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CENOZOIC TECTONIC EVOLUTION OF THE EASTERN ALPS – A RECONSTRUCTION BASED ON ^{40}AR/^{39}AR WHITE MICA, ZIRCON AND APATITE FISSION TRACK, AND APATITE (U/Th)-He THERMOCHRONOLOGY

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Abstract

The Cenozoic tectonic evolution of the Eastern Alps is defined by nappe assembly within the Penninic and Subpenninic units and their subsequent exhumation. The units above, however, are affected by extension and related faulting. By applying distinct thermochronological methods with closure temperatures ranging from ~450° to ~40°C we reveal the thermochronological evolution of the eastern part of the Eastern Alps. ^{40}Ar/^{39}Ar dating on white mica, zircon and apatite fission track, and apatite U/Th-He thermochronology were carried out within distinct tectonic units (Penninic vs. Austroalpine) and on host rocks and fault- related rocks (cataclasites and fault gouges) along major fault zones. We use particularly the ability of fission tracks to record the thermal history as a measure of heat transfer in fault zones, causing measurable changes of fission track ages and track lengths. Additionally, these studies will provide a general cooling and exhumation history of fault zones and adjacentcrustal blocks.

Key words: *thermochronology, Eastern Alps, Penninic, Austroalpine, Tauern Window, Koralm, faulting.*

1. Introduction

The Cenozoic evolution of the Eastern Alps (Fig. 1) is mainly characterized by the continent-continent collision between the European lower plate in the north and the Adriatic upper plate in the south, subsequent to the consumption of Penninic oceanic domains (for summary, see Neubauer et al., 2000; Schuster and Kurz, 2005). While the external parts of the European plate were deeply subducted and affected by the detachment of crustal slices and nappe stacking (e.g., Kurz et al., 1996; Schmid et al., 2004; Froitzheim et al., 2008), most parts of the Adria- derived units, termed as Austalpine and Southalpine, were almost completely exhumed and therefore close to the surface (e.g., Hejl, 1997; Pischinger et al., 2008).

During Cenozoic times the Eastern Alps are therefore characterized by a contrasting evolution of the lower plate units, i.e. the subduction of Penninic and Subpenninic units and their subsequent exhumation (e.g. Kurz and Froitzheim, 2002; Kurz, 2005, 2006) and upper plate units mainly affected by brittle faulting during orogen-parallel escape tectonics (lateral extrusion) (Ratschbacher et al., 1991; Frisch et al., 1998, 2000).

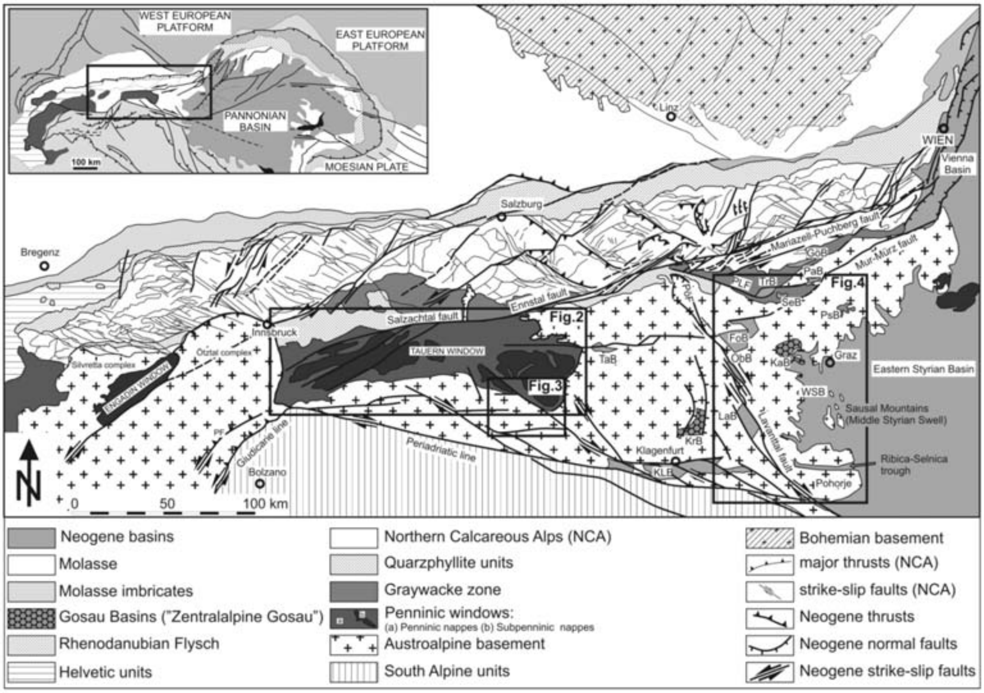

Fig. 1: Tectonic map of the Eastern Alps displaying major and minor Paleogene to Neogene fault systems (after Linzer et al., 2002). PLF = Palten – Liesing fault; PöF = Pöls fault; GöT = Göriach Basin; PaT = Parschlug Basin; SeT = Seegraben Basin; FoT = Fohnsdorf Basin; ObT = Obdach Basin; LaT = Lavanttal Basin; TaT = Tamsweg Basin; TrT = Trofaiach Basin; WSB = Western Styrian Basin; KrT = Krappfeld Gosau Basin; KaT = Kainach Gosau Basin.

By applying distinct thermochronological methods with closure temperatures ranging from ~450° to ~40°C (^{40}Ar/^{39}Ar dating on white mica, zircon and apatite fission track (ZFT, AFT), and apatite U/Th-He) we reveal the thermochronological evolution of distinct tectonic units of the Eastern Alps and provide the reconstruction of their tectonic evolution during Cenozoic times.

2. Geological setting

The Alps (Fig. 1) are the result of the still ongoing convergence between Africa and Europe. Plate tectonic units involved in the Alpine orogen are the European continent, two partly oceanic basins in the Penninic realm, and the Apulian (Adriatic) microcontinent including the Austroalpine and Southalpine units. In the area of the Eastern Alps (Fig. 1) the European continent is represented by the Helvetic Nappes. The European margin is represented by the Subpenninic nappes (in the Tauern Window these are the Venediger Nappe, Eclogite Zone, and Rote Wand – Modereck Nappe) (Fig. 2). Two partly oceanic basins in the Penninic realm (the Northpenninic Valais and the Southpenninic Piemont-Liguria) are represented by the Rhenodanubian Flysch, the Glockner Nappe, the Matrei Zone and the Klammkalk Zone.) The Adriatic (Apulian) microcontinent comprises the Austroalpine and Southalpine units (for review, see Schmid et al., 2004; Froitzheim et al., 2008).

In a geographical sense the Alps are divided into the E-W-trending Eastern Alps (Fig. 1), the Central Alps, and the arc of the Western Alps. Eastern, Central and Western Alps are characterized by a fundamentally different geological structure, geological evolution and, in part, a distinct geomorphology. East of the Tauern Window (Figs. 1, 2), the topography gradually changes from high elevations into the Neogene Styrian and Pannonian basin plains (Fig. 1) of a very low elevation above sea level.

The structure of the Eastern Alps is characterized by a system of fault zones (Fig. 1) that developed during late Oligocene to Miocene times. This fault system is related to orogen-parallel escape of Austroalpine units towards east, a process also termed as lateral extrusion (Ratschbacher et al., 1991). In the Eastern Alps this type of escape tectonics resulted in the final exhumation of Penninic and Subpenninic units within distinct tectonic windows (e.g., the Tauern and the Engadine Window) (Fig. 1), and in the subsidence of sedimentary basins along the eastern margin of the Eastern Alps (Styrian Basin) (Fig. 1) and along extrusion-related strike slip faults (Fig. 1) (Decker et al., 1993; Decker and Peresson, 1996). The latter mainly developed as pull-apart basins filled with intramontane molasse deposits. Time constraints on fault activity are mainly defined by the sedimentary deposits along these faults. Sedimentation within the intramontane molasse basins started around 18 Ma (e.g., Sachsenhofer et al., 2000). Another time constraint is given by the exhumation and cooling ages of Penninic and Subpenninic units in the Tauern Window, indicating that lateral extrusion started around 23.5 Ma (Frisch et al., 2000). Geochronological data from extrusion- related fault zones are rare and are only available from exhumed mylonitic shear zones in the vicinity of the Tauern Window (Müller et al., 2000, 2001; Mancktelow et al., 2001). Ages from pseudotachylites in the southwestern part of the Eastern Alps indicate a period of enhanced extrusion-related fault activity between 22 and 16 Ma (Mancktelow et al., 2001; Müller et al., 2001). Farther east, however, only the upper crustal sections affected by cataclastic deformation mechanisms are exposed.

Although the existing data indicate that the main part of orogen- parallel extension occurred during Early to Middle Miocene times (Frisch et al., 2000), seismic events along most of the extrusion- related faults indicate that these are still active (e.g., Reinecker and Lenhardt, 1999; Reinecker, 2000; Lenhardt et al., 2007; Frost et al., 2009) and that a certain amount of displacement should have proceeded from post- Middle Miocene to Recent times.

3. Study areas

In this study we present geochronological ages from: (1) The Subpenninic Eclogite Zone and Rote Wand-Modereck Nappe (Fig. 2) in order to constrain the timing of subduction of the southern European margin and its subsequent exhumation; (2) The southeastern margin of the Tauern Window (Fig. 3) in order to constrain the timing of exhumation of Penninic and Subpenninic units during the formation of the Tauern Window, the timing of faulting along its margins, and the thermochronological evolution of adjacent Austroalpine (upper plate) units; (3) the temporal evolution of the Lavanttal Fault Zone (LFZ) (Fig. 4), being related to the Miocene tectonic evolution of the Eastern Alps. These data provide important information on geochronological dating of faulting and the exhumation and uplift of adjacent Austroalpine basement blocks.

4. Geochronological data from the study areas

4.1 Subpenninic nappes (Tauern Window)

Radiometric $^{40}Ar/^{39}Ar$ ages from the Subpenninic nappes (Eclogite Zone and Rote Wand – Modereck Nappe) (Fig. 2) show that phengites formed under eclogite-facies metamorphic conditions retain their initial isotopic signature, even when associated lithologies were overprinted by greenschist- to amphibolite-facies metamorphism. Different stages of the eclogite-facies evolution can be dated.

An age of 39 Ma from the Rote Wand – Modereck Nappe is interpreted to be close to the burial age of

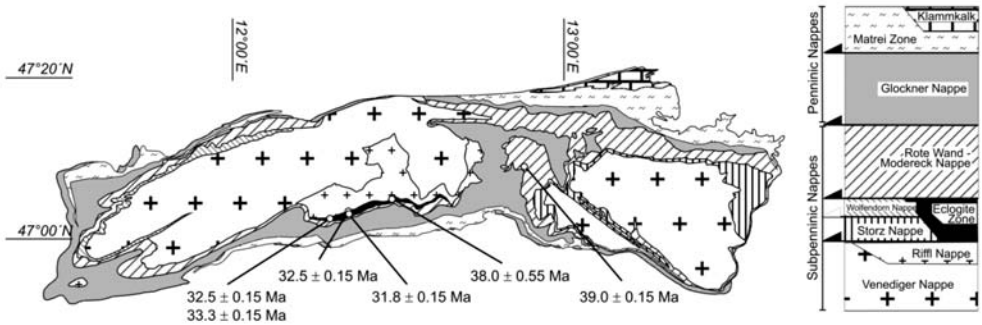

Fig. 2: Tectonic sketch map of the Tauern Window $^{40}Ar/^{39}Ar$- ages and sample locations (after Kurz et al., 2008).

this unit. Eclogite deformation within the Eclogite Zone started at the pressure peak along distinct shear zones, and prevailed along the exhumation path. Ages of *ca*. 38 Ma are only observed for eclogites not affected by subsequent deformation and are interpreted as maximum ages due to the possible influence of homogenously distributed excess argon. During exhumation deformation was localized along distinct mylonitic shear zones. This stage is mainly characterized by the formation of dynamically recrystallized omphacite and phengite. Deformation resulted in the resetting of the Ar isotopic system within the recrystallized white mica. Flat argon release spectra showing ages of 32 Ma within mylonites record the timing of cooling along the exhumation path, and the emplacement onto the Venediger Nappe (European margin). From the pressure peak onwards (*ca*. 25 kbar), eclogitic conditions therfore prevailed for almost 8-10 Ma. Ar-release patterns and $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlation analyses indicate no significant ^{40}Ar-loss after initial closure, and only a negligible incorporation of excess argon.

4.2 Southeastern margin of the Tauern Window

Four steep elevation profiles were investigated by zircon and apatite fission track and apatite (U-Th)/He dating, two in the Austroalpine unit and one each in the Subpenninic Hochalm and Sonnblick dome (Fig. 3).

Austroalpine basement units: The Kreuzeck block south of the Polinik fault yields systematically higher ages than the Polinik block north of the Polinik fault (Fig. 3). Two micaschist samples derived from the southernmost part of the Kreuzeck block yield higher ZFT ages (106.7 ± 8.5 and 103.1 ± 7.7 Ma) than previously recognized in this area. These ages are conform to the peak of Eo-Alpine metamorphism in Late Cretaceous times. In the northern part ZFT ages range between 67.8 ± 3.8 and 64.8 ± 3.5 Ma (Fig. 3). AFT ages range from 27.4 ± 2.3 to 19.6 ± 1.6 Ma with a positive relation between age and elevation. The mean track lengths for two apatite samples are 13.3 and 13.6 μm. Cooling rates as determined from zircon/apatite pairs and thermal history modeling demonstrate slow cooling in the order of ~4 °C/Ma between Late Cretaceous and Early Miocene time.

The two ZFT ages from the Polinik block are 39.1 ± 2.3 and 30 ± 1.8 Ma. AFT ages are systematically younger than those from the Kreuzeck block (between 19.4 ± 1.3 and 7.3 ± 0.9 Ma). The unimodal track length distribution indicates a single period of rapid cooling. Apatite (U-Th)/He ages are younger than the apatite fission track ages. The ages vary systematically with elevation.

Tauern Window: ZFT ages from the southeastern Tauern Window are rather uniform and range between 21.5 and 16.3 Ma. AFT ages of both domes show positive age-elevation correlation between 10.6 ± 0.9 and 7.8 ± 0.6 for the Sonnblick dome and 15.2 ± 1.3 and 7.4 ± 0.5 for the Hochalm dome.

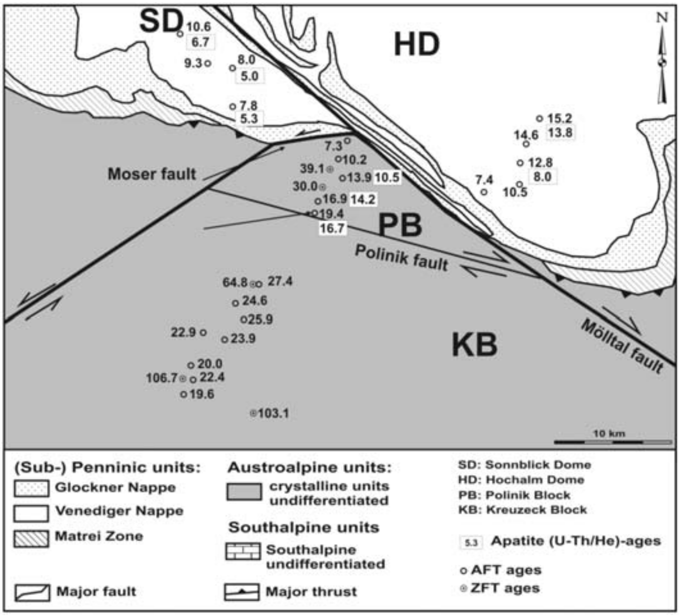

Fig. 3: Fission track (zircon, apatite) and (U-Th)/He ages in Ma from the southeastern Tauern Window and adjacent units (after Wölfler et al., 2008).

The mean track lengths are 14.4 μm and 14.5 μm indicating rapid cooling through the apatite partial annealing zone. Apatite (U-Th)/He ages from the Sonnblick dome range from 6.7 ± 0.4 to 5.0 ± 0.4 and are systematically younger than those from the Hochalm (13.8 ± 1.5 and 8.0 ± 1.1 Ma) (Fig. 3). Both He age sets show positive correlation with elevation. Mean Dpar (mean diameters of etch figures on prismatic surfaces of apatites parallel to the crystallographic c-axis)values of all analyzed samples range from 1.62 to 1.99 μm. They show no variation between different tectonic units and thus indicate uniform chemical composition of the apatite grains.

Within Austroalpine units thermal history modeling reveals tT paths characterized by slow cooling through Late Crateceous and Paleogene time until the Early Miocene, when the region was already near to the surface. In contrast, thermal modeling of the Polinik block demonstrates onset of rapid cooling around 20 Ma, followed by modest decrease in temperature from 12 Ma onwards.

In the Tauern Window the combination of AFT and (U-Th)/He data with ZFT ages from Dunkl et al. (2003) revealed a rapid cooling history (35 °C/Ma) between 20 and 12 Ma, followed by modest cooling until present. Assuming an increased geothermal gradient between 35 and 40 °C for the Tauern Window (Genser et al., 1996; Sachsenhofer, 2001) during Early and Middle Miocene times, this means exhumation rates in the range of 0.9–1 mm/y. This is valid for both the Hochalm and Sonnblick dome. For the latter the thermal model predicts another, short termed accelerated cooling event at 6 Ma, even with reduced initial track length.

The young (U-Th)/He ages between 6.7 and 5.0 Ma indicate that, when the last cooling event occurred, only the samples from the Sonnblick dome were in the apatite He partial retention zone, while the Hochalm dome and Polinik block had already passed through it. This final cooling event is explained as vertical movement of the Sonnblick dome relative to the Polinik block and the Hochalm dome that is accommodated by displacement along its southern and north-eastern margins (Fig. 3).

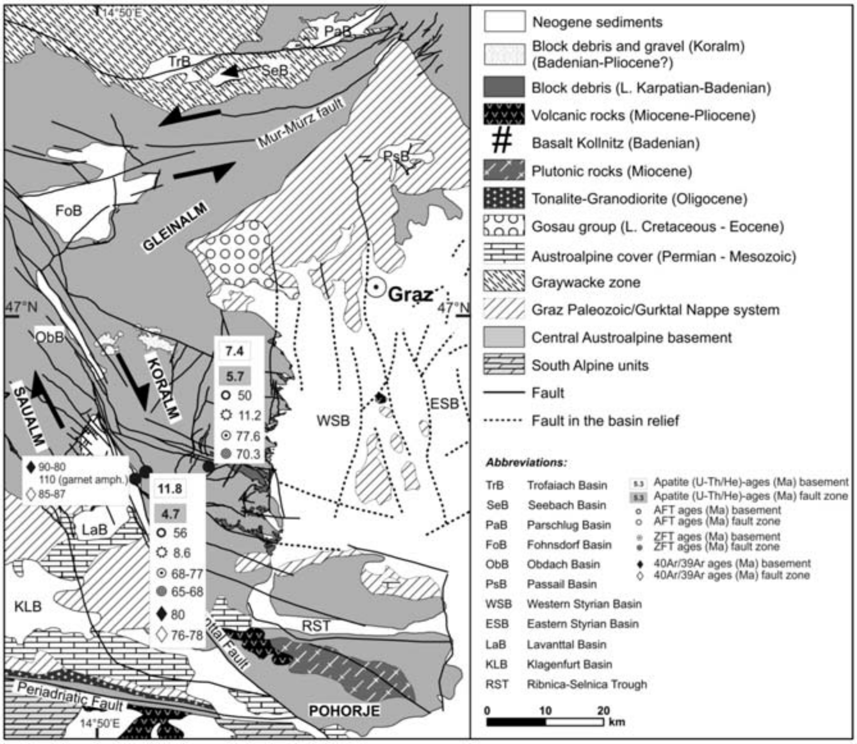

Fig. 4: $^{40}Ar/^{39}Ar$- ages, fission track (zircon, apatite) and (U-Th)/He ages in Ma from the Lavanttal fault zone and adjacent units (after Pischinger et al., 2008).

4.3 Lavanttal fault zone and adjacent Austroalpine units (Koralm massif)

The LFZ is generally described to be related to Miocene orogen-parallel escape tectonics in the Eastern Alps. $^{40}Ar/^{39}Ar$ dating on white mica, zircon and apatite fission track, and apatite U/Th-He thermochronology were carried out on host rocks and fault- related rocks (cataclasites and fault gouges) directly adjacent to the undeformed host rock (Fig. 4).

The main part of $^{40}Ar/^{39}Ar$ muscovite ages provided in this study is in accordance to the ages described from the adjacent Koralm Complex. The related plateau ages are therefore interpreted to represent the cooling of the host rocks below the closure temperature for the Argon isotopic system in muscovite (approximately 400-450° C) during Late Cretaceous times, i.e., between 80 and 90 Ma. Ages of *ca*. 110 Ma from eclogite- amphibolites most likely represent the timing of cooling during exhumation subsequent to eclogite facies metamorphism. Muscovites derived from cataclastic shear zones, however, show Argon release spectra characterized by reduced incremental ages for the first heating steps. This probably indicates Argon loss along the grain boundaries during shearing and lattice distortion, assuming that during stepwise heating Argon will be released from the muscovite rims at first. Samples from fault-related catclasites are characterized by a plateau age of *ca*. 78 Ma and highly reduced incremental ages, respectively, far below the protolith cooling ages described above. This is a strong indication for lattice distortion and related Argon loss during cataclastic shearing, and incomplete subsequent resetting of the argon isotopic system. As the incremental ages are in parts highly erratic, however, statements about the timing of shearing remain speculative.

Zircon fission track ages range between 77.6±5.5 and 64.8±4.6 Ma both within fault- and host rocks. Although all four fault/host rock sample-pair ages do overlap within the 1σ error, there is a clear trend of descending ages to the fault rocks. Track lengths were additionally analyzed and demonstrate reduced mean track lengths of 7.13±1.56 μm and 8.22±1.67 μm in fault core samples. By contrast, the samples from host rocks and damage zones show mean track lengths in the range of 10.00±0.97 μm to 10.42±1.03. Single grain ages are variable within the damage zones and fault core rocks and range between *ca*. 36.6 and 155 Ma.

Apatite fission track protolith ages range between 51.1±2.3 in the central part of the Koralm massif, and 37.7±4.3 Ma along its western margin, ages from fault- related rocks vary between 46.6 ± 4.7 and 43.3 ± 4.2 in the central part, and 43.6 ± 2.1 and 34.3 ± 1.8 Ma along the western margin of the Koralm massif. Single grain ages, however, are variable within all three fault core rocks and range from 76.5±12.3 to 3.6±1.3 Ma. These samples do not pass the chi-square test and can be decomposed into two age clusters. The dominant age components yield a weighted mean of 56.1±4.3 Ma and 8.6±2.6 Ma. Furthermore, the samples from the fault cores show significantly reduced mean track lengths (MTL). There is a clear relationship between single grain ages, MTL and Dpar values. Therefore the smallest Dpar values are associated with the youngest single grain ages and the shortest MTL´s.

Referring to the (U-Th)/He analysis a clear trend of decreasing ages from the host rock toward the damage zones and fault cores can be observed. The weighted mean age from the host rock is 11.8±0.8, from the damage zones 7.4±0.4 and 6.2±0.4 Ma and 4.7±0.3, 5.7±0.5 and 4.8±0.3 Ma from the fault cores.

5. Conclusions - Results

The subduction of the European margin resulted in eclogite facies metamorphism Subpenninic nappes (Eclogite Zone, Rote Wand-Modereck nappe) at about 40-42 Ma (Kurz et al., 2008). The Eclogite Zone ascended towards the surface within the subduction channel (Kurz & Froitzheim 2002; Kurz 2005), while subduction was still active. An age of ca. 38 Ma from undeformed eclogites is assumed to be a maximum age of this cooling event. Cooling of the Rote Wand – Modereck Nappe occurred approximately at the same time (39 Ma). The subsequent emplacement of the Rote Wand – Modereck Nappe along a major out-of-sequence detachment above at mid- to lower crustal levels may be dated at 33-31 Ma, as indicated by the phengite ages from the eclogite mylonites. Subsequently, the Penninic and Subpenninic nappes were emplaced onto the European margin.

Although accompanied by massive crustal thickening, this evolution within the lower plate (at lower crust and upper mantle conditions) is hardly reflected in the upper plate (Austroalpine units). Distinct signatures of faulting, derived from thermochronology, along the LFZ either indicate faulting prior or subsequent to Subpenninic nappe assembly.

The near-surface exhumation of Penninic and Subpenninic units and neighbouring Austroalpine basement units started during Early Miocene times, i.e. 15-20 Ma later. Two Phases are distinguished. Phase 1: Fast exhumation on both sides of the Penninic/Austroalpine boundary conforms with the period of lateral extrusion and tectonic denudation of the Tauern Window contents at 22-12 Ma. The jump to higher ages occurs within the Austroalpine unit along the Polinik fault zone, which therefore defines the boundary between the tectonically denuded units and the rather stationary orogenic lid (Wölfler et al., 2008). Phase 2: According to the occurrence of very young (U-Th)/He ages in the Sonnblick dome we demonstrate a second exhumation pulse at around 6 Ma, which is interpreted as a result of local tectonic complications along an extraction fault (Mölltal fault) (Fig. 3).

Similar to the Kreuzeck block south of the Tauern Window, exhumation and cooling of the Austroalpine units in the eastern part of the Eastern Alps was mainly completed at the end of the Cretaceous, as indicated by $^{40}Ar/^{39}Ar$ white mica and zircon fission track ages from the Koralm basement. During the main phase of lateral extrusion and formation of the Tauern Window, crustal blocks in the eastern parts of the central Eastern Alps therefore do not show significant vertical movement.

The final exhumation and uplift of the Koralm block is most probably related to vertical displacement along the LFZ from 12 Ma onward, as indicated by apatite fission track ages from fault zone cataclasites, and by apatite U/Th-He ages. Continuous displacement along the LFZ until Pliocene times is indicated by single grain apatite and U/Th-He ages. This late phase of fault activity can also be recorded along the southeastern margin of the Tauern Window, particularly along the Mölltal fault, by the final cooling of the Sonnblick dome (Fig. 3).

We therefore conclude that extrusion-related fault activity can be subdivided into three phases:

Phase 1: Formation of the Tauern Window and beginning of lateral extrusion around 23 Ma (e.g., Frisch et al., 1998). This phase, however, is only documented along the margins of the Tauern Window.

Phase 2: Fault activity migrated towards east, accompanied by the formation of intramontane molasse basins (Figs. 1, 2) (approx. 18-16 Ma) (e.g., Sachsenhofer et al, 2000; Pischinger et al., 2008). Vertical movement of Austroalpine units adjacent to these basins can not be resolved by thermochronological methods during this phase.

Phase 3: Final uplift of Austroalpine and (Sub-) Penninic units from 12 Ma onwards, also recorded by a mojor pulse of sedimentary input into the foreland Molasse basins (e.g., Kuhlemann et al., 2006).

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