Three lithospheric transects across the Alps and their forelands

explanatory text and figures in PDF-format (regarding the transects see the last three pages of this PDF file!)

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TRANSMED transects IV, V and VI: Three lithospheric transects across the Alps and their forelands

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1. General Introduction

The European Alps, located in south-central Europe, record the closure of several ocean basins located in the Mediterranean domain during the Late Cretaceous and Cenozoic convergence of the African (or Apulian) and European plates (e.g. Trümpy 1960, Frisch 1979, Haas et al. 1995, Stampfli et al. 2001a,b). In recent years it has become increasingly evident that the oceanic and continental paleogeographical realms, from which the Alpine tectonic units derive, were arranged in a rather non-cylindrical fashion. This led to important along-strike changes in the overall architecture of the Alps (Fig. 1), also reflected, for example, in the deep structure of the Alps (e.g. Pfiffner et al. 1997; Schmid and Kissling 2000), or, in the different age of the main metamorphic events (Tertiary in the Western Alps, Cretaceous in the Austroalpine units of the Eastern Alps, e.g. Gebauer, 1999; Thöni, 1999).

As discussed in this paper (see also Froitzheim et al. 1996) the Alps are the product of two orogenies, a Cretaceous one followed by a Tertiary one. While the former is related to the closure of an embayment of the Meliata Ocean into Apulia, the latter is due to the closure of the Alpine Tethys between Apulia and Europe (Haas et al 1995; Stampfli et al. 2001a,b).

In view of rather substantial along-strike changes, we chose to construct three transects. A first one (TRANSALP transect VI: section "ECORS-CROP") runs approximately E-W, from the Bresse Graben through the Jura Mountains and French-Italian Western Alps into the eastern Po Plain, midway between the Southern Alps and Apennines, ending at drill hole Battuda (Pieri and Groppi 1981), also crossed by transect V. This section (Roure et al. 1996b) mainly depicts late-stage, i.e. post-collisional ENE-WSW shortening in the French-Italian Western Alps, largely controlled by Oligocene-age WNW-directed indentation of the Adriatic micro-plate with, at its front, a slice of mantle material reaching the surface in the Ivrea Zone (Schmid and Kissling 2000; Ceriani et al. 2001).

The second TRANSALP transect V (section "NFP-20/EGT") is located at the transition between the "Western" and "Eastern" Alps, corresponding to the western limit of the Austroalpine nappes of the Eastern Alps (mapped as "Apulian Plate north of the Periadriatic Line" in Fig. 1) that runs almost perpendicular across the E-W-strike of the present-day Eastern Alps (Fig. 1). This most important lateral change within the European Alps coincides with the western front of the Austroalpine nappes, stacked towards the WNW during the Cretaceous orogeny (Froitzheim et al. 1994, 1996). Transect V crosses in a N-S direction the Bavarian Molasse Basin and the Alps (Schönborn 1992; Schmid et al. 1996a; Pfiffner et al. 1997), then in a NE-SW direction the northern Po Plain, making use of the subsurface information provided by AGIP wells and seismic sections (Pieri and Groppi 1981; Cassano et al. 1986), and ends SW of the front of the westernmost Apennines in the Monferrato hills.

The third TRANSMED transect VI (Section "Eastern Alps") was constructed through the Eastern Alps (Schmid et al in press). It runs N-S through the eastern Molasse Basin of Upper Austria, which substantially narrows between Bohemian Massif and Alps, and then crosses the Alps east of the Tauern window. At the Periadriatic Line the profile trace had to be displaced by some 80 km further towards the west owing to the lack of published information on the border area of Slovenia-Italy-Austria. Across the Southern Alps the profile still runs N-S, following a profile constructed by Nussbaum (2000) but then it runs in a NE-SW direction across the eastern Po Plain and across the front of the northern Apennines, again making use of AGIP-data (Pieri and Groppi 1981; Cassano et al. 1986). We chose this section, rather than the recently published TRANSALP section (TRANSALP Working Group, 2002) further to the west, for the following reasons. Firstly, our transect VI better depicts the Austroalpine nappe stack, that is eroded across the Tauern window traversed by TRANSALP; and secondly, TRANSALP is located too close to the transition zone across which the present-day subduction polarity of the Alps changes, as evident by comparing transect IV with transects IV and V. This polarity change was recently detected on the basis of high-resolution mantle tomography (Lippitsch 2002; Lippitsch et al. 2003).

A new tectonic map of the entire Alps (Schmid et al. in press) introduces non-specialists to the major units of the Alps in some greater detail than can be done here. This map is based on a combination of purely structural data and criteria regarding paleogeographical affiliation and/or tectono-metamorphic evolution and on the excellent maps of Bigi et al. (1990a,b, 1992). Fig. 1 presents a simplified version of this new tectonic map that depicts the paleogeographical provenance of the different tectonic units.

Following an introduction to the structure and evolution of the European Alps, we will present data on the deep structure of the Alps that served as a basis for constructing the lithosphere-scale features of the three transects. Finally, we will discuss the individual transects, including the most important data used, and the rational behind their interpretation.

2. Structure and evolution of the Alps

2.1 The major paleogeographic and tectonic units of the Alps

The map presented in Fig. 1 (Schmid et al. in press, modified after Froitzheim et al. 1996), serves as an overview of the major Alpine units. It also indicates the location of the TRANSMED – transects IV, V and VI, together with two additional profiles discussed later. Fig. 2 shows schematic versions of these transects. Map and profiles given in Figs. 1 and 2 assign all tectonic units, including those made up of high-grade metamorphic rocks, to particular paleogeographical realms. Because the TRANSMED transects were constructed according to criteria other than those of paleogeographical provenance, the reader is encouraged to make use of the profiles given in Fig. 2 in order to gain an overview of Alpine geology. Fig. 3 presents a schematic reconstruction of these paleogeographic realms for Triassic, Jurassic and Cretaceous times.

Of course, assignment of basement complexes, such as of the Lepontine dome of Southern Switzerland and northern Italy, to paleogeographic domains may appear rather speculative. However, the affiliations proposed in Fig. 1 are also supported by retro-deformations based on many tectonic, petrological and geochronological criteria (i.e. Froitzheim et al. 1996), taking into account intense post-collisional deformation (e.g. Schmid et al. 1996a, 1997). Despite many remaining uncertainties regarding paleogeographical affiliation, the map given in Fig. 1 highlights better the major tectonic features of the Alps than more detailed tectonic maps (e.g. Bigi et al. 1990a,b, 1992) that address readers particularly interested in details.

Many of the major paleogeographic units of the Alps, particularly those making up the so-called "Penninic" nappes, are only preserved as extremely thin slivers that were detached from the subducted European lithosphere (European margin), the southward adjacent oceanic domains of the Alpine Tethys (Valais and Piemont-Liguria Oceans, Fig. 3 and Stampfli 2000), and from the continental Briançonnais ribbon continent of the Western Alps, located between these oceans (but not in the Eastern Alps, the Briançonnais Terrane being interpreted to wedge out between the Engadine and Tauern windows, see Figs. 1 & 2). These "Penninic" units, including the Margna-Sesia fragment, a former extensionol allochthon that may be considered as part of the Penninic-Austroalpine transition zone (Trümpy 1992; Froitzheim and Manatschal 1996), were accreted as thin slices (i.e. nappes) to the Apulian upper plate (Austroalpine nappes and South Alpine units) during Cretaceous and Tertiary orogenies (Froitzheim et al. 1996). Some of them were severely overprinted by Cretaceous and/or Tertiary pressure- and/or temperature-dominated metamorphism. The term "Penninic" was avoided in Figs. 1 and 2, as it does not designate a particular paleogeographical domain. This Penninic nappe pile is clearly evident on the TRANSMED – transects IV, V and VI (see also Fig. 2) and will be discussed along with the other tectonic units that were derived from particular paleogeographic domains.

The following brief summary of the major tectonic units of the Alps, accompanied by Figs. 1, 2 and 3, is structured into sub-chapters, which refer to particular paleogeographical domains, going from external (north or west) to internal (south or east).

Tectonic units derived from the European margin

Transect IV crosses a substantial part of the European margin that constitutes the northern and western foreland of the Alps. Tertiary-age rifting in this foreland (Bresse graben of transect IV) during the formation of the European Cenozoic Rift System (Dèzes et al. in press) started in the Late Eocene and occurred contemporaneously with crustal shortening in the Alps and the Pyrenees. The Oligocene-Miocene Molasse Basin, representing the northern flexural foreland basin of the Alps, is not well developed in front of the Western Alps (transect IV). The internal parts of this foreland basin were involved in W-directed thrusting of the Penninic units during the Oligocene (e.g. Ceriani et al. 2001), while its external parts were affected by Miocene thick-skinned thrust propagation (formation of the external massifs and the Chaînes Subalpines, e.g. Fügenschuh and Schmid 2003), followed by thin skinned deformation of the European margin (Late Miocene to Pliocene deformation in the Jura Mountains, e.g. Philippe et al. 1996).

The Molasse Basin is, however, well developed in the transitional area between Western and Eastern Alps (e.g. western Bavarian Molasse Basin). It was mapped as "foreland basin" in the tectonic version of transect V. In this foreland basin, which began to subside during the Late Eocene, orogen-derived continental clastics were deposited during the Late Oligocene to Late Miocene (Roeder and Bachmann 1996), directly following a stage of accretionary wedge formation, preserved in some Lower Oligocene flysch units found on top of the Helvetic nappes, later thrust onto the Molasse Basin ("South Helvetic flysch", mapped as "accretionary wedge sediment" in the tectonic version of transect V).

In transect VI the Molasse foreland basin is considerably narrower and shallower as compared to transect V (Wagner 1996). Moreover, its sedimentary fill is dominated by orogen derived Oligocene to Early Miocene deeper water clastics. To the east of transect VI the Austrian Molasse Basin narrows down to less than 10km in the area of the southern tip of the Bohemian Massif basement spur.

The external massifs of the Western Alps and their sedimentary cover (Chaînes Subalpines of the French Alps in transect IV and para-autochthonous cover extending northward beneath the Molasse Basin in transect V) were strongly affected by Neogene thick-skinned thrusting. By contrast, the Eastern Alps are devoid of external massifs. Correspondingly, the European foreland is seen to uniformly dip southward beneath a flat-lying stack of Alpine nappes, until it gets affected by sinistrally transpressive faulting along the SEMP (Salzach-Ennstal-Mariazell-Puchberg) Line (transect VI). Note, however, that European crust rises up again in the Tauern window, i.e. in a more internal position.

The completely detached Helvetic cover nappes are also part of the European margin. However, Helvetic nappes in the strict sense (thin-skinned sedimentary fold-and-thrust belt, detached from their former pre-Mesozoic basement) only exist in the Swiss and westernmost Austrian Alps, traversed by transect V. In transect IV the lateral equivalents of the Helvetic nappes were involved in thick-skinned deformation (Chaînes Subalpines). In the Eastern Alps (transect VI) their paleogeographic equivalents largely remained unaffected by deformation and were consequently not detached, except for some thin tectonic slices found within flysch sediments (Rhenodanubian flysch). Note that in the foreland of the Eastern Alps Late Senonian and Paleocene strong intra-plate compressional deformation of the Helvetic shelf and the northward adjacent Bohemian Massif accounted for the partial destruction of their Mesozoic sedimentary cover (Ziegler 1990; Ziegler et al. 2002). Hence, the erosional remnants of the Helvetic sedimentary prism could not be detached. Moreover, in the Eastern Alps the front of the Penninic-Austroalpine nappe stack had advanced to its present position by the Early Miocene, and was only affected by dextrally transpressive out-of-sequence thrusting thereafter, occurring in connection with lateral extrusion (Ratschbacher et al. 1991; Frisch et al 1998).

The pre-Mesozoic basement, onto which the sediments now exposed in the Helvetic cover nappes were deposited, as well as more distal parts of the European upper crust, form part of the so-called “Penninic nappes”, and are referred to as “Subpenninic nappes” (Schmid et al. in press). These nappes predominantly consist of Variscan basement, the distal parts of which were mapped as “rifted crust” in the tectonic versions of the transects. Occasionally, the Mesozoic cover of these distal units was not detached. For example, this cover is particularly well preserved as “Untere Schieferhülle” in the Tauern window, projected below the surface in transect VI. The Subpenninic basement nappes, which were detached from their deeper crustal underpinnings (lower crust and upper mantle) during subduction, are presently exposed in the Lepontine dome (central part of the Alpine Orogen, exposed immediately west of and projected into transect V), as well as in the Tauern window (tectonic window exposed immediately east of transect VI and crossed by the TRANSALP profile given in Fig. 2d).

In case of the Lepontine dome, all units structurally located below the trace of the Valais suture zone (i.e. units referred to as “Subpenninic” in the pioneering work of Milnes 1974), including the Gotthard and Tavetsch “massifs”, as well as the eclogitic Adula nappe (Nagel et al. 2002), are attributed to the European margin (Fig. 1). Parts of these basement nappes, particularly the small “Tavetsch Massif” (Trümpy 1999), are considered to represent the basement of the Helvetic nappes. The latter were detached before the onset of metamorphism in the Lepontine dome (Schmid et al, 1996a).

In case of the Tauern window, the attribution of the central crystalline core and its cover to the European margin (Fig. 1) mainly follows two lines of evidence. Firstly, the Mesozoic cover of the central crystalline core of the window has strong affinities to the Helvetic realm of the northern Alps (Frisch 1975; Lammerer 1986). Secondly, following Froitzheim et al. (1996), the “Obere Schieferhülle” of the Tauern window has to be equated with the Bündnerschiefer of the Engadine window. The latter occupy a position below the easternmost remnants of the Briançonnais Terrane (Tasna nappe) and are therefore attributed to the Valais Ocean. Following the same reasoning as for the Lepontine dome, units below the Obere Schieferhülle, including the “eclogite zone” of the Tauern window (Kurz et al. 1998), have to be attributed to the European margin.

Penninic nappes derived from the Valais Ocean

Remnants of this oceanic domain (Trümpy 1955) and/or immediately adjacent distal continental margin units (i.e. Fügenschuh et al. 1999) form the “Lower Penninic nappes” (Schmid et al. in press). These units are also referred to as “North-Penninic” or “Versoyen” in the Western Alps, and as “Rhenodanubian flysch” or “Obere Schieferhülle” of the Tauern window in the Eastern Alps. They mostly lack pre-Mesozoic crystalline basement and predominantly consist of rather monotonous calcareous shales and sandstones, referred to as “Bündnerschiefer”, “Schistes Lustrés” or “Calcescisti”. Sedimentation of the Bündnerschiefer most probably started near the Jurassic-Cretaceous boundary (Steinmann 1994) and graded into deposition of flysch during the Tertiary (e.g. Prättigau and Rhenodanubian flysch). Only parts of these sediments were deposited on ophiolitic units, including exhumed sub-continental mantle (e.g. Florineth and Froitzheim 1994; Fügenschuh et al. 1999). For large parts of these Bündnerschiefer it is hard to decide, whether they were deposited on oceanic or distal continental crust (Briançonnais and/or European). Hence, units mapped as“ Valais Ocean” in Fig. 1 often also include sediments that were deposited on distal continental crust.

The rather narrow Valais Ocean began to open near the Jurassic-Cretaceous boundary. Sea floor spreading in this northerly branch of the Alpine Tethys was kinematically linked to the northward propagation of the Mid-Atlantic spreading axis and the separation of the Iberia-Briançonnais micro-continent from Europe. This entailed opening of an oceanic basin, that extended from the Bay of Biscay via the area of the future Pyrenees into the domain of the Valais Ocean to the north of the Briançonnais Terrane (Frisch 1979; Stampfli 1993). In the Eastern Alps, however, this opening must have taken place within an already existing oceanic realm, representing the eastern continuation of the Piemont-Liguria basin. Tectonic units attributed to the Valais Ocean in the Eastern Alps are derived from areas where sedimentation persisted into the Tertiary, as documented for units in the core of the Engadine window and the Rhenodanubian flysch (Oberhauser 1995), but only suspected for the "Obere Schieferhülle" of the Tauern window.

Remnants of this northern branch of the Alpine Tethys define a northern Alpine suture between the European margin and the continental Briançonnais Terrane (in case of the Western Alps), or an orogenic lid consisting of previously stacked Piemont-Liguria and Apulian (Austroalpine) units (in case of the Eastern Alps), respectively. This Valais Ocean closed during the Middle to Late Eocene. In respect to high-pressure units derived from the internal Briançonnais and Piemont-Liguria units, the Valais suture, together with the most distal parts of the European margin, defines a second and more external high-pressure belt, which extends from the Western Alps all the way into the Tauern window (Bousquet et al. 2002). Eclogitic mafic rocks are found in the Versoyen of the Western Alps and in parts of the Tauern window, while blueschists and other low temperature-high pressure rocks are preserved in the Engadine window (Bousquet et al. 1998).

Note that the units derived from the Valais Ocean are separated from those derived from the Piemont-Liguria Ocean by nappes derived from the Briançonnais Terrane (see below) in case of transects IV and V (see also Figs. 2a-c) across the Western Alps. This is, however, not the case in the Eastern Alps (transect VI and profiles depicted in Fig. 2d,e) where remnants of the intervening Briançonnais terrane are not present (see also Fig. 1).

Penninic nappes derived from the Briançonnais Terrane

Tectonic units derived from the continental Briançonnais Terrane (Fig. 1) constitute the "Middle Penninic nappes". As mentioned above, nappes derived from this micro-continent are only present in transects VI and V, where they often also include pre-Mesozoic basement. This basement was mapped as "rifted crust" in the tectonic version of the transects.

The Briançonnais micro-continent represents the eastern tip of the Iberia block that formed the northern passive continental margin of the Jurassic Piemont-Liguria Ocean before it was separated from Europe in conjunction with the opening of the Valais Ocean in Early Cretaceous times (Fig. 3c; Frisch 1979; Stampfli 1993), kinematically linked to the northward propagation of sea floor spreading in the Atlantic. The term "Briançonnais Terrane" also encompasses units immediately adjacent to either the Piemont-Liguria Ocean (i.e. Acceglio and Nappe de la Brêche of the Western Alps) or the Valais Ocean (i.e. Falknis nappe of the Eastern Alps). The Mesozoic cover of large parts of the Briançonnais micro-continent (particularly the Briançonnais s.str.) mainly consists of platform sediments with frequent stratigraphic gaps ("mid-Penninic swell", Trümpy 1960; mapped as "slope/rise undifferentiated" in the tectonic version of transects IV and V). These sediments are best preserved in the Mesozoic cover of the Zone Houillère of the French-Italian Western Alps and in the detached sediments of the Préalpes Romandes of Western Switzerland (Stampfli et al. 1998, 2002) and adjacent parts of Savoy. These sediments escaped intense deformation and high-pressure overprint.

The basement of the Mesozoic sediments of the Briançonnais Terrane is preserved in the "Zone Houillère" (="Upper Carboniferous" in the stratigraphic version of Transect IV, see also Fig. 2a) and in basement nappes such as the Gran Paradiso and M. Rosa nappes of France and Western Switzerland (Figs. 2a.b), or the Tambo and Suretta nappes of Eastern Switzerland (Fig. 2c). Some, but not all, of these basement nappes preserved at least parts of their Mesozoic cover. Some of them (e.g. M. Rosa) were overprinted by high-pressure metamorphism, while others (e.g. the Siviez-Mischabel nappe, i.e. the northern continuation of the M. Rosa nappe, Fig. 2b) escaped high-pressure overprint. While an unequivocal attribution of these basement nappes to the Briançonnais paleogeographic realm can be made in many places (e.g. Sartori 1990; Schmid et al. 1990), such an attribution remains speculative for basement nappes that did not preserve their Mesozoic cover.

Penninic nappes derived from the Piemont-Liguria Ocean

Tectonic units derived from the Piemont-Liguria Ocean (Alpine Tethys) and immediately adjacent distal continental margins (see Fig. 1 and schematic profiles of Fig. 2) are also referred to as "Upper Penninic nappes". They occupy the structurally highest position within the Penninic nappe stack in all transects (VI, V and VI), unless their original position was severely modified by large-scale post-nappe folding (Schmid et al. 1990; Bucher et al. 2003), as is locally the case also in transects VI and V (also see Figs. 2a,b, and c). These units consist of (i) ophiolites, including slices of exhumed sub-continental mantle (Trommsdorff et al. 1993), often grading into distal continental margin units (i.e. Manatchal and Nivergelt 1997; Manatschal and Bernoulli 1999); (ii) Bündnerschiefer (i.e. "Avers Bündnerschiefer", Oberhänsli 1978) or Schistes Lustrés (i.e. nappe du Tsaté, i.e. Escher et al. 1997), often containing ophiolitic slices or olistoliths; (iii) non-metamorphic cover nappes of very internal, but not exclusively oceanic origin, such as the Helminthoid flysch of the Western Alps (i.e. Kerkhove 1969; Caron et al. 1989) and (iv) ophiolitic mélanges such as the Matrei zone found at the rim of the Tauern window (Frisch et al. 1987; Kurz et al. 1998).

The Piemont-Liguria Ocean was located directly adjacent to the Apulian margin and south of the Briançonnais ribbon continent (Fig. 3). Units belonging to this ocean (Fig. 1) are made up of oceanic lithosphere that started to form during the Middle Jurassic (Froitzheim and Manatschal 1996), in the context of the opening of the Central Atlantic (Frisch 1979; Stampfli 1993). The onset of sea floor spreading was followed by deposition of radiolarites and aptychus limestones, lithologies that are rather diagnostic for the Piemont-Liguria Ocean and neighbouring parts of Apulia; they are not found in the northern branch of the Alpine Tethys, the Valais Ocean (see above). During the Cretaceous, deposition of trench deposits (Avers Bündnerschiefer of Eastern Switzerland and schistes lustrés of Western Switzerland and France, mapped as "clastics, including turbiditic sediments on oceanic lithosphere" in the tectonic versions of the TRANSMED transects) indicates that the southern (Apulian) margin of this basin had been converted into an active margin.

In eastern Switzerland, units derived from those parts of the Piemont-Liguria unit that are immediately adjacent to the Apulian margin (e.g. Arosa and Platta units) were already sutured with the Austroalpine units during the Cretaceous orogeny (Froitzheim et al. 1994). Other tectonic units attributed to this branch of the Alpine Tethys, particularly those of the Western Alps, comprise parts of the Piemont-Liguria Ocean that stayed open until the onset of Tertiary orogeny, when the accretionary wedge of the Alpine subduction system collided with the Briançonnais ribbon continent (e.g. Schmid et al. 1997; Stampfli et al. 1998, 2002). In the Western Alps (but not in the Eastern Alps), Tertiary-age high-pressure overprint of the Piemont-Liguria units, together with adjacent parts of the most internal Briançonnais Terrane, is very widespread (Gebauer 1999; Frey et al. 1999).

Where, according to our interpretation, no remnants of the Briançonnais ribbon continent occur, as in the Eastern Alps (Fig. 1, see also Froitzheim et al. 1996, Stampfli et al. 2001a,b), the attribution of some of the oceanic units to the Piemont-Liguria Ocean, rather than to the Valais Ocean, as shown in Fig. 1, was guided by the following criteria: (1) presence of radiolarites and aptychus limestone, (2) presence of rock assemblages that are characteristic for the ocean-continent transition found at the margin to Apulia, including mélanges containing Austroalpine (=Apulian) slivers, such as typically found at the rim of the Tauern window (e.g. Matrei zone, Frisch et al. 1989) and (3) evidence for early basin closure in the context of Cretaceous age top-W nappe stacking in the Eastern Alps, and/or, (4) absence of Tertiary-age sediments. Hence, in the Eastern Alps (transect VI), the attribution of Penninic units to one or the other ocean (Figs. 2d,e) is very much guided by the concept that two distinct orogenies, separated from each other by the Late Cretaceous extensional "Gosau event", affected the Eastern Alps (see Froitzheim et al. 1994). The Cretaceous orogeny affected only the more internal units of the Alps and led to suturing of internal Piemont-Liguria derived slices with the Apulia margin. However, suturing of units exposed in the Tauern and Rechnitz windows with the Austroalpine nappes, together with Upper Penninic slices derived from the Piemont-Liguria Ocean, occurred in the context of Tertiary orogeny. At that time, all units of the Eastern Alps, previously stacked during Cretaceous orogeny, were thrusted together over the Middle and Lower Penninic and the Subpenninic units presently exposed in these two windows.

Nappes derived from the Penninic-Austroalpine transition zone: the Margna-Sesia fragment

According to Froitzheim et al. (1996), small fragments, rifted off the most distal Apulian margin during mid-Jurassic opening of the Piemont-Liguria Ocean (Fig. 3b), were incorporated during the Late Cretaceous into the accretionary wedge along the active northern and western margin of Apulia, facing the still open Alpine Tethys. In the Grisons area such fragments (Margna-Sella basement-dominated nappes) are at least partly caught within ophiolitic units (see transect V, immediately north of the Periadriatic Line). The Sesia unit of the Western Alps, crossed by transect IV, underwent an Alpine tectono-metamorphic history that is different from that of the Austroalpine nappes and the Southern Alps. The Sesia unit, as well as numerous smaller slices embedded in the Piemont-Liguria units, were incorporated into the accretionary prism near the Cretaceous-Tertiary boundary (age of high-pressure overprint, e.g. Gebauer 1999; Dal Piaz et al. 2001) below the Dent Blanche nappe, while the Austroalpine nappes always remained in an upper plate setting after the Cretaceous (Eoalpine) orogeny.

In contrast to the Austroalpine units assigned to “Apulia” the pre-Alpine basement of the units assigned to the Margna-Sesia fragment (mapped as “rifted crust” in transects IV and V), including that of the Dent Blanche unit, comprises pieces of lower crust (e.g. Müntener et al, 2000). This lower crust exhibits close similarities to the basement at the western margin of the Southern Alps (Ivrea Zone, see transect IV), also attributed to the most distal part of Apulia with respect to the Alpine Tethys.

Austroalpine nappe system, derived from parts of the Apulian Plate presently found north of the Periadriatic Line

The term “Apulian Plate” denotes all continental paleogeographic realms situated south of the Alpine Tethys (Piemont-Liguria Ocean) and north of Neotethys (Fig. 3c). Hence this term also includes the southern foreland of the Alps. Moreover, as shown in Fig. 3, Apulia was bordered to the east by a westwards closing oceanic embayment that formed in Triassic times, referred to as Meliata Ocean. The derivatives of this ocean and adjacent distal passive continental margin will be treated below in a separate chapter. Only after closure of the Meliata Ocean during the Cretaceous orogeny, did Apulia north of the Periadriatic Line behave as a coherent block, forming a rigid orogenic lid of the Alps during the Tertiary orogeny.

To the north of the Periadriatic Line, remnants of the southern margin of the Piemont-Liguria Ocean (i.e. the Apulian Plate) are only preserved in the form of basement and cover slices (Austroalpine nappes), that are completely detached from their former deep crust and mantle-lithosphere. Around the Tauern window, along a thrust formed during the Tertiary orogeny, the Austroalpine nappes are seen to overlie Penninic units that consist of slivers derived from the distal European margin, as well as oceanic slivers derived from the Alpine Tethys, Figs. 1 & 2). The Austroalpine nappes were affected by a Cretaceous orogenic cycle, related to the closure of the Meliata Ocean (Fig. 3a) and its adjacent continental margin. The tectonic and metamorphic manifestations of this older orogenic cycle, referred to as “Eoalpine”, are clearly separated from the Tertiary orogeny by a late Cretaceous phase of extension and exhumation (Froitzheim et al. 1994), as well as by the deposition of the post-tectonic neo-autochthonous Gosau sediments (e.g. Faupl and Wagreich 1996). Overprinting relationships are well documented in Eastern Switzerland, i.e. at the Western-Eastern-Alps transition (Froitzheim et al. 1994). This most important lateral change within the European Alps coincides with the western front of the Austroalpine nappes, stacked towards the WNW during the Cretaceous orogeny. Note that this western front of the Austroalpine nappes of the Eastern Alps (mapped as “Apulian Plate north of the Periadriatic Line” in Fig. 1) runs almost perpendicular to the strike of the present-day Alps (Fig. 1 and Plate1). Only some very small Austroalpine klippen (units of the Northern Calcareous Alps) are preserved in Central Switzerland.

The Eoalpine (or Cretaceous) tectono-metamorphic event is well documented in the Austroalpine nappes of the Eastern Alps, but is not evident in the Western Alps. Only in parts of the Southern Alps (Lomardian basin) flysch deposits testimony of orogenic activity at that time (Bernoulli and Winkler 1990). Hence, the Tertiary-age eastern part of the Periadriatic lineament must have had a precursor in the Cretaceous (and earlier, see Dal Piaz and Martin 1998) forming the southern boundary of this Cretaceous orogen.

The Eoalpine orogenic cycle, however, was preceded by Late Jurassic thrusting of the distal passive margin facing the Triassic Meliata Ocean (i.e. the Hallstatt facies sediments, mapped as “Meliata Ocean and its distal passive margin” in Fig. 1; Gawlick et al. 1999), onto Austroalpine units derived from “Apulia”. This was possibly triggered by the obduction of parts of the Jurassic Vardar Ocean (Dinaridic ophiolites, Pamic 2002) that also occurred during the Late Jurassic (Fig. 3b).

The Cretaceous orogeny is interpreted to be related to a collisional event associated with the closure of the Meliata Ocean (Fig. 3a). The exact geometry and location of this embayment (Haas et al. 1995) is still a matter of debate. Its closure led to Cretaceous high-pressure (eclogitic) and/or temperature dominated metamorphic overprints (first discovered by Frank and co-workers, e.g. Frank

1987) in those parts of Apulia, which were presumably located closest to the Meliata Ocean. Note that the term "Apulia", as used in Fig. 1, refers to the southern (external Dinarides and highest Austroalpine nappes) as well as to the northern margin (lowermost Austroalpine nappes) of Apulia. As mentioned above, these units can only be considered as a single block during the Tertiary orogeny (Fig. 3c).

Tectonic units derived from the Meliata Ocean and its distal passive margin, including parts of the Austroalpine nappe system

Late Paleozoic to Mesozoic oceans, whose opening is kinematically unrelated to the opening of the Atlantic Ocean and the "Alpine Tethys", include “Neotethys”, the Triassic Meliata Ocean and the Jurassic Vardar Ocean within the area covered by Fig. 1 (see Fig. 3 for the paleogeographic location of these oceans). Remnants of the Vardar Ocean are only found in the Dinarides, but extremely scarce remnants of the Triassic Meliata Ocean are also found in the Alps (Mandl and Ondrejickova 1991, 1993) where they form tectonic slices within the nappe stack of the Northern Calcareous Alps containing very low grade metamorphic serpentinites, Triassic radiolarites, olistoliths and Jurassic flysch-type sediments. Units attributed to the distal passive margin of Apulia adjacent to the Meliata Ocean are more widespread and preserved in parts of the Austroalpine nappes (Hallstatt-facies of parts of the Juvavic nappes in the Northern Calcareous Alps; Gawlick et al. 1999; Mandl 2000). Such remnants are traversed by TRANSMED transect VI, and found as a thin band at the base of a highest out-of-sequence thrust sheet, referred to as “Juvavicum” (the highest tectonic unit within the Northern Calcareous Alps). Moreover, ophiolitic remnants of the Meliata Ocean are preserved as olistoliths in Jurassic mélange formations found in the Western Carpathians, east of the area depicted in Fig. 1 (Plasienka et al. 1997). Remnants of the Meliata Ocean, together with remnants of the Jurassic Vardar Ocean, occur in the internal Dinarides (Dinaridic ophiolite zone and Sava-Vardar zone, Pamic 2002) shown near the eastern margin of Fig. 1 in the area around Zagreb (Tomljenovic 2002).

In spite of the rare occurrences of remnants of this paleogeographical realm, the Triassic Meliata Ocean played a crucial role for understanding the Cretaceous orogeny. In Fig. 1 we tentatively assigned the high-pressure crystalline nappes of the Koralpe-Wölz high-pressure nappe system (Schuster et al. 2001; Schmid et al. in press) to this paleogeographic realm, being aware that this is speculative. These eclogitic units are traversed by transect VI and mapped as “Paleozoic with Eo-Alpine high-P metamorphic overprint”, although the age of the eclogitic protoliths is badly constrained. The Mesozoic cover of parts of this nappe system was completely detached prior to the Eoalpine high-pressure metamorphism, related to the final closure of the Meliata ocean.

Southern Alps and “Adriatic indenter”: Apulian Plate south of the Periadriatic Line

The various segments of the Periadriatic Line (fig. 1), namely, from west to east, the Canavese, Insubric, Giudicaria, Pustertal and Gailtal lines mark the western and northern boundary of the Southern Alps (Schmid et al. 1989). Together with the external Dinarides, the Southern Alps represent that part of the Apulian Plate which is located south of the Periadriatic lineament (e.g. Schmid et al. 1989), and that is often referred to as “Adriatic micro-plate” or “Adriatic indenter” (part of the greater Apulian Plate).

The Southern Alps are characterised by a dominantly south-verging fold- and thrust belt (e.g. Schönborn 1992, 1999). This young (dominantly Miocene) 10 to 15 km thick foreland prism consists of upper crustal slices, seen to still rest on the Adriatic middle and lower crust, including the Adriatic mantle-lithosphere, from which these slices were detached near the brittle-plastic transition of the granitic crust (see transects V and VI, and profiles of Figs. 2a-d).

Most of the Oligo-Miocene dextral strike slip along an E-W-striking branch of the Periadriatic Line (the Tonale Line located west of the Giudicaria Line, Fig. 1) of about 100km (Schmid and Kissling 2000, Stipp et al. in press) was taken up by dextral strike slip movements along the Simplon ductile shear zone and the Rhone-Simplon Line (Steck 1984, 1990). Hence, from Oligocene to probably recent times, the French-Italian Western Alps were kinematically linked to the WNW-moving Adriatic indenter, formed by the Southern Alps and the Ivrea Zone. Note that Ivrea Zone and the Ivrea geophysical body, crossed by transect IV, represent a piece of mantle-lithosphere and lower crust which form the rigid frontal part of the Adriatic indenter. According to Ceriani et al. (2001), the Adriatic indenter caused WNW-directed thrusting along the “Penninic front” of the Western Alps (limit between European margin and Valais or Briançonnais Terrane, respectively, see Fig. 2a and transect IV). During the late orogenic stages, WNW directed indentation of the Adriatic micro-plate affected also the European foreland (Fügenschuh and Schmid 2003), finally causing deformation in the western Molasse Basin and folding of the arcuate Jura Mountains (Burkhard and Sommaruga 1998).

The eastern parts of the Periadriatic Line (Pustertal and Gailtal lines), and their extension, the Balaton Line (Fodor et al. 1998) (Fig. 1), accommodated Miocene-age eastward extrusion of the Apulian Plate N of the Periadriatic Line (the Austroalpine nappes and their continuation into the Western Carpathians, including their Penninic underpinnings) (Ratschbacher et al. 1991). Simultaneously, the eastern part of the Southern Alps was displaced to the north across the sinistral Giudicaria Line, dissecting the formerly straight Periadriatic Line and causing severe Miocene N-S shortening in the Tauern window and contemporaneous E-W-extension in the tectonic units north of the Periadriatic Line across the Brenner and Katschberg normal faults (Fügenschuh et al. 1997; Genser and Neubauer 1989).

Tiza unit

This unit, whose exact paleogeographic origin (European vs. Apulian) is still a matter of debate (e.g. Csontos et al. 1992; Sandulescu 1984, 1994), is located east of the transects presented here and briefly described for reasons of completeness only. The Tiza unit (Haas et al. 2001), shown at the south-easternmost margin of the map presented in Fig. 1, forms the innermost parts of the northwestern Dinarides and the Romanian Carpathians. It is separated by the Mid-Hungarian Line (Csontos and Nagymarosy 1998) from the northerly adjacent eastern extension of the Southern Alps into Slovenia (mapped as "Apulian Plate S of Periadriatic Line" in Fig. 1) and the SW-NE-striking continuation of the internal Dinarides situated NE of Zagreb (mapped as "Meliata and its distal passive margin" in Fig. 1).

2.2 Important along-strike changes in the architecture of the Alpine Orogen, illustrated by transects across the Alps

Important progress has recently been made regarding the developments of large-scale geophysical-geological transects across the Alps (Pfiffner et al., 1997; Roure et al., 1996b; TRANSALP Working Group 2002). This involved the acquisition of high-resolution deep seismic sounding along such transects, and the interpretation of a wealth of geophysical data that was collected during the past 40 years (e.g. Kissling, 1993). This allows for a better understanding of the three-dimensional architecture of the Alps (i.e. Schmid and Kissling 2000).

Figs. 2a and 2b depict geological-geophysical transects (ECORS-CROP, i.e. TRANSMED transect IV, and NFP-20 WEST) across the Western Alps (Schmid and Kissling 2000; Marchand and Stampfli 1997; Escher et al. 1997), while the transect of Fig. 2c (NFP-20 EAST, i.e. TRANSMED transect V) crosses an area situated near the transition into the Eastern Alps (Schmid et al. 1996a, 1997; Marchand and Stampfli 1997). These profiles illustrate the following major changes, which occur along strike, when going from the Western Alps s.str. (Figs. 2a and 2b) towards what may be referred to as "Central Alps" (Fig. 2c): (1) Duplication of European lower crust in the Western Alps vs. wedging of Apulian lower crust into the European crust, (2) Apulian Moho rising towards the Alps (Ivrea body) vs. descending Apulian Moho at the base of the lower crustal wedge, (3) increasing amounts of back-thrusting in the vicinity of the Insubric Line (branch of the Periadriatic line crossed by TRANSMED transect V) and, (4) increasing amounts of Miocene shortening within the Southern Alps.

As discussed in more detail below, recent results of high-resolution tele-seismic tomography, focussing on the P-wave velocity structure of the lithosphere and upper mantle beneath the entire Alps (Lippitsch 2002; Lippitsch et al. 2003; Kissling et al. in press), revealed a change in subduction polarity between Western and Eastern Alps. The subducted European lithospheric slab, which dips beneath the Western Alps southeastward under the Apulian lithosphere, steepens eastwards and towards the Tauern window. East of a point located beneath the western part of the Tauern window, the Apulian lithospheric slab is seen to dip northward under the European lithosphere by some 170km (Lippitsch 2002; Schmid et al. 2003; Kissling et al. in press). At first sight this is surprising, since there is no indication for an along-strike change in the stacking order of the major paleogeographic and tectonic units of the Alps as is seen from Fig. 1. However, two major orogen-perpendicular post-collisional features coincide with this change in subduction polarity: the Giudicaria belt (Stipp et al. in press) and the Brenner normal fault (Fügenschuh et al. 1997). This suggests that the change in subduction polarity imaged by tomography was not established before some 20 Ma ago, i.e. when these across-strike features were activated.

Fig. 2d presents a re-interpretation of the TRANSALP geophysical-geological transect (TRANSALP Working Group, 2002; Schmid et al. 2003) in the light of these findings on the deep structure of the Alps. It emphasizes the importance of strike-slip faulting along the Inntal and Pustertal lines, adjacent to the Tauern pop-up structure, while the alterantive interpretation given by TRANSALP Working Group (2002) emphasises displacement along a thrust at the base of the Tauern window, referred to as "Sub-Tauern ramp". In terms of the deep structure, the transect given in Fig. 2d completely differs from that given by TRANSALP Working Group (2002). The TRANSALP section of Fig. 2d and Fig. 2e, corresponding to TRANSMED transect VI, show the Apulian Moho as descending northwards under the European lithosphere, as indicated by the tomographically defined lithospheric configuration (Lippitsch 1992; Lippitsch et al. 2003; Kissling et al. in press).

This re-interpretation explains the lack of a first-order separation between Southern Alps and External Dinarides. Such a separation would be expected if the Alps and Dinarides would still exhibit opposite subduction polarities, as they did during the Eocene. Since no separation is visible between Southern Alps and Dinarides (see Fig. 1), both are expected to presently occupy the same lower plate position. Instead, a major change occurs across Giudicaria belt and Brenner Line. We interpret both of these first-order tectonic features as the surface expression of a change in subduction polarity, which was initiated around 20 Ma ago and which had a profound effect on the style of post-collisional deformation. As discussed later (see description of TRANSMED transect VI, chapter 4.3), this change in subduction polarity might be an apparent one, when taking into account major dextral strike-slip movements along the Periadriatic lineament (including Balaton Line and Mid-Hungarian zone, Fig. 1), which is located between the Southern Alps and northern Dinarides and the Alps and Western Carpathians, respectively.

Note that the polarity of the suture between the Rhenodanubian flysch (Valais Ocean in Fig. 1) and the northern rim of the Austroalpine nappes (Apulian plate in Fig. 1) does not change along strike from west to east. This indicates that the northern rim of the Apulian (Austroalpine) upper plate remained unaffected by this Miocene change in subduction polarity, which only concerns the southern part of the transects given in Figs. 2d and 2e. By contrast, the northern deformation front of the Alps can be traced eastwards into the Carpathian loop (Csontos et al. 1992). There, subduction rollback and slab break-off was initiated at about 20 Ma ago. This rollback allowed for the (apparent?) change in subduction polarity, postulated to have occurred between the profiles of Fig. 2c and 2d, respectively.

TRANSMED transect VI (see Fig. 2e) best illustrates the Austroalpine nappe stack that preserved a thickness of some 10-20km in the area east of the Tauern window, an area that lacks substantial exhumation by late stage thrusting and/or orogen-parallel extension during the Tertiary. In this transect the Koralpe-Wölz high-pressure nappe system is interpreted as representing a former extrusion wedge located between the Silvretta-Seckau nappe system in its footwall and the Ötztal-Bundschuh and Drauzug-Gurktal nappe systems in its hanging wall. This extrusion channel exhumed high-pressure units that formed during the subduction of the western embayment of the Meliata Ocean (Figs. 2b and 2c) during the Late Cretaceous orogeny.

2.3 Evolution of the Alpine system and its forelands in time slices

The following discussion focuses on the evolution of the Alpine Orogen in an area crossed by TRANSMED transect V where timing is best constrained. Fig. 4 gives a timetable of orogenic activity, while Fig. 5 depicts cross sections along this transect for different time slices.

Cretaceous orogeny

The Late Cretaceous (or Eo-Alpine) orogeny is of Late Cenomanian to Campanian age in Eastern Switzerland and is regarded as independent and unrelated to the Tertiary orogeny owing to its different kinematic scenario (top WNW, hence almost orogen-parallel thrusting) and its separation by a Latest Cretaceous extensional event from Tertiary convergence (see Fig. 4). Further east and in Austria, both Cretaceous shortening and extension are older (see discussion in chapter 4). Apart from the Austroalpine nappes, this older orogeny only affects the Piemont-Liguria units of Eastern Switzerland (Arosa-Platta) whereas the rest of the Penninic units remained largely unaffected by this orogeny, which did not propagate further to the west beyond Eastern Switzerland, nor into the Briançonnais units. The southern margin of the Piemont-Liguria margin represented during the Late Cretaceous an active margin, as documented by the accretionary wedge of the schistes lustrées and by the eclogitisation of the Sesia unit around the Cretaceous-Tertiary boundary.

The attribution of a pre-Adamello phase in the Southern Alps (main deformation of Miocene age) to Cretaceous orogenic activity is uncertain. A precursor of the Insubric Line must have been active (separation between the detached crustal flakes of the Austroalpine nappe system from the Adriatic lithosphere which remained intact).

During the various stages of the Tertiary orogeny, the pre-structured Austroalpine nappe system, together with the Arosa-Platta ophiolites, formed a rigid upper plate (referred to as "orogenic lid" in Fig. 5), of which the Southern Alps formed part (not depicted in Figure 5a to 5c, but present at the southern margin of these figures).

Early Tertiary convergence and subduction (65-50 Ma)

Following closure of the last remnants of the Piemont-Liguria Ocean in eastern Switzerland, the youngest sedimentary cover of which now forms an accretionary wedge consisting of the Avers Bündnerschiefer during the Paleocene, the Briançonnais Terrane entered the subduction zone (Fig. 5a). In the Western Alps this southern ocean probably remained open somewhat longer. After about 200 km of N-S-convergence (13 mm/year), and following closure of the Valais Ocean, the distal margin of Europe (the future Adula nappe, see Nagel et al. 2002) entered the subduction zone at around 50 Ma (Table 1, Fig. 5b). Penetrative deformation during this time interval was largely restricted to the southernmost Penninic units, i.e. the Briançonnais Terrane (Tambo-, Suretta- and Schams nappes, see Fig. 4) and the Avers Bündnerschiefer of the Piemont-Liguria Ocean (Fig. 5b).

Tertiary collision (50-35 Ma)

During the middle and late Eocene (between Figs. 5b and 5d), an additional 200 km N-S plate convergence (corresponding to 15 mm/year) was taken up by the incorporation of the Valais Ocean and the distal European margin into a growing accretionary wedge below the orogenic lid formed by the Austroalpine nappes. Fig. 4 illustrates the migration of deformation and metamorphic events towards the northern foreland, reaching the area of the future Helvetic nappes by the end of the Eocene. Note that the total of some 400 km N-S convergence before the Oligocene across the Central Alps (Table 1) involved substantial sinistral strike slip movement across the future Western Alps. Hence, the Western Alps formed under a sinistrally transpressive scenario during Early Tertiary convergence and collision, with W-directed movements post-dating collision (see post-collisional stage 1).

Since the Alpine nappes in Fig. 5 exclusively consist of thin upper crustal slices (basement and/or its cover) detached from their lower crustal and mantle-lithosphere, all European (and Valais) lower crust (including parts of the upper crust) must have been subducted together with the mantle-lithosphere (Fig. 5c). Hence, N-vergent nappe stacking during this collisional stage took place within a growing accretionary wedge. After the subduction of the Briançonnais Terrane and the Valais Ocean more subduction-resisting un-stretched continental crust of the European margin entered the subduction zone. This triggered slab-break-off and the onset of magmatism north of the Periadriatic line (von Blanckenburg and Davies 1995). Radiogenic heat production within this granitic basement (Engi et al. 2001), in combination with slab break-off (depicted in Fig. 5e), led to a change in the thermal regime and to Barrovian-type (called, Lepontine) metamorphism (Nagel et al. 2002).

Post-collisional stage 1 (35-20 Ma)

Further growth of the accretionary wedge led to retro-thrusting of part of the material entering the subduction zone above the steeply, N-dipping Insubric Line (Fig. 5e and 5f). A "singularity point" (Beaumont et al. 1994) developed within the lower part of the upper crust, separating the subducting part of the European crust from that part of the wedge which was back-thrusted and sheared in order to be exhumed by erosion (this singularity point is near the bent arrow shown in Fig. 5f).

As can be seen from Fig. 4, forward thrusting of the Helvetic nappes along the Glarus thrust was contemporaneous with retro- or backward thrusting along the Insubric Line. The Alps evolve into a bivergent orogen, with a southern and northern foreland. Interestingly, the transition into bivergent thrusting coincides with increased rates of erosion due to the pop-up of the Central Alps between pro- and retro-thrusts, resulting in the transition from flysch-type to molasse-type sedimentation in the northern foreland (Sinclair and Allan 1992).

N-S directed plate convergence during this first post-collisional period amounted to about 60 km, slowing down to about 4.5 mm/year (Table 1). In map view, this time interval coincides with the WNW-directed movement of the Adriatic micro-plate (Ceriani et al. 2001), that was now decoupled from the Central Alps along the Periadriatic Line, where dextral strike-slip movement amounted to some 100 km. Kinematically, the Western Alps formed now part of the WNW-moving Adriatic micro-plate and were separated from the Central Alps along the Simplon ductile shear zone, and later on along the Rhone-Simplon Line (see Fig. 1). Note that continental rifting in Rhine and Bresse grabens falls into this same time interval (Dèzes et al. in press)

Post-collisional stage 2 (20-7? Ma)

Continued crustal overthickening within the central part of the Alpine Orogen by bivergent (retro- and pro-wedge) thrusting eventually led to rapid propagation of the deformation front from the Insubric Line towards the Po Plain (Southern Alps), as well as towards the northern foreland (thrusting at the base of the Aar Massif and within the southern Molasse Basin) at around 20 Ma ago. This is shown in Fig. 5e, while the timing constraints are given in Fig. 4. Regarding the Southern Alps, deformation stopped at around 7 Ma ago (Messinian unconformity).

In the northern foreland, however, the situation is more complex. During the late Serravallian (12 Ma), deformation suddenly stepped further into the foreland, now also incorporating the western part of the Molasse Basin and the Jura Mountains into the orogenic wedge (Burkhard and Sommaruga 1998). Whilst decollement along Triassic evaporites is recognized by most authors as being responsible for this forward stepping of the deformation front into the northernmost Jura Mountains up to the margins of the Upper Rhine and the Bresse grabens two questions remain unanswered:

(1) Did thin-skinned deformation stop at around 7 Ma in the Jura Mountains, that is, contemporaneous with foreland deformation in the Southern Alps? (2) How exactly did the arc of the Jura Mountains form? Clockwise rotation of the western part of the Molasse Basin and the northern Alps, or W to NW-directed indentation of the western part of the Central Alps?

In regard to the first question we can argue that present-day deformation is thick-skinned (Schmid 2000; Giamboni et al. 2004), hence it is likely that Jura-folding was a short-lived event (12-7 Ma). Regarding the second question we favour an indentation model with counter clockwise rotation of the Adriatic micro-plate during the Miocene. Assuming that relatively fast plate convergence across the Alpine system of Switzerland stopped at around 7 Ma, the 60 km plate convergence over the duration of this second post-collisional episode amounted to about 0.5 cm per year. Thus, plate convergence remained practically unchanged between 35 and 7 Ma. It will be interesting to compare this figure of 5 mm/year to GPS-derived present-day shortening estimates across the Alpine system once reliable estimates are available along this transect.

3. Lithosphere structure of the Alpine arc: new evidence from high-resolution teleseismic tomography

3.1.Introduction

The very successful European Geotraverse (EGT) (Blundell et al. 1992), of which TRANSMED transect V is a part, addressed the configuration of continental and oceanic lithosphere of a continuous lithospheric swath that extends all the way from northern Scandinavia to Tunisia. It provided consistent information on the present day structure of the lithosphere across different tectonic provinces ranging in age from Archean to recent. The following text, extracted from a recently submitted paper by Kissling et al. (in press), that presents work based on the rational of follow-up project within project EUROPROBE (Gee and Zeyen 1996) that elucidates different tectonic phases and processes of Alpine orogeny in time and space. Data were collected over time as part of EGT, EUROPROBE, including the specific French-Italian and Swiss crustal seismic reflection campaigns ECORS-CROP (Roure et al. 1990) and NRP20 (Pfiffner et al. 1997) and earlier deep seismic sounding experiments. Kissling et al. (in press) demonstrate how this recent mosaic of structural information, that mostly pertains to the crust, eventually leads to a consistent 3D picture of the lithosphere-scale tectonic evolution of the Alps, when combined with the latest results of the newly developed methods of teleseismic tomography.

To a large extend the geological findings reported in chapter 2 are based on the analysis of near-surface features. At the same time, and enforced by the concept of plate tectonics, it is obvious that the evolution of the Alpine Orogen can only be understood by an accompanying assessment of the detailed structural image of Alpine crust and the lower lithosphere. Active seismic experiments (Controlled Source Seismology CSS) began in 1956 in the Western Alps and were continued since throughout the Alps with increasing resolution of crustal structure. Especially near-vertical reflection surveys along several across-strike transects provided the necessary insight into mechanisms of collision between different continental crustal units.

During earlier stages of deep sounding various seismic methods, e.g. dispersion of seismic surface waves and initial analysis of travel-time analysis, 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 Müller (1997). Only the use of travel-time tomography, based on regional and teleseismic earthquakes, was able to decisively extend the depth range and to provide the desired resolution. Presently, the combination of these techniques allows to establish a three-dimensional image of the lithosphere down to depths of 400 km and to quantitatively unravel the evolution of the Alps.

3.2 Crustal structure

Classical deep seismic sounding using refraction and wide-angle reflection surveys provides a basic overview of the Alpine crustal structure to Moho depths, such as previously discussed (see chapter 2.2 and Fig. 2). Good information is available from a rather dense network of profiles in the Western Alps but much less is known from the Eastern Alps (for a compilation see Waldhauser et al. 1998). Interpretation of these data provides excellent information on the topology of the crust-mantle boundary and the average P-wave velocities used as input for an average 3D crustal model, as described below. In addition, characteristic structural details allowing for tectonic inferences can be derived in areas with favourable location and orientation of surveys.

A large number of along-strike profiles in the Central Alps, combined with a densely occupied refraction survey along the NS oriented TRANSMED transect V (Fig. 1), allowed for the derivation of a reasonably detailed crustal image in terms of P-wave velocities (Fig. 6), extending from the northern foreland and across the Alps and Po Plain to the Ligurian Sea (Buness 1992; Giese et al. 1992; Ye et al. 1995; Kissling et al. 1997). Beneath 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 and Hitz 1997) exhibiting little internal structure, a high-velocity layer in the middle to lower crust N of the Insubric Line, and major Moho offsets under 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-seismic transects. Four complete 2D Alpine crustal reflection transects are available so far: the ECORS-CROP transect of Fig. 2a (Roure et al. 1990); the central NFP-20 transect (see Pfiffner et al. 1997a); the eastern NFP-20 transect (Fig. 2c); and the transect TRANSALP (Fig. 2d; TRANSALP Working Group 2001, 2002). Depending on data quality, which is largely determined by the difficult topographic and geological conditions across the Alps, these transects provide the best available structural resolution of 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. Fig. 2 shows unified interpretations of the available near-vertical reflection surveys, including evidence from seismic refraction surveys and geological data. Going from the ECORS-CROP transect (our transect IV) towards the NFP-20 EAST transect (our transect V) the major common and/or contrasting features are (Schmid and Kissling 2000): (1) ESE to S directed subduction of European lithosphere; (2) Offset between European and Adriatic Moho as also seen in Fig. 6; (3) Duplication and back thrusting of lower European crust in the Western Alps (Figs. 2a,b) versus wedging of Adriatic lower crust into the European middle crust under the Central Alps (Fig. 2c), 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 W versus descending Moho at the base of the lower crustal wedge under the Central Alps; (5) E-wards increasing amounts of back thrusting in the vicinity of the Insubric Line, and; (6) strong shortening within the Southern Alps in a foreland fold-and-thrust-belt above the Adriatic lower crust, exposed in the Ivrea Zone (Handy and 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 (Fig. 7); for an overall compilation see Waldhauser et al. (1998), for the Western Alps see also Hirn et al. (1989) and 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 for assessing the quality of Moho reflections, depths, and crustal velocities was developed. This allowed for establishing a reproducible 3D crustal model yielding mean crustal velocities and a Moho contour map with minimum roughness within the estimated error estimates (Waldhauser et al. 1998).

This model (Fig. 7) serves several purposes. Firstly, it provides a good and reliable overview of crustal thickness and mean velocity and its position with respect to surface tectonics and other geophysical observations. Secondly, it reliably shows the location of offsets in the Moho where subduction does occur. Finally, it can be used to correct crustal travel-times for teleseismic tomography as discussed later. Fig. 7a shows the Alpine Moho contoured at 2 km intervals derived by interpolation of the migrated CSS travel time data located in the shaded areas and a perspective NE-SW view. The number and lateral distribution of shaded areas also provides a measure for the extremely high information density that is unique worldwide. The image of the Alpine crust-mantle boundary shows two offsets with three separate interfaces: The European, Adriatic, and Ligurian Moho. The European Moho features a continuous change from an eastward dip under the Western Alps to a southward dip under the Central Alps (see also Fig. 6). The Adriatic Moho is best imaged near the EGT-NFP20 profile, where it is updomed below the Po Plain between the European and Ligurian Moho. Near the southern rim it is overthrusted 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 TRANSMED transects IV and V). This Alpine Moho topography reflects the large-scale Alpine structure resulting from a latest phase of continental collision (Schmid and Kissling 2000).

Moho offsets and gaps, and their locations, play key roles in the tectonic interpretations of 3D lithospheric structures. The results obtained by networked wide-angle and near-vertical profiling proof that the Moho interface exists everywhere under the wider Alpine region. However, there is clear evidence for Moho offsets (Figs. 6 and 7) 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, as is the case for the Western Alps (but not the Eastern Alps), the sense of subduction can be inferred.

Lower crustal wedge structures

The high-resolution transect images depicted in Figs. 2a-c clearly show that there is no common crustal model, which would be valid for the entire Alpine arc in terms of a simple collision or shortening mechanism. The lower crustal wedges found in the Western Alpine transects, are special features. The lower crustal wedge found in the NFP-20 EAST transect (Fig. 2c) consists of Adriatic lower crust with a P-wave velocity of 6.5-6.6 km/s (Fig. 6). This wedge lies above European lower crust, as can also be derived from clear reflection-seismic data (Holliger and Kissling 1992). Its shape is additionally constrained by interpretations derived from CSS seismic refraction and wide-angle reflection observations (Fig. 7) such as given by Ye et al. (1995) and Schmid and Kissling (2000). According to the reconstructions given in Fig. 5, the northward insertion of this Adriatic crustal wedge occurred during middle to late Miocene times, and contemporaneous with the development of the Southern Alpine fold-and-thrust-belt within the upper Adriatic crust. Hence, it is a rather late and sudden feature during Alpine collision. This wedging requires complete detachment near the interface between lower and upper crust, and most likely also at the base of the Adriatic lower crust, that directly overlies the European lower crust, though this lower interface of the wedge is not clearly identified.

Shortening across the ECORS-CROP and NPF-20 WEST transects, geographically located nearby (Figs. 2a & b), predominantly took place within the external European and Briançonnais realms. The overall geometry also suggests south-directed subduction of the European Plate. Note however, that in these more westerly positioned transects, lower crustal wedging occurs within the European Plate (Schmid and Kissling, 2000). The clear identification of the top of the lower crust, based on the exact position of several refraction and wide-angle reflection profiles, allowed for the compilation of a contour map of the top of the lower crust (Fig. 8). Fig. 8 illustrates the configuration of the lower crustal structures and identifies the lateral extent of lower crustal wedges of different origin, located in the hinge zone between the NS striking Western Alps and the EW striking Eastern Alps. The Adriatic lower crustal wedge under the Central Alps and the European crustal wedge under the Western Alps (Fig. 8) meet at depth were the Simplon fault zone branches off the Insubric Line (Fig. 1) This indicates a rather abrupt change in the geometry of wedging below this important fault zone.

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". However, low-viscosity material 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 the interfaces of the wedges.

A semi-quantitative post-35 Ma kinematic reconstruction of ESE-WNW shortening along the ECORS-CROP and Central Alps transects is displayed in Fig. 9. The total amount of shortening is a composite of the westward strike-slip component of the Adriatic micro-plate relative to Europe and the amount of NS shortening along the EGT-NFP20 transect (Fig. 10, see discussion in Schmid et al. 1996a). As shown in Fig. 8, the Adriatic Moho rises to shallower depth and merges into the structure of the Ivrea Zone (see also Figs. 2a,b) at the western margin of the Po Plain. The subvertical position of rigid lower crustal and upper mantle material that rises to the surface probably is 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.

Crustal structure in the Eastern Alps

Recently, a fourth crustal transect given in Fig. 2d, profile TRANSALP, whose location in the Eastern Alps is shown in Fig. 1, was established by high-resolution reflection- and refraction-seismics and other geophysical methods (Lueschen et al. 2003; Bleibinhaus 2003; Ebbing et al. 2001; TRANSALP Working Group 2001, 2002), following much earlier work by Miller et al. (1977). The first interpretations of the data were presented by Lammerer and TRANSALP Working Group (2003) and by Castellarin et al. and TRANSALP Working Group (2003). Additional information on this transect is found in Nicolich et al. (2003).

The boundary between Western and Eastern Alps roughly coincides with the N-S-striking western margin of the Austroalpine nappes (Fig.1), which formed by top-WNW-suturing of the Austroalpine nappes with the Piemont-Ligurian Ocean during a first orogenic cycle during the Cretaceous (Froitzheim et al 1994). However, the more external Briançonnais micro-continent and Valais Ocean, bordering the European margin, were not sutured to the Austroalpine units before the end of a second orogenic cycle in the late Eocene. Another important boundary, running across strike and located immediately east of the western end of the Eastern Alps, is formed by the sinistrally transpressive Giudicaria belt. Sinistral shearing along the Giudicaria belt during the early Miocene caused north-directed indentation of the eastern part of the Southern Alps and massive NS shortening in the Tauern window. This was accompanied by lateral extrusion of the Eastern Alps E of the Brenner normal fault (Ratschbacher et al. 1991), associated with dextral strike slip along the Periadriatic Line (Fig. 1).

The interpretation of the TRANSALP transect, shown in Fig. 2d, only partly follows the one proposed by the TRANSALP Working Group (2002) regarding the near-surface structures, and strongly differs in terms of the interpretation of the deep structure. According to our interpretation the core of the Tauern window, made up of tectonic units derived from the European margin, has the appearance of a positive flower structure (Dobrin and Savit 1988). While we agree with one of the two models presented by the TRANSALP Working group (2002) regarding the continuation of south-dipping Tauern-window reflectors beneath the Southern Alps S of the Periadriatic Line, inherited from an initial stage of a south-directed subduction, we do not see enough evidence from the seismic data presented by the TRANSALP working group for an Adriatic lower crustal wedge indenting the European crust, as observed in the NFP20-EAST profile (see Fig. 2c). However, these data also are not clear enough to demonstrate that the Adriatic Moho descends northward under the European lithosphere, as drawn in Fig. 2d. However, in proposing the interpretation given in Fig. 2d we are strongly guided by the acquired high-resolution tomography data in an area located further to the E and near the TRANSMED transect VI (Lippitsch 2002; Schmid et al. 2003), data that will be further discussed below.

3.3 Lithospheric structure

Early models of lower lithospheric structure derived without crustal corrections

The above discussion on the TRANSALP section (Fig. 2d) and its relation to the more westerly positioned Alpine transects makes it clear that we need detailed knowledge on 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 potential differences in the regional structure between Western and Eastern Alps down to depths that at least correspond to the length of the subducted lithospheric slabs. Over the years a considerable effort was made to gain more insight into the relevant upper mantle structure. A critical summary of pre-1993 knowledge on lower lithospheric structure was provided by Kissling (1993), who concluded that there must be thickened lower lithosphere beneath or near the Alps, indicating a southerly and south-easterly dip under the Western Alps. To a large extent, these early results were based on surface-wave analysis and travel-time residual studies (Ansorge et al. 1992; Suhadolc et al. 1990; Babuska et al. 1990; Guyoton 1991; Viel et al. 1991), as well as on seismic tomography using data sets of limited accuracy, or covering only a small area in the SW Alps (Spakman 1991; Spakman et al. 1993; Cattaneo and Eva 1990). Methods and resolution were, however, not sufficient for detailed imaging of the 3D structure and, in particular, to properly resolve slab geometries. In the meantime travel-time tomography developed into a reasonably powerful tool for the resolution of global and large-scale regional upper-mantle structures by mainly using data collected by international seismic bulletins such as produced by the ISC.

Regarding the wider Alpine region, Fig. 11 depicts two important recent examples of an improved technique for resolving upper-mantle structure, based on travel-time inversions (Bijwaard and Spakman 2000; Piromallo and Morelli 2003). Both studies use the same ISC data with different selection and resolution criteria in the inversion process, but they are derived without crustal corrections. Fig. 11a depicts a vertical cross-section across the Eastern Alps through the model of Piromallo and Morelli (2003) showing a diffuse subvertical high-velocity body under the Alps, reaching down to the 410 km discontinuity. The section across the eastern part of the Western Alps (Fig 11b), presented by Bijwaard and Spakman (2000), is also based on a large set of ISC first P-wave arrival times. In this transect the high-velocity structure beneath the Alps appears to dip in a southerly direction. At a larger scale, the models by Piromallo and Morelli (2003) and Bijwaard and Spakman (2000) both postulate the presence of a high-velocity structure beneath the Alps, although in the latter model this structure varies rather unsystematically in a horizontal direction and may even disappear further E.

Summing up, 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 seismographs and reported to ISC. The significant error in the ISC data, and the lack of corrections for the effects of the 3D crustal configuration, seriously limit the resolution of detailed regional tomography. Hence, these detected lower lithosphere structures cannot be reliably correlated with the crustal structure, independently deduced by tectonic and/or geophysical methods such as the profiles depicted in Fig. 2, nor can they be used for discriminating between different hypotheses regarding the tectonic evolution of the Alpine Orogen.

Models of lower lithospheric structure based on high-resolution teleseismic tomography

In spite of the difficulties regarding the desired resolution, teleseismic tomography is a very valuable tool for obtaining reliable structural information in depth ranges which are hard to assess in detail with other methods. In order to increase the resolution of teleseismic tomography a new and alternative approach was developed (Arlitt et al. 1999; Waldhauser et al. 1998, 2002). Firstly, this approach uses a set of carefully selected teleseismic events with digital signals transformed to the same standard recording response. Secondly, a uniform picking routine for seismic phases results in a highly consistent data set. Finally and thirdly, a careful correction, accounting for 3D crustal contributions of the observed travel times, is applied. An a priori known crustal velocity model allows for carefully correcting the observed teleseismic travel times for crustal contributions (Waldhauser et al. 2002). These may account for up to 50 % of the total travel-time residuals.

Selected teleseismic events, that are evenly distributed and recorded in the sufficiently dense Austrian, French, German, Italian, Slovenian, and Swiss permanent seismic networks in the wider

Alpine region were merged, complemented by the passive seismic network of TRANSALP (see Lippitsch 2002; Lippitsch et al. 2003). The data set of this study consists of 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 permits to reliably resolve structures of about 60 km linear length in the upper mantle in most areas of the investigated region.

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

In the following we present the images of the lower lithosphere derived from high-resolution tomography. Then their relation to the independently determined crustal transects discussed earlier (Fig. 2) will be assessed, in order to construct lithosphere scale transects such as those presented in the TRANSMED transect IV, V, and VI and to eventually achieve a unified lithosphere model for the Alpine Orogen.

Fig. 12 is a detailed horizontal section (or map) of the Alpine lithosphere-asthenosphere system representative for the 135 to 165 km depth interval. The continuous high velocity structure beneath the Alps, found by Piromallo and Morelli (2003) in the same depth range, appears to be split into two separate slabs located beneath the Western and Eastern Alps, respectively, both again following the strike of the orogen. This separation is supported by strong differences in the structure of these two slabs, also clearly visible in vertical transects, as discussed below.

The same horizontal section also reveals a pronounced negative velocity anomaly beneath the eastern Po Plain. It remains unclear whether this is a singular and local feature, or alternatively, if it represents the northern part of an extended low velocity structure in the Adriatic micro-plate, as imaged by Piromallo and Morelli (2003).

It is important to note that the structures of the two major constituents of the lithosphere, the crust and the mantle-lithosphere, were not simultaneously derived, but separately and over many years. Hence, we cannot a priori expect that the locations of the crustal transects, selected on the basis of surface tectonic or practical experimental criteria, are at the same time ideally located in terms of a comparison with lower lithosphere sections. Firstly, Fig. 12, indicates the positions of three selected lithospheric profiles A-A', B-B' and C-C', that exhibit the very clear images of the newly derived 3D lower lithosphere slab geometries depicted in Fig. 13. Secondly, Fig. 12 also indicates the positions of the lithospheric profiles presented in Fig. 14, corresponding to the transects given in Fig. 2b, c and d, i.e. all profiles that happen to contain the well imaged crustal structures discussed earlier (Fig. 2). These tomographic images illuminate the upper mantle down to depths of 400 km.

Transect B-B' (Fig. 13b), located in the Western Alps and cutting at an angle across the TRANSMED transect V (NFP-20 EAST), displays the clearest image of the present European-Adriatic collision structure and related processes. European and Adriatic Moho, as derived from CSS surveys, serve as guidelines in the otherwise unresolved crustal structure, and 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 and identifiable as asthenosphere at that depth range. The amount of more or less undeformed subducted lower lithosphere, when interpreted to represent subducted continental lithosphere, implies a shortening of about 120 km since the onset of continental collision. For the first time this provides an independent measure of post-collisional shortening, against which palinspastic reconstructions (such as presented in Fig. 5 and 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 and Davies (1995). Significant low-velocity bodies in the NW and SE are connected with the Rhine Graben Rift System (Prodehl et al. 1995) and the Po Plain, respectively.

Transect A-A' (Fig. 13a) coincides with the ECORS-CROP crustal cross-section (Fig. 2a), incorporated into the lithospheric image at the appropriate scale and used as a basis for displaying TRANSMED transect IV. Dotted lines indicate the CSS derived European and Adriatic Moho. Continental European lower lithosphere is subducted ESE-ward beneath the Adriatic micro-plate, with the high-velocity material reaching a depth of at least 400 km. The variation of the velocity pattern at about 300 km depth may indicate a change in composition and origin of the subducted material at larger depth from continental to oceanic. The subduction angle clearly varies with depth, being subvertical to 250 km. At Moho depth, the European lower crust (Fig. 2a) ends against the adjacent high-velocity Ivrea body, and hence must bend into a subvertical position (Schmid and Kissling 2000). At about 100 km depth, the deeper parts of the European continental lithosphere are detached. Sue et al. (1999) also invoked slab detachment under the Western Alps in order to explain extensional earthquake mechanisms. The detachment may be accompanied by additional upwelling of asthenospheric material into a pronounced low-velocity region located immediately to the W of the locus of detachment, at 100-150 km depth in Fig. 13a.

The third transect C-C' (Fig. 13c), is representative for the mantle structure in the Eastern Alps. It lies E of the TRANSALP traverse (Fig. 12) and intersects profile EASTERN ALPS (TRANSMED transect VI), immediately E of the Tauern window. This transect again reveals a rather obvious subduction pattern. However, very surprisingly, the subduction polarity is opposite to that found in the Western Alps. The European lithosphere here represents the overriding plate. For obvious reasons, this configuration had to be chosen for presenting the lithospheric geometry in TRANSMED transect VI as well. In section C-C' through the 3D lithospheric model, the Adriatic lower lithosphere is found to have been subducted to the NE and beneath the European Plate down 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' further to the W. There is no indication for a detachment of the subducted lower lithosphere within the observed depth range. Transect C-C' reaches the Po Plain low-velocity anomaly, seen much clearer on Fig. 12, near its SW end.

The 3-D tomographic model leaves no doubt, that the dip direction of the subducted slab flips from a SE to a NE direction between transects B-B' and C-C', this flip occurring over a relatively short distance of about 80 km and between the two separate high-velocity volumes depicted in Fig. 12. This important transition occurs roughly beneath the Giudicaria tectonic lineament (Fig. 12) and beneath the TRANSALP profile given in Fig. 14c.

Fig. 13 presents the most important and clearest features concerning the structure of the Alpine mantle-lithosphere and its lateral variations in the form of representative lithosphere cross sections. The locations of these ideally chosen mantle sections do not coincide with the available crustal transects given in Fig. 2, except for transect A-A'. Hence, the lower-lithosphere and crustal structures were imaged for the remaining transects in Fig. 14.

The profile along the NFP20 WEST transect (Fig. 14a) shows crustal and lithospheric features that are nearly identical to those found in the ECORS-CROP transect shown in Fig. 13a, and confirms the sense of subduction and also the important role of the Ivrea body (Schmid and Kissling 2000). The transect given in Fig. 14b follows NFP 20 EAST/EGT and presents the basis for constructing TRANSMED transect V, running across the eastern margin of the Western Alps. It obliquely crosses transect B-B' (Fig. 13b). A careful analysis of the crustal data (Holliger and Kissling 1992; Pfiffner et al. 1997; Schmid et al. 1996a; Valasek and Müller 1997) led to the conclusion that a wedge of relatively rigid lower Adriatic crust was inserted into the European crust (Fig. 2c). Consequently, the sheared-off European lower crust was possibly subducted, together with its mantle-lithosphere, as interpreted in TRANSMED transect V. However, teleseismic tomography cannot resolve such detailed features within the subducted volume. Yet, as seen in Fig. 14b, the upper or lower boundary of the European lower crust can easily be extrapolated into the outlines of the SE-ward subducted high-velocity lower lithosphere.

The transition between the observed opposite subduction regimes between western and Eastern Alps can be seen on NS transect IV, running along the TRANSALP profile shown in Fig. 14c. Features of lower crustal wedging and indentation in profile view, as observed further W, are now replaced by a relatively narrow collision structure, located beneath the western end of the Tauern window, where the Giudicaria Line joins the Periadriatic Lineament (Schmid et al. 2003). The extended flat-lying piles of nappes observed in the W are here dramatically steepened up and the structure upholding the Tauern window very much resembles a large-scale flower structure, as commonly seen in sediments (Dobrin and Savit 1988). The polarity of subduction is not obvious, as is the case either further E (Fig. 13c) or further W (Fig. 13b) from the 2-D section alone. A series of additional cuts through the tomographic model not shown in Figs. 13 and 14, however, make it clear that the lithospheric structure of this profile resembles that which predominates beneath the easternmost Alps (Fig. 13c). A subvertical moderately high-velocity structure, 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 EW averaging of grid elements over about 100 km. This results in the inclusion of structural features from the western as well as the eastern subduction systems. Possibly, the derived tomographic image only reflects the northern end of the deep reaching left-lateral Giudicaria shear zone, along which no clear direction of subduction can be defined.

3.5 Conclusions and application of results of high resolution tomography to the Alpine TRANSMED transects

Careful analysis of the actively acquired seismic data for the crust evidenced the presence of different types and mechanisms of crustal wedging and indentation. These include features such as (1) back-thrusting or doubling of lower European crust as a consequence of its collision with the deep reaching rigid Ivrea part of the Adriatic micro-plate in the W (Fig. 2a and TRANSMED transect IV, Fig. 2b), and (2) wedging of lower Adriatic into European crust, implying intense shearing at the interface between upper and lower crust, leaving the European lower crust closely connected to its mantle-lithosphere (TRANSMED transect V, Fig. 2c). Another transect, i.e. TRANSALP through the Eastern Alps (Fig. 2d), positioned near the transpressive Giudicaria Line, lacks wedging within the lower crust. Note that Kummerow et al. (2003) have derived an independent and alternative NS 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 that is based on earlier CSS data and the new TRANSALP data. It differs, however, significantly in the southern part. There these authors propose a sub-horizontal crust-mantle boundary at 40 km depth. In contrast to transects mentioned so far, the crustal configuration along transect EASTERN ALPS (TRANSMED transect VI, Fig. 2e) is ill defined (Fig. 2e). For constructing this transect we made use of the Moho compilations provided by Dèzes and Ziegler (2004), essentially based on Waldhauser et al. (1998). Concerning the geometry of the Moho near the interface of the European and Adriatic plates along this transect (and along the TRANSALP section) we were exclusively guided by the lithospheric configuration provided by the high-resolution tomography.

The mechanism, by which large portions of crust and mantle-lithosphere disappeared during the latest continental collision process, as well as the location of the subducted remnants, remained a topic of discussion since the early hypothesis of "Verschluckung" (Laubscher 1970). Müller (1997) provided evidence for a of deeply south-dipping lithospheric root. South-dipping subduction in the Central Alps was also postulated and suggested based on the interpretation of active seismic and geological data, as well as seismic tomography (Fig. 11b) (Spakman et al. 1993; Pfiffner and Hitz 1997; Stampfli and Marchant 1997; Bijwaard and 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 high-quality teleseismic travel-time data, provides a quantitative assessment of the length of lithospheric slabs, that significantly varies along the orogen (Figs. 13a, b and c). Based on the estimates of post-collisional crustal shortening along the EGT and ECORS-CROP transects (Schmid and 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 by von Blanckenburg and 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 separating the two opposing subduction regimes in the Western and Eastern Alps, respectively, whose 3-D orientation suggests an angle of around 90 degrees between the two slabs. Note that in 3-D the European slab dips to the SE beneath the Western Alps, while the Adriatic slab in the Eastern Alps dips to the NE. This complex Alpine subduction system is obviously spatially connected with significant, deep-reaching left-lateral strike slip motion along the Giudicaria Line. We tentatively propose that the continental Adriatic lower lithosphere subducted to the NE beneath the Eastern Alps represents a remnant of the Eocene orogeny in the Dinarides, characterised 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 Giudicaria Line during the last 20 Ma. The reason for the detachment of the European slab at shallow depth (120 km) under the western transects ECORS-CROP and NFP20 WEST is unclear. It is possibly linked to the presence of strong Adriatic lower crust and mantle-lithosphere (Ivrea body), indicating that crust and mantle-lithosphere have to be studied as layers of different mechanical strength, and that this strength strongly varies laterally. The new 3D lithospheric picture for the wider Alpine region down 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 W to E.

The lithospheric configuration shown in the three Alpine TRANSMED transects is almost entirely based on the tomographic model of Lippitsch (2002) and Lippitsch et al. (2003) discussed above. Given the fact that the geometry of the high P-wave volumes is consistent with crustal geometries, inferred by independent methods, we assumed that the high P-wave velocity volumes roughly outline the geometry of the lithospheric slabs. Hence we contoured the outlines of these high P-wave velocity bodies in the simplest possible way, keeping in mind the inaccuracies involved in assigning P-wave velocities to the mantle, allowing to reliably resolve structures of about 60 km linear length in the upper mantle in most areas of the investigated region.

The most speculative part of the interpretations offered in the TRANSMED profiles concerns the exact geometry of the interface between crustal roots and mantle-lithospheric slabs. We are aware that, due to imbrications and/or ductile flow, there probably is no simple and sharp boundary between eclogitised crustal roots and the surrounding mantle. Also, processes such as on-going delamination of the mantle-lithosphere from the crustal roots, as tentatively drawn in case of TRANSMED transect V, may complicate this geometry. Since the wedging geometry of the Adriatic and European lower crust, as discussed above, suggests that the bulk of the lower crust is made up of high strength material, at least to a depth of some 50 km, we assigned a simple isopach geometry for the lower crustal roots, being aware that this is debatable and contradicts widely accepted views concerning a "weak lower crust". However, in spite of these difficulties, we regard the integration of crustal structures, derived from a combination of geological and geophysical methods, with the structure of the mantle, independently derived from high-resolution tomography, as sound. In this sense we hope that the TRANSMED transects will serve as good starting models for understanding Alpine geology at a lithospheric scale.

4. Data and interpretation of the crustal structure depicted in the TRANSMED transects

While constructing the Alpine TRANSMED transects IV-VI we applied the technique of axial projection of tectonic units (nappes) along strike, a classical method applied in Alpine geology since the pioneering days of Argand (e.g. Argand 1916). Of course, this method assumes a cylindrical geometry, i.e. it excludes along-strike changes. This assumption does not lead to serious errors, as long as the projection distance does not exceed a few tens of kilometres. Due to the presence of an axial plunge, particularly pronounced in case of TRANSMED transect V, considerable extrapolation is not only possible down-plunge, but also up-plunge, i.e. above the present-day surface of the earth.

It is important to note, however, that erosion acts simultaneously with orogeny. Hence, some of the tectonic units that we placed high (up to 20km) above the earth's surface have in fact never been at that elevation. However, such structures undoubtedly existed at lower elevation, albeit in modified form, during earlier orogenic stages (see serial reconstructions in Fig. 5). Nevertheless, we found it desirable to depict them in order to better understand the architecture of the spectacular Alpine collisional orogen and its temporal evolution.

4.1. TRANSMED transect IV (ECORS-CROP)

Alternative interpretations of deep crustal configuration

Previous interpretations of the deep crustal structure along the ECORS-CROP profile heavily relied on results of a wide-angle seismic experiment consisting of 5 radial fans (Hirn et al., 1989; Thouvenot et al., 1990). These data, together with results from gravity modelling (Bayer et al., 1989, 1996), led Nicolas et al. (1990, 1996) to propose the presence of an intermediate Moho reflector at a depth of about 30km beneath the Gran Paradiso Massif (reflector II in Nicolas et al., 1990, their Figure 4), underlain by a mantle wedge which connects eastward with the mantle part of the Ivrea geophysical body. Nicolas et al. (1990, their Figure 7) proposed that this mantle wedge was sliced off from the European lithosphere during lithospheric scale wedging. Alternatively, Roure et al. (1990, their Figure 6) interpreted this mantle wedge below reflector II to be directly connected with the mantle of the Adriatic lithosphere, indicating wedge-shaped indentation of Adriatic lithosphere into the European lithosphere, a model similar to interpretations along the NRP-20 East profile (Pfiffner, 1992; Schmid et al., 1996a). Another alternative interpretation is given in Marchant (1993) and Marchant and Stampfli (1997). More recently, Roure et al. (1996a, their Figure 1b) proposed that the high-density material beneath reflector II, the presence of which is indicated by gravity data (Bayer et al., 1989, 1996), does not represent mantle material at all, but could be made up of duplexes derived from the European lower crust. In fact, this third option offered by Roure et al. (1996a) is in fairly close agreement with our interpretation presented below.

Interpretation of deep crustal configuration

The deep crustal configuration shown for the TRANSMED transect IV follows that proposed by Schmid and Kissling (2000). It is primarily based on migrated high-angle reflection-seismic data of the ECORS-CROP transect, provided by Sénéchal and Thouvenot (1991). The migration provided by Sénéchal and Thouvenot (1991), based on the principle of the common tangent of two spherical wave fronts, served as the basis for the geological interpretation of the deeper crust (see Schmid and Kissling for more details). Key reflectors of the migrated ECORS-CROP data were orthogonally projected into a straight profile trace (Fig. 1).

Our interpretation incorporates also the results of wide-angle reflection and refraction seismic experiments (Ansorge, 1968; Hirn et al., 1989; Thouvenot et al., 1990). Rather than projecting the wide-angle reflection data onto the ECORS-CROP transect (Thouvenot et al., 1990), we followed the procedure outlined in Kissling (1993) and Waldhauser et al. (1998) to establish a 3-D crustal model with the experimentally determined seismic reflector elements located where they were actually imaged (see Fig. 7).

Parts of the top of the European lower crust beneath the most external parts of the Alps could be placed at the top interface of a band of strong reflectors evident on the migrated reflection data (Thouvenot et al., 1990) of the ECORS-CROP profile. Reflections located close to those of "reflector II" detected by the wide angle experiment of Hirn et al. (1989), were interpreted to represent the interface between the lower and upper European crust, rather than the top of a mantle slice, as proposed by Nicolas et al. (1990). This re-interpretation, together with other arguments outlined below, resulted in the postulated duplication of the entire European lower crust, the thickness of which is defined in the foreland (Schmid and Kissling 2000). This re-interpretation is compatible with the gravity data discussed by Bayer et al. (1989)

Unfortunately, the European lower crust looses its characteristic high-reflectivity towards the more internal parts of the Alps, a feature that is common to all seismic traverses across the Alps. Consequently, the exact thickening geometry of the European lower crust is not well constrained by seismic profiling, except for the Moho depth. We are aware of the fact, that the proposed lower crustal wedging might be considerably more complex than depicted in TRANSMED transect IV.

One of the key features, particularly well visible on un-migrated line drawings of the ECORS-CROP seismic reflection profile (Damotte et al., 1990), additionally supports wedging of European lower crust: a bundle of NW-dipping reflectors is discordant with respect to several SE-dipping events evident on the ECORS-CROP transect (see discussion in Schmid and Kissling 2000). This group of NW-dipping reflectors is taken to mark a foreland-dipping shear zone, or back-thrust, above the tip of the allochthonous European lower crust.

Furthermore, the interpretation in terms of wedging of European lower crust, discussed above, also heavily relies on the results of crustal 3-D tomography, based on well-located seismic events provided by Solarino et al. (1997). The NW boundary of the pronounced high-velocity perturbation, corresponding to the Ivrea geophysical body (a thick slab of predominantly mantle material, see Kissling 1984) appears steeply E-dipping to subvertical everywhere within the 3-D model of Solarino et al. (1997), that spans the arc of the Western Alps. The high-velocity Ivrea body abruptly terminates towards the WNW, adjacent to a low-velocity perturbation found at a depth of 20-35km (see Schmid and Kissling 2000, their Plate 2), which indicates that the wedges of European lower crust are clearly separated from the Ivrea mantle material down to a depth of 45 km by low velocity material, interpreted to mark the suture between the European and Adriatic lithospheres (TRANSMED transect IV; Subpenninic nappes, Valais and Piemont-Liguria sutures as depicted in Fig. 2a).

A group of strong subhorizontal reflections, evident on the migrated ECORS-CROP profile (Sénéchal and Thouvenot 1991), connects with two SE-ward dipping bands of high reflectivity, whose up-dip projection to the surface correlates with the Valais suture zone and the Penninic frontal thrust at its base (Antoine 1971; Mugnier et al., 1996; Marchant, 1993; Fügenschuh et al. 1999; Loprieno 2001; Ceriani et al. 2001). Hence, the geometry of the base of the Valais suture ("Valaisan" in Fig. 2a) is rather well constrained. All material below this Valais suture is inferred to be of more external origin with respect to the Valais suture and, therefore, assigned to the European lithosphere (Fig. 2a), which lends further support the postulate of wedging of the European lower crust below the Valais suture as shown in TRANSMED transect IV. Note, that closing of the Valais Ocean predates Oligocene to Early Miocene top-WNW thrusting at the Penninic frontal thrust, and is related to earlier (Eocene) top-N nappe stacking (Loprieno 2001; Ceriani et al. 2001).

In the more internal parts of the Alps crossed by TRANSMED transect IV the top of the Ivrea mantle rocks corresponds to reflector III of the wide angle experiment (Nicolas et al., 1990), and is also evident on the migrated ECORS-CROP reflection seismic line (Sénéchal and Thouvenot 1991) by a SE-dipping band of strong reflectors. In combination with the position of the Adriatic Moho given by Waldhauser et al. (1998), the up-bent geometry of the Adriatic lower crust, resting directly on the Ivrea mantle material, is well constrained. The up tilted NW edge of the Adriatic Moho can be directly correlated with the top of the Ivrea mantle slab. The Adriatic crust appears to be dissected by a group of back-thrusts that are buried beneath the sediments of the Po Plain, shown in the transect according to the interpretation of Roure et al. (1990).

Our interpretation of the deep crustal structure of the TRANSMED transect IV suggests that the allochthonous European lower crust slice acted as a flow-resistant wedge. The geometry of this wedging is analogous to a scheme proposed by Roure et al. (1990, their Figure 7) for the same ECORS-CROP section. Wedging of the lower crust, also found along the other Alpine transects (see discussion in chapter 3), implies a flow-resistant feldspar-dominated rheology for the lower crust and the activation of detachment surfaces at its top and near its base (Moho), respectively. Such a postulate is not unrealistic in the light of the concept of rheological stratification applied to a 2-layer (quartz and feldspar-dominated) crust (see Ranalli and Murphy, 1987; Handy 1989). We make use of the term "lower crustal wedge" rather than "wedge-shaped geometry of lower crust", being aware that, given our geometric-kinematic approach, rheological inferences remain speculative.

Interpretation of near-surface structures

The configuration of the Bresse graben is based on seismic profiling and drill hole data compiled by Bergerat et al. (1990). The structure of the NW foreland is drawn according to Philippe et al. (1996) concerning the Jura Mountains, and according to Guellec et al. (1990) and Mugnier et al. (1996) concerning the Chaînes Subalpines. The suspected frontal thrust of the Belledonne Massif shown in this transect (see also Fig. 2a) can only take up part of the total shortening of 55 to 60 km indicated by profile balancing (some 30 km in the Jura cover sequence plus around some 28 km in the Chaînes Subalpines) according to (Guellec et al., 1990). Hence, much of the shortening within this Mesozoic cover has to be taken up in the internal Belledonne and the M. Blanc Massifs, including the Penninic frontal thrust (see discussion in Mugnier et al., 1996). Shortening within the NW foreland occurred during an early Miocene phase (post-25 Ma, probably during the Aquitanian) in case of the frontal thrust of the Chaînes Subalpines, but during a later phase (Late Miocene to Pliocene) in case of the Jura Mountains (stratigraphic constraints discussed in (Guellec et al. 1990; Mugnier et al. 1990, 1996; Dèzes et al in press).

The Valaisan domain, a separate and more external oceanic suture zone with respect to the Piemont-Liguria Ocean (Frisch, 1979; Stampfli, 1993; Froitzheim et al., 1996), is thrust onto the allochthonous cover of the M. Blanc Massif (Ultradauphinois) along the most spectacular feature evident on reflection seismics: the Penninic frontal thrust. Details within the Valaisan domain (Plate 1) are drawn according to a recent structural analysis by Loprieno (2001); for a short summary see Fügenschuh et al (1999). Up-dip projection of two bands of high reflectivity, referred to earlier, indicates that these two bands correspond to the Ultradauphinois cover below the Versoyen unit (prasinites, interbedded with shales) and above the Pennine frontal thrust. Hence this late thrust, including the Versoyen unit, can be followed down to a depth of almost 15 km before it flattens out, according to our interpretation of the deep structure. The age of the Penninic frontal thrust is by now rather well constrained by fission track data (Fügenschuh and Schmid 2003) to be of Oligocene to Early Miocene age. This "Penninic frontal thrust" (brief "Penninic front", see Fig. 2a) denotes a late stage WNW-directed thrust, which post-dates earlier (i.e. Latest Eocene) top N stacking within the Valais domain (Fügenschuh et al., 1999; Loprieno 2001; Ceriani et al. 2001), associated with the decollement and thrusting of presently more externally located Penninic cover nappes, such as for example the Préalpes Romandes (Mosar et al., 1996; Bagnoud et al., 1998).

The large-scale structure within the more internal Penninic units attributed to the Briançonnais micro-continent (Gran Paradiso Internal Massif, Zona Interna or Vanoise-M. Pourri unit, Ruitor unit and Zone Houllière; Bucher at al. 2003), as drawn in the older version of the ECORS-CROP profile published by Schmid and Kissling (2000) based on literature data (e.g. Ballèvre and Merle 1993; Baudin 1987; Caby 1996; Elter 1972; Fabre 1961; Gouffon 1993; Vearncombe 1985), was modified according to new structural and metamorphic investigations by Bucher et al. (2003). This work (and Bucher et al., in press) revealed the occurrence of large-scale post-nappe folding of the more external Briançonnais-derived basement nappes in front of the Gran Paradiso Massif (Fig. 2a): namely the Ruitor basement unit and the Zona Interna or Vanoise-M. Pourri basement unit (Caby, 1996). This large scale post-nappe folding has to predate zircon fission track cooling ages of about 30 Ma obtained from the Gran Paradiso Massif (Hurford et al., 1991), indicating that before 30 Ma temperatures fell below those required for crystal plastic deformation under greenschist facies conditions. Note, that such large-scale nappe re-folding also characterises those parts of the TRANSMED transect V that are found in front of the Briançonnais-derived Tambo and Suretta nappes (Fig. 2c) and which formed contemporaneously ("Niemet-Beverin" phase of Fig. 4).

The region to the SE of the Gran Paradiso unit has been drawn according to the interpretation given by Roure et al. (1990). According to these authors, SE-directed thrusting, detected in the subsurface of the Po Plain, is of early Neogene age (around 25-22 Ma). Post-Oligocene upturning of the Ivrea Zone, related to this back-thrusting, is compatible with paleomagnetic evidence from Oligocene dykes intruding the western margin of the Ivrea Zone (Schmid et al., 1989). Thrusting within the eastern Po Plain east of the Ivrea Zone affected Oligocene to Aquitanian deposits (Gonfolite group), but is sealed by a Burdigalian unconformity.

Regarding the further continuation of the transect into the Po Plain, we followed profile Nr. 13 of Pieri and Groppi (1981), and integrated drill hole data, as well as seismic interpretations given therein. Regarding the deeper parts of the profile, interpretations given by Cassano et al. (1986, their Fig. 30) were adopted. The profile ends at drill hole Battuda, that is also traversed by TRANSMED transect V. Comparison with the latter transect shows that the middle Miocene and younger formations, which appear undeformed in the transect described here, are in fact involved in foreland-propagating deformation in transect V. However, post-Burdigalian and pre-Messinian southward propagation of the South Alpine thrust front does not reach TRANSMED transect IV situated south of this deformation front. Moreover, this South Alpine thrust front is known to die out westwards and hence does not cross TRANSMED transect IV (see Schumacher and Laubscher 1996 for further discussions). Miocene to recent northward-propagation of deformation in the westernmost northern Apennines, building up the Monferrato hills near Torino, stayed south of TRANSMED transect IV and is hence not visible in it.

Summary of timing constraints and 3-D kinematics

Constraints available suggest that all the major structures characterising the large-scale geometry of the Alpine part of TRANSMED transect IV formed during Oligocene and Neogene times (i.e. after 35 Ma), as schematically sketched and summarized in Fig. 9. Hence, most of the deformation visible in the NW-SE to WNW-ESE oriented ECORS-CROP section post-dates Early Tertiary collision and nappe stacking which was top-N, as is shown in Fig. 10, and which led to at least 350 km N-S-directed convergence in the eastern Central Alps between 65 and 35 Ma (Schmid at al. 1996a; see also Fig. 5). Tectonic activity, related to Tertiary collision, certainly also affected the Western Alps, but since this earlier nappe stacking is demonstrably associated with top-N displacements (Fügenschuh et al. 1999; Ceriani et al. 2001; Loprieno 2001) it cannot be properly imaged in the ECORS-CROP section.

The present-day arc of the Western Alps appears to be pre-structured by head-on Tertiary collision in the Central and Eastern Alps (see Fig. 5) and oblique collision associated with pre-35Ma sinistral transpression in the Western Alps, as is shown in Fig. 10 (see discussion in Schmid and Kissling 2000). After 35 Ma the arcuate shape was accentuated by a change towards WNW-directed movement and anticlockwise rotation of the Adriatic micro-plate (Fig. 10). Strain partitioning along the E-W striking parts of the Periadriatic and Rhone-Simplon shear zones (Fig. 1) permitted this WNW-directed movement to transmit significant amounts of WNW-directed transport into the Penninic units and the European foreland of the Western Alps (Ceriani et al. 2001), while shortening continued in a N-S-direction in the Central Alps (Schmid et al. 1996a). This also led to orogen-parallel extension and exhumation of the Lepontine dome. Post-35 Ma shortening along TRANSMED transect IV is estimated to amount to a mere 124km, as is shown by the vector triangle given in Fig. 9 (see detailed discussion in Schmid and Kissling 2000).

Peak pressure conditions in the most internal parts of the section derived from the internal parts of the Briançonnais micro-continent (Zona Interna, Gran Paradiso unit) and the Piemont-Liguria Ocean were reached at 50-43 Ma ago in the tectonic units derived from the Briançonnais domain (Dal Piaz et al. 2001, Bucher et al. in press). Note, however, that in the still more internal Sesia unit peak pressures were reached even earlier, i.e. near the Cretaceous-Tertiary boundary (Gebauer 1999; Dal Piaz et al. 2001). Exhumation and nappe stacking of the Penninic units took place during D2 (43-35 Ma) and led to exhumation of the Penninic high-pressure units of the Western Alps by extrusion within and parallel to a subduction channel (Bucher et al. 2003). Finally, large-scale nappe refolding (D3; 35-31 Ma), associated with subhorizontally oriented axial planes, indicating vertical shortening of a part of the former nappe pile in front of a very thick Gran Paradiso unit and below the Dent Blanche Austroalpine klippe, led to the final geometry, as shown for the internal Alpine parts of the transect.

It is important to note that all deformation that pre-dates top-WNW thrusting along the Roselend thrust, initiating at about 32 Ma ago, was related to sinistral transpression in the area of the future arc of the Western Alps (Schmid and Kissling 2000; Ceriani et al. 2001), as was first postulated by Ricou and Siddans (1986). These deformations predate top-W thrusting along the Roselend thrust, initiating at about 32 Ma ago (Fügenschuh and Schmid 2003). During this post-32 Ma deformation in the external Western Alps (Fig. 9), following the closure of the Valais Ocean, the internal units of the study area were only passively transported to the west, leading to their final exhumation by erosion at around 30 Ma (Hurford and Hunziker 1989; Fügenschuh and Schmid 2003).

From the Early Miocene onwards, fore- and back-thrusts were simultaneously active (Fig. 9). Deformation now started to propagate away from the Penninic front and into the European foreland. According to Fügenschuh and Schmid (2003) this thrust propagation led to thrusting of the M. Blanc External Massif and the onset of its exhumation, together with the internal Dauphinois cover and the northern frontal Penninic units (Valaisan) between 20-15 Ma, causing their erosion upon tilting in the back-limb of the culminations of the external massifs (Belledonne and M. Blanc Massifs, Fig. 2a). Thrusting also propagated into the Po Plain, albeit in moderate form, during Early Miocene times. Note however, that this thrusting is sealed by a Burdigalian unconformity (Roure et al. 1990). Hence, in contrast to what is observed further east in TRANSMED transects V and VI, deformation stopped in Mid-Miocene times in the part of the western tip of the Adriatic micro-plate that is traversed by TRANSMED transect IV.

Later stages of foreland thrusting were confined to the European foreland, where a latest stage of thrust propagation, beginning at about 12 Ma, is related to further imbrications by thrusting in the external Belledonne Massif and shortening within the Jura Mountains (Fig. 9). Hence, the thrust front jumped by some 80 km into the foreland and finally reached the margin of the Bresse graben (Burkhard and Sommaruga 1998).

4.2. TRANSMED transect V (NFP-20 EAST)

Interpretation of deep crustal configuration

This transect was part of the European Geotraverse (EGT), a geophysical traverse running from Scandinavia to North Africa (Blundell et al. 1992). At the same time it was part of a project of the Swiss Science Foundation (NFP-20), the results of which (together with results regarding the traverse NFP-20 WEST, given in Fig. 2b) were published in Pfiffner et al. (1997).

Along this transect, the lower crust is generally characterized by a significant increase in P-wave velocities with respect to the upper crust (Fig. 4) and by the onset of high reflectivity (Pfiffner and Hitz 1997). In the Alpine part of the transect, the upper and lower boundaries of the lower crust are similar to, but not identical in their position with the C1/C2 (top of the lower crust) and M1/M2 (Moho) layers as defined by Valasek (1992). The positions of these lower crustal interfaces are basically drawn after the results of refraction work (Ye 1992; Buness 1992), combined with an integrated interpretation of both refraction and reflection seismics (Holliger and Kissling 1992), as shown in detail by Schmid et al. 1996a (their plate 1).

The seismic velocities from Ye (1992) and Buness (1992), as shown in Fig. 6, also support other details of the interpretation given in TRANSMED transect V. Note that the velocities of around 6.5 to 6.6 km sec^{-1}, typical for the lower crust (with a notable exception for the lower crust of the N foreland), contrast with values between 6.0 and 6.2 km sec^{-1}, typical for the lower parts of the upper crust. Upper crustal low velocity layers are found in the basement of the external Molasse Basin at a depth of about 10km (5.8 km sec^{-1}). Upper crustal velocity inversions are also found within the lower Penninic nappes and beneath the Southern Alps (see Fig. 6 and Ye 1992 for details).

Furthermore, the position of the lower and upper boundaries of the lower crust is constrained by migrated wide-angle reflection data (modified from Hollinger and Kissling 1992; Ye 1992). It is important to stress the fact that the position of these interfaces and reflections within the lower crust is closely controlled by seven refraction profiles oriented parallel to the strike of the Alps (Holliger and Kissling 1991, 1992). These profiles intersect the TRANSMED transect V and the EGT refraction profile (Ye 1992). Hence, there is considerable 3-D control on the position of the reflectors within the lower crust. The procedure for their depth migration within the EGT profile is outlined in Holliger (1991) and Holliger and Kissling (1991, 1992).

During the integration of reflection- and refraction-seismic results, major reflections of the composite NFP-20 reflection lines E1, S1, S3 and S5 (for their locations, except that of S1 given in Fig. 8, see Pfiffner et al. 1997) were in a first step converted into digitized line drawings according to a procedure outlined by Hollinger (1991). In a second step, these digitized line drawings were projected into the EGT line coinciding with the E1 line of NFP-20. In a third step, the data were migrated in the N-S section (Holliger and Kissling, 1991). This projection was necessary to arrive at a more complete picture of this transect, because E1, coinciding with the EGT transect, terminates well N of the Insubric Line, that is well imaged in line S1, whose position is given in Fig. 8. For this projection Schmid et al. (1996a) followed Holliger (1991) and Holliger and Kissling (1991, 1992) arguing, that the integrated effects of structures at mid- and lower crustal levels are best reflected by the Bouguer gravity map (corrected for the effects of the Ivrea body, Kissling 1980, 1982). This ultimately (i.e. after migration) led to the deep crustal configuration as shown in TRANSMED transect V.

The following additional arguments support the procedure chosen: (1) Refraction work carried out along the EGT line (Fig. 6) provides independent evidence for the presence of a large lower crustal wedge beneath the Alps, that is compatible with the refraction-based model of Ye (1992), and additionally, the projected and migrated line drawings of the major reflectors. (2) The axial dip of the Alpine nappes to the E is discordant with respect to the European lower crust and Moho, independently indicating strong decoupling between the lower and upper crust. (3) There is excellent consistency between refraction and reflection data regarding the Insubric Line, which can be traced to great depth.

Within the Adriatic lower crustal wedge occur reflectors that cross each other in many places (see plate 1 in Schmid et al. 1996a). This points to some problems concerning either lateral continuity of this wedge or, alternatively, the projection and/or migration procedure. However, as pointed out by Holliger and Kissling (1992), this lower crustal wedge may in fact have a complicated, sheared internal structure and may represent a mélange body consisting of predominantly Adriatic lower crust and some material of oceanic crustal origin, having a density slightly higher than that of "normal" lower crust. It is clear, however, that this zone of high reflectivity is largely contained within the lower crustal wedge outlined by the refraction-based EGT crustal model (Fig. 6).

Steeply inclined reflectors, obtained along S1, are related to the Insubric Line (Bernoulli et al. 1990; Holliger 1991; Holliger and Kissling 1991; 1992), but project in the NFP-20 EAST section into a position 5-10km north of the Insubric Line. However, due to possible errors in projection and migration techniques, the exact location of these reflectors in relation to the Insubric mylonite belt remains speculative. In view of the parallelism between the Insubric mylonite belt and northward adjacent “Southern Steep Zone” (Schmid et al. 1989), these reflectors certainly document flattening of the Insubric mylonite belt at depth to an inclination of about 45°, from the 70° measured at the surface (Schmid et al. 1987, 1989), as shown in the TRANSMED transect V.

In the TRANSMED transect V, the upper boundary of the European and Adriatic lower crust, respectively, is not very well constrained in those parts of the northern and southern forelands of the Alps, where only refraction data are available. However, the position of the Moho is rather well constrained, as discussed in chapter 3 (see Fig. 7). Note, that up-warping of the Moho, and consequently also of the upper boundary of the lower crust, between Southern Alps and Apennines is rather well constrained. Furthermore, the position of this Moho arch coincides with an upper mantle low-velocity anomaly, as seen in Fig. 12.

A very remarkable and rather well constrained offset of the Moho occurs at the front of the easternmost Northern Apennines (see Figs. 6 and 7), as shown near the south-western end of the TRANSMED transect V, where the Ligurian Moho overrides the Adriatic Moho, presumably along a steep thrust and/or transpressive strike slip zone. As suggested by the data shown in Figs. 6 and 7, and confirmed by recent findings of Finetti et al. (2001) along a more southerly located transect through the northern Apennine, Moho-offsets and crustal-scale imbrications seem to be a common feature of this orogen.

Interpretation of near-surface structures

In the northernmost part if the transect, the data concerning the position of the basement top, the thickness of the Mesozoic cover and the stratigraphy of the unfolded part of the Bavarian Molasse Basin were taken from Lemcke (1988), mostly (except for drill hole Fronhofen) by laterally projecting borehole and seismic data. Thrusts and folds shown for the deformed Subalpine Molasse, characterised by a spectacular triangle structure, are based on surface data, and additionally, on the projection of a reflection-seismic profile recorded for hydrocarbon exploration, positioned immediately to the west of the NFP-20/EGT traverse (Stäuble and Pfiffner 1991a).

Along the NFP-20 EAST transect the basement of the autochthonous cover of the external Aar Massif, positioned below the pile of Helvetic nappes, is exposed in a small window. The geometry chosen for the structure of the top of basement of the Aar Massif, as shown in this transect, is based on "model 1" of Stäuble and Pfiffner (1991b), who evaluated the reflection-seismic response of alternative geometries by 2D normal incidence and offset ray tracing.

The Helvetic nappes, the sole of which is formed by the Glarus overthrust (Schmid 1975), are shown according to extrapolation of surface information obtained along the profile trace and the results of 3-D seismic modelling (Stäuble et al. 1993). Within the Helvetic nappes, the Säntis thrust separates the Jurassic strata of the Lower Glarus nappe complex from the Cretaceous strata of the Upper Glarus nappe complex (Pfiffner 1981). This Säntis thrust merely acts as a structural discontinuity resulting from the different style of shortening within Jurassic and Cretaceous strata. Note that the Helvetic cover nappes wedge out towards the south (beneath the locality "Sargans" indicated in the transect) and beneath the lower Penninic nappes that were derived from the Valais Ocean (see also Fig. 2c).

The higher Penninic and Austroalpine units, overlying the Helvetic nappes, are only exposed east of the transect and were projected onto it parallel to a direction N 70 E. In a first step, the profiles published by Allemann and Schwizer (1979) and Nänny (1948) were used. In a second step, and particularly concerning the area around the "Prättigau half-window" (indicated in TRANSMED transect V), these older data were modified according to more recent data by Weh and Froitzheim (2001). These authors projected their structural data from the Prättigau half-window into our transect with variable plunges. This projection shows that up-doming of the base of the Austroalpine nappes above the Aar Massif corresponds to the Prättigau half window in map view (Fig. 1), in accordance with the axial plunge of the Aar Massif to the east, as deduced from seismic profiling along strike (Hitz and Pfiffner 1994).

Very strong, south-dipping reflectors south of the Aar Massif, recorded along profile E1 (between Canova and Thusis, extending from 2.5 down to 4 seconds TWT (reflector "D" in plate 4 of Pfiffner et al., 1990b), have been attributed to the allochthonous cover of the southern Gotthard "Massif" (Etter 1987), representing a Subpenninic basement slice (Schmid et al. in press). Along the "Penninic Basal Thrust", units derived from the Valais Ocean were transported over the several Subpenninic slices or nappes, including the eclogite-bearing Adula nappe (Fig. 2c). The position and configuration of this major thrust was adopted from the final 3-D seismic model developed for the Penninic units by Litak et al. (1993).

Based on the same model constrained by 3-D seismic modelling (fig. 3a in Litak et al. 1993), the basal thrust zone of the Gotthard "Massif" (Urseren-Garvera zone) is steeply inclined to the south, and not strongly back-folded, as is observed further west along strike in the Lukmanier area (Etter 1987; Probst 1980), where a very late deformation phase led to the formation of a back-fold, the "Chiera synform" (see Fig. 4), situated south of the Gotthard "massif". Such back-folds are a feature typical for the southern part of the external massifs in western Switzerland (Escher et al. 1988; see Fig. 2b).

The geometry of the lower, middle and upper Penninic nappes in the northern and central parts of this transect was obtained by axial projection. In a first step, all major tectonic boundaries (fig. 3) were projected up and down plunge, strictly parallel to the N 70 E direction. This direction approximates the azimuth of most of the large-scale fold structures relevant to this part of the transect. Development of a series of cross-sections parallel to N 70 E, constructed on the basis of structure contour maps, allowed for projection with a variable plunge (10-35°). The different units were then projected into the transect along these strike-parallel sections by assuming that their thickness does not change along strike. Geological details shown in the projected units are drawn according to the geometries found where they are exposed (e.g. Schmid et al. 1990, 1997). In a second step, the profile was adjusted to conform to the 3-D seismic model of Litak et al. (1993). Hence, the overall geometry of the Subpenninic Adula and Simano nappes, derived from the distal European margin (see Fig. 2c), corresponds to that of Fig. 3a in Litak et al. (1993).

Lower, Middle and Upper Penninic nappes were refolded at a large scale (Schmid et al. 1990; Schreurs 1993, 1995), leading to inversions of the original nappe stack over significant portions of the transect, as is schematically depicted in Fig. 2c (and in more detail in TRANSMED transect V). Note that the units attributed to the Valais suture, originally situated below the units attributed to the Briançonnais terrane (Tambo and Suretta nappe), are folded back and over the Suretta nappe, including the Avers Bündnerschiefer that were derived from the Piemont-Liguria Ocean. Above a late stage normal fault (Turba normal fault, see Nievergelt et al., 1996) the nappe pile is upright, consisting of the Platta and Arosa ophiolitic units, derived from the Piemont-Liguria Ocean, at the base and the Austroalpine nappe stack on top.

The structure of the Southern Penninic zone, immediately north of the Insubric Line, is based on work, which addressed ascent and emplacement of the Bergell pluton (Rosenberg et al. 1995; Davidson et al. 1996; Berger et al. 1996), summarized in Schmid et al. (1996b). This is a spectacular pluton in the sense that its floor is exposed, and that its emplacement is syntectonic. In its northern part, the Bergell pluton tectonically overlies upper amphibolite to granulite grade migmatitic rocks of the Gruf complex that forms part of the Adula nappe.

The quartzo-feldspatic gneisses of the Gruf complex are overlain by a variety of other lithologies consisting of ultramafics, amphibolites, calc-silicates and alumo-silicates, concentrated in an almost continuous band that concordantly follows the tonalitic base of the Bergell pluton, exposed along its western margin (see map by Berger 1996). These lithologies at the base of the pluton are seen to be connected with the Chiavenna ophiolites and represent the southern continuation of the Valais Ocean suture zone (see Fig. 2c). The Piemont-Liguria Ocean are preserved in the roof of the Bergell intrusion. Consequently, this spectacular intrusion occupies a structural position that is comparable to that of the Briançonnais-derived Tambo and Suretta nappes. In fact, this intrusion was and was emplaced as a nappe-like structure, as originally proposed by Wenk (1973). Both ophiolitic sutures, the intervening pluton, and the orogenic lid formed by the Austroalpine nappes root in an overturned position within the "Southern Steep Belt". This is a belt of extremely deformed rocks that parallels mylonites associated with the sector of the Periadriatic line crossing this transect (the Insubric Line). The Insubric Line took up dextrally transpressive displacements during the Late Oligocene to Early Miocene. These displacements involve a vertical component of approximately 20km (Schmid et al. 1989), while the horizontal (strike-slip) component is estimated to be around 100km (Schmid and Kissling 2000).

The construction procedure in the Bergell area allowed for considerable vertical extrapolation, thanks to the pronounced axial plunge of the Bergell pluton as indicated from structural (Rosenberg et al. 1995) and petrological (Davidson et al. 1996) data. In a first step, the Tambo and Suretta nappes (Fig. 2c) were projected S-wards and upwards according to structure contour maps (Pfiffner et al. 1990a) and own data. However, to the south these nappes were vertically displaced across the Engadine Line by some 4km during a late stage (Schmid and Froitzheim, 1993), and this was taken into consideration when constructing that part of the transect. The base of the Bergell intrusion was drawn according to the projection of auxiliary profiles, based on structure contour maps (Davidson et al. 1996) and their projection along NE-SW striking folds deforming the base of the pluton. The roof of the intrusion was placed at the projected structural level presently exposed at the eastern margin of the pluton. This is a minimum elevation for this roof, since the eastern contact represents the side rather than the roof of the pluton (Berger and Gieré 1995; Rosenberg et al. 1996). The geometry of the Austroalpine nappes on top of the Bergell intrusion (see also Fig. 2c) is drawn after Liniger (1992) and Spillmann (1993).

The southernmost Alpine part of this transect, crossing the Southern Alps, was taken without modification from Schönborn (1992, cross section B of the enclosure) except for the northernmost part, where compatibility with the shape of the Insubric fault necessitated very minor adjustments. The profile is balanced, and retro-deformability was established at all stages by forward modelling. The deeper parts of the profile are kept as simple as possible and drawn according to the geometrical rules of the ramp and flat geometry indicated for basement and cover by surface data. The total amount of shortening (80km) within the sediments necessarily leads to the postulate that parts of the upper crustal and all of the lower crustal excess volume have to be looked for beneath the Insubric Line (Schönborn 1992; Pfiffner 1992). Note that the Adriatic lower crust may have been substantially thinned during Jurassic rifting and passive continental margin formation, since the Southern Alps were in a lower plate margin setting (Lemoine et al. 1987; Froitzheim and Eberli 1990; Manatschal and Bernoulli 1999). Hence, the wedge of Adriatic lower crust, underlying the Insubric line and Subpenninic units, very probably was tectonically thickened while shortening took place south of, and in front of the Insubric line within the Adriatic upper crust (i.e. Southern Alps). The section taken from Schönborn (1992) runs N-S. However, further south TRANSMED transect V starts to depart into a NE-SW direction near Milano (see trace indicated in Fig. 1) in order to incorporate borehole and seismic data published by Pieri and Groppi (1981).

The information regarding the Tertiary fill of the Po Plain and the front of the Northern Apennines is again that given by Pieri and Groppi (1981, their section 4), complemented by information on the top-basement and its Mesozoic cover from Cassano et al. (1986, their Fig. 21). The exact geometry of the frontal part of the easternmost part of the Northern Apennines, crossed by TRANSMED transect V, is not well constrained by the borehole and seismic data given in Pieri and Groppi (1981) below the Neogene sediments, that form piggy-back basins. Note that the Paleogene of the Monferrato Hills is in part made up of allochthonous flysch units (with Late Cretaceous sediments at their base), derived from the Ligurides (parts of the Piemont-Liguria Ocean) that were "back-thrust" (in respect to the polarity of the Alpine movements), i.e. thrust north- and north-eastward onto the Po Plain during Mid-Miocene and later times (Finetti et al. 2001; see also maps compiled by Bigi et al., 1990a,b, 1992). Furthermore, it is important to realise that such back-thrusting occurred in conjunction with the onset of west-directed Apennines-Maghrebides subduction that characterises the Alps-Betics retro-belt, as discussed by Carminati et al. (this volume). We interpreted a second thrust sheet (after Cassano et al. 1986), shown below borehole Quargnento, and mapped as Mesozoic in the stratigraphic version of TRANSMED transect V, to represent the Toscanides, i.e. allochthonous sediments detached from of the Apulian Plate during the Neogene orogeny of the northern Apennines (i.e. Finetti et al. 2001).

Details concerning the geometry of the deeper parts of the frontal thrust of the Apennines are not constrained at all. The geometry chosen for the interpretation given at the southern (in fact south western) end of TRANSMED transect V is guided by the following considerations. Firstly, the existence of an offset in the Moho, with the "Ligurian" Moho at much shallower depth, is not only well documented by the compilation data of Waldhauser et al. (1998; see Fig. 7 and seismic transect of Fig. 6), but is confirmed further south and along strike in the frontal parts of the Apennines, where Finetti et al. (2001) documented a vertical offset of the Moho by about 16km, associated with only some 36km shortening. Secondly, it is reasonable to associate the geophysically documented jump in Moho depth with thrusting at the front of the Apennines, and this automatically leads to an exceedingly steep up-thrust that traverses the entire crust. Thirdly, such steep thrusting is very likely to have reactivated an older (Oligocene to Early Miocene) sinistrally active strike slip zone that allowed for late stage indentation of the Adriatic micro-plate (Laubscher 1971, 1991; Schumacher and Laubscher 1996), in conjunction with the formation of the arc of the Western Alps, associated with late-stage top WNW thrusting in the Italian-French Western Alps (Fig. 10; Schmid and Kissling 2000; Ceriani et al 2001).

Summary of timing constraints and 3-D kinematics

Timing constraints for this transect are summarized in Figs. 4 and 5 and have already been discussed in chapter 2.3. Since geometry and evolution of the structures are rather well constrained along this transect, it is possible to provide estimates for the amount and velocity of N-S plate convergence during the Tertiary, as recorded by crustal shortening in this easternmost part of the Western Alps. These estimates are given in Table 1.

Tertiary shortening across this transect is approximately N-S during Tertiary orogeny, and is well documented by numerous structural studies along this transect. There are no abrupt changes in kinematics of movement, such as discussed when describing TRANSMED transect IV (see Figs. 9 and 10). Note, however, that substantial out-of-section movements did occur along the dextrally transpressive Periadriatic (Insubric) Line, kinematically decoupling the movements within Southern Alps and Adriatic micro-plate from those of the northern part of the Alps from the Oligocene onwards.

The kinematics of movement during the Cretaceous orogeny, however, were top-WNW as recorded in the Austroalpine units and those parts of the Piemont-Liguria derived ophiolites that were already sutured to the upper plate in Cretaceous times (Platta and Arosa tectonic units, see Fig. 2c) (e.g. Schmid and Haas 1989). Hence, this deformation cannot be adequately treated in a N-S section. E-W sections that illustrate Cretaceous-age nappe stacking, followed by Late Cretaceous collapse, are shown in Schmid et al. (1996), and this Creatceous orogeny will be briefly discussed below and in the context of describing TRANSMED transect VI. The latter transect exposes a much more complete section across the Austroalpine units, since it is positioned much further to the east, i.e. in the hinterland with respect to Cretaceous-age top WNW nappe stacking.

4.3. TRANSMED transect VI (EASTERN ALPS)

Interpretation of deep crustal configuration

The deep crustal configuration of this transect is not nearly as well constrained as in the other two transects. This also applies to the depth of the Moho. The transect is located east of the area compiled by Waldhauser et al. (1998) shown in Fig. 7, except for its NE-SW-running southernmost parts through Po Plain and the frontal Apennines. For constructing the transect we adopted the Moho compilation by Waldhauser et al. (2002), which was prepared for the crustal corrections of the high-resolution mantle tomography by Lippitsch et al. (2003), and that is practically identical with the compilation by Ziegler and Dèzes (2004) in the area of interest. Note that Moho depth is particularly ill constrained beneath the central parts of the Alps. Hence, the Moho offset depicted in this transect (see also Fig. 2e) is entirely based on evidence provided by the high resolution mantle tomography presented and discussed in chapter 3.

Regarding the geometry and thickness of the lower crust in the Alps, we extrapolated our interpretation of the reflection-seismic data available along the TRANSALP profile (Lüschen et al. 2003; Lüschen per. comm.) located further to the west (Fig. 1). As discussed in chapter 3, this interpretation of the deep structure (Schmid et al. 2003) considerably differs from that provided by TRANSALP Working Group (2001, 2002). This concerns particularly the Moho depth inferred for the Southern Alps by Kummerow et al. (2003), which is based on an analysis of receiver functions.

Interpretation of near-surface structures

This newly constructed transect was so far only published in a simplified form (Schmid et al. in press). It is based on the sheets 1: 50'000 of the Geologische Bundesanstalt Wien and on the maps of Exner (1990, and unpublished material). For constructing the profile, the existing transects by Prey (1980), Hoffmann et al. (2002), Mandl (2001) and Schmidt et al. (in prep.) were consulted.

Regarding the northern foreland, the transect is based on a profile provided by Kollmann (1977), based on reflection-seismic data and numerous drill holes, some of them reaching down to top basement of the Bohemian Massif (Zimmer and Wessely 1996). The near-surface structures of the Northern Calcareous Alps were taken from Mandl (2001).

In the Central Alpine area, south of the SEMP (Salzach-Ennstal-Mariazell-Puchberg) sinistral strike slip fault, another newly constructed profile across the easternmost Tauern window was projected beneath the base of the Austroalpine nappe stack, making use of a pronounced axial plunge towards the east and across the Katschberg normal fault (Genser and Neubauer 1989), that delimits this window to the east.

The Austroalpine nappe stack is drawn according to a new subdivision that is based on recent compilations by Schuster and Frank (1999) and Schuster et al. (2001), discussed in Schuster (2003) and Schmid et al. (in press), that are largely based on the degree of the Cretaceous metamorphic overprint (Fig. 15). We also used ideas proposed by Slapansky and Frank (1987) and Bouvier et al. (1972). The term “Middle Austroalpine” was avoided since this subdivision, proposed by Tollmann (1977), invokes correlations between the detached sediments of the Northern Calcareous Alps and the Austroalpine basement nappes that are incorrect in the light of more recent data (see discussion in Schuster and Frank 1999). Instead, we only used the terms Upper and Lower Austroalpine (Fig. 2e).

The Upper Austroalpine basement nappes were subdivided into four nappe systems which are, from top to bottom (see Fig. 12e): (1) Drauzug-Gurktal nappe system, including the Mesozoic cover of the Drauzug, located immediately to the north of the Periadriatic Line in our transect and south of the dextral strike slip zone that delimits the southern boundary of Alpine metamorphism, referred to as “SAM” by Hoinkes et al. (1999), (2) The Ötztal-Bundschuh nappe system with remnants of its Mesozoic cover, (3) the Koralpe-Wölz high-pressure nappe system comprising a series of basement units that are characterized by a significant, often pressure dominated, Eoalpine metamorphic overprint (Hoinkes et al, 1999; Schuster et al. 2001; see Fig. 15), and which include eclogitic MORB-type gabbros (Miller and Thöni 1997), and, (4) the Silvretta-Seckau nappe system. Following an early suggestion of Frank et al. (1983), we suspect that the eclogitic parts of the Koralpe-Wölz nappe system form the core of a recumbent fold (Fig. 15) with the high-pressure units in its core and lower grade rocks in its limbs (also see Fig. 2e and "Paleozoic with Eo-Alpine high-P overprint" in TRANSMED transect VI). We propose that these eclogitic units were exhumed towards the north within an extrusion wedge, which is back-folded in the southern part, i.e. north of the SAM (Fig. 15). This extrusion led to an inverted field metamorphic gradient at the base of the extrusion wedge (Fig. 15).

The southern part of this transect, located south of Periadriatic Line, was displaced some 75 km to the west in order to make use of an existing balanced cross section constructed by Nussbaum (2000). This offset in the profile trace has no significant effect on the deep structure, as the Moho depth contours are sub-parallel to the Periadriatic Line. This section across the Southern Alps by Nussbaum (2000) links up with section 11 of Pieri and Groppi (1981) across the Po Plain and the Ferrara thrust belt of the Northern Apennines. Their section, together with the interpretation given by Cassano et al. (1986), was the basis for displaying the subsurface of the Po Plain and the frontal parts of the Northern Apennines, largely buried under piggy-back basins and active in Late Neogene to recent times.

Summary of timing constraints and 3-D kinematics

Since this transect offers a rather complete section through the Austroalpine units it is appropriate to also discuss the pre-Tertiary history of the crystalline basement. During Permian to Early Triassic times (290-235 Ma) the Variscan orogen was affected by lithosphere-scale extension (Ziegler and Stampfi 2001), which led to basaltic intrusions into the lower crust, volcanism and a thermal imprint, expressed by a temperature dominated metamorphism. Subsequent thermal relaxation of the lithosphere caused subsidence allowing for to the deposition of up to more than 3 km thick shallow marine sediments.

Middle to Late Triassic times (235-210Ma) were characterised by the opening of the Meliata Ocean, which formed an embayment into a realm now occupied by the Austroalpine nappes and the Southern Alps (Fig. 3a). According to a working hypothesis proposed by Schmid et al. (in press), this embayment was located south of the main part of the future Northern Calcareous Alps, the Grauwackenzone and the Silvretta-Seckau nappe system, but north of the Ötztal-Bundschuh and Drauzug-Gurktal nappe systems, as well as north of the eastern part of the Southern Alps. The tectonic units representing this oceanic embayment, and/or its adjacent distal continental margin, are identified as such in Fig. 1.

The Jurassic to Early Cretaceous time interval (210-140Ma) was characterized by the opening of the Alpine Tethys in an area to the north of the present-day Austroalpine nappes. Further south, the former passive margin of the Meliata Ocean was affected by Late Jurassic transpressional tectonics (e.g. Gawlick et al. 1999; Mandl 2000) that are not yet fully understood, but that were contemporaneous with a phase of ophiolite obduction in the Dinarides (e.g. Pamic 2002) and the Hellenides (Bernoulli and Laubscher 1972).

The Cretaceous (or "Eoalpine") orogeny commenced at around 120 Ma during Mid-Cretaceous times, when the Northern Calcareous Alps were detached from their crystalline basement. This detachement must have occurred before metamorphism affected parts of the former crystalline basement of the Northern Calcareeous Alps, since the latter escaped metamorphism. From about 115 Ma onwards, compressional tectonics along the northern margin of the Austroalpine units indicate, that the former passive margin of Apulia that faces the Piemont-Liguria Ocean turned into an active one (Wagreich 2001). Early N to WNW-directed movements (i.e. Ratschbacher et al., 1989) preceded the peak of high-pressure metamorphism in the area south of the Northern Calcareous Alps, reached at around 100 Ma within the Koralpe-Wölz high-pressure nappe system (Thöni 1999). Development of this high-pressure belt and associated deformation were induced by the closure of the Meliata Ocean. Further west, in the area of TRANSMED transect V, however, Cretaceous (Eoalpine) compressional tectonics did not start before about 100 Ma (e.g. Schmid and Haas 1989, see Fig. 4).

The time interval 100-65Ma was characterised by exhumation of the high-pressure units to shallow crustal levels by N directed thrusting and S-SE directed back-folding (Schuster 2003). This was accompanied by a heterochroneous change from compression to extension, associated with the formation of the Gosau basins in the area of the Austroalpine nappes (Faupl and Wagreich 1996; Froitzheim et al. 1997). While sedimentation in the Gosau basins, sealing the nappe contacts, started as early as about 90 Ma ago (Late Turonian) in the east (area of TRANSMED transect VI), thrusting commenced only at about this time in the west (area of TRANSMED transect V), as documented by the youngest sediments found under the top-WNW thrusts in the area of Eastern Switzerland (Froitzheim et al. 1994; see Fig 4). In the west, the transition from compression to post-orogenic extension did not start before some 80 Ma (onset of "Ducan extension", as given in Fig. 4; Froitzheim et al. 1994).

The Tertiary orogenic cycle led to thrusting of a previously stacked and subsequently extended Austroalpine nappe stack over the Penninic units presently exposed in the Tauern window. Collision of the Austroalpine orogenic wedge with the European margin already occurred during the Paleocene in the Eastern Alps. This is in contrast to the Central Alps, where the intervening Valais Ocean did not close before the Middle Eocene. This collision was matched by the thick-skinned imbrication in the Bohemian Massif and the disruption of the Helvetic shelf (Ziegler et al. 2002). In the course, Eocene flexural subsidence of the foreland basin commenced. By the end of Eocene times, break-off of the subducted European lithosphere gave rise to magmatism north of the Periadriatic Line (Periadriatic intrusions), also widespread in the Eastern Alps (von Blanckenburg and Davis 1995). During the Oligocene and Early Miocene the nappe stack of the Eastern Alps advanced by perhaps as much as 250km to its present position (Wagner 1996). This was accompanied by a commensurate amount of renewed southward subduction of European continental lithosphere, penetrating considerably deeper into the asthenosphere as compared to TRANSMED transect V.

At around 20 Ma a drastic change occurred when lateral extrusion of the Eastern Alps commenced (Ratschbacher et al. 1991). This involved eastward displacement of the parts of the Eastern Alps situated between sinistral (i.e. SEMP Line) and dextral (i.e. SAM and Periadriatic Lines), strike-slip zones that traverse the TRANSMED transect VI (and the TRANSALP profile, Fig. 2d). Simultaneously with the onset of lateral extrusion in the Eastern Alps, sinistral strike-slip faulting dissected the Southern Alps and Periadriatic Line (Stipp et al. in press) along the Giudicaria Line. This led to north-directed indentation of the eastern part of the Southern Alps (Ratschbacher et al. 1991), invoked to be genetically linked to lateral extrusion, which is turn associated with extensional orogen-parallel unroofing along the Brenner normal fault and simultaneous up-doming of the Tauern window (Fügenschuh et al. 1997).

Drastic changes occurred around 20 Ma also at a lithospheric scale. The south-dipping European subduction slab, which did penetrate into the asthenosphere during the Oligocene and Early Miocene, started to tear off the lithosphere and began to retreat into the Carpathian loop (Wortel and Spakman 2000). This caused massive extension in the Pannonian Basin, also comprissing the eastern continuation of the Alps located north of the Balaton line (eastern continuation of the Periadriatic line), which did escape and were simultaneously extended eastwards.

Very likely, this retreat allowed for the change in subduction polarity, postulated to have occurred along the TRANSALP profile (Schmid et al. 2003). Note that at present, no separation between Southern Alps and Dinarides is evident at the earth's surface (see Fig. 1). Hence, both are expected to presently occupy the same, i.e. upper plate, position. A major change occurs, however, across Giudicarie belt and Brenner line in the border area between the two mantle-lithospheric slabs (European and Adriatic slabs, respectively), depicted in Fig. 12. It is proposed, that the change in subduction polarity between the TRANSALP transect (Schmid et al. (2003) and the TRANSMED transect VI postulated in this contribution, is only an apparent one. By taking into account the 3D-geometry of the entire Alpine-Pannonian-Dinaridic system, we propose a lateral northwestward movement of the NE-dipping Dinaridic mantle-lithospheric slab south of the Periadriatic line, identical with the "Adriatic" slab of Figure 12, and into TRANSMED transect VI, facilitated by the eastward retreat of the detached European slab into the Carpathian loop.

The Southern Alps east of the Giudicaria Line, crossed by TRANSMED transect VI, underwent some 50 to 70 km of orogen-perpendicular shortening after 20 Ma ago (Carulli and Ponton 1992; Nussbaum 2000), shortening that continues at the present, as is documented by the Friuli earthquakes. Very recent N-S convergence also characterised the front of the Northern Apennines, as can be inferred from the young age of thrusting documented by the borehole and reflection-seismic data (Pieri and Groppi 1981) in the Ferrara thrust belt, shown at the southern end of TRANSMED transect VI.

5. Conclusions

During the development of the tectonically complex Alpine arc several continental and oceanic plates were amalgamated. Analyses of crustal structures, derived from modern fieldwork, and geophysical deep sounding of the lithosphere-asthenosphere structure were combined into 3 major transects through the Alps. Particularly high-resolution teleseismic tomography, together with the correlation of tectonic units along strike, revealed a far more complex 3D geometry of the Alpine Orogen than hitherto believed. The inferred substantial along-strike changes are illustrated by the 3 transects selected for this presentation: (1) the ECORS-CROP transect (TRANSMED transect IV) through the French-Italian Western Alps, (2) the NFP-20/EGT transect (TRANSMED transect V) through the German-Swiss-Italian Alps located at the transition between western and Eastern Alps, and (3) the EASTERN ALPS transect (TRANSMED transect VI) through the German-Austrian-Italian Eastern Alps, to the east of the TRANSALP geophysical transect.

In the Western Alps (ECORS-CROP transect), the European Plate was subducted beneath the Adriatic micro-plate. The generally SE directed subduction of the European continental lithosphere can be followed along strike and into the most complete transect across the Alps located at the transition between Western and Eastern Alps (NFP-20/EGT). Further eastwards, the subduction angle gradually gets steeper and finally vertical under the westernmost part of the Eastern Alps (western Tauern Window and Giudicaria lineament). Quite unexpectedly, some 50 km further to the east the subducted continental lower lithosphere forms part of the Adriatic lithosphere and dips NE beneath the European Plate (EASTERN ALPS transect). This documents bipolar present-day slab geometries beneath the Alpine Orogen.

Major along-strike changes are also reflected in fundamental changes in the geometry and timing of nappe stacking. The West-Alpine nappe stack was severely overprinted by late stage (post-35 ma) west-directed indentation of the Adriatic micro-plate. The central profile is characterized by an impressive amount of Tertiary N-S-shortening, asymmetric and top-N initially, but completely reworked into a bi-vergent orogen during late-stage back thrusting and retro-thrusting. The EASTERN ALPS transect is characterized by a very thick pile of Austroalpine nappes, floating on European crust. This nappe stack, formed during 2 subsequent orogenies, a Cretaceous and a Tertiary one, is presently found in an upper plate position with respect to the Southern Alps. This due to a fundamental change in the 3D lithospheric configuration, that initiated at around 20 Ma ago and was triggered by the retreat of the European subduction slab into the Carpathian loop.

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References

Ansorge J (1968) Die Struktur der Erdkruste an der Westflanke der Zone von Ivrea, Schweiz. Mineral. Petrogr. Mitt. 48: 247-254

Ansorge J, Blundell D. Müller, St. (1992) Europe's lithosphere – seismic structure. In: Blundell D, Freeman R, Müller S (eds). A continent revealed: The European Geotraverse. Cambridge Univ. Press pp 33-70

Antoine P (1971) La zone des Brèches de Tarantaise entre Bourg-Saint-Maurice (Vallée de l'Isère) et la frontière Italo-Suisse. Travaux Laboratoire Géologique Faculté des Sciences, Thesis University Grenoble, France

Argand E (1916) Sur l'arc des Alpes Occidentales. Eclogae geol. Helv. 14: 145-204

Arlitt R, Kissling E, Ansorge J (1999) Three-dimensional crustal structure beneath the TOR array and effects on teleseismic wavefronts. Tectonophysics 314: 309-319

Babuska V, Plomerova J, Granet M (1990) The deep lithosphere in the Alps: A model inferred from P residuals. Tectonophysics 176: 137-165

Bagnoud A, Wernli R, Sartori M (1998) Découverte de foraminifères planctoniques paléogènes dans la zone de Sion-Courmayeur à Sion. Eclogae geol. Helv. 91: 421-429

Ballèvre M, Merle O. (1993) The Combin Fault: compressional reactivation of a Late Cretaceous-Early Tertiary detachment fault in the Western Alps. Schweiz. Mineral. Petr. Mitt. 73: 205-227

Baudin T (1987) Etude géologique du massif du Ruitor (Alpes franco-italiennes): Evolution structurale d'un socle briançonnais. Ph.D. thesis, Université de Grenoble, France

Bayer R, Carozzo MT, Lanza R, Miletto M, Rey D. (1989), Gravity modelling along the ECORS-CROP vertical seismic reflection profile through the Western Alps. Tectonophysics 162: 203-218

Bayer R, Lanza R, Truffert C (1996) Gravimetric and magnetic studies of the Western Alps in the context of the ECORS and ECORS-CROP projects; data and interpretations. Mém. Soc. géol. Fr. 170: 61-72

Beaumont C, Fullsack PH, Hamilton J (1994) Styles of crustal deformation in compressional orogens caused by subduction of the underlying lithosphere. Tectonophysics 232: 119-132

Berger A (1996) Geological-tectonic map of the Bergell pluton and surrounding country rocks (Southern Switzerland, Northern Italy). Schweiz. Mineral. Petrogr. Mitt. 76: plate

Berger A, Gieré R (1995) Structural observations at the eastern contact of the Bergell Pluton. Schweiz. Mineral. Petrogr. Mitt. 75: 241-258

Berger A, Rosenberg C, Schmid SM (1996) Ascent, emplacement and exhumation of the Bergell pluton within the Southern Steep Belt of the Central Alps. Schweiz. Mineral. Petrogr. Mitt. 76: 357-382

Bergerat F, Mugnier JL, Guellec S, Truffert C, Cazes M, Damotte B, Roure, F (1990). Extensional tectonics and subsidence of the Bresse basin: an interpretation from ECORS data. In: Roure F, Heitzmann P, Polino R (eds). Deep Structure of the Alps. Mémoire de la societée geologique Suisse 1: 145-156

Roure F, Heitzmann P, Polino R (eds). Deep Structure of the Alps. Mémoire de la societée geologique Suisse 1

Bernoulli D, Laubscher H (1972) The palinspastic problem of the Hellenides. Eclogae geologicae Helvetiae 65 (1): 107-118

Bernoulli D, Winkler W (1990) Heavy mineral assemblages from Upper Cretaceous South Alpine and Austro-alpine flysch sequences (N-Italy and S-Switzerland): source terranes and paleotectonic implications. Eclogae geologicae Helvetiae 83(2): 287-310

Bernoulli D, Heitzmann P, Zingg A (1990) Central and Southern Alps in southern Switzerland: Tectonic evolution and first results of reflection seismics. In: Roure F, Heitzmann P, Polino R (eds). Deep Structure of the Alps. Mémoire de la societée geologique Suisse 1: 289-302

Bigi G, Castellarin A, Coli M, Dal Piaz GV, Sartori R, Scandone P (1990a) Structural model of Italy sheet 1, 1:500000. Consiglio Nazionale delle Ricerche, Progetto Finalizzato Geodinamica, SELCA Firenze

Bigi G, Castellarin A, Coli M, Dal Piaz GV, Vai GB (1990b) Structural model of Italy sheet 2, 1:500000. Consiglio Nazionale delle Ricerche, Progetto Finalizzato Geodinamica, SELCA Firenze

Bigi G, Coli M, Cosentino D, Dal Piaz GV, Parotto M, Sartori R, Scandone P (1992) Structural model of Italy sheet 3, 1:500000. Consiglio Nazionale delle Ricerche, Progetto Finalizzato Geodinamica, SELCA Firenze

Bijwaard H, Spakman W (2000) Non-linear global P wave tomography by iterated linearized inversion. Geophysical Journal International 141, 71-82

Bleibinhaus F. (2003) Seismic profiling by the TRANSALP Working Group: refraction and wide-angle reflection seismic travel-time tomography. In: Nicolich R, Polizzi D, Furlani S (eds): Transalp Conference. Memorie di Scienze Geologiche 54: 23-26

Blundell D, Freeman R, Müller S (eds) (1992) A continent revealed: The European Geotraverse. Cambridge University Press 275pp

Bousquet R, Oberhänsli R, Goffé B, Jolivet L, Vidal O (1998) High pressure - low temperature metamorphism and deformation in the Bündnerschiefer of the Engadine window: Implications for the regional evolution of the eastern Central Alps. Journal of Metamorphic Geology 16: 657-674

Bousquet R, Goffé B, Vidal O, Patriat M, Oberhänsli R (2002) The tectono-metamorphic history of the Valaisan domain from the Western to the Central Alps: New constraints for the evolution of the Alps. Geol. Soc. Am. Bulletin 114: 207-225

Bouvier M. et al (1972) Blei und Zink in Österreich: Der Bergbau Bleiberg-Kreuth in Kärnten. Verlag des Naturhistorischen Museums Wien, 35 pp

Bucher S, Schmid SM, Bousquet R, Fügenschuh B (2003) Late-stage deformation in a collisional orogen (Western Alps): nappe refolding, back-thrusting or normal faulting? Terra Nova 15: 109-117

Bucher S, Ceriani S, Fügenschuh B, Ulardic Ch, Bousquet R, Schmid SM (in press) Tectonic evolution of the Briançonnais units along a transect (ECORS-CROP) through the French-Italian Western Alps. Eclogae geol.Helv.

Buness H (1992) Collision structures in the crust at the boundaries of the NW Adriatic plate, Ph.D thesis, Freie Univesität, Berlin, Germany(in German)

Burkhard M, Sommaruga A (1998) Evolution of the western Swiss Molasse Basin: structural relations with the Alps and the Jura belt. In: Mascle C et al. (eds) Cenozoic Foreland Basins of Western Europe.Geol. Soc. Spec. Publ., 134, 279-298

Caby R (1996) Low-angle extrusion of high-pressure rocks and the balance between outward and inward displacements of Middle Penninic units in the Western Alps. Eclogae geol. Helv. 89: 229-268

Carminati E, Doglioni C, Argnani A, Carrara G, Dabovski Ch, Dumurdzanov N, Gaetani M, Georgiev G, Mauffret A, Nazai S, Sartori R, Scionti V, Scrocca D, Séranne M, Torelli L and Zagorchev I (this volume) TRANSMED Transect III: Massif Central - Provence - Gulf of Lion - Provençal Basin - Sardinia - Tyrrhenian Basin - Southern Apennines - Apulia - Adriatic Sea - Albanian Dinarides - Balkans - Moesian Platform

Caron Ch, Homewood P, Wildi W (1989) The original Swiss flysch: a reappraisal of the type deposits in the Swiss Prealps. Earth-Science Reviews 26: 1-45

Carulli GB, Ponton M (1992) Interpretazione strutturale profonda del settore centrale Carnico-Friulano. Studi Geologici Camerti volume speciale (1992/2) CROP 1-1A: 275-284

Cassano E, Anelli L, Fichera R. Cappelli V (1986) Pianura Padana: Interpretazione integrata di dati geofisici e geologici. 73º Congresso Societa Geologica Italiana, Roma, AGIP, 27pp

Castellarin A, Dal Piaz GV, Fantoni R, Vai GB, Nicolich R, TRANSALP Working Group (2003). Lower crustal style and models along the southern sector of the Transalp Profile. In: Nicolich R, Polizzi D, Furlani S (eds) Transalp Conference. Memorie di Scienze Geologiche, 54: 245-248

Cattaneo M, Eva C (1990) Propagation anomalies in Northwestern Italy by inversion of teleseismic residuals. Terra Nova 2: 577-584

Ceriani S, Fügenschuh B Schmid SM (2001) Late-stage thrusting at the „Penninic Front" in the Western Alps between Mont Blanc and Pelvoux Massifs. Int. J. Earth Sciences 90: 685-702

Csontos L, Nagymarosy A (1998) The Mid-Hungarian line: a zone of repeated tectonic inversions. Tectonophysics 297: 51-71

Csontos L, Nagymarosi A, Horvath F, Kovac M. (1992) Tertiary evolution of the Intra-Carpathian area: a model. Tectonophysics 208: 221-241

Dal Piaz GV, Martin S (1998) Evoluzione litosferica e magmatismo nel dominio austro-sudalpino dall' orogenesi varisica al rifting permo-mesozoico. Riunione estiva S.G.I., Mem. Soc. Geol. It. 53: 43-62

Dal Piaz GV, Cortiana G, Del Moro A, Martin S, Pennacchioni G, Tartarotti P (2001) Tertary age and paleostructural inferences of the eclogitic imprint in the Austroalpine outliners and Zermatt-Saas ophiolite, Western Alps. Int. J. Earth Sci. 90: 668-684

Damotte BR, Nicholich M, Cazes M, Guellec S (1990) Mise en oeuvre, traitement et présentation du profil plaine du Po-Massif Central. In: Roure F et al (eds) Deep Structure of the Alps. Mém. Soc. géol. France 156: 65-76

Davidson C, Rosenberg C, Schmid SM (1996) Synmagmatic folding of the base of the Bergell pluton, Central Alps. Tectonophysics 265: 213-238

Dewey JF Helman ML, Turco E, Hutton DHW Knott SD (1989) Kinematics of the western Mediterranean. In: Coward MP, Dietrich D, Park RG (eds) Alpine Tectonics. Geol. Soc. London Spec. Publ. 45: 265-283

Dèzes P, Schmid SM, Ziegler PA (submitted) Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. Tectonophysics

Dobrin MB, Savit CH (1988) Introduction to Geophysical Prospecting, 4th edition. McGraw-Hill Book Company: 867 pp

Ebbing J, Braitenberg C Götze HJ (2001) Forward and inverse modelling of gravity revealing insight into crustal structures of the Eastern Alps. Tectonophysics 337: 191-208

Elter G (1972) Contribution à la connaissance du Briançonnais interne et de la bordure Piémontaise dans les Alpes Graies nord-orientales et considérations sur les rapports entre les zones du Briançonnais et des schistes lustrés, Memorie Istituti di Geologia e Mineralogia Università Padova 28: 1-19

Engi M, Berger A, Roselle,G (2001) The role of the tectonic accretion channel in collisional orogeny. Geology 29: 1143-1146

Escher A, Masson H, Steck A (1988) Coupes géologiques des Alpes occidentales suisses. Mémoires de Géologie Lausanne 2

Escher A, Hunziker JC, Marthaler M, Masson H. Sartori M Steck A (1997) Geologic framework and structural evolution of the western Swiss-Italian Alps. In: Pfiffner AO et al. (eds) Deep Structure of the Swiss Alps: Results From NRP 20. Birkhäuser, Basel, Switzerland: 205-221

Etter U (1987) Stratigraphische und strukturgeologische Untersuchungen im Gotthardmassivischen Mesozoikum zwischen dem Lukmanierpass und der Gegend von Ilanz. Ph.D. thesis Univ. Bern

Exner Ch (1990) Erläuterugen zur Geologischen Karte des mittleren Lungaus. Mitt. Ges. Geol. Bergbaustud. Österr. 36: 1-38

Fabre J (1961) Contribution à l'étude de la zone Houllière en Maurienne et en Tarantaise (Alpes de Savoie). Mém. Bur. Rech. Min. 2

Faupl P, Wagreich M (1996) Basin analysis of the Gosau Group of the Northern Calcareous Alps (Turonian-Eocene, Eastern Alps). In: Wessely G, Liebl W (eds) Oil and Gas in Alpidic Thrust Belts and Basins of Central and Eastern Europe. EAGE Special Publication 5: 127-135

Finetti IR, Boccaletti M, Bonini M, Del Ben A, Geletti R, Pipan M, Sani F (2001) Tectonophysics 343: 135-163

Florineth D, Froitzheim N (1994) Transition from continental to oceanic basement in the Tasna nappe (Engadine window, Graubünden, Switzerland): evidence for Early Cretaceous opening of the Valais Ocean. Schweiz. Mineral. Petrogr. Mitt. 74: 437-448

Fodor L, Jelen B, Marton M, Skaberne D, Car J, Vrabec M (1998) Miocene-Pliocene tectonic evolution of the Slovenian Periadriatic fault: Implications for Alpine-Carpathian extrusion models. Tectonics 17: 690-709

Frank W (1987) Evolution of the Austroalpine elements in the Cretaceous. In: Flügel HW, Faupl P (eds) Geodynamics of the Eastern Alps. Deuticke, Vienna: 379-406

Frank W, Esterlus M, Frey I, Jung G, Krohe A, Weber J (1983) Die Entwicklungsgeschichte von Stub- und Koralpenkristallin und die Beziehung zum Grazer Paläozoikum. Jber. Hochschulschwerp. S15/4, Graz: 263-293

Frey M, Desmons J, Neubauer F (1999) Metamorphic Maps of the Alps. CNRS (Paris) Swiss N.S.F. (Berne), BMfWFV and FWF (Vienna)

Frisch W (1975) Hochstegen-Fazies und Grestener Fazies - Ein Vergleich des Jura. N. Jb. Geol. Paläont. Mh. Heft 2: 82-90

Frisch W (1979) Tectonic progradation and plate tectonic evolution of the Alps. Tectonophysics 60: 121-139

Frisch W, Gommeringer K, Kelm U, Popp F (1989) The Upper Bündner Schiefer of the Tauern Window - A key to understanding Eoalpine orogenic processes in the Eastern Alps. In: Flügel W, Faupl P (eds) Geodynamics of the Eastern Alps. Deuticke, Vienna: 55-69

Frisch W, Kuhlemann J, Dunkl I, Brügel A (1998) Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion. Tectonophysics 297: 1-15

Froitzheim N, Eberli GP (1990) Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps, Switzerland. Geol. Soc. America Bull., 102: 1297-1308

Froitzheim N, Manatschal G (1996) Kinematics of Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). Geological Society of America Bulletin 108: 1120-1133

Froitzheim N, Schmid SM, Conti P (1994) Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. Eclogae geol. Helv. 87: 559-612

Froitzheim N, Schmid SM, Frey M (1996) Mesozoic paleogeography and the timing of eclogite-facies metamorphism in the Alps: A working hypothesis. Eclogae geol. Helv. 89: 81-110

Froitzheim N, Conti P, Van Daalen M (1997) Late Cretaceous, synorogenic, low-angle normal faulting along the Schlinig fault (Switzerland, Italy, Austria) and its significance for the tectonics of the Eastern Alps. Tectonophysics 280: 267-293

Fügenschuh B, Schmid SM (2003) Late stage of deformation and exhumation of an orogen constrained by fission-track data: a case study in the Western Alps. Bull. Geol. Society of America 115, 1425-1440

Fügenschuh B, Seward D, Mancktelow N (1997) Exhumation in a convergent orogen: the western Tauern Window. Terra Nova: 9 213-217

Fügenschuh B, Loprieno A, Ceriani S, Schmid SM (1999) Structural analysis of the Subriançonnais and Valais units in the area of Moûtiers (Savoy, Western Alps). Paleogeographic and tectonic consequences. Int. Jour. Earth Sciences 88: 201-218

Gawlick HJ, Frisch W, Vecsei A, Steiger T, Böhm F (1999) The change from rifting to thrusting in the Northern Calcareous Alps as recorded in Jurassic sediments. Int. Jour. Earth Sciences 87: 644-657

Gebauer D (1999) Alpine geochronology of the Central and Western Alps: new constraints for a complex geodynamic evolution. Schweiz. Mineral. Petr. Mitt. 79: 191-208

Gee DG, Zeyen H (1996) EUROPROBE 1996 – Lithosphere Dynamics: Origin and Evolution of Continents. EUROPROBE Secretariate, Uppsala University, Uppsala, Sweden: 138pp

Genser J, Neubauer F (1989) Low angle normal faults at the eastern margin of the Tauern window (Eastern Alps). Mitt. Österr. Geol. Ges. 81: 233-243

Giamboni M, Ustaszewski K, Schmid SM, Schumacher ME, Wetzel A (2004) Plio-Pleistocene transpressional reactivation of Paleozoic and Paleogene structures in the Rhine-Bresse Transform Zone (Northern Switzerland and Eastern France). Int. Jour. Earth Sciences: in press

Giese P, Buness H (1992) Moho depth. In Freeman R, St. Müller St (eds) A Continent Revealed: The European Geotraverse. Atlas of compiled data, Cambridge University Press, Cambridge (UK). 11-13 and Atlas Map 2

Gouffon Y (1993) Géologie de la nappe du Grand Saint-Bernard entre le Val de Bagnes et la frontière Suisse (Vallée d'Aoste, Italie). Mem. Géol. Lausanne 12: 1-147

Guellec S, Mugnier M, Tardy JL, Roure F, (1990) Neogene evolution of the western Alpine foreland in the light of ECORS data and balanced cross section. In: Roure F et al. (eds) Deep Structure of the Alps. Mém. Soc. géol. France 156: 165-184.

Guyoton F (1991) Seismicity and lithospheric structure of the Western Alps. PhD thesis, University of Grenoble (in French)

Haas J, Kovacs S, Krystin L, Lein R (1995) Significance of Late Permian-Triassic facies zones in terrane reconstructions in the Alpine-North Pannonic domain. Tectonophysics 242: 19-40

Haas J, Hamor G, Jambor A, Kovacs S, Nagymarosy A, Szenderkenyi T (2001) Geology of Hungary. Eötvös University Press, Budapest: 317pp

Handy MR (1989) Deformation regimes and the rheological evolution of fault zones in the lithosphere: the effects of pressure, temperature, grain size and time. Tectonophysics 163: 119-152

Handy MR, Zingg A (1991) The tectonic and rheological evolution of an attenuated cross section of the continental crust: Ivrea crustal section, Southern Alps, north-western Italy and southern Switzerland. Geological Society of America Bulletin 103: 236-253

Hirn A, Thouvenot F, Nicolich R, Pellis G, Scarascia S, Tabacco I, Castellano F, Merlanti F (1989) Mapping of the Moho of the Western Alps by wide-angle reflection seismics. Tectonophysics 162: 193-202

Hitz L, Pfiffner OA (1994) A 3-D crustal model of the eastern external Aar massif interpreted from a network of deep seismic profiles. Schweiz. Mineral. Petrogr. Mitt. 74: 405-420

Hofmann T, Mandl G, Peresson, H, Pestal, G, Pistotnik, J, Reitner J, Scharbert S, Schnabel W, Schönlaub HP (2002): Rocky Austria: Eine bunte Erdgeschichte von Östereich. Verlag Geol.Bundesanst, Wien: 63 pp

Hoinkes G, Koller F, Rantitsch G, Dachs E, Höck V, Neubauer F, Schuster R (1999) Alpine metamorphism of the Eastern Alps. Schweiz. Mineral. Petrogr. Mitt. 79: 155-181

Holliger K (1991) Ray-based image reconstruction in controlled-source seismology with an application to seismic reflection and refraction data in the Central Swiss Alps, Ph.D. thesis ETH Zürich No 9335: 156pp

Holliger K, Kissling E (1991) Ray theoretical depth migration: Methodology and application to deep seismic reflection data across the eastern and southern Swiss Alps. Eclogae geol. Helv. 84: 369-402

Holliger K, Kissling E (1992) Ray theoretical depth migration: methodology and application to deep seismic reflection data across the eastern and southern Swiss Alps. Eclogae geologicae Helvetiae 84: 369-402

Hurford AJ, Hunziker JC (1989) A revised thermal history for the Gran Paradiso massif. Schweiz. Mineral. Petrogr. Mitt. 69: 319-329

Hurford AJ, Stöckhert B, Hunziker JC (1991) Constraints on the late thermotectonic evolution of the Western Alps: evidence for episodic rapid uplift. Tectonics 10: 758-769

Kerkhove C (1969) La zone du flysch dans les nappes de l'Embrunais-Ubaye. Géologie Alpine 45: 5-204

Kissling E (1980) Krustenaufbau und Isostasie in der Schweiz. PhD thesis ETH Zürich

Kissling E (1982) Aufbau der Kruste und des oberen Mantels in der Schweiz. Geodätisch-Geophysikalische Arbeiten in der Schweiz, Schweiz. Geodätische Kommission 35: 37-126

Kissling E (1984) Three-dimensional gravity model of the Northern Ivrea-Verbano zone. In: Wagner JJ, Müller St (eds) Geomagnetic and Gravimetric Studies of the Ivrea Zone. Matér. Géol. Suisse, Géophys. 21: 55-61

Kissling E (1993) Deep structure of the Alps – what do we really know? Physics of the Earth and Planetary Interiors 79: 87-112

Kissling E, Ansorge J, Baumann M. (1997) Methodological considerations of 3-D crustal structure modeling by 2-D seismic methods. In: Pfiffner OA, Lehner P, Heitzmann P, Müller S, Steck A (eds) Deep Structure of the Swiss Alps. Birkhäuser Verlag Basel-Boston-Berlin: 31-38

Kissling E, Schmid SM, Lippitsch R, Ansorge J, Fügenschuh B. (submitted) Lithosphere structure and tectonic evolution of the Alpine arc: new evidence from high-resolution teleseismic tomography.

Kollmann K (1977) Die Öl- und Erdgasexploration der Molassezone Oberösterreichs und Salzburgs aus regional-geologischer Sicht. Erdöl-Erdgas-Z. 93. Sonderausgabe, Hammburg/Wien.

Kummerow J, Kind R, Oncken O, Wylegalla K, Scherbaum F (2003) Seismic profiling by the TRANSALP working group: receiver function image and Upper Mantle anisotropy. In: Nicolich R, Polizzi D, Furlani S. (eds) Transalp Conference. Memorie di Scienze Geologiche 54: 27-28.

Kurz W, Neubauer F, Dachs E (1998) Eclogite meso- and microfabrics: implications for the burial and exhumation history of eclogites in the Tauern Window (Eastern Alps) from P-T-d paths. Tectonophysics 285: 183-209

Lammerer B (1986) Das Autochthon im westlichen Tauernfenster. Jb. Geol. B.-A. 129: 51-67

Lammerer B, Weger M (1998) Footwall uplift in an orogenic wedge: the Tauern window in the Eastern Alps of Europe. Tectonophysics 285: 213-230

Lammerer B, TRANSALP Working Group (2003) The crocodile model and balancing the seismic section. In: Nicolich R, Polizzi D, Furlani S (eds) Transalp Conference. Memorie di Scienze Geologiche 54: 243-244

Laubscher HP (1970) Motion and heat in the Alpine orogeny (in German). Schweizerische Mineralogische und Petrographische Mitteilungen 50: 565-596

Laubscher HP (1971) The large-scale kinematics of the Western Alps and the northern Apennines and its palinspastic implications. Am. J. Science 271: 193-226

Laubscher HP (1991) The arc of the Western Alps today. Eclogae geol. Helv. 84: 631-659

Lemcke K (1988) Geologie von Bayern. I. Das bayrische Alpenvorland vor der Eiszeit. Erdgeschichte - Bau - Bodenschätze. E. Schweizbart'sche Verlagsbuchhandlung, Stuttgart: 175pp

Lemoine MP, Tricart P, Boillot G (1987) Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines): In search of a genetic model. Geology 15: 622-625

Liniger M (1992) Der ostalpin-penninische Grenzbereich im Gebiet der nördlichen Margna-Decke (Graubünden, Schweiz). Ph.D. thesis ETH Zürich

Lippitsch R (2002) Lithosphere and upper mantle structure beneath the Alps by high-resolution teleseismic tomography. PhD thesis, no. 14726, ETH-Zürich

Lippitsch R, Kissling E, Ansorge J (2003) Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. J. Geophys. Res. 108 (B8): 2376, doi:10.1029/2002JB002016

Litak RK, Marchant RH, Pfiffner OA, Brown LD, Sellami S, Levato L, Wagner JJ, Olivier R (1993) Crustal structure and reflectivity of the Swiss Alps from three-dimensional seismic modelling: 2. Penninic nappes. Tectonics12: 925-935

Loprieno A (2001) A combined structural and sedimentological approach to decipher the evolution of the Valais domain in Savoy, Western Alps. Dissertationen aus dem Geologisch-Paläontologischen Institut der Universität Basel 18: 285 pp

Lüschen E, Gebrande H, Millahn K, Nicolich R. (2003) Seismic profiling by the TRANSALP Working Group: deep crustal vibroseis and explosive seismic profiling. In: Nicolich R, Polizzi D Furlani S (eds) Transalp Conference. Memorie di Scienze Geologiche 54: 11-14

Manatschal G, Nievergelt P (1997) A continent-ocean transition recorded in the Err and Platta nappes (Eastern Switzerland). Eclogae Geol. Helv. 90: 3-27

Manatschal G, Bernoulli D (1999) Architecture and tectonic evolution of non-volcanic margins: present-day Galicia and ancient Adria. Tectonics 18: 1099-1119

Mandl GW (2000) The Alpine sector of the Tethyan shelf - Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. Mitt. Österr. Geol. Ges. 92 (1999): 61-77

Mandl GW (2001): Geologie der Dachstein-Region. In: Scheidler A, Boroviczeny F, Graf W, Hofmann T, Mandl G, Schubert G, Stichler W, Trimborn P, Kralik M. (eds) Pilotprojekt "Karstwasser Dachstein" Karsthydrologie und Kontaminationsrisiko von Quellen. Archiv für Lagerstättenforschung 21: 13-42

Mandl G, Ondrejickova A (199) Über eine triadische Tiefwasserfazies (Radiolarite, Tonschiefer) in den nördlichen Kalkalpen – ein Vorbericht. Jb. Geol. B.-A. 134/2: 309-318

Mandl G, Ondrejickova A (1993) Radiolarite und Conodonten aus dem Meliatikum im Ostabschnitt der NKA. Jb. Geol. B.-A. 136/4: 841-871

Marchant R (1993) The Underground of the Western Alps. Thesis, Univ. Lausanne: 137pp

Marchant RH, Stampfli GM (1997) Crustal and lithospheric structures of the Western Alps: geodynamic significance In: Pfiffner OA, Lehner P, Heitzman PZ, Mueller S, Steck A (eds.) Deep structure of the Swiss Alps - Results from NRP 20. Birkhäuser AG: 326-337

Miller Ch, Thöni M (1997) Eo-Alpine eclogitisation of Permian MORB-type gabbros in the Koralpe (Eastern Alps, Austria): new geochronological, geochemical and petrological data. Chemical Geology 137: 283-310

Miller H, Gebrande H Schmedes E. (1977) An improved structural model for the Eastern Alps derived from seismic refraction data including the Alpine longitudinal profile (in German). Geologische Rundschau 66: 289-308

Milnes AG (1974) Structure of the Pennine zone (Central Alps): a new working hypothesis. Geol. Soc. Am. Bull. 85: 1727-1732

Mosar J, Stampfli GM, Girod F (1996) Western Préalpes Médianes Romandes: Timing and structure. A review. Eclogae Geol. Helv. 89: 389-425

Müller S (1997) The lithosphere-asthenosphere system of the Alps. In: Pfiffner OA, Lehner P, Heitzmann P, Müller S, Steck A (eds) Deep Structure of the Swiss Alps. Birkhäuser Verlag Basel-Boston-Berlin, 338-347

Müntener O, Hermann J, Trommsdorff V (2000) Cooling history and exhumation of lower crustal granulites and upper mantle (Malenco, Eastern Central Alps). Journal of Petrology 41: 175-200

Mugnier JL, Guellec S, Ménard G, Roure F, Tardy M, Vialon P (1990) A crustal scale balanced cross-section through the external Alps deduced from the ECORS profile In: Roure F et al. (eds) Deep Structure of the Alps. Mém. Soc. géol. France 156: 203-216

Mugnier JL, Bergerat F , Damotte B Guellec S, Nicolas A, Polino R, Roure F, Tardy M, Truffert C (1996). Crustal structure of the Western Alps and their forelands, Mém. Soc. géol. France 170: 73-97

Nagel T, de Capitani C, Frey M, Froitzheim N, Stünitz H, Schmid, SM (2002) Structural and metamorphic evolution during rapid exhumation in the Lepontine domee (Southern Simano and Adula nappes, Central Alps, Switzerland). Eclogae geol. Helv. 95: 301-321

Nicolas A, Hirn A, Nicolich R, Polino R, ECORS-CROP Working Group (1990) Lithospheric wedging in the Western Alps inferred from the ECORS-CROP traverse. Geology 18: 587-590

Nicolas A, Polino R, Hirn A , Nicolich R, ECORS-CROP Working Group (1996) ECORS-CROP traverse and deep structure of the Western Alps: a synthesis. Mém. Soc. géol. France 170: 15-27

Nicolich R, Polizzi D, Furlani S (eds) (2003) Transalp Conference. Memorie di Scienze Geologiche 54: 268pp

Nievergelt P, Liniger M, Froitzheim N, Ferreiro-Mählmann R (1996) Early Tertiary extension in the Central Alps: The Turba mylonite zone.Tectonics 15: 329-340

Nussbaum Ch (2000) Neogene tectonics and thermal maturity of sediments of the easternmost Southern Alps (Friuli are, Italy). Unpublished PhD thesis Univerité de Neuchâtel, Switzerland

Oberhänsli, R (1978) Chemische Untersuchungen an Glaukophan-führenden basischen Gesteinen aus den Bündnerschiefern Graubündens. Schweiz. Mineral. Petrogr. Mitt. 58: 139-156

Oberhauser R (1995) Zur Kenntnis der Tektonik und der Paläogeographie des Ostalpeenraumes zur Kreide-, Paleozän- und Eocänzeit. Jb. Geol. B.A. 138: 369-432

Pamic, J. 2002: The Sava-Vardar Zone of the Dinarides and Hellenides versus the Vardar Ocean. Eclogae geol. Helv. 95, 99-113.

Pfiffner OA (1981) Fold-and-thrust tectonics in the Helvetic nappes (E Switzerland). In: Mc Clay KR, Price NJ (eds) Nappe Tectonics. Spec. Publ. Geol. Soc. London 9: 319-327

Pfiffner OA (1992) Alpine orogeny. In: D. Blundell et al. (eds) A Continent Revealed. The European Geotraverse. Cambridge University Press, Cambridge: 180-190

Pfiffner OA, Hitz L (1997) Geologic interpretation of the seismic profiles of the Eastern Traverse (lines E1-E3, E7-E9): eastern Swiss Alps. In: Pfiffner OA, Lehner P, Heitzmann P, Müller S, Steck A (eds) Deep Structure of the Swiss Alps. Birkhäuser Verlag Basel-Boston-Berlin: 73-100

Pfiffner OA, Klaper E, Mayerat AM, Heitzmann P (1990a) Structure of the basement-cover contact in the Swiss Alps. In: Roure F et al. (eds) Deep Structure of the Alps Mém. Soc. Geol. France 156: 247-262

Pfiffner OA, Frei W, Valasek P, Stäuble M, Levato L, Dubois L, Schmid SM, Smithson SB (1990b) Crustal shortening in the Alpine orogen: results from deep seismic reflection profiling in the Eastern Swiss Alps, line NFP 20-East. Tectonics 9: 1327-1355

Pfiffner OA, Lehner P, Heitzmann P, Müller S, Steck A (eds) (1997) Deep Structure of the Swiss Alps: Results from NRP 20. Birkhäuser Verlag Basel-Boston-Berlin: 380pp

Philippe Y, Colletta B, Deville E, Mascle A, (1996) The Jura fold-and-thrust belt: a kinematic model based on map-balancing. In: Ziegler PA, Horvàth F (eds.) Structure and prospects of Alpine basins and forelands. Peri-Tethys Memoire 2. Mém. Mus. natn. Hist. nat., Paris 170: 235-261

Pieri M, Groppi G (1981) Subsurface geological structure of the Po Plain, Italy. Pubblicazione nº 414 del Progetto Finalizzato Geodinamica, Consiglio Nazionale delle Ricerche, AGIP: 13pp. and plates.

Piromallo C, Morelli A (2003) P wave tomography of the mantle under the Alpine Mediterranean area. Journal of Geophysical Research 108 B2: 2065

Plasienka D, Putis M, Kovac M, Sefara, Hrusecky J (1997) Zones of Alpidic subduction and crustal underthrusting in the Western Carpathians. In: Grecula P et al (eds) Geological evolution of the Western Carpathians. Mineralia Slovaca - Monograph, Bratislava: 35-42

Prey S (1980) Die Geologie Österreichs in ihrem heutigen geodynamischen Entwicklungsstand sowie die geologischen Bauteile und ihre Zusammenhänge. In: Oberhauser R (eds) Der geologische Aufbau Österreichs. Springer, Wien: 8-117

Probst Ph (1980) Die Bündnerschiefer des nördlichen Penninikums zwischen Valser Tal und Passo di San Giacomo. Beitr. geol. Karte Schweiz NF153

Ranalli G, Murphy DC (1987) Rheological stratification of the lithosphere. Tectonophysics 132: 281-295

Ratschbacher L, Frisch W, Neubauer F, Schmid SM, Neugebauer J (1989) Extension in compressional orogenic belts: The Eastern Alps. Geology 17: 404-407

Ratschbacher L, Frisch W, Linzer HG, Merle O (1991) Lateral extrusion in the Eastern Alps, part 2: Structural analysis. Tectonics 10: 257-271

Ricou LE, Siddans AWB (1986) Collision tectonics in the Western Alps. In: Coward MP Ries AC (eds) Collision Tectonics. Geological Soc. Spec. Publ. 19: 229-244

Roeder D, Bachmann G (1996) Evolution structure and petroleum geology of the German Molasse Basin. In: Ziegler PA, Horvàth F (eds.) Structure and prospects of Alpine basins and forelands. Peri-Tethys Memoire 2. Mém. Mus. natn. Hist. nat., Paris 170: 263-284

Rosenberg CL, Berger A, Schmid SM (1995) Observations from the floor of a granitoid pluton: Inferences on the driving force of final emplacement. Geology 23: 443-446

Roure F, Polino R, Nicolich R (1990) Early Neogene deformation beneath the Po Plain, constraints on the post-collisional Alpine evolution. In: Roure F, Heitzmann P, Polino R (eds) Deep Structure of the Alps. Mémoire de la societé geologique Suisse **1**: 309-322

Roure F, Choukroune P, Polino R (1996a) Deep seismic reflection data and new insights on the bulk geometry of mountain ranges. C. R. Acad. Sci. Paris 322 série IIa: 345-359

Roure F, Bergerat F, Damotte B, Mugnier JL, Polino R (eds) (1996b) The ECORS-CROP Alpine seismic traverse. Mém. Soc. Géol. Fance 170: 113pp

Sandulescu M (1984) Geotectonica Romaniei. Editura Tehnica, Bucharest, 450pp

Sandulescu M (1994) Overview on Romanian geology. Rom. J. Tectonics Reg. Geol. 75 (Suppl. 2: ALCAPA II Field Guidebook.): 3-15

Sartori M (1990) L'unité du Barrhorn (Zone pennique, Valais, Suisse). Mém. Géol. (Lausanne) 6

Schmid SM (1975) The Glarus overthrust: Field evidence and mechanical model. Eclogae geol.Helv. 68: 251-284

Schmid SM (1993) Ivrea Zone and adjacent Southern Alpine basement. In: von Raumer JF, Neubauer F (eds) Pre-Mesozoic Geology of the Alps, Springer-Verlag: 567-583

Schmid SM (2000) Regional tectonics: from the Rhine graben to the Po Plain, a summary of the tectonic evolution of the Alps and their forelands. World Wide Web Address http://comp1.geol.unibas.ch/groups/3_1/schmid/Text_Schmid.html

Schmid SM, Haas R (1989) Transition from near-surface thrusting to intrabasement decollement, Schlinig Thrust, Eastern Alps. Tectonics 8: 697-718

Schmid SM, Froitzheim N (1994) Oblique slip and block rotation along the Engadine line, Eclogae geol. Helv. 86: 569-593

Schmid SM, Kissling E (2000) The arc of the Western Alps in the light of geophysical data on deep crustal structure. Tectonics 19/1: 62-85

Schmid SM, Zingg A, Handy M (1987) The kinematics of movements along the Insubric line and the emplacement of the Ivrea zone. Tectonophysics 135: 47-66

Schmid SM, Aebli HR, Heller F, Zingg A (1989) The role of the Periadriatic Line in the tectonic evolution of the Alps. In: Coward MP et al. (eds) Alpine Tectonics. Geol. Soc. London Spec. Publ. 45: 153-171

Schmid SM, Rück Ph, Schreurs G (1990) The significance of the Schams nappes for the reconstruction of the paleotectonic and orogenic evolution of the Pennine zone along the NFP 20 East traverse (Grisons, eastern Switzerland). Mém. soc. géol. France 156: 263-287

Schmid, S.M., Pfiffner, O.A., Froitzheim, N., Schönborn, G, Kissling, E. 1996a: Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics 15, 1036-1064.

Schmid SM, Berger A, Davidson C, Gieré R, Hermann J, Nievergelt P, Puschnig A, Rosenberg C (1996b) The Bergell pluton (Southern Switzerland, Northern Italy): overview accompanying a geological-tectonic map of the intrusion and surrounding country rocks. Schweiz. Mineral. Petrogr. Mitt. 76: 329-355

Schmid SM, Pfiffner OA, Schreurs G (1997) Rifting and collision in the Penninic zone of eastern Switzerland. In: Pfiffner AO et al. (eds) Deep Structure of the Swiss Alps: Results From NRP 20. Birkhäuser Verlag: 60-185.

Schmid SM, Fügenschuh B, Lippitsch R (2003) The Western Alps - Eastern Alps transition: tectonics and deep structure. In: Nicolich R, Polizzi D Furlani S (eds) Transalp Conference. Memorie di Scienze Geologiche 54: 257-260

Schmid SM, Fügenschuh B, Schuster R (in press) Tectonic map and overall architecture of the Alpine orogen. Eclog. Geol. Helv.

Schönborn G (1992) Alpine tectonics and kinematic models of the central Southern Alps. Mem. Sci. Geol. 44: 229-393

Schönborn G (1999) Balancing cross sections with kinematic constraints: The Dolomites (northern Italy). Tectonics 18: 527-545

Schreurs G (1993) Structural analysis of the Schamps nappes and adjacent tectonic units: implications for the orogenic evolution of the Penninic zone in eastern Switzerland. Bulletin de la Société géologique de France 164: 415-435

Schreurs G (1995) Structural analysis of the Schams nappes and adjacent tectonic units in the Pennine zone. In: The Schams nappes, part 2. Beitr. Geol. Karte Schweiz NF 167.

Schumacher ME, Laubscher HP (1996) 3D crustal structure of the Alps - Apennines join - a new view on seismic data. Tectonophysics 260: 349-363

Schuster R (2003) Das eo-Alpidische Ereigniss in den Ostalpen: Plattentektonische Situation und interne Struktur des Ostalpinen Kristallins. Arbeitstagung Geol. B.-A. Blatt 148 Brenner 2003: 141-159

Schuster R, Frank W (1999) Metamorphic evolution of the Austroaalpine units east of the Taauern window: indications for Jurassic strike slip tectonics. Mitt. Ges. Geol. Bergbaustud. Österr. 42: 37-58

Schuster R, Scharbert S, Abart R, Frank W (2001) Permo-Triassic extension and related HT/LP metamorphism in the Austroalpine - Southalpine realm. Mitt. Ges. Geol. Bergbaustud. Österr. 45: 111-141

Sinclair HD, Allen PA (1992) Vertical versus horizontal motions in the Alpine orogenic wedge: stratigraphic response in the foreland basin. Basin Research 4: 215-232

Sénéchal G, Thouvenot F (1991) Geometrical migration of line drawings: a simplified method apllied to ECORS data. In: Meissner R et al. (eds) Continental Lithosphere: Deep Seismic Reflection. Amer. Geophys. Union, Geodyn. Ser. 22: 401-408

Slapansky P, Frank W (1987) Structural evolution and geochronology of the northern margin of the Austroalpine in the northwestern Schladming crystalline (NE Radstädter Tauern). In: Flügel HW, Faupl, P (eds) Geodynamics of the Estern Alps, Deuticke Wien: 244-262

Solarino S, Kissling E, Sellami S, Smriglio G, Thouvenot F, Granet M, Bonjer K, Slejiko D (1997) Compilation of a recent seismicity data base of the greater Alpine region from several seismological networks and preliminary 3D tomographic results. Annali di Geofisica 11: 161-174

Spakman W (1991) Delay-time tomography of the upper mantle below Europe, the Mediterranean and Asia Minor. Geophysical Journal International 107: 309-332

Spakman W, vander Lee S, vander Hilst R (1993) Traveltime tomography of the European-Mediterranean mantle down to 1400 km. Physics of the Earth and Planetary Interiors 79: 3-74

Spillmann P (1993) Die Geologie des penninisch-ostalpinen Grenzbereichs im südlichen Berninagebirge. Ph.D. thesis ETH Zürich Nr. 10175

Stäuble M, Pfiffner OA (1991a) Processing, interpretation and modeling of seismic reflection data in the Molasse Basin of eastern Switzerland, Eclogae geol. Helv. 84: 151-175

Stäuble M, Pfiffner OA (1991b) Evaluation of the seismic response of basement fold-and-thrust geometry in the Central Alps based on 2-D ray tracing. Ann. Tectonicae 5: 3-17

Stäuble M, Pfiffner OA, Smithson SB (1993) Crustal structure and reflectivity of the Swiss Alps from three-dimensional seismic modelling (1) Helvetic nappes. Tectonics 12: 911-924

Stampfli G (1993) Le Briançonnais: Terrain exotique dans les Alpes? Eclogae Geol. Helv. 86: 1-45

Stampfli G (2000) Tethyan Oceans. In: Winchester JA et al. (eds) Tectonics and Magmatism in Turkey and the surrounding areas. Geol. Soc. London Spec. Publ. 173: 1-23

Stampfli G, Marchant R (1997) Geodynamic evolution of the Tethyan margins of the Western Alps. In: Pfiffner OA, Lehner P, Heitzmann P, Müller S, Steck A (eds) Deep Structure of the Swiss Alps. Birkhäuser Verlag Basel-Boston-Berlin: 223-239

Stampfli GM, Mosar J, Marchant R, Marquer D, Baudin T, Borel G (1998) Subduction and obduction processes in the western Alps In: Vauchez A, Meissner R (eds.) Continents and their mantle roots. Tectonophysics 296 (1-2): 159-204

Stampfli G, Mosar J, Favre Ph, Pillevuit A, Vannay JC (2001a) Permo-Mesozoic evolution of the western Tethys realm: the Neo-Tethys East Mediterranean Basin connection. In: Ziegler PA et al. (eds) Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins. Mém. Mus. natn. Hist. nat. Paris 186: 51-108

Stampfli GM, Borel G, Cavazza W, Mosar J, Ziegler PA (2001b) The paleotectonic atlas of the Peritethyan domain. CD ROM; European Geophysical Society.

Stampfli GM, Borel G, Marchant R, Mosar J (2002) Western Alps geological constraints on western Tethyan reconstructions. Journal Virtual Explorer 8: 77-106

Steck A (1984) Structures de déformation tertiaires dans les Alpes centrales (transversale Aar-Simplon-Ossola). Eclogae geol. Helv. 77: 55-100

Steck A (1990) Une carte des zones de cisaillement ductile des Alpes Centrales. Eclogae Geol. Helv. 83: 603-626

Steinmann, M (1994) Ein Beckenmodell für das Nordpenninikum der Ostschweiz. Jahrbuch der Geologischen Bundesanstalt 137: 675-721

Stipp M, Fügenschuh B, Gromet, LP, Stünitz H, Schmid SM (in press) Contemporaneous plutonism and strike-slip faulting along the easternmost segment of the Insubric line: the Tonale fault zone north of the Adamello pluton (Italian Alps). Tectonics

Sue C, Thouvenot F, Frechet J, Tricart P (1999) Widespread extension in the core of the Western Alps revealed by earthquake analysis. Journal of Geophysical Research 104(B11): 25,611-25,622

Suhadolc P, Panza GF, Müller St. (1990) Physical properties of the lithosphere-asthenosphere system in Europe. Tectonophysics 176: 123-135

Thöni M (1999) A review of geochronological data from the Eastern Alps. Schweiz. Mineral. Petr. Mitt. 79: 209-230

Thouvenot F, Paul A, Sénéchal G, Hirn A, Nicolich, R (1990) ECORS-CROP wide-angle reflection seismics: constraints on deepintrefaces beneath the Alps. In: Roure F, Heitzmann P, Polino R (eds) Deep Structure of the Alps. Mémoire de la Societé geologique Suisse 1: 97-106

Thouvenot F, Senechal G, Truffert C, Guellec S (1996) Comparison between two techniques of line-drawing migration (ray tracing and common tangent method). Mém. Soc. géol. France 170: 53-59

Tollmann A (1977) Geologie von Österreich. Band 1: Die Zentralalpen. Deuticke, Wien: 766pp

Tomljenovic B (2002) Strukturne Znacajke Medvednice i Samoborskoj gorja. PhD thesis, University of Zagreb: 208pp

TRANSALP Working Group (2001) European orogenic processes research transects the Eastern Alps. EOS: Transactions of the American Geophysical Union 82, 453: 460-461

TRANSALP Working Group (2002) First deep seismic reflection images of the Eastern Alps reveal giant crustal wedges and transcrustal ramps. Geophys. Res. Letters 29/10: 92-1 - 92-4

Trommsdorff V, Piccardo GB, Montrasio A (1993) From magmatism through metamorphism to sea floor emplacement of subcontinental Adria lithosphere during pre-Alpine rifting (Malenco, Italy). Schweiz. Mineral. Petrogr. Mitt. 73: 191-203

Trümpy R (1955) Remarques sur la corrélation des unités penniques externes antre la Savoie et le Valais et sur l'origine des nappes préalpines. Bull. Soc. Géol. de France 6ème série tome V: 217-231

Trümpy R (1960) Paleotectonic evolution of the Central and Western Alps. Bull. Geol. Soc. America 71: 843-908

Trümpy R (1992) Ostalpen und Westalpen - Verbindendes und Trennendes. Jb. Geol. B.-A. 135: 875-882

Trümpy R (1999) Die tektonischen Grosseinheiten im Bereich AlpTransit. In: Löw S, Wyss R (eds) Vorerkundung und Prognose der Basistunnels am Gotthard und am Lötschberg. Balkema Rotterdam: 21-29

Valasek P (1992) The tectonic structure of the Swiss Alpine crust interpreted from a 2D network of deep crustal seismic profiles and an evaluation of 3-D effects. Ph.D. thesis ETH Zürich No. 9637: 195pp and Appendix

Valasek P, Müller S, Frei W, Holliger K. (1991) Results of NFP20 seismic reflection profiling along the Alpine section of the European Geotraverse (EGT). Geophysical Journal International 105: 85-102

Valasek P, Müller S. (1997) A 3D tectonic model of the Central Alps based on an integrated interpretation of seismic refraction and NRP20 reflection data. In: Pfiffner OA, Lehner P, Heitzmann P, Müller S, Steck A (eds) Deep Structure of the Swiss Alps. Birkhäuser Verlag Basel-Boston-Berlin: 305-325

Vearncombe, J.R. (1985) The structure of the Gran Paradiso basement massif and its enveloppe, Western Alps. Eclogae geol. Helv. 78: 49-72

von Blanckenburg F, Davies, JH (1995) Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps. Tectonics 14: 120-131

Viel L, Berckhemer H, Müller S (1991) Some structural features of the Alpine lithospheric root. Tectonophysics 195: 421-436

Wagner LR (1996) Stratigraphy and hydrocarbons in the Upper Austrian Molasse Foredeep (active margin). In Wessely G, Liebel W (eds) Oil and Gas in the Alpidic Thrustbelt and Basins of Central and Eastern Europe. EAGE Spec. Publ. 5: 217-235.

Wagreich M (2001) A 400-km-long piggyback basin (Upper Aptian-Lower Cenomanian) in the Eastern Alps. Terra Nova 13: 401-406

Waldhauser F, Kissling E, Ansorge J, Müller S (1998) Three-dimensional interface modelling with two-dimensional seismic data: the Alpine crust-mantle boundary. Geophysical Journal International 135: 264-278

Waldhauser F, Kissling E, Ansorge J, Müller S (1998) Three-dimensional interface modelling with two-dimensional seismic data: The Alpine crust-mantle boundary. Geophysical Journal International 135: 264-278

Waldhauser F, Lippitsch R, Kissling E, Ansorge J (2002) High-resolution teleseismic tomography of upper-mantle structure using an a priori three-dimensional crustal model. Geophysical Journal International 150: 403-414

Weh M, Froitzheim N (2000) Penninic cover nappes in the Prättigau half-window (Eastern Switzerland): Structure and tectonic evolution. Eclogae geol. Helv. 94: 237-252

Wenk HR (1973): The structure of the Bergell Alps. Eclogae geol. Helv. 66: 255-291

Wortel MJR, Spakman W (2002) Subduction and slab detachment in the Mediterranean-Carpathian region. Science 290: 1910-1917

Ye S, Ansorge J, Kissling E, Müller S (1995) Crustal structure beneath the Swiss Alps derived from seismic refraction data. Tectonophysics 242: 199-221

Ziegler PA (1990) Geological Atlas of Western and Central Europe. 2nd. Ed. Shell Internat. Petrol. Mij., dist. Geol. Soc. Publ. House, Bath: 239 pp, 56 enclosures

Ziegler PA, Bertotti G, Cloetingh S (2002) Dynamic processes controlling foreland development – the role of mechanical (de)coupling of orogenic wedges and forelands. In: Bertotti G, Schulmann K, Cloetingh S (eds) Continental collision and the tectono-sedimentary evolution of forelands. EGU Stephan Müller Special Publications Series 1: 17-56

Ziegler PA, Dèzes P (2004) Crustal configuration of Western and Central Europe. In: Gee D, Stephenson R (eds) European Lithosphere Dynamics. Geol. Soc. London Memoir. See also Moho map available under http://www.unibas.ch/eucor-urgent

Ziegler PA, Stampfli GM (2001) Late Paleozoic Early Mesozoic plate boundary reorganisation: collapse of the Variscan orogen and opening of Neotethys In: Cassinis R (eds.) the continental Permian of the Southern Alps and Sardinia (Italy) regional reports and general correlations. Annali Museo Civico Science Naturali, Brescia 25: 17-34

Zimmer W, Wessely G (1996) Hydrocarbon exploration in the Austrian Alps. In: Ziegler PA, Horvàth F (eds.) Structure and prospects of Alpine basins and forelands. Peri-Tethys Memoire 2. Mém. Mus. natn. Hist. nat., Paris 170: 285-304

Table and Figure captions

Table 1
N-S convergence along TRANSMED transect V, derived from the scaled and area-balanced profiles depicted in Fig. 5

Fig. 1
Map of major paleogeographic and tectonic units in the Alps, after Schmid et al. (in press), modified and completed after an earlier version by Froitzheim et al. (1996).

Fig. 2
Schematic transects through the Alps. Sections a) to c) are after Schmid and Kissling (2000) and Schmid et al. (1996a). For section c) see also Escher et al. 1988, 1997. Section d) is after Schmid et al. 2003 and includes information from Lippitsch (1992) and TRANSALP working group (2003). Section e) is from Schmid et al. (in press). a) ECORS-CROP profile, corresponding to TRANSMED transect IV; b) NFP-20-West profile; c) NFP-20-East and EGT profile, corresponding to TRANSMED transect V; d) TRANSALP profile; e) EASTERN ALPS profile, corresponding to TRANSMED transect VI.

Fig. 3
Large-scale paleogeographical reconstruction, basically based on Stampfi et al. (2001), for a) Late Triassic, b) Late Jurassic and c) Late Cretaceous times. See also: Frank 1987, Stampfli 1993, Schmid et al. 1997, Schmid et al. in press.

Fig. 4
Correlation table showing age of deformation phases and metamorphism along TRANSMED transect V; after Schmid et al. (1996a).

Fig. 5
Scaled and area balanced sketches of the kinematic evolution of the eastern Central Alps from early Tertiary convergence (a-b) to collision (c) and post-collisional shortening (d-g); after Schmid et al. (1996a).

Fig. 6
Crustal cross-section along the European Geotraverse (EGT) across the Central Alps from the northern Alpine foreland to the Ligurian Sea based on active refraction and wide-angle reflection data. A to F denote shot points, numbers give P-wave velocities in km/s, M denotes crust-mantle boundary; after Ye et al. (1995).

Fig. 7
(a) Depth map of crust-mantle boundary in the wider Alpine region contoured at 2 km intervals, based on smoothest interpolation of 3D migrated CSS data. Numbers indicate isoline depth values. Broken bars indicate locations of wide-angle Moho reflection elements.
(b) Perspective SW view on the European (M^e), Adriatic (M^a), and Ligurian (M^l) Moho. The Ivrea Zone is indicated, while the Ivrea geophysical body is not shown).
Figures are after Waldhauser et al. (1998).

Fig. 8
Depth map of top of European lower crust in the N, of European lower crustal wedge in the W, of Adriatic lower crust in the N central region, and of Adriatic Moho in the S, showing location of main crustal transects (Fig. 3). Note also tentative depth extension of Insubric Line and location of high-velocity Ivrea material. The contour interval is 2km; after Schmid and Kissling (2000).

Fig. 9
Kinematic reconstruction of post-collisional (post-35 Ma) shortening in the Alps along the ECORS-CROP (=TRANSMED IV) transect in three episodes after Schmid and Kissling (2000). The vector triangle (top right) illustrates how the assumed total amount of post-collisional shortening (124km), corresponding to vector AE (movement of the Adriatic micro-plate in respect to Europe), was obtained from resolving 100km dextral strike slip between the Adriatic micro-plate and the Central Alps (vector AC) into the western transect. Vector CE results in 71 km N-S shortening within the Central Alps,

parallel to the NFP-20/EGT (=TRANSMED V) transect. See Schmid and Kissling (2000) for an extensive discussion.

Fig. 10
Simple kinematic retro-translation (length of vectors given in km) of some key tectonic features, as they appear in present day map view, accounting for the estimated amount of convergence between these features and the fixed European foreland: Position at present (orange), 35 Ma ago (green), and, 50 Ma ago (red). The position of the NW edge of the Adriatic micro-plate (present-day Insubric Line) was obtained by a 124 km retro-translation towards azimuth 125° (see inset of Figure 9) plus an 18° clockwise retro-rotation. The positions of the other tectonic features 35 Ma ago correspond to those given in Figure 9 (ECORS-CROP profile) and by a similar kinematic reconstruction in profile view along the NRP-20 east profile (Fig. 5), respectively. A common S-directed retro-translation by 195km between 35Ma and 50 Ma (corresponding to the N-S convergence between European foreland and Adriatic micro-plate for this time interval, as estimated by Schmid et al. (1996a) along the NRP-20 east profile, restores the configuration at the onset of collision in the Alps; after Schmid and Kissling (2000) where a further discussion is given.

Fig. 11
P-wave velocities 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 and Morelli (2003). Lower part shows section between thick horizontal bars on the map. Note the northerly vergence of subducted high-velocity material below 150 km depth under the Eastern Alps.
(b) NW-SE cross-section through the Central Alps after Bijwaard and Spakman (2000). For location see B-B’ in Figure 12. Note SE vergence of subducted European lithosphere. Note also the high-velocity material in the upper mantle transition zone between 400 and 620 km depth.

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

Fig. 13
Lower lithosphere transects; after Lippitsch et al. (2003): (a) A-A’ Western Alps with crustal transect ECORS-CROP as in Fig. 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 Fig 10b. Thin dashed line indicates lithosphere-asthenosphere boundary LAB.

Fig. 14
Combined crustal and lower lithosphere transects along high-resolution crustal geophysical-geological transects (Fig. 3b,c, d); after Kissling et al. (in press). For location and display mode see Fig. 12 II, III, IV: (a) NFP-20 WEST, (b) NFP-20 EAST/EGT, (c) TRANSALP.

Fig. 15
Map showing degree of Cretaceous-age (Eoalpine) metamorphism; after Schuster (2003). Note increase in grade of metamorphism from north to south up to the SAM ("Southern Border of Alpine Metamorphism" (Hoinkes et al. 1999). The SAM cuts this zonation, due to a Neogene dextral strike slip fault with a vertical component depicted in TRANSALP transect VI and also shown in the profile at the bottom of this figure. Note inverted field metamorphic gradient in the lower limb of a mega-fold north of the SAM, interpreted as being related to Late Cretaceous exhumation by extrusion. The extruded unit constitutes the Koralpe-Wölz high-pressure nappe system depicted in Fig. 2e, or the "Paleozoic with Eo-Alpine high-P overprint" shown in TRANSMED transect VI, respectively.

table 1: N-S convergence derived from the scaled and area balanced profiles depicted in Fig. 5 (after Schmid et al. 1996)

time interval	amount of convergence across the Alps	convergence rate	plate tectonic reconstruction (Dewey et al. 1989)
Early Paleocene to Early Eocene (65-50 Ma)	200 km inferred from relative displacement between points a and b in fig. 5. 116 km of thinned continental crust of the Briançonnais domain and the Valais ocean enter the subduction zone.	1.33 cm / a	0.22 cm / a 55 Ma 0.4 cm / a 51 Ma
Early to Late Eocene (50-40 Ma)	150 km inferred from relative displacement between points a and b in fig. 5. 150 km of distal European margin situated between the southern edge of the Helvetic domain and the southern tip of stable Europe enter the subduction zone.	1.5 cm / a	1.2 cm / a 38 Ma
Late Eocene to Oligocene (40-32 Ma)	45 km inferred from relative displacement between points a and c in fig. 5. Detachment of the Helvetic sediments and deformation within the Subpenninic nappes. Unknown amount of shortening in the vicinity of the Insubric line and in the Southern Alps: 45 km represent a minimum estimate only	at least 0.55 cm / a	
Oligocene to Early Miocene (32-19 Ma)	a total of 58 km consisting of: 33 km from relative displacement between points a and c in fig. 5 (including 6km out of a total of 21 km shortening in the Aar massif) 15 km from backthrusting along the Insubric line 10 km out of a total of 56 km post-Adamello phase shortening in the Southern Alps	0.45 cm / a	0.94 cm / a 19 Ma
Early Miocene to recent (19-0 Ma)	a total of 61 km consisting of: 15 km from shortening in the Aar massif 46 km from shortening in the Southern Alps	0.3 cm / a (0.5 cm / a if deformation stopped at 7 Ma)	0.3 cm / a 9 Ma 0.43 cm / a 0 Ma
Total time span (65-0 Ma)	more than 514 km	more than 0.79 cm / a	average: 0.72 cm / a amount of convergence: 481 km

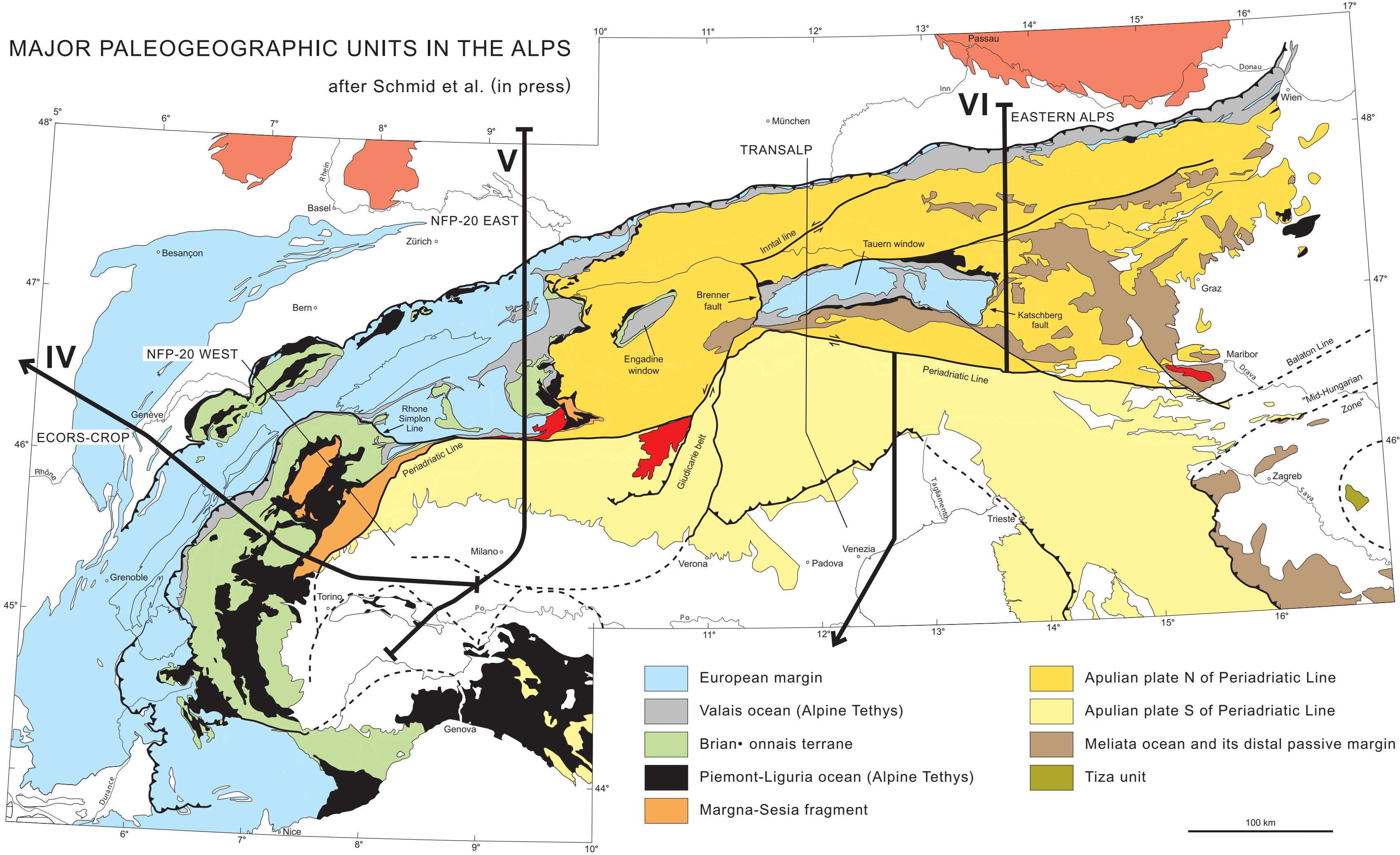

MAJOR PALEOGEOGRAPHIC UNITS IN THE ALPS
after Schmid et al. (in press)
V
VI
IV
EASTERN ALPS
TRANSALP
NFP-20 EAST
NFP-20 WEST
ECORS-CROP
München
Passau
Inn
Donau
Wien
Basel
Rhein
Zürich
Besançon
Bern
Genève
Rhône
Grenoble
Durance
Nice
Torino
Milano
Genova
Po
Verona
Padova
Venezia
Trieste
Tagliamento
Graz
Maribor
Drava
Zagreb
Sava
Inntal line
Tauern window
Brenner fault
Katschberg fault
Engadine window
Rhone Simplon Line
Periadriatic Line
Giudicarie belt
Balaton Line
"Mid-Hungarian Zone"
European margin
Valais ocean (Alpine Tethys)
Brian• onnais terrane
Piemont-Liguria ocean (Alpine Tethys)
Margna-Sesia fragment
Apulian plate N of Periadriatic Line
Apulian plate S of Periadriatic Line
Meliata ocean and its distal passive margin
Tiza unit
100 km

Fig. IV-VI. 1

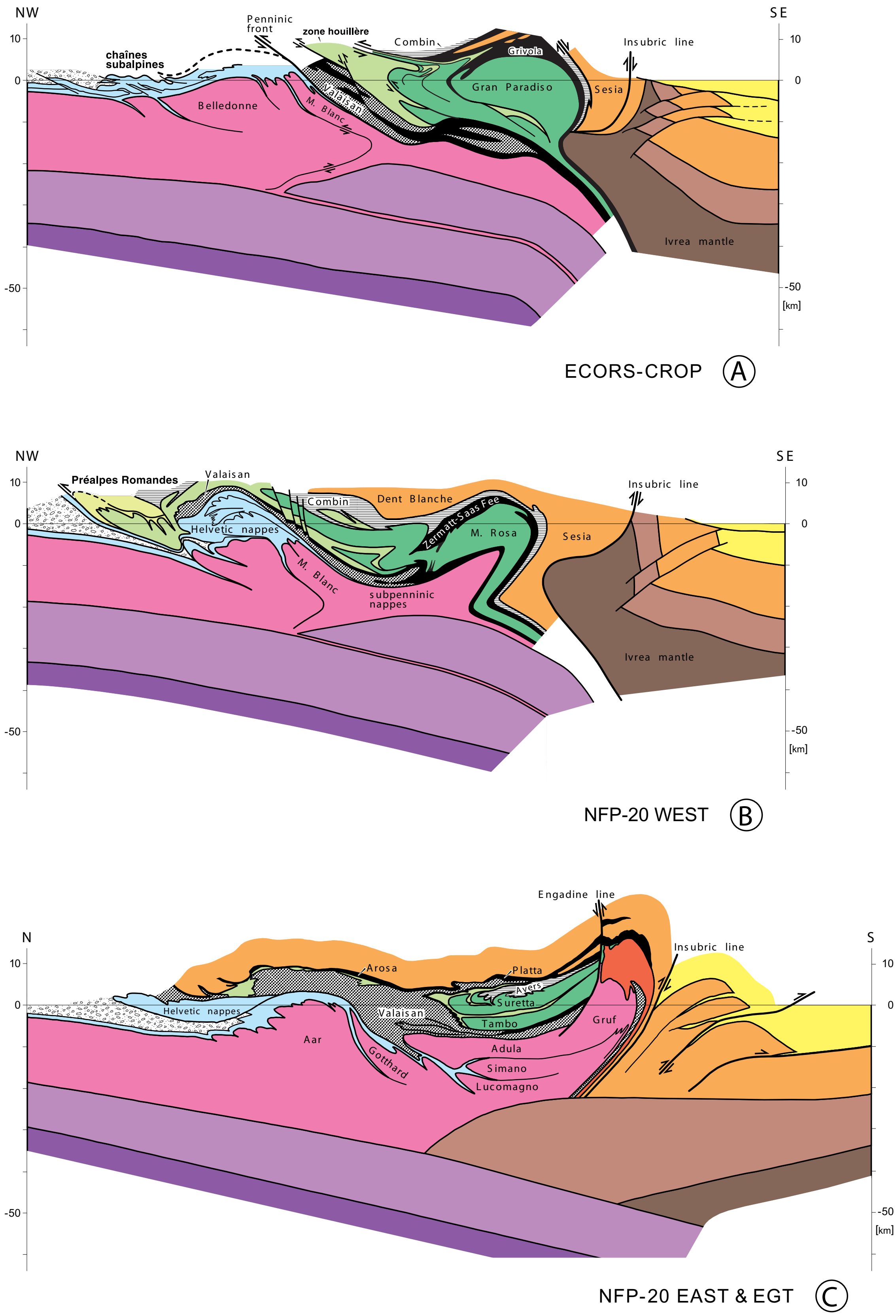

NW
SE
10
0
-50
[km]
Penninic front
zone houillère
Combin
Grivola
Insubric line
chaînes subalpines
Belledonne
Valaisan
M. Blanc
Gran Paradiso
Sesia
Ivrea mantle
ECORS-CROP
A
NW
SE
10
0
-50
[km]
Préalpes Romandes
Valaisan
Combin
Dent Blanche
Zermatt-Saas Fee
Insubric line
Helvetic nappes
M. Rosa
Sesia
M. Blanc
subpenninic nappes
Ivrea mantle
NFP-20 WEST
B
Engadine line
N
S
10
0
-50
[km]
Arosa
Platta
Insubric line
Avers
Suretta
Helvetic nappes
Valaisan
Tambo
Gruf
Aar
Adula
Gotthard
Simano
Lucomagno
NFP-20 EAST & EGT
C

Fig. IV-VI. 2 a-c

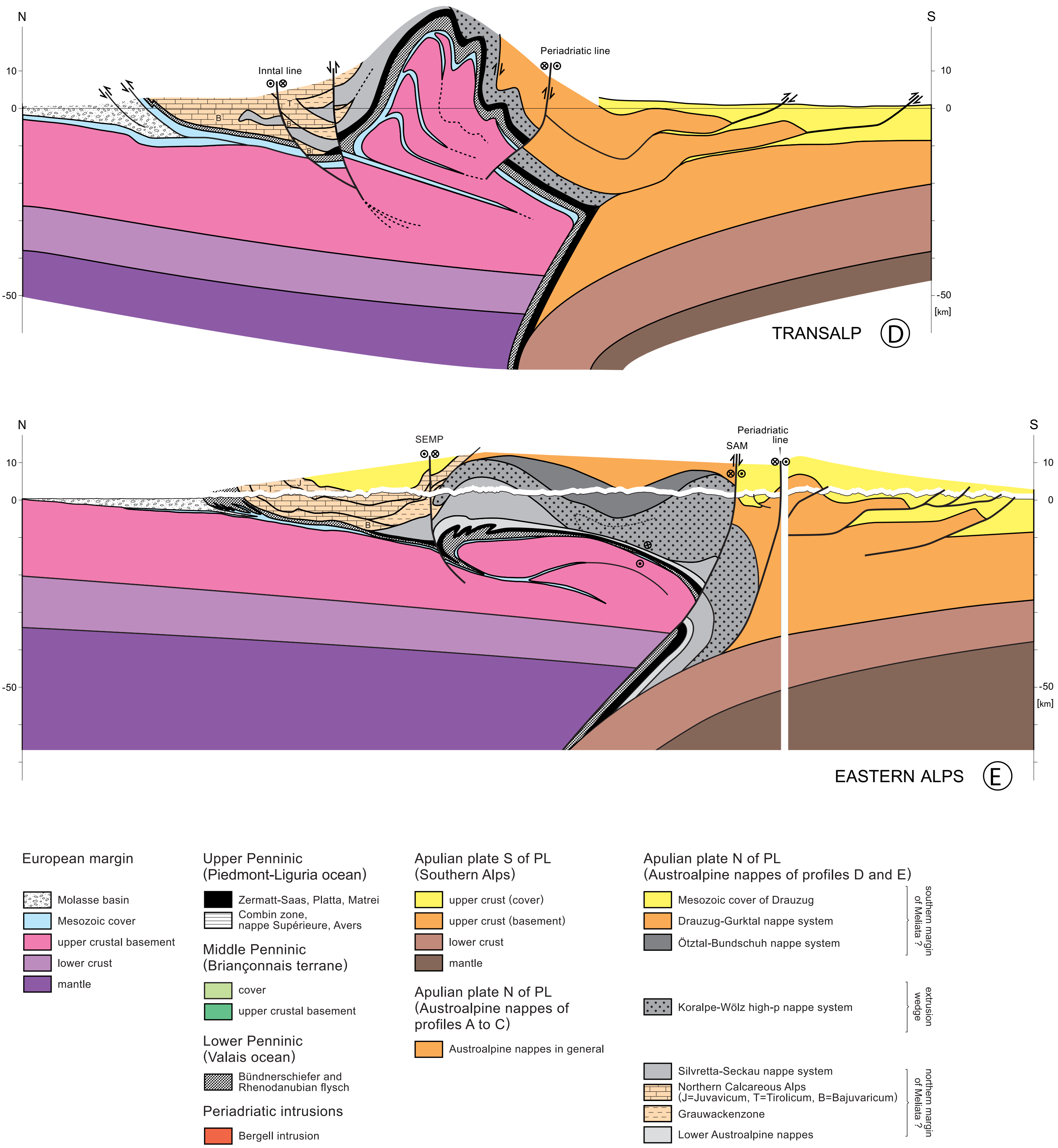

N
S
10
0
-50
[km]
Inntal line
Periadriatic line
B
T
TRANSALP
D
SEMP
SAM
Periadriatic line
J
EASTERN ALPS
E
European margin
Molasse basin
Mesozoic cover
upper crustal basement
lower crust
mantle
Upper Penninic
(Piedmont-Liguria ocean)
Zermatt-Saas, Platta, Matrei
Combin zone,
nappe Supérieure, Avers
Middle Penninic
(Briançonnais terrane)
cover
upper crustal basement
Lower Penninic
(Valais ocean)
Bündnerschiefer and
Rhenodanubian flysch
Periadriatic intrusions
Bergell intrusion
Apulian plate S of PL
(Southern Alps)
upper crust (cover)
upper crust (basement)
lower crust
mantle
Apulian plate N of PL
(Austroalpine nappes of
profiles A to C)
Austroalpine nappes in general
Apulian plate N of PL
(Austroalpine nappes of profiles D and E)
Mesozoic cover of Drauzug
Drauzug-Gurktal nappe system
Ötztal-Bundschuh nappe system
southern margin
of Meliata ?
Koralpe-Wölz high-p nappe system
extrusion
wedge
Silvretta-Seckau nappe system
Northern Calcareous Alps
(J=Juvavicum, T=Tirolicum, B=Bajuvaricum)
Grauwackenzone
Lower Austroalpine nappes
northern margin
of Meliata ?

Fig. IV-VI. 2 d,e

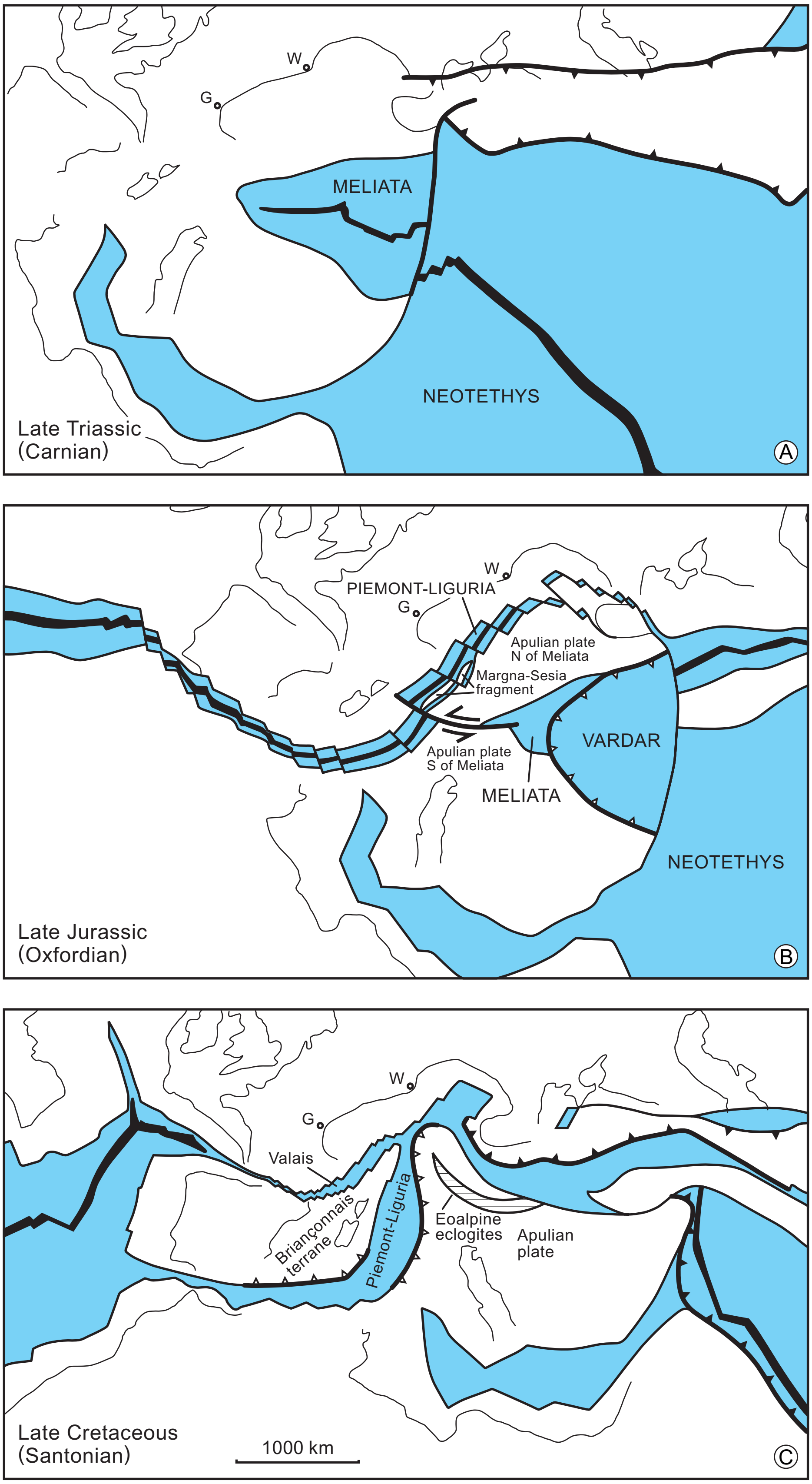

W
G
MELIATA
NEOTETHYS
Late Triassic
(Carnian)
A
W
PIEMONT-LIGURIA
G
Apulian plate
N of Meliata
Margna-Sesia
fragment
VARDAR
Apulian plate
S of Meliata
MELIATA
NEOTETHYS
Late Jurassic
(Oxfordian)
B
W
G
Valais
Briançonnais
terrane
Piemont-Liguria
Eoalpine
eclogites
Apulian
plate
Late Cretaceous
(Santonian)
1000 km
C

Fig. IV-VI. 3

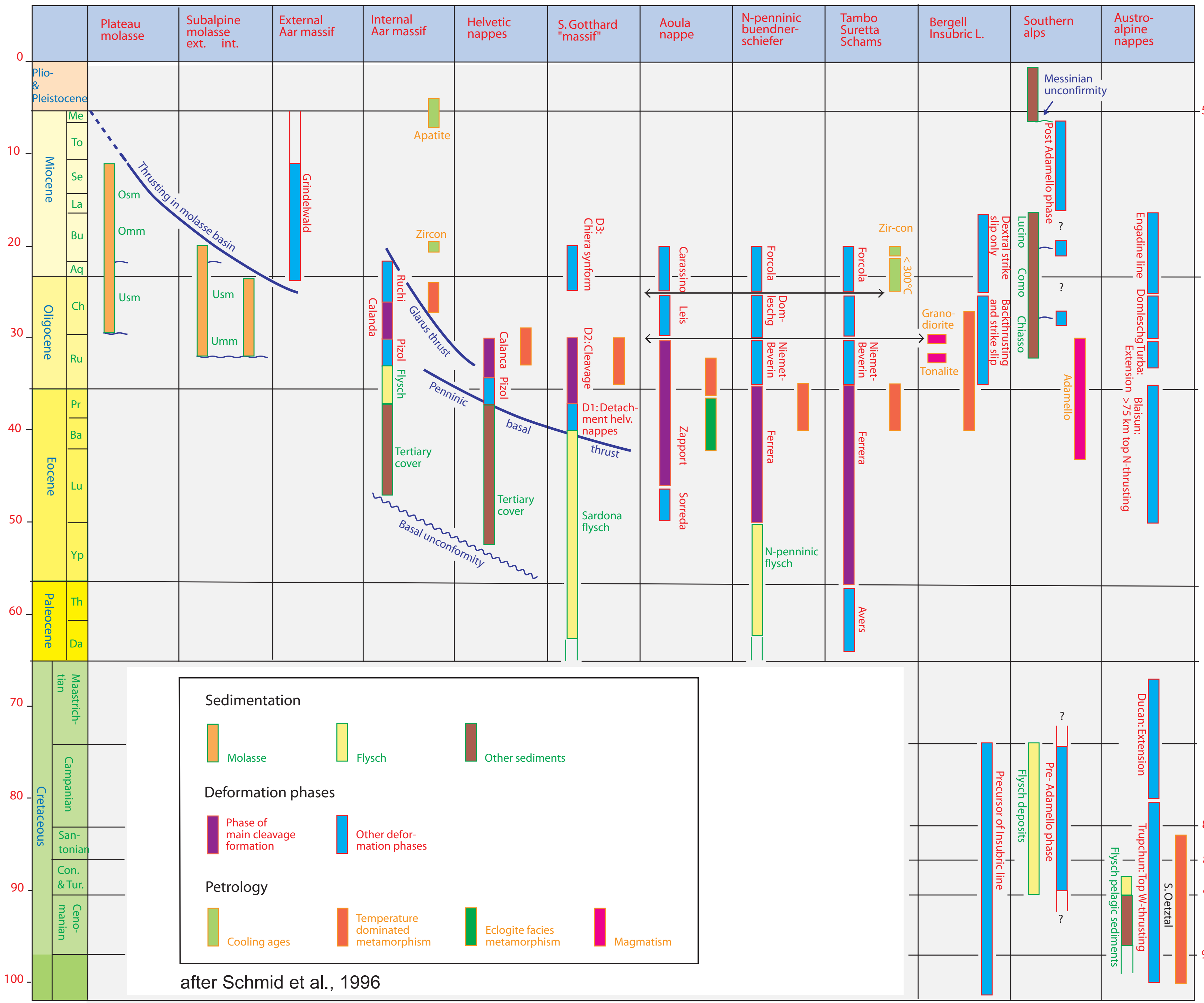

Plateau molasse
Subalpine molasse ext. int.
External Aar massif
Internal Aar massif
Helvetic nappes
S.Gotthard "massif"
Aoula nappe
N-penninic buendner-schiefer
Tambo Suretta Schams
Bergell Insubric L.
Southern alps
Austro-alpine nappes
Plio- & Pleistocene
Miocene
Oligocene
Eocene
Paleocene
Cretaceous
Me
To
Se
La
Bu
Aq
Ch
Ru
Pr
Ba
Lu
Yp
Th
Da
Maastrich-tian
Campanian
San-tonian
Con. & Tur.
Ceno-manian
0
10
20
30
40
50
60
70
80
90
100
5.2
23.3
35.4
65.0
74.0
83.0
86.6
90.4
97.0
Messinian unconfirmity
Osm
Omm
Usm
Umm
Thrusting in molasse basin
Grindelwald
Apatite
Zircon
Ruchi
Calanda
Glarus thrust
Pizol
Flysch
Tertiary cover
Penninic basal thrust
Basal unconformity
Calanca
Pizol
D3: Chiera synform
D2: Cleavage
D1: Detach-ment helv. nappes
Sardona flysch
Carassino
Leis
Zapport
Sorreda
Forcola
Dom-leschg
Niemet-Beverin
Ferrera
N-penninic flysch
Avers
Zir-con
< 300°C
Grano-diorite
Tonalite
Dextral strike slip only
Backthrusting and strike slip
Lucino
Como
Chiasso
Post Adamello phase
Adamello
Engadine line
Domleschg Turba: Extension
Blaisun: >75 km top N-thrusting
Precursor of Insubric line
Flysch deposits
Pre- Adamello phase
Ducan: Extension
Trupchun: Top W-thrusting
Flysch pelagic sediments
S.Oetztal
Sedimentation
Molasse
Flysch
Other sediments
Deformation phases
Phase of main cleavage formation
Other defor-mation phases
Petrology
Cooling ages
Temperature dominated metamorphism
Eclogite facies metamorphism
Magmatism
after Schmid et al., 1996

Fig. IV-VI. 4

Scaled and area-balenced sketches of the kinematic evolution of the eastern Central Alps from (a-b) early Tertiary convergence and subduction to (c) collision and (d-g) postcollisional shortening.

after Schmid et. al. (1996)

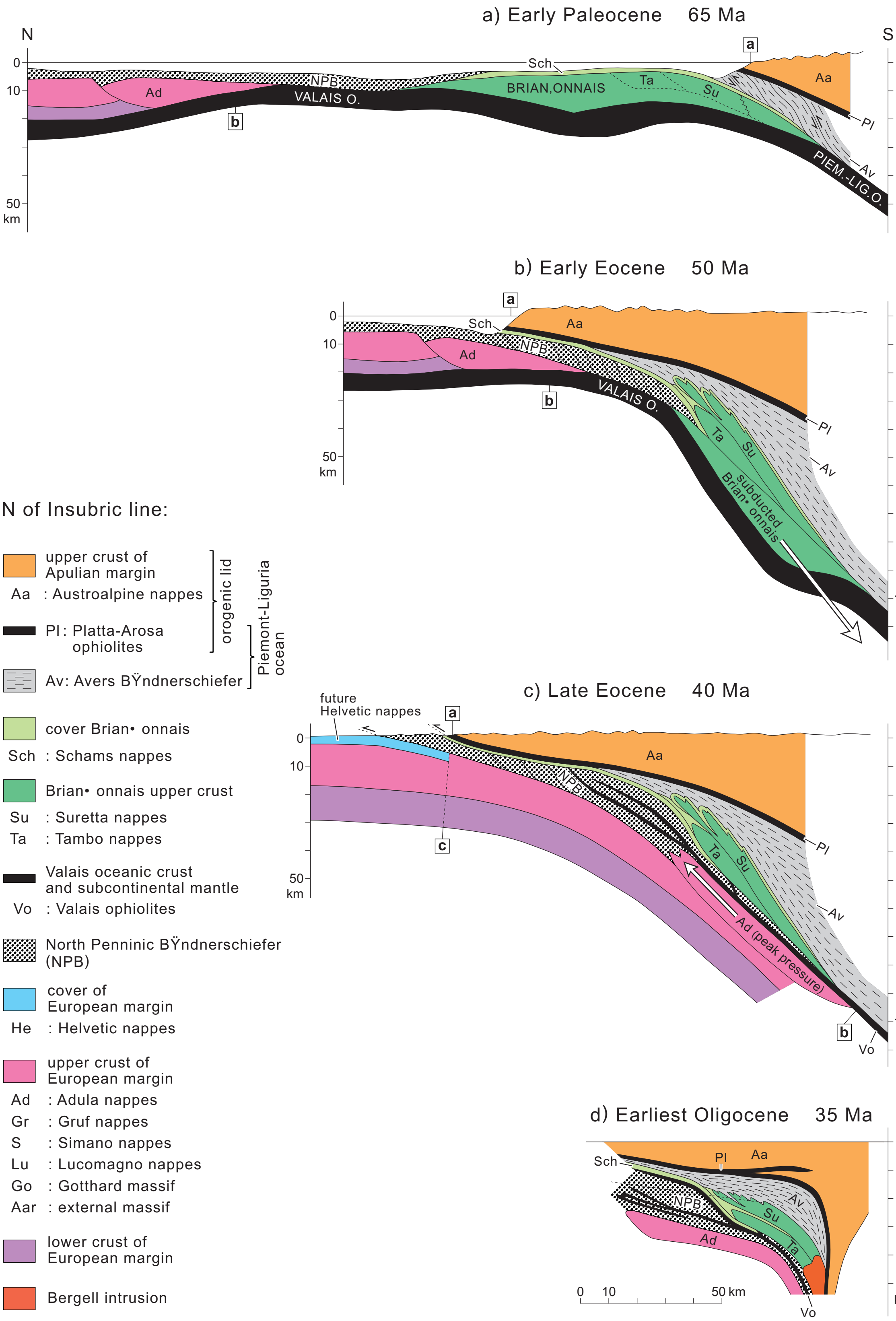


Fig. IV-VI. 5, a-d

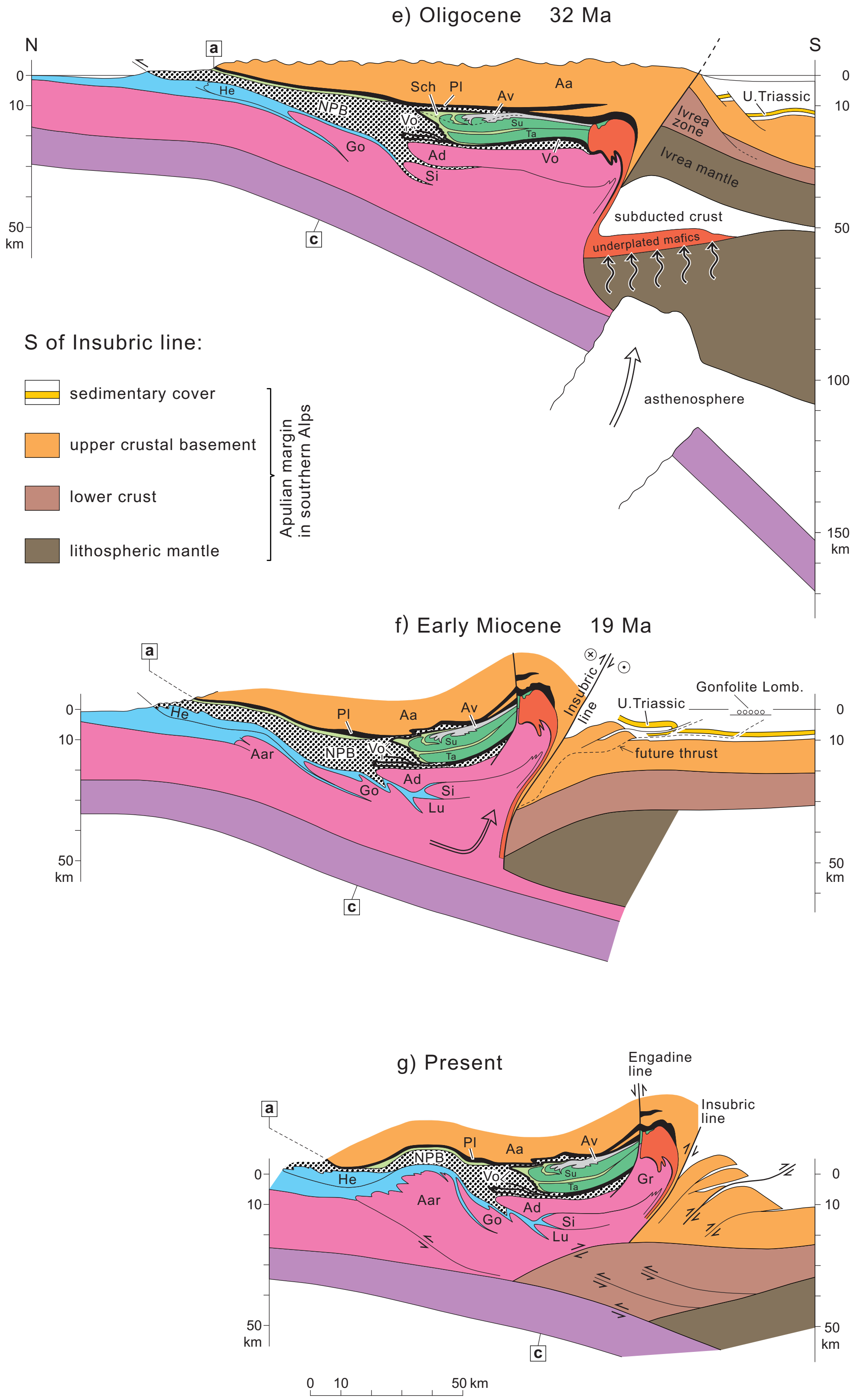
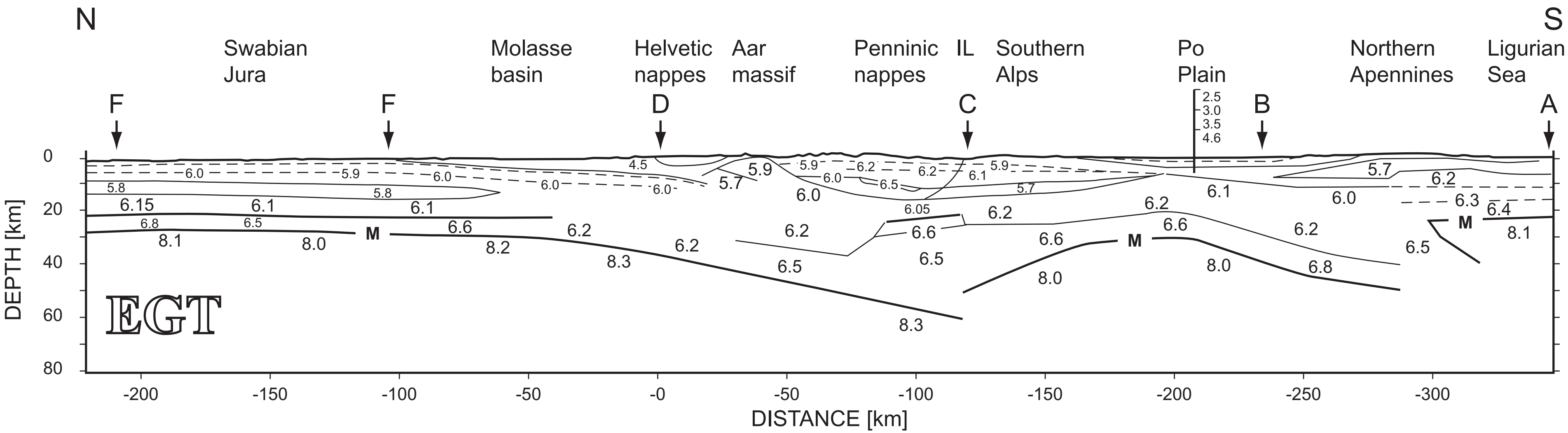
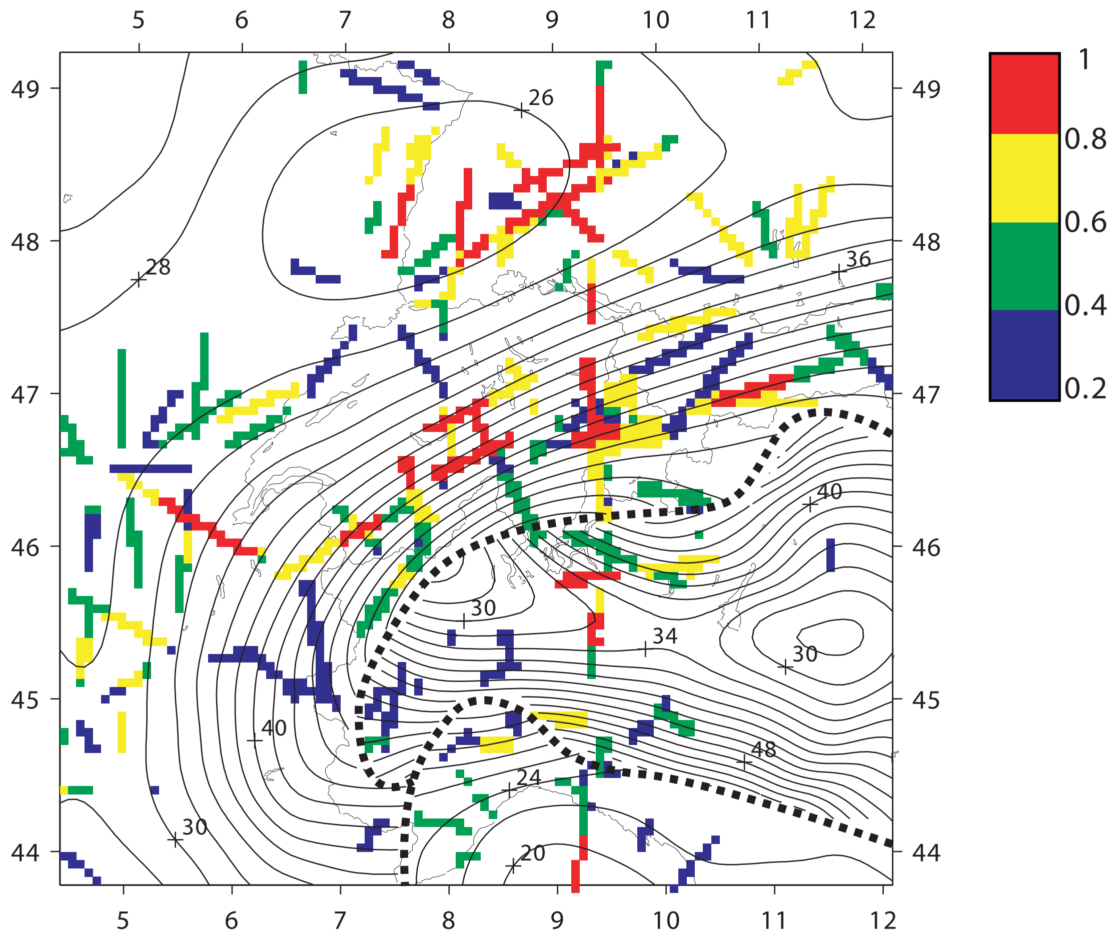

e) Oligocene 32 Ma
N
S
a
c
He
NPB
Go
Vo
Si
Ad
Sch
Pl
Av
Aa
Su
Ta
Vo
U.Triassic
Ivrea zone
Ivrea mantle
subducted crust
underplated mafics
asthenosphere
0
10
50
km
0
10
50
100
150
km
S of Insubric line:
sedimentary cover
upper crustal basement
lower crust
lithospheric mantle
Apulian margin in soutrhern Alps
f) Early Miocene 19 Ma
a
He
Aar
NPB
Vo
Pl
Aa
Av
Su
Ta
Ad
Go
Si
Lu
Insubric line
U.Triassic
Gonfolite Lomb.
future thrust
c
0
10
50
km
g) Present
Engadine line
Insubric line
a
He
NPB
Pl
Aa
Av
Vo
Su
Ta
Gr
Aar
Ad
Go
Si
Lu
c
0
10
50
km
0 10 50 km

Fig. IV-VI. 5, e-g

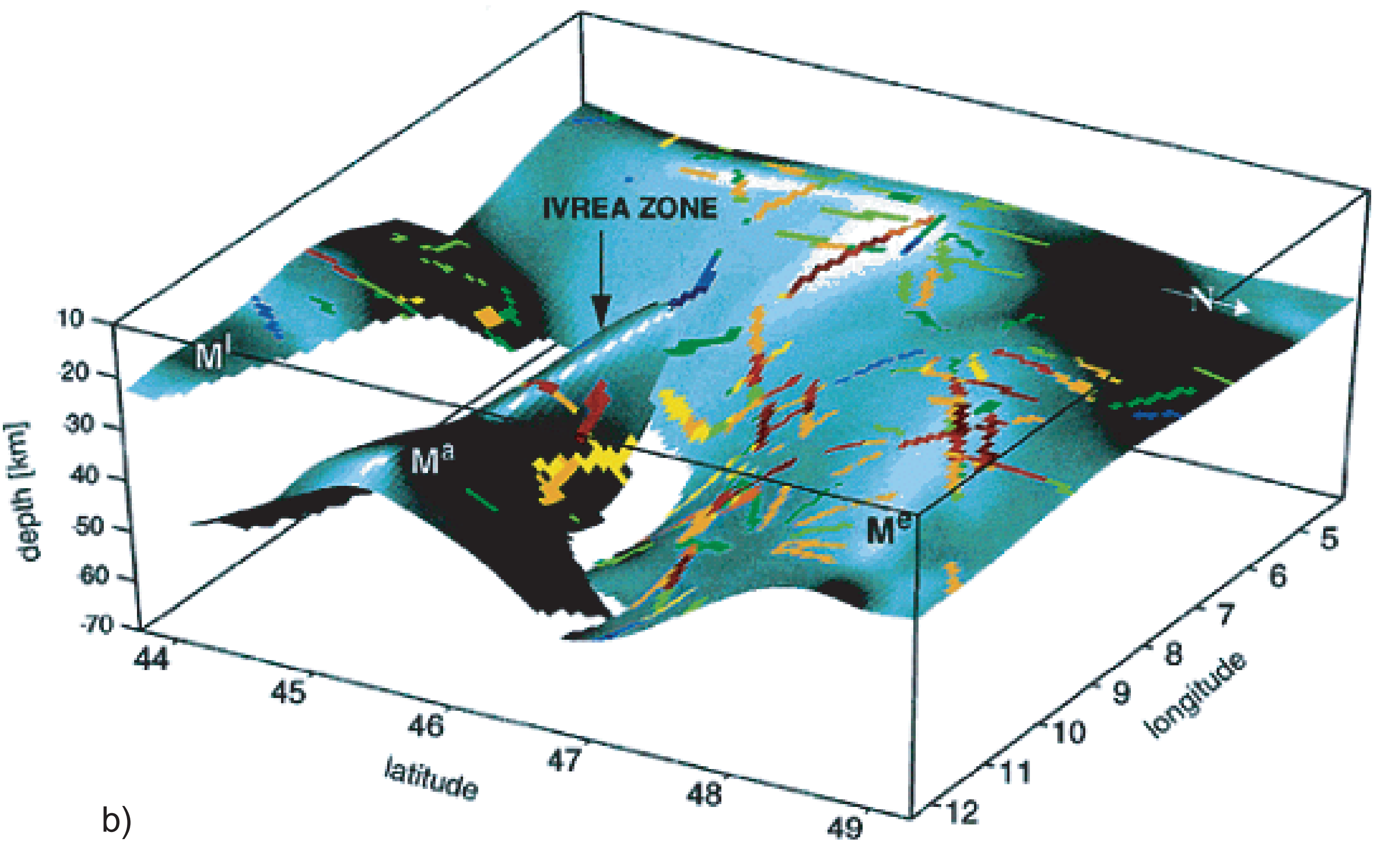


after Ye et al., 1995

Fig. IV-VI. 6



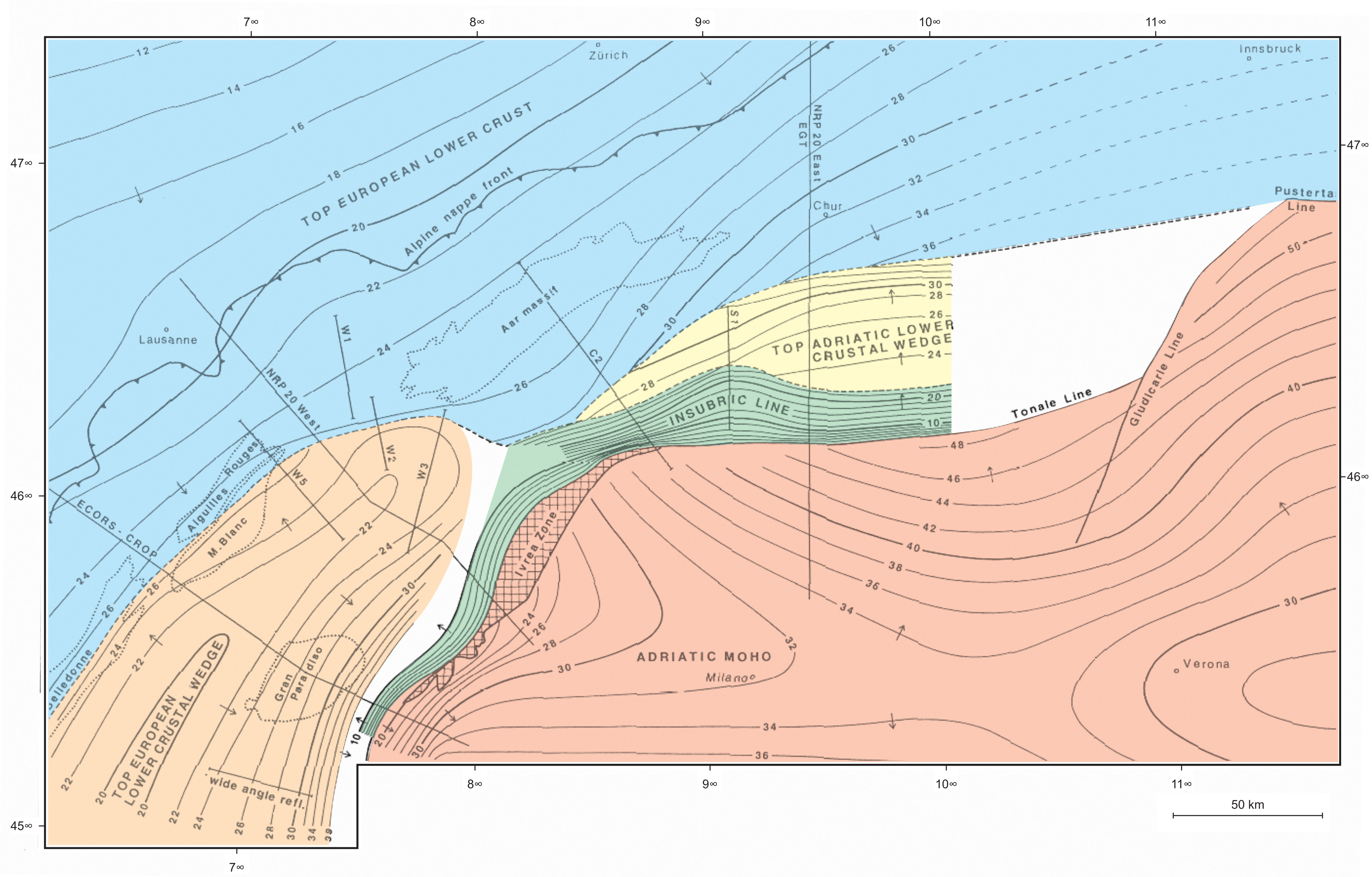
a)



b)

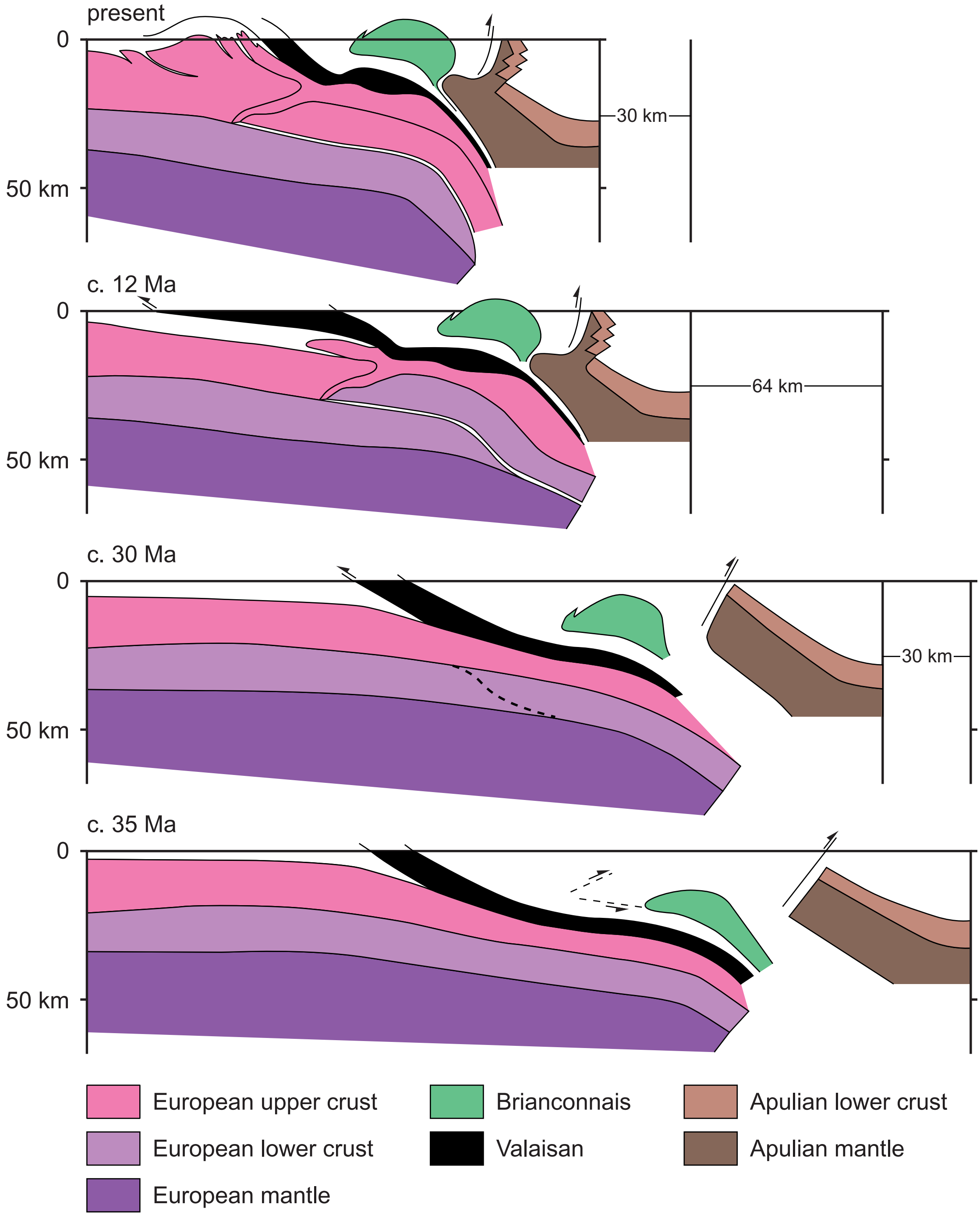
after Waldhauser et al. 1998

Fig. IV-VI. 7



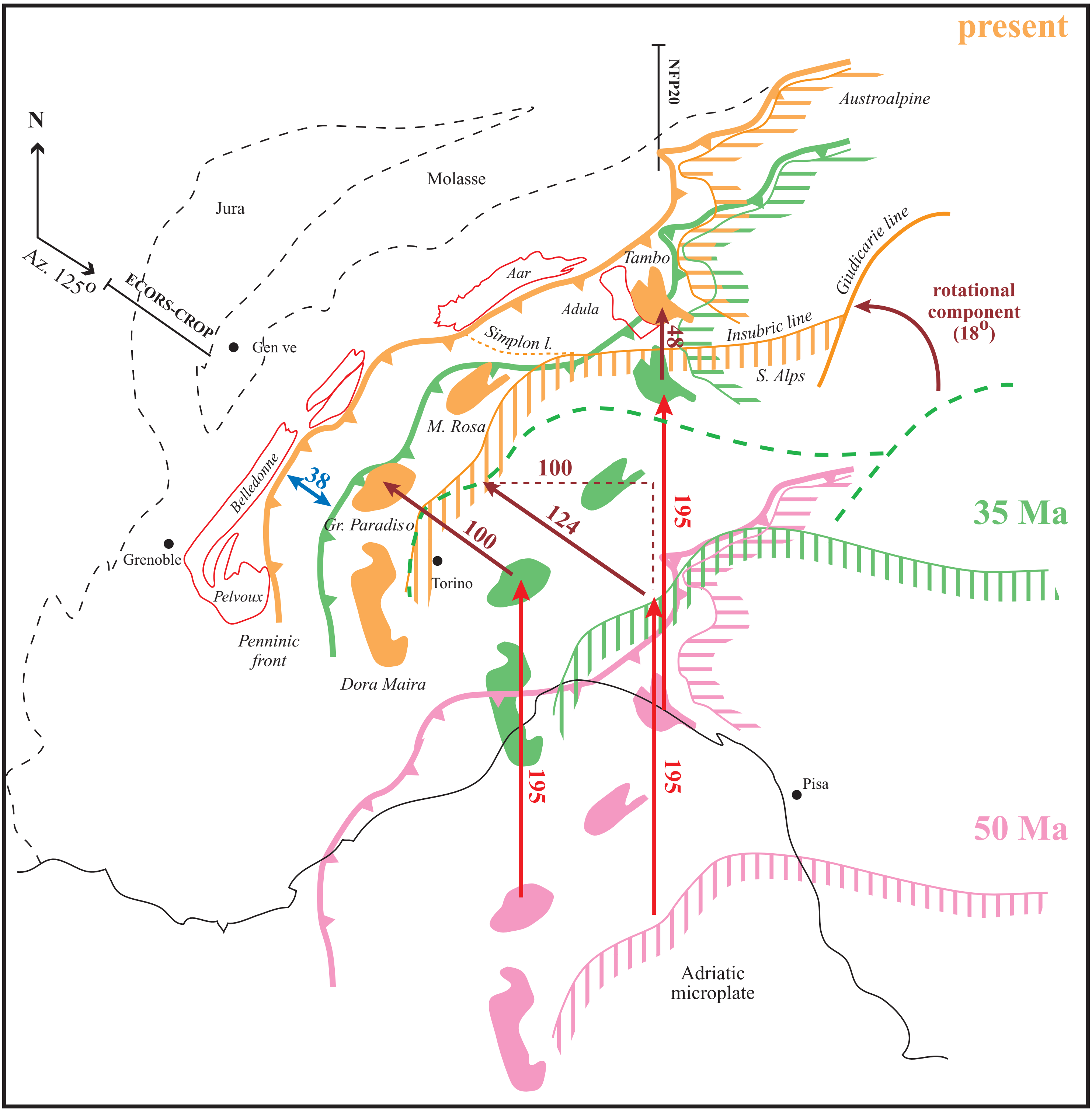
after Schmid and Kissling 2000

Fig IV-VI. 8



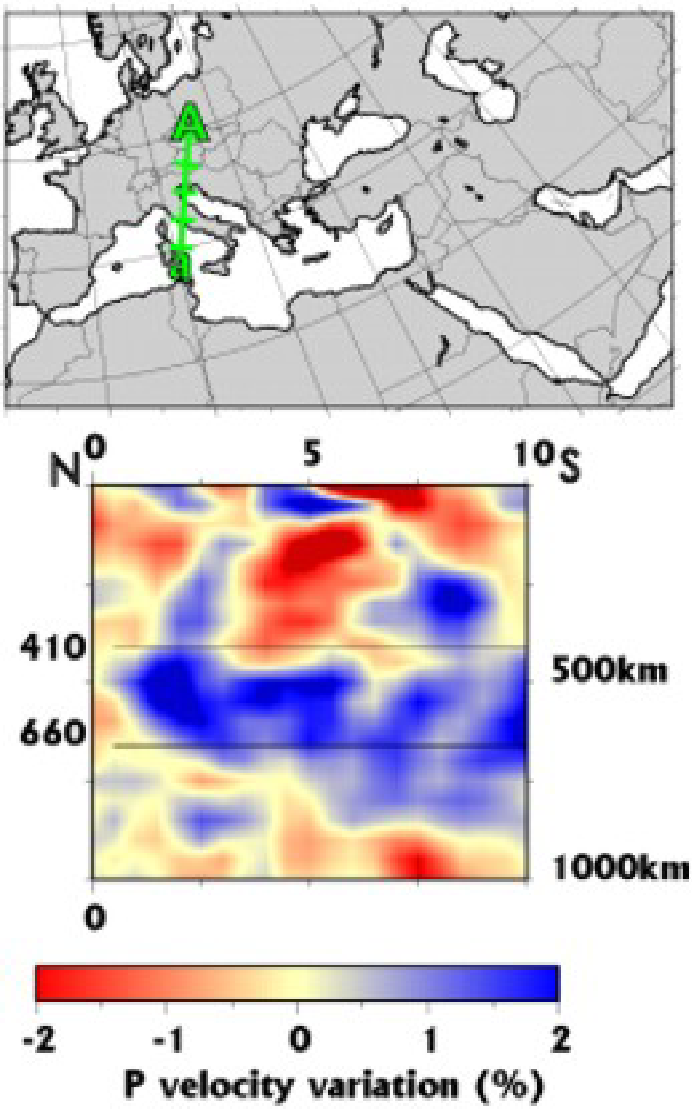
after Schmid and Kissling, 2000

Fig. IV-VI. 9



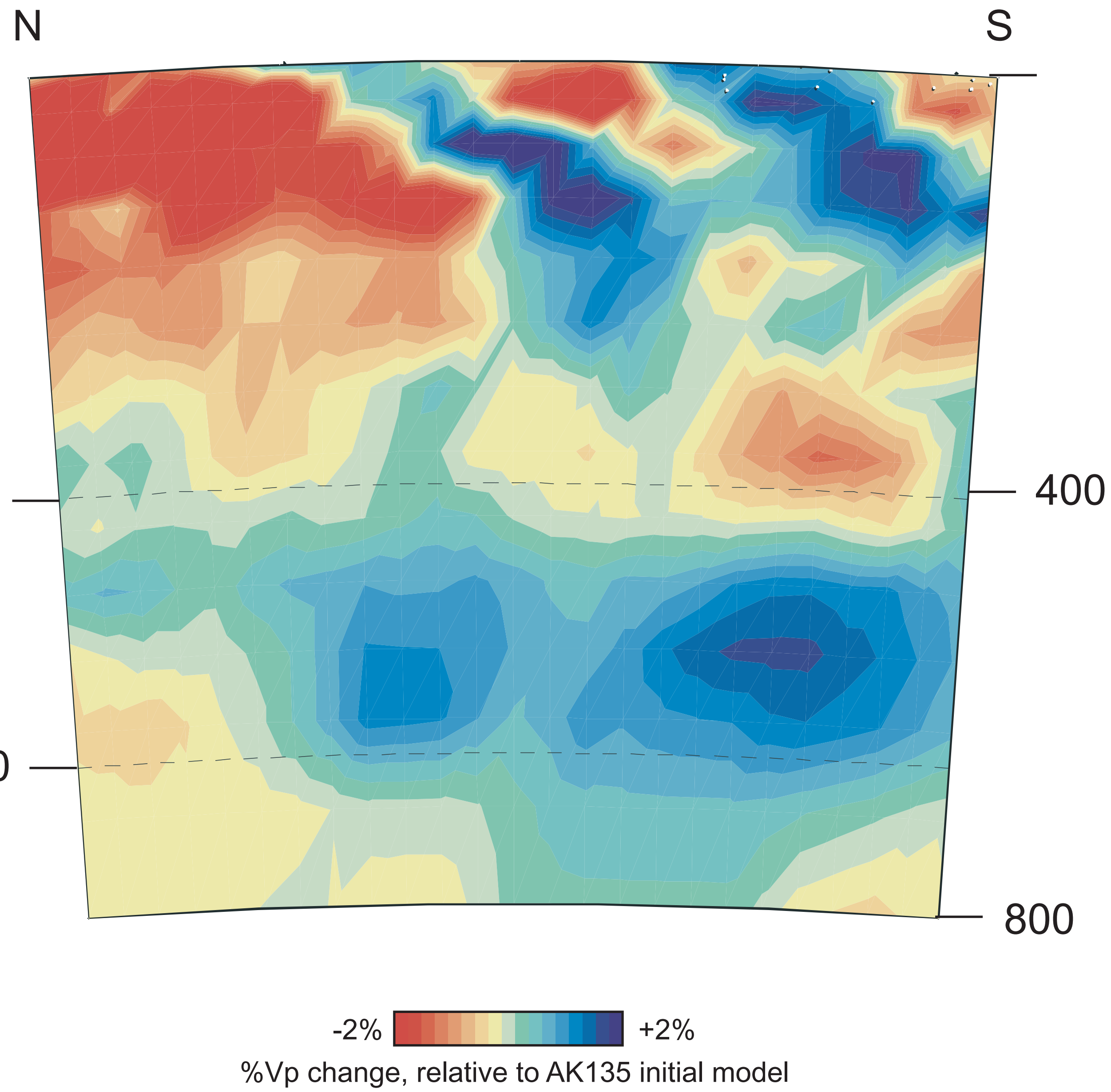
after Schmid and Kissling 2000

Fig IV-VI. 10



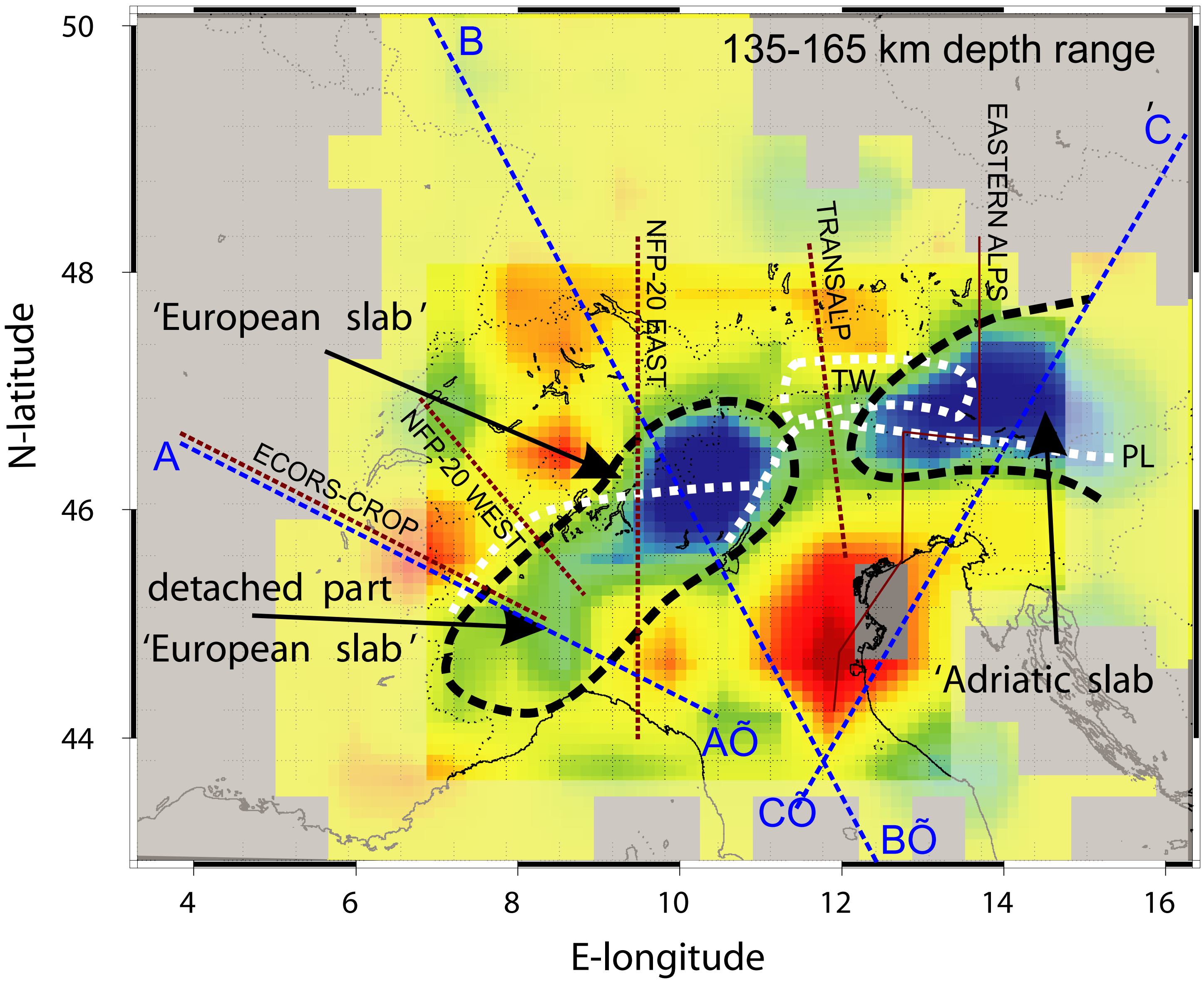
after Piromallo & Morelli, 2003

Fig. IV-VI. 11 a



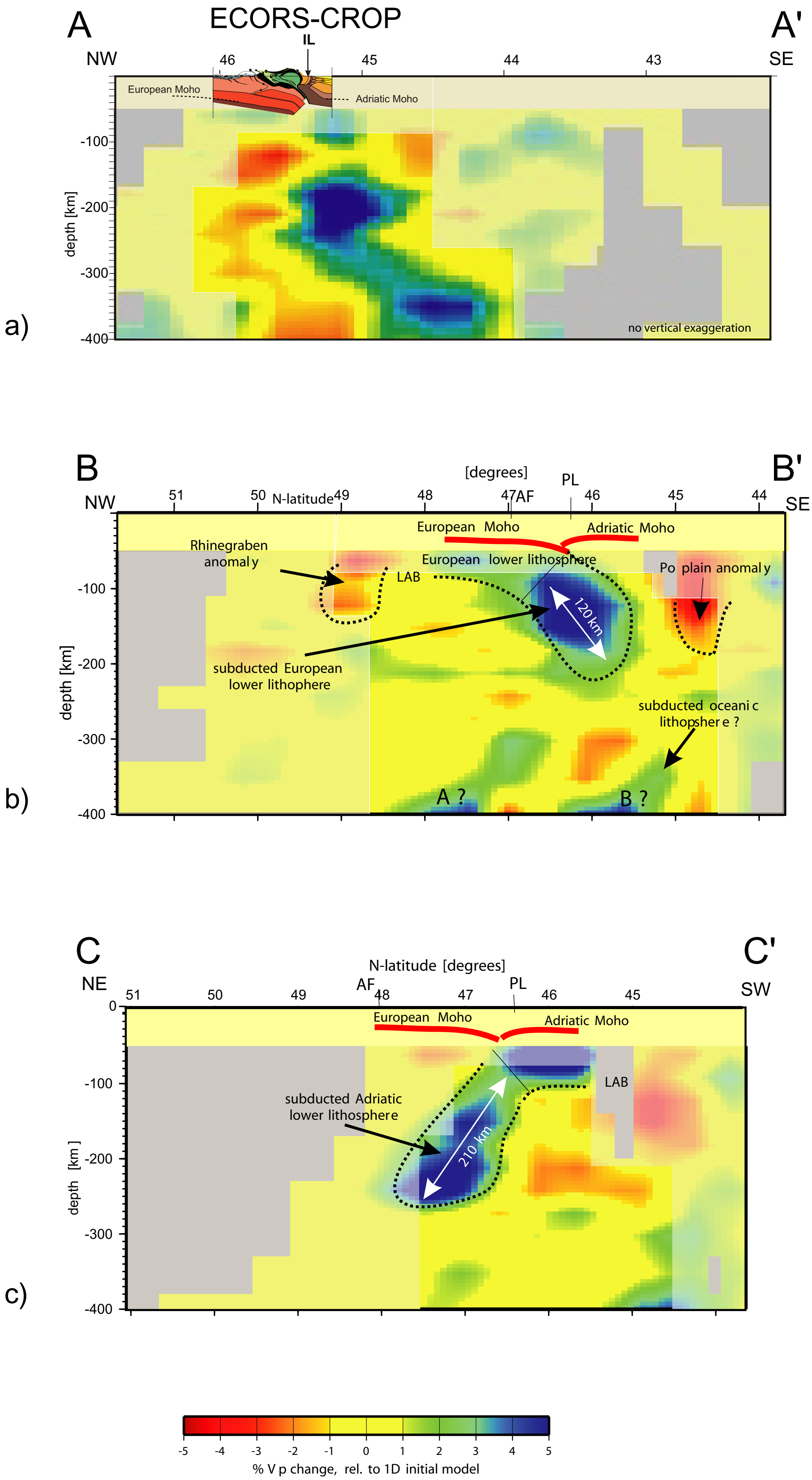
after Bijwaard & Spakman, 2000

Fig. IV-VI. 11 b



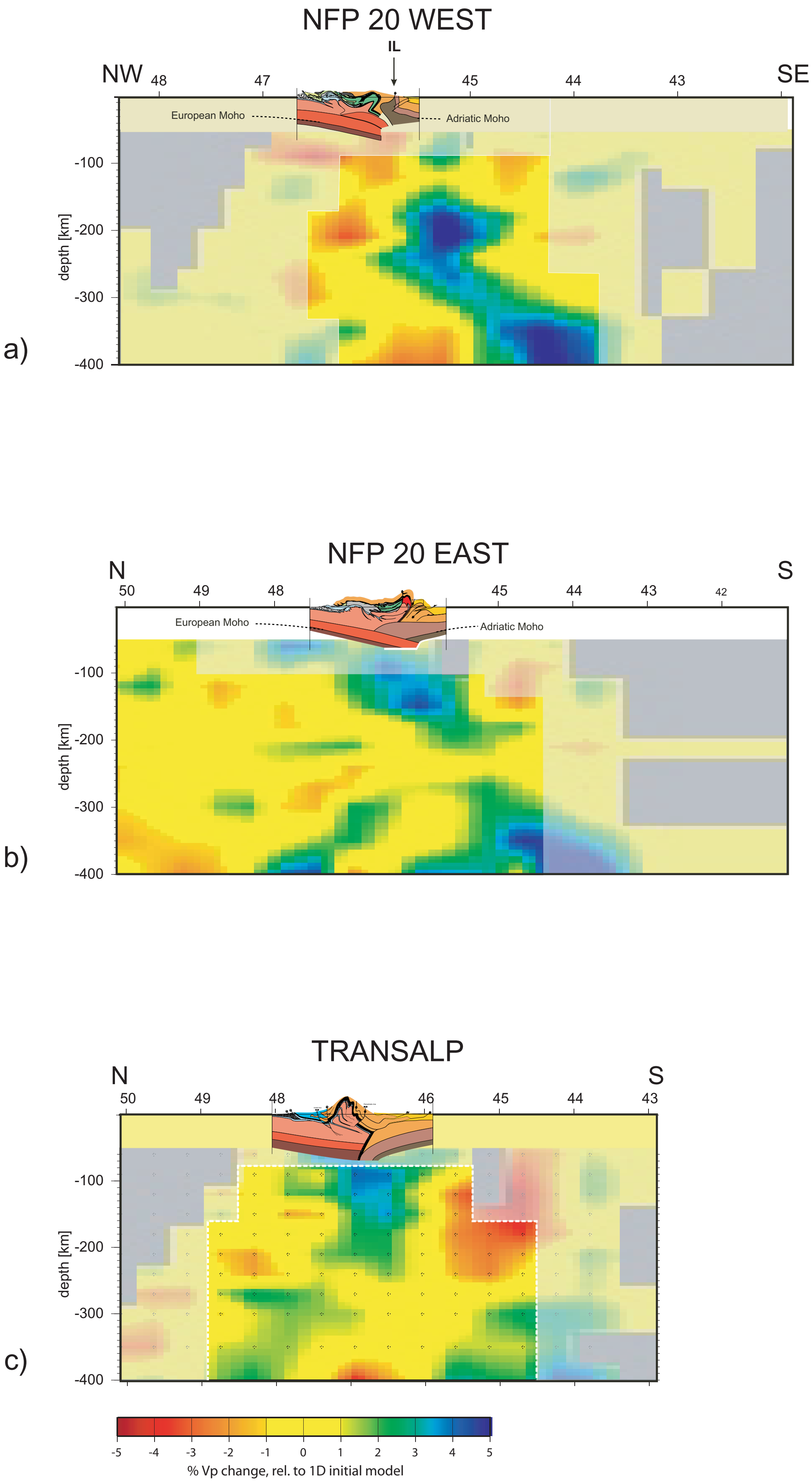
after Lippitsch et al. 2003

Fig. IV-VI. 12



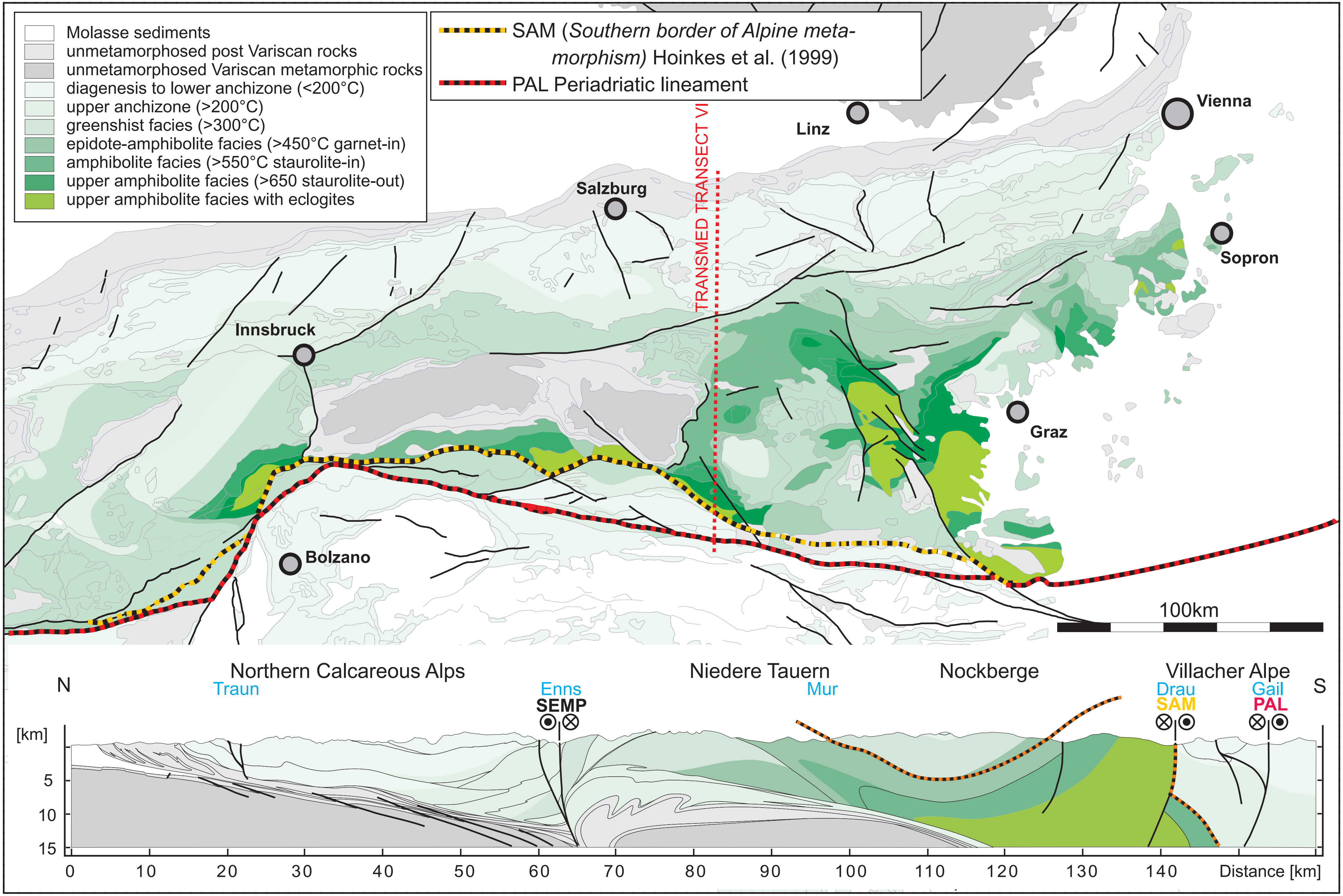
after Lippitsch et al. 2003

Fig. IV-VI. 13



after Kissling et al. in press

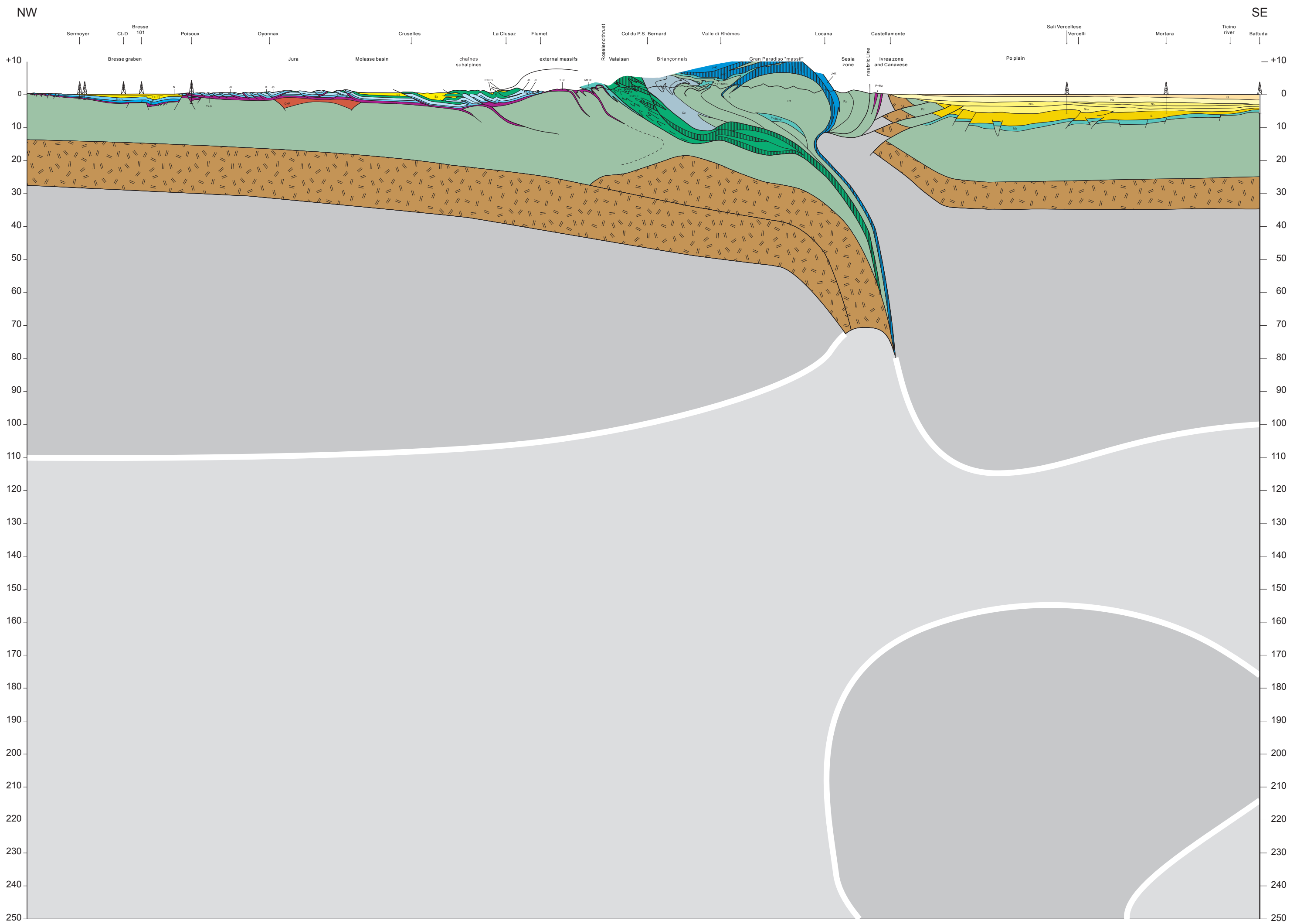
Fig. IV-VI. 14

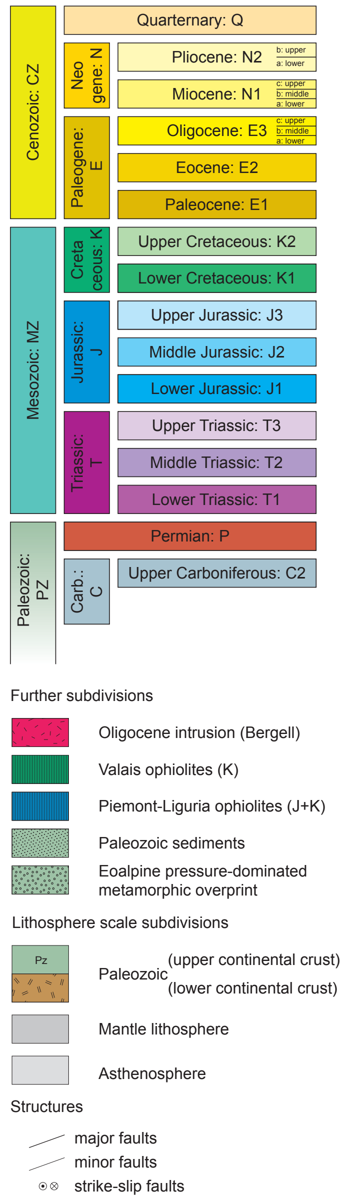


after Schuster 2003

Fig IV-VI. 15

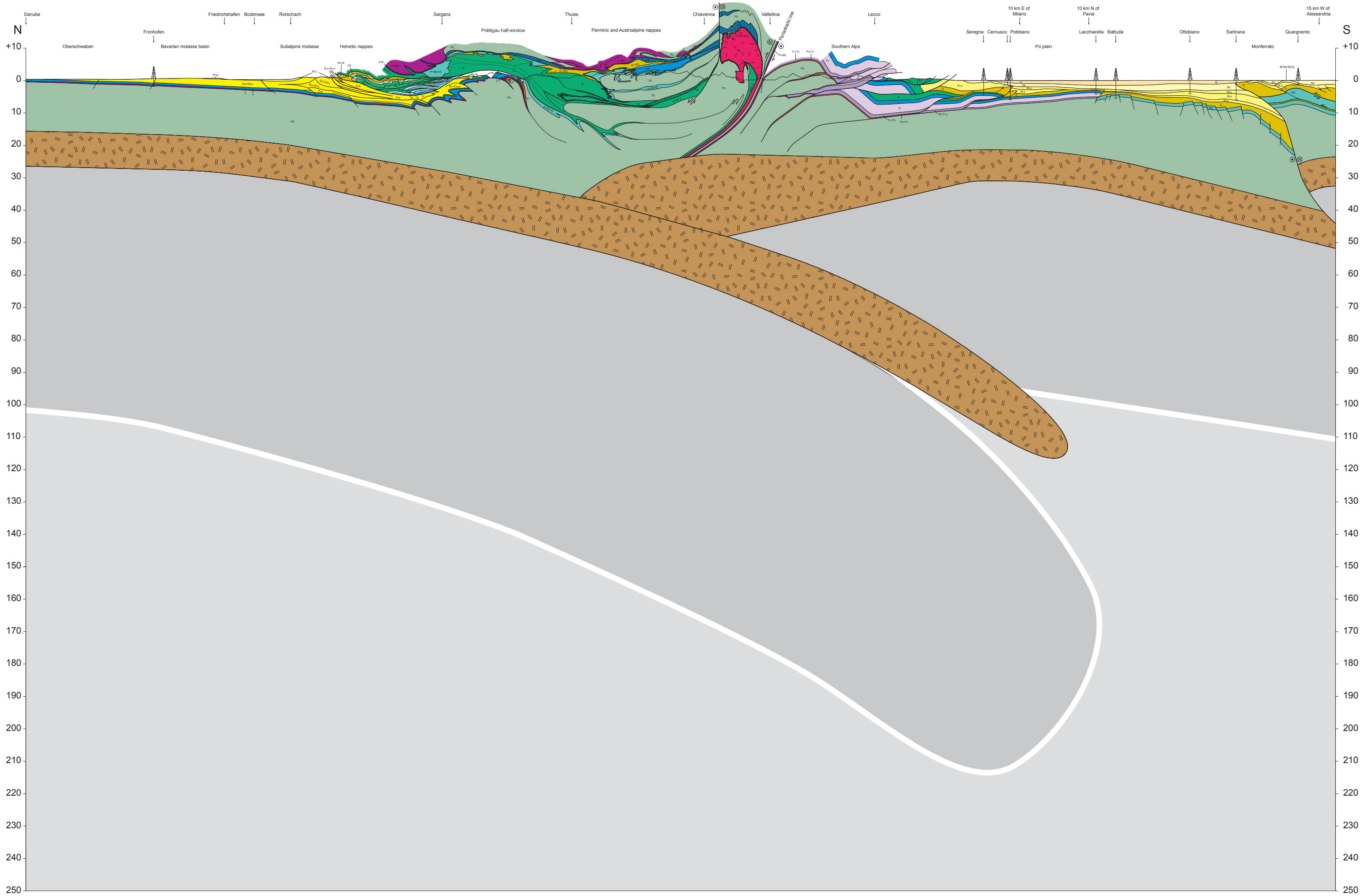
ECORS - CROP

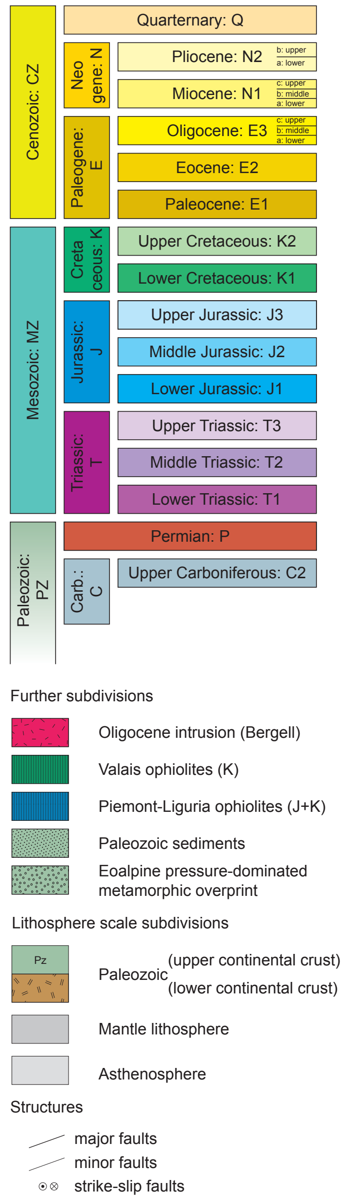




Stefan M. Schmid, Bernhard Fügenschuh, Eduard Kissling, Ralf Schuster (2004)
TRANSMED Transects IV, V and VI: Three lithospheric transects across the Alps and their forelands.
In: Cavazza W, Roure F, Spakman W, Stampfli GM, and Ziegler PA (eds) The TRANSMED Atlas: the Mediterranean Region from Crust to Mantle. Springer Verlag

NFP - 20 EAST





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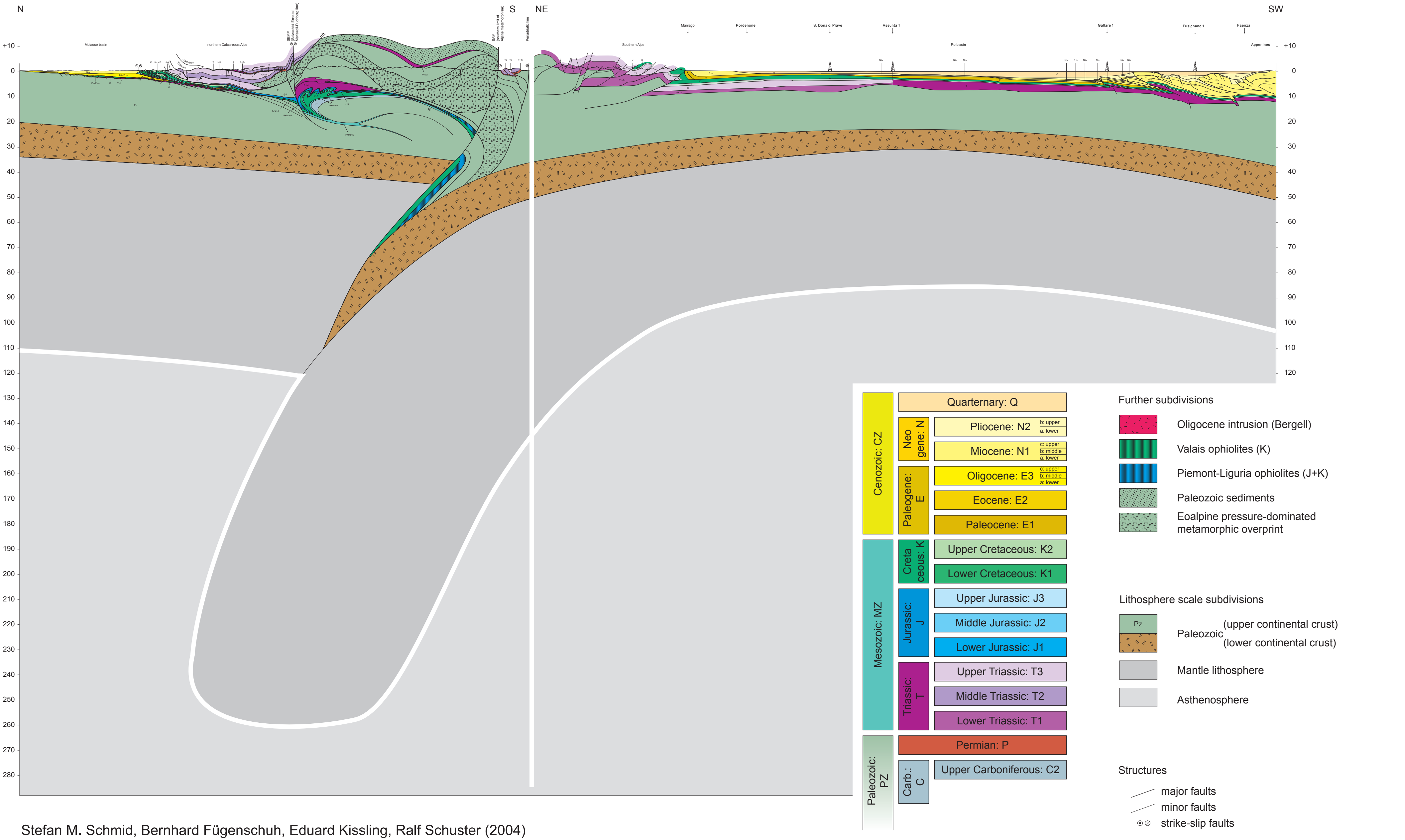
TRANSMED Transects IV, V and VI: Three lithospheric transects across the Alps and their forelands.
In: Cavazza W, Roure F, Spakman W, Stampfli GM, and Ziegler PA (eds) The TRANSMED Atlas: the Mediterranean Region from Crust to Mantle. Springer Verlag

EASTERN ALPS



Stefan M. Schmid, Bernhard Fügenschuh, Eduard Kissling, Ralf Schuster (2004)
TRANSMED Transects IV, V and VI: Three lithospheric transects across the Alps and their forelands.
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