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OROGEN-PARALLEL EXTENSION AND TOPOGRAPHIC GRADIENTS EAST OF THE TAUERN WINDOW: A POSSIBLE INDICATION OF INTRA-OROGENIC RAFT TECTONICS?

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ABSTRACT

N–S shortening in front of the Adriatic indenter, surface uplift and exhumation of the Tauern window area characterize the Late Oligocene to recent tectonic evolution of central sectors of the Eastern Alps. The resulting structures are typified by eastward tilted blocks, separated by extensional corridors. The eastward retreat of the subduction zone in front of the Carpathians induced strong Miocene E–W extension and basement subsidence in the Pannonian basin realm; surface uplift in the Tauern window area created E–W topographic and exhumation gradients, allowing the brittle upper crust to move along the mid-crustal ductile decollément level towards the east. Subject of research is the area between the viscous Penninic zone of the eastern Tauern Window and the overlying brittle Austroalpine basement units with deeply eroded/inverted basins on top. We use published apatite fission track (AFT) and apatite and zircon (U-Th)/He (AHe, ZHe) data from two sections of the Hohe Tauern to the east to constrain the E–W exhumation gradient. A W–E section along the southern Northern Calcareous Alps and sections along the Mur-Mürz fault zones are included for comparison, too. Based on AFT, ZHe and AHe data and assuming a thermal gradient of 30 ºC/km, a tilt angle of ca. 4° is found similar for both basement sections. This low gradient is close to a gradient typical for viscous material with low shear strength. These relationships imply that a gravitational collapse alone might be sufficient to explain the eastward motion of the brittle Austroalpine crust over a thick viscous Penninic layer. Flow above a low-friction viscous layer also explains the eastward tilting of blocks, including the Saualpe and Koralpe blocks, along ca. N–S antithetic high-angle dextral transtensional faults. The present-day structure east of the Tauern window within the Eastern Alps could be explained, therefore, by intra-orogenic raft tectonics, which represents the motion of an inclined brittle upper layer on a highly ductile, plastically deformed lower layer.

N–S Verkürzung an der Front des adriatischen Indenters, Hebung und Exhumierung des Tauernfensters prägen die Entwicklung zentraler Sektoren der Ostalpen vom späten Oligozän bis zur Gegenwart. Typische Parameter sind verkippte Gebirgsblöcke getrennt durch Extensionskorridore. Nach Osten orientiertes Zurückweichen der Subduktionszone an der Vorderseite der Karpaten bewirkte miozäne E–W Extension und Beckenabsenkung im pannonischen Bereich. Oberflächenhebung im Gebiet des Tauernfensters resultierte in einem topografischen bzw. Exhumationsgradienten, der es der spröden Oberkruste ermöglichte, sich entlang des mittleren krustalen duktilen Abscherhorizontes nach Osten zu bewegen. Gegenstand der Untersuchungen ist das Gebiet zwischen der viskos reagierenden penninischen Zone des östlichen Tauernfensters und dem darüber lagernden spröden ostalpinen Grundgebirge mit tief erodierten Becken. Der Exhumationsgradient wurde aus publizierten Apatitspaltspur- (AFT), Apatit und Zirkon-(U-Th)/He (AHe) sowie (ZHe) Daten aus zwei Bereichen der Hohen Tauern ermittelt. Zum Vergleich beziehen wir eine südlich der Nördlichen Kalkalpen gelegene Sektion und Abschnitte entlang der Mur-Mürz Störungszone in die Betrachtungen mit ein. Unter der Annahme eines Temperaturgradienten von 30°C/km ist der Neigungsgradient mit ca. 4° für beide Bereiche ähnlich. Ein derart niedriger Gradient ist typisch für viskoses Material mit geringer Scherfestigkeit, auf dem rigide Blöcke langsam durch Gravitation gleiten können. Diese Zusammenhänge bedeuten, dass ein durch Schwerkraft verursachter Kollaps ausreichen könnte, um die nach Osten gerichtete Bewegung der spröden ostalpinen Kruste über der viskosen penninischen Schicht zu erklären. Starke Oberflächenhebung in den Hohen Tauern und Fließen über eine friktionsarme viskose Schicht erklärt das ostwärtige Verkippen von Blöcken der Saualpe und Koralpe entlang antithetischer steiler ca. N–S streichender Abschiebungen. Somit lässt sich die gegenwärtige Struktur des Gebietes östlich des Tauernfensters mit intra-orogener Rafttektonik erklären, der Bewegung der geneigten Oberkruste auf einer duktilen mittelkrustalen Unterlage.

1. INTRODUCTION

The area north of The Eastern Alps exhibit a pronounced topographic gradient along the strike from the Tauern window area with the highest elevation to the low-lying Neogene Pannonian basin (Fig. 1). Several studies have focused on the late-stage structural evolution of the Eastern Alps; features such as extension, compression, the formation of the topography and drainage pattern, denudation, exhumation, and strikeslip faulting have been used to explain the processes that formed the present topography of the central Eastern Alps (Staufenberg, 1987; Neubauer and Genser, 1990; Hejl, 1997;

Reinecker, 2000; Frisch et al., 2000a, b; Székély et al., 2002; Schmid et al., 2004; Dunkl et al., 2005; Robl and Stüwe, 2005; Luth and Willingshofer, 2008). The overall present-day pattern of vertical motion may be described as uplift in the Tauern window area in the order of 1.5 mm/yr and subsidence in the Pannonian Basin (Ruess and Höggerl, 2002). In the Eastern Alps, the vertical surface motion is highly influenced by isostasy that is driven by erosion and active tectonic shortening caused by the indentation of the Adriatic plate against the European lithosphere (Ratschbacher et al., 1991; Champagnac et al., 2009). Cenni et al. (2013) and Serpelloni et al. (2013) observed heterogeneous uplift rates with a maximum of 5 ± 1.5 mm/yr in the easternmost Alpine parts. Nevertheless, it appears that the central Eastern Alps are far from being over-investigated. In particular, some observed features responsible for the development of the topography, e.g., the interplay between compression and extension (Frisch et al., 1998; Robl and Stüwe, 2005) provoke further investigations, which potentially result in new interpretations. Parameters such as age-elevation profiles of apatite fission track data that may provide estimates on exhumation rates, and elevation-distance profiles of blocks east of the Tauern window could possibly provide new insights into tectonic processes. Here, we assess existing apatite fission track (AFT) and apatite and zircon (U-Th)/He (AHe; ZHe) data to demonstrate the magnitude and timing of block tilting and explain with these new findings the present-day structure of eastern portions of the Eastern Alps.

Five cycles characterize the exhumation of the metamorphic basement east of the Tauern window, namely, the Late Cretaceous, Middle Eocene, Oligocene, Early – Middle Miocene and Pliocene to Recent events. Between these exhumation/surface motion stages, low or stagnating vertical movement led to relief destruction, the formation of planation surfaces and sedimentation (Dunkl et al., 2005). The total amount of Miocene erosion was most likely less than 1.5 km. Hejl (1997) found that ca. 800 m have been eroded from the Schladming crystalline basement since the end of the Miocene. Wölfler et al. (2008, 2011, 2012) suggest that exhumation constrained by apatite fission track ages of the Eastern Alps correlates well with increased sedimentation in the Middle Miocene. The estimated erosion rate of 0.04 km/Ma is in agreement with the AFT ages of Hejl (1997) and Reinecker (2000). AFT and AHe thermochronometers are sensitive to low-temperatures such as 110 to 60 °C and 80 to 40 °C, respectively. Cooling ages and their variations within an exhuming block suggest a strong relation to individual structures (Reiners and Brandon, 2006).

On passive continental margins, increasing rates of sedimentation and a weak evaporitic layer at the base of the sedimentary succession increase the downslope displacement of slope sediments and favor the development of normal faults (Mauduit et al., 1997), which has since been discussed as raft tectonics. Evidence of normal faulting indicates that rafting results

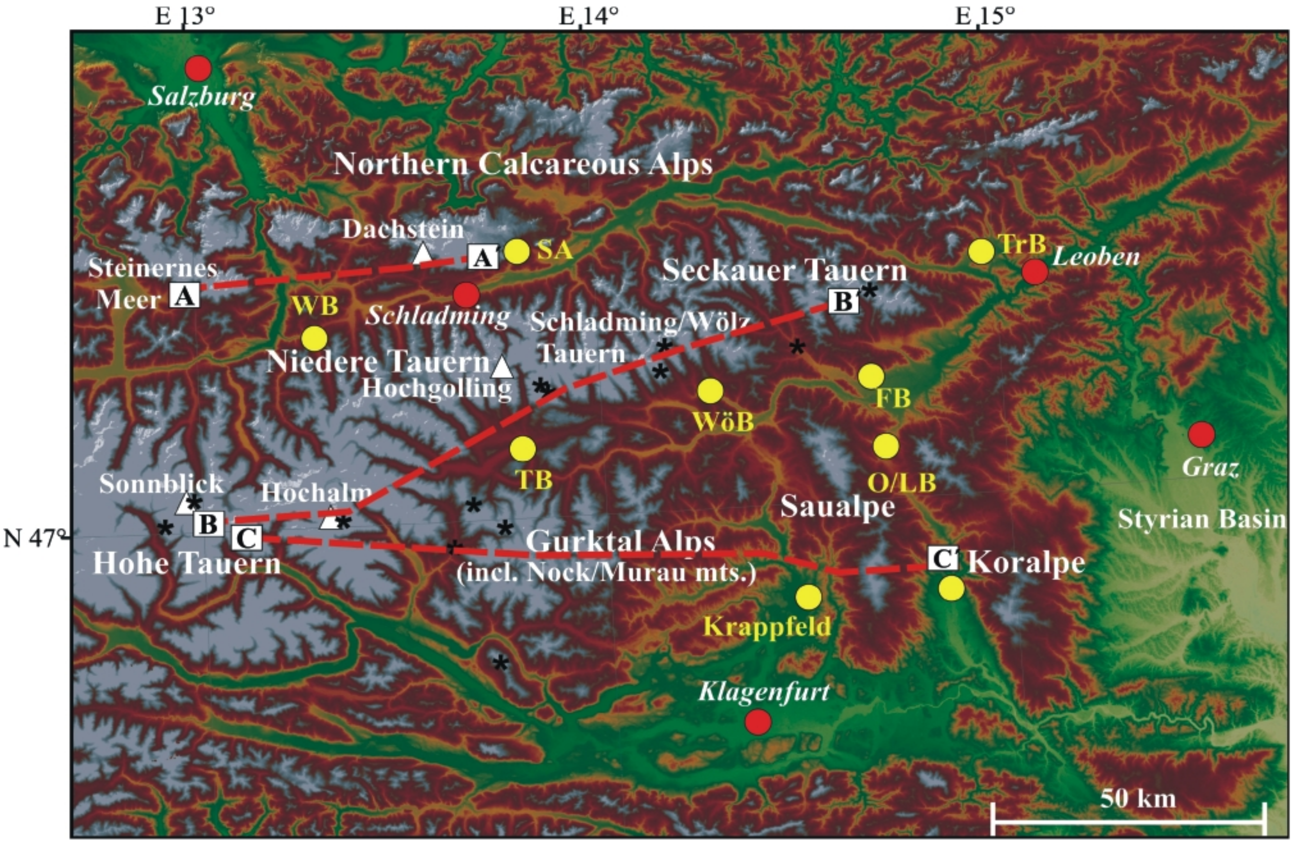

FIGURE 1: Digital elevation model giving a general overview of the research area with major towns, mountain peaks and sedimentary basins; abbreviations: WB – Wagrain Basin, SA – Stoderalm, TB – Tamsweg Basin, WöB – Wölz Basin, FB – Fohnsdorf Basin, TrB – Trofaiach/Leoben Basin, O/LB – Obdach/Lavant Valley Basins; star (*) indicates the sample locations; red dashed lines indicate the three sections of the study area.

from regional-scale extension (Peacock and Sanderson, 1997; Fort and Brun, 2012). Low slope-angles and the sedimentation rate play an important role for gravity gliding during which ductile layers act as décollements and separate folded parts from the basement (e.g., Fossen, 2010), and the overlying wedge is thinned out. A basal slope angle as low as ~ 2° is considered to be sufficient to trigger gravity gliding and syn-sedimentary extensional deformation. Gravity gliding-induced deformation may produce major normal fault structures (Mauduit et al., 1997). Structural domains of early stages of gliding are: (1) an undeformed central block where the overburden is translated without faulting; this segment undergoes rafting, (2) translation separates two domains of normal faulting, (3) block tilting during deformation and sedimentation, with faults dipping downslope, and accumulated imbricates at the toe of the glided masses. In short, raft tectonics could be characterized by the presence of relatively undeformed blocks separated by zones of deformation (Penge et al., 1999). These facts have been

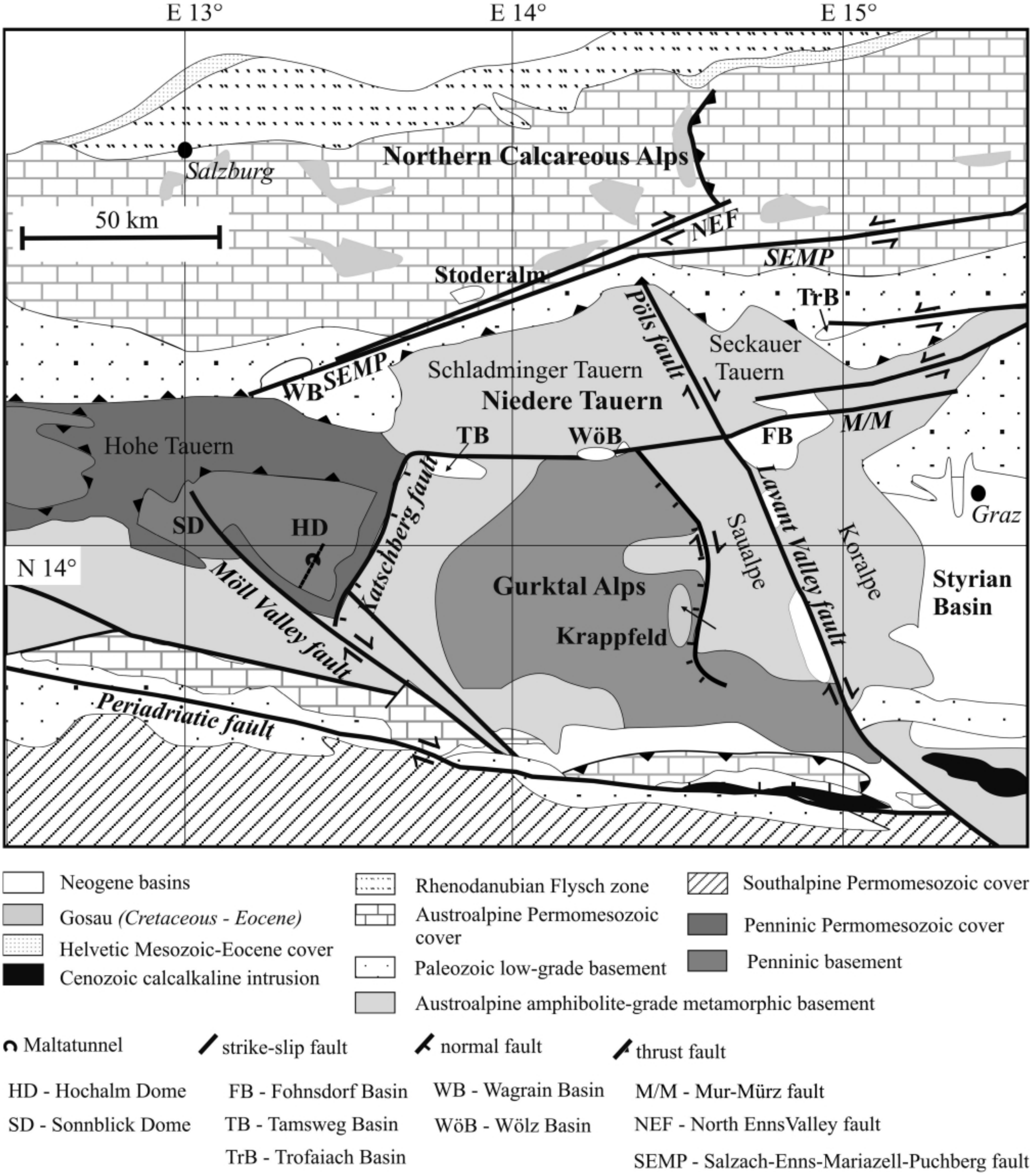

FIGURE 2: Simplified geological map with major structural units of the study area.

explained in the context of salt-tectonics using different laboratory models (Jackson et al., 1995; Mauduit et al., 1997; Brun and Fort, 2004; Jackson and Hudec, 2005). Several experiments on brittle–ductile models simulated the development of compressional structures and interactions between deformation and sedimentation (Brun and Fort, 2004). It seems that, at metamorphic depths, limestone or phyllite units can play the same role as salt does at shallower depths (Fossen, 2010). Neubauer and Genser (1990) interpreted surface structures of the eastern part of the Eastern Alps to have resulted from large-scale normal faults causing crustal thinning and the formation of sedimentary basins on top of the extended terrains. Their findings, applied on a smaller-scale, show conformance to the indicators of rafting.

Here, we apply the concept of raft tectonics to the eastern part of the Eastern Alps. We demonstrate that the present geomorphology and conditions precedent to raft tectonics such as gravitational gliding of brittle pieces of the crust on a viscous layer and the breakage of the sliding plate in extensional blocks prevailed in the study area. Thus, step by step, the above named parameters are closely investigated and the results reveal a fresh view on eastward directed extension and on rafting. The new interpretation might potentially allow to find indications for orogen-parallel raft-tectonics in other mountain belts, too.

2. GEOGRAPHIC AND GEOLOGIC SETTING OF THE STUDY AREA

The study area extends from N 46°30´to N 47°30´and E 13° to E 15° and comprises three characteristic sections (Fig. 1): (A) the Dachstein area as part of the Northern Calcareous Alps (NCA) north of the SEMP fault (Salzach-Enns-Mariazell-Puchberg fault). This section is taken as a reference horizon and is largely undisturbed by differential uplift as the NCA extend over 600 km in E−W direction; (B) in contrast, the eastern part of the Tauern window and the overlying Austroalpine units of the Niedere Tauern, framed by the Salzach-Enns fault in the north and delimited by the Mur-Mürz fault in the south exposes a generally east-dipping section; (C) a further section, south of the Mur-Mürz fault (Fig. 1) extends again from the eastern part of the Tauern window into the overlying Austroalpine units of the Gurktal Alps. Miocene basins are located along the Salzach-Enns fault (Wagrain Basin, Stoderalm) and along the Mur-Mürz fault zone (Tamsweg and Wölz, Fohnsdorf, Trofaiach and Leoben Basins). Further Miocene basins are located on the Austroalpine units and include the Krappfeld (Waitschach) Basin between the Gurktal Alps and the

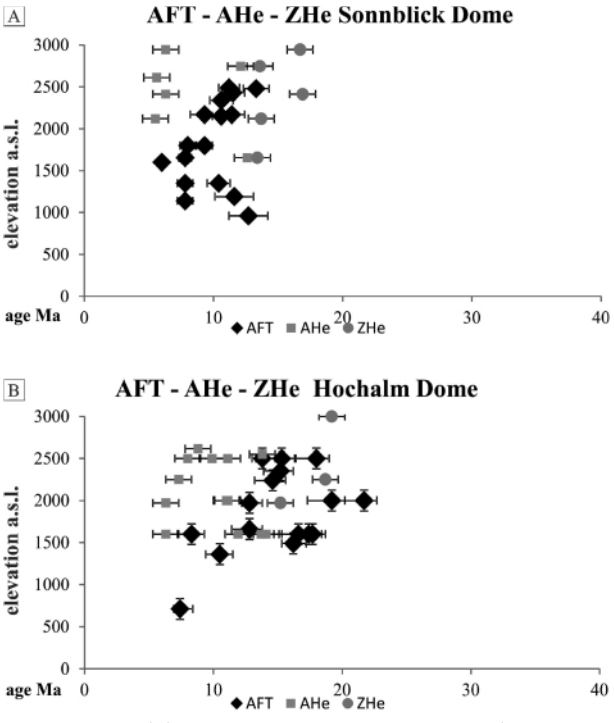

FIGURE 3: a) Sonnblick Dome; abbr.: AFT – apatite fission track; AHe – apatite (U-Th)/ He; ZHe – zircon (U-Th)/ He; data sources: Wölfler et al., 2011, 2012. b) Hochalm Dome; data sources: Staufenberg, 1987; Foeken et al., 2007; Wölfler et al., 2012.

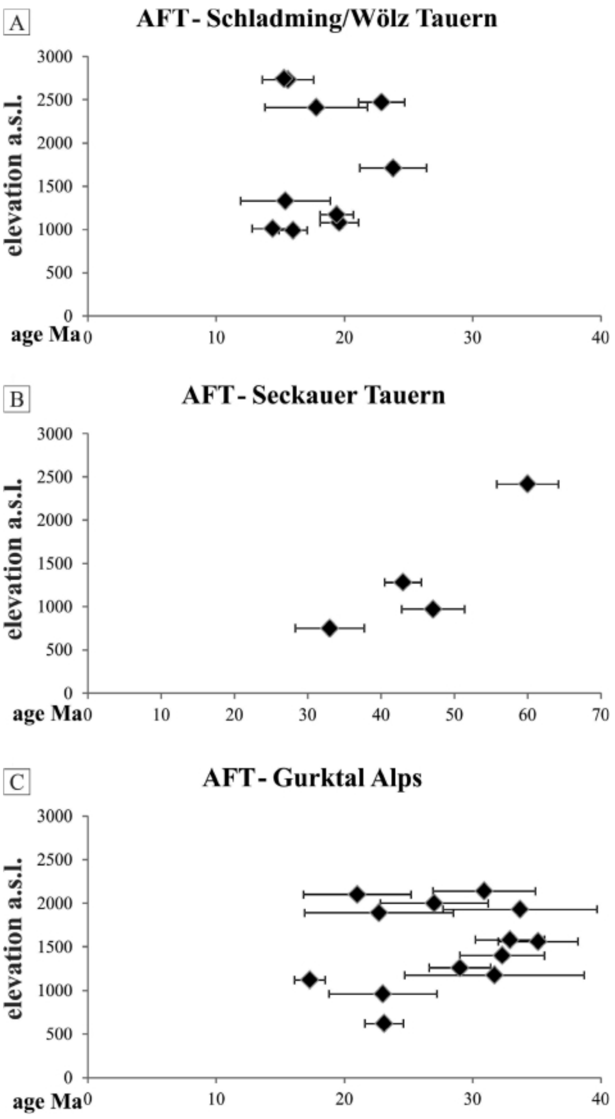

FIGURE 4: AFT age data of the major tectonic units. Data sources: Hejl (1997, 1998) and Reinecker (2000). a) Schladminger Tauern; abbr.: AFT – apatite fission track b) Seckauer Tauern; c) Gurktal Alps.

Saualpe block and the Obdach and Lavant Valley Basins between the Saualpe and Koralpe blocks (Figs. 1, 2).

The Tauern window in the Eastern Alps exposes Penninic units framed by the overlying Austroalpine units. The Penninic units consist of a basement complex with Paleozoic and older successions intruded by the Variscan Central Gneiss basement, and an overlying Mesozoic cover with a Jurassic ophiolite representing the infill of the Piemontais Ocean. Paleogene closure of the oceanic basin and subsequent collision and overriding by the Austroalpine units resulted in nappe stacking and pervasive overprint by Oligocene-Early Miocene metamorphism. Metamorphism reached amphibolite facies along the central E-W axis of the window, and upper greenschist facies conditions along the margins (Hoinkes et al., 1999). During the Miocene orogen-parallel extrusion, the Tauern window was exhumed by pull-apart of the Austroalpine upper plate (Genser and Neubauer, 1989; Frisch et al., 2000). Removal of the Austroalpine lid was partly achieved by displacement along low-angle normal shear zones, i.e., the Katschberg shear zone in the east (Genser and Neubauer, 1989). Within the eastern part of the Tauern window, the Variscan Central Gneiss is exposed in the Sonnblick Dome (3,106 m above sea level - a.s.l.) and in the Hochalm Dome (3,360 m a.s.l.).

In contrast to the Penninic units, Cretaceous tectonothermal events predominantly affected the Austroalpine units. Upper Cretaceous to Eocene Gosau basins discordantly overlay the uppermost Austroalpine units, whereas deeper units already cooled below ca. 100 – 110 °C during the Paleogene. Therefore, a strong thermal gradient can be assumed between the Penninic and the lowermost Austroalpine units for Oligocene to Miocene times.

The northern part of the Austroalpine basement units is exposed in the Niedere Tauern (Fig. 2). The morphology of the Niedere Tauern exhibits an immature landscape with steep slopes and elevations of up to 2,862 m a.s.l. (Hochgolling). The crystalline basement complexes of the Schladming/Wölz and Seckauer Tauern represent two blocks separated by the Pöls-Lavanttal fault zone. They consist of a Variscan basement with medium- to low-grade metamorphic rocks and a sparsely preserved low-grade metamorphic Mesozoic cover.

The Gurktal Alps also represent a part of the uppermost Austroalpine unit. The lithology consists of mostly low-grade metamorphic metavolcanics and metasediments. In contrast to the Niedere Tauern, the Gurktal Alps display flat, peneplain-like elevations between1,800 m and 2,200 m in the western part (Eder and Neubauer, 2000 and references therein), which gradually decrease in elevation to ca. 600 – 800 m in the east, where Miocene sediments are also preserved on peneplain-like surfaces (Thiedig, 1970; Kuhlemann et al., 2008).

The morphology to the east of the Gurktal Alps is constrained by the eastward tilted blocks of the Koralpe and Saualpe, which are separated by the Miocene dextral oblique-slip trans-

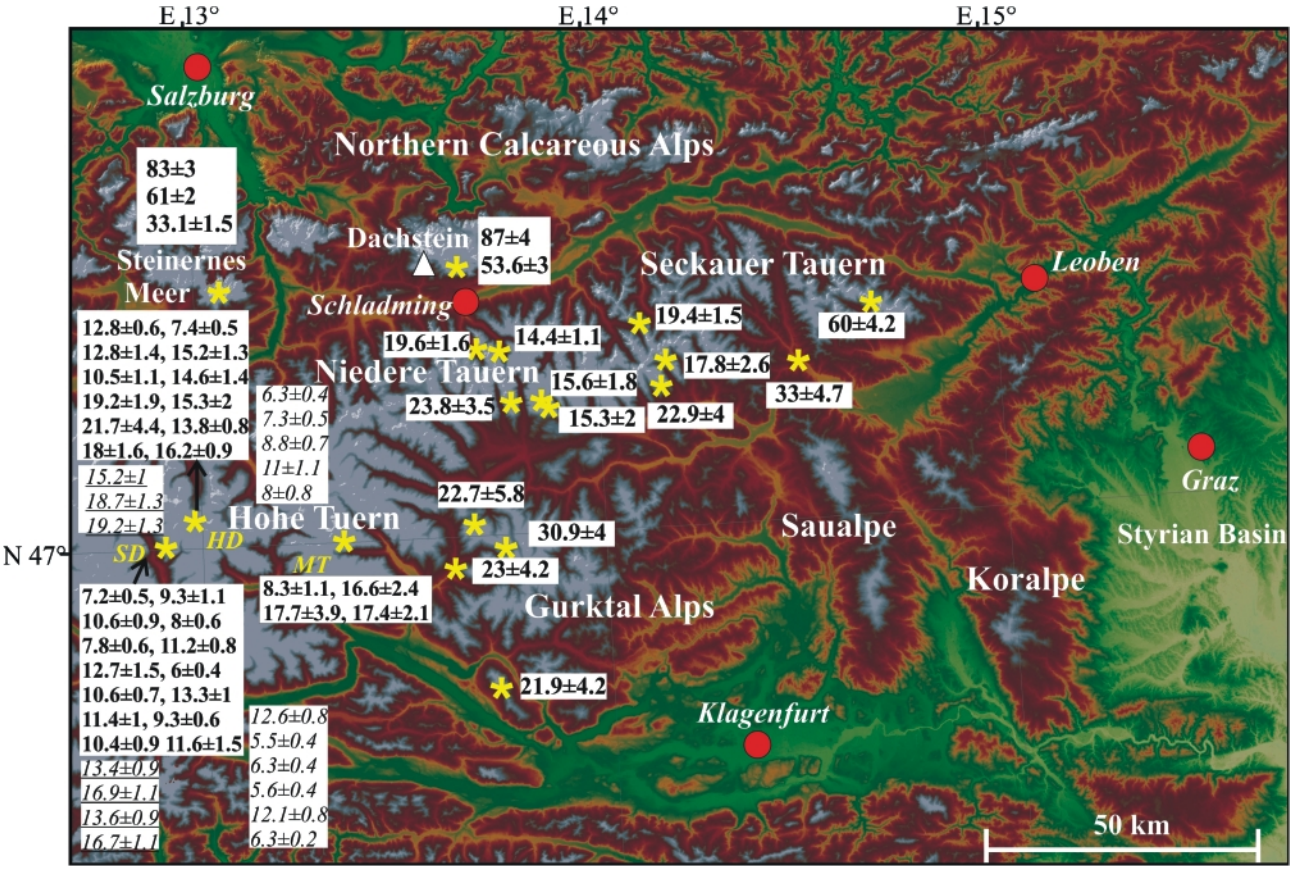

Figure 5: AFT (* indicates the sample locations), AHe (italic) and ZHe (italic underlined) data; Sonnblick and Hochalm Dome data are accumulated as the outcrops are too close together.

tensional Görtschitz Valley and Lavant Valley faults (Neubauer and Genser, 1990; Legrain et al., 2014).

3. Methodology

Published thermochronological data form the basis of this study (Stauffenberg, 1987; Hejl, 1997, 1998; Reinecker, 2000; Frisch et al., 2001; Foeken, 2007; Wölfler et al., 2008, 2011, 2012). In recent decades, a variety of thermochronological methods with increasing complexity was used to infer exhumation rates in the context of topographic gradients. We apply the following methods: a) AFT, AHe and ZHe dating; b) age-distance relationships, and c) the calculation of tilt angles. The calculation of the tilt angle is based on the assumption of a near-surface vertical thermal gradient of 30 – 33 ºC/km.

4. Results

4.1 Trends in the low-T thermochronological data

4.1.1 Eastern Tauern window

We plotted all published AFT, AHe and ZHe data from the Penninic basement of the Tauern window (Staufenberg 1987; Foeken et al. 2007; Wölfler et al. 2011, 2012). The data refers to the Sonnblick Dome (SD) south of the Möll Valley fault and the Hochalm Dome (HD) north thereof (Fig. 2); the Hochalm Dome data includes data from the surface of the Malta tunnel (Fig. 3a, b). At first sight, there is a clear trend of younger AFT cooling ages in the SD compared to the HD. The vertical age-elevation relationship of the Penninic rocks ranges between 21.7 ± 4.4 and 7.4 ± 0.4 Ma in the HD, and between 13.3 ± 1 and 6.3 ± 0.4 Ma in the SD; AFT and AHe data documents exhumation of the entire SD block between 15 and 5 Ma, whereas the exhumation of the HD occurred in two steps, between 25 and 15 Ma and between 10 and 5 Ma. Final exhumation of the two domes occurred contemporaneously.

4.1.2 Niedere Tauern and Gurktal Alps

The Schladming/Wölz Tauern and the Seckauer Tauern have already been subject of thermochronological and tectonic studies (Hejl, 1997, 1998; Eder and Neubauer, 2000; Reinecker, 2000; Keil and Neubauer, 2009). In a W–E section, the AFT data of these blocks indicate increasing cooling ages from west to east (Figs. 4a, b, 5). AFT data of the Schladming/Wölz Tauern display a similar cooling history as in the Hochalm Dome in the eastern Tauern Window. AFT-data from higher topographic levels of the Gurktal Alps are older than those from lower elevations of the Niedere Tauern (Fig. 4a, c).

4.2 Age – distance relationships

ENE-trending orogen-parallel Oligocene/Lower Miocene strike-slip faults separate the blocks of the Hohe Tauern/Niedere Tauern from the domains of the Gurktal Alps, from which the Mur-Mürz fault links with the ca. NNE-SSW striking Katschberg normal fault/shear zone at the eastern border of the Tauern window. Consequently, the linked normal-strike-slip fault system forms an extensional regime. Based on the assumption that the Dachstein plateau area of the NCA with ist Augenstein Formation was at the surface ~25 Ma ago (Frisch et al., 2001), the N- and S-sides of the study area are displayed horizontally (Fig. 6).

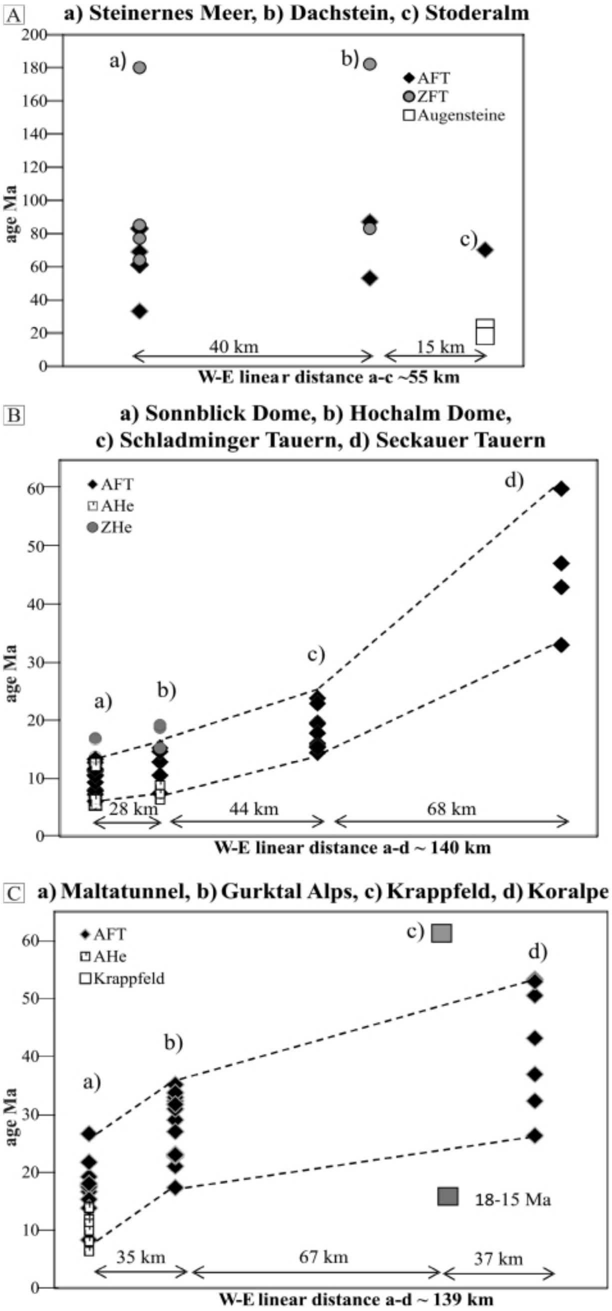

Figure 6: a) The section north of the SEMP fault serves as a reference to compare data with the southern sections. Oldest and youngest AFT ages: Steinernes Meer 83 ± 33 Ma, 33 ± 11.5 Ma; Dachstein 87 ± 4 Ma, 56 ± 6.3 Ma; note that deposition of the Augenstein Formation occurred coevally to the formation of the basin. b) Oldest and youngest AFT ages: Sonnblick Dome 13.3 ± 1 Ma, 7.4 ± 0.5 Ma; Hochalm Dome; 15.2 ± 1.3 Ma, 7.7 ± 0.5 Ma; Schladminger Tauern: 23.8 ± 3.5 Ma, 14.4 ± 1.1 Ma; Seckauer Tauern 60 ± 4.2 Ma, 33 ± 4.7 Ma. c) Oldest and youngest AFT-values: Malta tunnel 26.6 ± 4.1 Ma, 8.3 ± 1.1 Ma; Gurktal Alps 35.1 ± 3.1 Ma, 17.3 ± 1.2 Ma; Koralpe 53.3 ± 3.5 Ma, 26.3 ± 1.4 Ma.

a) The W–E section Steinernes Meer – Dachstein – Stoderalm (Fig. 6a) is a crucial element in regard to sedimentation of the Augenstein Formation. Following Frisch et al. (2001), AFT-age values support an Early Oligocene sedimentation age of the basal parts of the Augenstein Formation.; sedimentation ceased in the Early Miocene which indicates the uppermost depositional age limit for the Augenstein Formation. The Cenozoic relief evolution of the eastern parts of the Eastern Alps is confined to the end of the Augenstein Formation sedimentation. The formation of the Oligocene-Miocene Stoderalm Basin and the Augenstein sedimentation occurred simultaneously and prior to the surface rise of the NCA (Sachsenhofer, 1988). The Stoderalm Basin suggests syntectonic sedimentation; sedimentation not only occurred along longitudinal disruptions but also up to planation surfaces such as at the Stoderalm at 1,700 m a.s.l.

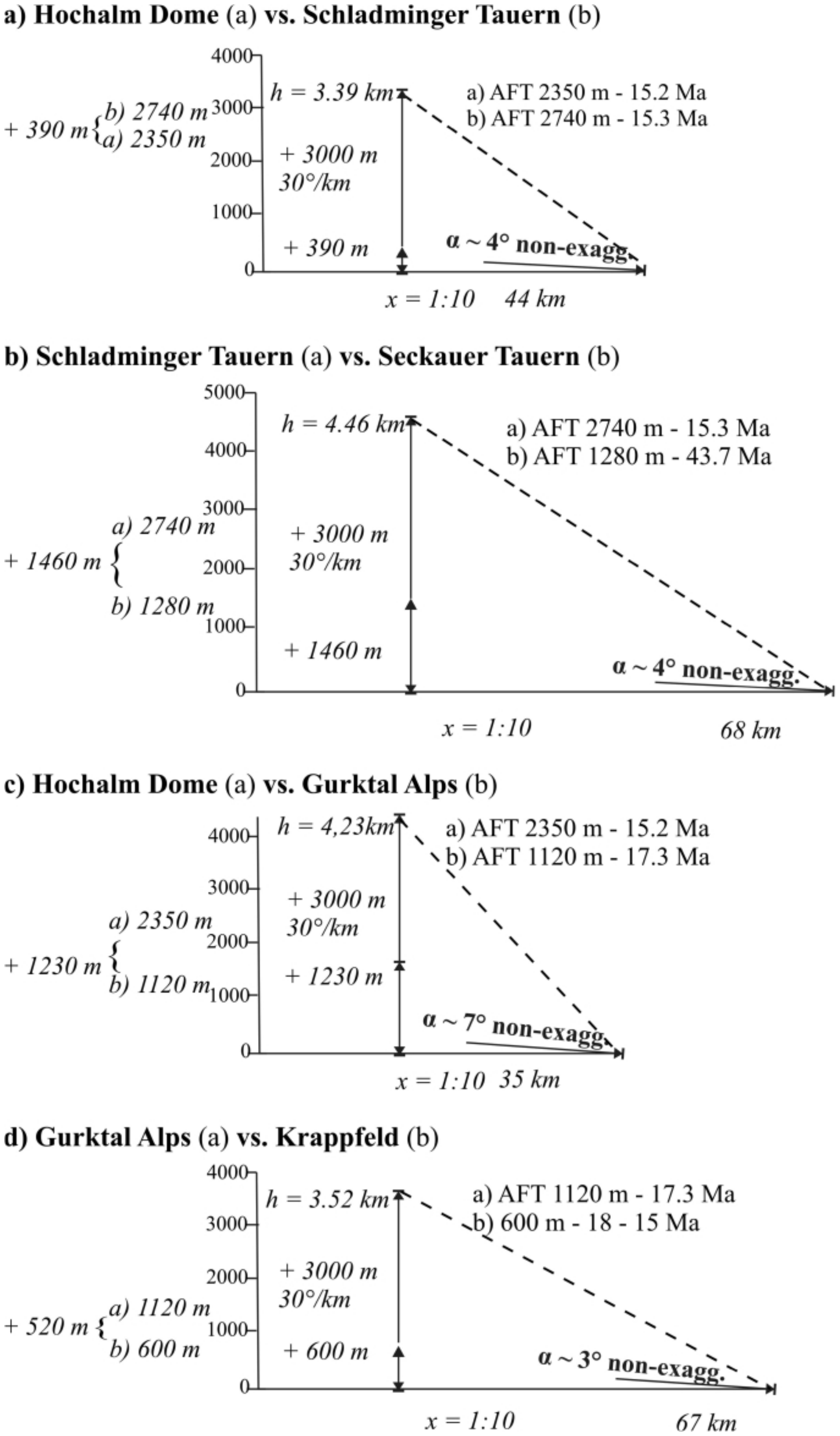

Figure 7: Calculation of overburden and dip angles of isotherms with following assumptions: youngest AFT ages at highest elevation; 100° isotherm of AFT cooling and a thermal gradient of 30°/km. Thin dashed line indicates ten times exaggeration of similar thermal/structural levels (in Early Miocene times) and indicates post-Early Miocene eastward tilting. Abbreviation: non-exagg. – non-exaggerated.

b) The W–E section Sonnblick Dome – Hochalm Dome – Schladminger Tauern – Seckauer Tauern is located south of the SEMP fault. AFT ages in vertical transects from each block cover a horizontal distance of ~ 140 km (Fig. 6b). The youngest cooling ages of each vertical transect increase continuously from W to E. The farther east the earlier exhumation began. This is interpreted as the result of denudational processes indicated by dashed lines in Figure 6b. The AFT-values of the Seckauer Tauern do not really fit into this section. The vertical transects of cooling ages document time-variable exhumation rates. The vertical transects in Figure 6b reconstruct a time-averaged pattern of exhumation over a wider area (Reiners and Brandon, 2006). Cooling ages between 60 ± 4.2 Ma and 33 ± 4.7 (Hejl, 1997) rather fit into the Gurktal Alps (Fig. 6c). The dextral Pöls-Lavanttal fault separates the Schladming Tauern block from the Seckauer Tauern. East of the fault system, Miocene pull-apart basins dominate (e.g., the Fohnsdorf, Seckau, and Leoben Basins along the sinistral Mur-Mürz fault systems and the Trofaiach Basin along the Trofaiach fault).

c) The section Malta tunnel – Gurktal Alps – Krappfeld – Koralpe (Fig.

6c) comprises a series of basins at the northern rim along the Mur-Mürz fault system, e.g., the Tamsweg, Oberwölz and Fohnsdorf Basins (Eder and Neubauer, 2000; locations in Fig. 1). The geometry of these basins represents a range of basin types including pull-apart and halfgraben basins, which formed a the lateral boundary of the east-moving block during gravitational gliding (Sachsenhofer, 1988; Neubauer et al., 2000; Strauss et al., 2001, Wagreich and Strauss, 2005). AFT ages from the Gurktal Alps and from the Koralpe are remarkably higher than the AFT and AHe ages from above the Malta tunnel located within the Hochalm Dome. The intra-montane Krappfeld Basin yields Upper Cretaceous cooling ages, as the formation occurred simultaneously in all basins (Dunkl et al., 2005). We suggest subsidence and sedimentation about 18 – 15 Ma ago, due to the fact that the Lower Miocene Waitschach Gravels, which are part of the Krappfeld Basin, were deposited on top of both the Upper Cretaceous Krappfeld Gosau sediments and on the metamorphic basement (Thiedig, 1970).

5. Dip angle of blocks

By combining all data, the thickness of eroded material was roughly estimated and the result is displayed in Figure 7. The assumptions are as follows: ~ 100° isotherm of AFT cooling and a thermal gradient of 30°C/km; we did not consider, that a thermal gradient might be higher due to compression.

The calculated vertical offset of the northern section between the Hochalm Dome and the Schladminger Tauern is 3.39 km (Fig. 7a). The calculation is based on the youngest AFT ages sampled at the highest elevation. Over a distance of 44 km, the dip angle is ~ 4° towards the east. The vertical offset between the blocks of the Schladminger and Seckauer Tauern accounts for 4.46 km, with a similar dip angle of 4° over a distance of 68 km (Fig. 7b). Calculations for the Seckauer Tauern use the mean value, as the AFT-data show hardly any correlation with elevation (Fig. 7b).

In the southern section, the dip angle between the Hochalm Dome and Gurktal Alps – horizontal distance 35 km – is somewhat higher (7°). The vertical offset of 4.23 km is in conformity with the section Schladminger Tauern – Seckauer Tauern, thus displaying a similar formation history (Fig. 7c). The Gurktal Alps versus Krappfeld again dips eastwards at ~ 3° (Fig. 7d).

These dip angles of only a few degrees are in themselves not impressive. However, in the context of normal faults they are obviously not the result of a simple high-angle extensional mechanism. Other processes seem to be involved. The low dip angles indicate a slow process that presumably started in the Early/Middle Miocene and potentially lasted until the Late Miocene/Pliocene boundary.

6. Discussion and conclusions

In general, the late-stage orogenic landscape of mountain belts is the result of the interplay between deformation processes and denudation. The Eastern Alps display a relatively simple pattern of internal deformation, including competing external processes. These include the indentation of the N-moving Adriatic microplate, resulting in the buildup of a high topography due to shortening in the Hohe Tauern region, and slab retreat in the Carpathians, triggering E–W back arc extension. The seismic anisotropy shows the west-east motion along the central axis of the Eastern Alps and is consistent with the eastward extrusion toward the Pannonian basin (Bokelmann, 2013), or E–W extension. There is no doubt that extrusional tectonics characterize the geomorphological and tectonic evolution of the Eastern Alps east of the Tauern window (Figs. 1, 2, 8). However, in our opinion, the impact of a thick brittle overburden as well as the fact that motion occurred on a viscous layer underlying the brittle Austroalpine nappe stack has not yet been considered.

The section Malta tunnel – Gurktal Alps – Krappfeld – Koralpe (Fig. 6c) comprises a series of basins at the northern rim along the Mur-Mürz fault system. This section is of particular interest, as the basin structures and their geometry correspond with other authors (Duval et al., 1992; Mauduit et al., 1997; Fort and Brun, 2012) in regard to raft tectonics.

From a structural point of view, the Tauern window with its ductilely deformed Penninic units represents the footwall, and the brittle-deformed Austroalpine units the hanging wall during Oligocene to Neogene extensional processes. The AFT ages of the SD show three distinct clusters as a function of the topographic elevation: Ages between 12.7±1.5 and 7.8±0.6 Ma at lower elevations (960 – 1,300 m a.s.l.) are followed by a younger cluster (9.3±0.6 to 6±0.4 Ma at ~ 1,800 m a.s.l.), and be-

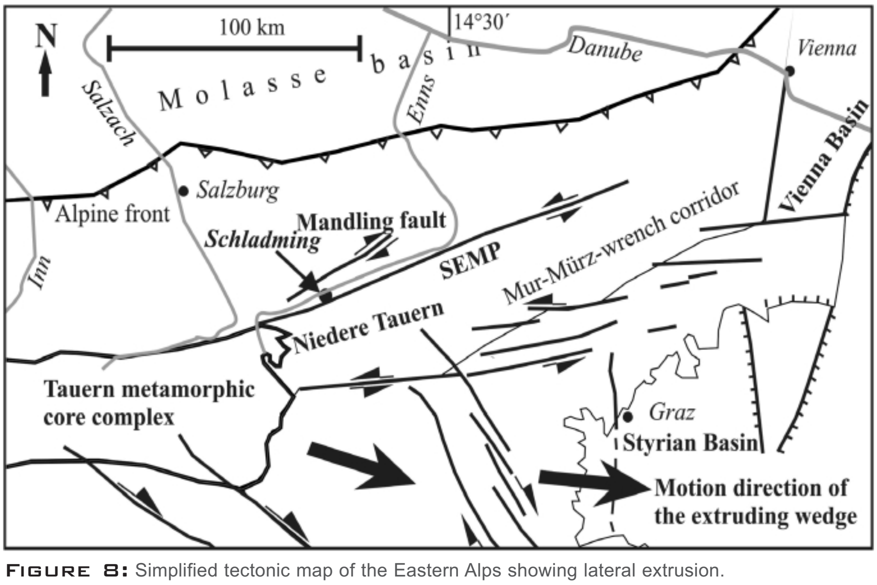

Figure 8: Simplified tectonic map of the Eastern Alps showing lateral extrusion.

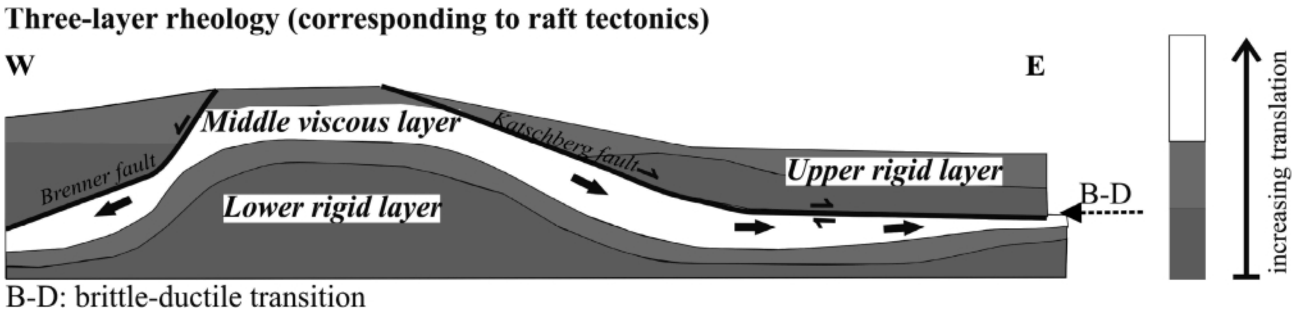

Figure 9: Modeling results in W–E section through the Tauern window (according to indentation experiments); arrow ( ) indicates direction of motion; modified after Zeng et al., 2001.

tween 1,800 – 2,480 m a.s.l. AFT ages increase, partly showing similar values to lower elevations (between 13.3±1 and 9.3±1.1 Ma). This trend cannot be observed in the HD, where data at elevations below 1,300 m are sparse. The older ages in a limited area, e.g., HD (2,000 m a.s.l. – 21. 7 ± 4.4 Ma, 19. 2 ± 1.9 Ma), could be explained by a horizontal thermal gradient and/or the activation of adjacent normal faults and thrust faults. The AHe-ages are generally younger than the AFT ages; ages younger than 15 Ma indicate a slower cooling rate, which followed rapid cooling at ~ 20 Ma (Foeken et al., 2007). Vertical age-profiles suggest time-integrated denudation rates of 160 – 240 m/Ma (Staufenberg, 1987); 2 to 3 km seems to be a plausible amount of erosion. Fault patterns along the study area reflect complications. Within the Austroalpine units, roughly ENE- trending orogen-parallel strike-slip faults dominate (SEMP and Mur-Mürz faults), whereas east of the Tauern window the NNE−SSW striking Katschberg normal fault/shear zone borders the blocks of the Niedere Tauern, Seckauer Tauern and the Gurktal Alps region. Based on the assumption of an interaction between these diverse fault patterns, the rock exhumation ends in a vertical throw of more than 15 km (Wölfler et al., 2013).

Remarkable and debatable is the AFT age of 23.8 ± 3.5 Ma in the Schladminger Tauern (Fig. 4a) and the much older age of 60 ± 4.2 Ma in the Seckauer Tauern (Fig. 4b). Reinecker (2000) suggests the former to have resulted from differential vertical tectonic movements between the locations; the latter could be explained by isolated down-sinking of a fault-bounded block, which is not obvious. The question of eastward tilting arises in the context of these two ages as the Schladminger Tauern were exhumed later. Tilting develops progressively during gradually increasing subsidence (Fort and Brun, 2012) or surface uplift. Tilting triggers also instability and regional-scale extension and is potentially associated with rafting. Thus, the high AFT-values, the evidence of normal faulting (Reinecker, 2000), and the presence of the relatively undeformed Gurktal Alps block during Neogene times, could be seen as characteristic indicators for raft tectonics.

If we consider that not only the crust, but the entire lithosphere is escaping eastwards (Bokelmann et al., 2013), then the thick calculated overburden east of the Tauern window should be of importance for the motion to the east. The huge overburden above the viscous layers and the small dip angles between the uplifting Tauern window area and the Austroalpine blocks trigger gravity spreading similar to what is known from passive continental margins (e.g., Brun and Fort, 2004). Figure 9 exhibits the result of numerical modeling of indentation by a finite element program (Zeng et al., 2001). It shows the section parallel to the Eastern Alps. In the case of a free eastern boundary, motion of blocks and E–W extension of the upper crustal sheet could be triggered under the following circumstances: (1) a thick layer of low-viscous rocks (corresponding to the calcite-rich Mesozoic cover rocks of Penninic units within the Tauern window) squeezed between the upper brittle layer (corresponding to the Austroalpine units), and a less viscous lower semi-brittle layer (Central Gneiss basement within the Tauern window); (2) sufficient exhumation and uplift of the brittle-ductile transition zone (which corresponds to the base of the Austroalpine units). The modeling also shows that the east-down topographic gradient is the trigger for gravity gliding and raft tectonics, and not necessarily the eastward retreat of the subduction in the Carpathians. The model could also be applied to other orogens with a strong along-strike topographic gradient.

In summary, apatite fission track data indicates eastward block tilting and is consistent with intra-orogenic raft tectonics. Dip angles of ~ 3–7° of the detachment and their thick crustal overburden indicate the slow process of gravitational gliding on a viscous layer. This study has brought provocative answers and proposes a significant contribution of a raft complex along a shallow-dipping detachment to the eastward orogen-parallel motion of blocks. Raft tectonics also explains the morphology of the eastern part of the Eastern Alps, particularly the apparent N–S trending eastwards tilted Gurktal Alps, Koralpe and Saualpe blocks.

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