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Tectonic map and overall architecture of the Alpine orogen

STEFAN M. SCHMID[1], BERNHARD FÜGENSCHUH[1], EDUARD KISSLING[2] & RALF SCHUSTER[3]

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ABSTRACT

The new tectonic map of the Alps is based on the combination of purely structural data with criteria regarding paleogeographical affiliation and/or tectono-metamorphic evolution. The orogenic evolution of the Alps is discussed using a combination of maps and paleogeographical reconstructions. It is proposed that the Alps are the product of two orogenies, a Cretaceous 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. The along-strike changes in the overall architecture, as for example revealed by geophysical-geological transects, are by far more substantial than hitherto believed. It appears that the Alps are still far from being over-investigated, as is demonstrated by many surprising recent findings based on field geology, laboratory results and geophysical methods of deep sounding.

ZUSAMMENFASSUNG

Die neue tektonische Karte der Alpen basiert auf einer Kombination von strukturellen Daten mit Kriterien der paläogeographischen Zugehörigkeit und/oder der tektono-metamorphen Entwicklung. Die Orogen-Entwicklung der Alpen wird anhand einer Kombination von Karten und paläogeographischen Rekonstruktionen diskutiert. Hierbei wird vorgeschlagen, dass die Alpen das Produkt von zwei Orogenesen sind: einer kretazischen, gefolgt von einer tertiären. Während erstere auf die Schliessung des Meliata-Ozeans zurückgeführt wird, ist letztere das Produkt der Schliessung der Alpinen Tethys zwischen Apulia und Europa. Die Änderungen in der Architektur der Alpen entlang dem Streichen sind weit wichtiger als bisher angenommen, wie am Beispiel geologisch-geophysikalischer Querschnitte illustriert wird. Es scheint, dass die Alpenforschung immer noch für Überraschungen gut ist. Dies zeigen neue Ergebnisse, die auf Feldforschung, Labormethoden und neue Methoden der geophysikalischen Tiefenerkundung abgestützt sind.

Introduction

The European Alps, located in south-central Europe, record the closure of ocean basins located in the Mediterranean region during convergence of the African and European plates (e.g. Trümpy 1960; Frisch 1979; Tricart 1984; Haas et al. 1995; Stampfli et al. 2001a). 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, also reflected, for example, in the deep structure of the Alps (e.g. Pfiffner et al. 1997b; Schmid & 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). In view of these changes the correlation of tectonic units between Western and Eastern Alps is not an easy task, and it is additionally hampered by a bewildering complexity in the nomenclature of regional tectonic units that often change names across national boundaries. In this contribution we locate the transition between what we refer to as "Western" and "Eastern" Alps in Eastern Switzerland (near transect NFP-20 East, see Fig. 1). The term "Western Alpine Arc" is used to denote the north-south striking westernmost part of the Alps (Fig. 1).

This contribution presents a new tectonic map of the entire Alps, the authors being aware of the above-mentioned difficulties. The map intends to introduce non-specialists into the major units of this orogen. At the same time map and text reflect current ideas and concepts of the authors. These are in part controversial and meant to provoke further studies and discussions. Apart from purely structural criteria we used paleogeographical affiliation for those tectonic units that preserved

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[1] Geologisch-Paläontologisches Institut, Department of Geosciences, Bernoullistr. 32, CH–4056 Basel, Switzerland. E-mail:Stefan.Schmid@unibas.ch; Bernhard.Fuegenschuh@unibas.ch.

[2] Institute of Geophysics, ETH Hoenggerberg, CH–8093 Zuerich, Switzerland. E-mail: kissling@tomo.ig.erdw.ethz.ch.

[3] Geologische Bundesanstalt, Rasumofskygasse 23, A–1031 Wien, Austria. E-mail: Ralf.Schuster@cc.geolba.ac.at.

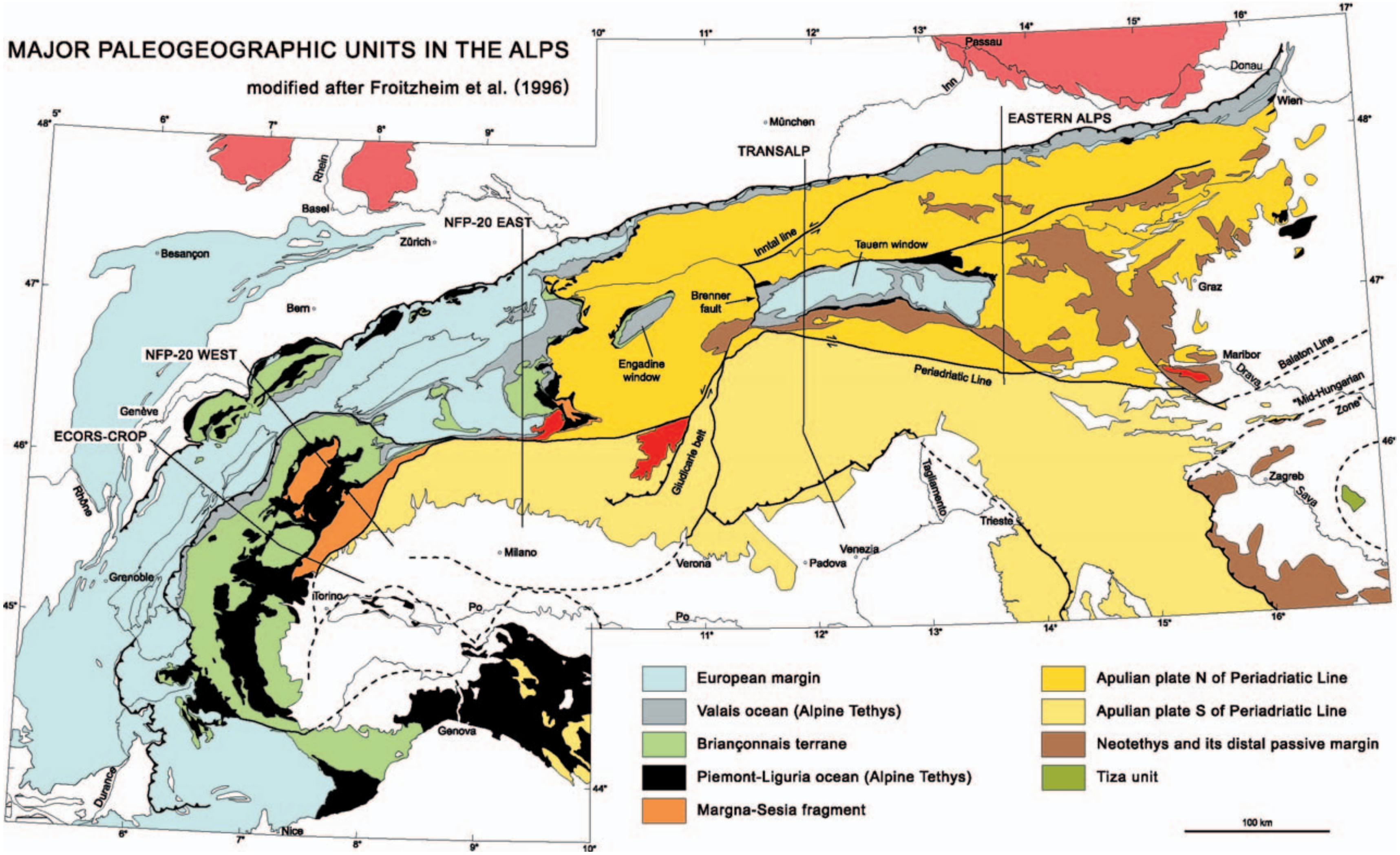


Fig. 1. Map of the major paleogeographic and tectonic units in the Alps.

their Mesozoic cover, and the Alpine tectono-metamorphic evolution in the case of high-grade metamorphic basement rocks (Mesozoic and/or pre-Mesozoic). We attempted to avoid too many local names and kept the number of mapped units as small as possible.

This paper also provides a short overview of the overall architecture of the Western and Eastern Alps and their forelands by presenting a series of large-scale cross-sections. These are largely based on recent geophysical-geological transects.

The major paleogeographical domains and tectonic units of the Alps

The map presented in Figure 1 (modified after Froitzheim et al. 1996) serves as an overview of the major Alpine units, facilitating reading of the more detailed tectonic map of Plate 1. This map assigns all tectonic units, including those made up of high-grade metamorphic rocks, to particular paleogeographical realms. Fig. 2 presents a simple reconstruction of these paleogeographical realms for Triassic, Jurassic and Cretaceous times. Gradually the opening of various oceanic domains separated pieces of continental lithosphere from each other (Fig. 2). Oceanic domains referred to as "Alpine Tethys" (Stampfli 2000), the Piedmont-Liguria and Valais oceans, are kinematically linked to the opening of the Atlantic Ocean. This is not the case for other (so-called "Tethyan") oceanic domains found further to the east, such as Neotethys, Meliata Ocean or Vardar Ocean (e.g. Haas et al. 2001).

Of course, the assignment of basement complexes, such as for example those found in the Lepontine dome of Southern Switzerland and Northern Italy, to paleogeographical domains may appear rather speculative at first sight. However, the affiliations proposed in Fig. 1 are consistent with a wealth of detailed tectonic and geophysical analyses, including attempts to retro-deform the intense post-collisional deformations (i.e. Pfiffner et al. 1997b; Schmid et al. 1996a, 1997), partly also based on petrological and geochronological considerations (i.e. Froitzheim et al. 1996). Despite many remaining uncertainties regarding paleogeographical affiliation, the map given in Fig. 1 highlights better the major tectonic features of the Alps than the more detailed tectonic map presented in Plate 1.

Many of the major paleogeographic units of the Alps are only preserved as extremely thin slivers that were detached from the paleogeographical realms depicted in Fig. 2. This is particularly so in the case of the so-called "Penninic" nappes. These are made up of slivers detached from (1) subducted European lithosphere (European margin), (2) the Valais ocean, (3) the Piedmont-Liguria ocean, and (4) from the Briançonnais ribbon continent of the Western Alps, located between the two above mentioned branches of the Alpine Tethys. Note, however, that the Briançonnais ribbon continent (or terrane) wedges out eastwards somewhere between the Engadine and Tauern windows (see Figs 1 and 2). Hence it is no more present in the Eastern Alps. These "Penninic" units, including the Margna-Sesia fragment, a former extensional allochthon that may be considered as part of the Penninic-Austroalpine transition zone (Trümpy 1992; Froitzheim & Manatschal 1996), were accreted as thin slices (i.e. nappes) to the upper plate formed by the Apulian 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 maintained in the tectonic map of Plate 1, albeit in a modified form, since this term is firmly established in Alpine literature. It is, however, avoided in Fig. 1 because it does not assign the tectonic units to a particular paleogeographical domain. Note also, that the Apulian plate in terms of a single continental plate (Fig. 2c) does not come into existence before the closure of the westwards closing embayment of the Meliata ocean in Cretaceous times (see Figs. 2a, b)

Apulian plate south of the Periadriatic line: Southern Alps and Adriatic indenter

The term "Apulian plate" denotes all continental paleogeographic realms situated south of the Alpine Tethys (Piedmont-Liguria ocean) and north of Neotethys (Fig. 2c). Hence this term also includes the Southern foreland of the Alps. Moreover, as shown in Fig. 2, 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 behave as a coherent block.

The various segments of the Periadriatic Line (Fig. 1), namely, from west to east, the Canavese, Insubric, Giudicarie, Pustertal and Gailtal lines mark the western and northern boundary of the Southern Alps (e.g. 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, 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. Castellarin et al. 1992; Schönborn 1992, 1999). This young (dominantly Miocene) 10 to 15 km thick retro-wedge 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 upper crust (see profiles of Figs. 3a-d). Note however, that older deformations also affected parts of the Southern Alps, as reported by Brack (1981) from the Adamello region (pre-40 Ma) and by Doglioni & Bosellini (1987) from the easternmost Southern Alps (SE-vergent Eocene Dinaric phase).

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 Giudicarie Line, Fig. 1) of about 100km

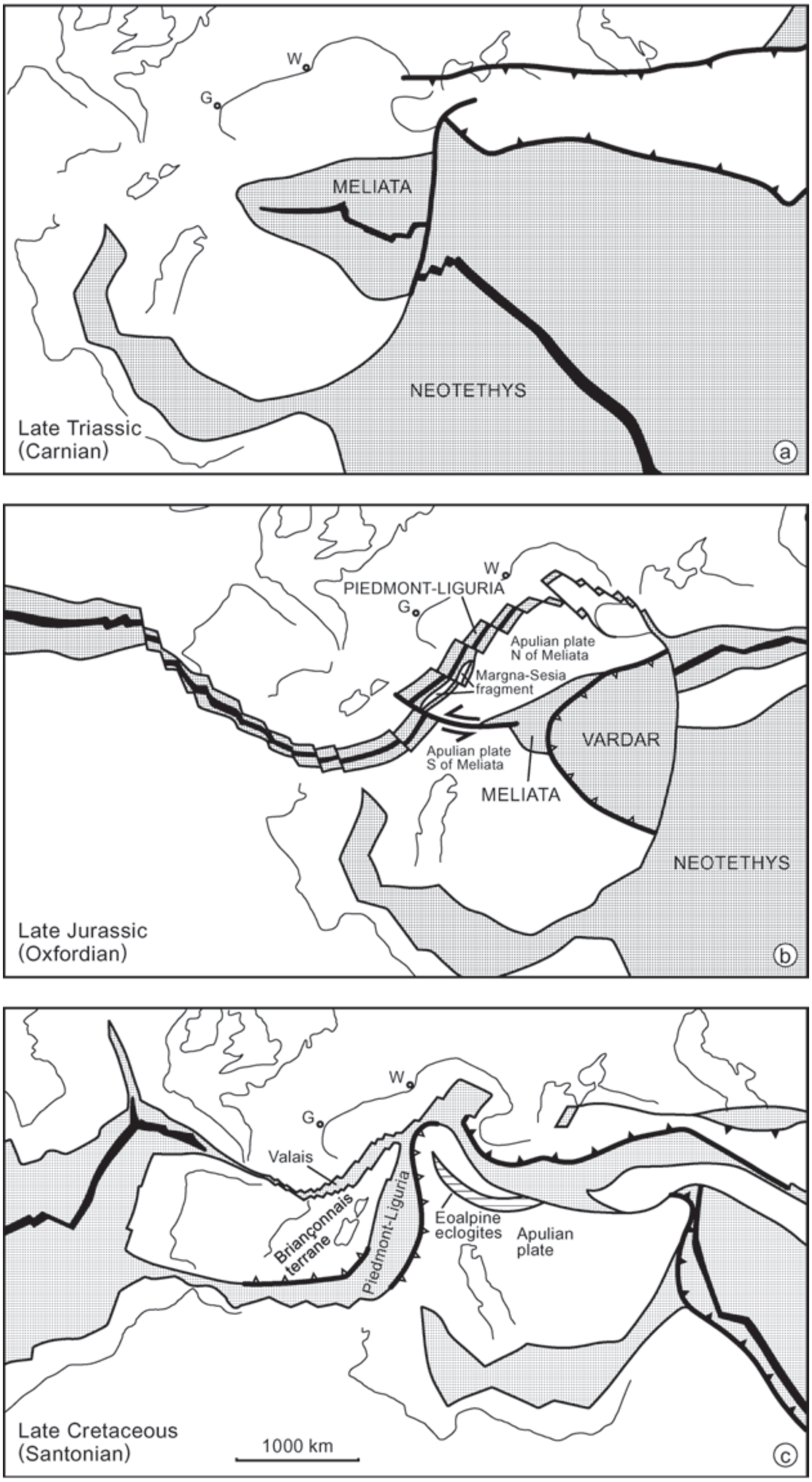


Fig. 2. Large-scale paleogeographical reconstruction for a) Late Triassic, b) Late Jurassic and c) Late Cretaceous times. G: Genève; W: Wien. After Frank 1987, Stampfli 1993, Schmid et al. 1997 and Stampfli et al. 2001.

(Schmid & 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), associated with Miocene-age normal faulting along the Simplon normal fault (Mancktelow 1990, 1992). Hence, from Oligocene to probably Recent times, the Western Alpine Arc was kinematically linked to the WNW-moving Adriatic indenter, formed by the Southern Alps including the Ivrea Zone, 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. 1). During the late orogenic stages, WNW directed indentation of the Adriatic micro-plate affected also the European foreland (Fügenschuh & Schmid 2003), finally causing deformation in the Molasse Basin and folding of the arcuate Jura Mountains (Laubscher 1961; Burkhard & 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; e.g. Ratschbacher et al. 1991). Simultaneously, the eastern part of the Southern Alps was displaced to the north across the sinistral Giudicarie Line (Stipp et al. in press), dissecting the formerly straight Periadriatic Line (but see for example Prosser 1998 for a differing view). This Neogene reactivation of the Giudicarie fault system, first formed during Mesozoic rifting (Castellarin et al. 1993), caused 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 & Neubauer 1989).

Apulian plate north of the Periadriatic line: Austroalpine nappe system

To the north of the Periadriatic Line, remnants of the southern margin of the Piedmont-Liguria Ocean (i.e. the Apulian Plate) are only preserved in the form of basement and cover slices (Austroalpine nappes). Most of them are completely detached from their former deep crust and mantle-lithosphere, but lower crustal slices are occasionally preserved (e.g. Martin et al. 1998). 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 of oceanic slivers derived from the Alpine Tethys (Figs. 1 and 2). The Austroalpine nappes were affected by a Cretaceous orogenic cycle, related to the closure of the Meliata Ocean (Fig. 2a) and its adjacent continental margin. In the Eastern Alps 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 & 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 Plate 1). Only some very small Austroalpine klippen (units of the Northern Calcareous Alps) are preserved in Central Switzerland.

This temporal subdivison into a first Cretaceous-age tectono-metamorphic event, followed by a second (Tertiary-age) orogenic cycle, the two being separated by Late Cretaceous extension, is only well documented in the Austroalpine nappes of the Eastern Alps (e.g. Villa et al. 2000). In the Western Alps, however, convergence and accretion of slices derived from the Piedmont-Liguria Ocean and the Margna-Sesia fragment (see below) represents a continuous process at the former passive margin of Apulia, ongoing from the Late Cretaceous to the Paleogene (Cortiana et al. 1998; Dal Piaz 1999; Dal Piaz et al. 2001). Hence, the slices derived from the Margna-Sesia fragment appear to have an Alpine tectono-metamorphic evolution that is distinctly different from that of the Austroalpine nappes of the Eastern Alps. This is one of the reasons for making a difference between the nappes derived from the Margna-Sesia fragment and those belonging to the Austroalpine nappe stack of the Eastern Alps in Fig. 1 and Plate 1.

Flysch deposits found in parts of the Southern Alps (Lombardian basin) (Bernoulli & Winkler 1990; Bergamo flysch of Bigi et al. 1990b), and possibly the pre-Adamello deformation reported by Brack (1981), indicate orogenic activity in parts of the Southern Alps at that time. Hence, the Tertiary-age eastern part of the Periadriatic lineament must have had a precursor in the Cretaceous (and earlier; see Dal Piaz & Martin 1998) forming the southern boundary of this Cretaceous orogen.

The Cretaceous (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; Mandl 2000), onto Austroalpine units derived from "Apulia". We interpret this Jurassic event as separate from the Eoalpine (Cretaceous) cycle. This Jurassic event is well developed in the Dinarides where it led to the obduction of parts of the Jurassic Vardar Ocean (Dinaridic ophiolites; e.g. Pamic 2002) during the Late Jurassic (Fig. 2b) onto an accretionary wedge that contains remnants of the former Meliata Ocean and onto the Apulian margin.

On the other hand, we interpret the Cretaceous (Eoalpine) orogeny to be related to a collisional event that led to the closure of the Meliata Ocean (Fig. 2a). 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. 2c).

Meliata Ocean and its distal passive margin

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 Stampfli et al. 2001a, 2001b, 2002). The exact paleogeographical location of these oceans is still controversial (see Fig. 2 for our interpretation of the paleogeographic location of these oceans, largely based on Stampfli et al. 2001a). No remnants of the Vardar Ocean and only extremely scarce remnants of the Triassic Meliata Ocean are found in the Alps (Mandl & Ondrejickova 1991, 1993) where they form tectonic slices containing very low-grade metamorphic serpentinites, Triassic radiolarites, olistoliths and Jurassic flysch-type sediments. However, units attributed to the distal passive margin of Apulia adjacent to the Meliata Ocean are more widespread in the Alps. They are 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). Remnants of this distal passive margin are found at the base of a highest out-of-sequence thrust sheet, referred to as "Juvavicum" (the highest tectonic unit within the Northern Calcareous Alps). East of the area depicted in Fig. 1, in the Western Carpathians, ophiolitic remnants of the Meliata Ocean are preserved as olistoliths in Jurassic mélange formations (Plasienka et al. 1997). Finally, 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 plays a crucial role for the understanding of 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; Schuster 2003; Schmid et al. in press) to this paleogeographic realm, being aware that this is speculative. 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.

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), enters the south-easternmost margin of the maps presented in Fig. 1 and Plate 1. The Tiza unit (Haas et al. 2001) forms the innermost parts of the north-Western Dinarides and the Romanian Carpathians. It is separated by the Mid-Hungarian Line (Csontos & 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).

Margna-Sesia fragment

According to Froitzheim et al. (1996), small fragments, rifted off the most distal Apulian margin during mid-Jurassic opening of the Piedmont-Liguria Ocean (Fig. 2b), 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. The Sesia unit of the Western Alps, also derived from the Apulian margin (Rebay & Spalla 2001) 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 Piedmont-Liguria units, were incorporated into the accretionary prism during the Late Cretaceous to the Paleogene (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 termination of Cretaceous (Eoalpine) orogeny, that was followed by Late Cretaceous extension (Ratschbacher et al. 1989).

The pre-Alpine basement of the units assigned to the Margna-Sesia fragment, including that of the Dent Blanche unit, comprises substantial 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), also attributed to the most distal part of Apulia with respect to the Alpine Tethys.

Piedmont-Liguria Ocean

The Piedmont-Liguria Ocean was located directly adjacent to the Apulian margin and south of the Briançonnais ribbon continent (Fig. 2). Tectonic units derived from the Piedmont-Liguria Ocean (Alpine Tethys) and immediately adjacent distal continental margins (see Fig. 1 and schematic profiles of Fig. 3) are also referred to as "Upper Penninic nappes". They occupy the structurally highest position within the Penninic nappe stack, unless their original position was severely modified by large-scale post-nappe folding (Schmid et al. 1990; Bucher et al. 2003; see Figs. 3a, b, and c).

Units belonging to this ocean (Fig. 1) are made up of relicts of oceanic lithosphere and/or exhumed sub-continental mantle (e.g. Trommsdorff et al. 1993; Froitzheim & Manatschal 1996). Drifting started during the Middle Jurassic, in the context of the opening of the Central Atlantic (e.g. 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 Piedmont-Liguria Ocean and neighbouring parts of Apulia; they are not found in the northern branch of the Alpine Tethys, the Valais Ocean (see below). During the Cretaceous, deposition of trench deposits (e.g. Avers Bündnerschiefer of Eastern Switzerland, schistes lustrés of Western Switzerland and France, parts of the calcescisti of the Italian authors) 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 Piedmont-Liguria unit that are immediately adjacent to the Apulian margin (e.g. Arosa and Platta units) were already accreted to 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 Piedmont-Liguria Ocean that stayed open until the onset of Tertiary collision, 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; Bucher et al. 2003). In the Western Alps (but not in the Eastern Alps), Tertiary-age high-pressure overprint of the Piedmont-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 Piedmont-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 accretion 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, the attribution of Penninic units to one or the other ocean (Figs. 3d, e) is guided by the concept that two distinct orogenies affected the Eastern Alps, separated from each other by the Late Cretaceous extensional "Gosau event", (see Froitzheim et al. 1994).

In the Eastern (and in the Western Alps) Cretaceous orogeny only affected the most internal parts of the Piedmont-Liguria Ocean, leading to the accretion of internal Piedmont-Liguria derived slices with the Apulia margin. However, final suturing of the structurally lower tectonic units exposed in the Tauern and Rechnitz windows with the Austroalpine nappes, including the previously accreted Upper Penninic slices derived from the Piedmont-Liguria Ocean, occurred in the context of Tertiary orogeny. At that time, all the units of the Eastern Alps already stacked during Cretaceous orogeny, were thrusted together over the rest of the Penninic, and in case of the Tauern window also the Subpenninic units, presently exposed in these two windows.

Briançonnais terrane

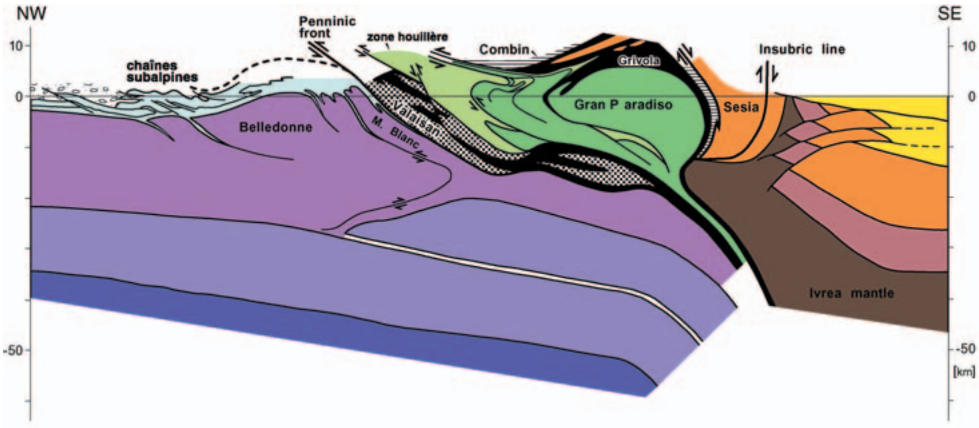
Tectonic units derived from the continental Briançonnais Terrane or micro-continent (Fig. 1) constitute the "Middle Penninic nappes". Before the opening of the Valais Ocean (see below) this paleogeographic realm represented the passive continental margin of Europe in respect to the Piedmont-Liguria Ocean. Later, the Briançonnais micro-continent, i.e. the eastern tip of the Iberia block, was separated from Europe in conjunction with the opening of the Valais Ocean in Early Cretaceous times (Fig. 2c; Frisch 1979; Stampfli 1993).

The term "Briançonnais Terrane" also encompasses units immediately adjacent to either the Piedmont-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", e.g. Ellenberger 1958; Trümpy 1960). These sediments are best preserved in the Mesozoic cover of the Zone Houillère of the Western Alpine Arc and in the detached sediments of the Préalpes Romandes of Western Switzerland (Stampfli et al. 1998, 2002) and adjacent parts of Savoy. Most of these sediments escaped intense deformation and high-pressure overprint.

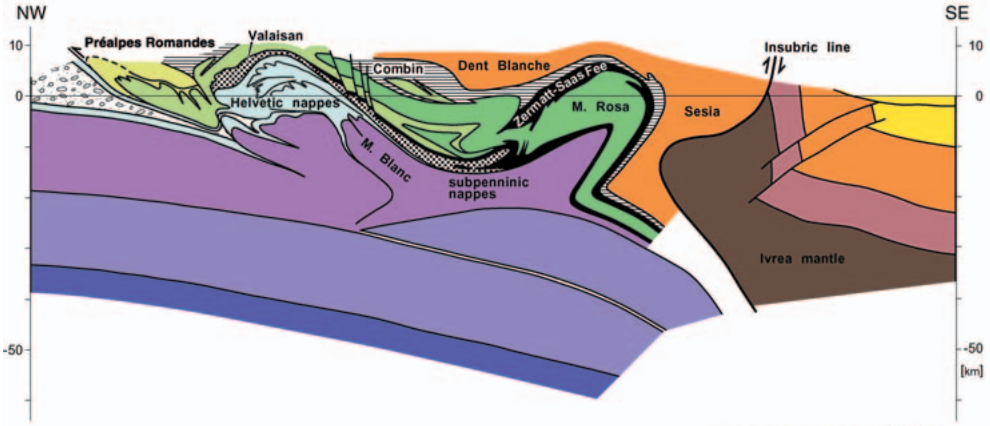
The basement of the Mesozoic sediments of the Briançonnais Terrane is preserved in the "Zone Houillère" (predominantly Late Carboniferous sediments, that were detached from their former Variscan basement; see Bucher et al. 2003) and in basement nappes such as the Grand St. Bernard nappe system, and the Gran Paradiso and M. Rosa nappes of France, Italy and Western Switzerland (Figs. 3a, b), or the Tambo and Suretta nappes of Eastern Switzerland (Fig. 3c). 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. parts of the Grand St. Bernard nappe system, i.e. the Siviez-Mischabel nappe representing the northern continuation of the M. Rosa nappe, Fig. 2b) escaped Eocene high-pressure (blueschist) overprint. While an unequivocal attribution of these basement nappes to the Briançonnais paleogeographic realm can be made in some places (e.g. Sartori 1990; Schmid et al. 1990), such an attribution remains speculative and or controversial (e.g. Froitzheim 2001; Keller & Schmid 2001) for basement nappes that did not preserve a diagnostic Mesozoic cover (e.g. Maggia nappe, M. Rosa nappe).

Valais Ocean

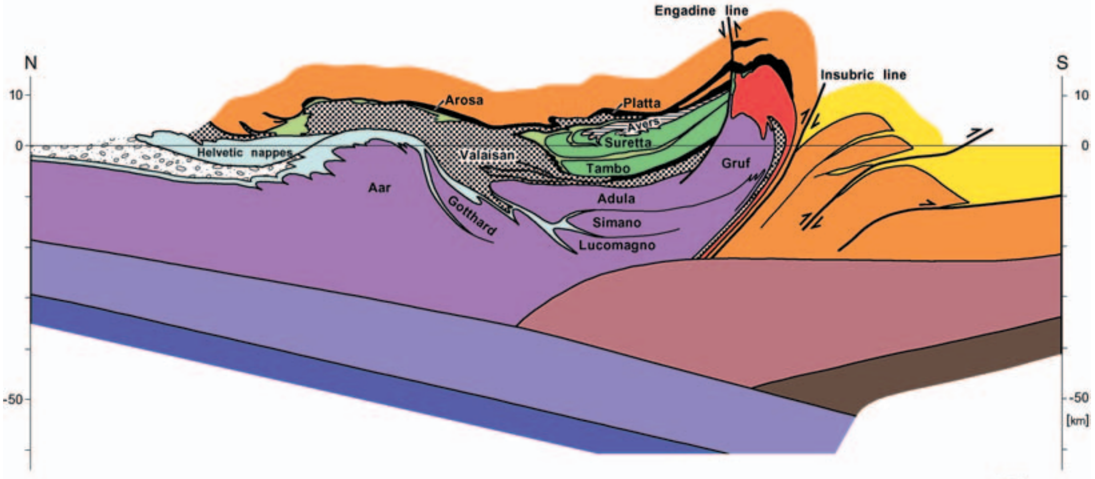
It has to be noted that the existence of a second and more northerly located branch of Alpine Tethys (Fig. 2c), the Valais



ECORS-CROP ⓐ

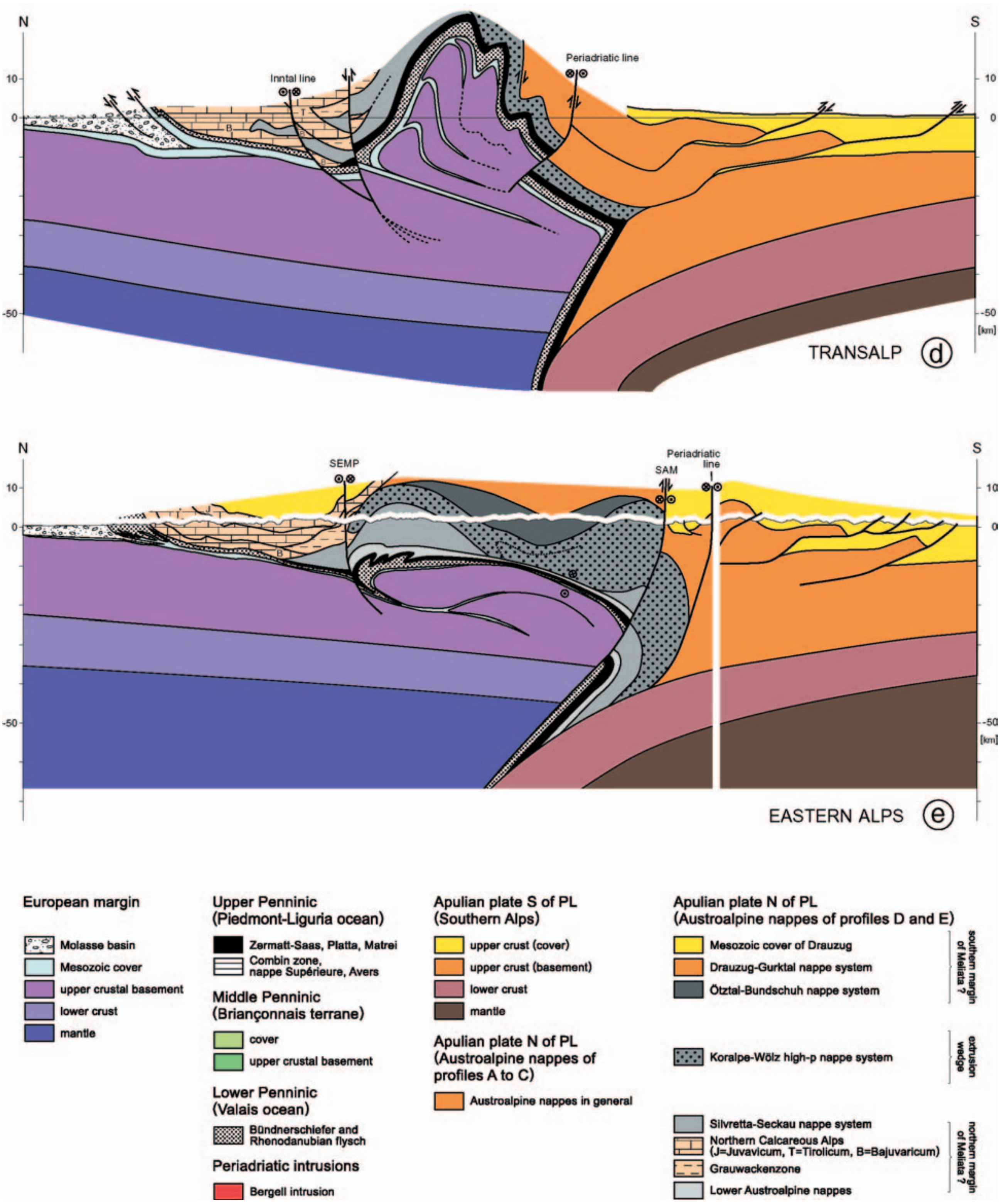


NFP-20 WEST ⓑ



NFP-20 EAST & EGT ⓒ

Fig. 3. Schematic transects through the Alps. Transects a) to c) are after Schmid & Kissling (2000) and Schmid et al. (1996). Transect d) is a provisional interpretation, modified after Schmid et al. 2003, and includes information from Lippitsch (2002) and seismic information from Transalp Working Group (2003). Transect e) is newly compiled by R. Schuster, the deep structure being exclusively based on tomographic information by Lippitsch (2002), for a detailed description of this transect see Schmid et al. in press. Note that the deep structure is relatively well constrained in case of transects a) to c). Regarding transect d) the geometry of the Moho at a depth of >60 km is still poorly constrained by reflection seismic data, while no reflection seismic information is available at all in case of transect e).



a) ECORS-CROP transect
b) NFP-20-WEST transect
c) NFP-20-EAST transect
d) TRANSALP transect
e) EASTERN ALPS transect

Ocean (Trümpy 1955), is still highly controversial. Hence, there is no mention of this domain, as one representing a second branch of oceanic lithosphere in much of the modern literature on the Alps (e.g. Dal Piaz 1999; Dercourt 2002). This work follows the propositions of Frisch (1979) and Stampfli (1993), because we regard the recently acquired evidence favouring the existence of the Valais ocean (e.g. Florineth & Froitzheim 1994; Steinmann 1994; Bousquet et al. 1998, 2002; Fügenschuh et al. 1999; Loprieno 2001; Ceriani et al. 2001) as robust enough by now.

Remnants of this oceanic domain and/or immediately adjacent distal continental margin units (i.e. Fügenschuh et al. 1999) form the "Lower Penninic nappes" (Schmid et al. in press). Units considered as derived from this ocean according to our interpretation are 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". Note, however, that the same or similar types of sediments are also found in units derived from the Piedmont-Liguria Ocean. Sedimentation of the Valais 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; e.g. Oberhauser 1995). Only parts of these sediments were deposited on ophiolitic units, including exhumed sub-continental mantle (e.g. Florineth & Froitzheim 1994; Fügenschuh et al. 1999; Loprieno 2001). For large parts of these Bündnerschiefer it is difficult 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 probably also include sediments that were deposited on distal continental crust.

The rather narrow Valais Ocean probably began to open in earliest Cretaceous times (e.g. Florineth & Froitzheim 1994; Loprieno 2001). According to Frisch (1979) and Stampfli (1993) sea floor spreading in this northerly branch of the Alpine Tethys 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. In the Eastern Alps, however, this Cretaceous spreading took place within pre-existing oceanic lithosphere, namely the eastern continuation of the Piedmont-Liguria basin. Tectonic units attributed to the Valais Ocean in the Eastern Alps (see section "Piedmont-Liguria ocean" regarding the criteria applied) 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" (or Glockner nappe) of the Tauern window.

Remnants of the Valais ocean define a northern Alpine suture (Goffé & Bousquet 1997; Bousquet et al. 1998, 2002) between the European margin and the continental Briançonnais Terrane (in case of the Western Alps), or an orogenic lid consisting of previously stacked Piedmont-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 Piedmont-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).

European margin

The European margin constitutes the northern and western foreland of the Alps. Tertiary-age rifting in this foreland 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 Alpine Arc where 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 & 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 Switzerland and Bavaria. This foreland basin began to subside during the late Eocene, orogen-derived continental clastics were deposited during the late Oligocene to late Miocene (Roeder & 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.

In Eastern Austria the Molasse foreland basin is considerably narrower and shallower as compared to Switzerland and Bavaria (Wagner 1996). Moreover, its sedimentary fill is dominated by orogen derived Oligocene to Early Miocene deeper water clastics. 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 and para-autochthonous cover of Switzerland extending northward beneath the Molasse Basin) were strongly affected by Neogene thick-skinned thrusting (Fig. 3a-c). By contrast, the Eastern Alps are devoid of external massifs. Correspondingly, the

European foreland is seen to either uniformly dip southward beneath a flat-lying stack of Alpine nappes (Fig. 3e), or, to rise up in a more internal position, as is the case in the Tauern window (Fig. 3d).

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. In the French Alps the lateral equivalents of the Helvetic nappes were involved in thick-skinned deformation (Chaînes Subalpines). In the Eastern Alps of Austria and Germany 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 Cretaceous 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.

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”, but are referred to as “Subpenninic nappes” here. These nappes predominantly consist of Variscan basement. Occasionally, the Mesozoic cover of these distal units was not detached, as for example, in case of the “Untere Schieferhülle” in the Tauern window. 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), as well as in the Tauern window.

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, we attributed the central crystalline core and its cover to the European margin (Fig. 1), contrary to earlier interpretations (e.g. Tollmann 1977). Our alternative interpretation is mainly based on 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), are also attributed to the European margin.

Most important base maps used for compiling the new tectonic map of the Alps (plate 1)

Sheets 1 to 3 of the qualitatively outstanding maps published in the “Structural model of Italy” (Bigi et al. 1990a, 1990b, 1992) served as base maps for the new tectonic map depicted in Plate 1. However, the geological information contained in this map was only partly used. The most important additional sources of information are referred to below. The great number of different tectonic units defined by Bigi et al. (1990a, 1990b, 1992) was reduced by assigning them to the smaller number of tectonic units given in Plate 1. Only the north-eastern and south-eastern corners near Vienna and in former Yugoslavia were outside the map of Bigi et al. (1990a, 1990b, 1992). In these areas the maps of Austria (Egger et al. 1999) and former Yugoslavia (Federal Geological Institute Beograd 1970), modified according to the findings of Tomljenovic (2002) were used as base maps.

Below we only list the most important base maps used for modifying the subdivisions used in Bigi et al. (1990a, 1990b, 1992). Additional references to the literature used for local modifications will be mentioned when briefly introducing the main tectonic units mapped in Plate 1 in a later chapter.

Regarding the Ligurian Alps, we largely followed the subdivisions given in a map provided by Cortesogno et al. (1993; their figure 1). The external part of the N-S-striking part of the Western Alpine Arc was mapped according to the tectonic subdivisions proposed by Ceriani et al. (2001). Many parts of the Penninic zone of Western Switzerland and adjacent France are drawn on the basis of information provided in a tectonic map by Steck et al. (1999). Concerning the Swiss territory, many details were also taken from the Tectonic map of Switzerland (Spicher 1976). In Eastern Switzerland, however, plate 1 is largely based on tectonic maps provided by Froitzheim et al. (1994) and Schmid et al. (1997). In the northern part of the Eastern Alps (Grauwackenzone and Northern Calcareous Alps) we largely followed the traditional subdivisions given in Plöchinger (1980). For the Tauern window the most important maps used were those of Becker (1993) and Kurz et al. (1998).

The subdivisions used for the basement-dominated Austroalpine units of the Eastern Alps, situated south of the Grauwackenzone and north of the Periadriatic line, have been completely revised. The traditional subdivision into Lower, Middle and Upper Austroalpine nappes, based on Tollmann (1977) was abandoned. We base our new subdivisions largely on those discussed and presented in Frank (1987), Schuster & Frank (1999) and Schuster et al. (2001). Particularly the tectonic map presented by Schuster et al. (2001, their figure 1) served as the most important base map for the area of the Austroalpine basement nappes.

Brief description of the major tectonic units used for compiling the new tectonic map of the Alps (plate 1)

For reasons of convenience this brief introduction is structured according to the map legend, given at the bottom of Plate 1. All units, including the most important references, will be briefly discussed by following the map legend of Plate 1 from top to base and left to right, respectively.

Various units

This group of units includes cover units that are post-tectonic in respect to certain tectonic events as well as the Periadriatic intrusions of Tertiary age.

Unit **Plio-Pleistocene** designs Late Neogene sediments found in the Po-Plain. In part they un-conformably overlie Alpine structures (Lombardy), in part they are deformed by late-stage Alpine thrusting (eastern part of the Southern Alps) and by the latest ("Neoapenninic"; Schumacher & Laubscher, 1996) stages of orogeny in the Apennines (Pieri & Groppi 1981). In the Pannonian basin, these youngest formations overlie older Tertiary sediments, mapped as "Tertiary cover in general" (see below).

Unit **Tertiary cover in general** comprises basins of different origin and age. The non- or less-deformed part of the Oligo-Miocene Molasse basin found north of the Alps represents the most prominent part of the foreland basin of the Alps. The intra-montane Miocene-age pull-apart basins, only found in the Eastern Alps, formed during lateral extrusion of the Austroalpine units. Sedimentation in these basins is contemporaneous with the age of a third group of sediments lumped into this unit: the Miocene fill of the Pannonian basin (Haas et al. 2001). Middle Miocene cover, deposited during the initial stages of the formation of this extensional basin, rims the Pannonian basin along its western and south-western margin. This older fill is discordantly covered by Late Miocene sediments that were partly inverted during Late Neogene to recent tectonic activity (Csontos et al. 1992).

Unit **Oligo-Miocene post tectonic cover** is unconformable on structures formed during Eocene nappe formation in the Ligurian Alps (top S in their present-day orientation), as well as on older structures (top N in their present-day orientation) within the Ligurian nappes of the Apennines (Bigi et al. 1990a, 1990b, 1992). However, part of this cover predates top-N thrusting of Ligurian Alps and Paleo-Apennines during the Burdigalian, and all of this cover predates top-N Neo-Apenninic, i.e. post-Messinian thrusting. Both these late stages of orogeny affected Alpes Maritimes, Ligurian Alps and Apennines together (Vanossi et al. 1994; Schumacher & Laubscher 1996).

Unit **Gosau beds** is of crucial importance for separating the Cretaceous from the Tertiary orogeny. These Late Cretaceous (post-Turonian) sediments un-conformably overlie Cretaceous-age nappe contacts. Hence they post-date the Cretaceous (Eoalpine) tectono-metamorphic event that affected the Eastern Alps (Faupl & Wagreich 1996).

Only the larger of the numerous **Periadriatic intrusions** are shown in Plate 1. In time and space these dominantly Oligocene-age intrusions are closely associated with contemporaneous strike-slip movements along the Periadriatic line (e.g. Martin et al. 1993; Berger et al. 1996; Stipp et al. in press).

Dinarides

The continental **Tiza unit** is part of the larger Tiza block, which makes up the innermost parts of the north-western Dinarides and the Romanian Carpathians. In the Slavonian hills east of Zagreb this unit forms the NE hinterland of the westernmost Dinarides (Pamic et al. 2002).

Unit **Internal Dinarides** includes the distal continental margin of Apulia adjacent to a branch of Neotethys, as well as mélange formations and/or ophiolitic slivers. Some mélanges of Jurassic age contain ophiolitic fragments of the Triassic Meliata Ocean (Babic et al. 2002). The ophiolitic units obducted onto the margin of the external Dinarides, including the above mentioned mélange formations, are of Mid-Jurassic age, however. These were obducted during the Late Jurassic (Dinaridic ophiolite zone). Other more internal parts of the Jurassic Vardar Ocean are reported to have closed during Late Cretaceous to Early Tertiary times (e.g. Pamic 2002).

The boundary between **external Dinarides** and adjacent Southern Alps (see below) is not a sharp one (e.g. Doglioni & Bosselini 1987). Both units belong to the Apulian plate south of the Periadriatic line and both are characterised by an interference of Eocene ("Dinaridic") and Neogene to recent deformations. The boundary between these two units, as shown in Plate 1, coincides with the southern boundary of a belt characterised by intense Neogene to recent top-S thrusting in the Southern Alps, and the northern boundary of an area dominated by Eocene-age top SW thrusting in the external Dinarides (Carulli & Ponton 1992; Schönborn 1999; Placer 1999; Nussbaum 2000).

Apennine

Unit **Ligurian nappes** comprises oceanic units that paleogeographically belong to the Piedmont-Liguria ocean (Alpine Tethys; Figs. 1 and 2). However, in contrast to the situation in the Alps, in the Apennines the remnants of this ocean presently form the upper plate in relation to units attributed to the Apulian plate (Laubscher 1971; Marroni et al. 2002). This is because the Ligurides (parts of the Piedmont-Liguria Ocean) 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 Bigi et al., 1990a, 1990b, 1992).

The underlying unit **Tuscan nappes**, being part of the Apulian plate, are exposed in windows surrounded by thrusts that formed during early stages of deformation in the Northern Apennines (Carmignani et al. 1978). Later the Apennines, together with the Ligurian Alps, became involved in Miocene to Pliocene thrusting and/or strike slip motions (Schumacher & Laubscher 1996; Marroni & Treves 1998).

Southern Alps

The unit **Lower crust of the Southern Alps** corresponds to the Ivrea zone. The Ivrea zone, structured during the Paleozoic, formerly formed the westernmost part of the passive continental margin of Apulia adjacent to the Piedmont-Liguria ocean (Schmid 1993) and later formed the tip of the Adriatic indenter, which extends in the subsurface all the way to Cuneo, located south of Torino (Schmid & Kissling 2000; Ceriani et al. 2001).

Unit **Upper crustal basement of the Southern Alps** comprises pre-Late Carboniferous basement units affected by Variscan deformation and metamorphism, unconformably overlain by Late Carboniferous to Permian sediments and/or associated volcanic and sub-volcanic formations in the western part of the Southern Alps. In the eastern Southern Alps this unit consists of older Paleozoic sediments that pre-date deposition of Late Carboniferous to Permian sedimentary or volcanic to sub-volcanic formations.

Late Paleozoic to Tertiary sediments constitute unit **post-Variscan volcanic and sedimentary cover of the Southern Alps**. These sediments, together with parts of unit "Upper crustal basement of the Southern Alps", are affected by Neogene top-S thrusting over unit "little deformed parts of the Adriatic micro-plate" and/or unit "external Dinarides" in the Southern foreland of the Alps.

Paleogeographically, unit **Adriatic micro-plate** forms part of the Apulian plate south of the Insubric line. It represents the little deformed rigid foreland of the Southern Alps, Apennines and northernmost external Dinarides. However, recent GPS data indicate that at present the Adriatic micro-plate no longer behaves as a single rigid indenter (Oldow et al. 2002).

Remarks concerning the subdivisions proposed for the Austroalpine nappes

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 & Frank 1999). Instead, we only use the terms Upper and Lower Austroalpine. Within the Upper Austroalpine we separated the detached Paleozoic and Mesozoic cover at the northern rim of the Eastern Alps from the Upper Austroalpine south of the Grauwackenzone ("Upper Austroalpine basement nappes" in Plate 1).

The legend of our map does not imply correlations between individual units of the Northern Calcareous Alps (including the Grauwackenzone), and individual units of the Upper Austroalpine basement nappes, respectively. However, in the following text such correlations will be discussed, mainly based on interpretative cross sections given in Fig. 3.

Northern Calcareous Alps and Grauwackenzone (Upper Austroalpine)

Detached Paleozoic (Grauwackenzone) and Mesozoic (Northern Calcareous Alps) cover units presently form a thin-skinned fold- and thrust belt positioned at the northern front of the Austroalpine nappes. The sediments are non- to weakly metamorphic (Frey et al. 1999) and they were stacked in a transpressional top-NW tectonic scenario during the Cretaceous (Eisbacher et al. 1990; Linzer et al. 1995). Detachment preceded the peak of high-pressure metamorphism, reached at around 100 Ma in the area south of the Northern Calcareous Alps, that belongs to the "Austroalpine basement nappes" (Thöni 1999). This supports early (i.e. Late Jurassic; e.g. Mandl 2000, and/or Early Cretaceous; e.g. Ratschbacher et al. 1989) detachment of at least the tectonically highest of these cover units from their former crystalline substratum found in the "Upper Austroalpine basement nappes".

Unit **Juvavic nappes** comprises a series of Mesozoic cover nappes, that presently occupy the tectonically highest position within the Northern Calcareous Alps. Hence these different units, mostly detached along Permian evaporites (Haselgebirge), may be regarded as a nappe system. Deformation within the Juvavic nappes, however, is poly-phase. Parts of the Juvavic nappes are characterized by Hallstatt facies (traditionally referred to as "Tiefjuvavicum" (Plöchinger 1980) and hence attributed to the distal passive margin of Apulia, facing the Meliata Ocean found further to the south (Figs. 1 and 2a, b). These sediments were detached during Late Jurassic tectonism (Gawlick et al. 1999; Mandl 2000). Consequently, subsequent (Cretaceous or Eoalpine) nappe stacking led to out-of-sequence thrusting. Thereby the "Hochjuvavikum", which had a more proximal (external) paleogeographic position (Dachstein facies), was emplaced out-of sequence onto the "Tiefjuvavicum", derived from the Hallstatt facies sediments, which originally occupied a more internal position. The present-day location of the former substratum of the Juvavic nappes remains unknown. While some authors (i.e. Neubauer et al. 2000) propose an origin of the Juvavic units characterised by Dachstein facies ("Hochjuvavikum") from the southern margin of the Meliata ocean (Fig. 2a), we follow Gawlick et al. (1999) and Mandl (2000) who convincingly demonstrate that all the paleogeographical domains represented by the Juvavic nappe system are derived from the same, i.e. the northern margin of the Meliata ocean. Assuming that the "Koralpe-Wölz high-P nappe system" represents a kind of suture, formed by units that were immediately adjacent to the Meliata Ocean (as suggested in Fig. 1) the former crystalline substratum of the

Juvavic nappes would have to be located tectonically below, or perhaps within this high-P nappe system. The latter formed during the closure of the westernmost embayment of the Meliata Ocean (see Fig. 2 and text below). However, most of this basement probably became subducted without subsequent exhumation in the course of the Eoalpine high-pressure event.

In some places Mesozoic sediments, that are part of the **Tirolian nappes**, are observed to represent the cover of the Grauwackenzone (i.e. Plöchinger 1980). These two units originally occupied the same paleogeographic position within the passive margin north of the Meliata Ocean, a position that is more proximal (or external), as compared to the Hallstatt realm. In many other places, however, the original stratigraphical contacts between Grauwackenzone and Tirolian nappes were obscured by subsequent tectonic overprints, postdating the detachment of both these units from their crystalline substratum.

The **Bavarian nappes**, including the "Cenoman-Randschuppe" form the lowermost nappe system within the Northern Calcareous Alps and consist of detached Mesozoic cover. At the northern rim of the Alps these nappes directly overly Penninic units, derived from the Alpine Tethys. Hence, their paleogeographic origin is distal in respect to the passive margin that was southerly adjacent to the Piedmont-Liguria ocean, but relatively more proximal (or external) in respect to the earlier formed passive margin north of the Meliata Ocean, as compared to the Juvavic and Tirolian nappes. Following Eisbacher et al. (1990) we regard one unit amongst the Bavarian nappes, the Lechtal nappe, simply as the Mesozoic stratigraphic cover of the Silvretta-Phyllitgneis-nappe (see also Nowotny et al. 1993), which is part of the Silvretta-Seckau nappe system described below. Consequently we interpret the other, mostly detached parts of the Bavarian nappe system to have originally represented the cover of the basement found in the rest of the Silvretta-Seckau nappe system (part of the Upper Austroalpine basement nappes).

The **Grauwackenzone** (Schönlaub 1980) represents the former substratum of the Tirolian nappes. This unit was detached from an unknown older substratum and has been paleogeographically positioned north of the Meliata Ocean (see above). Hence we do not parallelise the Paleozoic of the Grauwackenzone with that of the Gurktal nappe or with that of the Graz Paleozoic. The latter units are interpreted to have originated from west or south of the Meliata Ocean (see below), the suture being represented by the Koralpe-Wölz high-pressure nappe system (see below).

Upper Austroalpine basement nappes

Tollmann (1977) proposed that all the Upper Austroalpine units of the Northern Calcareous Alps were paleogeographically located to the south of most of the Austroalpine basement nappes (his "Middle Austroalpine"). He considered many of these basement nappes to have been derived from a "Middle Austroalpine" paleogeographic realm, a view we do not share. Following Frank (1987), Schuster & Frank (1999) and Schuster et al. (2001) we abandon the term "Middle Austroalpine". This of course implies that the Northern Calcareous Alps do not a priori occupy a tectonically higher position with respect to these basement nappes, which we also attribute to the "Upper Austroalpine" realm. Instead, we propose a subdivision of these Upper Austroalpine basement nappes into four nappe systems described below, largely following a tectonic scheme proposed by Schuster et al. (2001). Our subdivision is based on modern findings on the poly-metamorphic evolution of these basement nappes.

Unit **Mesozoic cover of Upper Austroalpine basement nappes** denotes Mesozoic cover of Upper Austroalpine basement nappes presently still found in direct stratigraphic contact with these basement nappes in areas situated south of the Northern Calcareous Alps. Note, however, that part of the cover of the Upper Austroalpine basement nappes, such as the Lechtal nappe (Bavarian nappes), was attributed to the Northern Calcareous Alps, as discussed above. Large occurrences of this Mesozoic cover are found near the western margin of the Austroalpine nappes: Landwasser-Ducan sediments (cover of Silvretta basement), Engadine Dolomites (cover of Campo-Sesvenna basement). Smaller occurrences represent the cover of the Ötztal and Bundschuh basement nappes (Brenner and Stangalm Mesozoic, respectively). A third and larger realm of Mesozoic sediments near the Periadriatic line (Drauzug Permo-Mesozoic) represents the stratigraphic cover of the Drauzug-Gurktal nappe system.

The structurally highest **Drauzug-Gurktal nappe system** comprises basement units located south of the Southern Border of Alpine Metamorphism, referred to as "SAM" by Hoinkes et al. (1999) and situated north of the Periadriatic lineament of the Eastern Alps. Steeply dipping fault systems of varying age delimit the southern boundary of Cretaceous (Eoalpine) metamorphic overprint. These are, from W to E, Tonale series, Meran-Mauls basement, Gailtal basement, Deferegger Alps and Strieden basement (Schuster et al. 2001). Furthermore, this nappe system also comprises the Graz Paleozoic, Gurktal nappe and Steinach nappe. These units are only locally overprinted by a rather low grade Eoalpine metamorphism. We therefore equate them with the units south of the SAM. Both groups of basement units are found in the hangingwall of the Koralpe-Wölz high pressure and/or the Ötztal-Bundschuh nappe systems (see below). Since some parts of this nappe system (Gurktal nappe and Graz Paleozoic) are unconformably covered by Gosau beds, while others (Strieden basement) are covered by non-metamorphic Mesozoic sediments in direct stratigraphic contact (Drauzug Mesozoic), we regard this nappe system to represent the tectonically highest units amongst the Upper Austroalpine basement nappes. It tectonically overlies the former suture of the Meliata embayment and/or its adjacent distal continental margin, marked by the Koralpe-Wölz high-pressure nappe system (see below). Hence it is regarded as being derived from that part of the Apulian plate, together with the Southern Alps and the Dinarides, that formed the southern margin of the Meliata ocean when Eo-alpine nappe stacking started (see Fig. 2 and profiles in Fig. 3 discussed later).

The **Ötztal-Bundschuh nappe system** occupies an intermediate tectonic position between Drauzug-Gurktal nappe system in its hanging wall, and Koralpe-Wölz high-pressure nappe system in its footwall. When Miocene orogen-parallel stretching, that occurred in the context of the un-roofing of the Tauern window during Miocene-age extrusion of the Austroalpine nappes and their Penninic underpinnings towards the east is retro-deformed (Frisch et al. 1998), it becomes clear that the Ötztal and Bundschuh nappes were originally connected. Furthermore, both nappes are characterised by a strong field metamorphic gradient regarding Eoalpine metamorphism: grade of metamorphism rapidly increases towards the base of this nappe system, i.e. towards the contact with units attributed to the Koralpe-Wölz high-pressure nappe system. However, the lateral continuity of this nappe system is very limited, partly due to Late Cretaceous normal faulting (i.e. Neubauer et al. 1995) and partly due to Tertiary strike slip movements (i.e. Mancktelow et al. 2001).

The **Koralpe-Wölz high-pressure nappe system** comprises a series of basement units that are characterized by significant, often pressure dominated, Eoalpine metamorphic overprint (Hoinkes et al. 1999; Schuster et al. 2001; Schuster 2003), and which include eclogitic MORB-type gabbros yielding Permian protolith ages (Miller & Thöni 1997). In many places high-P metamorphism was subsequently, i.e. during decompression, overprinted by Barrow-type metamorphism. While this nappe system is not observed in the westernmost part of the Eastern Alps, its constituents gradually become more widespread towards the eastern end of the Alps (Plate 1).

Schneebergzug and underlying southerly adjacent eclogitic units (Texelgruppe; e.g. Sölva et al. 2001) form the westernmost occurrences of this nappe system. Unfortunately the latter are sometimes referred to as "Southern Ötztal basement", although they, together with the Schneebergzug, tectonically underlie the Ötztal nappe along a N-dipping contact. Further to the east units belonging to this nappe system (northern Deferegger Alps, Schober and Polinik crystalline units) are in a sub-vertical position (Figs. 3d and e) and directly juxtaposed with the structurally higher Drauzug-Gurktal nappe system along steeply inclined Late Alpine faults, such as the DAV in the south. In the north these same units almost directly overlie the Tauern window.

The largest occurrences of the Koralpe-Wölz high-pressure nappe system are found east of the Tauern window. There, eclogitic units (i.e. Millstatt, Saualpe and Koralpe crystalline units) are underlain by basement units that indicate lower pressures and temperatures, attributed to the same nappe system (i.e. Wölz, Radentheim, Rappold and Strallegg crystalline units). This indicates an inverted metamorphic field gradient. In the south-east, however, a lower grade basement unit (the Plankogel crystalline complex, also attributed to the Koralpe-Wölz nappe system) overlies the eclogitic Koralpe unit. Also in the south-eastern part of the Alps the entire south-dipping Koralpe-Wölz high-pressure nappe system is overlain by the Ötztal-Bundschuh nappe system and ultimately, and above Late Cretaceous normal faults, the Drauzug-Gurktal nappe system. Hence, a normal metamorphic field gradient is found in the hanging wall of the eclogitic units (Schuster 2003).

Following an early suggestion of Frank et al. (1983), we suspect that the eclogitic parts of the Koralpe-Wölz system form the core of a recumbent fold, with lower grade rocks in its limbs (see Fig. 3e). We propose that these eclogitic units were exhumed towards the north within an extrusion wedge, similar to a scenario proposed by Engi et al. (2001) for the Lepontine Alps. Although this extrusion wedge largely consists of continental crust (apart from MORB-type mafics of Permian protolith age; Thöni & Jagoutz 1992, 1993) we attribute Cretaceous high-pressure metamorphic overprint and subsequent extrusion to collision between the northern and southern margins of the Meliata embayment (Fig. 2). The Silvretta-Seckau nappe system described below would represent the northern margin. The southern margin would be represented by the Ötztal-Bundschuh and Drauzug-Gurktal nappe systems. Furthermore, we suggest that the basement of the Koralpe-Wölz system, devoid of Mesozoic series, may have formerly underlain the early-detached cover presently found in Grauwackenzone and the Tirolian/Juvavic nappes.

All Upper Austroalpine basement nappes found near the western margin of the Austroalpine nappes in Eastern Switzerland (Languard and Campo-Sesvenna-Silvretta nappes) belong to the **Silvretta-Seckau nappe system**. There, they are seen to have been thrusted towards the WNW and over the Lower Austroalpine units of Eastern Switzerland during Eoalpine deformation ("Trupchun phase" of Froitzheim et al. 1994). The units belonging to the higher nappe systems (Koralpe-Wölz high-pressure and Ötztal-Bundschuh nappe systems) also have been thrust towards the WNW along the Schlinig thrust (Schmid & Haas 1989), along which they are cut out towards the west. This indicates that these higher nappes are not just missing by erosion in the west. Instead, these higher units that originated from a more proximal position in relation to the Meliata Ocean (Fig. 1), never reached the western rim of the Austroalpine realm in Eastern Switzerland. Further to the east, we not only attribute the Seckau crystalline complex to this nappe system, but also units traditionally assigned to the Lower Austroalpine nappe system, i.e. the Innsbrucker Quarzphyllit unit, the Schladming basement with its inverted cover (Becker 1992), as well as the Semmering unit. In the profile depicted in Fig. 3e, best illustrating the complete nappe stack of Upper Austroalpine basement nappes, the Schladming crystalline unit is seen to directly underlie the Koralpe-Wölz high-pressure nappe system.

Lower Austroalpine nappes

We only mapped those units as **Lower Austroalpine nappes** that were derived from a very distal (or external) paleogeographic position within the passive margin of Apulia adjacent to the Piedmont-Liguria Ocean. Such units are widespread in Eastern Switzerland, particularly along the south-western margin of the Austroalpine nappe system, and the development of the distal margin they represent is similar to that described for the Southern Alps (e.g. Froitzheim & Eberli 1990; Bertotti et al. 1993; Manatschal & Bernoulli 1999). Apart from the Err-Bernina nappe system, they also comprise the Ela nappe (Froitzheim et al. 1994). Slivers of Lower Austroalpine nappes, too small to be mapped at the scale of the tectonic map (Plate 1), are also found along the north-eastern margin of the Austroalpine nappes. While Lower Austroalpine nappes are virtually absent in the Engadine window, they are again occasionally found at the northern margin of the Tauern window (Tarntal nappes, Radstatt Tauern units). The Matrei zone at the southern margin of the Tauern window is a mélange that contains olistoliths derived from the Lower Austroalpine realm (Frisch et al. 1989), but was attributed to the Penninic nappes (see below). Furthermore, we mapped the Wechsel nappes found at the eastern margin of the Alps as part of the Lower Austroalpine nappe system.

The units mapped as **Nappes derived from Margna-Sesia fragment** are somewhat special in that they are derived from fragments that are interpreted to have been rifted off the most distal part of the Apulian margin as extensional allochthons during mid-Jurassic opening of the Piedmont-Liguria ocean (Froitzheim et al. 1996; Fig. 2b). These units, comprising Sesia-Lanzo zone and Dent Blanche nappe in Northern Italy and Western Switzerland, and Margna- and Sella nappes in Eastern Switzerland, respectively, occupy a transitional position between Austroalpine and Penninic units (Trümpy 1992).

Remarks concerning the term "Penninic nappes"

Classically, the term "Penninic nappes" includes nappes derived from all sorts of paleogeographic domains (European margin, Valais ocean, Briançonnais terrane and Piedmont-Liguria ocean), which is somewhat unfortunate. Nevertheless this term could hardly be abandoned completely, because it is too deeply entrenched in the Alpine literature. However, we decided not to completely follow the tradition by excluding those units as "Penninic", which formed part of the European margin. We denote these structurally lowermost metamorphosed units, widespread in the Lepontine dome and the Tauern window (Fig. 1), together with the Gotthard "massif", as "Sub-Penninic", following a suggestion by Milnes (1974).

Upper Penninic nappes

The units mapped as **Upper Penninic nappes** are predominantly derived from the Piedmont-Liguria Ocean (Alpine Tethys) and pieces of exhumed sub continental mantle of the immediately adjacent distal margin of Apulia. Occasionally, slices of the adjacent former passive margins (Apulia and/or Briançonnais) are intercalated (for example in the former "Combin Zone" in the sense of Argand 1916; e.g. Bearth 1967; Escher et al. 1997; Dal Piaz 1999). They normally occupy the structurally highest position within the Alpine nappe stack, unless their original position was severely modified by large-scale post-nappe folding (Schmid et al. 1990; Bucher et al. 2003). These units consist of (i) ophiolites, often grading into distal continental margin units (i.e. Manatschal & Nievergelt 1997); (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 Embrunais-Ubaye cover nappes (i.e. Kerkhove 1969) or the Nappes Supérieures of the Préalpes of Western Switzerland and adjacent France (i.e. Caron et al. 1989), respectively; (iv) and finally, ophiolitic mélanges such as the Matrei zone found at the rim of the Tauern window (Frisch et al. 1989; Kurz et al. 1998).

Some of these units, such as the cover nappes of the Embrunais-Ubaye area and Préalpes Romandes, are found at the front of the Western Alps and were detached early on, because they remained non-metamorphic (Frey et al. 1999). Others, such as the Upper Penninic nappes forming a very large part of the internal Western Alps, are mostly characterised by subduction-related Tertiary-age pressure-dominated metamorphism (i.e. Gebauer 1999) and associated deformation. Finally, the Upper Penninic units of the Eastern Alps (i.e. Arosa and Platta units of Eastern Switzerland, Matrei mélange of the Tauern window, Ybbsitz ophiolite unit in front of the Northern Calcareous Alps, and units in the Rechnitz window at the eastern margin of the Alps) formed part of a Cretaceous-age nappe stack (Froitzheim et al. 1994) and/or accretionary wedge (Frisch et al. 1989). They are characterised by an Eoalpine (i.e. Cretaceous) tectonic overprint associated with variable grades of metamorphism, ranging from non-metamorphic over greenschist to blueschist conditions (Frey et al. 1999).

Middle Penninic nappes

These units are part of the "Briançonnais terrane" (Fig. 1). An unequivocal subdivision into a more internal "Briançonnais" and a more external "Subbriançonnais" paleogeographical domain is only possible where cover sequences are well preserved.

The areas mapped as **Sedimentary cover of Middle Penninic basement nappes** comprise Mesozoic cover attributed to the Briançonnais terrane that remained in stratigraphic contact with the crystalline basement (i.e. Escher et al. 1997) and which are large enough to be mapped at the scale of the map presented in Plate 1. In many cases this Mesozoic cover is incomplete and only comprises those Triassic sediments that were situated below a principle detachment horizon (either the Lower Triassic or the Carnian evaporites, depending on facies; see Trümpy 1980, his fig. 33).

The **Middle Penninic basement nappes** partly consist of a pre-Late Carboniferous basement exhibiting pre-alpine metamorphism, and partly of mono-metamorphic Permo-Carboniferous fill (e.g. Baudin et al. 1993). This unit comprises all basement nappes whose origin is known or interpreted to have been part of the Briançonnais terrane. This attribution is well established in case of the basement slices that make up the former Bernhard nappe and its equivalents in the Western Alpine Arc (i.e. Gouffon 1993; Escher et al. 1997) and, in case of the Tambo and Suretta nappes of Eastern Switzerland (e.g. Schmid et al. 1990). In the case of what is historically referred to as "Internal Massifs", i.e. the Dora Maira, Gran Paradiso and Monte Rosa nappes, the attribution to the Briançonnais terrane (Keller & Schmid 2001), as depicted in Plate 1, is not undisputed. For the M. Rosa nappe, for example, a paleogeographic origin from the distal European margin has also been proposed (Froitzheim 2001).

Detached Middle Penninic cover nappes of the Western Alps are found at the front of the Western Alps, together with Upper Penninic cover nappes (Embrunais-Ubaye nappes, Préalpes Romandes, "Klippen" of Central Switzerland), or alternatively, behind a WNW-directed out-of-sequence thrust (Roselend thrust, also referred to as the "Penninic Front") in case of the Nappe du Pas-du-Roc in Savoie (Ceriani et al. 2001). The Schams, Falknis-Sulzfluh and Tasna nappes of Eastern Switzerland, however, are in more internal positions, i.e. situated below the orogenic lid formed by Upper Penninic and Austroalpine units (i.e. Schmid et al. 1990; Schreurs 1993).

Detached **Permo-Carboniferous sediments (Zone Houillère) and their Mesozoic cover** were mapped separately from the "detached Middle Penninic cover nappes" that exclusively consist of Mesozoic cover. These units were detached at the base of a voluminous Permian trough, referred to as "Zone Houillère" (Desmons & Mercier 1993). The Zone Houillère, whose pre-Carboniferous substratum remains unknown, forms the backbone of the Western Alps. In the area around the town of Briançon (France) these Carboniferous sediments are overlain by Permian deposits and finally by the classical Mesozoic series of the Briançonnais (Ellenberger 1958).

Lower Penninic nappes

This unit comprises sequences derived from the Valais Ocean and/or the immediately adjacent distal continental margin units (i.e. Fügenschuh et al. 1999). These units were not accreted to the Alpine orogen before the Tertiary.

Lower Penninic units attributed to the Valais Ocean are conspicuously absent in the southern part of the Western Alpine Arc. There, the Valais suture was sealed by Priabonian flysch (Cheval Noir unit; Ceriani et al., 2001). This flysch, hitherto attributed to the "Ultra-Dauphinois" (Barbier 1948), was mapped as **Tertiary flysch sealing Lower Penninic accretionary prism**.

The bulk of the Lower Penninic units mapped in Plate 1, however, are made up of unit **North-Penninic ophiolites and Bündnerschiefer**. In the northern part of the Western Alps parts of this unit, known as "Versoyen" (Elter & Elter 1965), are made up of fragments of oceanic crust that underwent Tertiary-age high-pressure metamorphism (Fügenschuh et al. 1999; Loprieno 2001; Bousquet et al. 2002). However, not all sediments attributed to the Lower Penninic nappes, also known as "Valaisan" or "Zone the Sion-Courmayeur" (Trümpy 1960; Escher et al. 1997) in Savoie and Western Switzerland, have been deposited on truly oceanic lithosphere. These Bündnerschiefer-dominated sediments represent a Cretaceous to Tertiary-age post-rift sequence, the so-called "trilogie Valaisanne" (Antoine 1971, Jeanbourquin & Burri 1991, Loprieno 2001), that can be followed all the way into the footwall of the Berisal nappe, situated at the western edge of the Lepontine dome.

Along the northern rim of the Lepontine dome unit "North-Penninic ophiolites and Bündnerschiefer" can be followed into Eastern Switzerland, where large volumes of Bündnerschiefer are exposed in the Prättigau half-window, as well as in the Engadine window, parts of the latter being again characterised by high-pressure metamorphism (Bousquet et al. 1998). Furthermore, we included the Niesen flysch of the Préalpes Romandes (Ackermann 1986) and the early-detached Sardona flysch of the Infrahelvetic units of Eastern Switzerland into this tectonic unit. Additionally, we also correlated the following units found along the southern margin of the Lepontine dome as belonging to the Lower Penninic nappes: Antrona ophiolites, Orselina series, Bellinzona-Dascio zone and Chiavenna ophiolites. This latter correlation is based on structural work in an area around the Bergell intrusion (e.g. Davidson et al. 1996; Berger et al. 1996; Schmid et al. 1996b).

In the Eastern Alps the Rhenodanubian flysch, which is also part of the Lower Penninic nappes, outcrops within a narrow corridor along the northern edge of the Austroalpine nappes, extending all the way from Eastern Switzerland to Vienna. This flysch unit is entirely made up of Bündnerschiefer-type sediments (Prey 1980; Oberhauser 1995). Finally, we also attributed the Bündnerschiefer-type sediments of the Glockner nappe (Obere Schieferhülle) in the Tauern window (Kurz et al. 1998) to this Lower Penninic unit and hence to the Valais ocean.

Sub-Penninic nappes

Units denoted as "Sub-Penninic", forming the structurally lowest parts of Lepontine dome and Tauern window, are interpreted as derived from the distal European margin (Fig. 1). Some of these basement-dominated units, together with the basement of the "Tavetsch massif", explicitly mapped as part of unit "Helvetic and Ultrahelvetic nappes" (Plate 1), represent the former crystalline substratum of the Helvetic and Ultrahelvetic nappes, detached before the onset of Tertiary-age metamorphism within the lowermost Sub-Penninic nappes.

The areas mapped as **Mesozoic cover of Sub-Penninic basement nappes** represent those cover units of the Sub-Penninic basement units that remained within the metamorphic cores of the Alps (Lepontine and Tauern domes) and which suffered Alpine metamorphism (Frey et al. 1999). This cover delineates nappe boundaries within the deepest Lepontine nappes. Only some of this cover, predominantly Mesozoic marbles and Bündnerschiefer, is strictly autochthonous with respect to the adjacent basement rocks. In other instances, i.e. in the case of the cover of the Gotthard "Massif" (Etter 1987), this cover was detached from its crystalline substratum. The cover of the Untere Schieferhülle of the Tauern window, sliced into several thrust sheets, also including parts of the crystalline underpinnings (Kurz et al. 1998), could only be schematically mapped at the scale of Plate 1.

The bulk of the Sub-Penninic units consists of **Non-eclogitic Sub-Penninic basement nappes**, overprinted by Tertiary-age Barrowian-type metamorphism (Frey et al. 1999). In the Lepontine dome, these nappes include, from base to top: Gotthard "Massif" (in reality a back-folded nappe; Milnes 1974), Verampio and Leventina gneisses, Simano-Antigorio and M. Leone nappes (Spicher 1976). In the Tauern window these nappes predominantly consist of Variscan basement, intruded by Late Variscan granitoids (Zentralgneis) (Lammerer & Weger 1998; Kurz et al. 1998),

Intensely sliced **Eclogitic Sub-Penninic basement units** are occasionally found at the top of the Sub-Penninic nappes, i.e. at the immediate base of the Lower Penninic nappes (Valaisan). In the Lepontine dome these mylonitic slices are known as Adula nappe or Cima Lunga nappe, whose outlines in Plate 1 were modified after Nagel et al. (2002). These eclogitic slices, and others recently found at the base of the Maggia nappe (Engi et al. 2001), are interpreted to have been part of an accretionary wedge or extrusion wedge that also includes parts of the Lower Penninic nappes (Schmid et al. 1996a; Engi et al. 2001). The Eclogite Zone of the Tauern window, also characterised by Tertiary-age eclogitic overprint (Zimmermann et al. 1994; Kurz et al. 1998), is interpreted to occupy a comparable structural position within the Alpine nappe stack. Note, however, that the eclogitic "internal massifs" of the Western Alps are attributed to the Middle Penninic nappes, since they overlie the Lower Penninic nappes, as is seen in the profiles of Figs. 3 a and b.

Northern Alpine foreland and Helvetic nappes

The classical area of the **Helvetic and Ultrahelvetic nappes** (Ramsay 1981; Pfiffner 1993), i.e. limestone-dominated cover nappes derived from the more proximal European margin, is restricted to the Alpine foreland of Switzerland and westernmost Austria. The base of the Helvetic nappes is drawn along the Glarus overthrust (Schmid 1975) and its equivalent in Western Switzerland, i.e. the base of the Diablerets nappe. A thin mylonitic slice of basement, referred to as Tavetsch Massif, positioned between Aar massif and Gotthard "Massif", is also mapped as Helvetic, since this basement slice is thrust over the Aar massif and its cover by a distance of at least 15km along a splay at the rear of the Glarus thrust (Pfiffner 1985).

Only a few and very thin Helvetic slices are found along the northern margin of the Eastern Alps in Central and Eastern Austria. This is due to the erosion of the Mesozoic passive margin sediments, that presently form the Helvetic nappes of Switzerland, during late "Senonian" to Paleocene foreland inversion, pre-dating thrusting in the Helvetic nappes (Ziegler et al. 2002). On the other hand, the sediments that were deposited SW of those making up the Helvetic nappes of Western Switzerland (Diablerets and Wildhorn nappes; e.g. Ramsay 1981) become progressively more autochthonous towards the SW, i.e. when moving into the cover referred to as "Dauphinois" in the Chaînes Subalpines of France (Ramsay 1989). There the Alpine foreland is made up of para-autochthonous slices (Gratier et al. 1989), except for thin allochthonous slices found east and south of the M. Blanc massif, mapped as part of the Helvetic nappes. South of the M. Blanc massif an out-of-sequence thrust known as "Penninic front" or "Roselend thrust" (Fügenschuh et al. 1999; Ceriani et al. 2001) laterally ramps into parts of the Dauphinois (classically referred to as "Ultradauphinois" in the French literature). These thrust sheets, which include a small part of the internal Pelvoux massif (the Combeynot massif) are mapped as lateral analogs of the Helvetic and Ultrahelvetic nappes.

Unit **Helvetic flysch** mostly comprises Late Eocene to Early Oligocene flysch (including nummulitic limestone at its base) deposited in an internal part of the Alpine foreland basin. Often this flysch un-conformably overlies the Mesozoic cover of the autochthonous to para-autochthonous external massifs in the Northern Alpine foreland (i.e. Sinclair 1997). In the French Alps this flysch, referred to as "Helvetic" in Switzerland, is known as "Grès d'Annot", "Grès de Champsaur" or "Flysch des Aiguilles d'Arves". In case of the Glarus area, this unit also includes early-detached Late Cretaceous to Paleogene cover slices of south-Helvetic origin (Blattengrat "flysch"; Lihou 1995), presently found below the out-of-sequence Glarus thrust, together with the Lower Penninic Sardona flysch.

Unit **Subalpine Molasse** is made up of south-dipping thrust slices of conglomeratic Molasse (Pfiffner 1986). These thrust sheets, that root below the external massifs in Eastern Switzerland (Pfiffner et al. 1997a) can be followed all along the northern rim of the Swiss and Austrian Alps. There they form a clearly defined northern front of the Alpine thrust sheets. The front of the external thrust sheets of the Western Alps is more diffuse, and Molasse deposits are often lacking (Lickorish and Ford 1998).

Unit **Deformed autochthonous and para-autochthonous pre-Tertiary cover of the Northern Alpine foreland** is restricted to the Western Alps where late stage thrusting propagated far into the foreland in Miocene to Recent times (Burkhard & Sommaruga 1998). These units comprise thick- and thin-skinned thrust sheets. The thick-skinned thrust sheets comprise the "External Massifs" and their cover, also referred to as "para-autochthonous Helvetic units" in Switzerland (including the Morcles and Doldenhorn nappes of Western Switzerland; Ramsay 1981), or as "Chaînes Subalpines" (Gratier et al. 1989) in France. Thin-skinned thrust propagation in the Late Miocene to Pliocene led to folding and thrusting in the Jura (Laubscher 1961; Burkhard & Sommaruga 1998) and in the southern part of the Chaînes Subalpines (Digne thrust, mapped within this unit in the south-western corner of Plate 1; Lickorish & Ford 1998).

Unit **Undeformed pre-Tertiary cover of the Northern Alpine foreland** comprises the rift flanks of Rhine- and Bresse graben, including the Rhine-Bresse transfer zone, uplifted in Oligo-Miocene times. Subsequent to Oligocene graben formation these areas were affected by very weak, presumably sub-Recent to Recent, shortening (Giamboni et al. 2004).

The basement outcropping in unit **External massifs of the Alps and Variscan basement of the Northern Alpine foreland** is connected below the Molasse basin and the Jura Mountains. Substantial Alpine shortening only affected the External massifs, while the far-field stress in the Alpine foreland is held responsible for at least part of the exhumation of Black Forest and Vosges during the Miocene (Laubscher 1987).

Five schematic transects through the Alps, illustrating important along-strike changes in the Alpine orogen

Important progress has recently been made regarding large-scale geophysical-geological transects across the Alps (Pfiffner et al. 1997b; Roure et al. 1990, 1996; Transalp Working Group 2002) involving high-resolution deep seismic sounding along such transects, and a wealth of geophysical data 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 & Kissling 2000).

Figs. 3a and 3b depict geological-geophysical transects (ECORS-CROP and NFP-20 WEST) across the Western Alps (Schmid & Kissling 2000; Escher et al. 1997), while the transect of Fig. 3c (NFP-20 EAST) crosses an area of Eastern Switzerland situated near the transition into the Eastern Alps (Schmid et al. 1996a, 1997). These profiles are interpreted according to criteria extensively discussed in Schmid & Kissling (2000). They illustrate the following major changes, which occur along strike, i.e. when going from the N-S striking part of the Western Alps (Figs. 3a) towards the Eastern Alps (Fig. 3b and 3c): (1) Duplication of European lower crust 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, and, (4) increasing amounts of Miocene shortening within the Southern Alps.

Recent results from high-resolution tele-seismic tomography, focussing on the lithosphere and upper mantle P-wave velocity structure beneath the entire Alps (Lippitsch 2002; Lippitsch et al. 2003) led to a 3-D tomographic model that, when integrated with the deep crustal structure along the Alpine transects depicted in Fig. 3, indicates a change in present-day subduction polarity that occurs within the Eastern Alps. This new finding is extensively discussed and confronted with the results of previous work elsewhere (Schmid et al. 2004). Note that regarding the Eastern Alps (Figs. 3d, e) the inferred crustal geometry considerably differs from that provided by TRANSALP Working Group (2001, 2002) and many of the crustal-scale interpretations given in Nicolich et al. (2003). 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.

According to this new interpretation of the lithosphere geometry, the European lithospheric slab descending towards southeast and underneath 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 imaged as dipping under the European lithosphere by some 170km (Lippitsch 2002; Schmid et al. 2003; Schmid et al. 2004). This finding is surprising at first sight, since there is no indication for an along-strike change in the stacking order of the major paleogeographic and tectonic units in the Alps, as is seen from Fig. 1 and Plate 1.

It is proposed that drastic changes at a lithospheric scale occurred at around 20 Ma ago (for a more extensive discussion see Schmid et al. 2004). 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 & Spakman 2000). This caused massive extension in the Pannonian Basin, also comprising 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 in the area of the TRANSALP profile (Fig. 3d). 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. lower plate, position. A major change occurs, however, across Giudicarie belt and Brenner line in the border area between the two mantle-lithospheric slabs (SE-dipping European and NE-dipping Adriatic slab, respectively). It is proposed, that the change in subduction polarity between the NFP-20 EAST & EGT transect (Fig. 3c) and the EASTERN ALPS transect (Fig. 3e) is only an apparent one. By taking into account the 3D-geometry of the entire Alpine-Pannonian-Dinaridic system, we propose a lateral north-westward movement of the NE-dipping Dinaridic mantle-lithospheric slab south of the Periadriatic line, identical with the Adriatic slab, and into profile EASTERN ALPS (Fig. 3e), facilitated by the eastward retreat of the detached European slab into the Carpathian loop. At the earth's surface two major orogen-perpendicular post-collisional features, that formed at around 20 Ma ago, coincide with this change in subduction polarity: Giudicarie belt (Stipp et al. in press) and the Brenner normal fault (Fügenschuh et al. 1997). This suggests that the change in subduction geometry imaged by tomography was not established before some 20 Ma ago, i.e. when these across-strike features started to form.

Fig. 3d presents a re-interpretation (Schmid et al. 2003) of the TRANSALP geophysical-geological transect (Transalp Working Group 2002) in the light of the new findings on the lithospheric geometry of the Alps based on high-resolution tomography (Lippitsch et al. 2003). It emphasizes the importance of strike slip faulting along Inntal and Pustertal lines, adjacent to the Tauern ductile pop-up structure, while the interpretation given by Transalp Working Group (2002) emphasises thrusting along a thrust at the base of the Tauern window, referred to as "Sub-Tauern ramp". The deep structure of the transect depicted in Fig. 3d completely differs from that proposed by Transalp Working Group (2002). Both Fig. 3d and 3e depict the Apulian Moho as descending northwards under the European lithosphere.

Note that the polarity of the suture between Rhenodanubian flysch (Valais ocean in Fig. 1) and northern rim of the Austroalpine nappes (Apulian plate in Fig. 1) does not change along strike from west to east (Figs. 1 and 3). This indicates that the northern rim of the Apulian (Austroalpine) upper plate remains unaffected by the Miocene change in subduction polarity, which only concerns the southern part of the transects of Figs. 3d and 3e.

Profile EASTERN ALPS (Fig. 3e), discussed in more detail in Schmid et al. (2004), illustrates the geometry of the Austroalpine nappe stack proposed in this work. It preserved a thickness of some 10-20km in the area east of the Tauern window, which lacks substantial exhumation by late stage thrusting and/or orogen-parallel extension during the Tertiary. In the profile of Fig. 3e the Koralpe-Wölz high-P nappe system is interpreted as representing a former extrusion wedge situated between the Silvretta-Seckau nappe system in its footwall and the Ötztal-Bundschuh and Drauzug-Gurktal nappe systems in its hanging wall. This extrusion wedge exhumed high-pressure units that formed during the subduction of the western embayment of the Meliata Ocean (Figs. 2b and 2c) during Cretaceous (Eoalpine) orogeny.

Conclusions

The new tectonic map (Plate 1) uses paleogeographical affiliation (Fig. 1) as well as tectono-metamorphic evolution, apart from purely structural criteria. It reflects the bewildering complexity of the Alpine orogen both in terms of its evolution in time, as well as in terms of important along-strike changes. Concerning the evolution in time, the maps (Plate 1, Fig. 1), in combination with a simple paleogeographical reconstruction (Fig. 2) illustrate and confirm the view that the Alps are the product of two orogenies, a Cretaceous one, that was followed by a Tertiary one (Froitzheim et al. 1996). 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.

Along-strike changes are more dramatic than hitherto believed, as is shown, for example, in the geophysical-geological transects presented in Fig. 3, based on combining a variety of methods in deep sounding with recent advances in laboratory methods and with the analysis of surface geological features by ongoing field work. In spite of their excellent 3D exposure and the enormous amount of available data (the attached list of references is far from complete), the Alps are still far from being over-investigated, as is particularly well demonstrated by many surprising recent findings.

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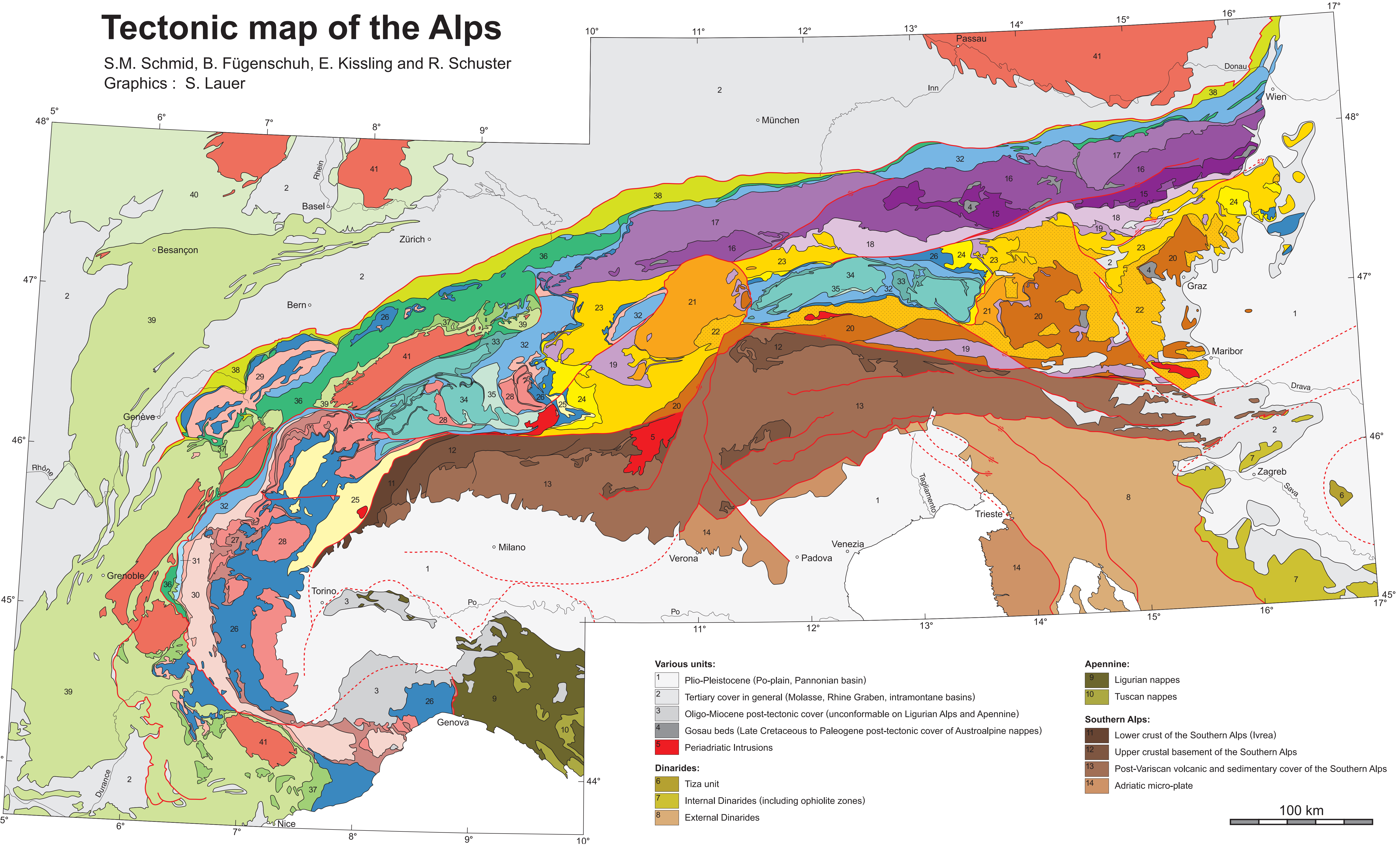
Tectonic map of the Alps

S.M. Schmid, B. Fügenschuh, E. Kissling and R. Schuster
Graphics : S. Lauer



Various units:

1	Plio-Pleistocene (Po-plain, Pannonian basin)
2	Tertiary cover in general (Molasse, Rhine Graben, intramontane basins)
3	Oligo-Miocene post-tectonic cover (unconformable on Ligurian Alps and Apennine)
4	Gosau beds (Late Cretaceous to Paleogene post-tectonic cover of Austroalpine nappes)
5	Periadriatic Intrusions

Dinarides:

6	Tiza unit
7	Internal Dinarides (including ophiolite zones)
8	External Dinarides

Apennine:

9	Ligurian nappes
10	Tuscan nappes

Southern Alps:

11	Lower crust of the Southern Alps (Ivrea)
12	Upper crustal basement of the Southern Alps
13	Post-Variscan volcanic and sedimentary cover of the Southern Alps
14	Adriatic micro-plate

100 km

Austroalpine Nappes:

Northern Calcareous Alps and Grauwackenzone (Upper Austroalpine):

15	Juvavic nappes (Mesozoic cover)
16	Tirolian nappes (Mesozoic cover)
17	Bavarian nappes (Mesozoic cover)
18	Grauwackenzone (Paleozoic, stratigraphic base of Tirolian nappes)

Upper Austroalpine basement nappes:

19	Mesozoic cover of Upper Austroalpine basement nappes
20	Drauzug-Gurktal nappe system (Tonale series, Steinach nappe, basement of Drauzug, Gurktal nappe, Graz Paleozoic)
21	Ötztal-Bundschuh nappe system (Ötztal and Bundschuh nappes)
22	Koralpe-Wölz high pressure nappe system (Schneebergzug, Millstatt, Wölz, Saualpe-Koralpe crystalline units)
23	Silvretta-Seckau nappe system (Campo-Sesvenna-Silvretta nappes, Innsbrucker Quarzphyllit, Schladming, Seckau, Semmering nappes)

Lower Austroalpine nappes:

24	Lower Austroalpine nappes (Ela, Err-Bernina nappes, Radstätter Tauern, Wechsel nappe)
25	Nappes derived from Margna-Sesia fragment (Margna-Sella, Sesia-Dent Blanche nappes)

Penninic nappes:

Upper Penninic nappes (Piedmont-Liguria ocean):

26	South-Penninic ophiolites, Bündnerschiefer or Schistes Lustrés, Nappes Supérieures des Préalpes, Helminthoid flysch and Matrei mélange

Middle Penninic nappes (Briançonnais terrane):

27	Sedimentary cover of Middle Penninic basement nappes
28	Middle Penninic basement nappes
29	Detached Middle Penninic cover nappes ("Sub-Briançonnais" and "Briançonnais")
30	Permo-Carbonifereous sediments (Zone Houllière) and their Mesozoic cover ("Briançonnais")

Lower Penninic nappes (Valais ocean):

31	Tertiary flysch sealing Lower Penninic accretionary prism (Cheval Noir Flysch)
32	North-Penninic ophiolites and Bündnerschiefer (including Rhenodanubian flysch)

Sub-Penninic nappes (distal European margin):

33	Mesozoic cover of Sub-Penninic basement nappes (including cover of "Gotthard Massif")
34	Non-eclogitic Sub-Penninic basement nappes (including "Gotthard Massif")
35	Eclogitic Sub-Penninic basement units

Northern Alpine foreland and Helvetic nappes:

36	Helvetic and Ultrahelvetic nappes (including Combeynot and Tavetsch "Massifs")
37	Helvetic flysch
38	Subalpine molasse
39	Deformed autochthonous and para-autochthonous pre-Teriary cover of the northern Alpine foreland (including the Jura Mountains)
40	Undeformed pre-Tertiary cover of the Northern Alpine foreland
41	External massifs of the Alps and Variscan basement of the Northern Alpine foreland

Plate 1 Tectonic map of the Alps