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Post-collisional orogen-parallel large-scale extension in the Eastern Alps

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Abstract

Large-scale extension affected the Eastern Alps during post-collisional lateral tectonic extrusion in Early and Middle Miocene times. The Tauern window was mainly tectonically exhumed by the 160-km pullapart of the rigidly behaving Austroalpine basement blocks forming the tectonic lid of the Penninic contents of the window. An evaluation of the syn-extrusion fault pattern reveals displacements of several tens of kilometers along the low-angle extensional shear zones at the western and eastern margins of the window, and along the important strike-slip fault zones north and south of the window. Large-scale shear is reflected by discontinuities in mineral cooling patterns across important shear zones. The cooling histories of the tectonic blocks show that the window boundaries during exhumation coincide only partly with the classical boundaries of the window defined by thrust units. Reconstruction of the exhumation history shows an asymmetric evolution of the Tauern window. We argue that the eastern and western low-angle extensional shear zones formed in sequence, which is reflected by different evolutions of the fragmentation and uplift history of the Austraolpine tectonic blocks to the east and west of the window.

In the Central and Eastern Alps, three structural domes, the Lepontin dome in the Central Alps and the Tauern and Rechnitz domes in the Eastern Alps, were formed by large-scale extension in Miocene times. Total E–W stretch amounts to more than 300 km and results in >70% extension. We propose that the Central and Eastern Alps are part of an extensional province that also includes the Pannonian basin and has a counterpart, separated by the Moesian indenter, in the Rhodope Mountains, the Aegean Sea and the Menderes Massif in Asia Minor. In these regions a number of mainly tectonically exhumed domes or deep sedimentary basins formed by Miocene large-scale extension.

Keywords: Eastern Alps; post-collisional history; large-scale extension; lateral tectonic extrusion; metamorphic core complex; Tauern window

1. Introduction

The Austroalpine mega-unit is exposed over the great part of the Eastern Alps. It derived from the African/Adriatic plate and formed the upper plate during Early Tertiary collision and nappe stacking (Frisch, 1979; Ratschbacher et al., 1989; Schmid et al., 1996). The Austroalpine mega-unit consists of a crystalline basement which experienced the Variscan amphibolite-facies metamorphism and Cretaceous (Eoalpine) metamorphic overprint, as well as of low-grade metamorphic Paleozoic terrains and a post-Variscan (Permian to Eocene) cover sequence (Fig. 1). The lower-plate units comprise the Penninic and the Helvetic mega-units. The Penninic mega-unit contains fragments of Variscan basement (Middle

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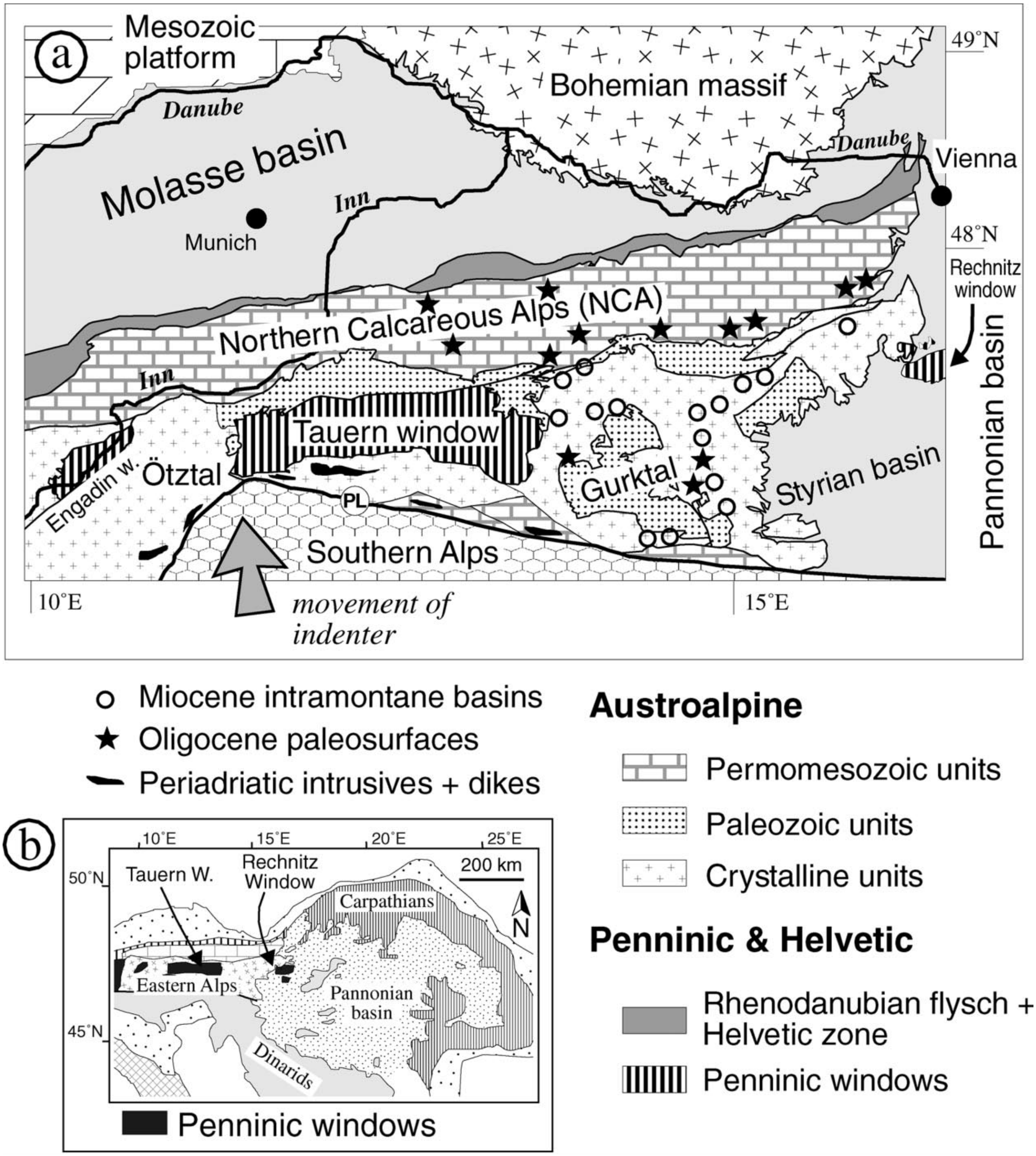


Fig. 1. (a) Geologic-tectonic overview of the Eastern Alps and their frame. PL, Periadriatic lineament. (b) The position of the Eastern Alps within the Alpine-Carpathian loop.

Penninic gneiss nappes derived from the European plate) which carry Mesozoic cover sequences, and oceanic realms formed during the Mesozoic disintegration of Pangaea (Upper Penninic ophiolite nappes, Lower Penninic Rhenodanubian flysch). It is exposed in the Engadin, Tauern and Rechnitz windows and in a narrow flysch belt at the northern front of the Eastern Alps (Figs. 1 and 3). The lowest mega-unit is the Helvetic unit which plays a subordinate role in the Eastern Alps. The Penninic units exposed in the windows experienced Early Tertiary metamorphism up to amphibolite facies grade. Their temperature maximum was attained in Oligocene times to be around 30 Ma (von Blanckenburg et al., 1989; Christensen et al., 1994; Inger and Cliff, 1994). Parts of the Penninic terrains were subjected to preceding subduction-related high-pressure metamorphism in Eocene times (Zimmermann et al., 1994).

The modern structural shape and topographic pattern of the Eastern Alps started to evolve around the Early/Late Oligocene boundary. Around that time, following the Adria–Europe collision, nappe stacking and crustal thickening attained its culmination point (Schmid et al., 1996), and breakoff of the subducted Penninic oceanic slab, as proposed by von Blanckenburg and Davies (1995), probably set a benchmark in the evolution of the orogen. Calc-alkaline intrusions and mafic dike swarms line up along the Periadriatic lineament and are considered to be the consequence of slab breakoff (von Blanckenburg and Davies, 1995). The peak of Periadriatic magmatism coincides with the appearance of the first large conglomerate fans formed in the Molasse zone of the Central (= Swiss) and the western Eastern Alps around 30 Ma (Schiemenz, 1960; Schlunegger et al., 1996) indicating fast-growing relief in the orogenic body. We relate this sudden supply of coarse material from the orogenic body to an important pulse of surface uplift following the main event of slab breakoff.

Lateral tectonic extrusion (Ratschbacher et al., 1991a) rearranged the structural pattern and created the present elongate shape of the Eastern Alps (Fig. 1) in Early to Middle Miocene times. Lateral tectonic extrusion is ascribed to a combination of gravity-driven orogenic collapse because of an overthickened and thermally equilibrating lithosphere, and tectonic escape along conjugate fault zones driven by tangential forces due to continuing N–S convergence between the Adriatic microplate and the European plate. A retreating subduction zone in the Intracarpathian (Pannonian) region to the east provided the space for material flow towards the east (Ratschbacher et al., 1991a). Eastward migrating subdution retreat in the Intracarpathian basin was proposed by Royden et al. (1982) and since supported by evidence from the structural evolution, migration of magmatism and paleomagnetic results (Zweigel, 1997).

Lateral extrusion occurred by rigid block movement without substantial block-internal deformation in the Austroalpine realm, which formed the upper plate during collision. Flow was ductile in the Penninic substratum, but deformation passed into the brittle field during the extrusion process in the fast-exhuming Penninic windows. Large-scale extension in the Austroalpine orogenic lid was responsible for the formation of the Penninic windows (Frisch et al., 1998). The classical Tauern window detected at the beginning of this century (Termier, 1903) in the center of the Eastern Alps (Fig. 1) embraces 5000 km^2 and is the largest.

In this paper, we examine the fault pattern that was activated during the extrusion process in the Eastern Alps, and focus on the large-scale extension responsible for the exhumation of the Tauern window. We present a model for the formation of the 160-km pull-apart of the Tauern domal structure in the frame of the post-collisional tectonic evolution of the Eastern Alps and examine the role of tectonic and erosional denudation of the window. Finally, we draw attention to similar structures elsewhere in the Alps and in other regions of the European Alpides that also underwent large-scale extension in Miocene times.

2. Block movements during lateral tectonic extrusion

Lateral tectonic extrusion probably started around the Oligocene–Miocene boundary, but the main phase of block movement was in late Early and early Middle Miocene time (Ratschbacher et al., 1991a; Frisch et al., 1998). The most important tectonic event of the extrusion process was a rapid pulse of exhumation in the Tauern and Rechnitz windows and the simultaneous disintegration of the upper-plate Austroalpine

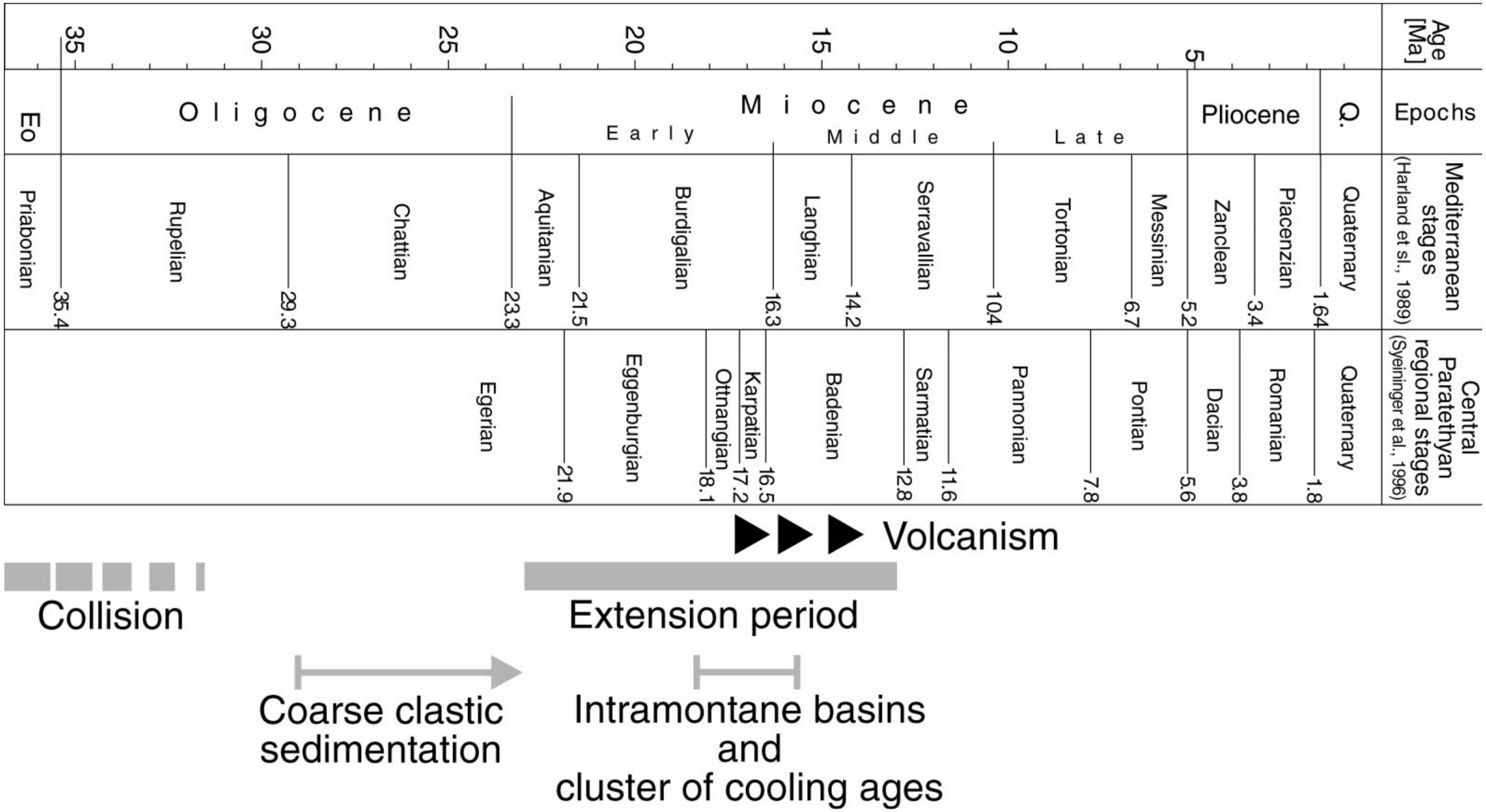


Fig. 2. Overview of important events in the Eastern Alps during Oligocene and Miocene times. Paratethys time scale as used in this paper (Steininger et al., 1996), and correlation with Mediterranean time scale (Harland et al., 1989).

unit. Dunkl and Demény (1997) demonstrated that the Penninic contents of the Rechnitz window in the transition zone between Alps and Pannonian basin (Fig. 1) experienced a marked temperature drop around 17 Ma. Tari (1996) places the main period of core complex formation in the Rechnitz window into the time interval of 17.5–16.5 Ma (late Ottnangian–Karpatian; for Paratethys time scale, see Fig. 2; Steininger et al., 1996). Exhumation of a metamorphic gneiss dome in the eastern Tauern window was modeled by Cliff et al. (1985) to have been in the order of 5 mm/a for a 1 Ma period around 17 Ma, preceded and followed by exhumation rates ≤1 mm/a. Surface uplift due to the fast exhuming Penninic domes (still hidden beneath the Austroalpine lid at that time) led to enhanced erosion, which is recorded by a pronounced peak in Late Ottnangian–Karpatian times in the sedimentation rate of the northern foreland molasse (Kuhlemann et al., 1997).

A phase of fault activity is recorded along the Periadriatic lineament south of the Tauern window by K/Ar and Ar/Ar ages of 18–16 Ma from newly formed mica in mylonites of a kilometer-sized fault-bounded lenticular body that was exhumed by subhorizontal large-scale movement (Läufer et al., 1997). Ar/Ar-dating on pseudotachylytes from accompanying faults of the Periadriatic lineament system in both its western and eastern section yielded ages in the range of 19–16 Ma (Müller, 1996), although earlier movements along this lineament have been important (Zingg and Hunziker, 1990).

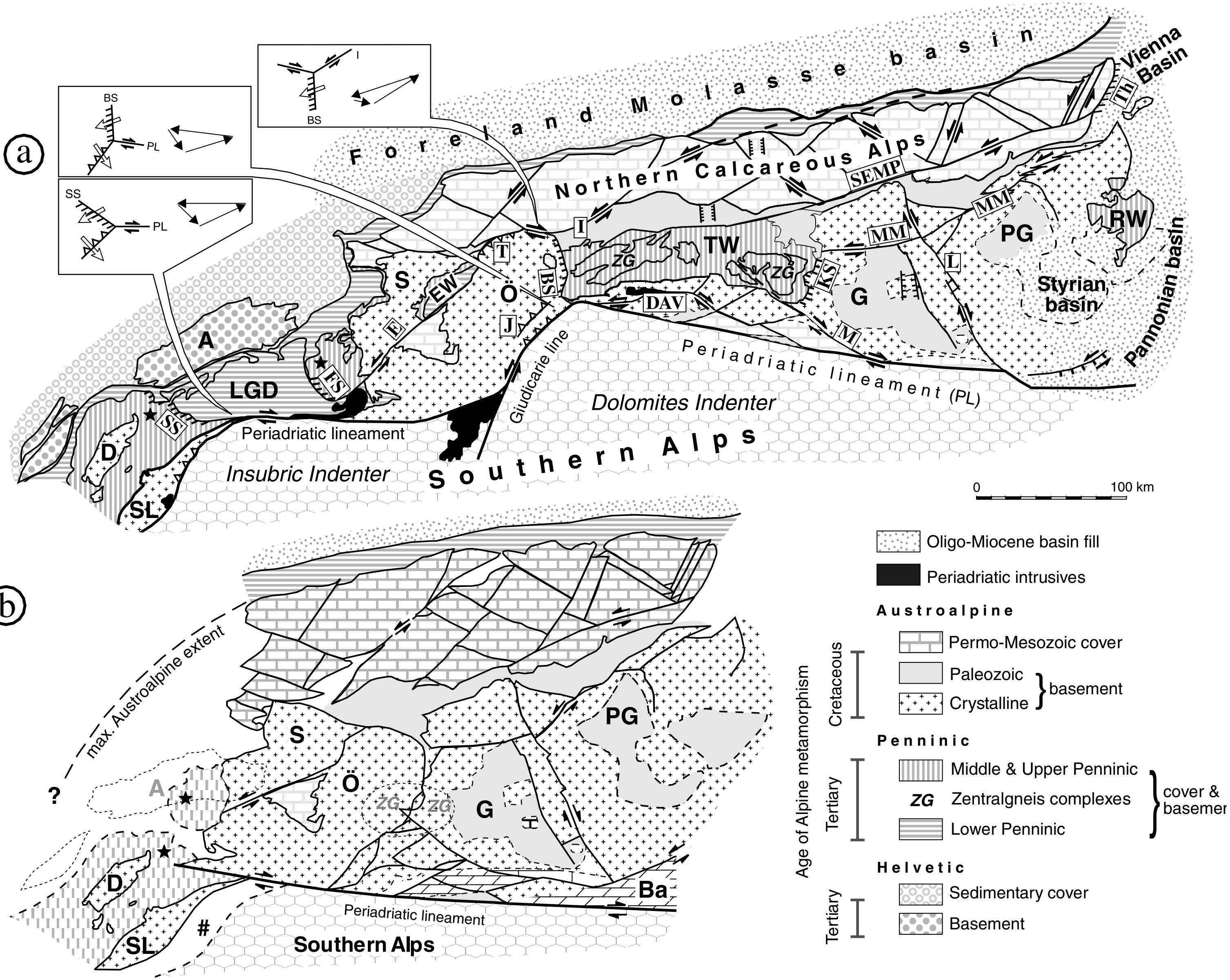
Substantial block movement in the Austroalpine realm is also well constrained by the creation of a large number of intramontane basins in Ottnangian to Karpatian times in the eastern Eastern Alps (Fig. 1a; see Tollmann, 1985, for review). These basins experienced marked subsidence in Karpatian and Early Badenian times. Average sedimentation rates in the mainly clastic sequences, which were supplied from local sources, attained values of >1 mm/a in the Karpatian. Isolated fault-bounded basins along the main tectonic lines were progressively filled, probably forming a coherent basin in Badenian times (Dunkl et al., 1998; Frisch et al., 1998). Sedimentation waned within the Badenian in most of the intramontane basins.

The Pannonian basin with its western appendices, the Vienna and the Styrian basin (Fig. 3a), shows a similar evolution. The syn-rift stage (17.5–16.5 Ma) was followed by a wide-rift stage in the Early to Middle Badenian (ca. 16.5–13.8 Ma) (Tari, 1996). Extension in the Pannonian basin was irregularly distributed (Tari et al., 1992). The detailed extension and subsidence history of the Pannonian basin is contained in the sedimentary record and subsurface structures as revealed by boreholes and seismic data. An important phase of volcanic activity affected the southeasternmost part of the Eastern Alps (Fig. 2) in Karpatian and Early Badenian times (Balogh et al., 1994).

The tectonic event around 17 Ma was connected with substantial E–W extension in the Eastern Alps and the Pannonian basin and responsible for a radical change in the tectonic, topographic and hydrographic evolution (Frisch et al., 1998). It laid the foundation stone for the modern face of the Eastern Alps. Around the Badenian/Sarmatian boundary (13 Ma), the extension process was terminated (Dunkl and Demény, 1997; Dunkl et al., 1998). Continuing extension at low rates in Late Miocene and Pliocene times is recorded by Tari (1996) for the western Pannonian basin. From fault plane analysis, Peresson and Decker (1997) infered Late Miocene inversion of the escape fault pattern under E–W compressional stress. They relate this inversion event to soft collision in the Eastern Carpathians and stress transmission across the Pannonian basin. Continuing the N–S contraction in the Eastern Alps caused a later reactivation of escape faults generally in the original mode of motion (Reinecker, 2000).

3. Displacement zones of the extrusion pattern

In this section we describe the most important displacement zones of the extrusion pattern and their importance in the extrusion process. First we focus on the fault and shear zones that play a role in the exhumation of the Tauern window, the most striking tectonic feature of the Eastern Alps, and then briefly characterize the extrusion fault pattern within the surrounding Austroalpine zone. The Tauern window was mainly exhumed along shear zones that originated in the Austroalpine lid and partly prograded into the Penninic terrain of the window (Fig. 4). The following compilation is taken from our own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I
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Periadriatic intrusives
Austroalpine
Permo-Mesozoic cover
Paleozoic
Crystalline
basement
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Middle & Upper Penninic
ZG Zentralgneis complexes
Lower Penninic
cover & basemer
Tertiary
Helvetic
Sedimentary cover
Basement
Tertiary
Age of Alpine metamorphism

unpublished observation and from the literature where indicated. Displacement values along fault and shear zones are inferred from the offset of geological features and lithotectonic units as well as from contrasting thermal histories. All described fault and shear zones played an important role during the extrusion process. Some of the faults already existed and performed major displacement prior to Miocene extrusion (e.g. the Periadriatic lineament; Schmid and Kissling, 1997).

3.1. Fault and shear zones bounding the Tauern window

The $160 \times 30\ km^2$ sized Tauern window exposes the lower-plate Penninic sequences (Figs. 1a and 3). Alpine maximum temperatures (around 600°C in the deepest exposed parts; Hoernes and Friedrichsen, 1974) and maximum ductility were reached around the Early/Late Oligocene boundary (von Blanckenburg et al., 1989; Inger and Cliff, 1994). Rapid exhumation in the Miocene led to the formation of dome-like structures by the uprise of Variscan granitoids that were transformed into gneisses ('Zentralgneis', Figs. 3 and 4) during Eocene–Oligocene metamorphism. Exhumation mainly occurred by tectonic denudation in the course of large-scale extension of the Austroalpine lid (Frisch et al., 1998).

3.1.1. The Brenner low-angle extensional shear zone (BS)

The western boundary of the Tauern window is a first-order low-angle extensional shear zone along which high structural levels of the Austroalpine mega-unit of the Ötztal block are displaced against different units of the Tauern window. At its northern termination, the BS is transformed into the Inntal fault with ca. 80 km sinistral displacement (Fig. 3a). In the south, the motion of the BS is mainly transformed into dextral displacement of the Gailtal-Pustertal fault zone, which is a part of the Periadriatic lineament (Figs. 3a and 4e).

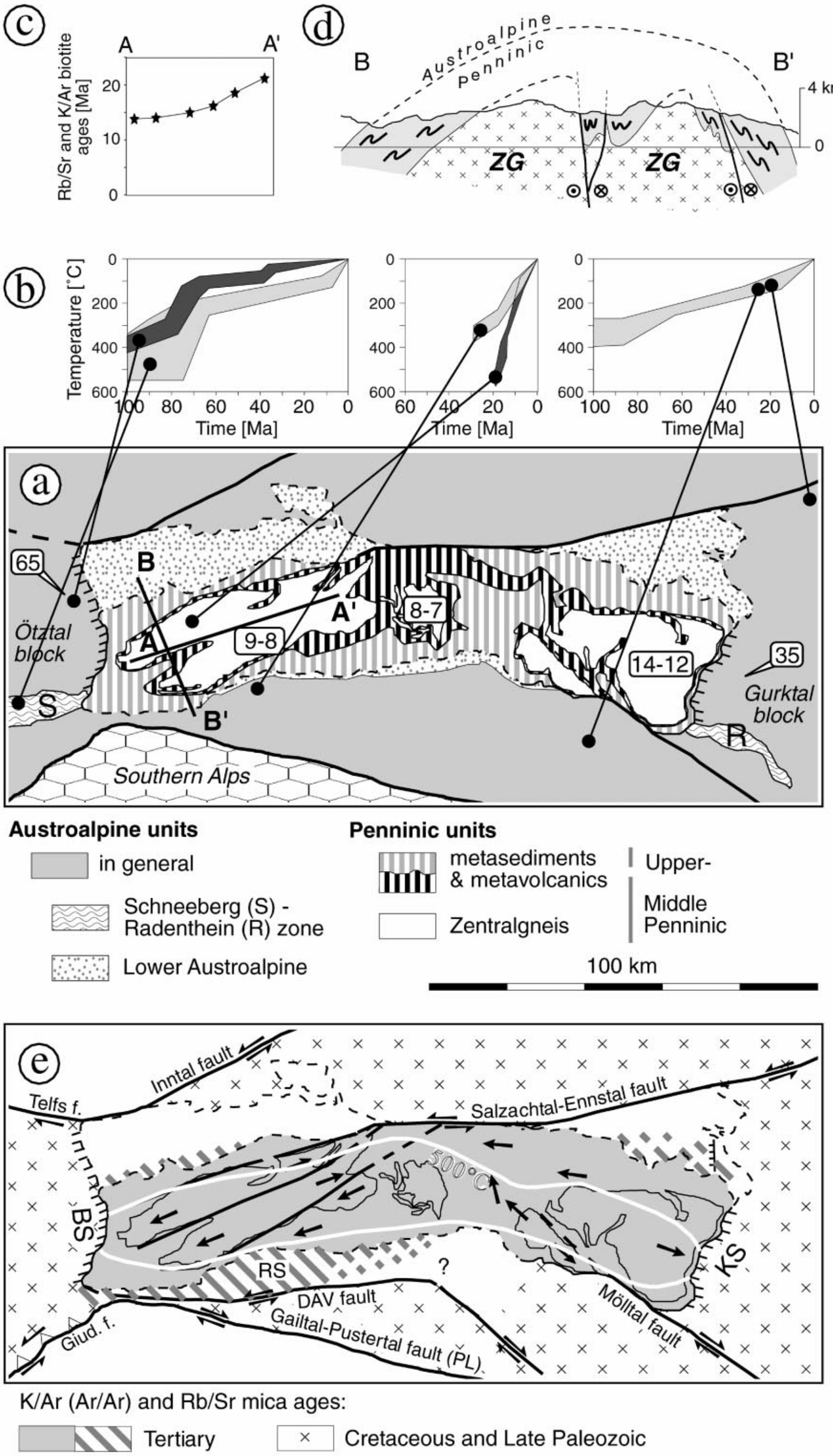
The history of the BS starts with highly ductile deformation, probably soon after passage of the thermal peak of the Penninic rocks. Penetrative ductile thinning already started before the thermal peak was reached and affected the higher parts of the Penninic stack (Selverstone, 1988, 1993). In the up to 400 m thick mylonite zone shear sense indicators consistently show normal, i.e. top-to-WSW, displacement (Behrmann, 1988; Selverstone, 1988; Fügenschuh et al., 1997). Dips of the mylonitic foliation and plunges of the mylonitic lineation are $<30°$, and in many places $<20°$.

Geochronologic data show a significant jump in cooling ages across the BS. Mica ages in the Austroalpine hanging wall block away from the shear zone indicate Late Cretaceous cooling of Eoalpine metamorphism (Thöni and Hoinkes, 1987). This is in contrast to the generally Late Oligocene to Middle Miocene mica cooling ages along the culmination of the Tauern window (Raith et al., 1978; see review by Genser et al., 1996). A similar jump is shown by Paleogene zircon and apatite fission track ages contrasting with Middle to Late Miocene ages along the BS and in the Penninic units (Fig. 4a; Grundmann and Morteani, 1985; Fügenschuh et al., 1997).

3.1.2. The Katschberg low-angle extensional shear zone (KS)

The eastern boundary of the Tauern window is an ESE dipping low-angle extensional shear zone, the Katschberg shear zone (KS). The KS, described in detail by Genser and Neubauer (1989), is the counterpart of the BS. A several hundred meters thick layer of quartzose phyllites in Lower Austroalpine position represents a

Fig. 3. (a) Geologic sketch of the Eastern and Central Alps with most important tectonic lines active during lateral tectonic extrusion in Early to Middle Miocene times. Insets show triple junctions and kinematics of moving blocks at terminations of the Brenner and Simplon shear zones and the respective vector diagrams of relative movement. (b) Palinspastic reconstruction for pre-extrusion times (Late Oligocene). Tectonic blocks and units: A, Aar massif; Ba, Bakony block; D, Dent Blanche nappe; G, Gurktal block; Ö, Ötztal block, PG, Paleozoic of Graz; S, Silvretta block; SL, Sesia Lanzo block. Metamorphic domes and windows: EW, Engadin window; LGD, Lepontin gneiss dome; RW, Rechnitz window; TW, Tauern window. Low-angle extensional shear zone: BS, Brenner; FS, Forcola; KS, Katschberg; SS, Simplon shear zone. Escape faults: DAV, Defereggen-Antholz-Vals; E, Engadin; I, Inntal; L, Lavanttal; MM, Murtal–Mürztal; SEMP, Salzachtal-Ennstal-Mariazell-Puchberg; Th, Thermen fault zone. Thrusts (Ötztal block): J, Jaufen; T, Telfs thrust. Stars to both sides of LGD in (a) correlate with the stars in (b) for better orientation. # in (b) shows space between Southern Alps and SL that was probably consumed during Miocene thrusting (see Schmid et al., 1989).


c
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S
A
A'
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9-8
8-7
14-12
35
Gurktal block
R
Southern Alps
Austroalpine units
in general
Schneeberg (S) - Radenthein (R) zone
Lower Austroalpine
Penninic units
metasediments & metavolcanics
Zentralgneis
Upper-
Middle Penninic
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e
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Salzachtal-Ennstal fault
500°C
BS
RS
KS
DAV fault
Giud. f.
Gailtal-Pustertal fault (PL)
Mölltal fault
K/Ar (Ar/Ar) and Rb/Sr mica ages:
Tertiary
Cretaceous and Late Paleozoic

strongly thinned sequence and separates ductile Penninic units in the footwall from brittle Austroalpine basement in the hanging wall. The Penninic units in the footwall are also strongly thinned out and partly truncated. Foliation dips and lineation plunges are mostly <30°. At its southern termination, the displacement of the KS is transformed into eastward accelerating dextral displacement along the Mölltal fault (Fig. 4e; see below). The northern termination of the KS is not well defined. Near the easternmost tip of the Penninic units it probably splits up, the motion being transferred into several oblique-normal shear zones or more distributed oblique-normal shear in the Lower Austroalpine unit between the Penninic units and the Austroalpine crystalline basement (Fig. 4a). This is indicated by mica ages younging from Cretaceous to Miocene from higher to lower structural levels within the Lower Austroalpine unit (Slapansky and Frank, 1987).

Like the BS, the KS also marks an important jump in mineral cooling ages. Cretaceous mica ages in the Austroalpine contrast to Oligocene–Miocene ages within the window (Frank et al., 1987). Oligocene apatite fission track ages in the Austroalpine Gurktal block contrast with Miocene ages in the Penninic contents of the window (Fig. 4a; Staufenberg, 1987; Hejl, 1997).

3.1.3. The Salzachtal fault (shear) zone

The Salzachtal fault (shear) zone is the western segment of the Salzachtal–Ennstal–Mariazell–Puchberg (SEMP; Ratschbacher et al., 1991a; Fig. 3a) line (see below). This segment along the northern edge of the Tauern window mainly affects quartz-mica rich schistose rocks of both the Penninic zone to the south and the Austroalpine unit (Paleozoic Greywacke zone) to the north, rotated into subvertical positions. In its eastern part, where it forms the northern boundary of the eastern Tauern window, it is well exposed. Features such as mylonites with SC fabrics and extensional crenulation cleavage overprinted by cataclstic shear show that deformation there started in the ductile–brittle transition field and passed into the brittle field (Herrmann, 1989). In a 100–200 m thick vertical shear zone calcite is recrystallized, whereas quartz shows crystal plasticity but no recrystallization indicating temperatures <300°C during deformation (Passchier and Trouw, 1996). Cataclastic overprint is strong and ubiquitous. Shear indicators are generally sinistral but pass into quasi-coaxial (pseudosymmetric) patterns in the center of the shear zone, indicating high shear strain. The western termination of the Salzachtal fault zone is ill defined. Splay fault zones probably partition the amount of displacement and enter the Penninic realm of the window (Fig. 4e). There, gneiss mylonites with crystal–plastic behavior of feldspar indicate temperatures exceeding 500°C (Reicherter et al., 1993).

The SEMP fault reaches higher crustal levels towards the east. East of the NE corner of the Tauern window the Salzachtal shear zone continues along the Ennstal (valley), where it enters the Austroalpine mega-unit with deformation in the brittle or, in schistose rocks, quasi-ductile field (Ennstal fault segment).

3.1.4. The Mölltal fault (shear) zone

The Mölltal fault zone is another important feature of the extrusion pattern, which is exposed at a high structural level in its southeastern part and progressively exhumed from greater depth towards the NW (Fig. 4e). It shows an apparent dextral offset in the order of 40 km in the SE where it separates two Austroalpine blocks. In its central segment it forms a shear zone along the boundary between the Tauern

Fig. 4. (a) Tectonic sketch of the Tauern window and its surroundings. Positions of profiles in (c) and (d) are shown. Numbers give apatite fission track ages in Ma (Grundmann and Morteani, 1985; Staufenberg, 1987; Fügenschuh et al., 1997; Hejl, 1997). (b) Typical cooling paths of tectonic units (Frank et al., 1987; plus references as in (a). (c) Biotite cooling ages along profile AA' showing systematic younging from E to W (Raith et al., 1978). (d) NNW–SSE profile BB' through western Tauern window showing post-T_{max} arching by N–S contraction. Note Z- and S-shaped parasitic folds on northern and southern flank of the cupola, respectively (Frisch, 1977), ZG, Zentralgneis. (e) Contrasting metamorphic histories (Borsi et al., 1978; Frank et al., 1987; Slapansky and Frank, 1987; Dingeldey et al., 1997) defining tectonothermal boundaries of the window. Transitional zones exist in the Lower Austroalpine units in the NW and NE corners of the window and in the Rieserferner slab (RS) to its south. Zone of dark shading and hatching defines $T > 300$°C in Oligocene times. 500°C isotherm indicated by the white line (Hoernes and Friedrichsen, 1974). Arrows show plunge of penetrative stretching lineation in Penninic units. BS, KS, Brenner and Katschberg shear zones; DAV, Defereggen-Antholz-Vals fault zone; PL, Periadriatic lineament; Giud. F., Giudicarie fault.

window and the Austroalpine basement. Tauern rocks are extremely sheared in a ductile manner with limited brittle overprint (Exner, 1962). In its northwestern continuation the shear zone penetrates into the interior of the Tauern window for ca. 25 km, where several individual shear zones in a belt of steep dips were described by Kurz and Neubauer (1996). As can be evaluated from geological mapping (Exner, 1964), the offset abruptly decreases in this segment due to transformation of lateral displacement into normal-oblique detachment along the Penninic roof detachment. In a mass of schistose Penninic rocks further northwest, the shear zone becomes undetectable.

3.2. Pull-up structure west of the Tauern window

In front of the tip of the Southern Alps indenter, where the Eastern Alps are narrowest and show maximum shortening during the extrusion process (Fig. 3), the Ötztal block formed a pull-up structure characterized by divergent thrusting, with an out-of-sequence thrust onto the Northern Calcareous Alps (NCA) (Telfs thrust, *nomen novum*; see Linzer et al., 1995), and backthrusts (with lateral components) onto the Southalpine block (Giudicarie fault) and within the Ötztal block (Jaufen fault) (Fig. 3a; Schmid and Haas, 1989). The uplift of the Ötztal block related to this process has been dated by means of apatite fission track geochronology as Early Miocene (ca. 18 Ma; Elias, 1998).

Further west, the Silvretta block is separated from the Ötztal block by the sinistral Engadin fault (Fig. 3a; Schmid and Froitzheim, 1993). Along this line, the Engadin window, containing Penninic sequences partly correlated with series in the Tauern window, is opened along a sinistral overstep forming a pull-apart structure. Contrasting mica cooling ages across the window boundaries (pre-Alpine or Cretaceous vs. Tertiary; Thöni, 1981) again show that substantial extensional movements along the Austroalpine/Penninic boundary have taken place during post-collisional exhumation. The sinistral displacement along the Engadin fault zone is in line with continuous N–S convergence that was accommodated by both pull-up (vertical extension) and lateral escape (E–W extension).

3.3. Collapse and escape structures east of the Tauern window

The Austroalpine basement area east of the Tauern window is characterized by block segmentation along conjugate strike slip fracture zones and dilatational features like grabens and pullapart basins filled with Miocene sediments. In this area the present mean elevations of tectonic blocks show a consistent decrease from west to east. This reflects the accelerating eastward migration of individual blocks during tectonic extrusion and large-scale extension above the Tauern window, as it is evident from the lateral extrusion model (Ratschbacher et al., 1991a) and the palinspastic restoration (Frisch et al., 1998). Individual block paths are also manifested by differential exhumation and uplift. In contrast to the area west of the Tauern window, E–W extension in combination with N–S and vertical shortening results in an overall constrictional geometry of strain.

3.3.1. The Salzachtal–Ennstal–Mariazell–Puchberg fault system

The Salzachtal segment of the Salzachtal–Ennstal–Mariazell–Puchberg (SEMP) fault system is an element bounding the Tauern window (see above). The ENE-trending Ennstal segment in its eastern continuation shows a sinistral offset of about 60 km. Towards the east it enters the NCA, where the offset decreases (Mariazell-Puchberg segment; Linzer et al., 1995; Fig. 3a), which is already evident from its considerably less pronounced morphologic expression. Releasing bends are responsible for transtensional sections along the SEMP line, which are characterized by negative flower structures and basin formation.

The sinistral displacment diminishes to values not more than a few kilometers near the eastern termination of the SEMP, where it is transformed into the normal Thermen fault system, the western boundary of the Vienna pullapart basin (Fig. 3a). The eastward decrease in displacement is because of transformation into splay faults. Our palinspastic reconstruction of the pre-extrusion situation (see below) shows a more distributed extrusion fault pattern in the NCA than in the central zone of the Eastern Alps to the south. This results in differential displacement along the SEMP line, because pullapart distances between tectonic blocks of the central zone were by far largest above the Tauern dome structure. Sinistral displacement along the SEMP line within the NCA was transferred into a series of conjugate NNE trending sinistral and WNW trending dextral faults.

3.3.2. The Murtal–Mürztal fault system

The Murtal–Mürztal fault system is a complex, mainly sinistral, fault system decorated by a number of transtensional or pullapart basins (Figs. 1a and 3a). Near its eastern termination it forms the southern boundary of the Vienna pullapart basin (Royden, 1985) and transforms the sinistral into E–W distensional displacement of the Vienna basin. The Vienna basin, on a larger scale, repeats the situations of small pullapart basins at left-handed oversteps along the SEMP and Murtal–Mürztal fault systems.

3.3.3. The Pöls–Lavanttal fault system

The NNW trending, dextral Pöls–Lavanttal fault system crosses the Murtal fault system in a complex interference zone. Dextral offset as deduced from displaced lithological units amounts to ca. 8 km along the Pöls segment north and to ca. 10 km along the Lavanttal segment south of the Murtal–Mürztal fault. The Lavanttal fault formed pullapart basins at right-handed oversteps. In its southern part where it separates basement from Tertiary strata of the Lavanttal basin, the fault displays a vertical throw of >2 km. The nature of the Lavanttal basin is probably an oblique graben structure formed in a transtensional regime. Near its southern termination the Lavanttal fault cuts and offsets the Periadriatic lineament by about 20 km (Fig. 3a).

3.4. The area south of the Tauern window

The Austroalpine basement south of the Tauern window is dissected by ENE-trending sinistral and ESE-trending dextral faults, which intersect at a more acute angle than the according fault systems east of the Tauern window or in the NCA (Fig. 3a) indicating higher N–S shortening of the region. The Austroalpine basement immediately to the south of the Penninic units of the western and central Tauern window and north of the Defereggen–Antholz–Vals fault zone (Fig. 4e) are stucturally concordant with the Penninic window contents with respect to the last (Oligocene–Miocene) ductile deformation (Kleinschrodt, 1987). They show no differences in mineral cooling ages across the Penninic/Austroalpine boundary (Frank et al., 1987). This means that no major vertical throw has taken place along the southern margin of the Penninic unit (which is marked in contrast to its western and eastern margins) and that the blocks bordering the window represent the structurally deep levels of the Austroalpine basement prior to window denudation. A jump in mineral cooling ages, however, occurs along the oblique-sinistral Defereggen–Antholz–Vals fault zone within the Austroalpine basement (Kleinschrodt, 1987). This fault zone separates a zone of Oligocene–Miocene mica cooling ages in the north from mostly Variscan ages in the south (Borsi et al., 1978).

The structural and thermal continuity during exhumation across a part of the southern Penninic/Austroalpine boundary of the Tauern window has important bearing for the definition of the window and for its exhumation history. This will be discussed below.

3.4.1. The Pustertal–Gailtal segment of the Periadriatic lineament

The Periadriatic lineament, a 700 km long lithospheric rupture, separates the Southern Alps from the main body of the Alps (Fig. 3a). Pre-Miocene dextral offset amounts to >100 km (Schmid and Kissling, 1997). A displacement of this magnitude is impossible in the present geometric configuration of the lineament due to its apparent 80-km horizontal offset by the oblique–reverse Giudicarie fault system. Our palinspastic reconstruction of the pre-Miocene (pre-extrusion) situation shows that the Periadriatic lineament restores to a straight line allowing large-scale displacement (Fig. 5b; Frisch et al., 1998).

During the extrusion period, renewed dextral displacement in the order of several tens of kilometers took place along the Pustertal–Gailtal segment east of the Giudicarie fault. Dextral sense of motion is indicated by data from fault-plane analysis and map-scale Riedel shears (Polinski and Eisbacher, 1992; Läufer et al., 1997). Fault activity in Early and Middle Miocene times (ca. 19–16 Ma) was dated on newly formed white mica by the K/Ar and Ar/Ar methods (Müller,

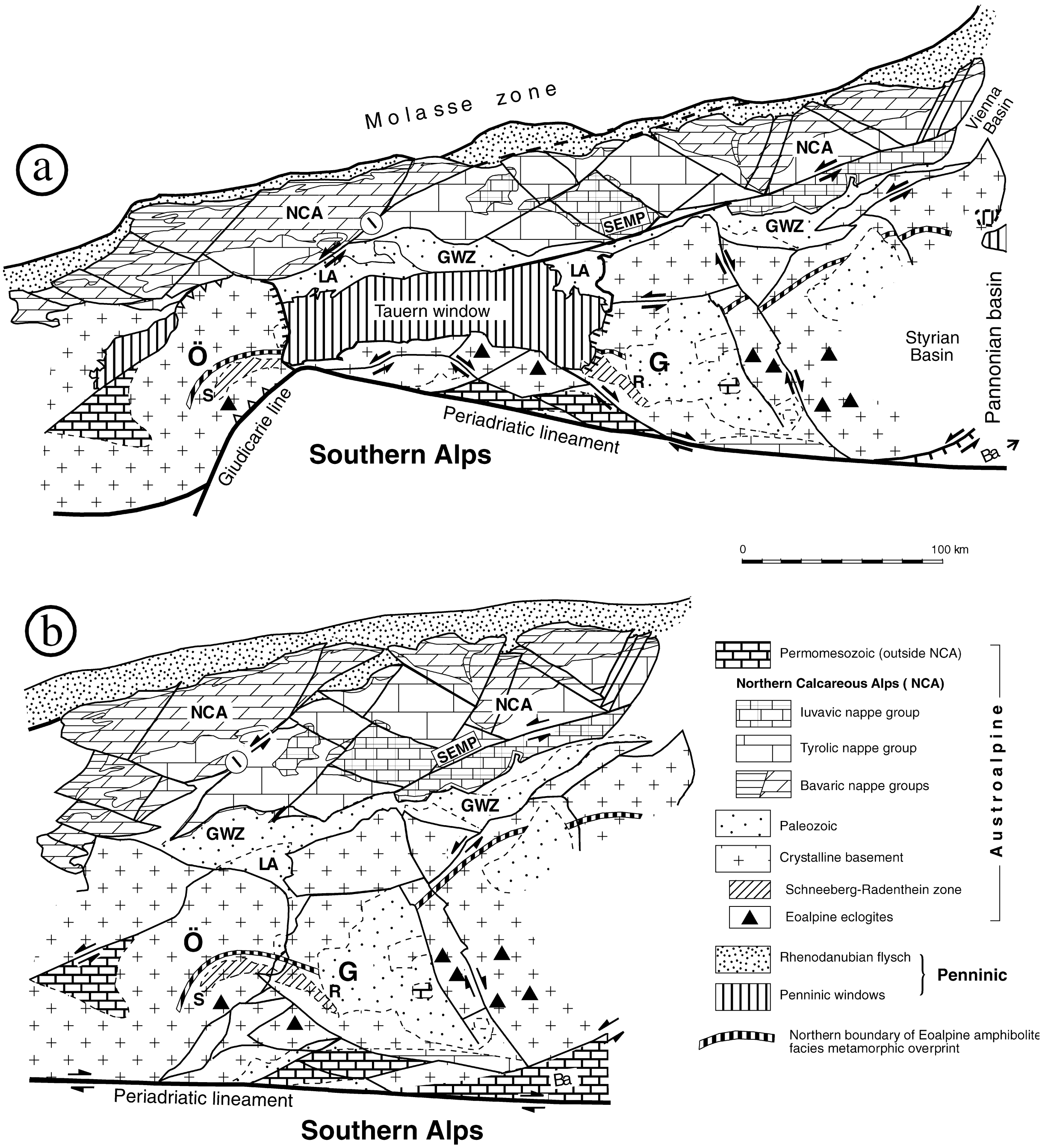

Fig. 5. (a) Geologic sketch of the Eastern Alps with most important tectonic lines active during lateral tectonic extrusion in Early to Middle Miocene times. (b) Palinspastic reconstruction for pre-extrusion times (Late Oligocene) after Frisch et al. (1998). Shown are several features disrupted by the lateral tectonic extrusion process: Internal nappe groups within the Northern Calcareous Alps (NCA); Greywacke zone (GWZ); Lower Austroalpine terrains (LA); Ötztal (Ö) and Gurktal (G) blocks and Schneeberg (S) and Radenthein (R) zones as part of Austroalpine basement unit; boundary between Eoalpine (Cretaceous) greenschist and amphibolite facies overprint in the Austroalpine crystalline basement; Eoalpine eclogite occurrences. Ba, Bakony. I, SEMP, Inntal and Salzachtal-Ennstal-Mariazell-Puchberg fault zones.

1996; Läufer et al., 1997). The dextral displacement resulted in a faster eastward block motion north of the Pustertal–Gailtal fault than south of it. Transpression led to the formation of flower structures (Laubscher, 1983) or the rapid exhumation of fault-bounded, lens-shaped blocks (Läufer et al., 1997). Exhumation of such a block in the order of several kilometers is evident from Early Miocene cooling below 300°C. It was accomplished by the subhorizontal displacement as evidenced by shallowly plunging stretching lineations. These data imply a dekakilometric horizontal displacement component. The mica ages also suggest that part of the displacement along the Periadriatic lineament occurred in Early Oligocene time (Läufer et al., 1997).

3.5. Behavior of the northern Eastern Alps during tectonic extrusion

The NCA experienced the same overall E–W extension as the central crystalline zone to its south (Frisch et al., 1998). They are dissected by a great number of faults (shown schematically in Figs. 3a and 5a), created or reactivated during lateral extrusion. The resulting, generally lozenge-shaped blocks carried out individual movements, mostly differential horizontal translations also including vertical movements and tilts (Linzer et al., 1995).

The Inntal fault that separates the western and the central part of the NCA played a major role in the E–W stretching process during lateral extrusion. The Inntal fault is an ENE-trending sinistral strike-slip fault with an overall displacement of ca. 80 km. At the western termination of the Inntal fault normal displacement of the Brenner shear zone is transformed into the horizontal displacement of the Inntal fault (Fig. 3a).

A number of NE to NNE trending sinistral strike-slip faults in the central and eastern NCA contribute to the overall stretching of the NCA and reduce the displacement along the SEMP towards the east by partitioning the displacement between the SEMP master fault and its splays. Along several of these faults the amount of displacement, which is generally <10 km, decreases from SW to NE, part of the displacement being transformed into thrusting or folding. Conjugate (E)SE trending dextral faults are of less importance during extrusion and mostly reactivated transfer faults formed during Cretaceous nappe stacking (Linzer et al., 1995). On the map scale, the about 40 km wide NCA show necking caused by the stretching process during extrusion, especially evident around the Inntal fault zone (Fig. 3a).

North of the NCA, E–W stretching also affected the unmetamorphosed but largely schistose Rhenodanubian Flysch zone (Fig. 1a) and the Folded Molasse zone, which forms the frontal thrust imbricates of the orogen. This is shown in the flysch zone by quasi-ductile dekakilometric necking along strike and displacement along dominantly ENE trending fault zones (Fig. 3a). Similar deformation probably affected the Folded Molasse zone. Part of the unfolded Foreland Molasse sediments was deposited simultaneously with the extrusion process. Therefore, we suggest that the tectonized Molasse zone near the orogenic front acted as an accommodation zone between the stretched Alpine body and the unstretched crystalline substratum and its immediate sedimentary cover (Frisch et al., 1998). This crystalline basement forms the southward continuation of the Bohemian Massif (Fig. 1a), which experienced Late Paleozoic metamorphism, and was a cold and rigid body during Alpine orogeny.

4. Palinspastic restoration of the pre-extrusion situation in the Eastern Alps

For the pre-extrusion palinspastic reconstruction (Figs. 3b and 5b) we choose the time around the Early/Late Oligocene boundary (ca. 29 Ma). This time is near the thermal peak in the Penninic domain of the Tauern window (von Blanckenburg et al., 1989; Christensen et al., 1994; Inger and Cliff, 1994), when nappe stacking was already completed and the lower-plate Penninic material attained maximum ductility. This time is also near the start of the substantial relief formation in the Central and western Eastern Alps (Frisch et al., 1998).

For the palinspastic restoration of the Eastern Alps, the Tauern window plays a key role. The cooling histories of the contents of this large structure and its frame are fundamentally different (Genser et al., 1996; Fügenschuh et al., 1997; Hejl, 1997; Fig. 4b). The sharp contrast of the geochronologic data and the structural pattern prove that the Tauern window was exhumed by tectonic rather than by erosive denudation. Therefore, the palinspastic restoration in the central zone of the Eastern Alps can be performed by the re-arrangement of the present puzzle of the Austroalpine tectonic blocks, since these blocks behaved as rigid elements with no or negligible internal deformation during lateral extrusion. Erosion in most of these blocks did not exceed a few kilometers in Neogene times as indicated by pre-Neogene apatite or zircon fission track data (Fig. 4a; Fügenschuh et al., 1997; Hejl, 1997). The restoration should therefore result in an Austroalpine mass with coherent internal structures that completely covers the Tauern window in its retrodeformed state. The ductile rocks of the Tauern window experienced stretching in an E–W direction, documented by a penetrative stretching lineation (Fig. 4e; Selverstone, 1988; Ratschbacher et al., 1989) parallel to the flow direction during tectonic extrusion. This lineation also shows that the contents of the Tauern window experienced substantial E–W elongation (Lammerer and Weger, 1998).

The pre-extrusion restoration of the Austroalpine basement terrain was achieved by backward motion along the conjugate strike-slip fault system and the closure of the Tauern window by block translation (Figs. 3 and 5). It shows that the Ötztal and Gurktal blocks, now 160 km apart, fit together, thus covering the Tauern window. Normal movement along the Brenner and Katschberg extensional shear zones was transformed into large-scale strike-slip movement along the boundaries of escaping crustal wedges. Additional N–S striking graben structures played a minor role in the extension process, but are of importance in the Pannonian basin (e.g. Tari et al., 1992).

The restoration results in an excellent fit of geologic features and lithotectonic and metamorphic zones that were disrupted in the course of extrusion tectonics (Fig. 5; Frisch et al., 1998). The polymetamorphic (Variscan and Alpine) Austroalpine crystalline basement forms a coherent body in the restored puzzle. Within this body, the Eoalpine (Cretaceous) greenschist, amphibolite, and eclogite metamorphic facies zones restore to continuous belts, as are the disrupted monometamorphic Schneeberg and Radenthein zones west and east of the Tauern window. The Lower Austroalpine units, now exposed in the northwestern and northeastern corners of the Tauern window, form a coherent body in the restoration (although buried beneath higher Austroalpine units at that time). The Greywacke Zone, consisting of low-grade metamorphic Paleozoic sequences, also restore to a more coherent body after retrodeformation along the fault pattern.

Good fit of disrupted internal nappes of the NCA is achieved by large-scale retrodeformation along the Inntal and SEMP master faults, and minor retrodeformation along other faults (Fig. 5). The Bavaric nappe group, which represents the structurally lowest level and is disrupted by about 90 km in the central section of the NCA in their present configuration, forms a coherent belt after restoration. This is mainly achieved by retrodeformation along the Inntal fault. Segments of the Tyrolic nappe group were also disrupted by the Inntal fault and restore to a continuous belt; the apparent imperfect fit (Fig. 5) results from the erosional nature of the present nappe boundaries. The Iuvavic nappe group, representing the structurally highest level, restores to a continuous zone by retrodeformation along the SEMP line.

The most striking result is that the Periadriatic lineament, in its present course disrupted (and blocked) by the Giudicarie fault along the western border of the Southern Alps indenter tip, restores to a straight line (Fig. 5), thus allowing for considerable strike-slip movement (>100 km dextral displacement in pre-Miocene times; Schmid and Kissling, 1997). We place the Bakony mountains from western Hungary into the open wedge south and southeast of the Gurktal block (Fig. 5b). The Bakony mountains are known for the similarity of their Jurassic facies compared to the Southern Alps (Kázmér and Kovács, 1985).

Our reconstruction results in about 50% or 170 km extension in an E–W direction for the entire Eastern Alps since the onset of extrusion (excluding extension above the Rechnitz window in the Alps/Pannonian basin transition; see below). The separation of the Ötztal and Gurktal blocks is responsible for the most part of the overall extension in the Austroalpine basement. A major role in the extension process is overtaken by the Inntal fault for the NCA. Minor amounts of E–W stretching are attained by graben structures and lozenge-shaped escape blocks (Figs. 3 and 5). The escape blocks east of the Tauern window have largely transtensional border faults ornamented with pullapart basins.

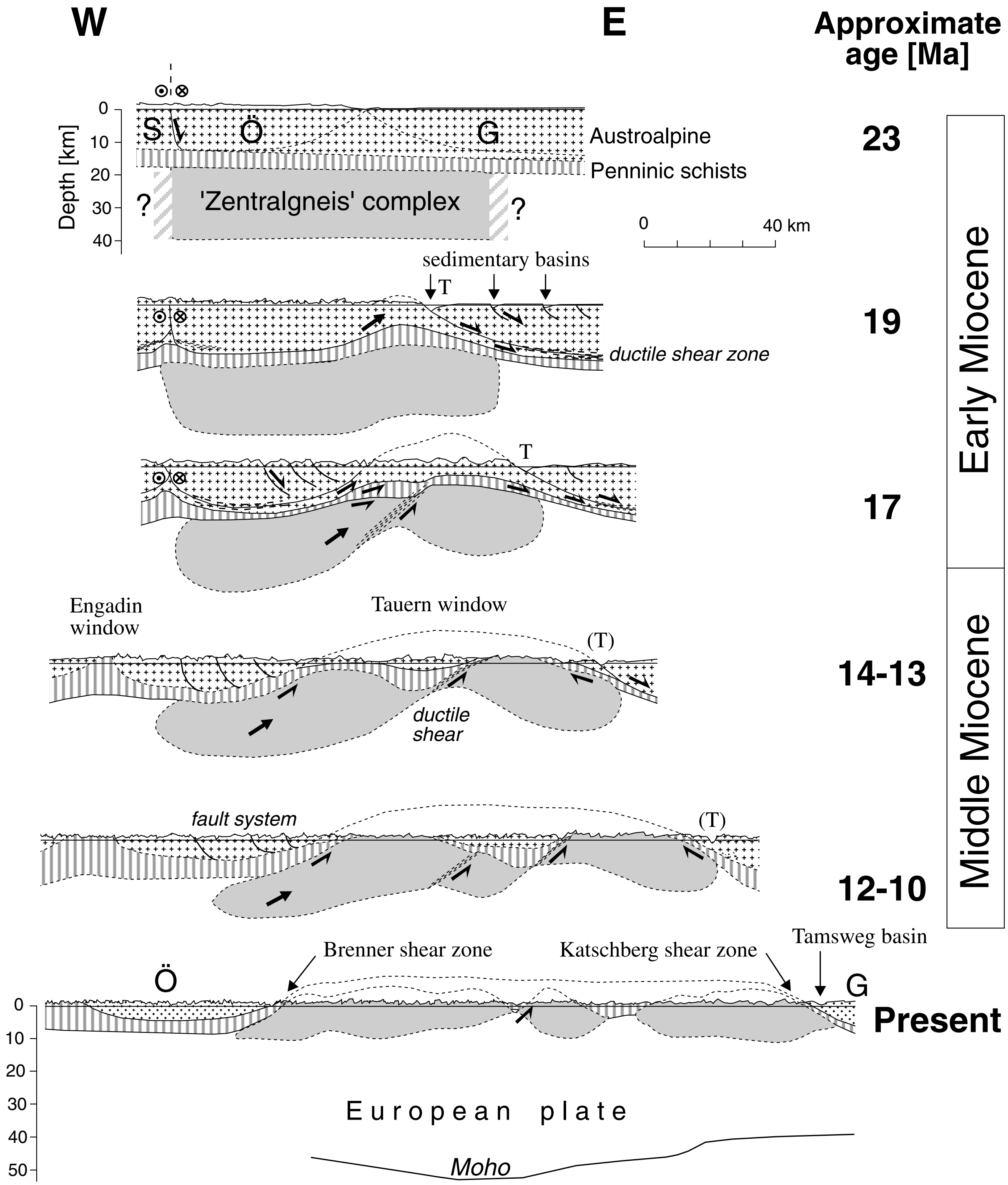

Fig. 6. Formation of Tauern window by Early to Middle Miocene tectonic denudation in a series of W–E profiles, and present-day section. Note ductile deformation and mega-boudinage of Zentralgneis complex. Moho in present-day section after Posgay et al. (1991). Ö, G, Ötztal and Gurktal tectonic blocks; T, Tamsweg basin.

Continuing N–S convergence accompanied the large-scale E–W extension of the Eastern Alps and was partly accommodated by it. Evidence for post-collisional N–S shortening comes from thrusting at the orogenic front which terminated around the Early/Middle Miocene boundary (ca. 17 Ma; Peresson and Decker, 1997), and from the intra-orogenic deformation during the extrusion process as described in this paper. Post-collisional N–S shortening in the Alps is in line with the Oligo-Miocene Africa–Europe convergence as deduced from the continental wander paths calculated from the magnetic anomaly patterns in the Atlantic ocean (Dewey et al., 1989). Syn-extrusion N–S shortening in the Eastern Alps was largest in front of the tip of the Southern Alps indenter (meridian of the Brenner line; Figs. 3 and 5), where it amounts to 54% or 113 km. From there to the east, post-collisional N–S convergence systematically decreased as the Eastern Alps broaden, and reached a value of 17% or 40 km at their eastern margin (Frisch et al., 1998). Part of the N–S convergence in the western Eastern Alps is compensated by vertical extension (Ötztal pull-up, arching of Tauern window). The area east of the Tauern window is characterized by vertical shortening, reflected by crustal thinning.

The Brenner shear zone, flattening out in shallow crustal levels (see Fig. 6; Axen et al., 1995), is the upper crustal manifestation of a discontinuity of lithospheric dimension. This conclusion is drawn from data showing the depth of the lithosphere/asthenosphere interface, which indicate a pronounced discontinuity and lithospheric thickness minimum along the Brenner meridian (Babuška et al. 1990; Marchant 1993), where the Southern Alps protrude farthest north. This lithospheric break continues into the Southern Alps where extensional structures are inferred from a depression in the area immediately east of the Giudicarie line.

5. The Tauern window — tectonostratigraphic versus tectonothermal definition

Conventionally, the Tauern window is shown as a structure containing three major tectonostratigraphic units formed by thrusting during collision and crustal stacking. From deeper to higher structural levels, these are (Fig. 4a): (1) the Middle Penninic nappe system consisting of Variscan basement (including the Zentralgneis complexes) and post-Variscan cover; (2) the Upper (South) Penninic nappe system consisting of Mesozoic ophiolites and their sedimentary cover; and (3) Lower Austroalpine slices comprising early Paleozoic and post-Variscan metasedimentary sequences. The Lower Austroalpine unit forms a discontinuous zone around the Penninic interior of the window. The whole structure is framed by (higher) Austroalpine Variscan crystalline and metasedimentary basement sequences (Fig. 3a). In the tectonostratigraphic sense the window is therefore defined by the thrust boundaries which define tectonostratigraphic units. Generally the boundary between the Lower Austroalpine and the higher Austroalpine units is taken as the window boundary.

Since the Tauern window is a feature mainly exhumed by tectonic denudation, and the main tectonic shear zones active during exhumation only partly follow the tectonostratigraphic boundaries, we propose an alternative definition of the window in tectonothermal terms. According to this definition, the main boundary of the window coincides with the interlinking shear zones encircling the rocks exhumed from deeper crustal levels and defining the main jump in mineral cooling ages (Fig. 4). Along this shear zone system, the units that had been in mid-crustal levels prior to window formation were brought against units that already had an upper-crustal position. Most of these high-level units forming the frame around the window in tectonothermal terms are characterized by the presence of Paleozoic and Mesozoic sequences that had never been deeply buried.

The tectonothermal boundary of the Tauern window is not sharp in all places, but partly characterized by a broad transition zone with distributed shear, as in the Lower Austroalpine terrains in the NW and NE corners of the window, or by an obliquely exhumed slab with a diffuse hinge zone as in the southern part of the window. According to the tectonothermal definition, we consider the Austroalpine basement slab to the south of the Penninic units and north of the Defereggen–Antholz–Vals fault (shear) zone as a part of the window ('Rieserferner slab'; Fig. 4e). This slab is the only rock body within the Austroalpine crystalline basement displaying Miocene resetting of mica ages (Borsi et al., 1978). The eastern boundary of this slab is not sharp, since mica-cooling ages become older and are transitional to pre-Tertiary ages in the main mass of the Austroalpine crystalline basement. The western part of the Rieserferner slab was therefore exhumed from a deeper crustal level during extrusion than its eastern part. The eastern boundary is a diffuse zone acting as a hinge between deeply buried and shallower parts of the Austroalpine basement before extrusion. The tectonothermal boundary of the Tauern window cannot be sharply defined along this hinge zone.

Like the tectonostratigraphic subdivision of the Tauern window, the tectonothermal definition also implies a complex internal structure and reveals that the window contains units that were exhumed from different crustal levels. The tectonothermal boundary of the Tauern window separates Cretaceous or Late Paleozoic mica ages outside the window from Oligocene–Miocene ages inside the window (Fig. 4e). Like in the eastern Rieserferner slab, this boundary is diffuse in the northeastern and northwestern corners of the window, where transitional zones are developed within the Lower Austroalpine unit as shown by mineral cooling ages (Slapansky and Frank, 1987; Dingeldey et al., 1997). From the metamorphic grade attained during Paleogene metamorphism it is clear that these parts of the window have been shallower than most if not all of the Penninic contents. However, as far known there is no major jump in metamorphic grade or mineral cooling ages between the Penninic and the Lower Austroalpine units. The Lower Austroalpine units take an intermediate position between the interior of the window and its high-level frame. The Lower Austroalpine units in the NW and NE corners of the window formed a coherent mass prior to the extension process but were disrupted along the Salzachtal fault.

Internal boundaries in the window defining units with contrasting late-Alpine cooling paths are not yet detected. However, the juxtaposition of sequences that experienced Paleogene high-pressure metamorphism prior to the Oligocene regional-metamorphic thermal peak, and sequences that lack the former but experienced the latter, also requires considerably differing cooling paths in the interior of the window. These differing cooling histories have been brought into line before the Oligocene thermal peak, i.e. well before the eventual exhumation of the window during the extrusion process (Christensen et al., 1994; Zimmermann et al., 1994).

6. Formation of the Tauern window as the result of large-scale extension

Based on models for the formation of metamorphic core complexes proposed by Wernicke (1981), Wernicke and Burchfiel (1982), Selverstone (1988), Hodges et al. (1987), Lister and Davis (1989), Snoke et al. (1990), Buck (1991), and John and Foster (1993) and many others, we undertake the attempt to sketch the kinematic procedure of the exhumation and the formation of the Tauern window. Important constraints are structural data, mineral cooling ages, and erosion mass balances for the time of exhumation as deduced from sediment accumulation rates in the foreland.

Owing to the gradients in crustal thickness and topography as well as available free space in the Intracarpathian (Pannonian) basin by retreating subduction, the flow direction of material during collapse and core complex formation was toward the east (Ratschbacher et al., 1991a). This implies asymmetry of the Tauern window structure during formation, which is recorded by the formation of intramontane basins only east of the window (Fig. 1a), by east-dipping high-angle normal faults in the hangingwall blocks above the master low-angle extensional shear zones (Fig. 6), and by systematically differing mineral cooling ages in the window interior (Fig. 4). The asymmetry is also mirrored by the preservation of pre-extrusion paleosurfaces east of the window (Fig. 1a; Winkler-Hermaden, 1957), whereas uplift and much deeper erosion affected most of the area west of it (Fügenschuh et al., 1997; Elias, 1998).

Although there is no direct dating of the period of main activity of the shear zones bounding the Tauern window, the Brenner extensional shear zone (BS) at the western boundary of the window is inferred to have formed in sequence to the Katschberg extensional shear zone (KS) (Fig. 6). This scenario is not only supported by the logic of the formation of an asymmetric core complex but also by the following reasons: differing apatite fission track age clusters within the Tauern window (Grundmann and Morteani, 1985; Staufenberg, 1987) show that Zentralgneis in the eastern part of the window was exhumed earlier than in the western part (Fig. 4a). We interpret this in terms of tectonic denudation starting in the eastern part of the later window by active eastward migration of Austroalpine tectonic blocks (Fig. 6). Unilateral syntectonic basin formation in the Austroalpine unit above the eastern detachment, the Katschberg shear zone (KS), and the different present-day erosion levels east and west of the window support this interpretation.

The geometries of the Brenner and Katschberg shear zones during their formation are inferred to be listric with high-angle dips in the brittle upper crustal levels and low-angle dips where they merge into the ductile Penninic level. The listric nature of the KS was also documented by a longitudinal seismic profile (Aric et al., 1987). The listric geometry of the KS is able to explain sedimentary basins as being formed as rollover structures at the trailing edge of the eastward moving blocks, but negative flower structures along sinistral strike-slip faults appear to be more frequent. The Tamsweg basin (Fig. 6) is interpreted to be a combination of both (Zeilinger et al., 1999). It contains local debris from the surrounding Austroalpine unit but no Penninic material and was brought into close vicinity to the exhuming Penninic window contents during its travel along the listric detachment zone. Today this basin is positioned within a few kilometers from the Penninic contact, the Penninic rocks rising about 2000 m above the Miocene basin fill.

The Ötztal-Silvretta block (Fig. 3) maintained a constant position in terms of longitude relative to the southernmost Molasse zone, where an alluvial fan received marker pebbles from a distinct source in the Silvretta mountains over a long period of time (ca. 23–13 Ma; Brügel, 1998). Therefore, we consider the Ötztal block as relatively fixed and assume that the hot and ductile Penninic material from beneath this block slipped eastwards along the Brenner shear zone (BS), thus exhuming during its travel (Fig. 6). This process, during which the Ötztal block played a passive role and was pushed up by the Southalpine indenter, is able to explain the lack of a rollover structure and the absence of sedimentary basins in the Ötztal block, as well as the Miocene heating of the central Ötztal block (underplated by the Penninic material) as recorded by reset apatite fission track ages (Elias, 1998). It also explains the systematic younging of mineral cooling ages from E to W in the western gneiss dome of the Tauern window (Fig. 4c; Raith et al., 1978). The Ötztal block maintained an elevated position of the basement above the BS. Neogene erosion in its eastern part was minimal. Zircon and apatite, within distances of a few kliometers from the BS, yield Paleogene (pre-extrusion) fission track ages (Fügenschuh et al., 1997); in the same region Paleozoic and Mesozoic sequences representing a high tectonic level in the nappe stack are preserved on top of the crystalline basement. In contrast, at greater distance (>20 km) from the BS the Ötztal block experienced surface uplift and erosion in Middle to Late Miocene time as documented by apatite fission track thermochronology (Elias, 1998). Uplift was enabled by the fragmentation of the Ötztal block along N–S trending, east-dipping high-angle normal faults and upward motion of the respective footwall blocks. Such faults are recognized in the eastern part of the Ötztal block (Fig. 6) but are probably more widespread. Vertical offsets there are on the order of several hundred meters.

Considerable E–W stretching in the Tauern window is indicated by a pronounced stretching lineation which is a dominant feature and shows constant orientation in space over large areas (Fig. 4e; Ratschbacher et al., 1989). Major deviation from the generally E–W trending stretching direction occurs only in the central part of the window, where a structural depression between the eastern and western gneiss domes caused flow deviation in the highly mobile schistose rocks between the more competent gneiss cores. The otherwise consistent orientation of the stretching lineation (forming a slightly arcuate structure) and its association with the dominant cleavage overprinting older structures and formed under falling temperatures indicate that they are associated with the late evolution of the Penninic rock sequences during exhumation.

The low-angle shear zones at the western and eastern boundaries of the Tauern window coincide with the Penninic/Austroalpine boundary along most of their extent in the presently exposed level. The Penninic/Austroalpine boundary represents the main detachment horizon during the extension process, into which the shear zones merged. This horizon is predestined for detachment due to the strong competence contrast between the largely brittle gneissic lithologies of the Austroalpine crystalline basement and the highly ductile schistose rocks of the upper Penninic levels. Mylonite horizons within the window, however, indicate that motion was partly distributed in the ductile level.

E–W stretching during the extension process not only disrupted the Austroalpine lid but also deformed and boudinaged the gneiss cores (Zentralgneis complexes) which are widespread in the window and form the lowest structural level exposed (Figs. 3 and 4). The gneiss cores consist of a complex suite of Variscan granitoids (Finger et al., 1993) and remainders of their roof preserved in synclinoria between individual granitoid bodies. Tertiary metamorphism and extensional deformation during exhumation strongly modified the shapes of the individual, originally approximately circular bodies to elongate gneiss cores (Lammerer and Weger, 1998). Stretching of the gneiss bodies was in an E–W direction (WSW–ENE in the western and WNW–ESE in the eastern part of the window), parallel to the prominent stretching lineation (Fig. 4e). The stretching process led to dekakilometric boudinage of the gneiss masses (Fig. 6), which we consider to have formed a complex but coherent Variscan batholith body (only schematically shown in the uppermost profile of Fig. 6). These mega-boudins form schist-mantled cores, well visible in map view (Fig. 4a). The necks between the gneiss boudins are filled with Penninic schistose material mantling the gneiss cores. The more competent Austroalpine gneisses do not trace the pinch and swell structures of the Zentralgneis unit. The mantling schists compensate for the boudinage of the gneiss cores.

According to apatite fission track ages (Staufenberg, 1987; Fig. 4a), the passage of the gneiss cores through the apatite partial annealing zone during exhumation did not occur simultaneously. The eastern core complex shows the oldest ages (14–12 Ma, normalized to the 1800 m elevation level) and therefore is considered to be the first having reached the surface (Fig. 6). These age data are in line with the first appearance of Zentralgneis pebbles in the Foreland Molasse around 13 Ma (Brügel, 1998). The earlier uplift of the eastern core complex conforms with the inferred in-sequence formation of the Katschberg and Brenner shear zones. The western core complex passed through the apatite partial annealing zone ca. 4–5 Ma later, while slipping from beneath the Ötztal unit which is reflected by systematically westward younging ages (Grundmann and Morteani, 1985). A small central gneiss core separated from the western core complex and shows still slightly younger apatite fission track ages.

The stretching process in the Tauern window was accompanied by continuing N–S convergence due to the northward motion of the Southern Alps and may have been also triggered by it. Evidence for the N–S convergence during exhumation of the Tauern rocks is the arching of the gneiss cores along E–W trending axes (parallel to the stretching lineation; Fig. 4e). Arching affects all stratigraphic horizons (e.g. the Zentralgneis/cover interface or marker lithologies; Fig. 4d), nappe boundaries (e.g. between Middle and Upper Penninic nappes; Fig. 4a), and the metamorphic isograds (Fig. 4e) and therefore occurred during the exhumation process. A good part of N–S shortening in the Tauern window during exhumation is therefore balanced by vertical extension. Arching started early during exhumation, since the arched isograds are cut by the extensional shear zones at the western and eastern window margins (Fig. 4e; Hoernes and Friedrichsen, 1974). On the other hand, arching must have been concomitant with rapid (tectonic) denudation, because adequate particle paths are impossible under several kilometers overburden in a purely compressional regime (Stüwe, 1997). Second-order folds prove that arching in fact occurred under a N–S compressional regime. Folds of decimeter- to hektometer-size accompany both flanks of the arches. They are south-vergent on the northern flanks and north-vergent on the southern flanks, thus indicating reverse motion along the flanks, i.e. N–S shortening (Frisch, 1977; Fig. 4d).

7. Rates of vertical and horizontal movements

In a pioneer work, England (1981) calculated from the sediment volumes in the circum-Alpine basins that an average of at least 15 km has been eroded from the Alps in post-Oligocene times. Kuhlemann et al. (1997) carried out a detailed study for the Eastern Alps and calculated eroded sediment volumes derived from this part of the orogen in 1 Ma intervals. Sediment volumes were recalculated to solid rock volumes, suspension and solution volumes removed from the system were estimated. According to this calculation, 225,000 km^3 of solid rock were eroded from the Eastern Alps in the last 34 Ma, which means an average removal by erosion of 3.5 km. These data highly contrast to the results of England (1981) but are in agreement with the fission track age pattern. Higher erosion rates, however, are to be expected from the Central and Western Alps, which are included in the study of England (1981).

If we accept that the duration of the extrusion process was about 10 Ma (23–13 Ma) and that Penninic rocks were exhumed from 15 to 20 km depth to the surface during this process, then an average exhumation rate of 1.5–2 mm/a results. This is 15–20 times the average erosion rate of 0.1 mm/a, calculated for the Eastern Alps since the beginning of the Oligocene. Extrusion was, however, by no means a process with constant rates of movement. During an inner time window of about 3 Ma duration (ca. 18–15 Ma), disintegration of the Austroalpine orogenic lid, connected to enhanced block movement and tectonic denudation of the Tauern window, led to a complete rearrangement of the tectonic and erosional/depositional situation in the extrusion channel (tectonic 'revolution'; Frisch et al., 1998).

During most of the extrusion period, the average erosion rate for the entire Eastern Alps dropped below 0.1 mm/a. We relate this drop mainly to lowering of the mean elevation of the orogen due to the gravitational collapse. However, with ca. 0.2 mm/a the average erosion rate shows a pronounced spike at 17 Ma (Kuhlemann et al., 1997). We interpret this erosional spike as an effect of updoming related to enhanced exhumation in the area of the later Tauern window. Tauern window denudation (tectonic and erosional) possibly exceeded 5 mm/a during a short period (1–1.5 Ma) around 17 Ma (Cliff et al., 1985), otherwise it remained around 1 mm/a during the extrusion period.

The mass balance in the sedimentary basins that received material from the Eastern Alps during the extrusion period shows that there is a considerable lack of material that could have been eroded from Austroalpine crystalline basement rocks above the Tauern window, which was already pointed out by Selverstone (1985). In the period from 23 to 13 Ma, about 54,000 km^3 of rock were removed from the

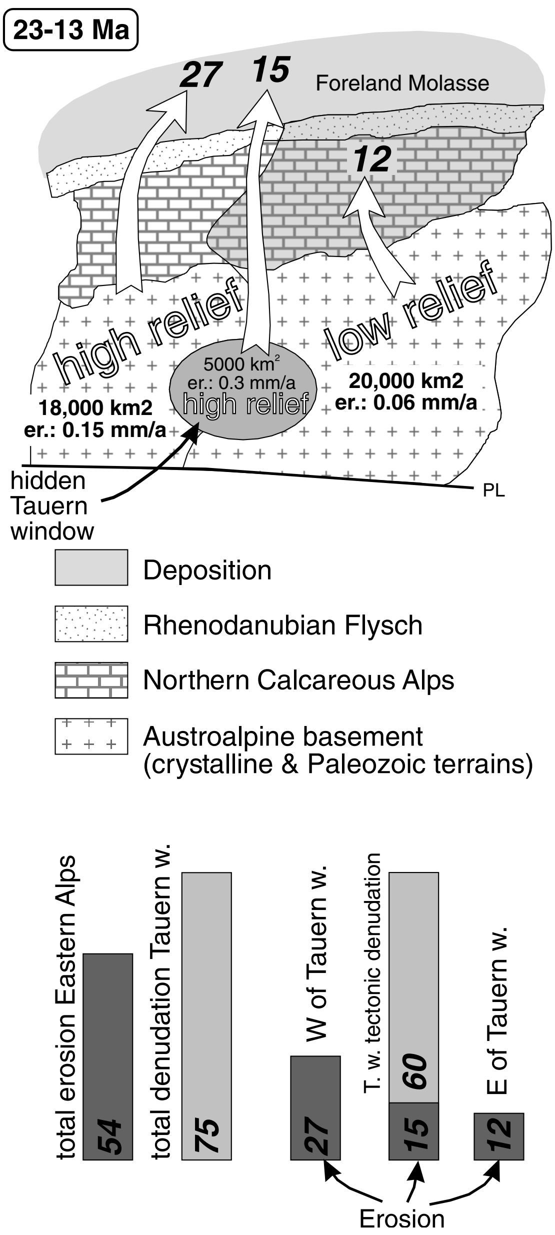

Fig. 7. Sedimentary mass balance for the entire Eastern Alps during the extrusion period (23–13 Ma) to address the question of tectonic versus erosional denudation of Tauern window. Sketch map shows: buried Tauern window (dark shaded ellipse); high relief area in Austroalpine basement W of Tauern window and in western Northern Calcareous Alps; low relief area in Austroalpine basement E of Tauern window; deposition areas in Foreland Molasse and on top of eastern Northern Calcareous Alps (for reconstruction of topographic relief and other details, see Frisch et al., 1998). Indicated are erosion areas in km^2 and erosion rates in mm/a estimated from fission track data and other geologic evidence. Columns at bottom show mass calculations for erosion and tectonic denudation. Bold italic numbers are 1000 km^3 of solid rock. T.w., Tauern window; er., erosion rate.

Eastern Alps (Fig. 7). During the same period, a minimum of 75,000 km^3 of Austroalpine lithotypes was removed from above the later Tauern window. If we accept, as an estimate based on zircon and apatite fission track geochronology, that during the same 10 Ma 27,000 km^3 with an erosion rate of 0.15 mm/a were eroded from the high-relief area W of the later Tauern window, and 12,000 km^3 with an erosion rate of 0.06 mm/a from the low-relief area E of the later Tauern window (for topograhic reconstruction, see Frisch et al., 1998, 2000), then only 15,000 km^3 or 20% of erosional removal remain for the Austroalpine lid above the Penninic units of the later Tauern window. Although there are several uncertainties in this calculation, the result, in principle, remains the same, if other input values are reliable: the great part of the removal of Austroalpine material above the Tauern window was by tectonic denudation, and erosion played only a minor role.

These calculations are in line with the tectonic reconstruction. Taking into account that part of the Austroalpine basement wedge beneath the Brenner and Katschberg low-angle shear zones escaped erosion due to southward tilt (Rieserferner slab; Fig. 4e), about 75–80% of the Austroalpine material above the Penninic units now exposed in the window were removed by tectonic processes.

The horizontal movement rates for the 160 km E–W pullapart of the Ötztal and Gurktal blocks in order to exhume the Tauern window average to 16 mm/a for the entire extrusion process. Total horizontal displacement along the listric shear zones have been about the same (ca. 80 km) for each shear zone for the part within the Austroalpine units. This is deduced from the transformation of the ca. 80 km lateral displacement of the Inntal fault into the Brenner extensional shear zone (see above), which therefore took up about half of the overall extension associated with the formation of the Tauern window. The relative displacement between Ötztal block and Zentralgneis unit was, on the other hand, less than this value, because of E–W stretching of the Zentralgneis unit in the order of 60% during the extrusion process. In our reconstruction, the movement of the western Zentralgneis core relative to the Ötztal block was in the order of 60 km, and that of the eastern Zentralgneis core relative to the Gurktal block in the order of 40 km (Fig. 6). Axen et al. (1995) estimated 33–63 km horizontal slip component for the Brenner shear zone.

The average pullapart rate of 16 mm/a was clearly also unevenly distributed throughout the period of extension. Since the exhumation rate of the Tauern rocks accelerated from about 1 mm/a to about 5 mm/a for a short period around 17 Ma (Cliff et al., 1985), it may be deduced that horizontal E–W directed pullapart rates around 10 mm/a or slightly above accelerated to several centimeters per year for a short period of enhanced block movement around 17 Ma.

8. Large-scale extension in the Eastern and Central Alps — part of a continent-scale extensional corridor

There remain two other Penninic exposures surrounded by Austroalpine units in the Eastern Alps: the Engadin window to the west of the Tauern window, and the Rechnitz window in the transition zone between Alps and Pannonian basin (Fig. 3a; for the latter, see Tari, 1996). None of them contains gneiss cores at the exposed level. We argue that the Engadin window is a place where the Middle Penninic gneisses, present as Zentralgneis cores in the Tauern window, have been pinched out by mega-boudinage, and Penninic schistose rocks accumulated. Seismic profiles suggest that the ophiolite bearing Mesozoic schistose rocks form a thick layer down to approximately 9 km depth, where Lower Penninic gneissic rocks and their cover form a flat-lying reflector (Fig. 6; Pfiffner and Hitz, 1997). The mode of formation of the Engadin window differs from that of the Tauern window in that it does not form a large core complex structure. According to its position at the NE-trending sinistral Engadin fault and its fault-parallel elongate shape, we suggest that it opened up at a sinistral overstep along the fault dissecting the Austroalpine basement (Fig. 3). The resulting pullapart structure led to uplift of the mainly schistose Penninic substratum. Erosion, therefore, played a minor role in the exhumation history of that window also.

Like in the Tauern window, the main (extensional)

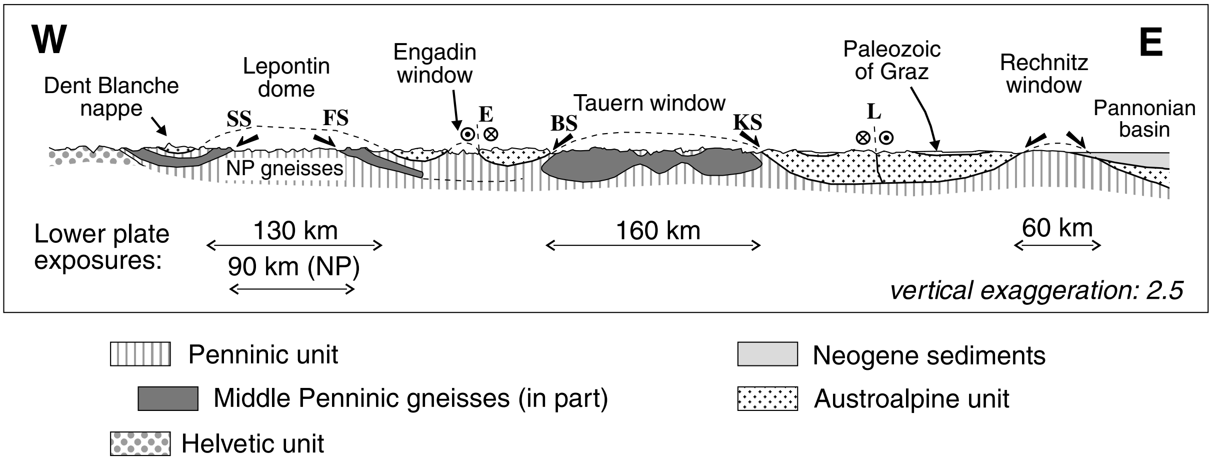

Fig. 8. W–E profile through the Central and Eastern Alps showing exposures of lower plate units by large-scale extension of upper plate. Length of profile ca. 850 km. SS, FS, BS, KS, Simplon, Forcola, Brenner, Katschberg shear zones; E, L, Engadin, Lavanttal fault. NP, North (Lower) Penninic.

detachment around the Rechnitz window is the Austroalpine/Penninic boundary at the presently exposed level (Figs. 3a and 8). The amount of pull-apart of the Austroalpine lid is in the order of 60–80 km (Tari, 1996). We consider the detachment plane continuous with that of the Tauern window. This view is in contrast to Tari (1996), who argue that the detachment of the Rechnitz window is unrelated to that of the Tauern window and reaches the surface at a certain mylonitic level within the Austroalpine unit. However, the proposed mylonitic shear zone at the base of the Paleozoic of Graz (Figs. 3a and 8) was geochronologically dated as Late Cretaceous (Frank et al., 1983). Therefore, ductile motion along this shear zone is clearly related to the Cretaceous orogenic event that affected the Austroalpine realm. Ratschbacher et al. (1991b) related the top-to-E movement along this shear zone to extensional movements in response to Cretaceous, intra-Austroalpine nappe stacking.

The formation of the Rechnitz window (Dunkl and Demény, 1997; Dunkl et al., 1998) and the Tauern window occurred simultaneously. The Rechnitz window was nearly entirely denuded by tectonic processes, since during the most important part of the extrusion process (ca. 18–15 Ma) sediments were deposited on top of the structure. Erosion, therefore, can only have played a role in the early stages of its formation and was, at that time, subordinate due to the low relief of the region. This was probably enabled by the existence of an active continental margin above a retreating subduction zone (Royden et al., 1982) to the east of the window, and the submarine topographic gradient connected hereto.

The internal zone of the Central Alps shows another large-scale metamorphic domal structure, the Lepontin gneiss dome (Figs. 3a and 8), in which recumbent Penninic basement gneiss nappes, separated by thin veneers of Mesozoic schists, are arranged in two subdomes. Middle Penninic gneiss nappes are separated from Lower (North) Penninic gneiss nappes by large-scale extensional shear zones, but extension was more distributed and also affected higher levels up to the base of the Austroalpine unit (e.g. Schmid et al., 1989; Ring et al. 1991). There appears to be a general younging of the activity along the extensional shear zones from higher to lower structural levels (Nievergelt et al., 1996).

The most prominent low-angle extensional shear zone within the Central Alps is the Simplon low-angle extensional shear zone (SS; Figs. 3a and 8; Mancktelow, 1985). This shear zone, concerning its mode of motion, its importance in post-collisional history, and age, has recently been correlated with the Brenner low-angle extensional shear zone (Selverstone, 1988; Mancktelow, 1997). The SS, however, is exposed at a deeper structural level as compared to the Brenner shear zone, in that it has an intra-Penninic

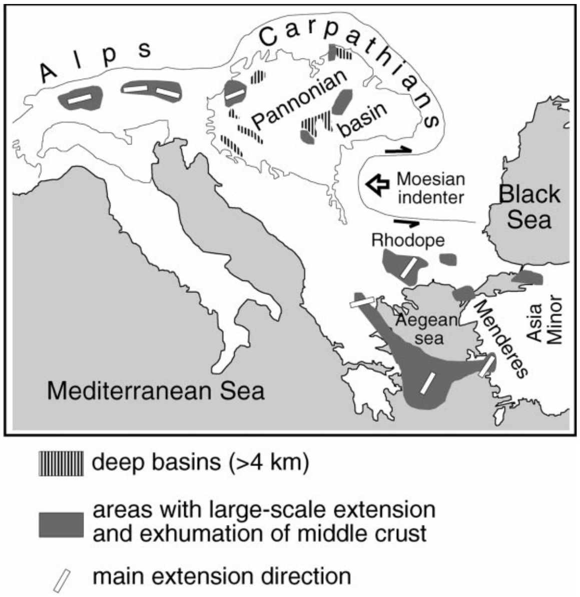

Fig. 9. Extensional provinces in the Alpine Pannonian and the Rhodope-Aegean-Menderes regions. Sketch shows areas with large-scale extension and exhumation of middle crust as well as deep basins formed during Early and Middle Miocene times. Main extension directions are indicated. The provinces are separated by the westward moving Moesian indenter (Kázmér and Dunkl, 1997).

position separating the Lower Penninic gneiss nappes attributed to the North Penninic realm, from Middle Penninic gneiss nappes (Figs. 3a and 8). Displacement along the SS is top-to-WSW (Steck and Hunziker, 1994), similar to that of the BS. According to Hubbard and Mancktelow (1992) and Mancktelow (1997) the main phase of activity of the SS was around the Early/Middle Miocene boundary (ca. 18–15 Ma). The counterpart of the SS on the eastern flank of the Lepontin dome appears to be the Forcola extensional shear zone (FS) with top-to-E displacement (Figs. 3a and 8). Higher shear zones like the Turba mylonite zone with the same mode of movement appear to be older (Oligocene) and are related to early stages of updoming and extension (Nievergelt et al., 1996).

The Simplon and Forcola shear zones are flanking the Lower Penninic Lepontin gneiss dome to the W and E, respectively, and encounter an area with the youngest mineral cooling ages (Hunziker et al., 1992). Across both fault zones cooling ages show jumps. The fault zones display a maximum of 90 km pullapart of the Middle Penninic gneiss units above the exhuming core of the Lepontin dome. The relation of the detachment between Lower and Middle Penninic units on the E and W flanks of the Lepontin dome to the detachment between Penninic and Austroalpine units on the E and W flanks of the Tauern dome remains unclear. The overall Austroalpine pullapart above the Lepontin dome is probably larger than 100 km. Recent geochronologic data suggest that major displacement in Penninic lithologies at or near the base of the Austroalpine unit on both flanks of the dome are of Paleogene age (Nievergelt et al., 1996; Butler et al., 1997). Therefore, Miocene extension appears to concentrate on the intra-Penninic level in the Central Alps.

As in the Tauern window, the eastern subdome of the Lepontin gneiss dome reveals older mineral cooling ages than the western subdome (e.g. Schmid et al., 1989; Steck and Hunziker, 1994). We therefore propose a similar mode of formation of this large dome as for the Tauern window, with possibly older generation of large-scale extensional shear zones on the eastern flank than on the western flank of the dome.

Fig. 3b shows the attempt of a palinspastic reconstruction of the internal part of the Central Alps for the period before the formation of the Lepontin dome. As a consequence, the restored shape of the Central Alps is changed considerably, and the crystalline basement massifs of the Helvetic zone, the structurally lowest mega-unit of the Alps, are also changed in their position relative to the Penninic and Austroalpine units of the Eastern Alps. The Aar massif (Fig. 3) comes much closer to the Zentralgneis unit of the later Tauern window. The close relationship of both units during the Mesozoic evolution was repeatedly emphasized (Frisch, 1977; Lammerer, 1986). At the junction between the Periadratic lineament and the Simplon shear zone, a triple point evolves whose kinematic geometry is shown in Fig. 3a (inset). A very similar triple junction exists in the analogous place of the Tauern window, where the Brenner shear zone joins the Periadriatic lineament.

As pointed out by Schmid et al. (1989), the Lepontin dome and the Tauern window are both situated in front of a north(west)ward protruding Southalpine indenter. We therefore suggest that continuing convergence between the Adriatic plate and the

European foreland has an important triggering function for the escape of crustal blocks in E–W direction and the large-scale extension in the Central and Eastern Alps. During indentation, the Southalpine block broke apart into two major pieces separated by the Giudicarie line. The Insubric indenter (Schmid et al., 1989) to the west caused the large-scale extension in the Central Alps, the Dolomites indenter (*nomen novum*) to the east caused the large-scale extension in the Eastern Alps (Fig. 3a).

In conclusion, the three large-scale extensional features in the Central and Eastern Alps (Lepontin, Tauern and Rechnitz domes; Fig. 8) exhumed ductile material from mid-crustal levels by pullapart of the brittle layer. E–W extension of the brittle layer amounts to more than 300 km between the Dent Blanche Austroalpine klippe and the Pannonian basin. All three domes were formed in Lower and Middle Miocene times. Overall stretching along this E–W trending segment of the Alpine chain, now 750 km long, was in the order of 70–90%. This means that the predominating E–W stretch of the Alps is a young, post-collisional artifact. Prior to Miocene large-scale extension, the Alps were not elongated in an E–W direction, but rather showed a SW–NE arrangement of tectonic elements. This is in line with the present distribution of the three mega-units of the Alps: The lowest, Helvetic mega-unit, is broadly exposed in the Western and Central Alps. The highest, Austroalpine mega-unit, on the other hand, is an East-Alpine feature where it covers most of the area, originally extending far into the Central Alps, where it had its (probably SW–NE trending) front (Fig. 3b).

The metamorphic domes in the Central and Eastern Alps are not isolated features. We draw attention to the fact that metamorphic core complexes of Early to Middle Miocene age are a widespread feature in SE Europe as far east as Asia Minor (Fig. 9). The core complexes in the Alps are genetically connected with metamorphic domes and deep sedimentary basins in the Pannonian region (Tari, 1996; Dunkl and Demény, 1997), in which Miocene E–W extension was on the order of 200 km. We suggest a genetic relationship to another large-scale extensional province in the Rhodope–Aegaean–Menderes region, where a large number of core complexes formed under an E–W to NNE–SSW extensional regime during the same period (e.g. Lister et al., 1984; Bozkurt and Park, 1994; Gautier and Brun, 1994; Hetzel et al., 1995). The Alpine-Pannonian and Rhodope–Aegaean–Menderes extensional provinces are separated by a zone without large-scale extensional features in front of the westward moving Moesian indenter (Fig. 9; Kázmér and Dunkl, 1997).

The Miocene extension in the Alps nearly reached the same magnitude as the overall extension across the Basin-and-Range province (ca. 100% extension, present E–W distance ca. 700 km; Hamilton, 1987), but by far not its areal extent. The entire extensional region from the Alps to the Menderes Massif, however, is in fact of continental dimension. We interpret the extension as the response to overthickening of crust due to preceding (Paleogene) crustal stacking. Lateral material flow was enabled by unconstrained margins in the Pannonian basin and the Eastern Mediterranean basin.

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