Geophysical investigation of the crust of the Upper Adriatic and neighbouring chains

Rinaldo Nicolich

Abstract   The Adria domain and the neighbouring chains (Alps, Apennines, Dinarides) are presented with images and interpretative models indicating their main crustal characteristics as revealed by the geophysical prospecting (gravity, receiver functions, wide-angle seismic and near vertical reflections). The collision with the adjacent blocks has implied deformations of the lower crust and of the crust–mantle boundary with accretionary wedging of slabs of lithosphere, entire crust or upper crust, respectively. The position of the main decoupling levels within the subducting lithosphere like the Sub Tauern Ramp in the Eastern Alps is the key parameter for the post-collision evolution. Decoupling levels at the top of the lower crust or at the base of the upper crust also might have played a dominant role in the orogenic movements controlling the present-day crustal architecture. According to the recent acquisitions a triple junction among Adria, Pannonian and European crusts is proposed near Katschberg, at the eastern edge of the Tauern Window, with Pannonian acting as upper plate in the collision with Europe and with Adria: Europe underthrusts Adria and Pannonian and Adria underthrusts Pannonian fragments. Finally, Adria underthrusts the Apennines along the western side of the Adriatic Sea. The paper revisits the geophysical data (mainly reflection and refraction seismic) to evidence resolution and penetration limits in the exploration of crustal structures.

Keywords   Adriatic domain · Crustal structures · Refraction/reflection seismic · Wide angle seismic · Geophysical prospecting

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1 Introduction

Geophysical investigations are applied to explore the structures of the crust defining parameters like the propagation velocities of seismic waves generated by sources operating at the Earth surface, the underground bodies' density distribution, the magnetic, resistivity, conductivity rock properties and the acoustic impedance variation with reflectivity images. All these approaches possess different resolution and penetration and usually only a combination of the different results can complete the information needed for significant geological synthesis. Active seismic prospecting can give major information in the first 50–60 km of the lithosphere. Larger depths are investigated by earthquake hypocentre distribution or by tomographic analysis of teleseismic events.

The most appropriate exploration tools are reflection seismic and Deep Seismic Soundings (DSS) or Wide Angle Refraction/Reflection (WAR/R). The near-vertical reflection seismic method, subsequent to the improvements in data acquisition and processing with increased dynamic range of digital data and more powerful processing software, provides signals easily interpreted in geological terms. WAR/R yield propagation velocities at depth with greater accuracy. Both reflection and refraction techniques, separately used, supply results which are different in nature, though complementary. Wide-angle reflection data alone with fans acquisition were successfully employed for imaging the complex geometries of the M-interface on collision belts once information was available about an approximate position at depth of the target.

The Bouguer gravity anomalies are mostly enlightening the uppermost geological features, the geometry of the crust–mantle boundary and the lower crust densities in accordance with seismic velocities. Both the seismic and gravity interpretation take mutual advantage by iterative use of the two data sets and of the constraints posed to fulfill both observed data. The gravity field can be used to extend the interpretative models beyond the seismic profile. 3D gravity models have been presented to control the laterally variable crustal architecture (see for ex. Ebbing et al. 2006).

The geophysical models and the reflection seismic images with their well-resolved small-scale heterogeneities can be extended on larger depths by teleseismic "receivers functions", P to S converted signals, illuminating the lithosphere from below which can give information on the main converter, the M-discontinuity, or on wide velocity gradient zone. An example is given in Kummerow et al. (2004), where the base of the crust and intracrustal structures in the Eastern Alps are recognized. It is not so immediate with other lower-resolution teleseismic tomography procedures.

In Fig. 1 a simplified geologic/tectonic map of the northern Adriatic area and the trace of the transects are discussed in the text. The structural setting of the northern Adriatic domain is the result of the convergence of the plate margins producing a foreland–foredeep area consumed by the advancing neighbouring orogenic chains. It represents a rather stable continental crustal block with a long evolution history starting from Paleozoic as documented in the outcropping successions in the uplifted retro-belt of the Southern Alps (Bigi et al. 1992). Permo-Mesozoic thickness variations and the inherited structural heterogeneities controlled the evolution but preserved the strength of the Adriatic lithosphere with its rigid response to the subduction and collision processes and with frontal parts strongly indented into the Alpine chain.

The basic structural components of the present Alps, Dinarides and Apennines orogenies are the results of the severe Cenozoic compressional deformations. In the following, the current interpretations and open debates about the structure and geodynamics of crust
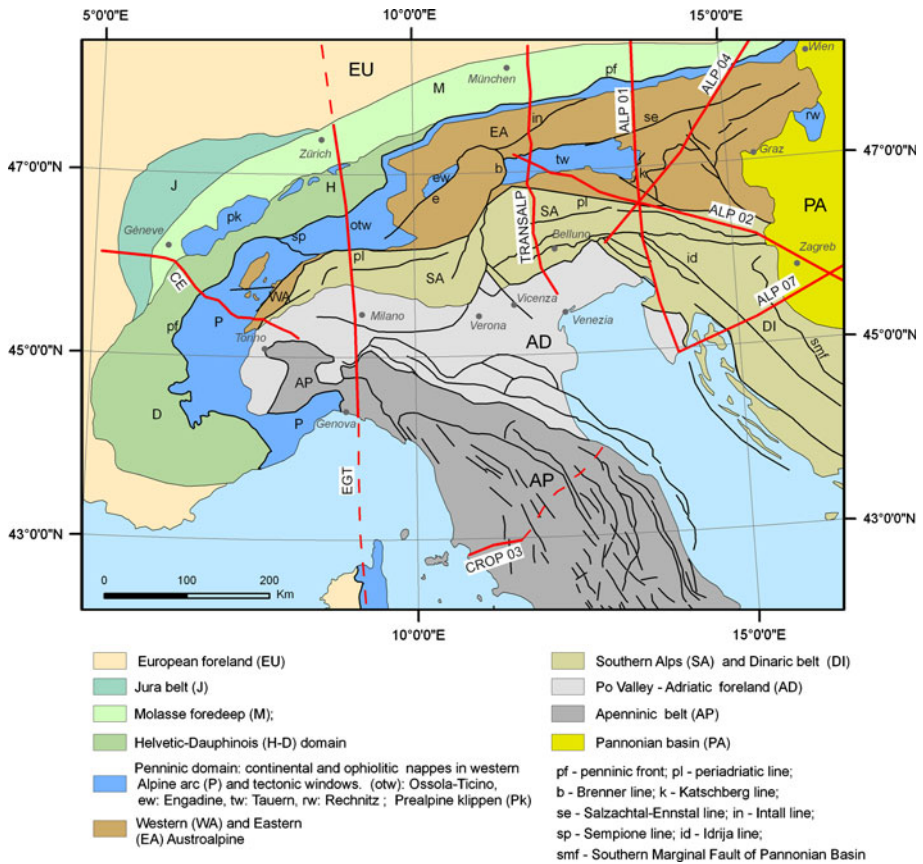
Fig. 1 A simplified geologic/tectonic map showing main structures and the trace of the transects presented in the text

and lithosphere of the study area will be presented with regard to the data obtained with geophysical measurements and especially with active seismic methods.

First the definition of the seismic nature of the Moho discontinuity, in terms of its position, topography, smoothness and continuity; second, the lower crust contribution in the complexities of the collision mechanisms; third, the presence of decoupling levels within the subducting lithosphere or the intracrustal ones, related to the Neogenic evolution, an insight into the processes that built the geological structures of the upper crust.

The crust of the Adria domain (AD) to the west is bounded by the Apennine chain (AP), to the north by the Alpine chain and the European crust (EU) and to the east by the Dinarides (PA′), considered (Brückl et al. 2010) a fragment of the Pannonian domain (PA). Most elements of the present-day structure of Adria are the results of tectonic events since the opening of Tethys in Jurassic times. The convergence of Europe and Africa during Cretaceous with oceanic lithosphere subduction includes the final Eocene collision in the Eastern Alps and Late Oligocene–Neogene (neo-Alpine) post-collisional events. The Adria movement toward Europe formed the Dinaric orogene active from Cretaceous to Miocene. The roll back of the Carpathian subduction left space for the development of the Pannonian basin since Late Oligocene to Pliocene. The compression between Europe and the

indenting Adriatic microplate generated the tectonic forces driving the extrusion and escape of the Eastern Alps towards the unconstrained Pannonian basin. The polarity of the subduction of Europe beneath Adria and Pannonian fragments is still debated with a nearly south-east directed Alpine slab accepted for the Western and Central Alps and a north-directed subduction proposed in the Eastern Alpine domain (Lippitsch et al. 2003). The Adria collision with the Apennines developed from late Miocene to Quaternary, presently active with a south-eastward directed subduction plane as proposed by Di Stefano et al. (2009), with the upwelling of the asthenosphere and related thermal softening of the crust.

2 Geophysical investigations of the crust in the Adria domain

The most numerous studies were concentrated on the Alpine chain with the purpose to combine the outcrop observations with geophysical measurements. Since 1956, controlled source refraction profiles were recorded, starting from the Western Alps, with joint international co-operations among the confining countries. Analog recorders were used and spacing between stations and the number of the acquired profiles were related to the availability of instruments and operators from different participating countries. Reliable results were obtained only on the gross changes in crustal thickness and on the main velocity structures, but the data quality increased as years go following the technological evolution.

The "Lago Lagorai" operations should be mentioned in the Eastern Alps (Closs and Morelli 1962) with other profiles recorded moving from the shot site in Eschenlohe as well as the transect Innsbruck-Vicenza (Cf. the data revision by Scarascia and Cassinis 1997). ALP′75 DSS project (Yan and Mechie 1989) and the "SudALP" venture (Italian Explosion Seismology Group 1981). A very long N–S profile was acquired in the frame of the European GeoTraverse (EGT: Ansorge et al. 1992).

The resolution of the WAR/R method did not allow the necessary definition in the areas of rapidly changing structures, when a reduced number of shot points and observations (receivers) were employed. With very few sampled deep points, the resolving power in the ray-tracing modelling decreases and the smoothed interpolations can imply misleading interpretations.

New projects in 1986 in the Western Alps utilized reflection seismic updated technologies. The CROP-ECORS profile (Damotte et al. 1990) was followed by the Swiss NRP20 network (Pfiffner et al. 1997) and by CROP-Alpi Centrali (Cernobori and Nicolich 1994). Wide-angle fans and WAR/R profiles were added (Thouvenot et al. 1990; Waldhauser et al. 1998; Valasek et al. 1991) to better approach the geological complexities with a combination of methods and techniques.

The reflection seismic exploration of the chain has reached the peak with the TRANSALP transect in the Eastern Alps (Lueschen et al. 2006), acquired with updated instruments and completed with multidisciplinary approaches: acquisition of explosive reflections and wide-angle profiles with a 3D control of the deep structures; gravity measurements and compilation of Bouguer anomalies map from Bavaria to the Adriatic sea (Zanolla et al. 2006); recording of seismological data with a permanent network of stations.

ALP2002 project returned to the WAR/R methodologies but with many shots, several profiles and a large number of narrow spaced recording instruments, investigating Eastern Alps and Central Europe (Brückl et al. 2003, 2010).

The Apennine chain and the Ligurian and Tyrrhenian internal extensional zones were explored by DSS and reflection seismic (Giese et al. 1981; Ansorge et al. 1992; Makris

et al. 1999; Mauffret et al. 1999). CROP profiles investigated Tuscany and the Apennines (Decandia et al. 1998), while CROP-Mare (Scrocca et al. 2003) illuminated the deep offshore structures.

## 3 Moho and lower crust structures

Scarascia and Cassinis (1997) reinterpreted homogeneously the old DSS profiles from the central to the eastern Alpine sector, while Waldhauser et al. (1998) reprocessed data of the Western Alps including the Po Plain and Dézes and Ziegler (2001) completed a map which is of interest for the study area (Fig. 2). The map requires more detailed adjustments after the recent TRANSALP and ALP 2002 acquisitions, but in general it represents a good picture of the positions of the different provinces: Europe (EU), Adria (AD), Apennines (AP), the Pannonian fragments (PA, PA′).

The collision of Adria with the adjacent blocks has involved deformation of the lower crust and of the crust–mantle boundary with accretionary wedging of slabs of lithosphere, entire crust or upper crust, respectively, where geophysical prospecting can contribute with few constraints and the seismic images from the near-vertical reflections can be hardly improved. The most influential parameter for the post-collision evolution depends on the position of the main decoupling level within the subducting lithosphere, but intracrustal decouplings might have played a dominant role in the orogenic movements controlling the present-day crustal architecture.

In Fig. 3 the Bouguer anomalies for the study area with the position of the deep basins, the deep roots of the orogens and of the high-density bodies at shallow depth.

Abrupt changes of the M-discontinuity in depth and dips were marked in the Western Alps by wide-angle fan seismic profiling, which were of primary importance for the interpretation of the deep interfaces disclosed in the reflection seismic sections (CROP-ECORS project, CE in Fig. 1, Thouvenot et al. 1990).

The root zone of the chain was well outlined down to 55-km depth and a shallow structure in the Briançonnais zone (Fig. 4) in the 25–30 km depth range was interpreted as
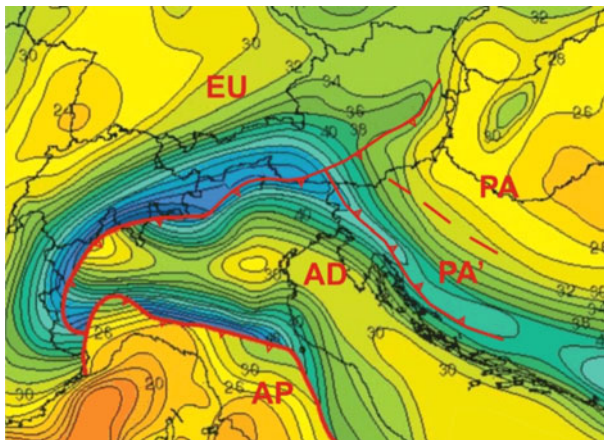

Fig. 2 Moho depth map, modified from Dézes and Ziegler (2001). The boundaries among Europe (EU), Adria (AD), Apennines (AP) and the Pannonian fragments (PA and PA′) are marked
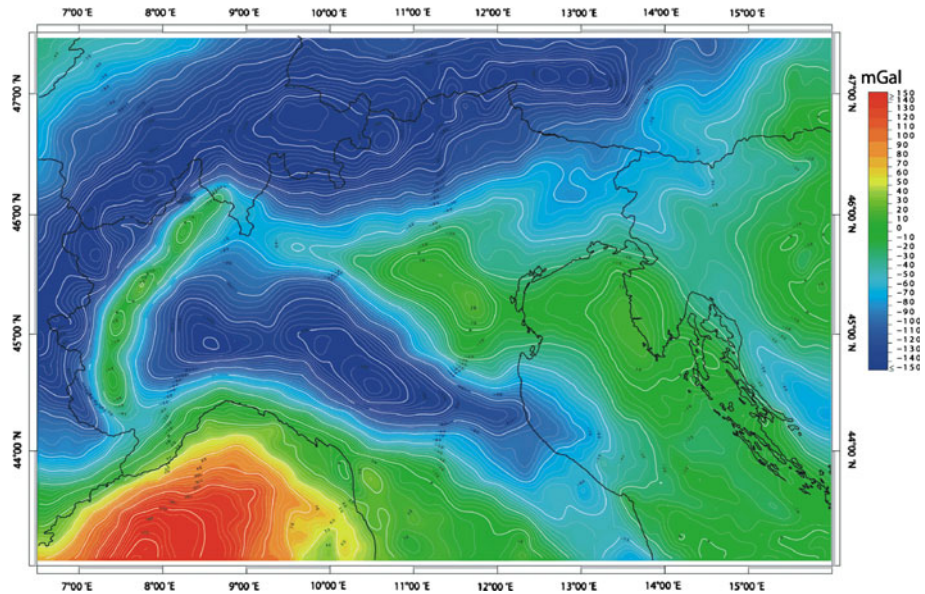
Fig. 3 Bouguer anomalies map with 2.67×10^3 kg/m^3 reduction density (Zanolla 2006, personal communication). The anomalies are sensitive to the near-surface high-density bodies (e.g. Ivrea and Sesia–Lanzo crest in the Western Alps), to the deep basins and to the deep roots of the orogens

a flaking of the lithosphere under the chain. Moreover, the anomalous upper mantle is made intricate by the hinterland Moho, more than 35 km deep under the Po plain, raising in a stepwise fashion to less than 25 km approaching the Canavese fault zone. Organizing the sampling interval of reflectors along the cross sections and the shot-receivers distance in the fan in order to have reflections around the critical distance, the wavelet reflected from the Moho is known to be very energetic and it can be identified with the maximum amplitude signal. In the eastern part of the crustal model presented in Fig. 4, the dramatic imbrication of the upper mantle and M-discontinuity is the most impressive feature. The strong reflector at a depth of only 13 km represents the crust–mantle boundary, base of the outcropping Ivrea lower crust body containing ultramafic inclusions.

The complex deep crustal structures in the western-central domains are nicely signed in Fig. 5 by a gravimetric model along a profile from the internal crystalline massifs in Switzerland to the Ligurian Sea, crossing the Milano belt, the western Po plain and the northern Apennines arc. The model was based on the European GeoTraverse results and on the Swiss NRP 20 and CROP-Alpi Centrali joint investigations and shows the collisions among Europe, Adria and Apennines. The model settles the European Moho at depths of 60–70 km beneath the Po Plain with the Apennines overthrust down-bending the Adria Moho to about 40 km depth. The model was constrained with details in central Alps by wide-angle fan and near-vertical reflection seismic (Schmid et al. 1996 and references therein). Within the strongly deformed internal Alpine domain, poorly characterized in the seismic data, some images obtained with wide-angle fans were attributed to an Adriatic lower crust indenter or to complex structured melange consisting of European and Adriatic lower crusts (Hitz 1995). The structural disharmony of the allochthonous outcropping nappes with respect the European lower crust in that region implies an intracrustal decoupling mechanism located near the top of the lower crust indenter and acting during
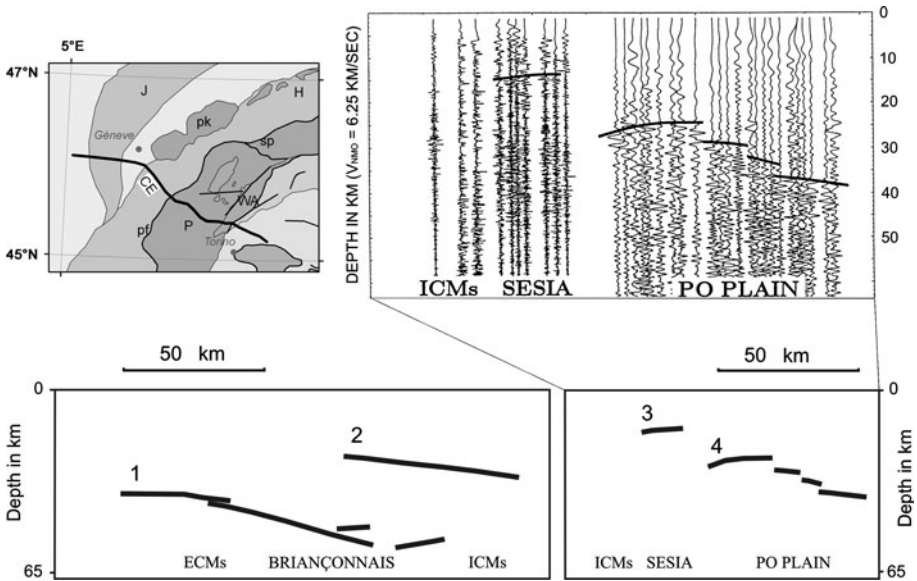
Fig. 4 A crustal model from wide-angle fan with a stepwise M-discontinuity reflection images along a transect from the Po Plain to Gran Paradiso (from Thouvenot et al. 1990, modified), intersecting Sesia–Lanzo zone and Canavese line which marks the eastern limit of the chain (profile CROP-ECORS, CE in Fig. 1). Reflections are picked on the seismic section using a maximum amplitude criterion and trace correlation. *ICMs* Internal crystalline massif; *ECMs* external crystalline massif. At the *bottom* the crustal scheme with main discontinuities across the whole Western Alpine chain

the uplifts of the external crystalline massifs. This detachment interface controlled the Neogenic history of the chain and the present day architecture and was also proposed for the collision north of the Milano belt (Cernobori and Nicolich 1994).

The TRANSALP reflection seismic acquisitions across the eastern Alps correctly revealed the Adria lower crust indenter (see for ex. Castellarin et al. 2006). It shows the images of the Tauern antiform (according to the ductile extrusion model) along the Sub-Tauern Ramp (STR) representing the main decoupling level within the subducting lithosphere. STR is responsible for the Inn valley seismicity, but at large depths it might act as a ductile shear zone without release of seismic energy. In Fig. 6 the vibroseis depth migrated seismic section with a schematic interpretation from the Tauern area to the Venetian plain (see its extent in Fig. 7); in Fig. 7 the receiver functions for the whole TRANSALP transect with line drawing of combined vibroseis and explosive data (TRANSALP Working Group 2002; Kummerow et al. 2004). The receiver functions very precisely indicate the European crust–mantle transition and its southward prolongation reaching 55–60 km depth, distinct from the Adria Moho positioned at 40 km depth, flat or slightly dipping northward. Remarkable images of lower crust structures are displayed at the southern end.

The south-directed subduction of Penninic oceanic crust is well imaged and 3D complementary acquisitions in TRANSALP, gravity modelling (Ebbing et al. 2006) and ALP2002 experiments confirm the lateral continuity to the east of the EU underthrusting AD. A velocity anisotropic distribution was found within the extruded TW but with small differentiations and uncertain separation of heterogeneity from anisotropy. Foliation and lamination generated by the lateral escape of the TW can be responsible for the anisotropy. Significant velocity differences in the middle and lower crust between the northern
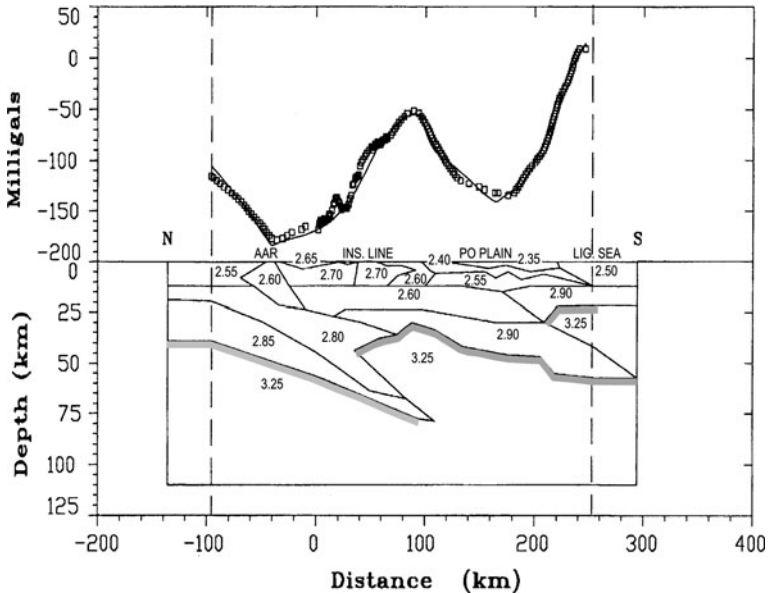
Fig. 5 The gravimetric model (from Marson et al. 1994) along the European GeoTraverse (EGT in Fig. 1), crossing the Alps, the Po Plain and the Apennines, down to the Ligurian Sea. The model settles the European Moho at 60 km or more beneath the Po Plain with AD Moho down-bended to about 40 km by the Apennines overthrust
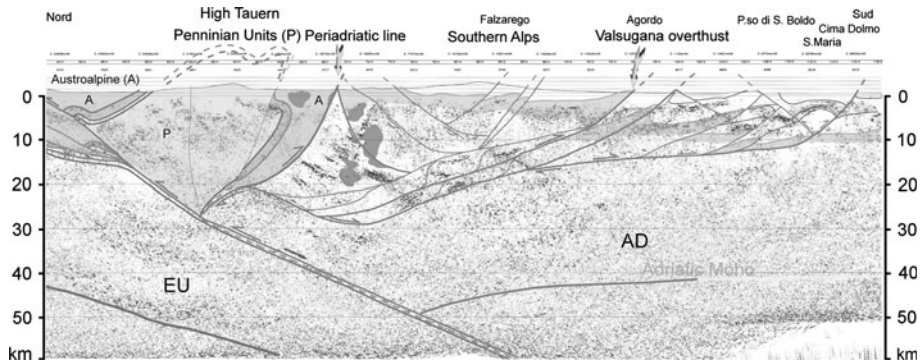
Fig. 6 Reflection vibroseis TRANSALP depth migrated section and geological interpretation from the Tauern Window to the Venetian plain. The section extends over the southern sector of the TRANSALP transect as shown in Fig. 7 on the *top* of receiver functions image

(5.8–6.6 km/s) and southern part (6.1–6.8 km/s) is a major feature revealed by wide-angle seismic tomography (Bleibinhaus and Gebrande 2006). High velocities of the Adriatic crust indicate stronger, more rigid formations than on the European side, where the EU weaker plate is forced down in the collision. The peculiarity was confirmed by ALP2002 experiments and can help to explain the elevated seismicity attributed to the Adria block. This seismicity is associated with the ongoing deformation in the Southern Alps and in the Dinarides or to the relative movements among Adria, Europe and Pannonia. The N–S
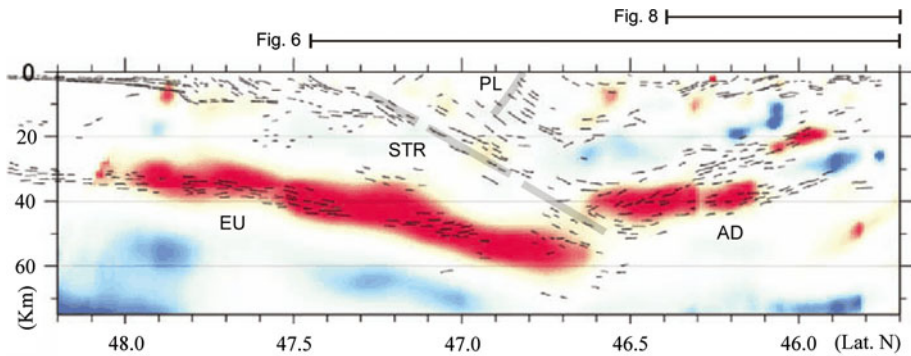
Fig. 7 Receiver function and combined explosive and vibroseis depth migrated data line drawing along TRANSALP transect (from Lueschen et al. 2006, modified). The extent of the seismic sections presented in Figs. 6 and 8 are indicated on the *top*

oriented Adria/Europe convergence is partly compensated in the upper plate by the backthrusting processes with a predominant frontal collision perpendicular to the active front along the Southern Alpine thrust belt (Bechtold et al. 2009; Brückl et al. 2010). The oblique movement of Adria with respect to the thrust front of the External Dinarides is accompanied eastward by the dextral strike-slip faults and extensions related to the to the still on-going eastward and south-eastward tectonic escape of the Eastern Alps (Grenerczy and Kenyeres 2006; Weber et al. 2006).

The Periadriatic (Insubric) Line (PL) is weakly recognizable in the seismic sections crossing the chain, which cannot confirm without any doubt its northward dip. In the Central Alps the Insubric line, reaching a maximum depth of 20 km, can be correlated with crustal thickening and the maximum Moho depth, a position arising from the Neogene post-collision deformation of the chain. In the Pannonian domain, PL is no more a first-order structure, but a strike-slip accompanying the crustal thinning and the escape of the crustal fragments towards SE.

Of interest is the feature found at the southern end of the TRANSALP profile where a duplication of the lower crust in the Belluno–Vicenza area is imaged in the explosive stack section (Fig. 8, from Castellarin et al. 2006, extent in Fig. 7). This lower crust thickening was already mentioned by Deichmann et al. (1986) and Panizza et al. (1981) on the base of DSS data. It corresponds to a pronounced positive gravity anomaly, the Verona–Vicenza high and the north-eastward directed Belluno nose (map in Fig. 3, locations in Fig. 1), with high velocities in the upper crust (6.2–6.4 km/s in the interval between 12 and 18 km) and for the lower crust (6.4–7.0 km/s), reached at 20–25 km and dipping northward with two branches, the lowermost matching up the Moho that, from less than 30 km near Vicenza, steeply jumps to 40 km before of the Valsugana thrust belt area. This scenery might be related to the pre-Alpine evolution of the region with uncertain mechanism (Castellarin et al. 2006), presenting a duplication of the lower crust recognized on north and north-east flanks of the Milano–Verona–Central Adriatic crest.

Reflection profiles are absent in large parts of the eastern chain. One relatively short profile was shot in Austria, at the transition from the chain to the Neogene Pannonian basin (NESTMK, Grassl et al. 2004). Interesting aspects of the upper and lower crust units are here related to the collision between EU and PA and to the subsequent extension of PA,
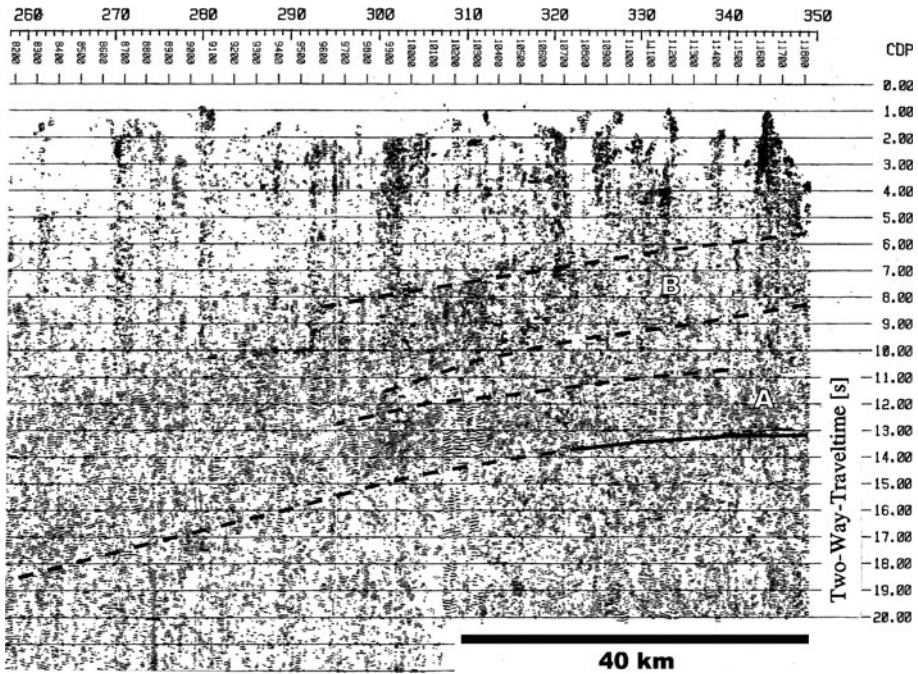
Fig. 8 Lower crust duplication in the Belluno area from TRANSALP explosive section (after Castellarin et al. 2006). The sector covered by the section is shown on the *top* of the receiver functions in Fig. 7

with intracrustal decoupling levels and some deep reflections to be assigned to the EU, underthrusted beneath PA.

The TRANSALP lateral extrusion model with the STR as a lithospheric decoupling separating the AD from EU, with EU underthrusting AD crust, was reinforced by ALP2002 WAR/R acquisitions (see the position map in Fig. 1 with thickened lines tracking the published profiles by Brückl et al. (2007); Grad et al. (2009); Šumanovac et al. (2009) and the interpretative sections for ALP-02 and -01, based on velocities indications, in Figs. 9 and 10). ALP-02 profile runs nearly along the strike of the Eastern Alps and shows in the eastern sector the Moho uplift due to the Pannonian rift. ALP-01 runs parallel to the Dinaric chain in the southern segment, but in the Alpine segment it shows the vertical offset between the European plate and the overriding Adria like along TRANSALP and ALP-02 profiles. ALP-04 profile runs roughly oblique to the thrust belts and plate boundaries. On this profile (Fig. 11) the Adria mantle was posed at about 45 km depth, as recognized in ALP-01 and -02 sections, almost the same position of a narrow PA fragment underthrusted by the EU mantle. Uplift of the Moho is the most noteworthy feature that accompanies the transition to the Pannonian rift domain associated with the Carpathian subduction with crustal thinning and the tectonic escape from the Alpine collision area towards the unconstrained margin of that basin (see ALP-02 section in Fig. 9 and ALP-07 in Fig. 12).

The profile ALP-07 (Fig. 12), crossing the Dinarides front, shows a M-discontinuity dipping from 30 km in Istria to 40 km beneath the internal Dinarides (Velebit chain) and rising after, with some undulations and discontinuities, to 20 km in the Pannonian basin (Šumanovac et al. 2009). The subduction called for Adria under PA is not visibly imaged with the wide-angle seismic profiles and might be positioned apparently in correspondence
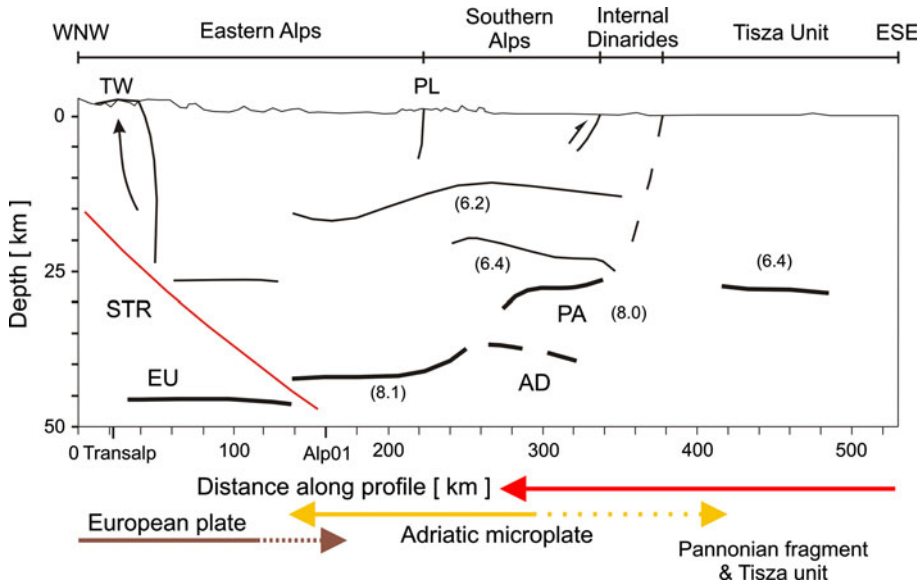
Fig. 9 The tectonic interpretation of the ALP-02 profile crossing TRANSALP in the TW area and extending south-eastward to Croatia (from Brückl et al. 2007, modified). The Tauern extrusion model, the Sub-Tauern ramp were fixed considering also the TRANSALP and neighbouring old DSS results. EU underthrusting AD and the uplift of the PA-Moho are shown. *PL* indicates the position of the Periadriatic (Insubric) line
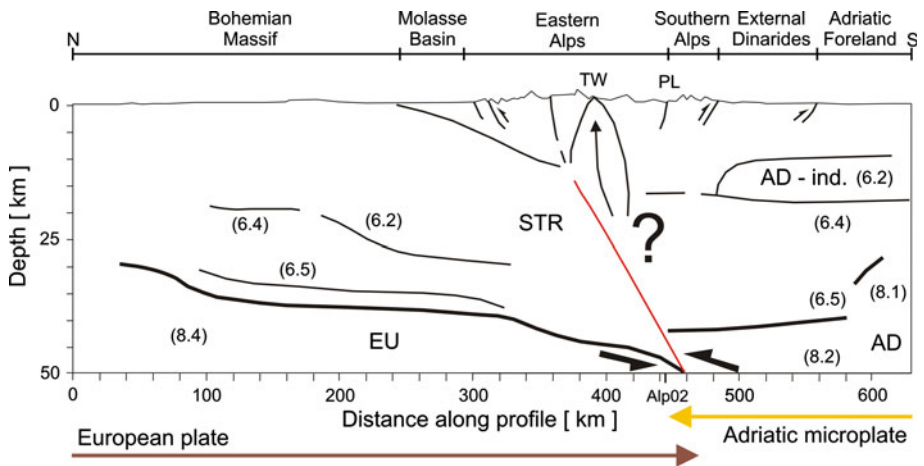

Fig. 10 ALP-01 profile (from Brückl et al. 2007, modified) evidences the EU underthrusting AD, the vertical step of the Moho towards the Adriatic foreland and the AD indenter beneath the External Dinarides. *STR* Sub-Tauern Ramp

of the eastern border of the Velebit chain. The Adria subduction process was active up to late Miocene while the Oligocene–Pliocene rifting of the Pannonian basin modified the crustal boundaries with a new Moho. Anyway, the above authors (Brückl et al. 2007) are proposing three types of crust: the Dinaric crust (Adria?), a transition zone corresponding approximately to the Sava depression (PA′ fragment), the Pannonian crust (PA) beneath
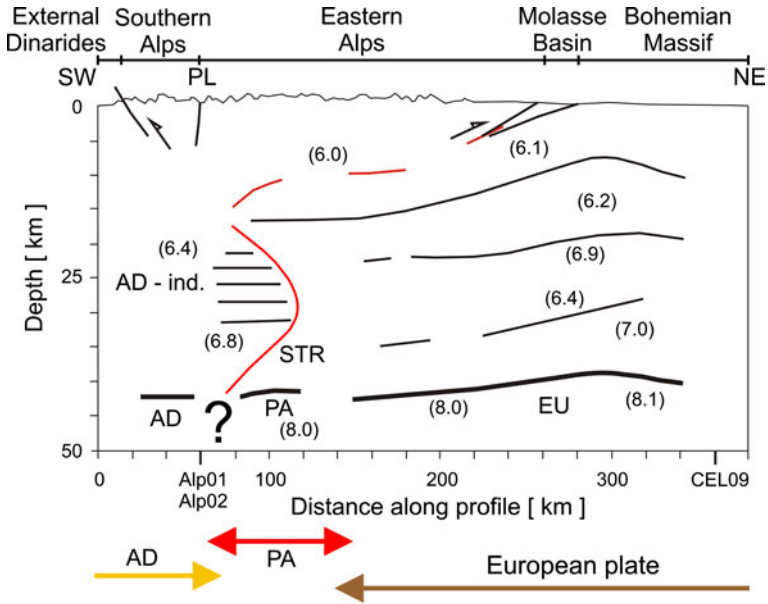
Fig. 11 ALP-04 profile (from Grad et al. 2009, modified) with PA fragment between AD and EU and AD-ind. with highly reflective layers. Sub-Tauern Ramp (*STR*) represents the boundary between AD and EU
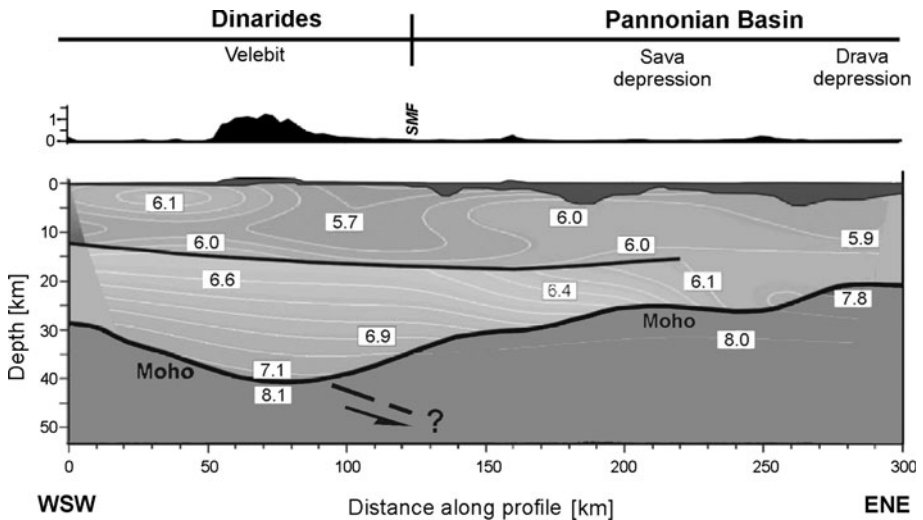
Fig. 12 The model for the ALP-07 profile, completed using tomographic inversion, ray tracing techniques and gravity data (from Šumanovac et al. 2009, modified). The profile crosses the northern Dalmatian islands and the Velebit chain, ending in the Pannonian basin. *SMF* Southern Marginal Fault of the Pannonian Basin

the Drava depression and three major decoupling levels are interpreted between the three lithospheres: under Drava depression, under Sava depression, beneath the Dinarides.

The AD is interested by a vertical step in the M-discontinuity moving from Istria (approximately 30 km depth) to north (about 47 km) along the profile ALP-02 (Fig. 9) and

again from Istria to the Dalmatian coasts along ALP-07 profile (Fig. 12) with a M-depth from 30 to about 40 km but with a more gentle transition). This morphology suggests a similarity with the southern part of the TRANSALP profile with high-velocity upper crust and Moho, from less than 30 km near Vicenza, steeply jumping to 40 km before of the Valsugana thrust belt area north from the Verona–Vicenza–Belluno gravity high, as discussed previously (Figs. 1, 3, 8).

Intracrustal features in the Adria domain are present on the profile ALP-04 (Fig. 11) with an indenter at depth of about 20 km, 10-km thick, characterized by high reflectivity layers stack, marking a laminated lower crust or the presence of mafic intrusions. In the middle-upper crust, from 6 to 15 km depth, a high-velocity block (roughly 6.2 km/s), extending from Istria to the point where the Dinaric and southern Alpine thrusts interfere and crustal thickening occurs, is called AD indenter (Fig. 10), a crustal interval apparently not affected by deformation during collision. This body with relatively high velocity might be of importance for the seismotectonic of the area. It is limited by a basal detachment evidenced at about 18 km depth. A similar intracrustal discontinuity, at 12–17 km depth, is much more extended in the profile ALP-07 (Fig. 12) where it delimits a two-layered crust with the Dinaric thrusts in the upper unit. The velocity of the Dinarides stack of thrusts is high (approximately 5.9–6.0 km/s) and beneath the basal detachment the velocities reach 6.5–6.6 km/s. The Istria block represents the stable part of Adria that emerge from the Adriatic Sea contrasting the westward migration of the Dinarides.

On the western margin of Adria, in the Apennine internal extensional domains, a lower crust is imaged in sections and interpretative models as a zone of mobilized lithothermal masses: at the transition from the Ligurian sea to the Apennine chain (Makris et al. 1999), in the Tuscan Archipelago (Mauffret et al. 1999) and Tuscan geothermal province (Giese et al. 1981). The mobilized and upwelled asthenosphere (Locardi and Nicolich 2005) can be responsible of the lower crust lamination by magmatic intrusions as proposed in Tuscany presented on the western sector of the profile CRP-03 (position in Fig. 1, section in Fig. 13 and Accaino et al. 2006). The magmatic
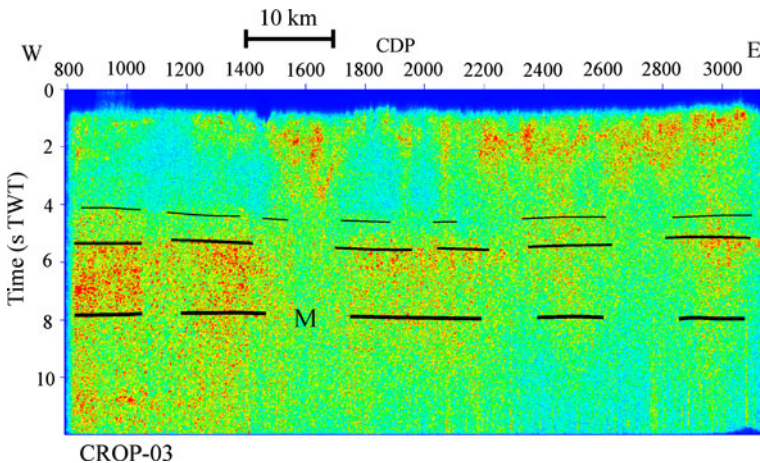
Fig. 13 Western sector of the CROP-03 profile, reprocessed data with strength added (Accaino et al. 2006). The Apennine internal extensional domains in the Tuscan geothermal province are characterized by a reflective lower crust from about 5 to 8 s TWT (from 4 to 5 s a transition zone) with the Moho (M) at the base. Magmatic intrusions in the upper crust are proposed within the blue transparent (dispersive) zones

fluids are coming from a partially molten mantle wedge from below of the M-horizon (see also Fig. 6 in Di Stefano et al. 2009). The intrusion of mantle-derived magmas releases heat at the base of the crust, induces anatexis in the overlying crustal rocks and produce granitoids melts, quickly migrating towards higher levels, leaving behind progressively depleted restites with a sharp distinction of denser materials and lighter anatectic melts and metamorphosed volcano-sedimentary rocks. At the contact between the hot mantle wedge and the cold opposing and passive Adriatic mantle the reflection seismic data give scanty information about the AD subduction and also hypocentres are here not clearly distributed along a Benioff plane. It is necessary to utilize the procedures of the passive seismic tomography to see at larger depths a more precise image of the collision between the Tyrrhenian mantle/asthenosphere and the Adria passive plate boundary (Di Stefano et al. 2009).

The M-discontinuity on the Adriatic Sea main axis is located at around 30 km depth with a lower crust about 10 km thick, as revealed by the CROP-Mare reflection profiles (Scrocca et al. 2003).

4 Conclusions

A triple junction among AD, PA, or PA fragments, and EU is proposed near Katschberg, at the eastern limit of the Tauern Window, with PA acting as upper plate in the collision with EU and with AD. AD underthrusts PA fragments, EU underthrusts AD and PA. This framework was delineated on the basis of WAR/R 2D and 3D modelling and of gravity (Behm et al. 2007) and was supported by Moho deflection analysis and elastic plate modelling. The reconstruction of the tectonic activity indicates a Pannonian fragment moving along south-east right lateral strike slip lithospheric faults relative to Adria and east/north-east relative to Europe, Adria moving toward north and obliquely thrusting under the Pannonian fragment corresponding to the Dinaric chain. The data led us to hypothesise of an AD bracket together with the large Pannonian domain. The upper crust is here characterized by the Dinaric thrusts (upper plate) moving westwards, opposed by the Istria massive Mesozoic shelf domain, the stable part of AD, which emerge from the Adriatic Sea.

The subduction of Adria mantle/lithosphere toward north in the Eastern Alps defined by teleseismic tomography cannot be confirmed or plainly denied because of the relatively poor penetration power of refraction and reflection seismic. In the first 50 km the seismic data confirm a unique south-dipping polarity of EU along the whole Alpine orogene. Anyway it is worth to remember that unclear velocity structure of the upper crust may influence the tomography data and the newly proposed ALP2002 interpretations may increase the definition of the teleseismic tomography with better outlined parameters for computations. Also lateral structures and heterogeneities near the triple junction may influence the data presentation. The extensions with the lateral extrusion towards the Pannonian domain moved differently the upper crust from the lower crust and upper mantle with disharmony and poor correlation between the outcropping geological structures (old, recent) and the deep movements. The tomography may illuminate the heritage of old geodynamic processes in an area.

In the Western Alps the dramatic imbrication of the upper mantle and crust is the most impressive feature revealed by wide-angle fan profiles.

The Apennines overthrust the western margin of AD lithosphere with the presence of a pronounced flexure but reflection seismic data give scanty information about the

subduction, probably because of the limited penetration in collision zones. The seismic crustal image obtained in the internal extensional domains is more instructive.

The lower crust setting of the AD plays a major role in the definition of the crust structure and evolution. However, it is not simple the effort to isolate in terms of velocities or reflectivity the different bodies because the physical differences are small and tectonic melanges may dominate the thickened crusts after collision. The joint WAR/R velocities and the deep reflection seismic profiles can be the winning solution and can give definitive answers to the role of the Adria indenters, of the lower crust duplication along the northern flank of the main Adriatic crest, of the lithospheric faults and intracrustal detachments controlling the reciprocal movements of the upper and lower crust and mantle and of the seismicity in the key points of the Adria domain.

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