| Mitt. Österr. Geol. Ges. | ISSN 0251-7493 | **92** (1999) | 117-134 | Wien, Juli 2000 |
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# The Eastern Alps: Result of a two-stage collision process

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8 Figures

**Abstract**

The present structure and the Late Paleozoic to Recent geological evolution of the Alps are reviewed mainly with respect to the distribution of Alpidic, metamorphic overprints of Cretaceous and Tertiary age and the corresponding ductile structure. According to these data, the Alps as a whole, and the Eastern Alps in particular, are the result of two independent Alpidic collisional orogenies: The Cretaceous orogeny formed the present Austroalpine units sensu lato (extending from bottom to top of the Austroalpine unit s. str., the Meliata unit, and the Upper Juvavic unit) including a very low- to eclogite-grade metamorphic overprint. The Eocene-Oligocene orogeny resulted from an oblique continent-continent collision and overriding of the stable European continental lithosphere by the combined Austroalpine/Adriatic continental microplate. A fundamental difference seen in the present-day structure of the Eastern and Central/Western Alps resulted as the Austroalpine units with a pronounced remnants of a Oligocene/Neogene relief are mainly exposed in the Eastern Alps, in contrast to the Central/Western Alps with Penninic units, which have been metamorphosed during Oligocene. Exhumation of metamorphic crust, formed during Cretaceous and Tertiary orogenies, arose from several processes including subvertical extrusion due to lithospheric indentation, tectonic unroofing and erosional denudation. Original paleogeographic relationships were destroyed and veiled by late Cretaceous sinistral shear, Oligocene-Miocene sinistral wrenching along ENE-trending faults within eastern Austroalpine units and the subsequent eastward lateral escape of units exposed within the central axis of the Alps. Eastward extrusion was facilitated by the above-mentioned sinistral wrench corridors and the dextral E- to ESE-trending Periadriatic fault system due to the indentation of the rigid Adriatic/Southalpine indenter.

## Introduction

Facts and models with respect to Alpine geology have made rapid progress during the last decades, mainly due to detailed paleogeographical, structural, petrological and geochronological investigations. Together with deep reflection seismic profiling, this increase in information allowed new insights into the present-day structure and inspired new models which fundamentally changed ideas on the geology of the Western and Swiss Central Alps (e.g., NICOLAS et al., 1990; PFIFFNER, 1992; SCHMID et al., 1996; PFIFFNER et al., 1997). A similar effect is expected for the Eastern Alps as data from the TRANSALP program, in which first seismic results are now apparent, become available (TRANSALP WORKING GROUP, 2000).

This review synthesizes the principal structural data of the Eastern Alps with respect to the distribution of the Alpine metamorphic overprint, its chronology and the general tectonic framework. It also includes some redefinitions of paleogeographic and tectonic units exposed within the Eastern Alps that appear to be neccessary according to data in its present state. The time scale calibrations follow those established by GRADSTEIN and OGG (1996) for the Paleozoic and early Cenozoic, those proposed by GRADSTEIN et al. (1994) for the Mesozoic and calibrations proposed by RÖGL (1996) for the Paratethyan Oligocene-Neogene.

Aspects of the structure and tectonic evolution of the Eastern Alps were reviewed in JANOSCHECK and MATURA (1980), OBERHAUSER (1980, 1995), TOLLMANN (1977, 1985, 1987), FLÜGEL and FAUPL (1987), FRANK (1987), HOINKES et al. (1999), PFIFFNER (1992), THÖNI (1999), THÖNI and JAGOUTZ (1993), FROITZHEIM et al. (1996), EBNER (1997), EBNER et al. (1998; this volume); FAUPL (1997), DALLMEYER et al. (1998) and in contributions dealing with the structure close to the boundary between the Eastern and Western Alps in PFIFFNER et al. (1997). Plate-scale aspects were compiled in FRISCH (1979), DEWEY et al. (1989), DERCOURT et al. (1993), HAAS et al. (1995), STAMPFLI (1993, 1996), CHANNELL and KOZUR (1997), PERESSON and DECKER (1997a), STAMPFLI and MARCHANT (1997), STAMPFLI and MOSAR (1999) KRYSTYN and PILLER in PILLER et al. (this volume).

## Tectonic units of the Alps

In a geographical sense the Alps are divided into the E-trending Eastern Alps and the arc of the Western Alps, divided by the Rhine valley south of Bodensee (Lake Constance) and its southward extension (Fig. 1). The Eastern and Western Alps display a fundamentally different geological structure (see below), geological development and in

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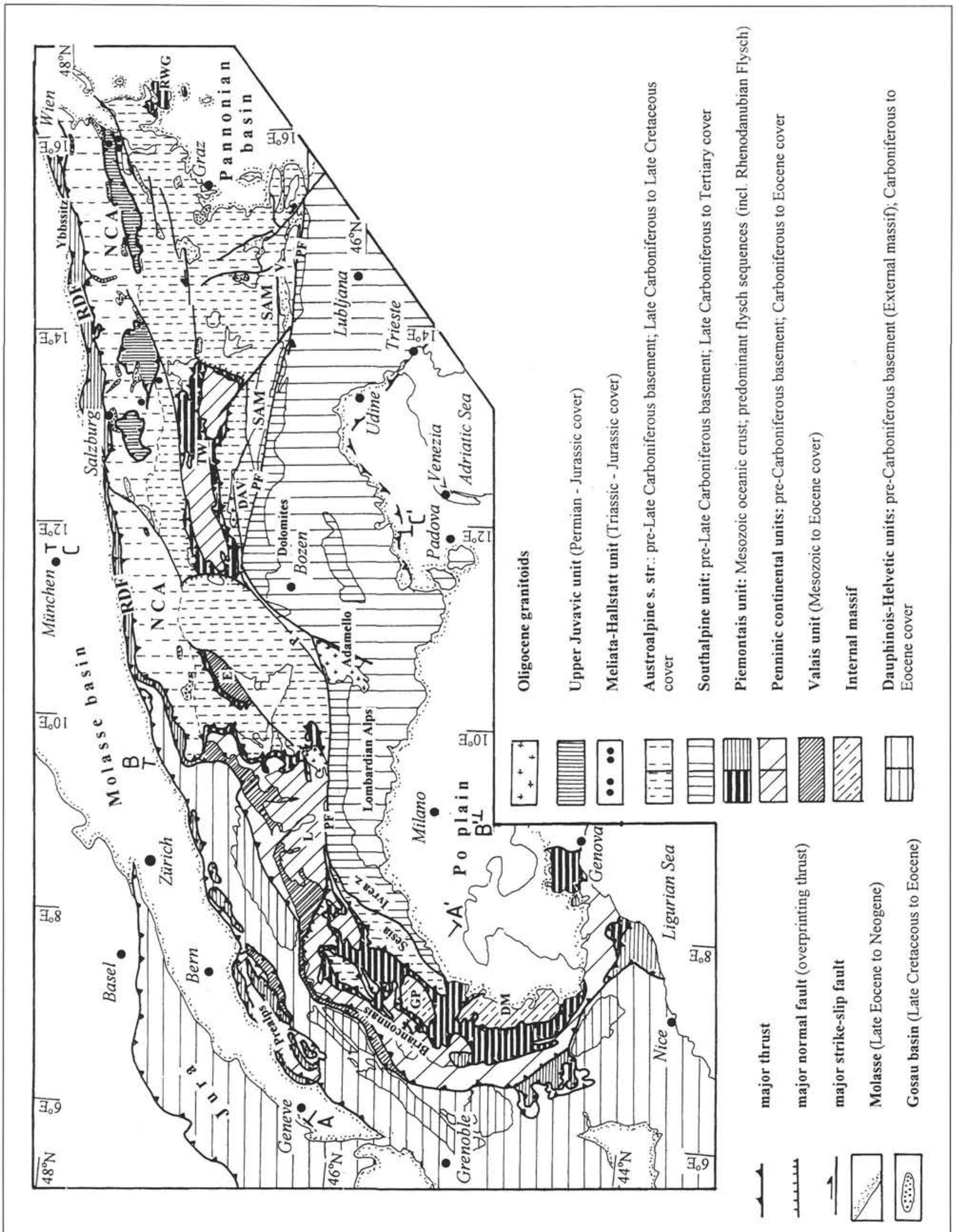



Fig. 1

Simplified tectonic map of the Alps (modified after BIGI et al. (1989). A-A´, B-B´, C-C´display orientations of sections shown in Fig. 4. Abbreviations: DAV – Deffreggen-Antholz-Valles fault, DM – Dora Maira massif, E – Engadin window, GP – Gran Paradiso massif, L – Lepontin gneiss dome, PF – Periadriatic fault, RDF – Rhenodanubian Flsch zone, RWG – Rechnitz window group, TW – Tauern window, V – Viktring fault.

part a distinct geomorphology. The most prominent mountain peaks are along the central axis in the Eastern Alps, the Swiss Central and French/Italian Western Alps. East of the Tauern window area, the topography gradually changes from high elevations in the Hohe Tauern area into the Neogene Pannonian basin with its plains and very low elevation above sea level (Figs. 1, 2).

The Alps as a whole include the following major tectonic units proceeding from bottom to top and from N (W) to S (E) (e.g., DAL PIAZ, 1992, 1993; DEBELMAS et al., 1983; TRÜMPY, 1980, 1997; TOLLMANN, 1977; FRANK, 1987; FAUPL, 1997; PFIFFNER et al., 1997) (Figs. 1, 2):

(1) The stable European continental lithosphere, which is flexed and also carries the Late Eocene to Neogene Molasse Basin, the northern peripheral foreland basin of the Alps. The Swiss-French Jura is an externally located thin-skinned fold-thrust belt (e.g., TRÜMPY, 1980, 1997). The European basement is exposed in several massifs adjacent to the Alps (Bohemian, Black Forest, Vosges and French Central Massifs);

(2) the Dauphinois/Helvetic units forming a thin-skinned fold-thrust belt that comprises Late Carboniferous to Eocene cover sequences detached from the European lithosphere and the External massifs which constitute pre-Alpine basement rocks and Helvetic Late Carboniferous to Cretaceous cover sequences (e.g., TRÜMPY, 1980; DEBELMAS et al., 1983);

(3) the Valais units, which represent the infilling of a mainly Cretaceous rift zone on an attenuated continental crust and which also comprises possible oceanic lithosphere (e.g., PFIFFNER, 1992; ESCHER et al., 1997; FÜGENSCHUH et al., 1999);

(4) the Brianconnais units, which represent a microcontinent rifted off from stable Europe during the opening of the Valais trough (FRISCH, 1979; STAMPFLI, 1993);

(5) the Piemontais units with an oceanic lithosphere (Penninic ocean in Fig. 3) in the Western Alps; the Glockner ophiolitic nappe (KOLLER & HÖCK 1990) exposed within the Tauern window and its correlatives exposed in other windows along the central axis of the Eastern Alps. The Ybbsitz ophiolite (DECKER, 1990; SCHNABEL, 1992) and overlying flysch sequences, as well as the Rhenodanubian flysch zone with remnants of a trench filling alone without any substrate, may represent part of this zone, although other authors argue for a Valais origin. The Valais, Brianconnais and Piemontais units are conventionally combined as Penninic units and assigned as North, Middle and South Penninic units, respectively;

(6) the Austroalpine s. str., a continental unit which includes remnants of a Triassic passive continental margin originally facing towards the Meliata ocean (e.g., LEIN, 1987; MANDL, this volume) and a Jurassic passive continental margin which faced towards the Penninic (Piemontais) oceanic tract (e.g., FRISCH, 1979; FROITZHEIM and MANATSCHAL, 1996);

(7) the Meliata unit with its small remnants of the sedimentary infilling of an oceanic trough and the adjacent distal continental margins (e.g., MANDL and ONDREJICKOVA, 1991; KOZUR and MOSTLER, 1992; MANDL, this volume);

(8) the Upper Juvavic unit that exclusively comprises the Late Paleozoic to Mesozoic cover sequences of a passive continental margin (see SCHWEIGL and NEUBAUER, 1997 for discussion);

(9) and finally, the Southalpine unit juxtaposed along the Periadriatic fault against the Austroalpine units sensu strictu. The Southalpine unit is a continental unit that is largely similar to the Austroalpine unit sensu strictu. The Slovenian trough represents a major Permian to Triassic rift basin on a continental basement within that unit. The Southalpine unit is considered to represent the northern extension of the stable Adriatic microplate, which also includes the Po plain and the adjacent Adriatic Sea (e.g., CHANNEL et al., 1979). It forms the southern external retro-arc orogenic wedge within the Alpine orogenic system (e.g., DOGLIONI and FLORES, 1997; SCHMID et al., 1996; SCHUMACHER et al., 1997).

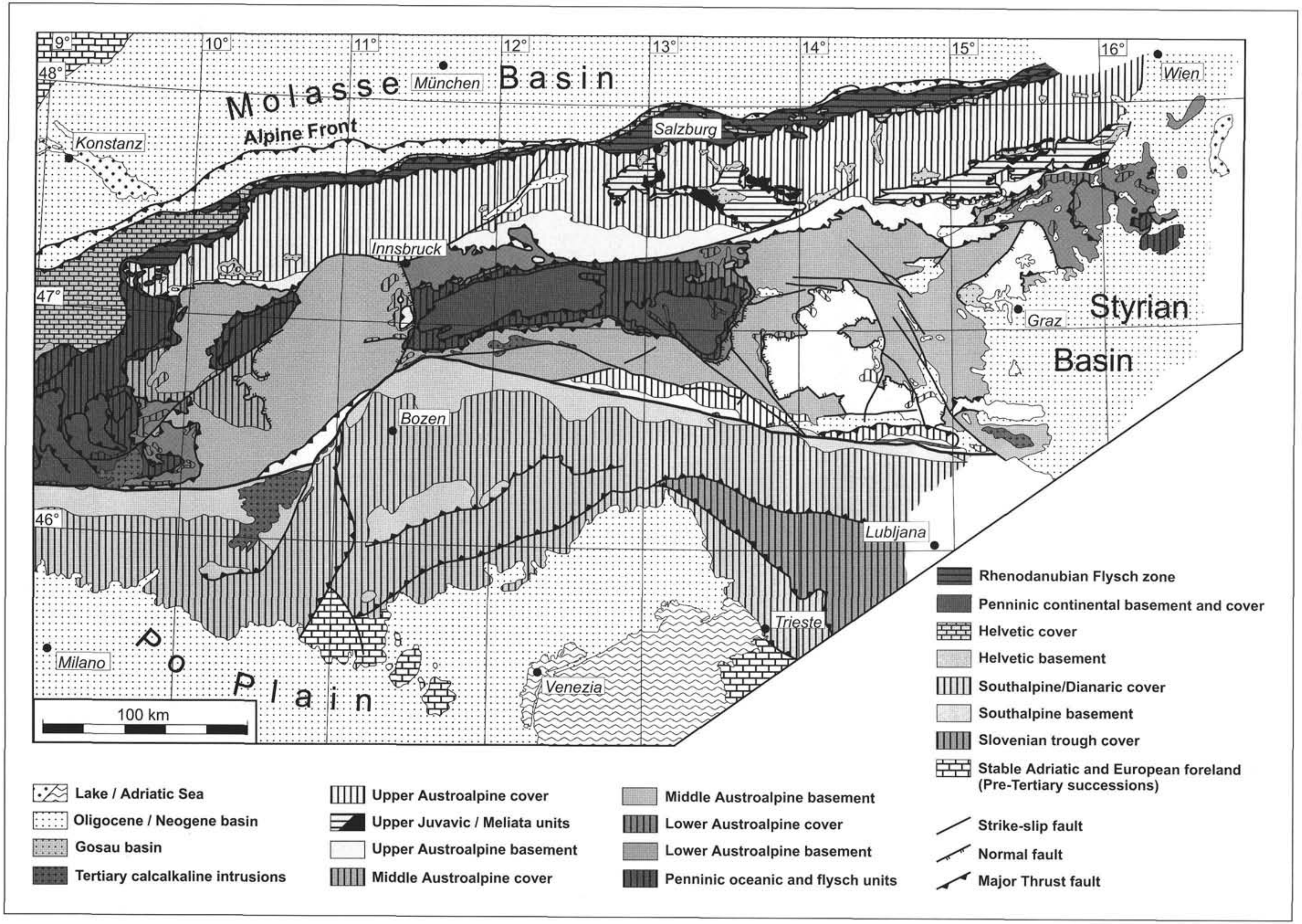
Compared with previous interpretations, the Ybbsitz ophiolite and the subdivision of the previous Austroalpine units into three different tectonic units are newly introduced. In this paper, we limit the use of the Austroalpine unit (s. str.) to the pile of nappes of continental origin in the footwall of remnants of the Meliata oceanic and transitional continental cover sequences (see below). Consequently, the overlying Upper Juvavic units derive from a separate continental unit and are excluded from the Austroalpine units s. str., although this interpretation is highly controversial. Based on the occurrence of Meliata-derived rocks, structurally beneath the Upper Juvavic unit, KOZUR (1992) and SCHWEIGL and NEUBAUER (1997) argued for the distinction of two passive continental margin successions. GAWLICK et al. (1999) *and* MANDL *(this volume) argue for non-separation and an* emplacement of the Hallstatt and Meliata units over the Upper Juvavic unit.

In terms of metamorphism, these Alpine units reveal fundamental differences. The Austroalpine s.str., Meliata-Hallstatt and Upper Juvavic units display Cretaceous-age metamorphism throughout the Alps, the Penninic and Helvetic units show Eocene to Oligocene regional metamorphism (see DESMONS et al., 1999; FREY and FERREIRO-MÄHLMANN, 1999; FREY et al., 1999; HOINKES et al., 1999). The Southalpine units are unmetamorphic, except for narrow zones adjacent to the Periadriatic fault, which display an anchi- to epizonal Cretaceous and Oligocene metamorphic overprint (LÄUFER et al., 1997; RANTITSCH, 1997).

## Europe-related, Helvetic and Penninic continental units

Units comprising the stable Jurassic-Cretaceous European continental domain, including the former, southerly adjacent shelf, are widely exposed along the external Western Alpine arc. These units consist of thick Jurassic, Cretaceous and Paleogene shallow water sediments, some intra-shelf basins and syn-rift half-grabens. The Helvetic cover nappes are largely detached from their basement and were transported towards NW. The basement is exposed in the External massifs, from the Aar to the Argentera Massif. The External massifs are interpreted to represent thrust wedges that were detached from the European lithosphere during late stages of the Alpine collision (ROURE et al., 1990; ESCHER et al., 1997; PFIFFNER et al., 1997).

The Valais units mainly comprise schistes lustrés intercalated by metabasalts. The Schams nappes of eastern Switzerland (SCHMID et al., 1996) and some units exposed within


9°
10°
11°
12°
13°
14°
15°
16°
48°
47°
46°
Molasse Basin
München
Wien
Alpine Front
Konstanz
Salzburg
Innsbruck
Styrian Basin
Graz
Bozen
Lubljana
Trieste
Milano
Po Plain
Venezia
100 km
Lake / Adriatic Sea
Oligocene / Neogene basin
Gosau basin
Tertiary calcalkaline intrusions
Upper Austroalpine cover
Upper Juvavic / Meliata units
Upper Austroalpine basement
Middle Austroalpine cover
Middle Austroalpine basement
Lower Austroalpine cover
Lower Austroalpine basement
Penninic oceanic and flysch units
Rhenodanubian Flysch zone
Penninic continental basement and cover
Helvetic cover
Helvetic basement
Southalpine/Dianaric cover
Southalpine basement
Slovenian trough cover
Stable Adriatic and European foreland (Pre-Tertiary successions)
Strike-slip fault
Normal fault
Major Thrust fault

the Engadin window are correlated with the Valais units (TRÜMPY, 1980, for discussion).

The Penninic continental units are exposed within the Tauern window within the so-called Venediger nappe and the overlying Rote Wand-Modereck nappe complex (e.g., KURZ et al., 1996, 1998, and references therein). The basement is composed of the Habach-Storz Groups with Late Proterozoic to Early Paleozoic island arc successions and back arc ophiolite, as well as a widespread Variscan granite suite, collectively known as Central Gneisses. The Central Gneisses are exposed within several structural domes along the central structural axis of the antiformal Tauern window (Figs. 1, 2; LAMMERER and WEGER, 1998; NEUBAUER et al., 1999c). The cover sequences include fossil-bearing Carboniferous sequences evident in the western Tauern window, minor Permian and Triassic sequences and thick Jurassic-Cretaceous sequences exposed within the Silbereck, Hochstegen and Kaserer Groups (e.g., LAMMERER, 1986; KURZ et al., 1998 and references).

## Penninic (Piemontais) ophiolite

The Piemontais-Ligurian ophiolites are widely exposed in the Western Alps and include ultramafic rocks, pillow basalts and a few gabbro and plagiogranite bodies (LAGABRIELLE and POLINO, 1988; VANOSSI, 1991). These are overlain by calcareous metasediments (schistes lustrés). The oceanic lithosphere formed during the Jurassic at a slow spreading ridge. Recent U-Pb zircon dating confirm the Middle Jurassic age of ophiolite formation (RUBATTO et al., 1998).

In the Eastern Alps, the Glockner ophiolite is considered to represent the extension of the Penninic units of the Western Alps. Penninic oceanic sequences of the Eastern Alps are outcropping within the Engadin, Tauern and Rechnitz windows (e.g., HÖCK and MILLER, 1987; HÖCK and KOLLER, 1989; KOLLER and HÖCK, 1990).

In the Engadin window, the Idalpe ophiolite is a well-preserved ophiolite with an only weak metamorphic overprint (e.g., KOLLER and HÖCK, 1990). The Glockner nappe of the Tauern window represents a dismembered ophiolite and the sedimentary infilling, mainly calcareous micaschists, laid on top of it (HÖCK and MILLER, 1987). The Rechnitz window group exposes ophiolitic successions with serpentinites, prasinites and carbonate schists (KOLLER, 1985). These are within two nappes, an upper ophiolite nappe with serpentinites at the structural base and a lower nappe, which includes carbonate schists and carbonate olistostromes (Köszeg conglomerate).

The Rhenodanubian Flysch zone (Fig. 2) extends along northern margins of Eastern Alps and comprises Early Cretaceous to early Late Eocene turbidite sequences. These are considered to represent the infilling of the Penninic trough, either the Valais or Piemontais basin. The presence of a dismembered Late Jurassic ophiolite indicates an oceanic basement for the upper tectonic units of the Rhenodanubian Flysch zone (DECKER, 1990; SCHNABEL, 1992). The lower units relate to the Ultra-Helvetic margin and are considered to represent the southward extension of Helvetic passive continental margin of stable Europe (see FAUPL and WAGREICH, this volume for details; MATTERN, 1999).

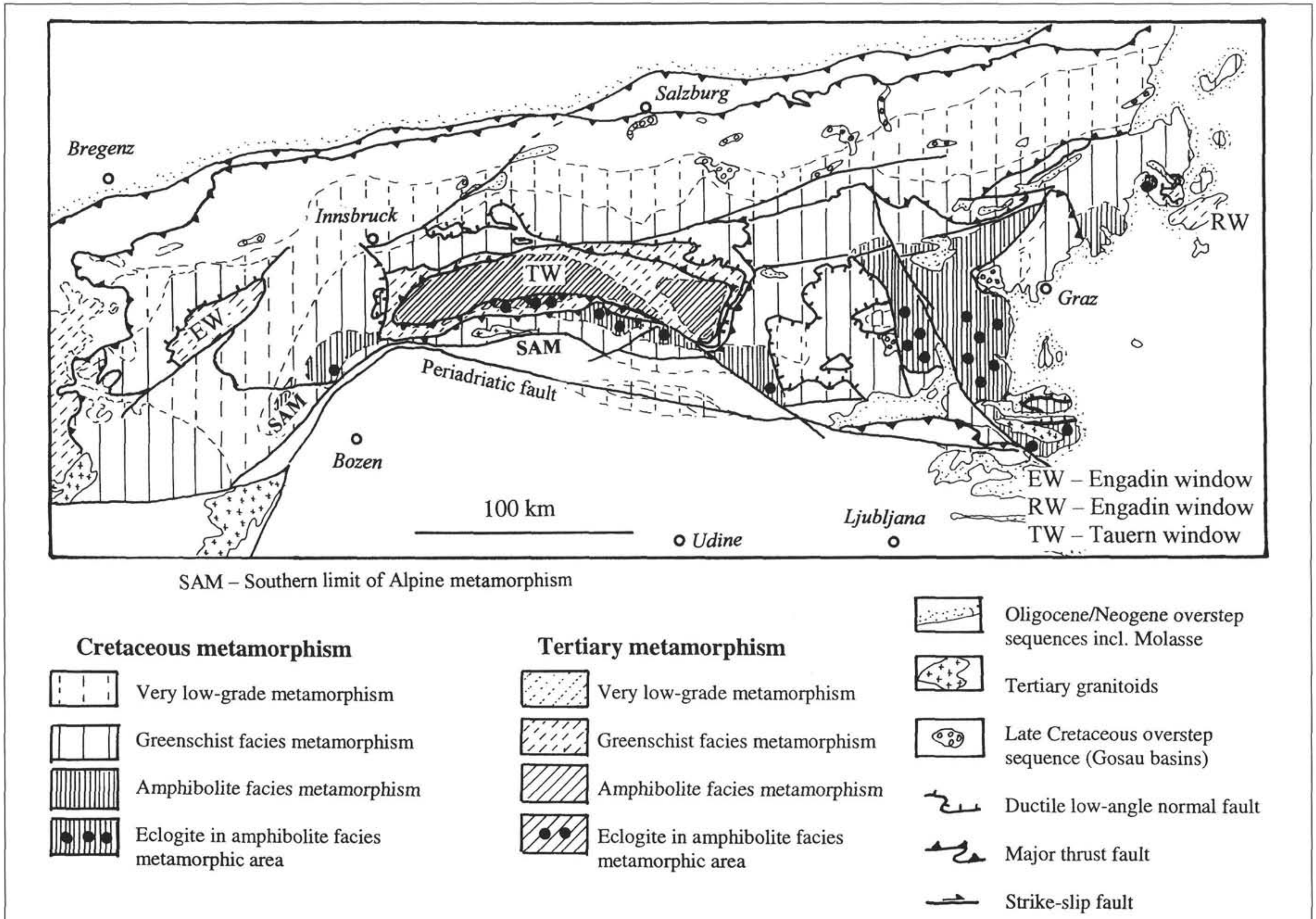
← Fig. 2
Simplified geological map of the Eastern Alps (modified after BIGI et al., 1989).

## Austroalpine units s. str.

The Austroalpine units s. str. represent a continental basement-cover nappe pile, which received its essential internal nappe structure during the Cretaceous orogenic events (e.g., RATSCHBACHER, 1986; DALLMEYER et al., 1998). They can basically be divided into the Central Eastern Alps with dominant basement exposure and the Northern Calcareous Alps with predominant Permian to Cenozoic cover sequences (Figs. 1, 2).

Although subject of controversy (CLAR, 1973; FRANK, 1987; TOLLMANN, 1987), the subdivision into Lower, Middle and Upper Austroalpine nappe complexes in the Eastern Alps is easily applicable over large portions of the Austroalpine nappe pile, which is bound to the south by the SAM fault zone (SAM: southern limit of Alpine metamorphism; HOINKES et al., 1999). The Lower Austroalpine nappe complex includes units exposed along the southwestern margin of the Eastern Alps (e.g., Err-Bernina and Campo nappes), the Innsbruck-Reckner and Radstadt nappes around the Tauern window and the Kirchberg-Stuhleck and Wechsel nappes along the eastern margin of the Eastern Alps, all having an originally northwestern paleogeographic position. The broadly developed Middle Austroalpine nappe complex extends from the western to the eastern margin of the Eastern Alps. The Upper Austroalpine nappe complex includes the Steinach nappe, the Graywacke zone nappes and the overlying Tirolic and Bajuvaric nappes of the Northern Calcareous Alps. The Gurktal, Graz and Steinach nappe complexes form large klippens on Middle Austroalpine units of the central Eastern Alps, the Graywacke zone nappe complex and the overlying Northern Calcareous Alps are located along the northern leading edge of the Austroalpine nappe complex. These Upper Austroalpine units were derived from an originally southeastern paleogeographic position. Therefore, the Middle Austroalpine units take an intermediate paleogeographic position (e.g., TOLLMANN, 1987). The general Cretaceous nappe transport direction was towards the WNW and N, respectively (e.g., RATSCHBACHER, 1986; KROHE, 1987).

The southern limit of the Alpine metamorphism (of Cretaceous-age) represents an east-trending system of polyphase faults, which juxtapose Austroalpine units with a strong, generally amphibolite and eclogite grade metamorphism to the north against mostly very-low grade Austroalpine units in the south. Proceeding from west to east, the SAM consists of various segments of previously known faults. The western sectors of the SAM represent a zone of important, mostly Oligocene, sinistral strike-slip displacement with an oblique-slip, S-down component. The eastern sectors (east of the Isel fault) represents a zone of Late Cretaceous sinistral strike-slip shear with a subordinate normal component, too. No large-scale nappe structures within the Austrolapine units exposed within the SAM and the Periadriatic fault are preserved, except flower structures related to the Periadriatic fault (POLINSKI and EISBACHER, 1992; NEMES et al., 1997).



Salzburg
Bregenz
Innsbruck
TW
EW
SAM
SAM
Periadriatic fault
Bozen
Graz
RW
100 km
Udine
Ljubljana
EW – Engadin window
RW – Engadin window
TW – Tauern window
SAM – Southern limit of Alpine metamorphism
Cretaceous metamorphism
Very low-grade metamorphism
Greenschist facies metamorphism
Amphibolite facies metamorphism
Eclogite in amphibolite facies metamorphic area
Tertiary metamorphism
Very low-grade metamorphism
Greenschist facies metamorphism
Amphibolite facies metamorphism
Eclogite in amphibolite facies metamorphic area
Oligocene/Neogene overstep sequences incl. Molasse
Tertiary granitoids
Late Cretaceous overstep sequence (Gosau basins)
Ductile low-angle normal fault
Major thrust fault
Strike-slip fault

The composition and evolution of the Austroalpine basement units is not considered in detail here. However, it must be noted that each Alpine nappe comprises a basement that differs from under- and overlying basement units in composition, age and degree of pre-Alpine tectonothermal events (e.g., NEUBAUER et al., 1999b; SCHÖNLAUB and HEINISCH, 1993; NEUBAUER and HANDLER, this volume). For example, the Upper Austroalpine units comprise continuous fossiliferous Ordovician to Early Carboniferous sequences affected by a late Variscan and/or Cretaceous very low- to low-grade metamorphic overprint. In contrast, the Middle Austroalpine units comprise a mostly medium-grade metamorphic basement, which includes only minor successions that correlate to Ordovician to Carboniferous sequences.

Cover sequences deposited on the Austroalpine basement include a nearly continuous, conformable Late Carboniferous to early Late Cretaceous succession of rift, carbonate platform, shelf margin and later pelagic formations. The principal rift phase occurred during the Permian and resulted in a rapid tectonic subsidence during the Triassic, when a passive continental margin was formed opposing the Meliata-Hallstatt ocean towards the SE (e.g., LEIN, 1987; SCHWEIGL and NEUBAUER, 1997) (Fig. 4). A second, Jurassic rift phase created the Piemontais oceanic basin by rifting off the stable European continent forming another passive continental margin facing towards the NW (e.g., FRISCH, 1979). Resulting structures along this passive margin are half-grabens filled with escarpment breccias (e. g., HÄUSLER, 1987). Asymmetric simple shear is supposed to lead to exhumation of subcontinental mantle lithosphere and the formation of the continental Margna (western margin of eastern Alps), Hippold (northwest of the Tauern window) and the questionable Sesia extensional allochthons (FROITZHEIM and MANATSCHAL, 1996; HEIDORN et al., 2000).

## Meliata unit

The Meliata unit comprises distal continental margin deposits and recently detected oceanic sedimentary rocks of Middle Triassic to Doggerian age (KOZUR, 1992; MANDL and ONDREJICKOVA, 1991; KOZUR and MOSTLER, 1992). These include Middle and Late Triassic pelagic carbonates, Late Triassic radiolarites and the Doggerian Florianikogel Fm. with shales, volcanogenic greywackes and ashfall tuffs. Greywackes and tuffs indicate a volcanic source of subduction-related origin (NEUBAUER et al., 1999d). Recent $^{40}Ar/^{39}Ar$ dating of single mica from Doggerian greywackes yielded Early Jurassic ages (HILBERG, 1998; NEUBAUER et al., 1999d). The features of the Florianikogel Fm. can be interpreted as recording the presence of a Doggerian accretionary wedge.

Furthermore, salt melanges (Permian and Scythian strata) are often connected with the structural sole of the Meliata unit, generally understood to represent the primary lowermost sequence of this unit (KOZUR, 1992). The salt melange is connected with serpentinites, melaphyres and a few gabbro bodies. The melaphyres have an alkaline basaltic affinity (KIRCHNER, 1980). Gabbro and melaphyres record some uncertain Permian ages. Therefore, these rocks are interpreted as recording incipient Permian rifting (KIRCHNER, 1980).

← Fig. 3
Simplified map of Alpine metamorphism in the Eastern Alps (after FREY et al., 1999).

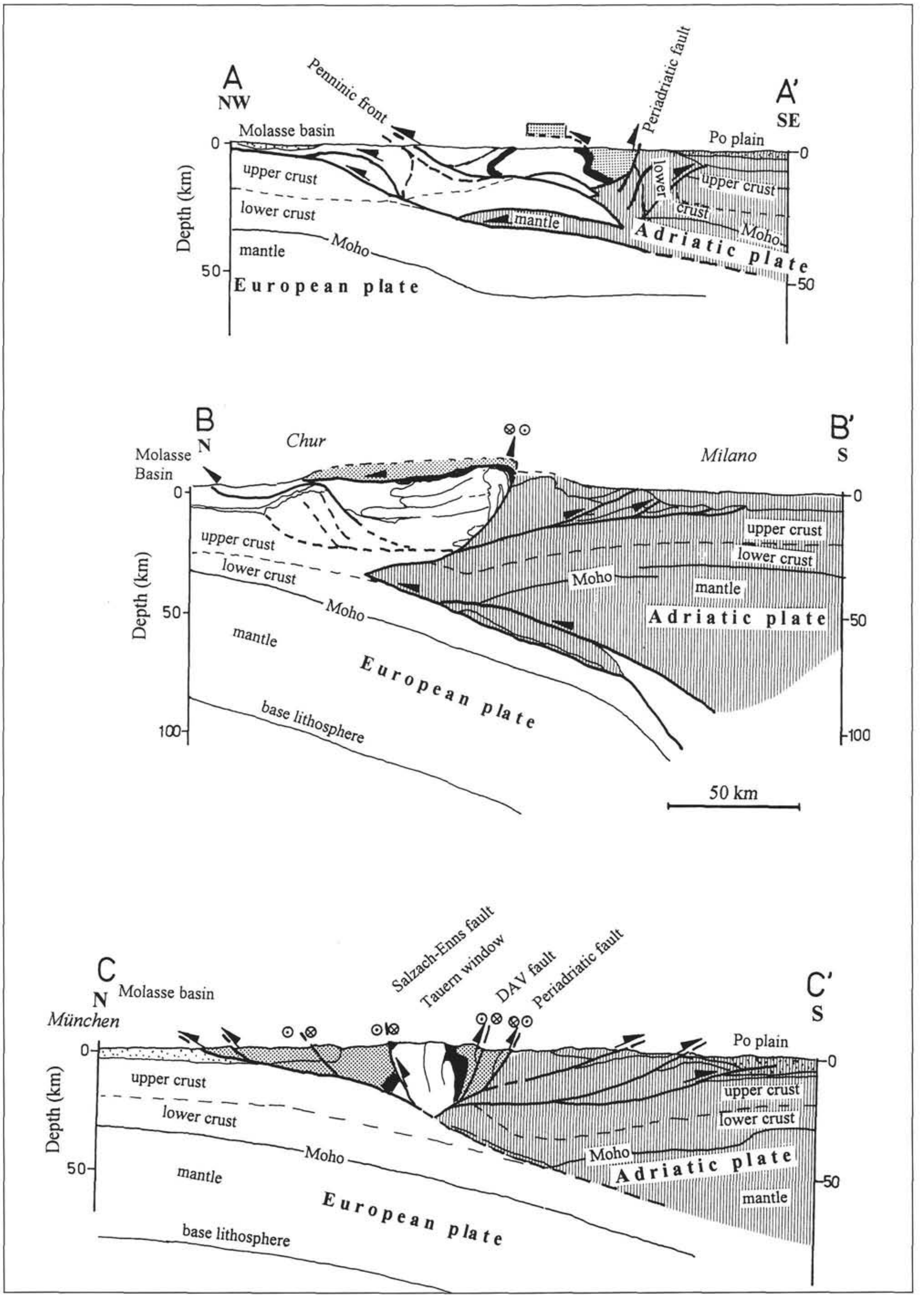
## Upper Juvavic unit

Upper Juvavic units include a continuous, Permian to Triassic section with some rare Jurassic formations (TOLLMANN, 1985). The Upper Juvavic units form several large tectonic klippens on top of the Hallstatt-Meliata units within the eastern half of the Northern Calcareous Alps (Figs. 1, 4). The sequences display remarkable differences when compared to the Tirolic-Bajuvaric nappe complex. These mainly include thick Late Triassic Norian reefs in the Upper Juvavic nappe, in contrast to the Norian lagoonal Hauptdolomit facies and presence of Rhaetian reefs in the Tirolic-Bajuvaric nappe (LEIN, 1987; SCHWEIGL and NEUBAUER, 1997). The Jurassic sequence is incomplete and only records some thin Liassic limestones and Malmian reefal limestone in the northwesternmost exposures.

## Southalpine unit

The Southalpine unit includes a continental basement exposed along the Periadriatic fault and a continuous Late Carboniferous to Oligocene cover succession. Two main rift phases affected the Southalpine unit: NW-SE extension during the Permian resulted in the formation of a swell and trough topography, which governed deposition from the Permian to Cenozoic (e.g., SCHUMACHER et al., 1997, and references). Permian magmatic underplating by mantle melts in the Ivrea zone (e.g., VOSHAGE et al., 1990) may have been associated with crustal extension. Progressive onlap of the Paleotethys from the SE reached the Carnic Alps during the Late Carboniferous, whereas the South Tyrolian Dolomites arose during the Late Permian and the Lombardian Alps came about during the Middle Triassic. A strong tectonic subsidence phase during Middle Triassic times in the eastern to central sectors of the Southern Alps was associated with magmatism in the central Southern Alps. A second rift phase during the Late Triassic to Early Jurassic mainly affected western sectors and resulted in the formation of pronounced troughs, thinning of the crust and exhumation and cooling of middle crustal levels (e.g., BERTOTTI et al., 1993, 1999; SCHUMACHER et al., 1997).

The deposition of the Late Cretaceous Lombardian flysch in the western Lombardian Alps originating from a northern source heralds ongoing deformation, which is not otherwise evidenced in the Southern Alps. The structure of the Southern Alps is dominated by E-trending, top-S-directed thrusts, which brought up basement rocks on top of the cover (e.g., DOGLIONI and BOSSELINI, 1987; CARMINATI et al., 1997). The earliest thrusts in the western part of the Southern Alps were formed before the intrusion of the Adamello (prior to ca. 42 Ma; SCHÖNBORN, 1992). In eastern sectors, c. WNW-trending, SSW-directed structures were formed during the Paleogene, believed to represent a Dinaric trend (DOGLIONI, 1987; DOGLIONI and BOSELLINI, 1987). These structures were overprinted by Oligocene to Recent structures, which also


A
NW
Penninic front
Periadriatic fault
A'
SE
Molasse basin
Po plain
upper crust
lower crust
mantle
Moho
European plate
Adriatic plate
Depth (km)
B
N
Chur
Milano
B'
S
Molasse Basin
upper crust
lower crust
Moho
mantle
European plate
Adriatic plate
base lithosphere
Depth (km)
50 km
C
N
München
Molasse basin
Salzach-Enns fault
Tauern window
DAV fault
Periadriatic fault
C'
S
Po plain
upper crust
lower crust
Moho
mantle
European plate
Adriatic plate
base lithosphere
Depth (km)

← Fig. 4
Three transects of the Alps: a – Transect of the Western Alps (simplified after NICOLAS et al., 1990, and ROURE et al., 1990); b – transect across the eastern Central Alps (after SCHMID et al., 1996); transects of Western and eastern Central Alps are based on deep seismic reflection profiling; c – transect across the Eastern Alps (modified after LAMMERER and WEGER, 1998, and ROEDER, pers. comm.), and extrapolating the structures of section B-B´ towards the east.

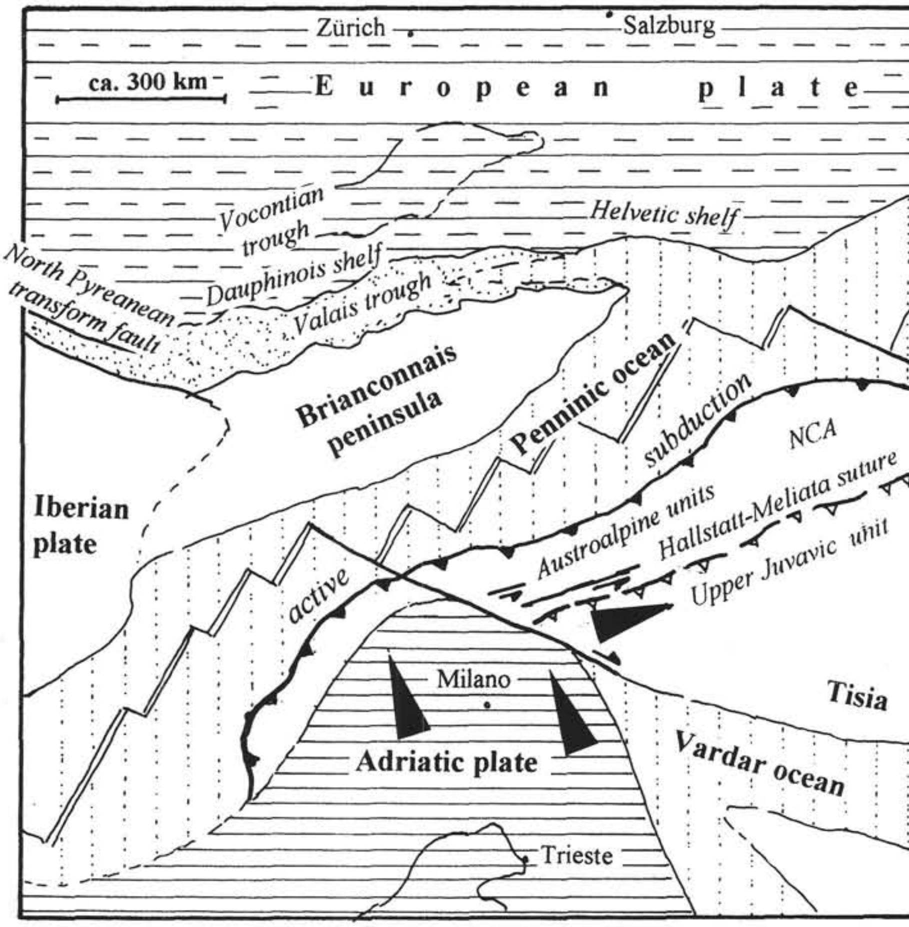



Fig. 5
Roughly Early/Late Cretaceous paleogeographic map of the Alps based on CHANNELL and KOZUR (1996). The arrows indicate inferred plate movement directions. Note suggested eastward extrusion of Austroalpine units sensu due to indentation by the Adriatic microplate.

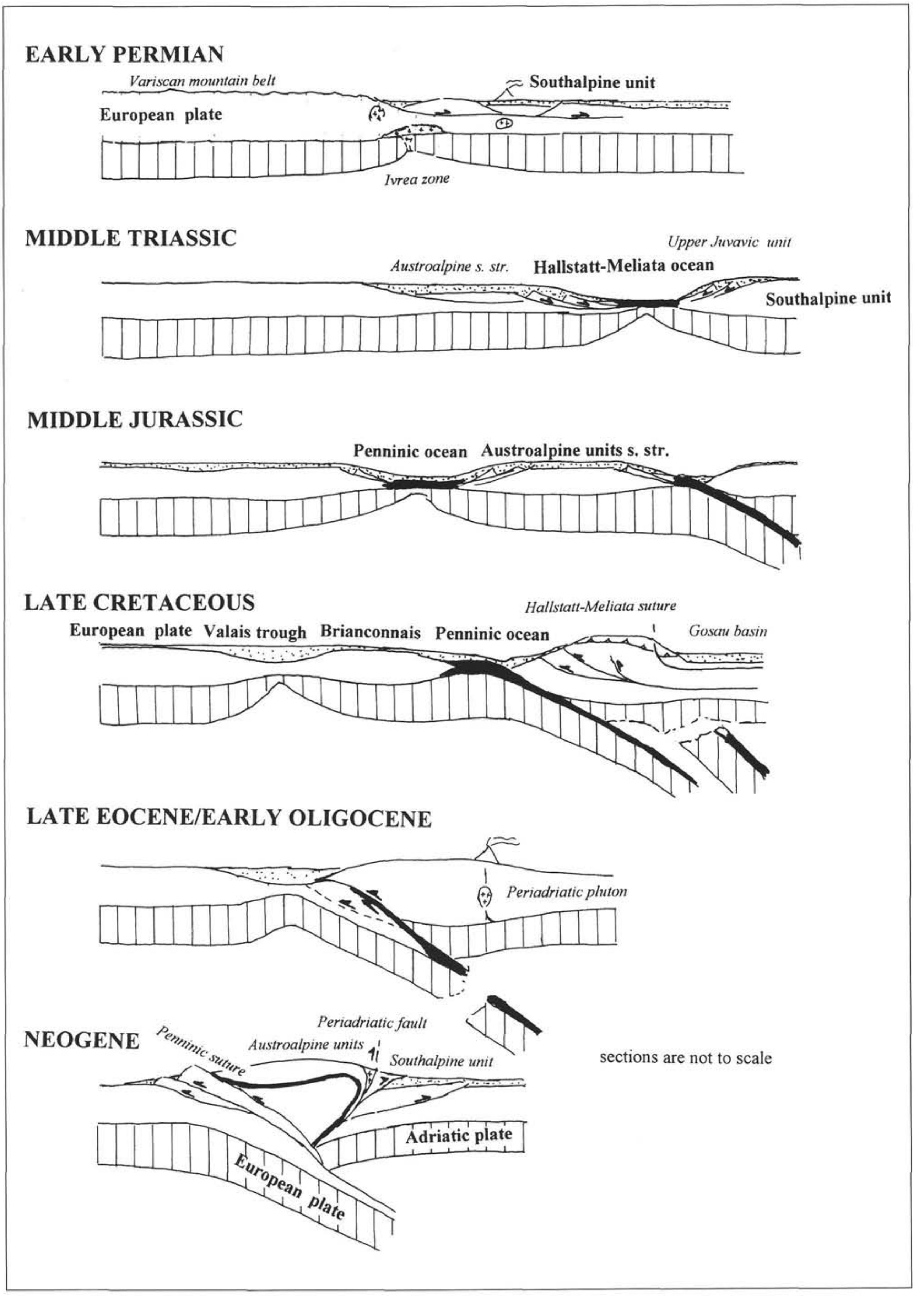
involved the basement. S-directed thrusting is still going on in these locations, as earthquakes with a dominant thrust component and GPS data indicate (CARMINATI et al., 1997; SCHUMACHER et al., 1997; BRESSAN et al., 1998; MIERLO, et al., 1997; CAPORALI and MARTIN, 2000).

## Tectonic evolution

In terms of metamorphism and associated deformation, the Eastern Alps and the Alps as a whole are divided into three units (Fig. 3): (1) The Austroalpine units str., the Meliata-Hallstatt units and the Upper Juvavic units, which were overprinted by Cretaceous W- to NW-directed, ductile thrusting and associated metamorphism; (2) the Penninic continental and oceanic units and the Dauphinois-Helvetic units that were overprinted by Cenozoic metamorphism and associated N- to W-directed ductile deformation; and (3) Southalpine units, which have remained largely unaffected by metamorphism, except in northernmost sectors adjacent to the Periadriatic fault and mainly deformed during the Cenozoic, S-directed thrusting and shortening (LÄUFER et al., 1997; RANTITSCH, 1997). Furthermore, increasing evidence for Permian metamorphism should be noted; it is interpreted as relating to crustal extension, magmatic underplating and intrusion of mafic magmatic rocks.

In the following, we discuss the principal stages of the Permian to Recent tectonic evolution (Figs. 6, 7, 8). Some stages of the tectonic evolution are also discussed at more length: For the Triassic/Jurassic by MANDL (this vol.), for the Cretaceous by FAUPL and WAGREICH (this vol.) and for the Cenozoic by STEININGER and WESSELY (this vol.). Note that the tectonic evolution of the Eastern Alps also controls the formation of mineral resources, coal and hydrocarbons (EBNER et al., this volume; HAMILTON et al., this volume; SACHSENHOFER, this volume).

The Alpine tectonic evolution started with Permian rifting immediately following the Variscan orogeny and after deposition of Late Carboniferous molasse sediments in all future continental domains. Rifting may have resulted from continuous dextral shear between Gondwana and Laurussia (e.g., MUTTONI et al., 1996). Pronounced Early to Late Permian tectonic subsidence and extension commenced in the eastern Southalpine units, where a carbonate platform was established during the Permian and the Paleotethys sea transgressed towards the west (WOPFNER, 1984). Further evidence for divergence and extension of the lithosphere during the Permian was the emplacement of gabbros, low-pressure metamorphism due to unroofing of metamorphic core complexes and magmatic underplating, e.g. in the Ivrea zone (VOSHAGE et al., 1990; THÖNI and JAGOUTZ, 1993; SILETTO et al., 1993; THÖNI, 1999). However, the main phase of tectonic subsidence in the Austroalpine tectonic units was during the Middle Triassic. A new shelf carbonate platform was established within the Southalpine, Austroalpine s. str. and Upper Juvavic domains. Ladinian and Upper Triassic radiolarites are considered to represent the infilling of the Meliata oceanic basin, from which the westernmost remnants are found in the eastern Northern Calcareous Alps.


EARLY PERMIAN
Variscan mountain belt
Southalpine unit
European plate
Ivrea zone
MIDDLE TRIASSIC
Upper Juvavic unit
Austroalpine s. str.
Hallstatt-Meliata ocean
Southalpine unit
MIDDLE JURASSIC
Penninic ocean
Austroalpine units s. str.
LATE CRETACEOUS
Hallstatt-Meliata suture
European plate
Valais trough
Brianconnais
Penninic ocean
Gosau basin
LATE EOCENE/EARLY OLIGOCENE
Periadriatic pluton
NEOGENE
Penninic suture
Periadriatic fault
Austroalpine units
Southalpine unit
Adriatic plate
European plate
sections are not to scale

A further independent rift stage during the Late Triassic and Early Jurassic led to the opening of the (South) Penninic, Piemontais-Ligurian ocean (Fig. 6). On the other hand, the Meliata oceanic basin started to close during the Jurassic, most likely not later than the Middle Jurassic, based on the record of the Lammer unit S of Salzburg (GAWLICK, 1996; GAWLICK et al., 1999) and of the Florianikogel Formation (HILBERG, 1998). The final closure occurred during the Early Cretaceous with the formation of a deep sea trench (Roßfeld basin). The trench-type Roßfeld basin was already proposed by FAUPL and TOLLMANN (1978). At the same time, the Valais basin opened (Fig. 5). Collision between Austroalpine units s. str. in a footwall position and the Upper Juvavic units in a hangingwall position occurred during the early Late Cretaceous, with the formation of a nappe pile of basement-cover nappes exposed in the south and cover nappes in northern, external domains (FRANK, 1987; DALLMEYER et al., 1998). Nappe stacking was directed to the NW and W and likely prograded from the SE to NW (e.g., RATSCHBACHER, 1986; RATSCHBACHER and NEUBAUER, 1989; RING et al., 1989; HANDLER, 1994; LINZER et al., 1995, 1997). The Late Cretaceous Gosau basins sealed the Meliata suture and nappe structures (Fig. 7b).

The formation of Gosau basins in the Eastern Alps was associated with sinistral wrenching, normal faulting at shallow crustal levels and exhumation of eclogite-bearing crust within the Austroalpine units (NEUBAUER et al., 1995, 1999a; FROITZHEIM et al., 1997; WILLINGSHOFER et al., 1999a, b). Furthermore, WAGREICH (1995) suggested tilting of the Austroalpine nappe stack towards the NW, which was associated with final shortening, thrusting and doming in deep levels of the Austroalpine crust (B. BECKER, 1993; HANDLER, 1994; DALLMEYER et al., 1998; MÜLLER et al., 1999).

The final closure of the Piemontais ocean occurred not earlier than the Early Eocene (Figs. 6, 8a), because of (1) the presence of pelagic Eocene sediments in Penninic units both in the Eastern and Western Alps and (2) the Eocene ages of high-pressure metamorphism (RUBATTO et al., 1998). Obviously, the subduction not only included oceanic crust, but also distal Penninic continental crust, both in the Eastern and Western Alps. Upper sectors of the crust were detached from the downgoing continental lithosphere, due to the lowering of strength because of temperature increase. Exhumation of these crustal pieces was associated with final thrusting, tectonic unroofing and surface denudation within the uprising mountain chain (e.g., RATSCHBACHER et al., 1989; GENSER et al., 1996; SCHMID et al., 1996; FÜGENSCHUH et al., 1997; FRISCH et al., 1998; NEUBAUER et al., 1999c).

The final collision was driven by oblique indentation of the Adriatic microplate into the Alpine nappe edifice (Fig. 8b). This resulted in Late Eocene/Oligocene subsidence of the peripheral Molasse Basin and slab break-off of the subducted lithosphere (VON BLANCKENBURG and DAVIES, 1995; GENSER et al., 1998). Subsequent Oligocene/Early Miocene sinistral wrenching and later eastward extrusion of blocks in the Eastern Alps were due to the indentation of the Adriatic microplate forming the West-Alpine arc due to westward motion of the Southalpine block (e.g., RATSCHBACHER et al., 1991; SCHMID and KISSLING, 2000 and references). Slab break-off resulted in intrusion of magmatic suites and dykes along the future Periadriatic fault (DEUTSCH, 1984; VON BLANCKENBURG and DAVIES, 1995). Due to effects of ca. S-directed back-thrusting along the Periadriatic fault and within the Southalpine units, upper crustal levels of the downgoing Penninic and European continental lithosphere were delaminated and accumulated within a double-vergent orogenic wedge (e.g., SCHMID et al., 1996; ESCHER et al., 1997; BONINI et al., 1999). Therefore, exhumation of metamorphic crust was achieved by the combined effects of shortening and gravity-driven tectonic unroofing in upper levels of the crust.

← Fig. 6
Tectonic evolution of units exposed in the westernmost Eastern Alps (based on PFIFFNER, 1992, NEUBAUER, 1994, SCHMID et al., 1996, SCHWEIGL and NEUBAUER, 1997, STAMPFLI and MARCHANT 1997; and DALLMEYER et al., 1998). Legend: Vertical hatching – mantle lithosphere; black – oceanic crust; dots – sedimentary cover; crosses – plutonic rocks; no pattern – continental crust.

A model of the Triassic to Cretaceous tectonic evolution of units exposed in the westernmost Eastern Alps is shown in Fig. 6. Essential arguments for an independent Cretaceous orogeny within the Austroalpine units are: The Cretaceous age (c. 95-90 Ma: THÖNI and MILLER, 1996) of eclogite metamorphism with pressures of ca. 18 kbar within Austroalpine basement units, which argues for the subduction of continental crust; the superposition of Austroalpine continental crust by oceanic units exposed in the Western Carpathians and their Late Jurassic blueschist-facies metamorphic overprint (e.g., KOZUR, 1992; DALLMEYER et al., 1996; FARYAD and HENJES-KUNST, 1997); the sealing of early Late Cretaceous thrusts within Upper Austroalpine units in the Eastern Alps by Gosau (Late Cretaceous to Middle Eocene) basins, which are associated with exhumation of deeply buried, continental metamorphic crust exposed in the Middle Austroalpine units (NEUBAUER et al., 1995; FROITZHEIM et al., 1997; KOROKNAI et al., 1999). This led to juxtaposition of Middle Austroalpine eclogite-/amphibolite-grade metamorphic rocks and Upper Austroalpine very low-grade to low-grade metamorphic rocks along ductile low-angle normal faults.

The internal ductile deformation of Austroalpine units stopped during the latest Cretaceous and large portions were exhumed during the Paleogene to shallow crustal levels (e.g., NEUBAUER et al., 1995; HEJL, 1997, 1998). Furthermore, the entire Austroalpine units were peneplained no later than the Early Neogene (THIEDIG, 1970). This is evidenced by the presence of large-scale peneplain surfaces east of the Tauern window, some Oligocene and numerous Miocene coal-bearing sedimentary basins and early Tertiary, Eocene to Oligocene, apatite fission track ages (PETRASCHECK 1926/1929; WINKLER-HERMADEN, 1957; STAUFENBERG, 1987; NEUBAUER et al., 1995; HEJL, 1997; FÜGENSCHUH et al., 1997; SACHSENHOFER et al., 1997; FRISCH et al., 1998; ZEILINGER et al., 1999; EDER and NEUBAUER, 2000 and references). The internal deformation of these basins, generally of transtensional and transpressional character, was always at shallow, brittle crustal levels. The preservation of these peneplains and Eocene sedimentary sequences in some places over the entire eastern sectors of the Eastern Alps excludes large vertical displacement in excess of approximately three kilometers after the Eocene (THIEDIG, 1970; FRISCH et al., 1998).

This contrasts with the Tertiary evolution of the Western Alps, where subduction of continental crust commenced at

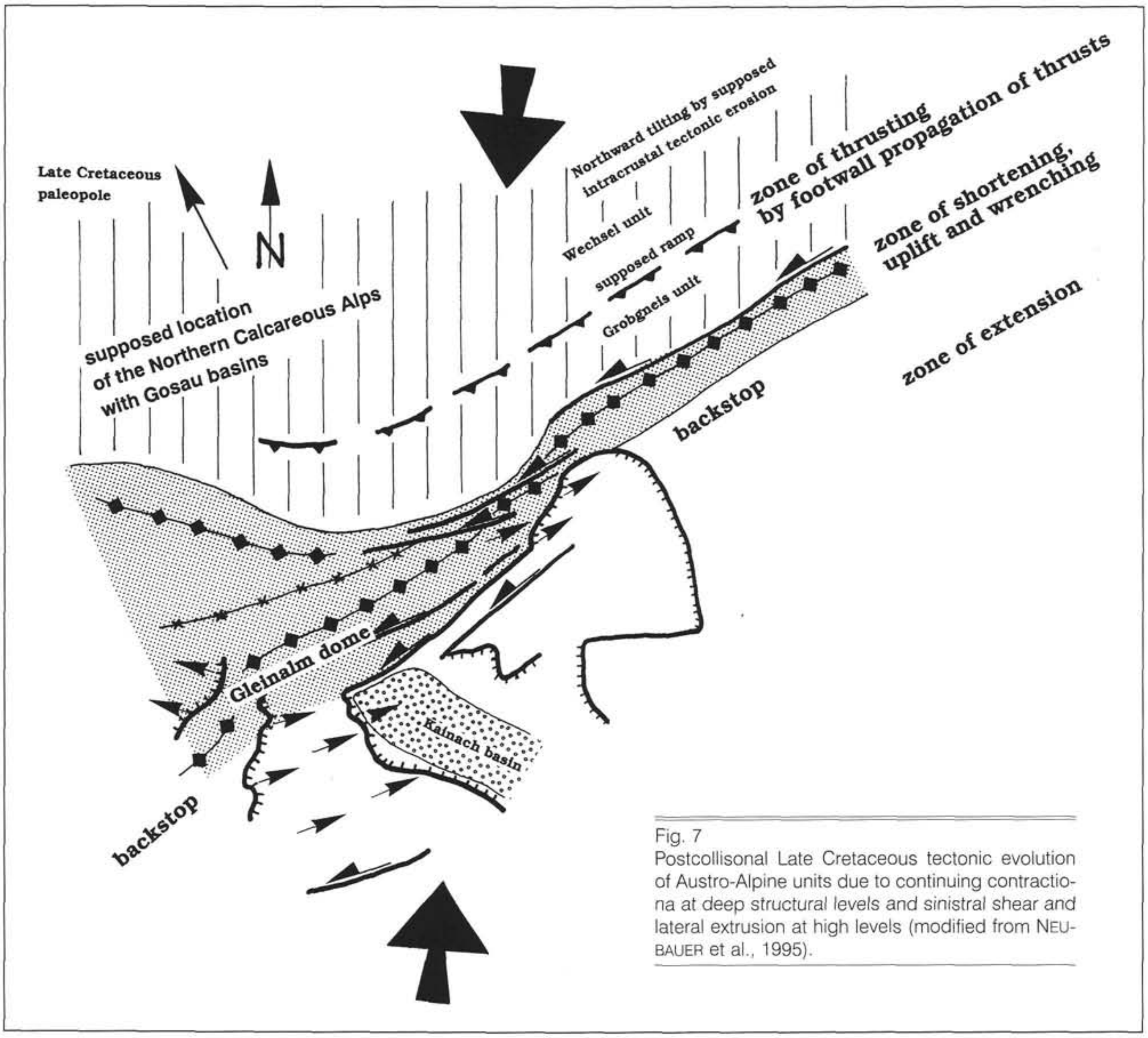
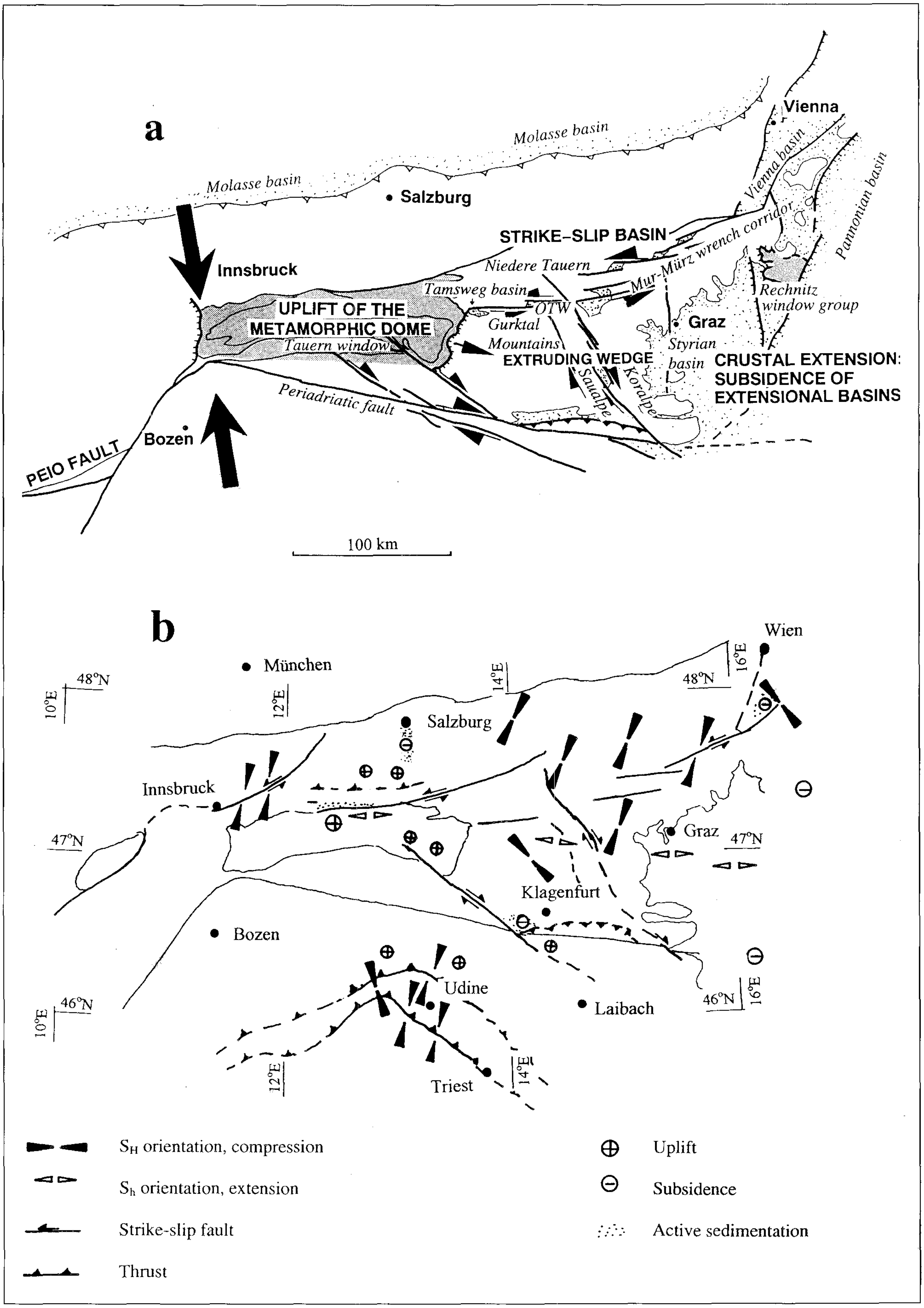



Fig. 7
Postcollisonal Late Cretaceous tectonic evolution of Austro-Alpine units due to continuing contractiona at deep structural levels and sinistral shear and lateral extrusion at high levels (modified from NEUBAUER et al., 1995).

the Cretaceous to Tertiary boundary. Collision between Europe-related and Austroalpine continental units occurred during the Eocene and subsequent shortening continuously prograded until the Oligocene. At this stage, oblique shortening was partitioned into frontal thrusting and orogen-parallel strike-slip, the latter occurring especially along the Insubric fault. During this stage, both tectonic unroofing and surface denudation started, which allowed exhumation of previously buried Penninic continental and oceanic units.

Penninic units of the Eastern Alps were overridden by the combined Austroalpine units sensu latu taking place during the Late Paleogene. This is proved by the presence of Eocene pelagic limestones within Penninic successions exposed within the Engadin window (for reference, see OBERHAUSER, 1995) and the presence of Eocene blueschists within the ophiolitic Reckner nappe (DINGELDEY et al., 1997). Recent $^{40}Ar/^{39}Ar$ age dating gave an Eocene age for NW-directed ductile shear within the basal Austroalpine thrust unit (LIU et al., 2000). Initial thrusting was directed towards the NNE (GENSER, 1992; KURZ et al., 1996, 1998), the same as the earlier NNE-directed subduction-related and decompressional fabrics within eclogites of the distal continental margin sequences of the Tauern window (KURZ et al., 1997, 1999). Subsequent W-directed ductile deformation within the Tauern window during initial exhumation of previously buried Penninic sequences during the Oligocene and Neogene was related to ongoing stacking. Exhumation in the window was a result of the indentation by the Southalpine indenter, tectonic unroofing along upper margins of Penninic sequences and the eastwards escape of the Austroalpine tectonic wedge (GENSER and NEUBAUER, 1989; RATSCHBACHER et al., 1989, 1991; SACHSENHOFER, 1992, this volume; NEUBAUER et al., 1999c, 2000, and references therein). The wedge is confined by sinistral wrench corridors to the N, including the Oligocene to Lower Miocene Salzach-Enns-Mariazell-Puchberg fault, the Miocene to Recent Mur-Mürz fault and the dextral Periadriatic fault to the south (NIEVOLL,

Fig. 8 →
Stages of Tertiary tectonic evolution. a – Miocene lateral extrusion (after NEUBAUER, 1994 and EDER and NEUBAUER, 2000; OTW – Oberwölz-Tamsweg wrench corridor); b – Quaternary and Recent tectonics (after REINECKER and LENHARDT, 1999 and own unpublished data).


a
Molasse basin
Molasse basin
Salzburg
Vienna
Vienna basin
Pannonian basin
STRIKE-SLIP BASIN
Mur-Mürz wrench corridor
Innsbruck
Niedere Tauern
Tamsweg basin
OTW
Rechnitz
window group
UPLIFT OF THE
METAMORPHIC DOME
Gurktal
Mountains
Graz
Tauern window
Styrian
basin
EXTRUDING WEDGE
CRUSTAL EXTENSION:
SUBSIDENCE OF
EXTENSIONAL BASINS
Saualpe
Koralpe
Periadriatic fault
Bozen
PEIO FAULT
100 km
b
Wien
München
48°N
10°E
12°E
14°E
16°E
Salzburg
Innsbruck
47°N
Graz
Klagenfurt
Bozen
Udine
46°N
Laibach
Triest
S_H orientation, compression
S_h orientation, extension
Strike-slip fault
Thrust
Uplift
Subsidence
Active sedimentation

1985; UNZOG, 1989; RATSCHBACHER et al., 1991; SCHMIDT et al., 1991; PERESSON and DECKER, 1997a, b; WANG and NEUBAUER, 1998). The Periadriatic fault and the Southalpine unit also were involved in an important stage of back-thrusting towards the S (NEMES, 1996; CASTELLARIN and CANTELLI, 2000), due to flake tectonics similar to those found in the Western Alps (Fig. 2).

As mentioned before, the Eastern Alps are affected by earthquakes. These occur along the sinistral Mur-Mürz and Innsbruck fault zones and along thrust zones of the Southern Alps (REINECKER and LENHARDT, 1999). In accordance with older geodetic and recent GPS data (e.g., SENFTL and EXNER, 1973; CAPORALI and MARTIN, 2000), seismicity indicate that N-S shortening and lateral eastward extrusion is still going on (GUTDEUTSCH and ARIC, 1987; REINECKER and LENHARDT, 1999 and references). In situ stress measurements and warping of the whole crust of the easternmost sectors of the Eastern Alps and of the Pannonian Basin suggest similar ca. N-S shortening as it is observed in Quaternary sediments, too (A. BECKER, 1993; HORVATH and CLOETINGH, 1996; VAN HUSEN, this volume).

## Acknowledgements

The authors gratefully acknowledge discussions with many persons including Jacqueline DESMONS, Garry EISBACHER, Martin FREY, Wolfgang FRISCH, Niko FROITZHEIM and Walter KURZ during the course of this study. We acknowledge the careful reviews of an earlier version of the manuscript by Wolfgang FRISCH and Stefan SCHMID. Lisa STALEY corrected the English. Work has been supported by grants (nos. P8652-GEO and P9918-GEO) of the Austrian Science Foundation.

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Manuscript received: 17. 11. 1998 ●
Revised version received: 25. 04. 2000 ●
Manuscript accepted: 25. 04. 2000 ●