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Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion

Wolfgang Frisch *, Joachim Kuhlemann, István Dunkl, Achim Brügel

Institut für Geologie und Paläontologie, Universität Tübingen, Sigwartstrasse 10, D-72076 Tuebingen, Germany

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Abstract

This paper presents a new palinspastic restoration of the Eastern Alps for Neogene time and an attempt to reconstruct the Neogene palaeogeology, palaeotopography and palaeohydrography in connection with the structural evolution. The Eastern Alps underwent radical horizontal displacement during the Neogene due to large strike-slip systems and formation of structural windows. Our *palinspastic reconstruction* considers: (a) the rearrangement of tectonic units dismembered during tectonic extrusion, (b) the tectonic denudation driven by displacement of the crystalline blocks, (c) geochronological arguments, and (d) the sedimentary record of the syn-extrusion basins. The rearrangement of tectonic blocks results in a remarkably good fit of highly dismembered zones both in crystalline and sedimentary areas and shows the pre-Miocene unstretched pattern of the Eastern Alps, reduced to 65% of its present-day E–W elongation. Using this structural frame and considering the sedimentary record, a set of *palaeogeologic and palaeotopographic sketch maps* with the palaeo-river systems is presented for three time slices (pre-, syn- and post-extension situation). In *Late Oligocene* and Early Miocene times, the western Eastern Alps were already mountainous, whereas the eastern part of the orogen formed lowlands or hilly areas. Enhanced block movement in the course of the extrusion process around the *Early/Middle Miocene* boundary led to the formation of intramontane sedimentary basins and a fault-induced reorientation of the drainage pattern, which forms the basis of the modern river system in the area east of the Tauern window. This region, where pre-Miocene land surfaces are preserved, probably became a mountainous area not before *Late Miocene* time and never reached the elevations of the areas further west. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

A fundamental topographic difference between the Central (mainly Swiss) Alps and the Eastern (mainly Austrian) Alps is that the Central Alps generally display high relief as well as high mean and maximum elevations, while in the Eastern Alps these parameters are systematically decreasing from west to east (Fig. 1b). The Central Alps comprise a large number of peaks >4000 m in altitude in all geologic mega-units (the Helvetic, Penninic, and Austroalpine domains), whereas the Eastern Alps remain below 4000 m. We consider these differences in land surface features as the immediate expression of Miocene to Recent tectonics which is characterized

* Corresponding author. Tel.: +49 7071 2972 493; Fax: +49 7071 5059; E-mail: frisch@uni-tuebingen.de

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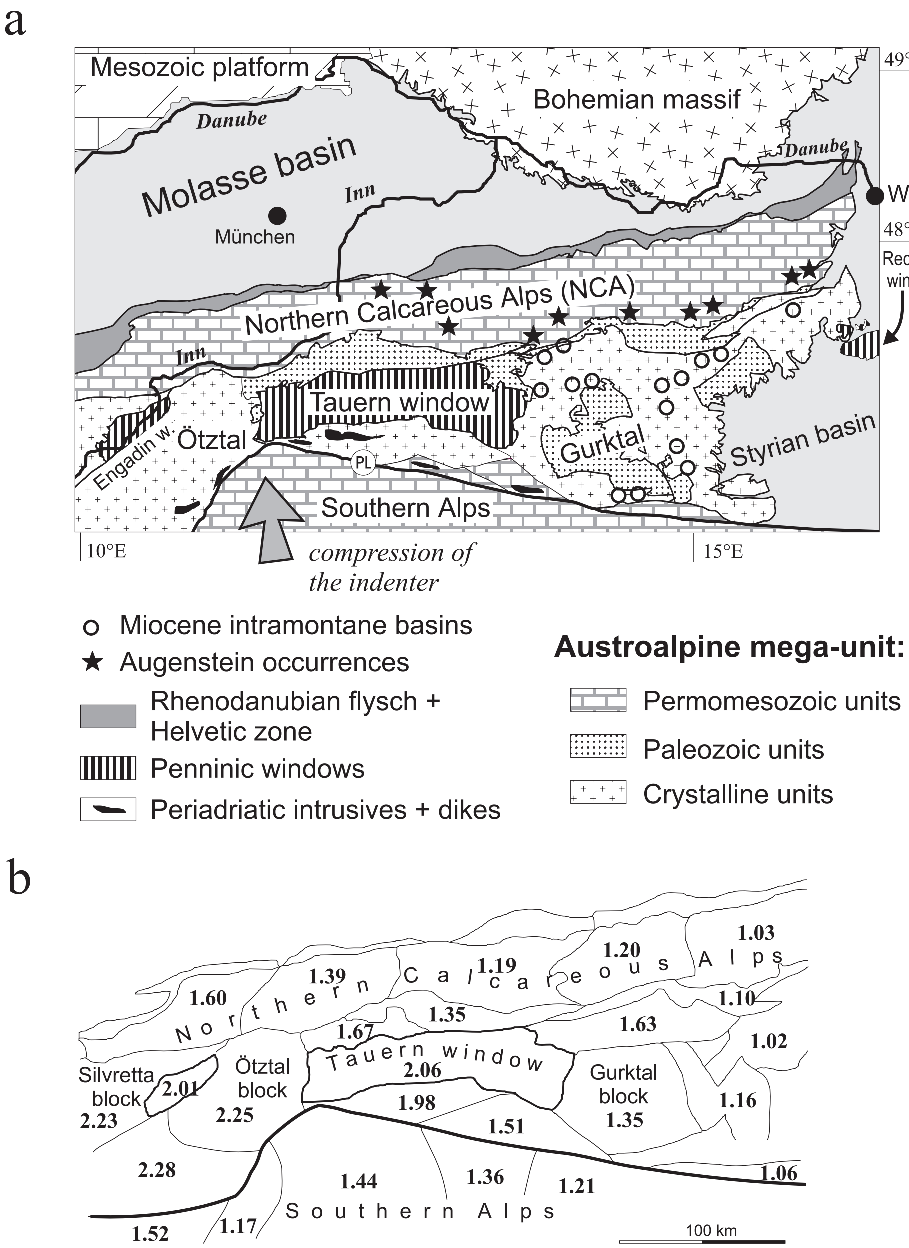


Fig. 1. (a) Simplified geologic map of the Eastern Alps. Also shown are locations of Miocene intramontane basins and probably Late Oligocene to Early Miocene Augenstein occurrences. *PL* = Periadriatic lineament. (b) Mean present-day elevations (in km) of different blocks in the Eastern Alps and the eastern Southern Alps.

by ongoing crustal thickening in the Central Alps and the westernmost Eastern Alps (Marchant, 1993; Schmid et al., 1996) and lateral extrusion tectonics in the Eastern Alps east of the Brenner line (Fig. 2a).

Late Tertiary lateral tectonic extrusion in the Eastern Alps (Ratschbacher et al., 1991) is a combination of gravity-driven orogenic collapse and crustal escape driven by tangential forces. During lateral tectonic extrusion, material from the thickened and thermally equilibrating crustal wedge of the Eastern

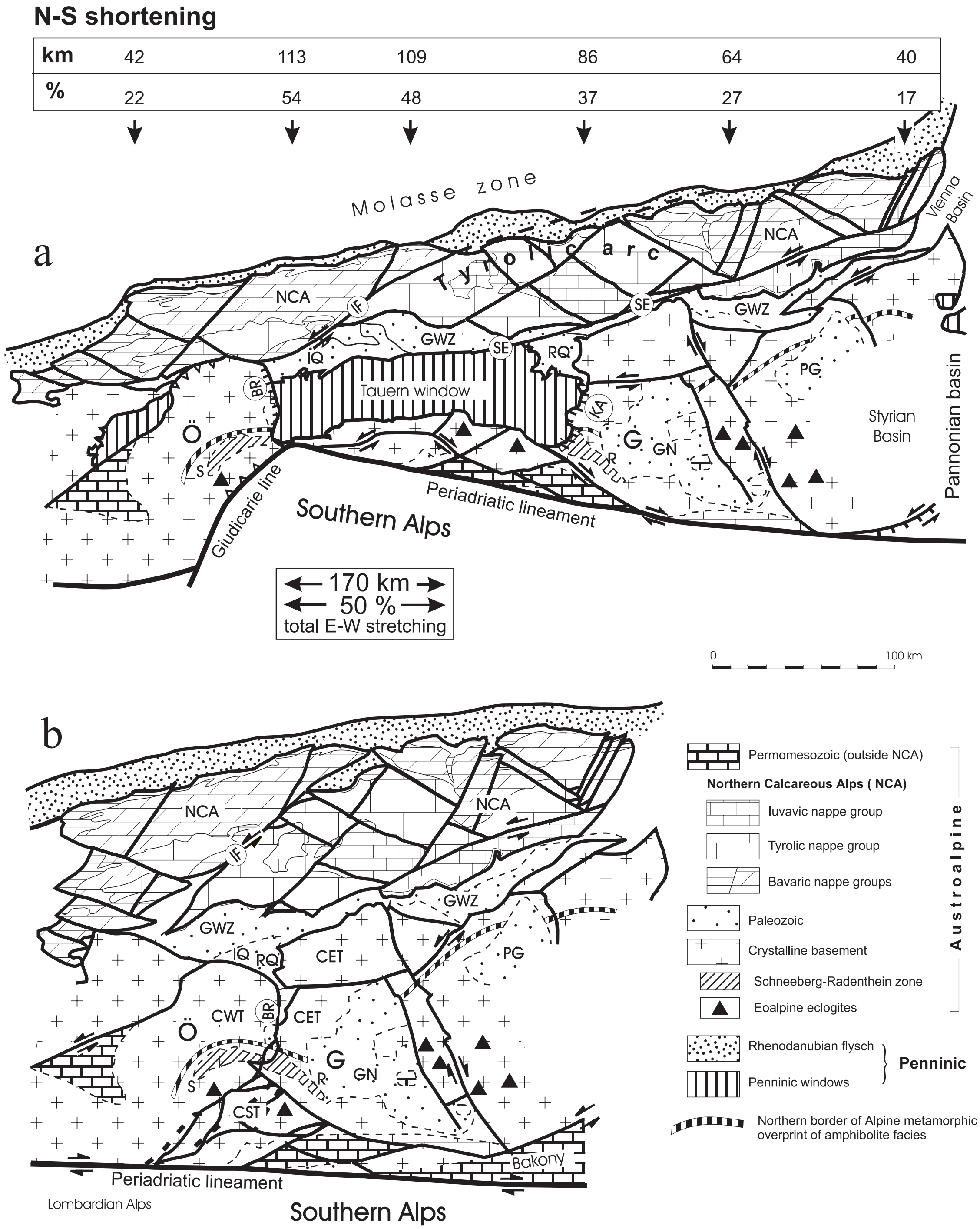


Fig. 2. (a) Geologic–tectonic map of the Eastern Alps and (b) palinspastic reconstruction of the pre-extrusion situation in Oligocene time around 30 Ma. Values (in km and percent) for post-Oligocene E–W extension as well as N–S shortening between Periadriatic lineament and northern boundary of NCA are shown. *Ö*, *G* = Ötztal and Gurktal blocks; *NCA* = Northern Calcareous Alps; *GWZ* = Greywacke zone; *GN* = Gurktal nappe; *GP* = Palaeozoic of Graz; *IQ*, *RQ* = Innsbruck and Radstadt quartzphyllite areas; *CWT*, *CST* = *CET* = Austroalpine crystalline basement west, south, and east of Tauern window; *S*, *R* = Schneeberg and Radenthein zones; *IF* = Inntal fault; *SE* = Salzachtal–Ennstal fault; *BR*, *KA* = Brenner and Katschberg lines (low-angle extensional shear zones).

Alps migrated eastward along the extrusion channel between the Southalpine indenter and the northern foreland (Fig. 1). Crustal stacking and additional thickening by the indentation of the relatively rigid Southalpine block, with the Bohemian massif forming a high-strength buttress, caused gravitational collapse in the Eastern Alps and crustal flow towards the eastern unconstrained margin where a retreating subduction zone in the Carpathians (Royden et al., 1982) created space in the Pannonian basin. Crustal escape of wedge-like blocks towards the east along conjugate master and minor fault zones enhanced the eastward motion (Fig. 2a).

The concept of lateral extrusion is in agreement with both differences in crustal thickness and the actual topographic pattern of the Eastern Alps. The eastward decrease in elevations in the extrusion area goes conform with crustal thinning and reflects details of the extrusion process. Lateral extrusion therefore plays the most important role in shaping the actual surface of the Eastern Alps.

Lateral extrusion mainly occurred in Early and Middle Miocene time (ca. 23–13 Ma) and followed Eocene–Oligocene collision and nappe stacking. During collision the Austroalpine mega-unit was thrust over the Penninic units which contain ophiolite remnants from the Penninic ocean formed in Jurassic time. The Penninic units of the Eastern Alps are exposed along the northern margin of the orogen (Rhenodanubian flysch) and in windows along its central axis (Fig. 1a). Geochronologic data from the lower-plate Penninic rocks in the Tauern window constrain their Oligocene thermal peak and rapid Miocene exhumation starting under highly ductile conditions (see Genser et al., 1996). In contrast, the Austroalpine realm behaved essentially rigidly in Tertiary time. Differential vertical movement paths in the Austroalpine unit are revealed by Miocene and Palaeogene apatite fission track data, respectively (Fügenschuh, 1995; Hejl, 1997). Thrusting of the orogenic body onto the molasse foreland was mainly completed in Early Miocene time (Steininger et al., 1986). Hence, there is probably only little overlap in time with tectonic extrusion.

This paper discusses late Tertiary movements of tectonic blocks of the Eastern Alps and the evolution of the topographic and drainage pattern of the mountain range. We present a new palinspastic restoration of the Eastern Alps for pre-extrusion (Late Oligocene) times and discuss the changes during the extrusion period, in which the denudation of the Tauern window played a key role. Late Oligocene and Miocene palaeogeologic sketch maps, showing also topographic and hydrographic features, are presented for the first time. Our reconstructions are based on field and literature data on post-collisional tectonics, the sedimentary record in the molasse and intramontane basin deposits, and geochronologic data including fission track ages. For stage nomenclature and absolute ages we use the Paratethys time scale (Steininger et al., 1990).

2. Behaviour of tectonic blocks during lateral extrusion

The extrusion area is characterized by the segmentation of the Austroalpine mega-unit into a number of tectonic blocks (Fig. 2a). The Austroalpine realm is composed of pre-Alpine crystalline basement, low-grade metamorphic Palaeozoic terrains (e.g., Greywacke zone, Gurktal nappe, Palaeozoic of Graz), and post-Variscan (mainly Mesozoic) cover sequences (e.g., Northern Calcareous Alps) (Fig. 1a, 2a). The western boundary of the extrusion wedge is marked by the Inntal fault which dissects the Northern Calcareous Alps, and the Brenner low-angle extensional shear zone which forms the western boundary of the Tauern window (Fig. 1a). In the following, we examine the behaviour of different zones in the Eastern Alps during lateral tectonic extrusion (Fig. 2).

2.1. Tauern window

In the Penninic Tauern window, peak pressures ($\geq$1 GPa) of Alpine metamorphism were reached in about Eocene time, and peak temperatures 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 (‘Zentralgneis’). Apatite fission track ages calculated to the 1000 m level are in the range of 14–7 Ma in the eastern and 12–5 Ma in the western part of the window (Grundmann and Morteani, 1985;

Staufenberg, 1987). Exhumation in the Tauern window with average rates in the order of 1–2 mm/a was largely by tectonic denudation during the Miocene, as indicated by structural, geochronologic, and thermobarometric data (Cliff et al., 1985; Grundmann and Morteani, 1985; Staufenberg, 1987; von Blanckenburg et al., 1989; Inger and Cliff, 1994). The western and eastern borders of the window are marked by large-scale low-angle extensional shear zones, the Brenner and Katschberg shear zones, respectively (Fig. 2a; Behrmann, 1988; Selverstone, 1988; Genser et al., 1996). Ottnangian to early Badenian (ca. 18–15 Ma) sediments in the intramontane basins, including basins in the immediate vicinity of the eastern window boundary (Fig. 1a), still lack pebble material derived from the Penninic contents of the Tauern window (Exner, 1949). We consider the first candidates from the Tauern window to be serpentinite and gneiss pebbles contained in conglomerate fans of the Molasse zone from about 13 Ma onwards.

2.2. Pull-up structure west of the Tauern window

In front of the tip of the Southalpine indenter the continuing collisional N–S contraction prevailed throughout the extrusion period. As a result, the Ötztal block formed a pull-up structure characterized by divergent thrusting with an out-of-sequence thrust onto the Northern Calcareous Alps (Linzer et al., 1995) and a backthrust onto the Southalpine block (Doglioni, 1987). Tectonic pull-up is reflected by the highest mean elevations, the largest area with peaks >3000 m altitude, and the highest relief of the Eastern Alps (up to 3000 m). Apatite fission track data (Elias, 1998) and conglomerates with distinct lithologies in the Molasse basin confirm Middle to Late Miocene exhumation and uplift of the central and western parts of the Ötztal block. An eastward tilt and/or N–S-trending normal faults with downthrown eastern blocks enabled a higher structural level to be preserved near the eastern margin of the Ötztal block. This is indicated by remnants of Mesozoic cover sequences and pre-Miocene apatite fission track ages (Fügenschuh, 1995). We interpret these data in terms of fragmentation and rotation above the west-dipping listric Brenner low-angle extensional shear zone, which separates the Ötztal block and the Tauern window (Fig. 2a; Behrmann, 1988; Selverstone, 1988).

2.3. Collapse structures east of the Tauern window

The Austroalpine basement area east of the Tauern window is characterized by eastward motion, block segmentation along conjugate strike-slip fracture zones (Fig. 2a), and dilatational features like grabens and pull-apart basins filled with Miocene sediments. Individual block paths are also manifested by differential exhumation and uplift. In the area east of the Tauern window E–W extension was more prominent and N–S contraction relatively less important as compared to the area west of the Tauern window. Over a distance of ca. 200 km crustal/lithospheric thicknesses decrease along strike of the orogen from about 50/170–220 km at the eastern edge of the Tauern window to about 27/60 km in the western Pannonian basin (Babuška et al., 1990; Ratschbacher et al., 1991). The systematic decrease in present-day mean elevations from west to east (Fig. 1b), together with an increasing number of syntectonic sedimentary basins towards the east, lined up along the mostly transtensional fault zones, reflects the accelerating eastward migration of individual blocks.

2.4. Lozenge-shaped blocks south of the Tauern window

The Austroalpine basement south of the Tauern window is dissected by ENE-trending sinistral and ESE-trending dextral faults. This results in lozenge-shaped tectonic blocks which are interpreted to have migrated eastward relative to the Ötztal block (Fig. 2). Some of the faults, in addition to their lateral displacement, display prominent vertical throws, the northern block being upthrown relative to the southern block. This is evidenced by jumps in mica cooling ages (Borsi et al., 1978). During extrusion tectonics, the northern blocks, closer to the Tauern window margin, were exhumed from greater depths than blocks further south, which experienced only limited exhumation as also indicated by the preservation of Mesozoic cover rocks (Fig. 2a) representing a high level in the Austroalpine domain.

2.5. Northern Calcareous Alps (NCA)

The NCA experienced the same overall E–W extension as the central crystalline zone to its south

(Fig. 2). They are an integral part of the extrusion channel, together with the Rhenodanubian flysch zone along and beneath their northern margin. The northern margin of the extrusion channel is an indefinite zone positioned in the southern Molasse trough, where sedimentation occurred contemporaneous with the extrusion process. The NCA are dissected by a great number of strike-slip faults created or reactivated during lateral extrusion. The resulting, often lozenge-shaped blocks (Fig. 2) carried out individual movements, mostly differential horizontal translations but also pull-ups and tilts (Linzer et al., 1995; Peresson and Decker, 1997). The Inntal fault, with a sinistral displacement in the order of 75 km, is responsible for a major part of the overall E–W extension in the NCA. In the NCA, there is again a general trend of decreasing present-day elevations towards the east, but this pattern is influenced by lithologic differences and pre-extrusion tectonic features.

2.6. Southern Alps

The eastern part of the Southern Alps (east of the Giudicarie line; Fig. 2a) acted as an indenter to the Eastalpine orogen (Ratschbacher et al., 1991). However, they also experienced considerable E–W extension. This is evidenced by lozenge-shaped blocks that moved along conjugate fault systems, total eastward migration of blocks increasing in an eastward direction. The Periadriatic lineament, which separates the Eastern Alps from the Southern Alps, therefore did not separate domains showing completely different mechanical behaviour. We argue that the eastern Southern Alps formed a broad transition zone between the proper extrusion channel in the Eastern Alps and the interior of the Adriatic plate, the proper indenter.

3. Palinspastic restoration of the pre-extrusion situation

For the pre-extrusion palinspastic reconstruction we choose the time around 30 Ma (Oligocene) as this time is: (1) near the thermal peak in the Penninic domain of the Tauern window (von Blanckenburg et al., 1989; Inger and Cliff, 1994), thus giving the lower-plate Penninic material maximum ductility as an important prerequisite for gravitational collapse (Ratschbacher et al., 1991; Genser et al., 1996); (2) near the start of substantial mountain uplift and of transport of important volumes of coarse (pebble-sized) clastic material from the western Eastern Alps into the Molasse basin at the base of the Egerian (= base of the Chattian) stage (ca. 29 Ma) (Schiemenz, 1960). This uplift creates a topographic gradient as another prerequisite for the collapse.

For the palinspastic restoration (Fig. 2b) we were guided by two lines of thought:

(1) The Tauern window, a 160 $\times$ 30 km large structure, plays a key role for the extrusion mechanism. Highly differing cooling histories within the window and in its immediate frame (Fügenschuh, 1995; Genser et al., 1996; Hejl, 1997) prove that the Tauern window was exhumed by tectonic rather than erosive denudation. Erosion alone is an insufficient mechanism to remove ca. 20 km of cover above the Tauern window in the time given (ca. 10 Ma) and to account for the rapid exhumation in Early to Middle Miocene times that may have attained values as high as 50°C/Ma or 3.6 to >5 mm/a (Cliff et al., 1985; von Blanckenburg et al., 1989). Crystalline material that may have derived from the Austroalpine lid above the Tauern window is not contained in the syngenetic sedimentary basins in adequate proportions to explain denudation purely by erosion.

(2) The palinspastic restoration can be performed by the rearrangement of the present puzzle of the Austroalpine crystalline basement blocks, since they behaved as rigid elements (with only minor internal deformation) during lateral extrusion. Erosion rates in these basement blocks were generally low or moderate in Neogene time as indicated by apatite fission track data (Fügenschuh, 1995; Hejl, 1997). The restoration should result in a coherent Austroalpine basement mass that completely covers the Tauern window in its retrodeformed shape. The Penninic Tauern window was highly ductile at that time and experienced stretching in an E–W direction parallel to the last and dominating stretching lineation and to the flow direction during tectonic extrusion. The overall good fit of the palinspastic restoration confirms the validity of these lines of thought.

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 (Fig. 2b). It shows that the Ötztal and Gurktal blocks, now 160 km apart (Fig. 2a), fit together, thus covering the Tauern window. Normal movement along the Brenner line was transformed into large-scale sinistral movement along the Inntal fault in the Northern Calcareous Alps (NCA) and into dextral movement along the Periadriatic lineament (Fig. 2a). The importance of normal faulting by forming N–S-striking graben structures was limited in the area east of the Tauern window, but increased further east under the Miocene cover of the Pannonian basin.

The restoration (Fig. 2b) results in a convincing fit of geologic features and lithotectonic zones that were disrupted in the course of extrusion tectonics:

(a) The polymetamorphic (Variscan and Alpine) Austroalpine crystalline basement forms a coherent body in the restored puzzle. Within this body, the Schneeberg and Radenthein zones form a single coherent belt (Fig. 2); these zones are characterized by similar rock sequences and an amphibolite-facies grade monometamorphic Alpine history (Schimana, 1986). The eo-Alpine (Cretaceous) metamorphic zonation with greenschist, amphibolite, and eclogite facies zones also restores to continuous belts (Fig. 2).

(b) Terrains of Palaeozoic low-grade metamorphic sequences disrupted by the sinistral Salzachtal–Ennstal fault (Fig. 2a) give coherent bodies after retrodeformation along the fault. This applies to the Greywacke zone (the immediate basement to a part of the NCA) as well as to the Innsbruck and Radstadt quartzphyllite zones (both part of the Palaeozoic basement of the 'Lower Austroalpine' tectonic unit in the frame of the Tauern window). The latter are associated with Mesozoic sequences (not shown in Fig. 2) and were still buried beneath higher Austroalpine units at that time. The Palaeozoic sequences contain a good part of soft rocks with quasi-ductile behaviour during tectonic extrusion.

(c) Good fit of the internal nappes of the Northern Calcareous Alps is achieved by large-scale retrodeformation along the Inntal and Salzachtal–Ennstal master faults. The 'Tyrolic arc' in the central part of the NCA, where more internal (Tyrolic) nappes protrude to the northern front of the NCA, divides the lower (Bavaric) nappe groups in a western and an eastern domain (Fig. 2a). Our reconstruction allows for a continuous belt of the Bavaric nappe groups and also results in a better fit of the Tyrolic nappe group on both sides of the Inntal fault (taking into account that the present nappe boundaries are erosional which explains minor misfits). The highest (Iuvavic) nappe group also forms a more coherent terrain in the restoration.

(d) The Penninic Rhenodanubian flysch zone along the northern margin of the Eastern Alps is disrupted in the surroundings of the Inntal fault (75 km sinistral displacement). Although we suppose decoupling between the NCA and their highly incompetent Penninic substratum, the latter also experienced considerable E–W stretching.

(e) The Periadriatic lineament, in its present course disrupted (and blocked) by the Giudicarie fault along the western border of the Southalpine indenter tip, restores to a straight line allowing for considerable strike-slip movement (ca. 100–150 km dextral displacement in pre-Miocene time) (see Bögel, 1975). According to Kázmér (1984), we place the Bakony mountains from western Hungary into the open wedge south and southeast of the Gurktal block (Fig. 2b). The Bakony mountains are known for their Jurassic facies relations to the Lombardian Alps in the western Southalpine domain. In our restoration, both domains come in close neighbourhood.

Our reconstruction results in 50% or 170 km extension in E–W direction for the entire Eastern Alps since the onset of extrusion (Fig. 2). The separation of the Ötztal and Gurktal blocks is responsible for a good part of the overall extension in the Austroalpine basement. A similar major role is taken by the Inntal fault in respect of extension in the NCA. Minor amounts of E–W stretching are attained by graben structures and lozenge-shaped escape blocks. The escape blocks east of the Tauern window have largely transtensional border faults, ornamented with pull-apart basins. The post-collisional convergence between the Adriatic plate and the European foreland was compensated by E–W extension in the area east of the meridian of the (later) Tauern window, where vertical shortening also played an important role (Ratschbacher et al., 1991). West of the Tauern window, N–S convergence resulted in vertical extension and the formation of the Ötztal pull-up.

The N–S contraction during tectonic extrusion can also be quantified from our palinspastic reconstruction. The approximate Miocene shortening in N–S direction for the Eastalpine body between the Periadriatic lineament and the northern margin of the NCA is shown in Fig. 2 for different meridians; an additional amount of shortening in the order of 10 km along the Alpine front (southernmost Molasse zone; Wagner, 1996) has to be added. West of the Brenner line, i.e., west of the extrusion wedge, Miocene shortening within the Eastalpine body was moderate, ca. 22% or 42 km, which is somewhat higher than the value (15 km) derived for a section near the Central/Eastern Alps boundary by Schmid et al. (1996). The difference is due to considerable N–S shortening and E–W stretching in the (western) NCA (Fig. 2), whereas Schmid et al. (1996) calculated the Neogene shortening north of the Periadriatic lineament from the Helvetic basement, a structurally much deeper tectonic unit which was decoupled from the Austroalpine realm by the intermediate ductile Penninic suite.

Further east, in front of the tip of the Southalpine indenter, shortening was most intense (54% or 113 km). The northward protrusion of the Southern Alps is not reflected along the northern front of the Eastern Alps, the resulting high value of N–S shortening is compensated by E–W extension along the Brenner and Katschberg low-angle extensional shear zones and the Inntal strike-slip fault zone as well as by vertical extension. From the meridian of the indenter tip toward the east, Miocene N–S shortening systematically decreased to a value of 17% or 40 km near the eastern margin of the Alps. This goes along with crustal thinning, i.e., vertical shortening, in the area east of the Tauern window.

Taking a period of 10 Ma for the lateral extrusion process, the average E–W extension rate would be 17 mm/a, and the maximum N–S shortening rate (in front of the indenter) 11 mm/a. Movement rates, however, were heterogeneous during this period and had a pronounced climax around 17 Ma.

The break along the Brenner line is probably of lithospheric dimension. This conclusion is drawn from preliminary data showing the depth of the lithosphere/asthenosphere interface, which indicate a pronounced discontinuity with a lithospheric thickness minimum near the Brenner meridian (Babuška et al., 1990; Marchant, 1993), where the tip of the Southalpine indenter protrudes farthest north. The break continues into the Southern Alps where distensional structures are inferred from topographic expressions in the area immediately east of the Giudicarie line.

4. Geology, topography and drainage pattern in Egerian time (29–22 Ma)

Highest elevations in Egerian time (i.e., the period from 29 to 22 Ma, comprising the Chattian and Aquitanian stages) are found in the area west of the Brenner–Inntal line. Conglomerate-rich alluvial fans along the southern margin of the Eastalpine Molasse zone were established only in this western part at the base of the Egerian (Fig. 3; Schiemenz, 1960). Pebble spectra indicate that the fans west of the Chiemgau fan were nearly exclusively fed from the Northern Calcareous Alps and the Rhenodanubian flysch zone. Only the drainage system that supplied the Hochgrat fan, from the Aquitanian (23 Ma) on, incised a local source in the Austroalpine crystalline basement of the Silvretta block (Fig. 3; Schiemenz, 1960), delivering granite gneiss pebbles with a distinct lithology and chemistry. The Chiemgau fan, however, from 23 Ma on, received substantial amounts of crystalline pebbles that were transported by the palaeo-Inn river from the crystalline area west of the Brenner line (Skeries and Troll, 1988). Transport of coarse pebble material over large distances indicates a mountainous relief in the erosion area. The Inntal furrow (indicating that the Inntal fault was already active around the Oligocene/Miocene boundary) screened the crystalline material from the western fans and diverted it to the east (Fig. 3).

Andesite/dacite pebbles in the Chiemgau fan yield whole rock and hornblende K/Ar and apatite fission track ages between 37 and 30 Ma and suggest that volcanic edifices (Fig. 3) crowned the Periadriatic intrusive bodies that are presently exposed along the Periadriatic lineament (Fig. 1). These intrusives are mainly of tonalitic composition, emplacement ages cluster around 30 Ma (von Blanckenburg and Davies, 1995). The volcanic sources are completely eroded today, dike swarms which are supposed to represent feeder channels, are frequent. The volcanic

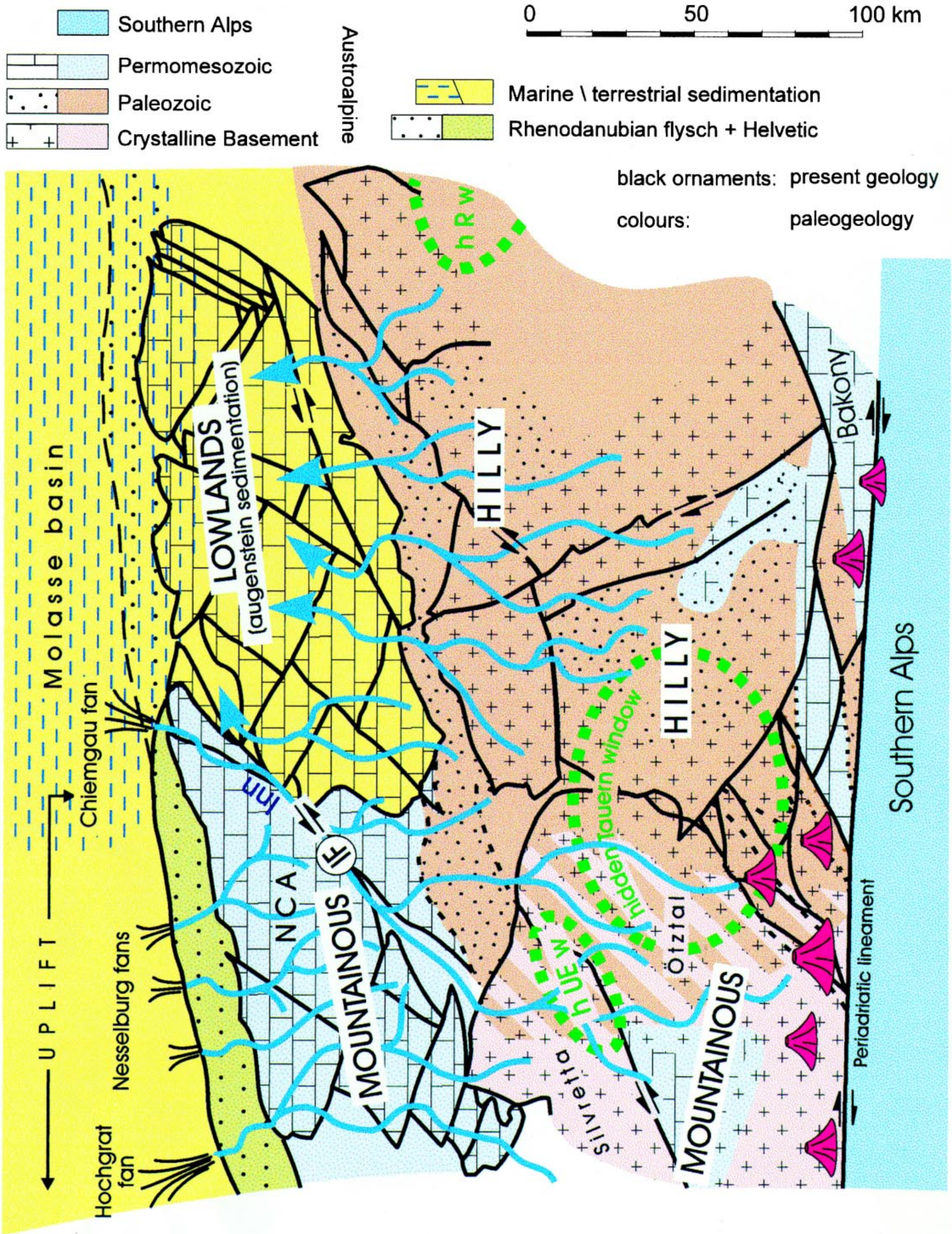


Fig. 3. Palaeogeologic sketch map of the Egerian (mainly pre-extrusion) stage (29–22 Ma), palaeotopographic features also indicated. Colours give palaeogeologic situation, black ornaments show present exposures as in Fig. 2 for reference. Blue lines, suggested drainage system. *NCA* = Northern Calcareous Alps; *IF* = Inntal fault; *hUEw*, *hRw* = hidden Unterengadin and Rechnitz windows (Penninic). Red cones, eroding volcanic edifices belonging to Periadriatic magmatic belt.

or subvolcanic pebbles in the Molasse zone indicate that the catchment area of the river system reached as far south as the Periadriatic magmatic belt, which is located south of the present-day main water divide.

In the eastern Molasse basin, the deep-marine Puchkirchen formation (see marine part of the Molasse basin in Fig. 3) took up important amounts of detrital material up to pebble size. It includes crystalline rocks and carbonates whose provenance, however, remains uncertain. Sources in the crystalline zone of the Eastern Alps are under discussion (Malzer, 1981; Wagner, 1996). We suggest that the palaeo-Inn river delivered the crystalline material into the Puchkirchen formation via the Chiemgau fan.

The NCA east of the Inntal line were not exposed in Egerian time but were the site of deposition of conglomerates and sands of the 'Augenstein' formation, on top of a slight relief (Fig. 1a, Fig. 3). The Augenstein ('eye-stone' because of ancient ophthalmologic use of the frequent quartz pebbles) formation probably formed a coherent, up to several hundred metres thick sheet of siliciclastic sediments on top of the central and eastern NCA. Only small remnants are preserved on elevated karst plateaus (up to 2500 m). These sediments were deposited by braided rivers in lowlands not much above sea level, and probably passed into the marine molasse to the north. The clastic material derived almost exclusively from low-grade metamorphic areas. The polycrystalline quartz pebbles (generally $>$40%) derived from quartz mobilisates contained in low-grade metamorphic rocks, as shown by phyllitic remnants preserved in fold hinges. They mirror large exposures of phyllites in the source areas. The source areas were widely distributed low-grade metamorphic Palaeozoic terrains (Greywacke zone and equivalents) and the Permoscythian, mainly siliciclastic basal sequence of the NCA. From the general absence of crystalline material we conclude that the Austroalpine crystalline basement now situated east of the Tauern window was completely covered by the low-grade metamorphic Palaeozoic sequences. This area formed a moderately elevated, probably hilly area which delivered the Augenstein material due north (Fig. 3). A higher relief would have created deeply incising rivers cutting into the crystalline basement. The exact age of the Augenstein deposition is unknown due to the lack of fossils, but geologic evidence shows that deposition must have occurred in Egerian and Eggenburgian times, prior to the Ottnangian–Karpatian distensional event (see below). Similar ages were considered by other authors (see Tollmann, 1968).

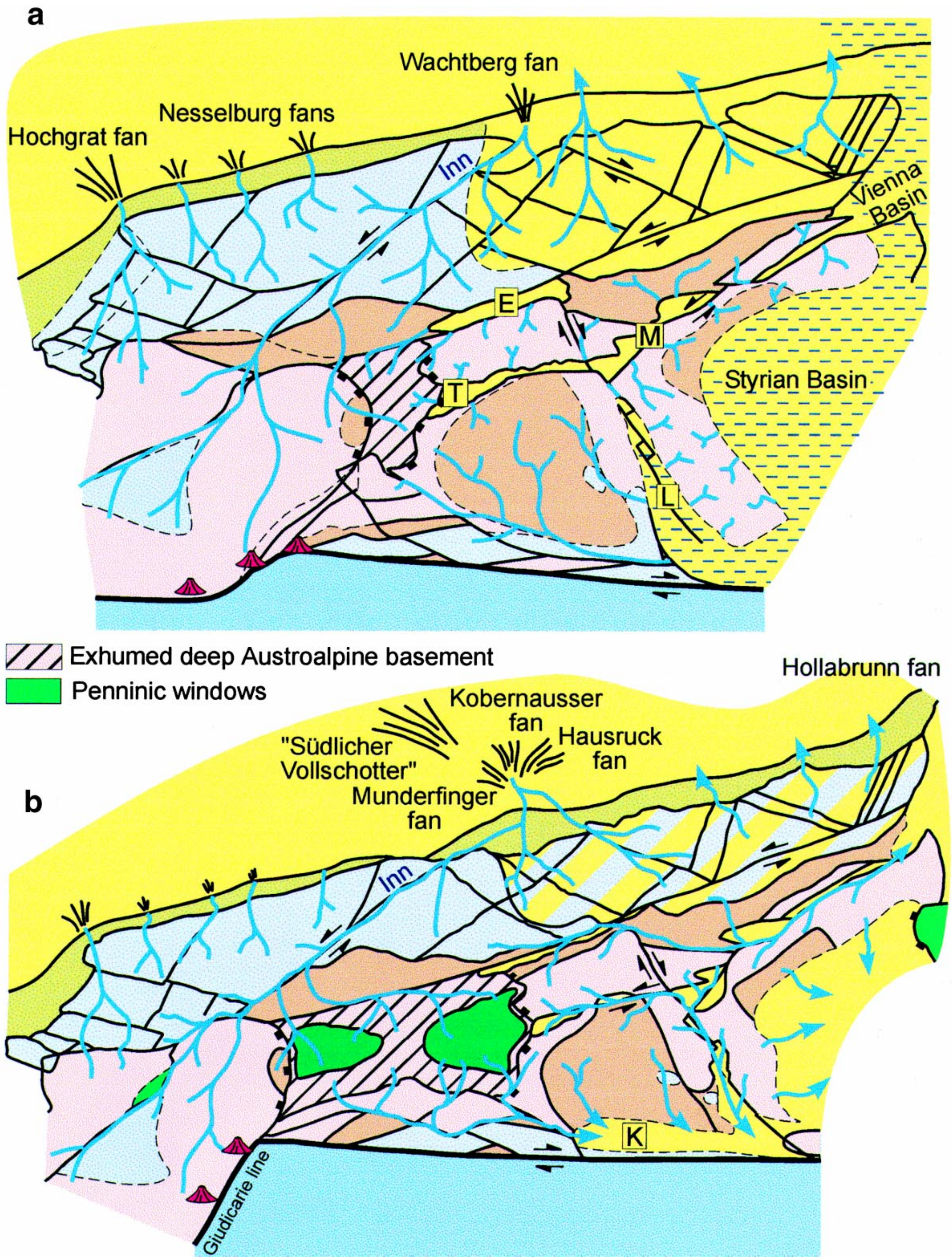
5. Geology, topography and drainage pattern during the main extrusion period (Ottnangian to early Badenian, 18–15 Ma)

An important distensional event during lateral tectonic extrusion occurred in about Ottnangian or Karpatian to early Badenian times (ca. 18–15 Ma). East of the (already updoming but still closed) Tauern window a number of intramontane basins formed as pull-apart or transtensional structures along major strike-slip fault zones (Ennstal, Mur–Mürztal, Lavanttal) or on top of a roll-over structure (Tamsweg basin) (Fig. 1a, Fig. 4a). Although the history of the basins is partly badly constrained in age, the available data show that rapid subsidence and sedimentation occurred in a short time span in Ottnangian/Karpatian to early Badenian times around 18 to 15 Ma (see Ratschbacher et al., 1991).

The Pannonian basin and minor basins on its western margin (Styrian basin, Vienna basin; Fig. 4a) also show major subsidence and onset of marine sedimentation in Karpatian and early Badenian times (Steininger et al., 1988; Decker, 1996). The main extensional phase in the Pannonian basin, the escape area for Eastalpine extrusion tectonics, was between 17 and 13 Ma (Karpatian–Badenian) (Royden et al., 1982).

A cluster of radiometric ages confirms a major event and enhanced motion of tectonic blocks around

Fig. 4. Palaeogeologic sketch maps of: (a) the Ottnangian to early Badenian (mainly syn-extrusion) stages (18–15 Ma); and (b) the Sarmatian and Pannonian (mainly post-extrusion) stages (13–8 Ma). Colours as in Fig. 3. Eroded Austroalpine crystalline basement above Tauern window indicated by hatching. Extrusion causes formation of intramontane basins east of (later) Tauern window: E = Ennstal basins; T = Tamsweg basin; M = Mur–Mürz basins; L = Lavanttal basin; K = Klagenfurt basin.


a
Wachtberg fan
Nesselburg fans
Hochgrat fan
Inn
Vienna Basin
E
M
T
L
Styrian Basin
Exhumed deep Austroalpine basement
Penninic windows
Hollabrunn fan
Kobernausser fan
"Südlicher Vollschotter"
Hausruck fan
Munderfinger fan
b
Inn
K
Giudicarie line

18–16 Ma (von Blanckenburg et al., 1989; Dunkl and Demény, 1997; Läufer et al., 1997). In the eastern gneiss dome of the Tauern window, Cliff et al. (1985) modelled a short-lived event around 17 Ma with high exhumation rates in the order of 5 mm/a flanked by preceding and succeeding rates ≤1 mm/a.

As a consequence of the tectonic movements, the drainage and sedimentation patterns fundamentally changed in the central and eastern part of the Eastern Alps. The following important changes occurred (Fig. 4a). (a) Pebble material from the crystalline basement and andesitic/dacitic volcanoes in the western Eastern Alps were brought along the Inntal furrow to molasse fans further east (Wachtberg fan, Ottnangian) indicating a major active phase of the Inntal fault along its entire length. (b) The deposition of Augenstein formation sediments terminated with the formation of the intramontane basins along major fault zones east of the later Tauern window, since these depressions screened the material supply from south of the NCA. (c) The Augenstein material started to be eroded from the central and eastern NCA and to be redeposited in the Molasse foredeep (residual gravels with enrichment of quartz pebbles to 75–80%). (d) The newly formed intramontane basins are rich in components derived from Austroalpine crystalline material. This indicates that the sheet of Palaeozoic rocks was removed in large parts of the area east of the later Tauern window and crystalline basement was at disposal for erosion. On the other hand, even basins close to the present margin of the Tauern window (Tamsweg, Ennstal basins; Fig. 4a) do not contain material from inside the window, although the Penninic contents of the window underwent rapid exhumation at that time. The intramontane basins probably formed a coherent sediment sink with the Styrian (Pannonian) basin and were filled up in Middle Miocene time to a higher level than the present one.

The western part of the Eastern Alps remained mountainous. The palaeo-Inn river was the most important river in the Eastern Alps, dewatering the high areas west of the Brenner line. The NCA west of the Inn river did not undergo major changes. The basement area east of the Tauern window became more differentiated in topography by the formation of the intramontane basins. Its northward drainage pattern decomposed to a more complex drainage system. Valley-like depressions formed along the major fault zones, and drainage towards the Pannonian basin in the east gained importance (Fig. 4a). This Early/Middle Miocene tectonic and geographic revolution in the eastern part of the Eastern Alps forms the basis for the modern river system and topography.

6. Geology, topography and drainage pattern in Sarmatian to Pannonian times (13–8 Ma)

Pebble and heavy mineral spectra (Herbst, 1985) suggest that the Tauern window was probably opened around 13 Ma. Differences between sedimentation age and apatite fission track ages from molasse pebbles and sandstones of only 3–4 Ma reveal fast cooling in the erosion area.

In the Molasse zone a large fan system (Munderfinger–Kobernausser–Hausruck fan system including ‘Südlicher Vollschotter’) was established in Sarmatian and Pannonian times (ca. 13 to 8 Ma) by the palaeo-Inn river (Fig. 4b). The conglomerates contain marker pebbles from the Austroalpine crystalline basement west of the Tauern window (symplectitic eclogite, pseudotachylite, green granite gneiss) and from the siliciclastic base of the western NCA (red Scythian quartzite), redeposited material from the Augenstein formation, and material suspected to derive from the Penninic contents of the Tauern window (serpentinite, granite gneisses, quartzites). NCA material is rare in the fan system but becomes increasingly important from about 10 Ma on, and is frequent in the Hollabrunn fan of mainly Pannonian age (Steininger et al., 1986) in the eastern Molasse zone (Fig. 4b). This indicates that the Augenstein formation was still being eroded, and substantial uplift of the central and eastern NCA did not occur before mid-Pannonian time (ca. 10 Ma).

In the area east of the Tauern window, a drainage pattern with important features similar to the present one with rivers draining to the east, was established. It followed the main tectonic lines of lateral extrusion (Fig. 4b).

Sedimentation in the Molasse zone west of the spur of the Bohemian Massif (Fig. 1a) ceased around 8 Ma (Lemcke, 1988). By that time, transverse rivers from the interior of the orogen no longer unloaded material at the immediate front of the orogen but continued further north where they joined the palaeo-Danube river (in a position similar to the present one) as the longitudinal drainage system delivering its load into the Paratethys to the east. Adopting the model of Burbank (1992), this change in the foreland depositional pattern with the longitudinal drainage far off the mountain front reflects substantial uplift in the orogen. We argue that by this time surface uplift in the central and eastern NCA became important, and the basement areas east of the Tauern window developed an increasing relief.

7. Conclusions

Based on tectonic analysis, geochronologic data, the sedimentary record and provenance indicators, we reconstructed the palinspastic situation of the Eastern Alps in post-collisional times. Our restoration shows that large-scale E–W stretching during orogenic collapse and lateral escape was not only a fundamental feature of the central crystalline zone of the mountain range (‘extrusion channel’ of Ratschbacher et al., 1991), but was of the same magnitude in the NCA and also affected the eastern Southern Alps. The incompatibilities between the stretched NCA and the non-stretched Bohemian massif are mainly accommodated by the syntectonic molasse sediments.

The palinspastic restoration shows a convincingly good fit of lithologic zones dismembered during extrusion. Moreover, the Periadriatic lineament restores to a straight line thus allowing for considerable pre-extrusion right-lateral motion, which is well-constrained by the disruption of facies zones in Mesozoic sequences. In pre-extrusion (Oligocene) times, the Eastern Alps did not yet exhibit an elongated shape with an E–W-trending long axis. The present stretched shape is essentially the product of Early to Middle Miocene tectonic extrusion.

Analysis of the record in the Molasse and intramontane basins is a powerful tool for the reconstruction of the post-collisional dynamics of the orogen and allows conclusions on the exposed rocks in the eroding areas and of the topographic and hydrographic situation. In Early Oligocene time there was no significant subaerial relief throughout the Eastern Alps. An important characteristic of the geologic and topographic evolution of the Eastern Alps is the difference between the part west of the Brenner–Inntal line and the area further east from the Late Oligocene on. Late Oligocene uplift in the western part of the Eastern Alps caused a mountainous relief there and is supposed to be related to uplift in the area of the Lepontine dome in the Swiss Alps (Merle et al., 1989). This event is reflected by the transport of coarse clastic material also into the Swiss Molasse foredeep since Late Oligocene time (Lemcke, 1988). Coarse clastic material in the Eastalpine Molasse zone during this period is restricted to its western part.

The eastern Eastern Alps formed lowlands or hilly areas until Late Miocene time. The central and eastern NCA were covered by sands and conglomerates (the Augenstein formation) in Late Oligocene to Early Miocene times and were thus part of the Molasse zone during this period. The clastic material derived from hilly Palaeozoic terrains in the south. The region of the later Tauern window, however, is inferred to have formed a rugged relief in Early to Middle Miocene times when rapid exhumation and updoming forced the Austroalpine lid to break apart. Mountainous topography is supposed to have governed this area since then. The Penninic contents of the Tauern window became exposed in Middle Miocene time.

Enhanced block movement during tectonic extrusion around the Early/Middle Miocene boundary led to the rearrangement of the north-directed drainage system east of the (later) Tauern window (Miocene ‘tectonic revolution’). A mainly orogen-parallel, fault-dominated drainage system was established together with intramontane basins decorating transtensional fault zones. In the area east of the Tauern window there is no simple water divide system today, a situation which is inherited from this time due to the complex pattern of fault-bounded blocks. The intramontane basins east of the later Tauern window caught up important volumes of crystalline basement material from local sources, which was meanwhile exhumed from beneath the Palaeozoic cover. Orogen-parallel valleys prevented material supply from the Palaeozoic and crystalline sources due north onto the central and eastern NCA, which finally led to the erosion of the Augenstein formation and its redeposition further north in the Molasse basin.

The opening of the Tauern window was essentially a tectonic process. The jumps in radiometric ages (Fügenschuh, 1995; Genser et al., 1996; Hejl, 1997) across the large-scale low-angle extensional shear zones at the western and eastern boundaries of the window (Behrmann, 1988; Selverstone, 1988; Genser et al., 1996) show that a high level of Austroalpine basement borders a deep level within the window over a short distance. The vertical throws along the Brenner and Katschberg low-angle extensional shear zones was in the order of 15–20 km. Only south of the Tauern window, Miocene cooling ages similar to those within the window suggest that deep levels of the Austroalpine lid are exposed. Thus, a great part of the lid above the window appears to be preserved in the window frame, and only a minor part became victim of erosion.

The topographic evolution of the Eastern Alps shows that elevations that would allow a differentiation into climatic provinces as they exist today (the Atlantic, Mediterranean and Pannonian province, with their triple junction in the eastern Eastern Alps), were not attained before Late Miocene/Pliocene times. This is corroborated by palaeoclimatic data (V. Mosbrugger, pers. commun., 1996).

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