers.

The central cross-lines Q3, Q4 and Q5 were studied by the prestack-migration technique (Hähle, 2003). Amplitudes of the Vibroseis gathers were distributed along isochrones, determined by the seismic velocity model of Bleibinhaus and Gebrande (2005-this volume), and then stacked. This depth-migration algorithm, called 'Isochrone Migration,' was originally developed for wide-angle field configurations as an alternative to 'Kirchhoff-Depth-Migration' (Simon et al., 1996) and extended to include seismic anisotropy in the uppermost crust (Hähle, 2003). For robustness, amplitudes were corrected for spherical spreading, subsequent AGC (automatic gain control) and transformed to envelopes. The data were migrated onto E–W sections 2 km apart and then stacked (Figs. 9 and 10). This procedure was particularly useful for E–W sections. The same procedure applied to N–S oriented sections provided less resolution as compared to the conventional stacking workflow. The position of the pre-stack depth-migrated E–W sections of the cross-lines Q3, Q4 and Q5 relative to the N–S depth-migrated Vibroseis main line is shown in Fig. 8. The location of the central E–W sections of Q3 and Q4 and the southern section of Q5, respectively, is almost consistent with the location of the corresponding receiver lines and centred relative to the main line. The lowermost reflections

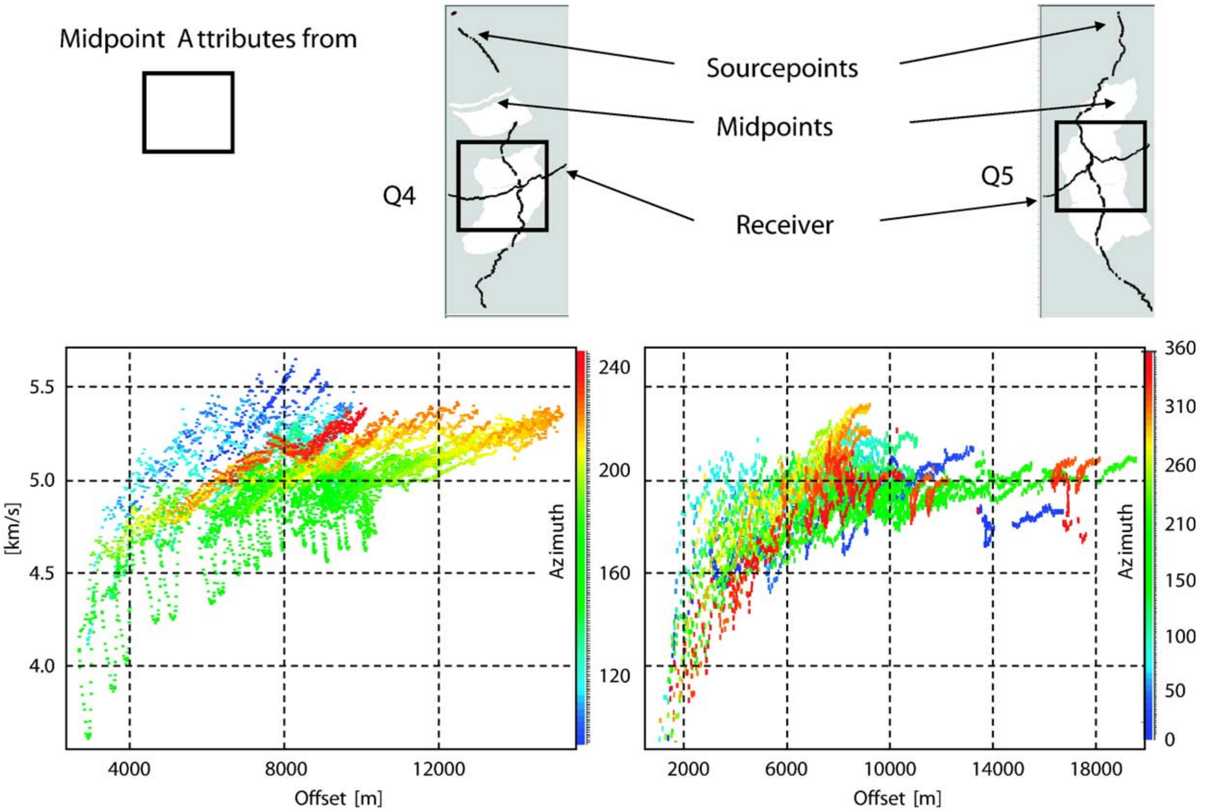

Fig. 7. Variation of P-wave average velocities of first arrivals with azimuth and offset. Left: cross-line Q4 (at southern rim of the Tauern Window), right: Q5 (south of the Periadriatic Lineament). Values are depicted from areas marked by a frame within the source–receiver-midpoint coverage (on top). First-break picks with offsets lower than 2 km are excluded. Azimuths are colour-coded, differently in both figures. Note systematically increased velocities in E−W direction at cross-line Q4. Velocities at all azimuths increase with offset because of increasing depth penetration of diving waves.

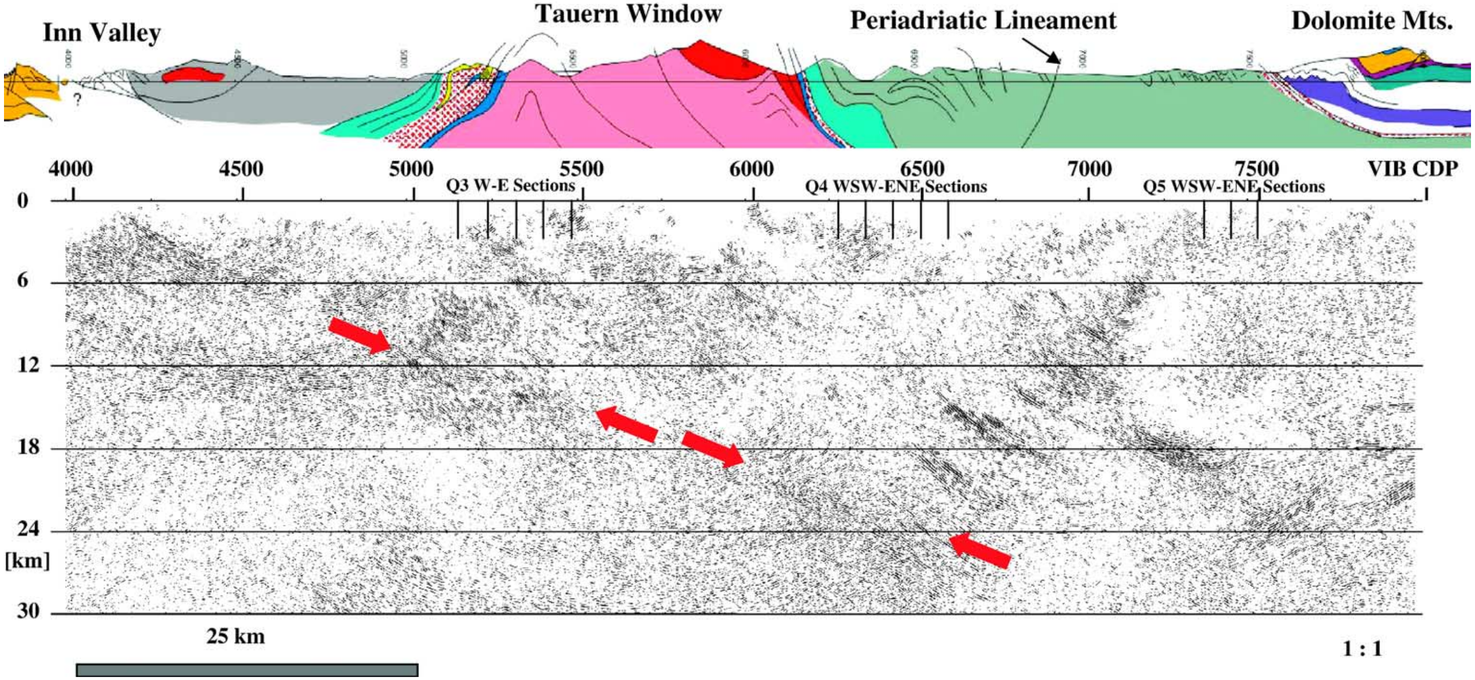

Fig. 8. Depth-migrated N−S section between the Inn Valley and the Dolomite Mountains (modified from Lüschen et al., 2005-this volume). The section corresponds to main-line stack section of Fig. 5. Thick arrows mark position of reflection patterns associated with the interpreted Sub-Tauern-Ramp. Tick marks at the horizontal axis mark the position of W−E sections shown in Fig. 9 (Q3, Q4) and Fig. 10 (Q5).

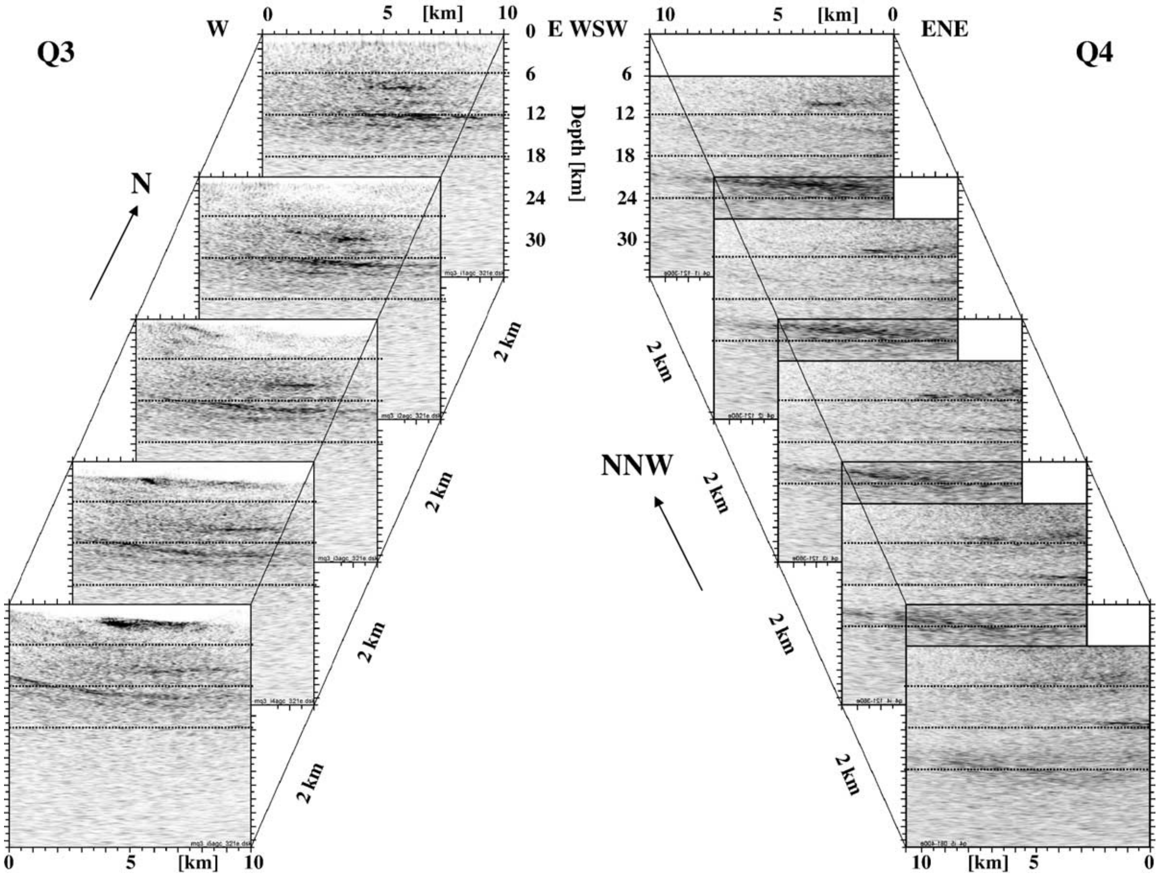

Fig. 9. Pre-stack migration of common-source gathers recorded on cross-lines Q3 and Q4 (from Hähle, 2003). The migration algorithm is based on the 'Isochrone Migration' (Simon et al., 1996) and consideration of seismic anisotropy in the uppermost crust. For robustness, amplitudes were corrected for spherical spreading, subsequent AGC (automatic gain control) and transformed to envelopes. The data were than migrated onto E−W sections 2 km apart and then stacked. The central section is almost consistent with the location of the receiver line. Note strong horizontal exaggeration of the scales. Depth lines at 6, 12, 18 and 24 km depth enable correlation with N−S section in Fig. 8.

shown in cross-lines Q3 and Q4 (Fig. 9) correspond to the 'Sub-Tauern-Ramp' mentioned before (compare Figs 8 and 9, note scales). Although the main dip component is about N–S, the reflections of the 'Sub-Tauern-Ramp' also show remarkable easterly dip components. In the eastern half of Q4 there are reflections visible in the hanging wall of the 'Sub-Tauern-Ramp,' being not visible in the main line. This might be an indication that the transparent zone is caused by a granitic pluton, outcropping as the 'Riesenferner Granite' little further east. The cross-line Q5 is located where the N–S stack section of the main line shows a pronounced criss-cross pattern (compare Figs. 5 and 6). The southward dipping elements have been migrated northward (compare Fig. 8), only visible in the northernmost E–W sections of Q5 as weak elements with westerly dip components. In contrast, a thick bundle of reflections at about 18 to 24 km depth appears on the N–S section (Fig. 8) as well as on the E–W sections of Q5 (Fig. 10), identical with the pronounced pattern shown by the explosive seismic image (Fig. 4). There is obviously no significant dip component to be seen in Figs. 4 8 and 10. This reflector pattern is interpreted as root zone of the 'Sub-Dolomites-Ramp' (TRANSALP Working Group, 2002), a large back-thrust system outcropping as Valsugana overthrust further south (compare Castellarin et al., 2005-this volume).

4. Conclusions

Cross-line recording proved to be a valuable and economic companion experiment of the TRANSALP seismic reflection transect through the Eastern Alps. Originally designed for three-dimensional control along the north–south running main transect, additional unexpected information on seismic anisotropy and alternative, gap-filling images of crucial parts of the main transect could be obtained. We recommend this approach as particularly useful for transects with difficult terrain and environments where unfavourable noise and geological conditions prohibit efficient deep reflective seismic wave recording and interpretation.

Conventionally processed sections along N–S running common-midpoint (CMP) binning lines confirm and strengthen the predominance of midcrustal reflective structures of the ‘Sub-Tauern-Ramp’ beneath and south of the Tauern Window. Velocity analysis of the first arrivals exhibit about 10% higher average velocities of east–west propagating P-waves, compatible with paleo-strain-dominated rock anisotropy, recorded on cross-lines at the Tauern Window. Pre-stack depth migration of cross-line recordings indicate that the dominant dip direction of particularly strong reflections of the Sub-Tauern-Ramp is in the north–south plane, but show also easterly dip components. Further to the south, reflections of the presumed root zone of the Sub-Dolomites-Ramp are almost sub-horizontal.

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, Rome) and the company ENI-AGIP (Milan). The TRANSALP partners are from universities of Munich, Leoben, Bologna, Salzburg, Milan, Rome, Trieste, ETH Zürich and 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., Milan, Italy, GEOTEC Sp.A., Campobasso, Italy, and O.G.S., Trieste, Italy, for their excellent and enthusiastic work in difficult terrain and under difficult logistical conditions, even during winter. We appreciate administrative services provided by the GFZ Potsdam. The seismic programme is accompanied by other interdisciplinary research projects funded and coordinated by the Deutsche Forschungsgemeinschaft (DFG), Österreichischer Fonds zur Förderung der wissenschaftlichen Forschung and the Consiglio Nazionale delle Ricerche (CNR).

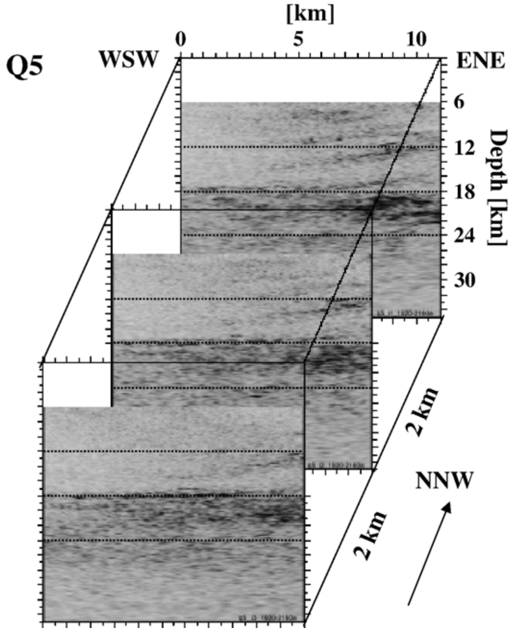

Fig. 10. Pre-stack migration of common-source gathers recorded on cross-line Q5 (from Hähle, 2003). For processing details see Fig. 9. Depth lines at 6, 12, 18 and 24 km depth enable correlation with N−S section in Fig. 8.

Table 1
Cross-line spread and recording parameters, others than those of the main line (see Lüschen et al., 2005-this volume)

Number of cross-lines	7 (Q1−Q7)
Length of cross-lines	20 km
Spacing of cross-lines	30−35 km
Contractors	Q1 DMT; Q2, Q5 JOANNEUM; Q3, Q4, Q6 THOR; Q7 GEOITALIA
Recording system in slave mode or directly connected to main line spread: number of recording channels	SUMMIT 2 (Q1, Q2, Q5): 240 ch ARAM 24 (Q3, Q4, Q6): 400 ch SERCEL 368 (Q7): 200 ch
Geophone group spacing	40−80 m
Sources per cross-line	All vibrator points and explosive shot points on main line between tiepoints with adjacent cross-lines plus shot points off-end on cross-lines fired repeatedly
Nominal CMP coverage	Variable, depending on binning and sources
Nominal CMP bin size and coverage (Vibroseis)	50 m (N−S), 20−40 m (E−W); 1-fold

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