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The structure of the Alps: an overview

F. Neubauer [1], J. Genser [1], R. Handler [1] and W. Kurz [2]

[1] Institut für Geologie und Paläontologie, Hellbrunnerstr. 34, A-5020 Salzburg, Austria.
[2] Institut für Geologie und Paläontologie, Heinrichstr. 26, A-8010 Graz, Austria

Abstract

New data on the present structure and the Late Paleozoic to Recent geological evolution of the Eastern Alps are reviewed mainly in respect to the distribution of Alpidic, Cretaceous and Tertiary, metamorphic overprints and the corresponding structure. Following these data, the Alps as a whole, and the Eastern Alps in particular, are the result of two independent Alpidic collisional orogens: The Cretaceous orogeny formed the present Austroalpine units sensu lato (including from footwall to hangingwall the Austroalpine s. str. unit, the Meliata-Hallstatt units, and the Upper Juvavic units), the Eocene-Oligocene orogeny resulted from continent-continent collision and overriding of the stable European continental lithosphere by the Austroalpine continental microplate. Consequently, a fundamental difference in present-day structure of the Eastern and Central/Western Alps resulted. Exhumation of metamorphic crust formed during Cretaceous and Tertiary orogenies resulted 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, and Oligocene-Miocene sinistral wrenching within Austroalpine units, and subsequent eastward lateral escape of units exposed within the central axis of the Alps along the Periadriatic fault system due to the indentation of the rigid Southalpine indenter.

Introduction

Facts and models on Alpine geology made rapid progress during the last decades, mainly due to detailed paleogeographical, structural, petrological and geochronological investigations. These, together with deep reflection seismic profiling allowed new insights into the present-day structure and triggered new models which fundamentally changed ideas on Alpine geology (e.g., NICOLAS ET AL., 1990; PFIFFNER, 1992; PFIFFNER et al., 1997).

This review intends to synthesize principal structural data of the Eastern Alps in respect to the distribution of Alpine metamorphism. The review also includes some redefinitions of paleogeographic and tectonic units exposed within the Eastern Alps that appear to be neccessary according to the present state of data. The time scale calibrations follow that of the Paleozoic and early Cenozoic by Gradstein and Ogg (1996) of the Mesozoic proposed by Gradstein et al. (1994), and of the Paratethyan Oligocene-Neogene proposed by Rögl (1996).

Aspects of the tectonic evolution Eastern Alps were reviewed in JANOSCHECK and MATURA (1980), OBERHAUSER (1980, 1995), TOLLMANN (1977, 1986, 1987), FRANK (1987), THÖNI AND JAGOUTZ (1993), FROITZHEIM et al. (1996), EBNER (1997) and FAUPL (1997). The evolution of the pre-Alpine basement is reviewed in VON RAUMER and NEUBAUER (1993).

Tectonic units

The Alps are divided in a geographical sense into the E-trending Eastern Alps and the arc of the Western Alps, divided by the meridional Rhine valley south of the Bodensee and its southward, meridional extension. Eastern and Western Alps display fundamentally different geological structure (see below), geological development and in part a distinct geomorphology. The most prominent mountain peaks are along the central axis in the Eastern and Swiss Central Alps, and more internally located in the Western Alps forming here an asymmetric topographic profile. East of the Tauern window area, the topography gradually changes from high elevations into the Neogene Pannonian basin with its plains and a very low elevation above sea level (Fig. 1).

The Alps as a whole include the following tectonic units from footwall to hangingwall, respectively from N to S, and NW to SE (e.g., DAL PIAZ, 1992; DEBELMAS, 1997; TRÜMPY, 1980, 1997a, b; TOLLMANN, 1977; FRANK, 1987; FAUPL, 1997) (Figs. 1, 2, 3):

(1) The stable respectively south- and eastwards flexured European continental lithosphere which also carries the late Eocene to Neogene Molasse basin, the northern peripheral foreland basin; and the Swiss-French Jura, an externally located thin-skinned fold-and thrust belt (e.g., TRÜMPY, 1980, 1997a, b);

(2) the Dauphinois/Helvetic units, a thin-skinned fold and thrust belt, that nearly exclusively comprise 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 (DEBELMAS et al., 1983);

(3) the Valais units which represent the infilling of a mainly Cretaceous rift zone on attenuated continental to likely oceanic crust (PFIFFNER, 1992);

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

(5) the Piemontais units with oceanic lithosphere in the Western Alps; the Glockner ophiolitic nappe exposed within the Tauern window and ist correlatives exposed in other windows along the central axis of the Eastern Alps, the Ybbssitz 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. The Valais, Brianconnais and Piemontais units are conventionally combined to Penninic units also 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 which originally faced towards the Hallstatt-Meliata ocean (e.g., LEIN, 1987) and a Jurassic passive continental margin which faced towards the Penninic (Piemontais) oceanic tract;

(7) the Hallstatt-Meliata units with its remnants of the infilling of a small oceanic trough and the adjacent distal continental margins;

(8) the Upper Juvavic unit that exclusively comprises late Paleozoic to Mesozoic cover sequences of a passive continental margin;

(9) and finally, the Southalpine unit juxtaposed along the Periadriatic Fault to the Austroalpine units s. str.. The Southalpine unit is another continental unit that is largely similar to the Austroalpine unit s. str.. 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).

The Alps are sometimes divided into external, sedimentary, unmetamorphic units and internal units dominated by highly deformed metamorphic rocks. This division applies well in Western Alps. There, the *external zones* include : (1) the Dauphinois-Helvetic zone comprising External basement massifs and their Late Carboniferous to Mesozoic cover, and Mesozoic-Cenozoic cover sequences separated into so-called Subalpine massifs. Both basement and cover massifs are clearly allochthonous in the Swiss Western Alps; and, more internally located, (2) the Ultradauphinois-Ultrahelvetic zone.

In the Eastern Alps, the external zones are small and include the Helvetic/Ultrahelvetic zones, the latter imbricated with the Rhenodanubian Flysch zone, a Penninic unit. From a structural point of view, the Northern Calcareous Alps also belong to unmtemorphic external zones.

The Southalpine unit is considered as the southern external retro-arc orogenic wedge within the Alpine orogenic system (e.g., DOGLIONI and FLORES, 1997; SCHMID et al., 1996).

Compared with previous interpretations, the Ybbssitz ophiolite and the subdivision of the previous Austroalpine units into three different tectonic units are 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 Hallstatt-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.. For further details, see SCHWEIGL and NEUBAUER (1997).

In terms of metamorphism, these units display fundamental differences. The Austroalpine s.str., Meliata-Hallstatt and Upper Juvavic units display Cretaceous-age metamorphism all over the Alps, the Penninic and Helvetic units Eocene to Oligocene regional metamorphism. The Southalpine units are unmetamorphic except 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

The Penninic continental units are exposed within the Tauern window within the so-called Venediger nappe and the overlying Riffl-Modereck nappe complex (e.g., KURZ et al., 1998b, and references therein). The basement is composed of the Habach-Storz Groups with Late Proterozoic to Early Paleozoic island arc successions, the Stubach Group, an Early Paleozoic back arc ophiolite, and widespread Variscan granite suite, collectively known as Central Gneisses. The Central Gneisses are exposed within several structural domes along the central structral axis of the antiformal Tauern window. The cover sequences include fossil-bearing Carboniferous sequences exposed 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., 1998b).

Penninic ophiolites

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 exposed within the Engadin, Tauern, and Rechnitz windows (e.g., HÖCK and KOLLER, 1989; KOLLER and HÖCK, 1989).

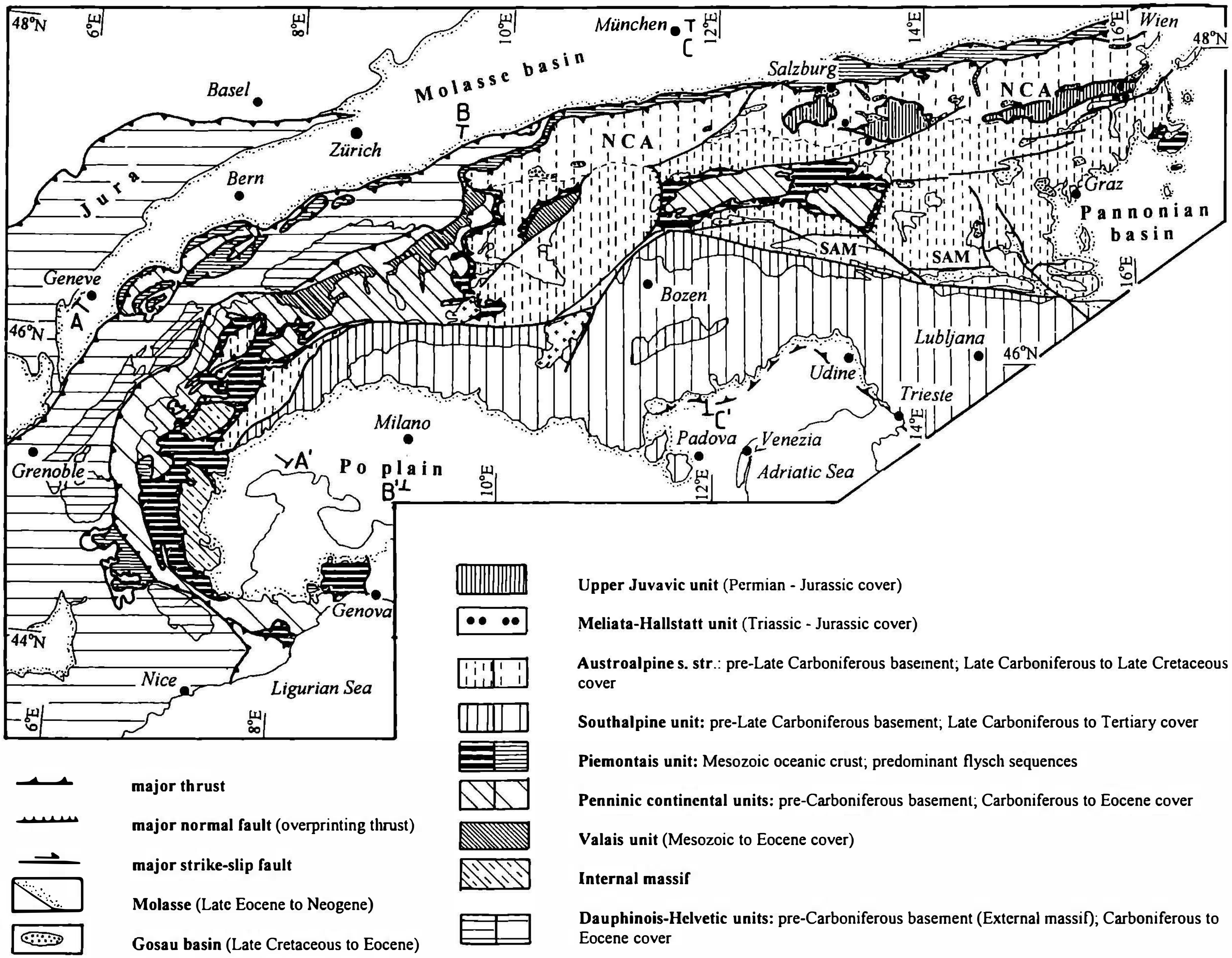

Fig. 1. Simplified tectonic map of the Alps (modified after BIGI et al. (1989).

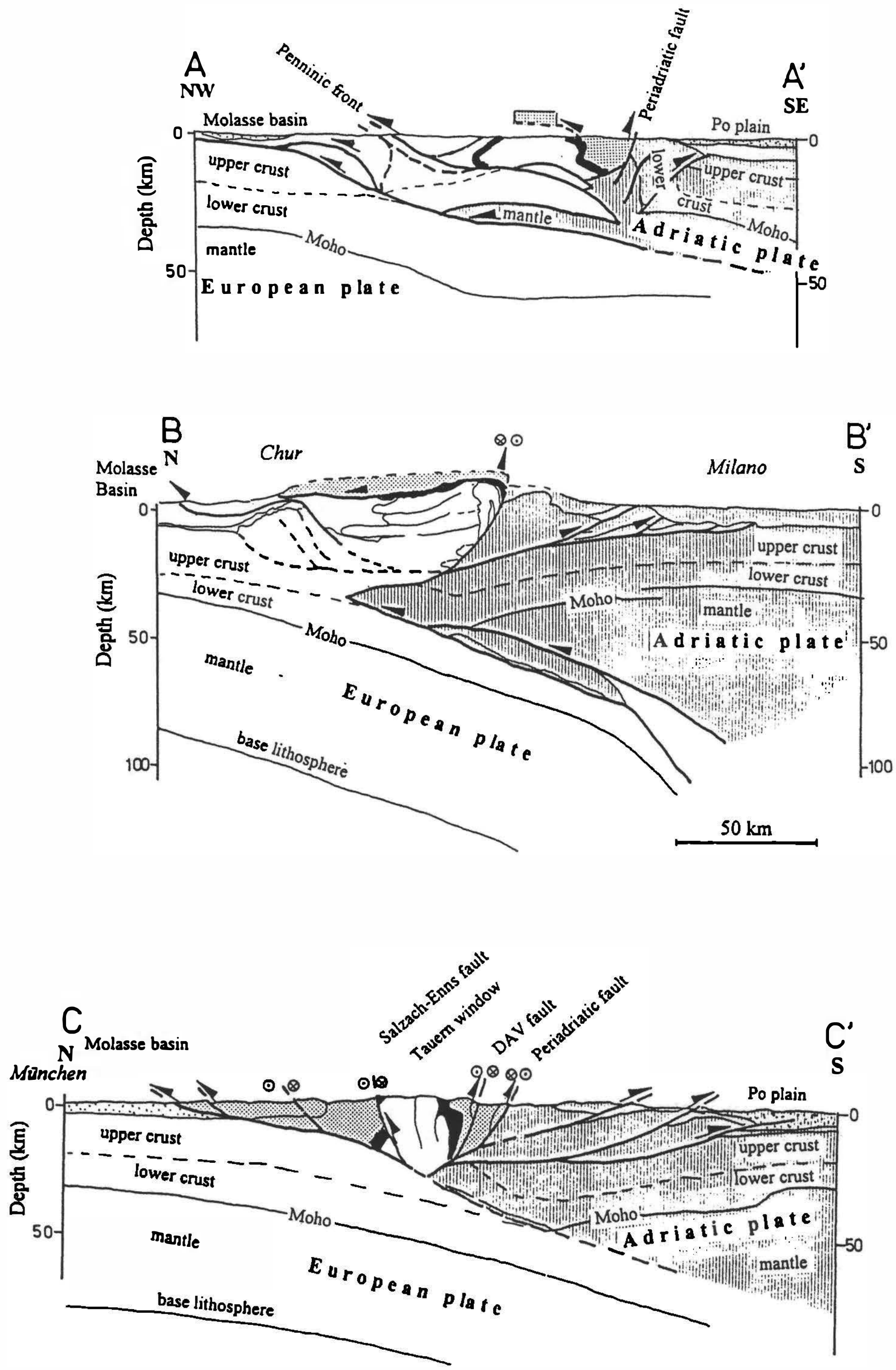

Fig. 2. Three transects of the Alps: a - Transect of the Western Alps (simplified after NICOLAS *et al., 1990 and* ROURE *et al., 1990); b - transect across the eastern Central Alps (after* SCHMID *et al., 1986); transects of Western and eastern Central Alps are based on deep seismic reflection profiling; c - transect across the Eastern Alps (modified after* LAMMERER *and* WEGER, *1998, and* ROEDER, *1980, and extrapolating the structures of section b towards the east.*

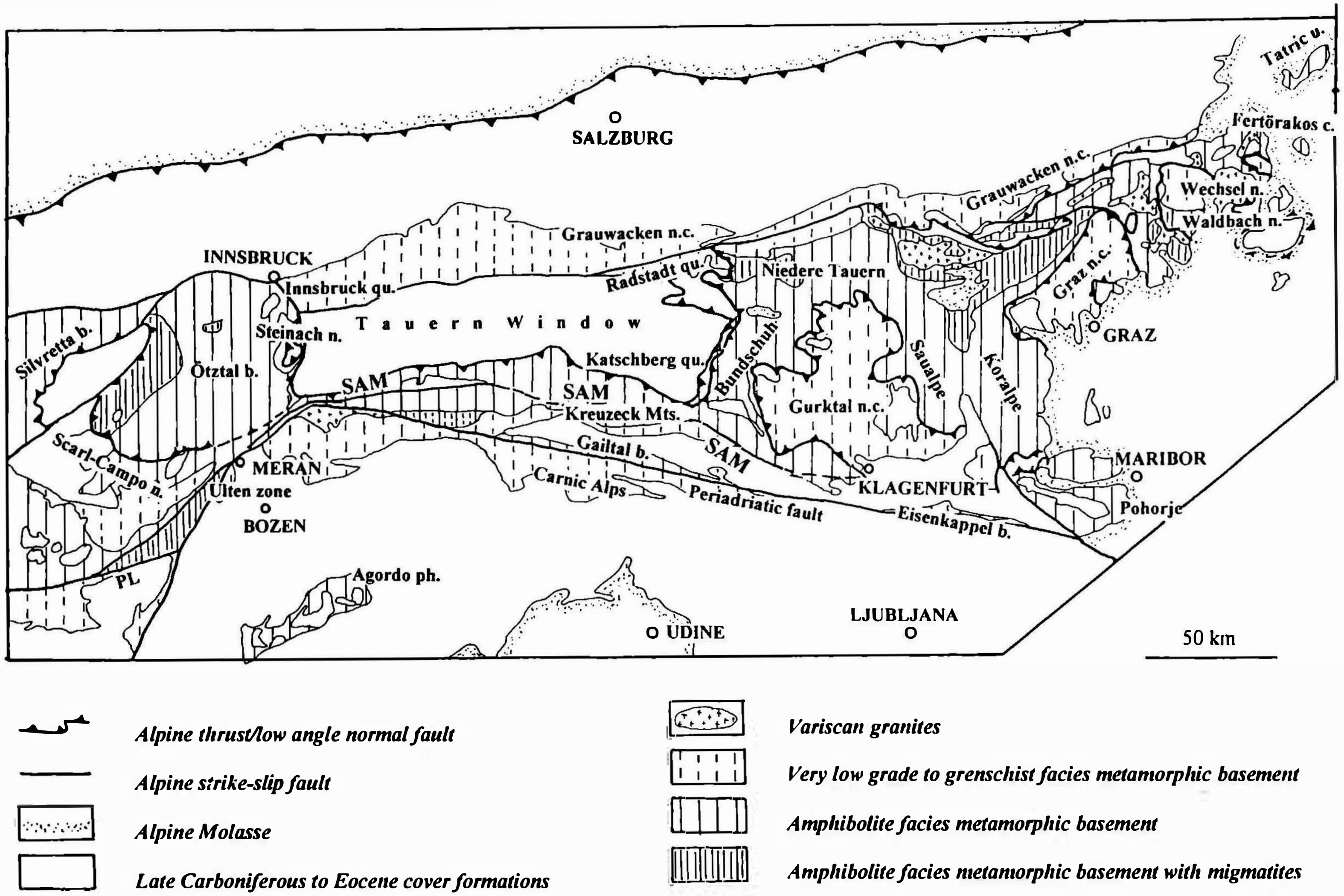

Fig. 3. Map of Austroalpine units sensu lato and Southalpine units of the Eastern Alps displaying extent of pre-Alpine metamorphism in basement units.

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 calcmicaschists, laid down on top of it (HÖCK and MILLER, 1987). The Rechnitz window group exposes ophiolitic successions with serpentinites, prasinites, and carbonate schists 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) (KOLLER, 1985).

Austroalpine unit s.str.

The Austroalpine s. str. represents a continental, basement-cover, thick-skinned nappe pile which received its essential internal nappe structure during the Cretaceous orogenic events (e.g., RATSCHBACHER, 1986; DALLMEYER et al., 1998). They can be divided basically into the Central Eastern Alps with dominant basement sequences and Northern Calcareous Alps with predominant Permo-Cenozoic cover sequences (Fig. 4, 5). Although fierely discussed (CLAR, 1973; FRANK, 1987; TOLLMANN, 1987), subdivision into Lower, Middle and Upper Austroalpine nappe complexes is easily applicable over large portions of the Austroalpine nappe pile which is bounde to the south by the SAM (southern limit of Alpine metamorphism; see below). The Lower Austroalpine nappe complex includes units exposed along the southwestern margin of 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 western to eastern margins of the Eastern Alps. The Upper Austroalpine nappe complex includes the Steinach nappe, the Grauwackenzone nappes and the overlying Tirolic and Bajuvaric nappes of the Northern Calcareous Alps, the Gurktal and Graz nappe complexes forming klippens, Grauwackenzone nappe complex and the overlying Northern Calcareous Alps along the northern leading edge of the Austroalpine nappe complex. These Upper Austroalpine units were derived from an originally southeastern paleogeographic position. The Middle Austroalpine units take, therefore, an intermediate paleogeographic position. The general nappe transport direction was towards WNW and N, respectively (RATSCHBACHER, 1986; KROHE, 1986).

The southern limit of Alpine (Cretaceous-age) metamorphism (SAM: term created by G. HOINKES) represents a c. east-trending system of polyphase faults which juxtaposes Austroalpine units with a strong, generally amphibolite and eclogite grade metamorphism to the north mostly againts very-low grade Austroalpine units in the south. The SAM consists, from west to east, of the Peio-, Passeier-Jaufen-, Defreggen-Antholz-Vals- (DAV), Isel-, Zwischenbergen-Wöllatratten-, Ragga-Teuchl-, Siflitz-, and Viktring fault zones. Western sectors of the SAM represent a zone of important, mostly Oligocene sinistral strike-slip displacement with an oblique-slip 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 Austrolapine units exposed within the SAM and the Periadriatic fault are preserved except flower structures related to the Periadriatic fault.

The composition and evolution of the Austroalpine basement units is not considered here in detail. 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 (NEUBAUER and FRISCH, 1993; NEUBAUER and SASSI, 1993; SCHÖNLAUB and HEINISCH, 1993). E.g., the Upper Austroalpine units comprises continuous fossiliferous Ordovician to early Carboniferous sequences affected by a late Variscan and/or Cretaceous metamorphic overprint. In contrast, the Middle Austroalpine units comprise exclusively medium-grade metamorphic basement that only minor successions represent correlatives of 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 and shelf margin and later pelagic formations. The principal rift phase occurred during the Permian and resulted in rapid tectonic subsidence during the Triassic, where a passive continental margin was formed opposing the Meliata-Hallstatt ocean towards the SE (e.g., LEIN, 1987; SCHWEIGL and NEUBAUER, 1997) (Fig. 4, 5). A second, Jurassic rift phase created the Piemontais oceanic basin by rifting off the stable European continent, and another passive continental margin facing towards NW. Resulting structures along this passive margin are halfgrabens filled with escarpment breccias. Asymmetric simple shear is supposed to lead to exhumation of subcontinental mantle lithosphere and the formation of the continental Margna, Hippold and the questionable Sesia extensional allochthons (FROITZHEIM and MANATSCHAL, 1996; HEIDORN, 1998).

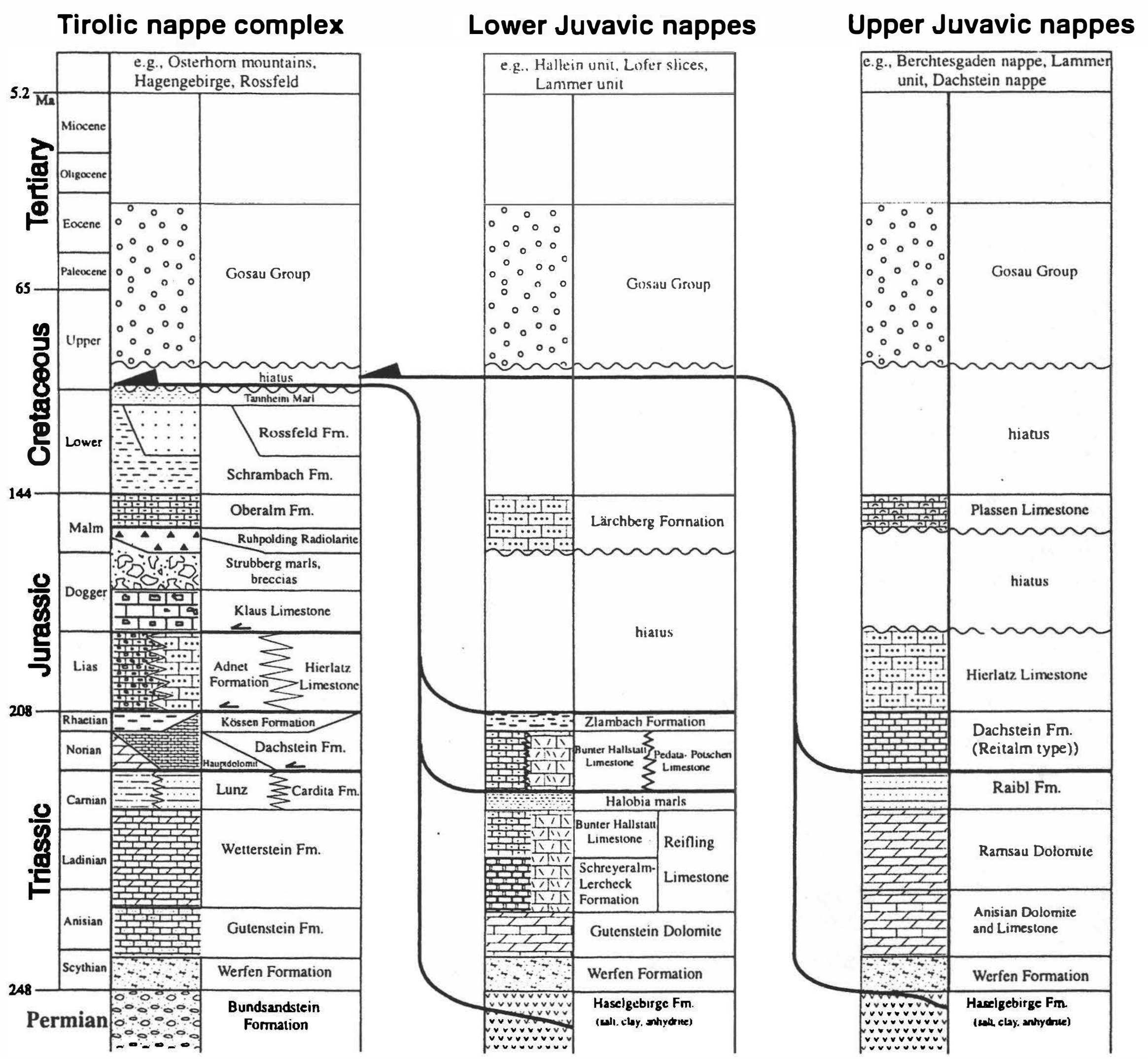

Fig. 4. Stratigraphic sections of units exposed within the Northern Calcareous Alps (from Schweigl and Neubauer, 1997).

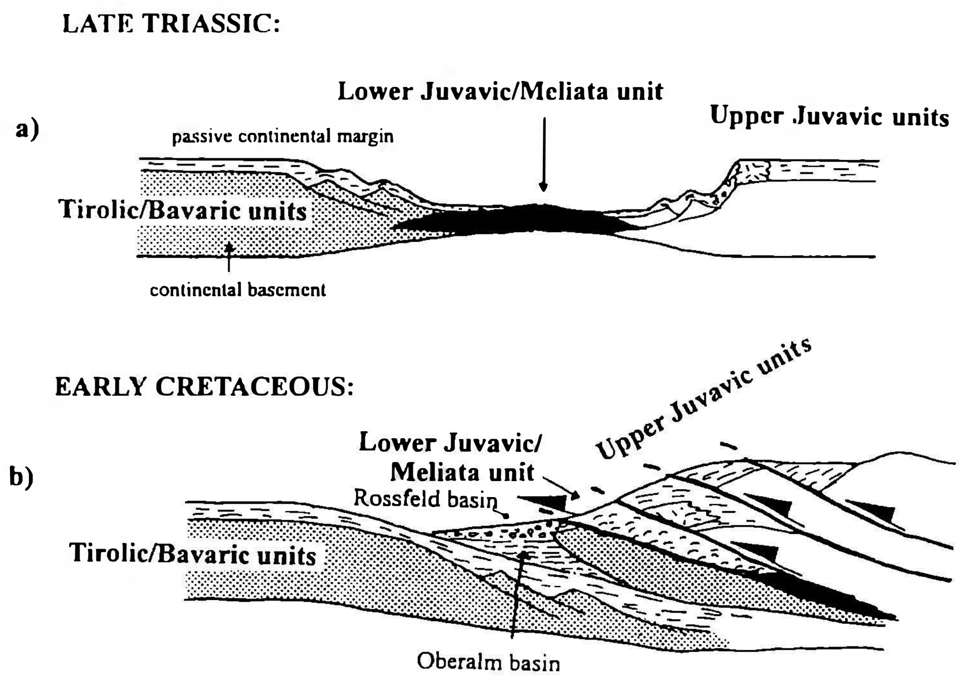

Fig. 5. Schematic (a) Late Triassic and (b) Lower Cretaceous paleogeography of Upper Juvavic, Meliata-Hallstatt and Austroalpine units sensu stricto (Tirolic/Bajuvaric units). (From Schweigl and Neubauer, 1997).

Hallstatt-Meliata units

The Hallstatt-Meliata units comprise distal continental margin deposits (Hallstatt facies) (LEIN, 1987; MANDL and ONDREJICKOVA, 1991) and the recently detected oceanic sediments of Middle Triassic to Dogger age (KOZUR, 1991; MANDL and ONDREJICKOVA, 1991; KOZUR and MOSTLER, 1992). These include Middle and Late Triassic pelagic carbonates, Late Triassic radiolarites and Doggerian shales, volcanogenic greywackes and ashfall tuffs. Greywackes and tuffs indicate a volcanic source of subduction-related origin (NEUBAUER, unpubl. data).

Furthermore, salt melanges (Permian and Scythian strata) are often connected with the structural sole of the Hallstatt-Meliata unit generally interpreted to represent the primary lowermost sequence of this unit (KOZUR, 1991). If this is true, some doubts are apparent because of strong structural destruction of this unit. Anyway, 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 appear to record some doubtful Permian ages. These rocks are interpreted, therefore, to record incipient Permian rifting (KIRCHNER, 1980).

Upper Juvavic unit

Upper Juvavic units include a continuous Permian to Triassic section with some rare Jurassic sediments. 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 to the Tirolic-Bajuvaric nappe complex, mainly including thick Late Triassic Norian reefs in the Upper Juvavic nappe in contrast to the Norian lagoonal Hauptdolomit facies and presence of Rhaethian reefs in the Tirolic-Bajuvaric nappe (SCHWEIGL and NEUBAUER, 1997). The Jurassic sequence is incomplete and only record some thin Liassic limestones and Malmian reefal limestone in the northwesternmost exposures.

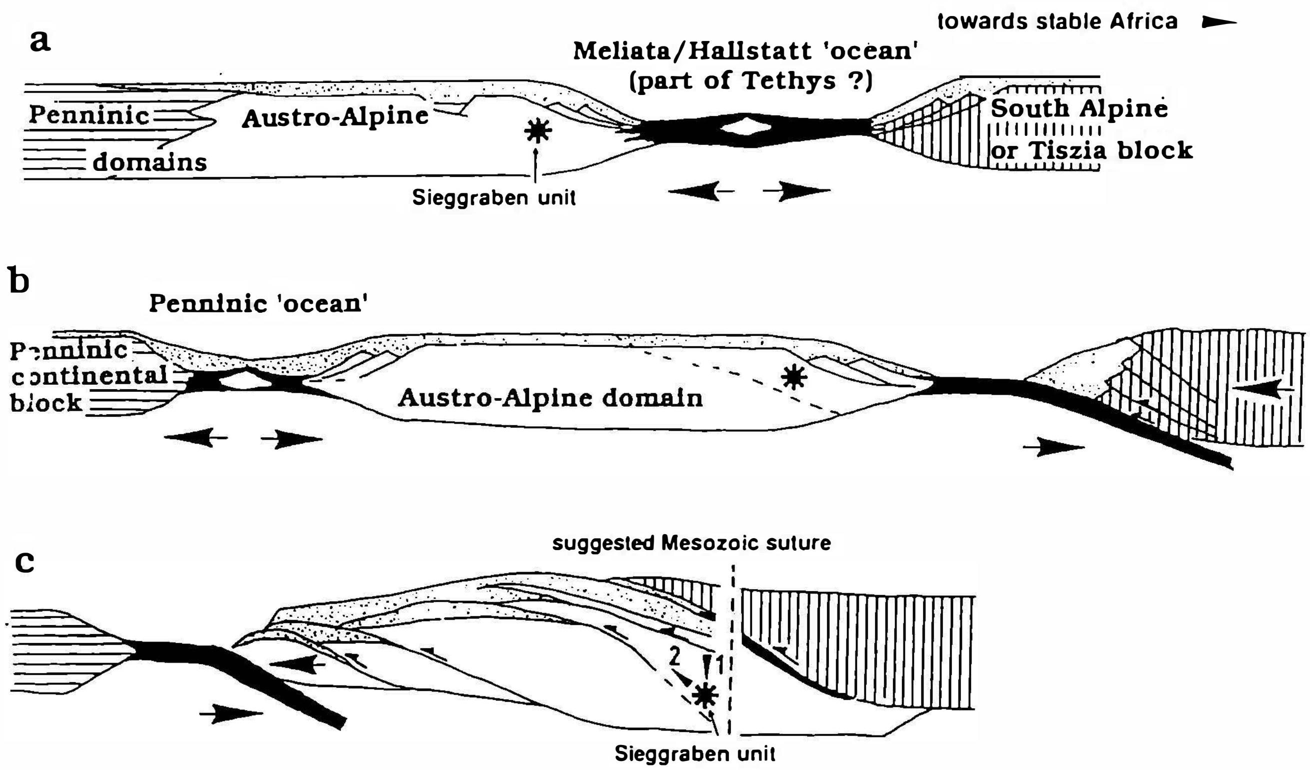

Fig. 6. Tectonic evolution of units exposed in the eastern Central Alps (modified after Neubauer, 1994).

Southalpine unit

The Southalpine unit includes a continental basement exposed along the Periadriatic fault, and a continuous Late Carboniferous to Oligocene sequence. Two main rift phases affected the Southalpine unit: NW-SE extension during Permian resulted in the formation of a swell and high topography which governed deposition from Permian to Cenozoic. 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 (definition of the Tethys was by SUESS, 1887) from the SE reached the Carnic Alps during the Late Carboniferous, South Tyrol during the Late Permian, and the Lombardian Alps during the Middle Triassic. A strong tectonic subsidence phase during Middle Triassic times in 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 formation of pronounced troughs, thinning of the crust and exhumation and cooling of middle crustal levels (e.g., BERTOTTI et al., 1993).

The deposition of the Late Cretaceous Lombardian flysch in the western Lombardian Alps with northern source heralds ongoing deformation which is not evidenced otherwise in Southern Alps. The structure of the Southern Alps is dominated by c. E-trending, top-S-directed thrusts which brought up basement rocks on top of cover (e.g., DOGLIONI and BOSSELINI, 1987; CARMINATI et al., 1997). The earliest thrusts in the western Southern Alps were formed before intrusion of the Adamello (before ca. 42 Ma; BRACK, 1980). In eastern sectors, c. WNW-trending, SSW-directed structures were formed during the Paleogene, believed to represent a Dinaric trend (DOGLIONI and BOSELLINI, 1987). These structures were overprinted by Oligocene to Recent structures which also involved the basement (CARMINATI et al., 1997).

Tectonic evolution

In terms of metamorphism and associated deformation, the Alps are divided into three units: (1) The Austroalpine units s.l., Meliata-Hallstatt units, and Upper Juvavic units which were overprinted by Cretaceous deformation, W- to NW-directed, ductile thrusting; (2) the Penninic continental and oceanic units, and the Dauphinois-Helvetic units which were overprinted by Cenozoic metamorphism and associated N- to W-directed ductile deformation; and (3) Southalpine units which are largely unaffected by metamorphism except northernmost sectors adjacent to the Periadriatic fault and which were mainly deformed during Cenozoic, c. S-directed thrusting and shortening.

A model of the Triassic to Cretaceous tectonic evolution of units exposed in the eastern Central Alps is shown in Fig. 6. Essential arguments for an independent Cretaceous orogeny within Austroalpine units are: the Cretaceous age (c. 95-90 Ma: THÖNI and MILLER, 1997) of eclogite metamorphism with pressures of c. 18 kbar within Austroalpine basement units which argues for a 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, 1987); 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

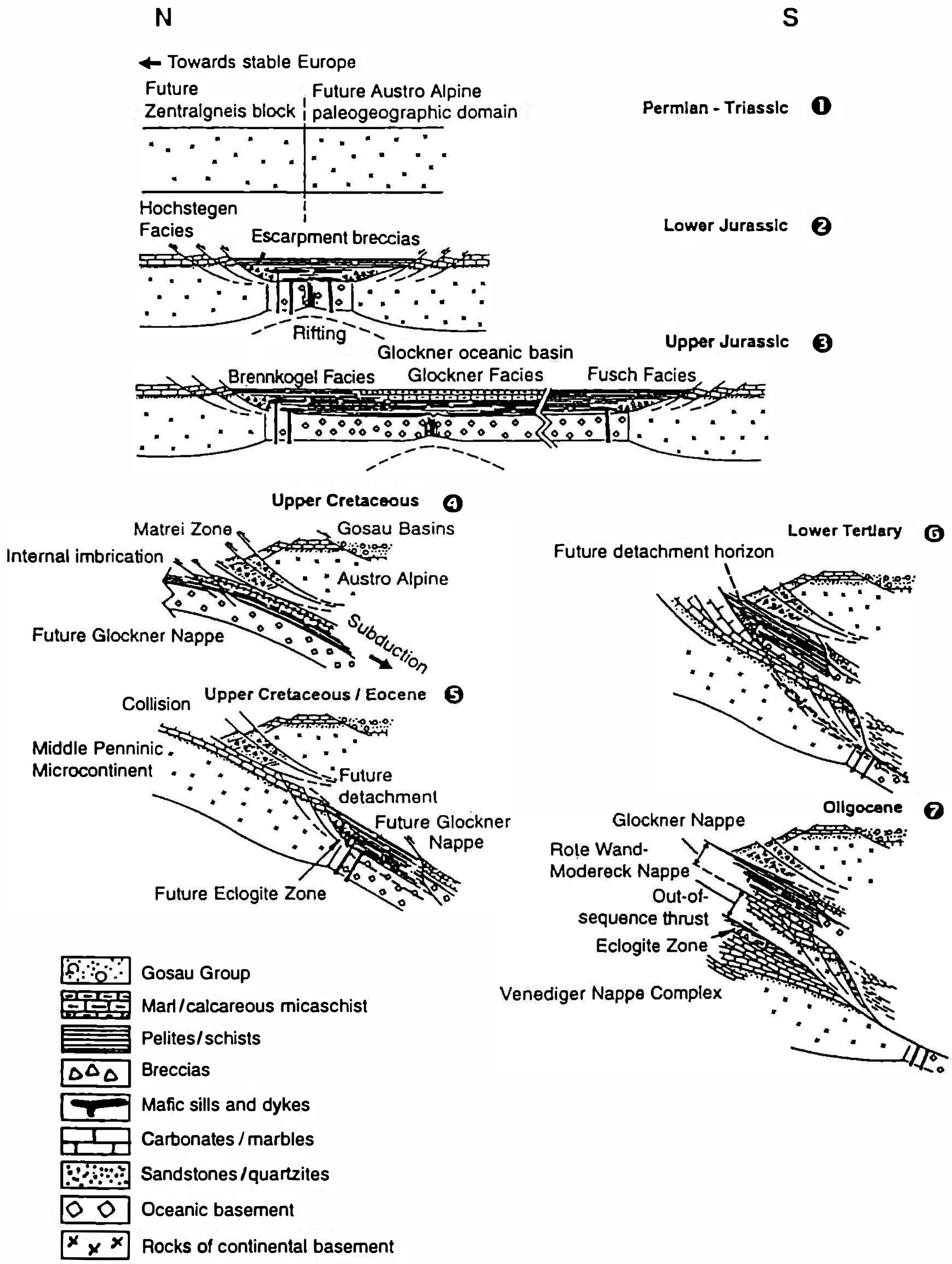

Fig. 7. Schematic tectonic evolution of Penninic units exposed in the Tauern window (from Kurz et al., 1998b).

present-day Middle Austroalpine units (NEUBAUER et al., 1995; FROITZHEIM et al., 1997). The internal ductile deformation of Austroalpine units stopped during the latest Cretaceous, and large portions were exhumed during the Paleogene to shallow crustal levels. Furthermore, the entire Austroalpine units were peneplained not later than the early Neogene, as it evidenced by the presence of large-scale peneplaine surfaces east of the Tauern window, some Oligocene and numerous Miocene sedimentary basins ande early Tertiary apatite fission tarck ages (Hejl, 1997). The internal deformation, generally of transtensional and transpressional character, of these basins was always at shallow, brittle crustal levels. The preservation of these peneplaines (and Eocene sedimentary sequences in some places) over the entire eastern sectors of the Eastern Alps excludes large vertical displacement in excess of c. 3 kilometres after the Eocene.

A model displaying the tectonic evolution of Penninic units is shown in Fig. 7. Penninic units were overridden by the combined Austroalpine units sensu lato not before Paleogene because of 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). Initial thrust were directed towards the NNE (Genser, 1992; Kurz et al., 1998b) same as earlier NNE-directed subduction-related and decompressional fabrics within eclogites of the distal continental margin sequences of the Tauern window (Kurz et al., 1998a). Subsequent W-directed ductile deformation within the Tauern window was related to exhumation of previously buried Penninic sequences during the Oligocene and Neogene. Exhumation was due to indentation by the Southalpine indenter, tectonic unroofing along upper margins of Penninic sequences and eastwards escape of a tectonic wedge (Ratschbacher et al., 1991). The wedge is confined by sinstral wrench corridors to the N, including the Oligocene to Lower Miocene Salzach-Enns-Mariazell-Puchberg fault: RATSCHBACHER et al., 1991; WANG and NEUBAUER, 1998), the Miocene to Recent Mur-Mürz fault and the dextral Periadriatic fault to the S (Fig. 8). The Periadriatic also has an important stage of back-thrusting towards the S due to flake tectonics similar as found in the Western Alps (Fig. 2).

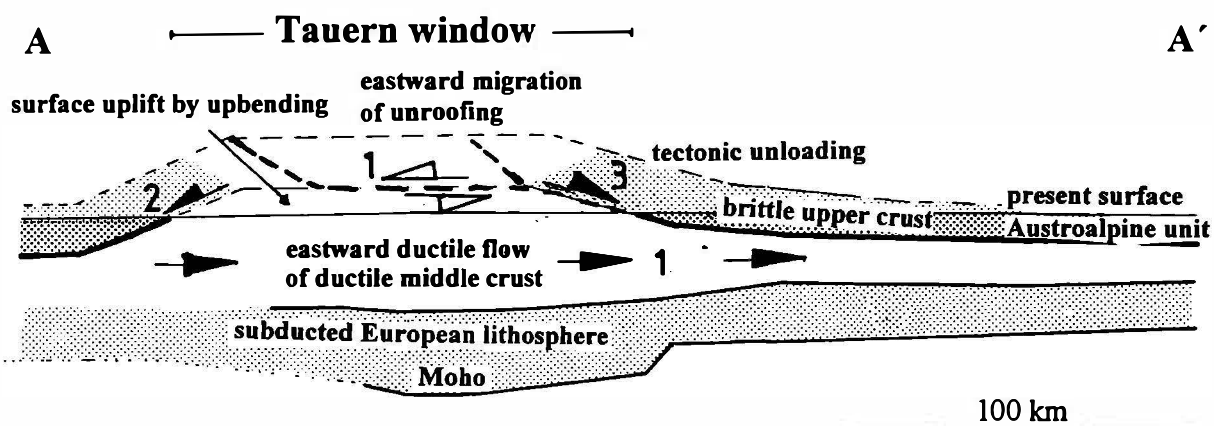

Fig. 8. Schematic evolution of escape tectonics and related phenomena (modified from Neubauer, submitted).

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