Lithosphere structure and tectonic evolution of the Alpine arc: new evidence from high-resolution teleseismic tomography

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Abstract: Several continental and oceanic plates and/or terranes amalgamated during the formation of the tectonically complex Alpine arc. Reliable knowledge of the present structure of the lithosphere–asthenosphere system throughout the Alpine arc from the Western through the Central to the Eastern Alps is crucial for understanding the evolution of this orogen and the current interaction of lithospheric blocks, and additionally, for assessing the amount and orientation of lithosphere subducted in the geological past. We have compiled results from earlier geophysical studies and reinterpretations of existing seismic and geological data for the Alpine crust and Moho. High-resolution teleseismic tomography was used to produce a detailed 3D seismic model of the lower lithosphere and asthenosphere. The combination of these techniques provides new images for the entire lithosphere–asthenosphere system, showing significant lateral variations to depths of 400 km. Over the years the crustal structure has been determined extensively by active seismic techniques (deep seismic sounding) with laterally variable coverage and resolution. For a closer view three international seismic campaigns, using mainly near-vertical reflection techniques in the Western, Central and Eastern Alps, were carried out to assess the crustal structure with the highest possible resolution. The synoptic reinterpretation of these data and an evaluation of existing interpretations have allowed us to construct four detailed deep crustal transects across the Alps along the ECORS-CROP, NFP-20/EGT and TRANSALP traverses. In addition, contour maps of the Moho for the wider Alpine region and of the top of the lower crust were compiled from existing seismic refraction, near-vertical and wide-angle reflection data. Substantial structural differences in the structure of the deep crust appear between the Western, Central and Eastern Alps: doubling of European lower crust in the west resulted from collision with the Ivrea body; indentation of lower Adriatic crust between European lower crust and Moho occurred in the Central Alps; and a narrow collision structure exists under the transitional area between the western and eastern subduction regime under the Tauern Window of the Eastern Alps, where the crustal structure resembles a large-scale flower structure. Most recently, high-resolution teleseismic tomography based on the *a priori* known 3D crustal structure and compilation of a high-quality teleseismic dataset was successfully developed and applied to derive reliable detailed images of the lower lithosphere. Along strike of the Alps a fast slab-like body is revealed which in the western part is subducted beneath the Adriatic microplate. In the Western Alps detachment of parts of the lower continental slab occurred, possibly induced by the Ivrea body, which acted as a buttress in the collision process of the European and Adriatic plates. The generally SE-directed subduction of the European continental lithosphere changes gradually from west to east to almost vertical under the westernmost part of the Eastern Alps (western Tauern Window and Giudicarie lineament). Unexpectedly, some 50 km further east the subducted continental lower lithosphere is now part of the Adriatic lithosphere and dips NE beneath the European plate. Our tomographic image documents clear bipolar slab geometries beneath the Alpine orogen. The depth extent of the subducted continental lithospheric slab agrees rather well with estimates of post-collisional crustal shortening for the Western and Central Alps. This kinematic control on amounts of lateral motion of the collision zone in the west also allows estimates of the subduction and collision process in the Eastern Alps. The new 3D lithospheric picture for the wider Alpine region to 400 km depth demonstrates the clear connection and interaction between the deep structure of the lithosphere–asthenosphere system and near-surface tectonic features as seen today. It provides new and unexpected evidence for the entire Alpine tectonic evolution, a process which obviously changes significantly from west to east.

The very successful European Geotraverse (EGT) (Blundell *et al.* 1992) was based on the concept of a continuous continental swath extending from northern Scandinavia to Tunisia. It provided consistent present-day information regarding the lithospheric structure across each of the tectonic provinces, ranging in age from Archaean to recent. The present paper, however, is partly based on the rationale of an equally important follow-up project, namely EUROPROBE (Gee & Zeyen 1996). This project elucidates tectonic phases and processes in various European areas in time and space, one of these areas being the Alpine orogeny. In recent years data on the Alps were collected as part of the EGT and EUROPROBE projects, during specific French–Italian and Swiss crustal seismic reflection campaigns, ECORS-CROP (Roure *et al.* 1990) and NRP20 (Pfiffner *et al.* 1997), respectively, as well as during earlier deep seismic sounding experiments. We will demonstrate that this recent mosaic of structural information, which mostly pertains to the crust, eventually leads to a consistent 3D picture for the lithospheric-scale tectonic evolution of the Alps when combined with the latest results from newly developed methods of teleseismic tomography.

Several continental and oceanic plates and/or terranes amalgamated during the formation of the tectonically complex present-day Alpine arc, which is characterized by very major along-strike changes in crustal structure from the Western (French–Italian) to the Central (Swiss–Italian) and Eastern (Austrian–Italian) Alps. The attribution of the various tectonic units of the Alps to particular palaeogeographical domains (Fig. 1) is based on stratigraphical analysis and retro-deformation of nappe stacking. The remnants of the following major palaeogeographical units, whose present-day position is indicated in Figure 1, are found at present in the Alps (after Froitzheim *et al.* 1996; Schmid 2000; see Schmid *et al.* 2004*a,b* for a revised overall architecture of the Alpine orogen):

(1) The European margin: external massifs and their cover, Helvetic cover nappes and their presumed basement forming the lowermost Penninic units (Sub-Penninic nappes) and almost reaching as far south as the Insubric–Periadriatic line.

(2) The late Jurassic–Cretaceous Valais ocean (Alpine Tethys), which closed during the late Eocene collision: remnants predominantly consist of Cretaceous-age Bündnerschiefer and are found within the Lower Penninic nappes.

(3) The Piemont–Ligurian ocean (Alpine Tethys) of mid-Jurassic to Early Cretaceous age: largely subducted below the Adriatic microplate since the onset of Late Cretaceous (Eoalpine) to Tertiary orogeny although slivers are preserved within the Upper Penninic nappes.

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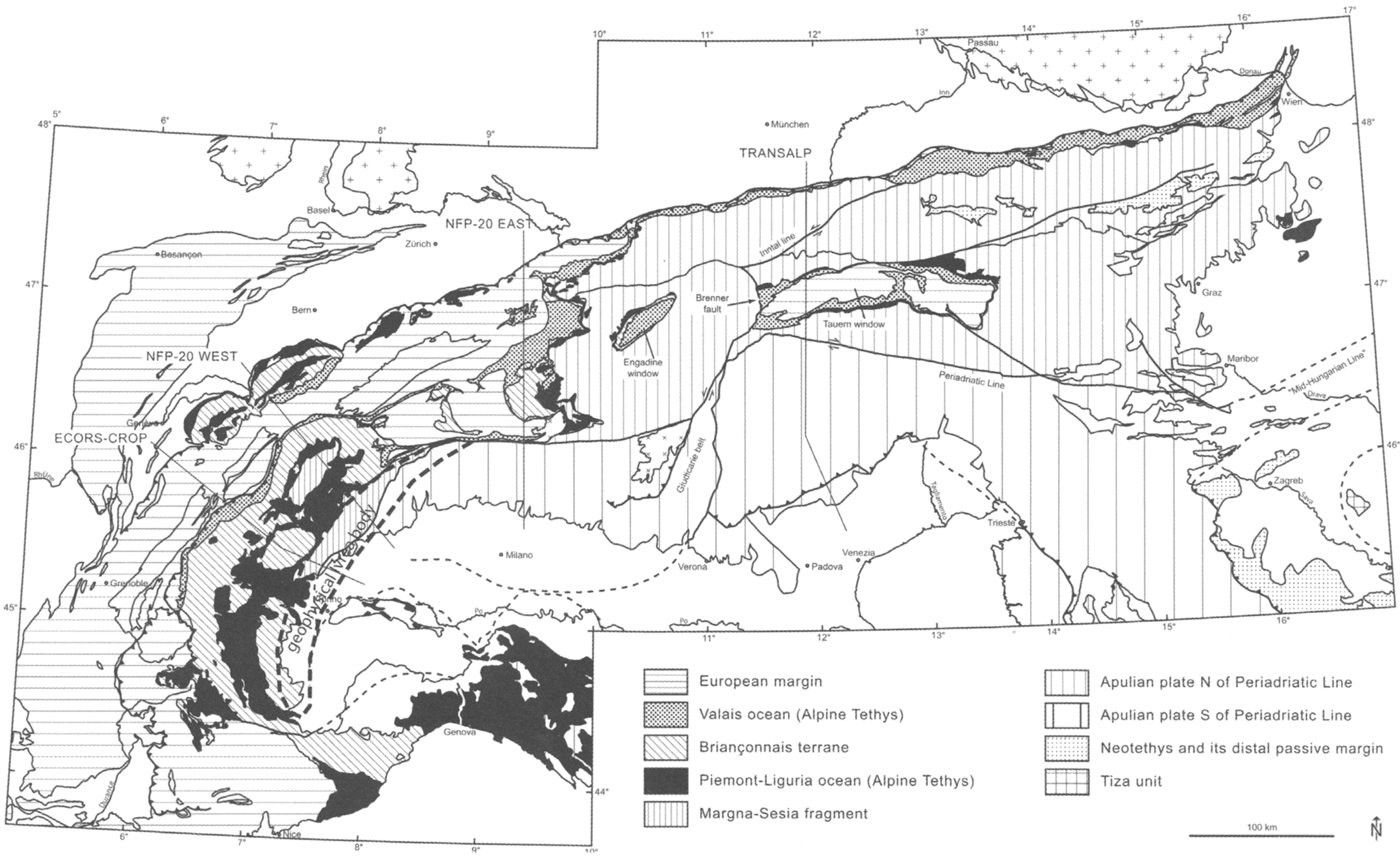

Fig. 1. Sketch map of palaeogeographical units in the Alps (modified after Froitzheim *et al.* 1996) with locations of the four crustal geophysical–geological transects shown in Figures 3, 13 and 14 (see also Fig. 12 for location of the lithosphere profiles). Bold dashed contour outlines the Ivrea geophysical body; fine dashed contours indicate extrapolated tectonic lineaments. Details of surveys on ECORS-CROP, NFP-20 WEST and EAST, TRANSALP have been given by Roure *et al.* (1990), Pfiffner *et al.* (1997) and TRANSALP Working Group (2002), respectively.

(4) The Briançonnais microcontinent or terrane: originally situated between the two above-mentioned oceans and part of the European margin before being rifted off along the future Valais ocean, preserved as Middle Penninic cover and basement nappes, but only in the Western And central Alps.

(5) The Margna–Sesia fragment: a small splinter of the Apulian margin rifted off during the opening of the Piemont–Ligurian ocean, later incorporated into the accretionary wedge forming at the active northern margin of Apulia, and forming a part of the Lower Austroalpine nappes.

(6) The Apulian plate south of the Periadriatic line: part of the Apulian plate referred to as 'Adriatic plate' and including the Ivrea body at its western margin, consisting of rigid south Alpine lower crustal rocks that were exhumed already during Mesozoic rifting.

(7) The Apulian plate north of the Insubric line: parts of the Apulian plate at present forming most of the Austroalpine nappes, that is thin crustal flakes floating on the remnants of the Piemont–Ligurian ocean.

(8) The Neotethys and its distal passive margin: mostly only the remnants of the distal passive margin of the Apulian plate facing Neotethys are preserved in the Alps (the Triassic-age Meliata ocean, a second former ocean, originally located SE of the Alpine Tethys, was closed by early Cretaceous times) and form small parts of the Austroalpine nappe system (restricted to the Eastern Alps of Austria).

To a large extent the above-mentioned palaeogeographical findings are based on the analysis of near-surface evidence. The concept of plate tectonics showed clearly that the evolution of the Alpine orogen could be understood only by the additional assessment of the detailed structural image of Alpine crust and lower lithosphere. Active seismic experiments (controlled source seismology; CSS) began in 1956 in the Western Alps and have continued since then throughout the Alps with increasing resolution of crustal structure. In particular, near-vertical reflection surveys along several across-strike transects provided the necessary insight into mechanisms of collision between continental crustal units.

Earlier, various other seismic methods (e.g. dispersion of seismic surface waves and initial analysis of travel times) were used to derive first images of the Alpine lower lithospheric structure. However, until now these structures could not be resolved precisely enough, although knowing their geometry is indispensable for the understanding of the evolution of the Alps. For a summary of earlier results and their significance the reader is referred to Kissling (1993) and Mueller (1997). Only travel-time tomography, based on regional and teleseismic earthquakes, provided the desired resolution at the decisive depth range. We are fully aware that seismic anisotropy represents additional information. However, currently detailed and reliable anisotropy information covering a significant part of the volume under study is missing. At present, the combination of the available techniques and data allows us to establish a 3D image of the lithosphere to depths of 400 km and to quantitatively unravel the evolution of the Alps.

Crustal structure

Classical deep seismic sounding with refraction and wide-angle reflection surveys provides a basic overview of the Alpine

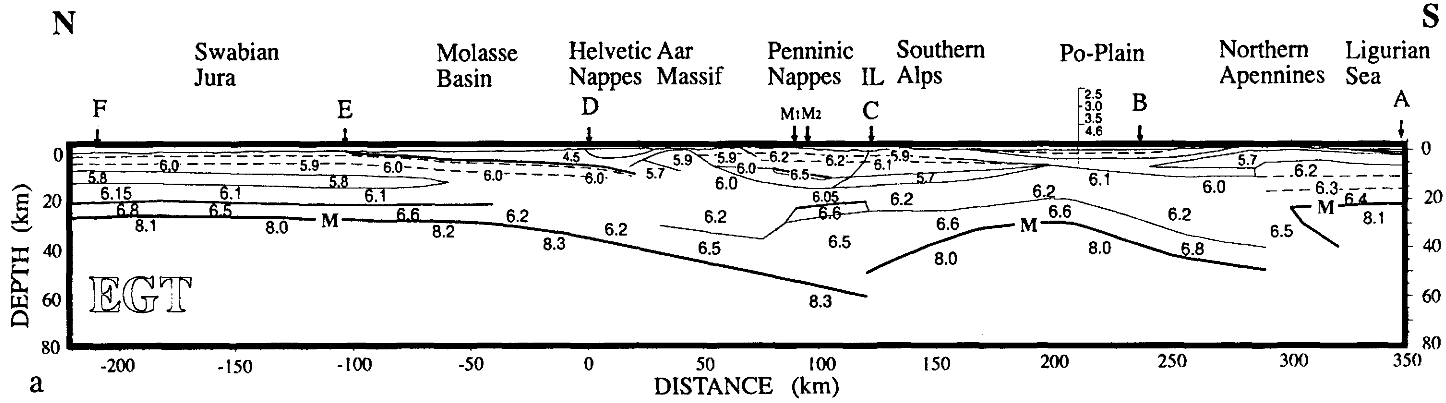

Fig. 2. Crustal cross-section along the European Geotraverse (EGT) across the Central Alps (NFP-20 East in Fig. 1) from the northern Alpine foreland to the Ligurian Sea derived from active refraction and wide-angle reflection data. A–F, shot points; IL, Insubric line; numbers give P-wave velocities (in km s^{-1}); M, crust–mantle boundary (after Ye *et al.* 1995).

crustal structure to Moho depths. Good information is available from a rather dense network of profiles in the Western and Central Alps, but much less is known from the Eastern Alps (for a compilation see Waldhauser *et al.* 1998). Interpretation of these data along profiles with various orientations provides excellent information on the topography of the crust–mantle boundary and on the average P-wave velocities used as input for an average 3D crustal model as described in the next section. In addition, characteristic structural details allowing for tectonic inferences can be derived in areas with favourable location and orientation of surveys.

The large number of along-strike profiles in the Central Alps, combined with a densely occupied refraction survey along the north–south-oriented EGT (NFP-20 East in Fig 1; Fig. 4), allowed the derivation of a reasonably detailed crustal image in terms of P-wave velocities (Fig. 2) extending across the Alps and the Po Plain from the northern foreland to the Ligurian Sea (Buness 1992; Ye *et al.* 1995; Kissling *et al.* 1997), also including a careful error assessment (Waldhauser *et al.* 1998). Underneath the very variable and complicated sedimentary cover and the Alpine nappes, the main features of the Alps are the deep-reaching autochthonous Aar Massif (Pfiffner & Hitz 1997), which exhibits little internal structure, a high-velocity layer in the middle to lower crust north of the Insubric line, and two clear Moho offsets underneath the Alps and the northern Apennines, where lower European and Adriatic lithosphere are subducted under the Adriatic and Ligurian plates, respectively.

This velocity information is a prerequisite for a satisfactory interpretation of near-vertical reflection transects. Figure 1 shows the location of four 2D Alpine crustal reflection transects (western transect ECORS-CROP, Roure *et al.* 1990; central and eastern transects NRP20, Pfiffner *et al.* 1997; Eastern Alps transect TRANSALP, TRANSALP Working Group 2001, 2002; Gebrande *et al.* 2006). Depending on the data quality, which is largely determined by the difficult topographic and geological conditions across the Alps, these transects provide the best available structural resolution for the entire crust. Structural details at depth can directly be incorporated into the near-surface geological and tectonic structure. However, these transects are limited in number. Figure 3 (Schmid & Kissling 2000; Schmid *et al.* 2003, 2004*a*) shows unified interpretations of these available near-vertical reflection surveys, including evidence from seismic refraction surveys and geological data along the three western transects and a preliminary interpretation of the TRANSALP transect. Going from the ECORS-CROP to NFP20-EAST (the TRANSALP profile will be discussed later) major common and/or contrasting features are (Schmid & Kissling 2000): (1) ESE- to south-directed subduction of European lithosphere; (2) offset between European and Adriatic Moho, as also seen in Figure 2; (3) duplication and back-thrusting of lower European crust in the Western Alps (Fig. 3a and b) and wedging of Adriatic lower crust into the European middle crust under the Central Alps (Fig. 3c), respectively, covered by a stack of piled up and refolded upper crustal flakes (the Alpine nappes) in all three transects; (4) Adriatic Moho rising towards the Alps in the west and descending Moho at the base of the lower crustal wedge under the Central Alps; (5) eastwards increasing amounts of back-thrusting in the vicinity of the Insubric line; (6) strong shortening within the southern Alps in a foreland fold and thrust belt above the Adriatic lower crust (Schönborn 1992), which is exposed in the Ivrea Zone (Handy & Zingg 1991; Schmid 1993).

Moho topography

As mentioned above, a wealth of CSS crustal profiles in the wider Alpine region provides ample information on the Moho topography, depicted in Figure 4 (for an overall compilation see Waldhauser *et al.* 1998; for the Western Alps see Hirn *et al.* 1989; Thouvenot *et al.* 1990). Wide-angle reflections from the crust–mantle boundary are the most reliable and clear signals on most of these profiles. Based on these data, a method was developed that assesses the quality of Moho reflections, depths and crustal velocities (Kissling *et al.* 1997). Based on this method a reproducible 3D crustal model was established, comprising mean crustal velocities and a Moho contour map with least roughness within the estimated error estimates (Waldhauser *et al.* 1998). This model (Fig. 4) serves several purposes. First, it provides a good and reliable overview for variations in crustal thickness and mean velocity, and the relative position of these features with respect to surface tectonics and other geophysical observations. Second, it reliably shows the location of offsets of the Moho where subduction does occur. Third, it can be used to correct crustal travel times for teleseismic tomography, as discussed below. Figure 4a shows the contours of the Alpine Moho in 2 km intervals as derived by interpolation of the migrated CSS travel-time data located in the shaded areas, and Figure 4b shows a perspective NE–SW view of these surfaces. The number and lateral distribution of shaded areas also provides a measure of the high information density, which is unique worldwide. The image of the Alpine crust–mantle boundary shows two offsets, resulting in three separate Moho interfaces, namely the European, Adriatic and Ligurian Moho. The European Moho features a continuous change from an eastward dip under the Western Alps to a southern dip under the Central Alps, as already seen in the detailed transects of Figure 3. The Adriatic Moho is best imaged near the EGT-NFP20 profile, where it is up-domed below the Po Plain between the European and the

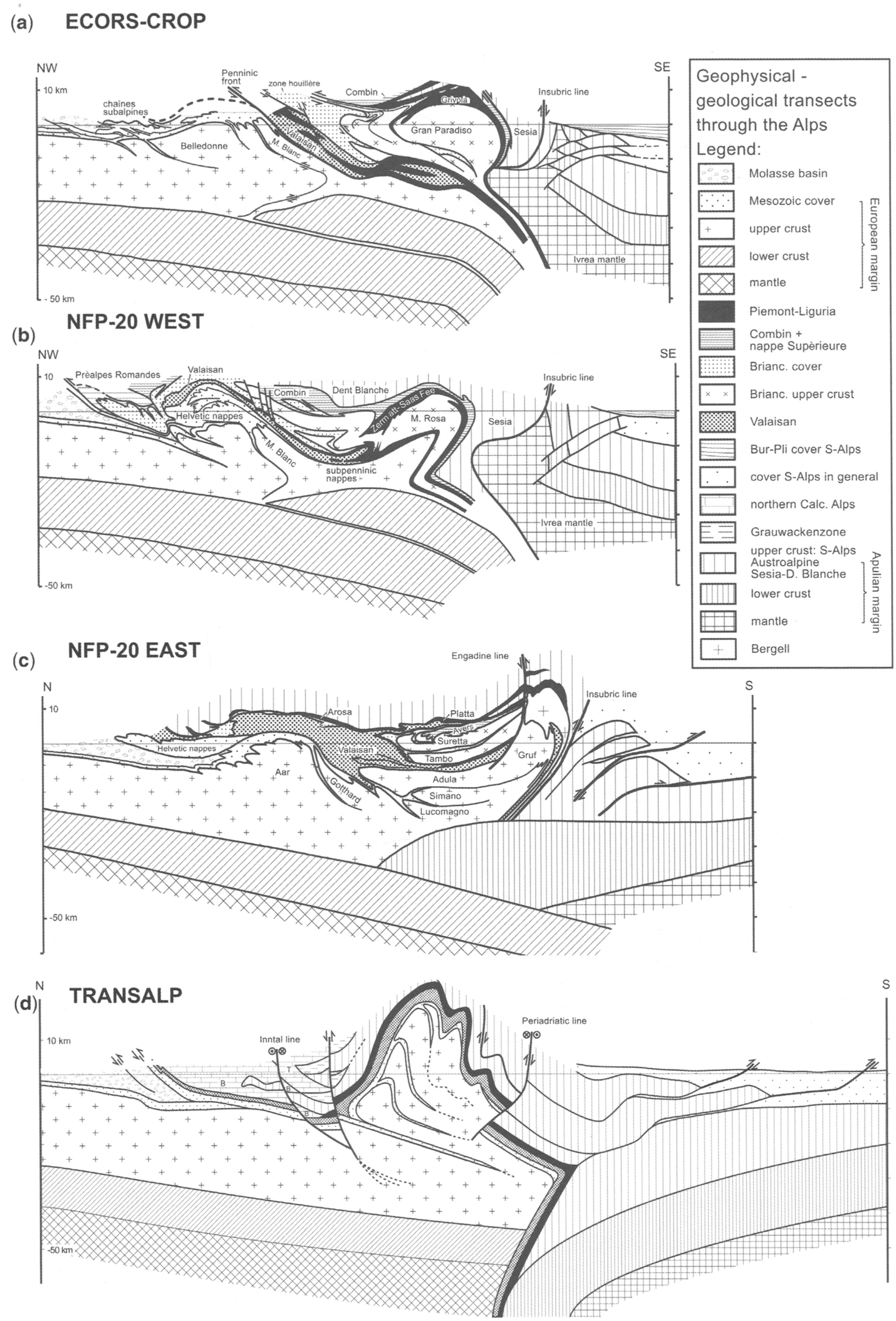

Fig. 3. Crustal geophysical–geological transects through the Alps (after Schmid *et al.* 2004*a*). (For locations see Figs 1 and 12.)

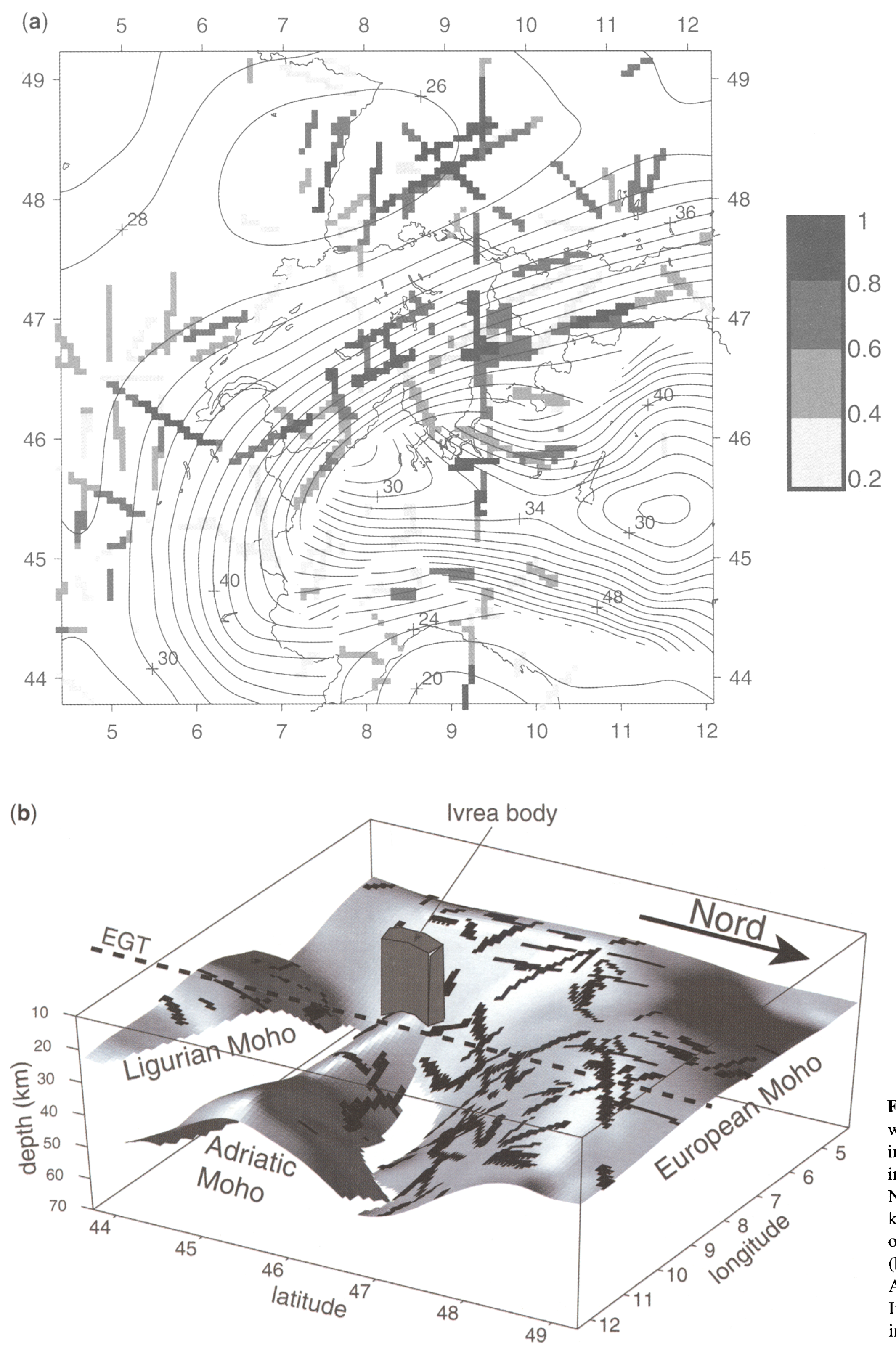

Fig. 4. (**a**) Crust–mantle boundary in the wider Alpine region contoured at 2 km intervals derived from smoothest interpolation of 3D migrated CSS data. Numbers indicate isoline depth values in kilometres. Broken bars indicate locations of wide-angle Moho reflection elements. (**b**) Perspective SW view on the European, Adriatic and Ligurian Moho. The Ivrea geophysical body is schematically indicated (after Waldhauser *et al.* 1998).

Ligurian Moho. Near the southern rim it is overthrust by the Ligurian crust, and at the western margin of the Po Plain the Adriatic Moho merges into the structure of the Ivrea Zone (see also Fig. 3b). This Alpine Moho topography reflects the large-scale Alpine structure resulting from the latest stage of continental collision (Schmid & Kissling 2000).

Moho offsets and gaps, including their location, play key roles in tectonic interpretations of 3D lithospheric structure. A gap in otherwise continuous seismic information (Fig. 5) (e.g. as seen along near-vertical reflection profiles) could be interpreted as a zone of symmetric subduction of lithosphere, or so-called 'Verschluckungs-Zone', as proposed by Laubscher (1970). However, Valasek *et al.* (1991) and Holliger & Kissling (1992) imaged the expected Moho structure in the same area where no near-vertical reflections were observed (Fig. 5). Those workers used wide-angle data from CSS cross profiles and wide-angle reflections along the EGT-NFP20, respectively. The results obtained by networked wide-angle and near-vertical profiling prove that the Moho interface exists everywhere under the wider Alpine region. However, there is clear evidence for Moho offsets (Figs 3 and 5),

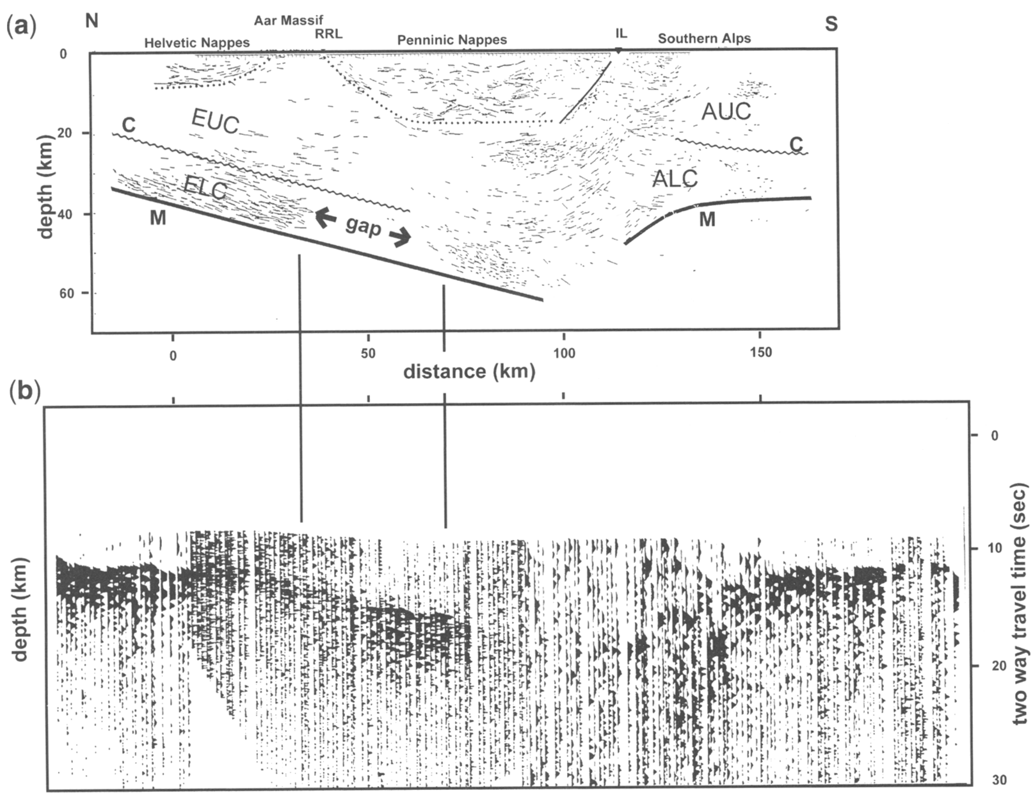

Fig. 5. Combination of crustal structure and Moho depth along NFP-20 EAST/EGT transect (Fig. 1). (**a**) Line drawings of migrated near-vertical reflections and generalized seismic crustal structure derived from orogen-parallel refraction profiles (Holliger & Kissling 1992). Continuous line indicates Moho (M), wavy line the top of lower crust (C), dotted line the base of Penninic and Helvetic nappes, fine line the Insubric line; RRL, Rhine–Rhône line. AUC, Adriatic upper crust; ALC, Adriatic lower crust; EUC, European upper crust; ELC, European lower crust. (**b**) Normal incidence representation of wide-angle Moho reflections along the EGT refraction profile perpendicular to the orogen across the Central Alps. The gap in the reflectivity signal from the lower crust is clearly covered by wide-angle reflection data (Valasek *et al.* 1991; Valasek & Mueller 1997).

indicating asymmetric subduction geometries. Hence, the Moho is not a continuous interface. Laterally bounded Moho signals define these offsets. Provided their relative positions are clearly defined, the sense of subduction can be inferred.

Lower crustal wedge structures

The high-resolution transect images shown in Figure 3a–c clearly show that there is no common crustal model that would be valid for the entire Alpine arc in terms of a simple collision or shortening mechanism. Special features are the lower crustal wedges as found in the western and central Alpine transects. The wedge in the lower crust of the central transect (Fig. 3c) consists of Adriatic lower crust with a P-wave velocity of 6.5–6.6 km s^{-1} (Fig. 2). This wedge lies above lower European crust, as can be derived from the clear reflection seismic data visible in Figure 5a. It is bounded by the Adriatic upper to lower crustal interface C and by the Adriatic Moho M. Its shape also agrees with the interpretation of CSS seismic refraction and wide-angle reflection observations (Fig. 2) by Ye *et al.* (1995) and Schmid & Kissling (2000). According to palinspastic reconstructions (Schmid *et al.* 1996, 1997), the northward intrusion of the wedge occurred during mid- to late-Miocene times and was contemporaneous with the formation of a fold and thrust belt within the upper Adriatic crust of the southern Alps. Hence, wedging is a rather late and suddenly appearing feature during the Alpine collision. It should be noted that this wedging requires complete detachment near the interface between lower and upper crust, and probably also at the base of the Adriatic lower crust that directly overlies the European lower crust, although this lower interface of the wedge is not clearly identified. Figure 6 (courtesy of Schönborn, pers. comm., based on Schönborn 1992) gives a perspective NW–SE view of the Alpine crustal model along the EGT-NFP20 transect, revealing the late-collisional wedging of Adriatic lower crust into the subducting European plate with the uncovered detachment interface of upper to lower crust. Rectangular arrows indicate the Late Miocene to present-day NNW–SSE-oriented maximum horizontal stress direction that produced significant lateral extrusion of the Eastern Alps to the east (Ratschbacher *et al.* 1991).

Shortening in the two western transects, which are located close together (Fig. 3a and b), predominantly occurred within the external European and Briançonnais realms. The overall geometry suggests south-directed subduction of the European plate, as can also be inferred from the central transect (Fig. 3c). It should be noted, however, that in the western transects lower crustal wedging occurs within the European plate, as was extensively discussed by Schmid & Kissling (2000). The clear identification of the top of the lower crust, based on the exact position of the detailed near-vertical reflection profiles, together with the location derived from refraction and wide-angle reflection profiles between them, allowed the compilation of a contour map for this internal crustal interface (Schmid & Kissling 2000). Figure 7 shows the topography of the Conrad discontinuity (top lower crust) and identifies the lateral extent of lower crustal wedges of different origin, situated in the hinge zone between the north–south-striking Western Alps and the east–west-striking Eastern Alps. The Adriatic lower crustal wedge under the Central Alps and the European crustal wedge under the Western Alps (Figs 3 and 8) meet at depth below the location where the Simplon fault zone branches off the Insubric line; that is, about halfway between NFP20 reflection profile segments W3 and C2 in Figure 7. This indicates a rather sharp transition from Western to Central Alps at depth.

In accordance with recent findings in exhumed high-pressure rocks (Lund *et al.* 2004) the geometry of this wedging of Adriatic and European lower crust, as discussed so far, suggests that the bulk of the lower crust is made up of high-strength material, contrary to a widely held belief in a 'weak lower crust' by the geoscience community (e.g. Meissner & Kusznir 1987; Banda & Cloetingh 1992; Willingshofer & Cloetingh 2003). Such low-viscosity material, however, must be present within relatively thin layers forming the interfaces of the lower crustal wedges with the upper crust and the upper mantle, respectively, allowing for detachment near these interfaces bounding the wedges.

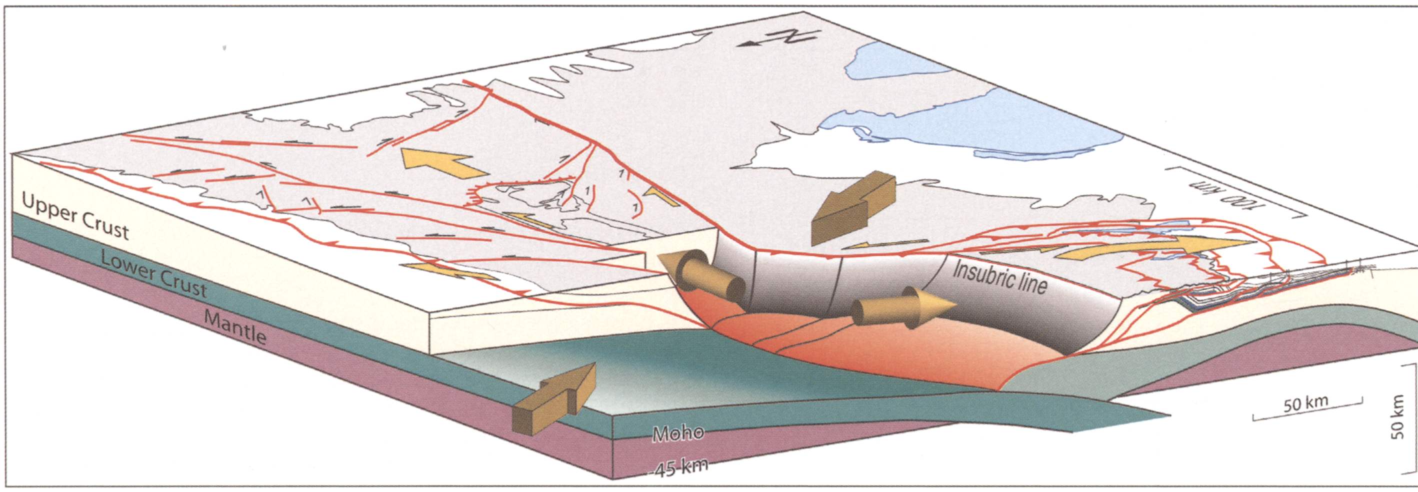

Fig. 6. Perspective NW–SE view of the Alpine crustal model with the NFP-20/EGT transect at the western edge, showing the late collisional wedging of lower Adriatic crust into the subducting European plate with uncovered detachment of upper to lower crust interface. Rectangular arrows indicate the present-day NNW–SSE-oriented horizontal stresses; round arrows indicate lateral escape movement of the upper crustal units to the east and SW (courtesy of G. Schönborn, after Schönborn 1992).

A quantitative post-35 Ma kinematic reconstruction of SE–NW shortening along the ECORS-CROP and Central Alps transects is displayed in Figure 8. The total amount of shortening is a composite of the westward strike-slip component of the Adriatic plate relative to Europe and the amount of north–south shortening along the EGT-NFP20 transect (Schmid *et al.* 1996). As shown in Figure 7 the Adriatic Moho rises to shallower depth and merges into the structure of the Ivrea Zone (see also Fig. 3a and b) at the western margin of the Po Plain. The subvertical orientation of rigid lower crust and upper mantle material that rises to the surface is probably responsible for the presence of a backstop, causing the relatively young back-thrusting and doubling of the European lower crust under this part of the Western Alps.

Eastern Alpine crustal structure

A fourth and latest crustal transect (Fig. 3d) TRANSALP was established across the Eastern Alps (Fig.1) by high-resolution reflection and refraction seismic survey and other geophysical methods (Ebbing *et al.* 2001; TRANSALP Working Group 2001, 2002; Bleibinhaus 2003; Lueschen *et al.* 2003), following much earlier work by Miller *et al.* (1977). First interpretations of the data were presented by Lammerer & TRANSALP Working Group (2003) and Castellarin *et al.* (2003). Additional information on this transect has been given by Nicolich *et al.* (2003).

The boundary between the Western and Eastern Alps coincides roughly with the north–south-striking western margin of the Austroalpine nappes (Fig. 1, western margin of Apulian plate north of the periadriatic line), which formed by top-to-the WNW suturing of the Austroalpine units with the Piemont–Ligurian ocean during a first orogenic cycle in the Cretaceous (Froitzheim *et al.* 1994). However, the more external Briançonnais microcontinent and Valais ocean, bordering the European margin, were not sutured to the Austroalpine units before the end of a second orogenic cycle in the latest Eocene (e.g. Schmid *et al.* 1996). Another important boundary running across strike and situated immediately east of the western end of the Eastern Alps is formed by the

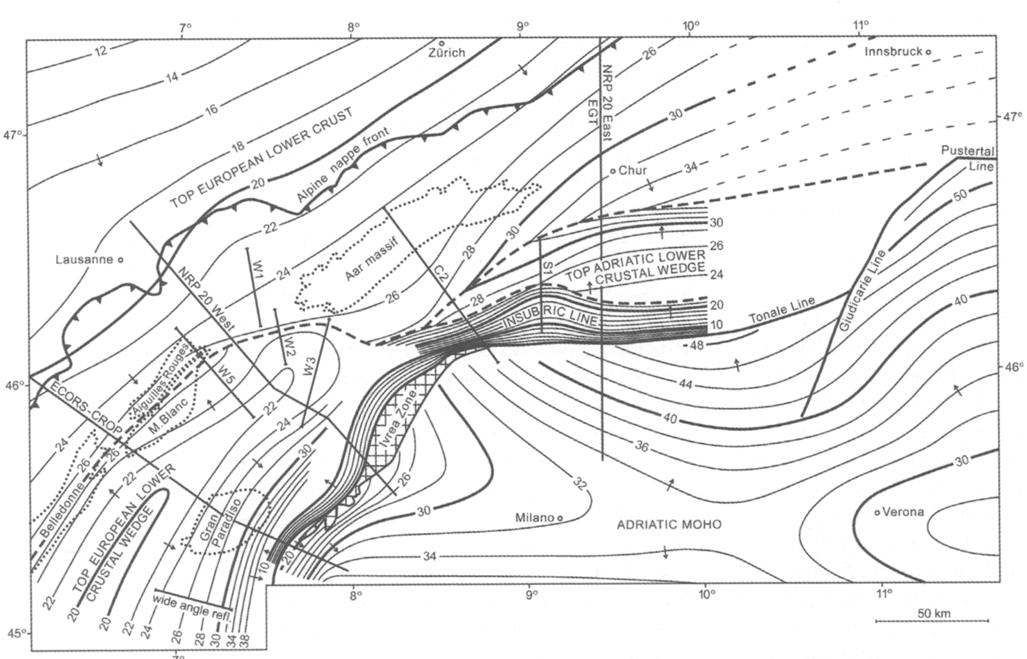

Fig. 7. Contour map of top of European lower crust in the north, top of European lower crustal wedge in the west, top of Adriatic lower crust in the north–central region, and of Adriatic Moho in the south with position of main crustal transects (Fig. 3). The tentative depth extension of the Insubric line and location of high-velocity Ivrea material (after Schmid & Kissling 2000) should also be noted.

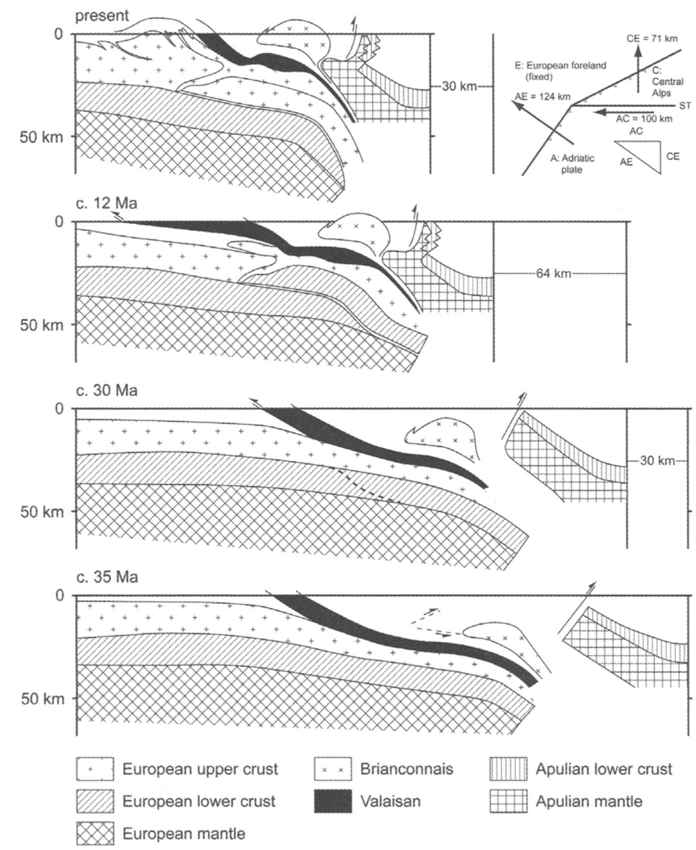

Fig. 8. A kinematic reconstruction of post-collisional (post 35 Ma) shortening along the western transect. The vector triangle (top right) illustrates how the total amount of post-collisional shortening (124 km) of vector AE (movement of Adriatic microplate relative to stable Europe) is composed of 100 km dextral strike slip between the Adriatic microplate and the Central Alps (vector AC) onto the western transect; 71 km of vector CE results in north–south shortening within the Central Alps parallel to the NFP-20/EGT transect (after Schmid & Kissling 2000).

sinistrally transpressive Giudicarie belt (Fig. 1). Sinistral shearing along the Giudicarie belt during the early Miocene caused north-directed indentation of the eastern part of the southern Alps and massive north–south shortening in the Tauern Window (Fügenschuh *et al.* 1997; Stipp *et al.* 2004). This was accompanied by lateral extrusion of the Eastern Alps east of the Brenner normal fault (Ratschbacher *et al.* 1991) associated with dextral strike slip along the Periadriatic line (Fig. 6).

The interpretation of the TRANSALP transect shown in Figure 3d only partly follows that proposed by the TRANSALP Working Group (2002) regarding the near-surface structures and it drastically differs in terms of the interpretation of the deep structure. We attribute the core of the Tauern Window to tectonic units of the European margin, this core having the appearance of a flower structure (Dobrin & Savit 1988). We agree with one of the two models presented by the TRANSALP Working Group (2002) regarding a continuation of south-dipping Tauern Window reflectors underneath the southern Alps south of the Periadriatic line inherited from an initial stage of south-directed subduction. However, we do not see enough evidence for an Adriatic lower crustal wedge indenting the European crust from the seismic data presented by the TRANSALP Working Group such as observed in the NFP20-EAST profile (see Fig. 3c) further west. In fact, these data are also not clear enough to indicate an Adriatic Moho descent northward under the European lithosphere as drawn in Figure 3d, either. However, when proposing the interpretation given in Figure 3d, we are strongly guided by data indicating a NE-oriented subduction of south Alpine lithosphere recently revealed by high-resolution tomography in an area situated immediately to the east (Lippitsch 2002; Lippitsch *et al.* 2003; Schmid *et al.* 2003). These data will be discussed below.

Lower lithosphere

Early models of lower lithospheric structure derived without crustal corrections

As clearly follows from the discussion above, the tectonic evolution and structure of the Alps cannot be understood or reconstructed without reliable and sufficient knowledge of the 3D structure of the lower lithosphere and the lithosphere–asthenosphere boundary at least in terms of P-wave velocity distribution. Any technique chosen has to resolve possible differences in the regional structure between the Western, Central and Eastern Alps to depths of at least the penetration of the lithospheric slabs. Therefore, over the years a considerable effort was made to gain more insight into the relevant upper mantle structure. Kissling (1993) compiled a critical summary of pre-1993 knowledge on lower lithospheric structure and concluded that there exists a thickened lower lithosphere beneath or near the Alps that indicates a southerly and southeasterly dip under the Central and Western Alps, respectively. These results were mainly based on surface-wave analysis and travel-time residual studies (Babuska *et al.* 1990; Suhadolc *et al.* 1990; Guyoton 1991; Viel *et al.* 1991; Ansorge *et al.* 1992) as well as on seismic tomography using datasets of limited accuracy or covering only a small area in the SW Alps (Cattaneo & Eva 1990; Spakman 1991; Spakman *et al.* 1993), respectively. However, methods and resolution were not sufficient to image the 3D structure in detail and, in particular, to properly resolve slab geometries. Since then, travel-time tomography has developed to a powerful tool for the resolution of global and large-scale regional structures in the upper mantle by mainly using data collected by international seismic bulletins such as those produced by the International Seismological Centre (ISC).

Regarding the wider Alpine region we show two important cases of upper mantle structure recently derived by travel-time inversions (Bijwaard & Spakman 2000; Piromallo & Morelli 2003). Both examples use the same ISC data with different selection and resolution criteria in the inversion process. Piromallo & Morelli (2003) showed a continuous structure of high-velocity material underlying the Alps from west to east, as seen in a map view in terms of P-wave velocity variations at a depth of 150 km. This structure is rather diffuse at shallow levels and disappears with increasing depth. Piromallo & Morelli (2003) applied corrections for global non-spherical velocity structure outside the model volume of the wider Mediterranean area but did not apply crustal corrections. Figure 9a depicts a vertical cross-section in the Eastern Alps through the model of Piromallo & Morelli (2003). A diffuse subvertical high-velocity body is seen under the Alps, reaching the 410 km discontinuity. The vertical section across the Central Alps (Fig. 9b) derived by Bijwaard & Spakman (2000) is again based on a large set of ISC first P-wave arrival times without crustal corrections. In this transect the high-velocity structure beneath the Alps appears to dip in a southerly direction. On a larger scale, the two models by Piromallo & Morelli (2003) and Bijwaard & Spakman (2000) agree regarding the existence of a high-velocity structure beneath the Alps. However, in the latter model this structure varies rather unsystematically in a horizontal direction, and it may even disappear further east.

In summary, these tomographic mantle models were derived without crustal corrections. Furthermore, they were obtained by inversion of P-wave travel times determined with different picking routines from seismograms recorded on a variety of

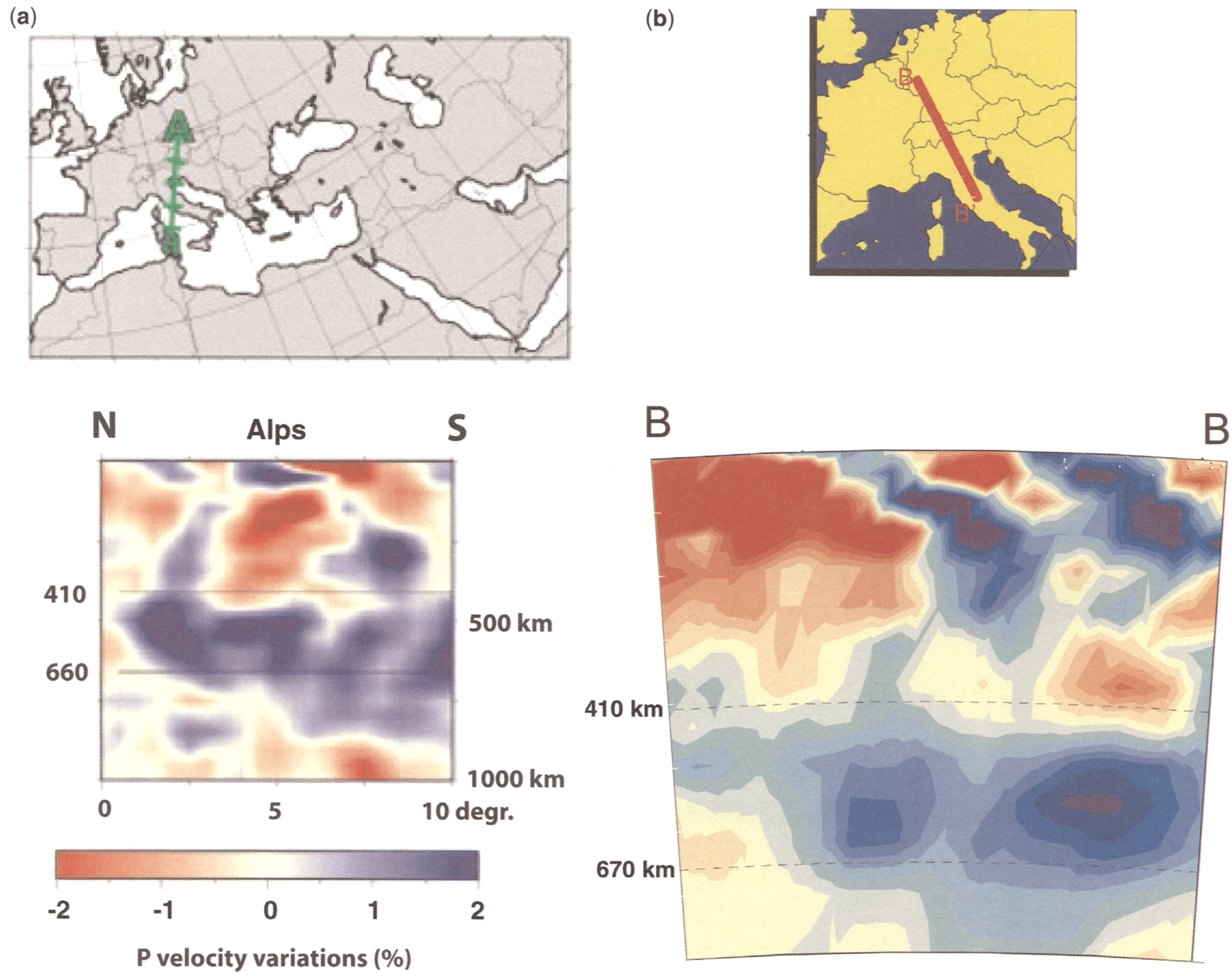

Fig. 9. P-wave velocities as derived by travel-time tomography. Crustal structure is not resolved in both cases. (**a**) NE–SW lithospheric cross-section from Central Europe to northern Africa across the Eastern Alps after Piromallo & Morelli (2003). Lower part shows section A–a′. The northerly vergence of subducted high-velocity material below 150 km depth under the Eastern Alps should be noted. (**b**) NW–SE cross-section through the Central Alps after Bijwaard & Spakman (2000). (For location see B–B′ in Fig. 12.) The SE vergence of subducted European lithosphere, and the high-velocity material in the upper mantle transition zone between 400 and 620 km depth should be noted.

seismographs and reported to ISC. The significant error in the ISC data and the uncorrected effects of the 3D crustal structure seriously limit the resolution of this kind of regional tomography. Hence, the detected structure in the lower lithosphere cannot be correlated clearly with independently determined geophysical and/or tectonic evidence (Fig. 3), nor can it be used to discriminate between hypotheses for the tectonic evolution of the Alpine orogen.

Lower lithospheric structure based on high-resolution teleseismic tomography

In spite of the difficulties regarding the desired resolution discussed above, teleseismic tomography is a very valuable tool to obtain reliable basic structural information in depths ranges that are hard to assess in detail with other methods. To further increase the resolution of teleseismic tomography we recently developed a new and different approach (Waldhauser *et al.* 1998, 2002; Arlitt *et al.* 1999), which can only be summarized here. This procedure uses: (1) a set of carefully selected teleseismic events with digital signals transformed to the same standard recording response; (2) a uniform picking routine for seismic phases resulting in a highly consistent dataset; (3) a careful correction of observed travel times for 3D crustal contributions. Figure 10a schematically shows the ray paths from a single teleseismic event to an array of recording stations through the standard Earth model IASP91. These signals traverse the comparatively slow crust above the study area in a subvertical direction. The lack of crossing rays within the crust prevents a reliable resolution of lateral velocity variations in this crustal layer. Therefore, a representative evenly gridded 3D model (Fig. 10b) was compiled for the Alpine crust from all available seismic data obtained by active CSS methods in terms of mean crustal velocity structure, Moho topography, and sedimentary basins (see Fig. 4). This *a priori* known crustal velocity model allows us to correct the observed teleseismic travel times for the carefully calculated crustal contribution (Waldhauser *et al.* 2002), which may account for up to 50% of the total travel-time residuals.

In a second step we merged selected evenly distributed teleseismic events (Fig. 11b) recorded at sufficiently dense Austrian, French, German, Italian, Slovenian and Swiss permanent seismic

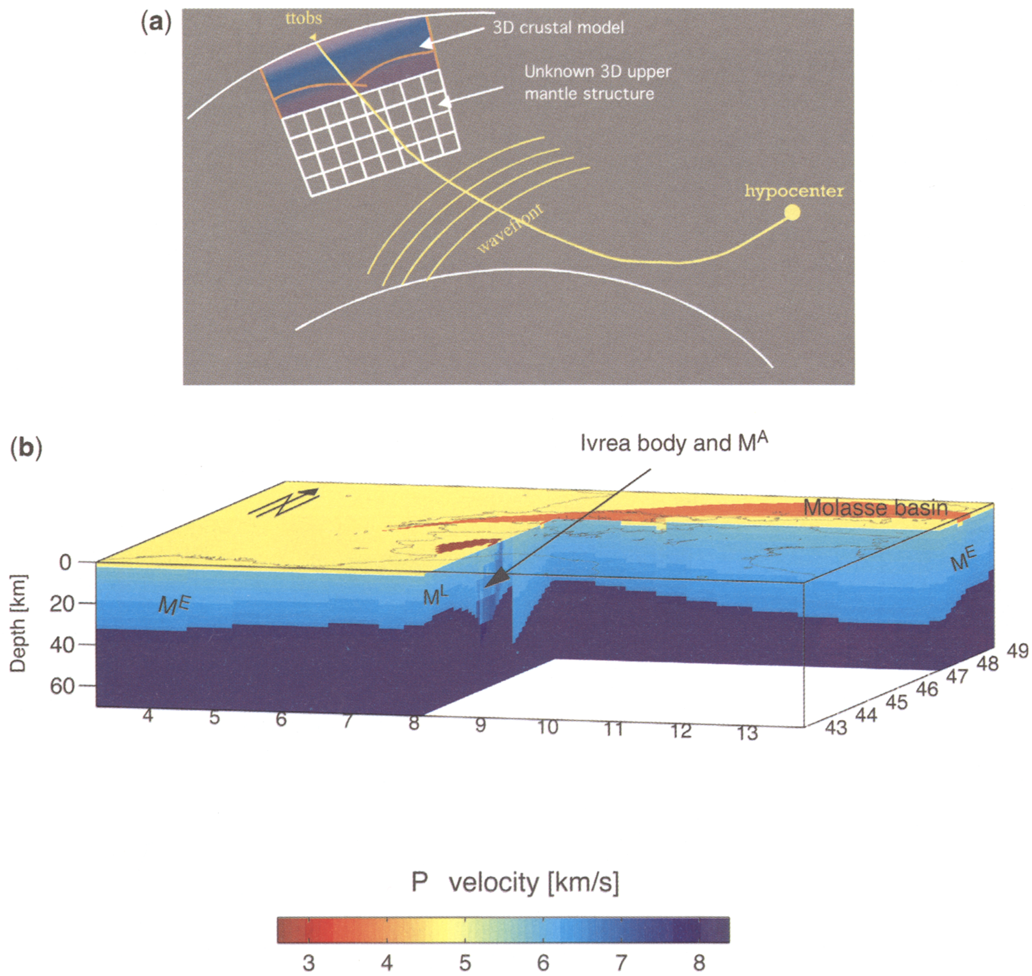

Fig. 10. (**a**) Schematic ray path diagram for teleseismic events recorded at a given station array. Observed travel times contain contributions from mantle, lower lithosphere and crust. Crustal contributions are determined independently for correction of observed total travel times. (**b**) Perspective NW view of 3D Alpine crustal P-velocity model to 70 km depth used for the calculation of crustal travel times, shown in a cut-away display. M^E, European Moho; M^L, Ligurian Moho; M^A, Adriatic Moho.

networks in the wider Alpine region, and, additionally, at the passive seismic network of TRANSALP (Fig. 11a) (Lippitsch 2002; Lippitsch *et al.* 2003). The dataset of this study consists of the travel times of 4698 manually picked first arrivals from 79 events with even azimuthal distribution. Absolute travel times from the selected events were used to determine an initial reference subcrustal velocity model for the investigated area. Sensitivity and resolution tests with synthetic data show that a combination of non-linear inversion, high-quality teleseismic data and the use of the *a priori* 3D crustal model allows us to reliably resolve structures of about 60 km linear length in the upper mantle in most areas of the investigated region.

Seismic structure of the Alpine lithosphere derived by integrating crustal and mantle structure

In the following we present images of the lower lithosphere derived from high-resolution tomography, and we then assess their relation to the independently determined crustal transects discussed above to achieve a unified lithosphere model for the Alpine orogen. Figure 12 shows a detailed map view of the Alpine lithosphere–asthenosphere system for the 135–165 km depth interval. The continuous high-velocity structure beneath the Alps found by Piromallo & Morelli (2003) at the same depth range is now split into two separate slabs, situated in the Western to Central and Eastern Alps, respectively. Both again follow the strike of the orogen. As will be discussed below, such a clear separation is supported by strong differences in the structure of these two slabs which are clearly visible in the vertical transects. There are also indications for further differentiations in the structure of the western slab. The same horizontal section additionally reveals a pronounced negative velocity anomaly situated under the eastern Po Plain. It remains unclear whether this represents a singular local feature, or alternatively, the northern part of an extended low-velocity structure in the Adriatic plate as imaged by Piromallo & Morelli (2003) and Di Stefano *et al.* (2006).

The seismic images of the two major lithospheric constituents, crust and mantle lithosphere, were not derived simultaneously but separately and over many years. Hence, we cannot *a priori* expect that the locations of crustal transects, selected on the basis of surface tectonic or practical experimental criteria, are also the most suitable transects for optimally representing lower lithosphere structure and geometries. The profiles in Figure 12 indicate the positions of three lithosphere profiles, A–A′, B–B′ and C–C′, that exhibit very clear images of the newly derived 3D lower lithosphere slab geometries (Fig. 13) in blue. Figure 12 also shows the positions of four lithospheric profiles I–IV (Figs 13a and 14), that contain the well-imaged crustal structures discussed earlier with respect to Figure 3, in red. The tomographic images illuminate the upper mantle to depths of 400 km and reflect the current status of the complex processes that shape the Alpine orogen today.

Transect B–B′ (Fig. 13b), situated at the transition from the Central to the Eastern Alps (Fig. 12) displays the clearest image of the present European–Adriatic collision structure and process. European and Adriatic Moho, as derived from CSS surveys, serve as guidelines for fixing the crustal structure that remains unresolved by mantle tomography, and they define the location of the suture at depth. The high-velocity volume subducted to the SE, outlined by a dashed line, clearly distinguishes the European lower lithosphere from the surrounding area exhibiting background velocities identifiable as asthenosphere in that depth range. The amount of more or less undeformed subducted lower lithosphere, when interpreted as continental, implies a shortening of *c.* 120 km since the onset of continental collision. For the

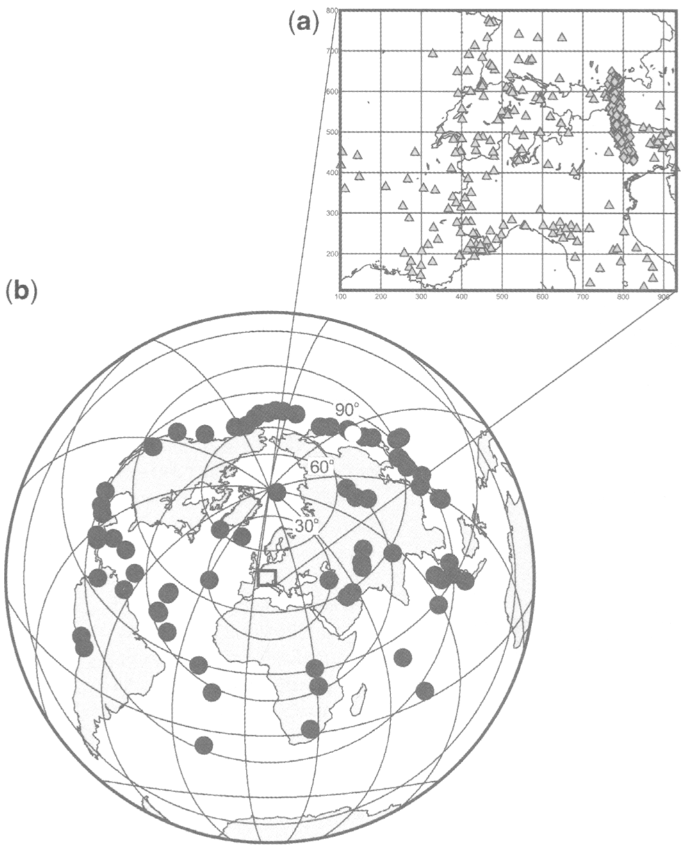

Fig. 11. Seismic stations and teleseismic events used for the tomography study. (**a**) Location of permanent and temporary seismic networks in the wider Alpine region and (**b**) location of selected earthquakes. These are evenly distributed and were recorded with high quality.

first time this provides an independent measure of post-collisional shortening, against which palinspastic reconstructions based on crustal structure can be checked, assuming that the transect runs parallel to the direction of subduction. Further high-velocity volumes visible between 350 km and 400 km are not yet reliably identified. They might be remnants of earlier subducted and detached oceanic lithosphere, as suggested by von Blanckenburg & Davies (1995) to explain magmatic intrusions found along the Periadriatic Lineament. Significant low-velocity bodies at shallow asthenospheric depth appear beneath the southern Rhine Graben and the Po Plain. Further information on the Rhine Graben rift system has been given by Prodehl *et al.* (1995) and Lopes Cardozo & Granet (2003). Transect A–A′ (Fig. 13a) in the Western Alps is chosen to coincide with crustal cross-section I (Figs 12 and 3a) provided by ECORS-CROP, now incorporated into the lithospheric image at proper scale. Dotted lines indicate the CSS-derived European and Adriatic Moho. In general, continental European lower lithosphere is subducted east to SE beneath the Adriatic microplate, with the high-velocity material reaching a depth of at least 400 km. The variation of velocity pattern at about 300 km depth may indicate a change in origin of the subducted material at greater depth from continental to oceanic. The slope of the subducted lithosphere clearly varies with depth, being subvertical to 250 km with a slight tendency of rollover. At Moho depth the thrust wedge formed by European lower crust (Fig. 3a) ends against the adjacent high-velocity Ivrea body and bends into the subvertically oriented high-velocity lower lithosphere (Schmid & Kissling 2000). At about 100 km depth detachment of the deeper parts of the European continental lithosphere has occurred, possibly induced by the Ivrea body, which seems to have acted as a buttress in the collision process of the European and Adriatic plates, leading to the present subvertical orientation. Sue *et al.* (1999) also have invoked slab detachment under the Western Alps to explain extensional earthquake mechanisms. The detachment may be accompanied by additional upwelling of asthenospheric material in the pronounced low-velocity region immediately to the west of the detachment.

A third transect, C–C′ (Fig. 13c), representative for the mantle structure in the Eastern Alps, lies east of the TRANSALP traverse (Fig. 12). It again reveals a rather obvious subduction pattern, although, very surprisingly, with a subduction polarity opposite to that found in the Western Alps, as the European lithosphere here represents the overriding plate. In this section through the 3D lithospheric model, the Adriatic lower lithosphere is found to have been subducted to the NE and underneath the European plate to a depth of 270 km. Using the suture between European and Adriatic Moho as reference, the total shortening since collision amounts to some 210 km, significantly more than observed for the SE-directed subduction along transect B–B′ situated further west. There is no indication of a detachment in the subducted lower lithosphere within the observed depth range. Transect C–C′ reaches the Po Plain low-velocity anomaly seen more clearly in Figure 12 near its SW end. The 3D tomographic model clearly documents that the dip direction of subduction flips from SE to NE between transects B–B′ and C–C′. This flip occurs over the relatively short distance of about 80 km and between the two separate high-velocity volumes shown in Figure 12. This important transition occurs roughly beneath the Giudicarie tectonic lineament and beneath the TRANSALP profile, and is illustrated in more detail in Figure 14.

Figure 13 presents the most important and clearest features of the Alpine lower lithosphere and its lateral variations in the form of representative cross-sections. As the locations of these mantle sections, ideally chosen for depicting mantle structures, do not coincide with the available crustal transects depicted in Figure 3, additional sections are provided in Figure 14. This figure combines the lower lithosphere and crustal structures in the form of whole lithosphere transects that also incorporate the crustal images within the 3D tomographic model crustal images at their proper locations I–IV (Fig. 12). The combined sections A–A′ and I have already been shown and discussed above as part of Figure 13a. Crustal profile II (Fig. 14a) along the NFP20 WEST transect shows structural features that are nearly identical to those found in the combined profile along the ECORS-CROP transect shown in Figure 13a. It confirms the sense of subduction and also the important role of the Ivrea body, which probably caused the detachment of a lower European crustal wedge (Schmid & Kissling 2000). Probably, it is also responsible for the observed slab detachment of lower lithosphere visible under the crustal transect. Further to the south both the lithospheric transects A–A′ and the deep structure under crustal profile II cover nearly the same area and exhibit near-identical velocity patterns.

The transect shown in Figure 14b follows crustal profile III (NFP 20 EAST/EGT) across the eastern margin of the Western Alps and it obliquely crosses transect B–B′ (Fig. 13b; see also Fig. 12). A careful analysis of the crustal data (Holliger & Kissling 1992; Schmid *et al.* 1996; Pfiffner *et al.* 1997; Valasek & Mueller 1997) led to the conclusion that a wedge of relatively rigid lower Adriatic crust did indent the European crust. Consequently the sheared-off European lower crust possibly was subducted together with its lower lithospheric substratum (Pfiffner *et al.* 1997). However, teleseismic tomography cannot resolve such a detailed feature within the subducted volume; yet, as seen in Figure 14b, the lower boundary of the European lower crust can most easily be extrapolated into the outlines of the high-velocity lower lithosphere subducted towards the SE. This could also suggest that only a small part of the lower continental European crust has been subducted (Burg *et al.* 2002).

The difference in strength and rigidity between the European crust in the north and the Adriatic crust in the south, which includes the deep-reaching Ivrea body at its western end

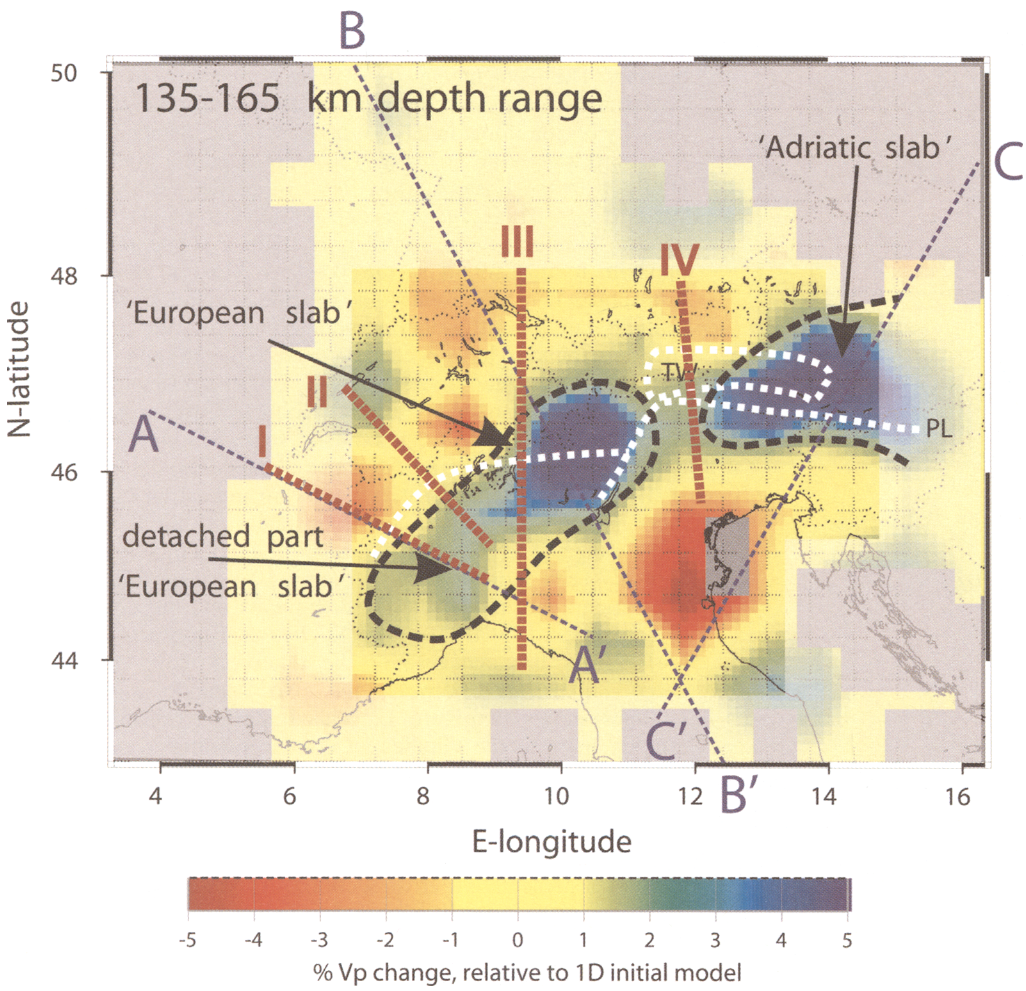

Fig. 12. P-wave velocity distribution between 135 and 165 km depth, with linear interpolation between inversion cells (from Lippitsch 2002; Lippitsch *et al.* 2003). Velocity variations are plotted relative to a 1D initial reference model determined from absolute travel times for the research area. Areas with no resolution are left grey; areas with critical resolution are displayed in pale colours. Thick black dashed lines indicate areas of high-velocity European and Adriatic lower lithosphere, which is subducted east to SE and north to NE under the Western and the Eastern Alps, respectively. Thick white dashed lines indicate (from west to east) the Insubric, Giudicarie and Periadriatic lineaments (PL) and the Tauern Window (TW) as part of the Eastern Alps. Red dashed lines I, II, III and IV mark locations of crustal geophysical–geological transects (see Figs 1 and 3). Blue dashed lines A–A′, B–B′ and C–C′ mark locations of lower lithospheric transects (Fig. 13). Dark red area indicates the Po Plain anomaly.

(Figs 13a and 14a) but normal continental crust further east, has probably caused the contrasting deep lithospheric structures between the westernmost Western Alps and the eastern part of the Western Alps traversed by the EGT profile. The necking of the high-velocity material, seen at around 300 km depth under transects A–A′ and II (Figs 13a and 14a), is confirmed by the narrow vertical separation of high-velocity material (Fig. 14b) at 250 km depth, as is seen under the southern extension of the obliquely crossing transect III. This may suggest an increasing separation of detached and subsiding dense high-velocity material from east to west.

The transition between the opposite subduction regimes characteristic for the Western and the Eastern Alps, respectively, can be seen on the north–south-oriented transect IV that corresponds to the TRANSALP profile shown in Figure 14c. Features of lower crustal wedging and imbrications as observed further west are now replaced by a relatively narrow collision structure situated under the western end of the Tauern Window where the Giudicarie line joins the Periadriatic Lineament (Schmid *et al.* 2003). Here the originally flat-lying piles of nappe structures, as observed in the west, is dramatically steepened, and the structure under the Tauern Window resembles a large-scale flower structure as commonly seen in sediments (Dobrin & Savit 1988). Judging from the 2D section alone, the polarity of subduction is not as obvious as it is either further east (Fig. 13c) or further west (Fig. 13b). The location of profile TRANSALP in the horizontal section provided for a depth of 150 km (Fig. 12, profile IV), however, makes it clear that the lithospheric structure underneath this profile represents the transition zone between west and east. Hence, very probably it is already similar to that which predominates underneath the Eastern Alps, as is depicted in Fig. 13c and in another lithosphere-scale transect, 'EASTERN ALPS', discussed elsewhere (Schmid *et al.* 2004*b*). A subvertically oriented structure characterized by moderately high velocity, without sharp boundaries, extends to 220 km depth into the surrounding asthenosphere. Parts of the diffuse geometrical outlines of the high-velocity material are caused by the east-to-west averaging of the grid elements over about 100 km, which has resulted in the inclusion of structural features from the western as well as the eastern subduction systems. Possibly, the derived tomographic image reflects only the northern end of the deep-reaching left-lateral Giudicarie shear zone along which no clear direction of subduction can be defined.

Discussion and conclusions

This study compiles and combines the major features of the 3D structure of the crust with the 3D structure of the lower lithosphere in terms of its P-wave velocity distribution. Until recently, and for strictly methodological reasons, crust and lower lithosphere were investigated and interpreted separately. Thanks to the latest advancement of deep crustal exploration techniques with higher resolution, for example appropriate combined refraction, near-vertical and wide-angle reflection seismic surveys, together with high-resolution teleseismic tomography, particularly including crustal corrections for the lower lithosphere, these structural units can now be explored together. This allows for a better understanding of their unseparable roles in tectonic evolution. It also provides a much better understanding of the derived present-day 3D structure in time and space, even within comparatively small orogens such as the Alps.

The careful analysis of the actively acquired seismic data for the crust indicated and proved the existence of different types and

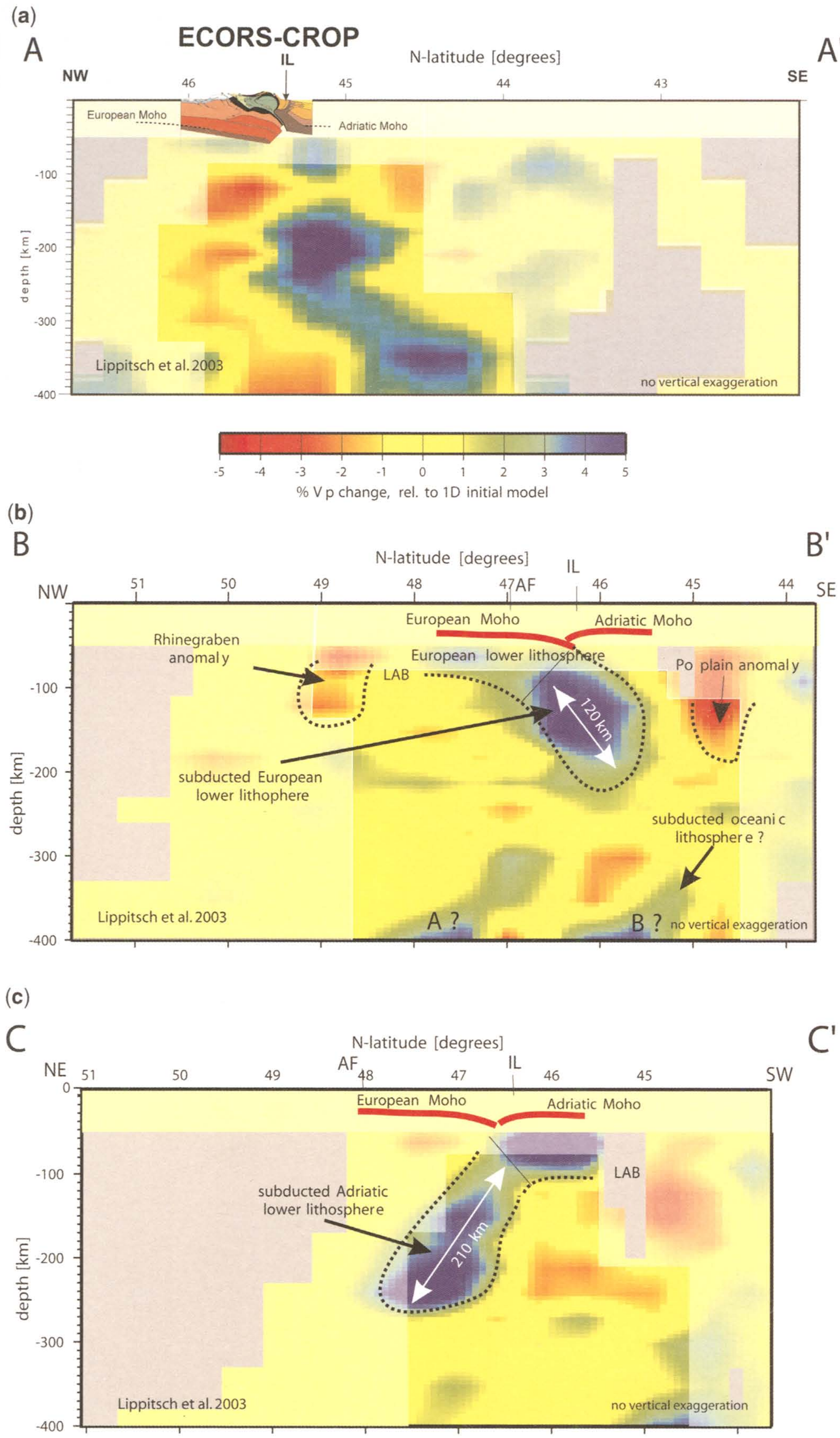

Fig. 13. Three lower lithosphere transects that exhibit very clear images of the newly derived 3D lower lithosphere slab geometries: (**a**) A–A′, Western Alps, with superimposed crustal transect ECORS-CROP as depicted in Figure 3a; (**b**) B–B′, Central Alps, (**c**) C–C′, Eastern Alps. (For location and display mode see Fig. 12.) Crustal layers are set to zero velocity deviation, with Moho topography taken from the 3D crustal model in Figure 10b. Bold dashed line indicates lithosphere–asthenosphere boundary (LAB). IL, Insubric line; AF, Alpine front.

mechanisms of wedging and indentation. These include features such as (1) back-thrusting or doubling of lower European crust as a consequence of the collision with the deep-reaching rigid Ivrea part of the Adriatic plate in the west, and (2) wedging of lower Adriatic into European crust, implying intense shearing at the interface between upper and lower crust and leaving the European lower crust closely connected to its lower lithospheric underpinnings.

The fourth transect, that is TRANSALP through the Eastern Alps, positioned near the transpressive Giudicarie line, lacks wedging

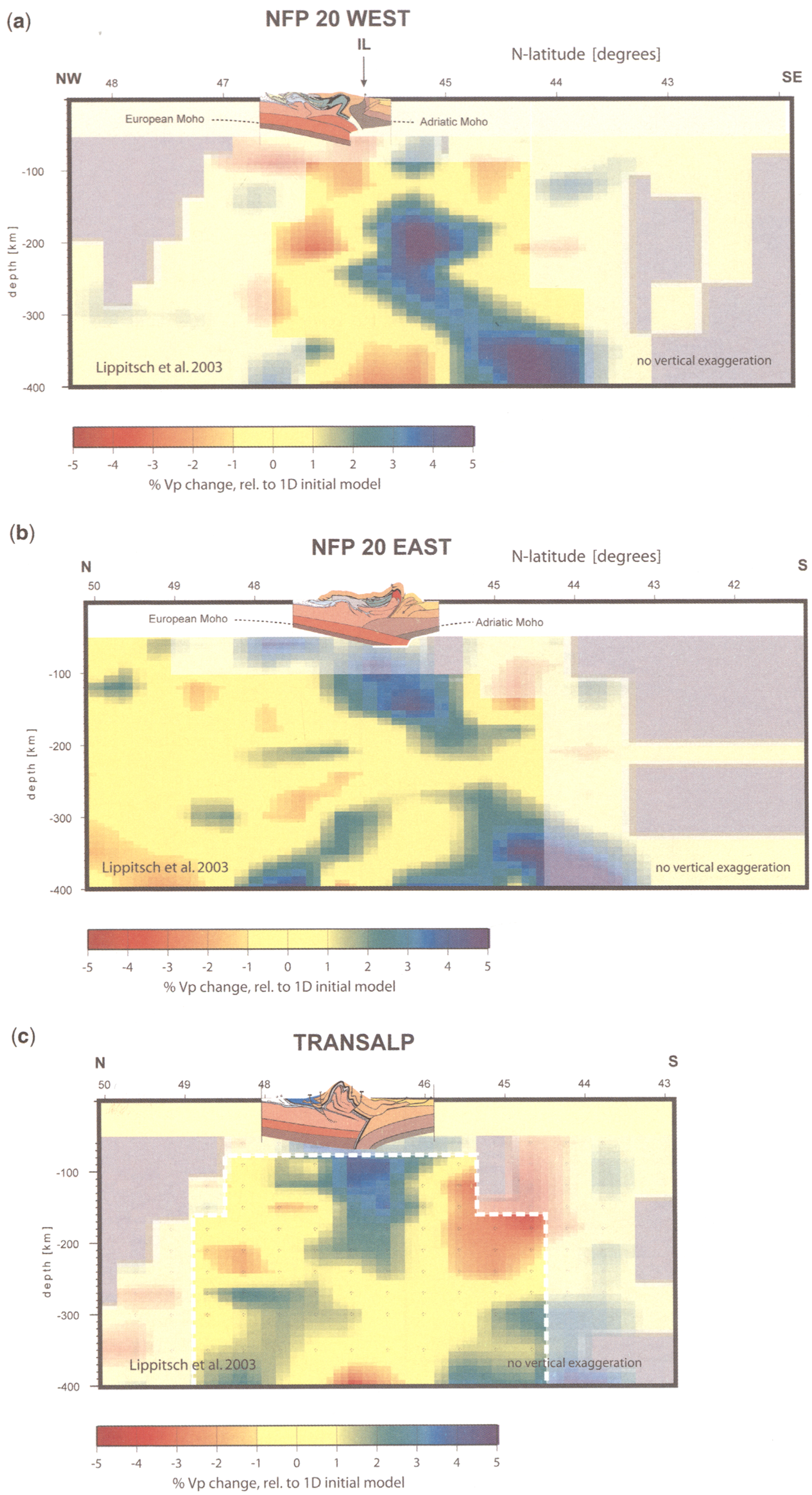

Fig. 14. Combined crustal and lower lithosphere transects along the high-resolution crustal geophysical–geological profiles depicted in Figure 3b–d (see Fig. 13a for the ECORS-CROP crustal transect depicted in Fig. 3a). Location and display mode are shown in Figure 12, profiles II, III and IV. (**a**) NFP-20 WEST; (**b**) NFP-20 EAST/EGT; (**c**) TRANSALP.

within the lower crust. Kummerow *et al.* (2003, 2004) have derived an independent and alternative north–south cross-section that features the Moho along the TRANSALP transect based on receiver function analysis. In an area between the northern Molasse Basin and the centre of the orogen this cross-section agrees with our compilation, which is based on earlier CSS data and the new TRANSALP data. However, it differs significantly in the southern part. There, Kummerow *et al.* proposed a subhorizontal crust–mantle boundary at 40 km depth. It will be highly interesting to know which type of lower crustal collision scheme will be found further east, where the extensive ALP2002 active seismic experiment was carried out recently (Brueckel *et al.* 2003; Gebrande *et al.* 2006).

The mechanisms by which large portions of lower crust and lithosphere disappeared during the latest continental collision process, as well as the location of the subducted remnants, have been a topic of discussion since the early hypothesis of 'Verschluckung' (Laubscher 1970). Mueller (1997) provided evidence for a lithospheric root of deeply south-dipping structures. South-dipping subduction in the Central Alps was also postulated and suggested based on the interpretation of active seismic experiments, geological data and seismic tomography (Fig. 9b) (Spakman *et al.* 1993; Pfiffner & Hitz 1997; Stampfli & Marchant 1997; Bijwaard & Spakman 2000).

The present work, which is based on the construction of a representative 3D crustal model for crustal travel-time corrections, combined with the use of high-quality teleseismic travel-time data, provides a quantitative assessment of the length of lithospheric slabs, which varies significantly along the orogen (Fig. 13a–c). Based on the estimates of post-collisional crustal shortening along the EGT and ECORS-CROP transects (Schmid & Kissling 2000), we identify the slab beneath the Central Alps to represent lower continental lithosphere (Figs 13b and 14b). The detached slab beneath the inner arc of the Western Alps (Figs 13a and 14a), however, is likely to contain continental and oceanic lithosphere. This strongly supports the model of von Blanckenburg & Davies (1995), who postulated (oceanic) slab break-off early during collision at least for parts of the Alpine subduction zone.

The increased resolution allows for the separation of two nearly opposing subduction regimes in the Western and Eastern Alps, respectively, the 3D structure suggesting an angle of nearly 100° between the strike of the two slabs (Fig. 12); it should be noted that, in three dimensions, the European slab dips to the SE underneath the Western Alps, whereas the Adriatic slab in the Eastern Alps dips to the NE. This complex Alpine subduction system is obviously connected with significant deep-reaching left-lateral strike-slip motion along the Giudicarie line. We tentatively propose that the continental Adriatic lower lithosphere subducted to the NE underneath the Eastern Alps represents a remnant of Eocene orogeny in the Dinarides, characterized by NE-directed subduction according to geological evidence. This piece of lithosphere is interpreted to have been laterally displaced and inserted into the Alps by dextral movements along the Periadriatic line, combined with sinistral transpression along the Giudicarie line during the last 20 Ma (see discussion by Schmid *et al.* 2004*b*). The slab detachment at shallow depth (120 km) under the western transects (ECORS-CROP and NFP20 WEST) was probably caused by the adjacent strong Adriatic lower crust with the Ivrea body as its surface expression. This again shows that crust and lower lithosphere have to be studied in the context of a plate that consists of layers of different mechanical strength, and that possibly exhibits strong lateral variations, when modelling orogenic subduction–collision processes. The new 3D lithospheric picture for the wider Alpine region to 400 km depth demonstrates the tight connection between the deep structure of the lithosphere–asthenosphere system and near-surface tectonic features. It provides new and unexpected evidence for the younger Alpine tectonic evolution, a process that obviously induced significant changes in the architecture of the Alps and their lithospheric roots from west to east.

Listing the names of all the colleagues in geology and geophysics who contributed over the years with data and valuable research would go almost beyond the length of this paper. We would like to collectively thank all of them. Special thanks go to all colleagues and seismological services in the wider Alpine region who provided us with the teleseismic data. G. Schönborn is thanked for providing us with the visualization depicted in Figure 6. Careful reviews by U. Achauer and an anonymous reviewer are gratefully acknowledged.

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