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Cenozoic relief evolution of the Eastern Alps – constraints from apatite fission track age-provenance of Neogene intramontane sediments

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Abstract

Fission track (FT) ages of detrital apatites from Middle Miocene sandstones of the intramontane basins of the Eastern Alps register the surface distribution of FT ages of the Alps in its former stage of evolution. We have used the apatite detrital thermochronology method to describe the significance and distribution of Cenozoic exhumation phases of the eastern part of the Eastern Alps. Additionally we have completed the knowledge on the provenance indicators of the Neogene basin remnants of the Eastern Alps and integrated these sedimentological features in the interpretation of the apatite FT age distributions.

According to the fission track age spectra of the detrital apatites, three age terrains can be characterized for the Middle Miocene: (1) a northern and central source area with Cretaceous, Paleocene and Eocene apatite FT ages, (2) a region along the southern margin of the Eastern Alps, dominated by Oligocene FT ages, and (3) a small source area of Miocene ages in the rapidly exhuming Pohorje (Bacher) mountains. On the basis of pebble lithologies, transport indicators and facies data, we propose a reconstruction on the sediment transport and burial pattern for the study area in Middle Miocene time. During the Early-Middle Miocene basin formation period sediments covered the Eastern Alps between the Tauern Window and the Pannonian basin more widely than preserved today. The dewatering trend was usually from west to east and we suppose that the major belts of sediment remnants (Ennstal, Noric depression and Drau valley) indicate the valleys of three major rivers during Middle Miocene: Paleo-Enns, Paleo-Mur-Mürz and Paleo-Drau. Their positions were more-or-less similar to the present situation of the rivers. We consider the valley fillings of these paleo-rivers as the western continuation of the Pannonian/Styrian basin system.

The exhumation of the metamorphic basement and relief building in the Eastern Alps east of the Tauern Window occurred in five distinct cycles in Late Cretaceous, Middle Eocene, Oligocene, Early to Middle Miocene and Pliocene times. Between these periods slow or even stagnating vertical movements allowed relief destruction, planation and sedimentation. The post-Gosau compressional event generated exhumation in the Middle Eocene. From this event on, the surface of the metamorphic areas was dominated by Eocene apatite FT ages as recorded in detrital apatites in Neogene sandstones. The vertical offsets during post-Oligocene exhumation phases were limited and Eocene apatite FT ages are still preserved at the summits and in elevated paleosurface remnants of the metamorphic blocks east of the Tauern Window.

Spaltspurendatierungen an detritischen Apatiten mittelmiozäner Sandsteine von intramontanen Becken der Ostalpen zeigen die Verteilung der Spaltspurenalter an der Oberfläche zur Zeit der Sedimentation. Wir benützen die Abkühlungsgeschichte detritischer Apatite um die Bedeutung und Verteilung tertiärer Exhumationsphasen in den östlichen Ostalpen herauszuarbeiten. Für die Interpretation der Verteilung der Apatit-Spaltspurenalter nutzen wir auch sedimentologische Indikatoren zur Herkunft der neogenen Beckensedimente.

Aufgrund der Spektren der Spaltspurenalter detritischer Apatite können drei Liefergebiete spezifischen Abkühlalters charakterisiert werden: (1) ein Liefergebiet im Norden und in den Zentralalpen mit kretazischen, paleozänen und eozänen Altern, (2) ein Liefergebiet entlang des Südrandes der Ostalpen mit oligozänen Altern und (3) ein relativ kleines Gebiet mit miozänen Altern im Bacher (Pohorje) Gebirge. Auf der Basis von Geröll-Lithologien, Transportindikatoren und Faziesdaten schlagen wir eine Rekonstruktion des Sedimenttransportes und der Sedimentation der intramontanen Becken im Mittel-Miozän für das Arbeitsgebiet vor. Während der früh- bis mittelmiozänen Beckenentwicklung war die Sedimentbedeckung der Ostalpen zwischen dem Tauernfenster und dem pannonischen Becken viel weiter verbreitet als heute. Die Entwässerung erfolgte hauptsächlich von West nach Ost und wir vermuten, dass die Zonen der bis heute erhalten gebliebenen neogenen Becken (Ennstal, norische Depression und Drautal) die Täler großer Flußsysteme im Mittel-Miozän markieren: Paläo-Enns, Paläo-Mur-Mürz und Paläo-Drau. Ihre Lage ähnelt der der heutigen Flußsysteme. Wir betrachten die Talfüllungen der Paläoflüsse als die westliche Fortsetzung des pannonisch/steirischen Beckensystems.

Die Exhumation des metamorphen Grundgebirges und die Reliefentwicklung der Ostalpen östlich des Tauernfensters fand in fünf Phasen während der späten Kreidezeit, des Mitteleozäns, des Oligozäns, des Früh-/Mittelmiozäns und des Pliozäns statt. Zwischen diesen Phasen verlangsamten oder stagnierten die vertikalen Bewegungen, was zu Reliefabbau, Einebnung und Sedimentation führte. Während des mittleren Eozäns bewirkte die postgosauische Kompression eine Exhumation des Gebirges. Seit diesem Event dominieren eozäne Apatit-Spaltspurenalter die Oberfläche der metamorphen Gebiete, wie an detritischen Apatiten aus den neogenen Sandsteinen dokumentiert ist. Der vertikale Versatz während der postoligozänen Exhumationsphasen war begrenzt und eozäne Apatit-Spaltspurenalter finden sich heute noch in den Gipfelregionen und gehobenen Überresten der Paläo-Oberflächen kristalliner Blöcke östlich des Tauernfensters.

1. Introduction

The study area is situated in the Eastern Alps between the Tauern Window in the west and the Pannonian basin in the east. This region differs from the other parts of the Alps because (i) although it is in the axis of the mountain chain relatively low average elevation is characterististic (between 800 m and 1400 m), (ii) this is the largest and most intact Austroalpine area of the Alps, composed of formations with pre-Cenozoic metamorphism, and (iii) this region hosts many tectonically determined depressions, filled with Neogene sediments, which have been addressed as intramontane basins (Tollmann, 1986).

Paleozoic and Mesozoic Austroalpine formations are dominant in this region, overprinted by Variscan and Late Cretaceous metamorphism. High temperature geochronometers (Ar/Ar and Rb/Sr) show predominantly Variscan and Cretaceous ages in the Austroalpine lid, while the underlying Penninic formations experienced a Late Cenozoic metamorphism (Miocene cooling ages are typical). Thus, the Cretaceous and Miocene tectonic and metamorphic evolution of the study area is well documented. However, the evolution of the area during Paleogene times is less known due to the sporadic sedimentary record and the relative low abundance of geochronological data from this time period (see e.g. compilations of mica Ar ages and zircon fission track (FT) ages in Genser et al., 1996 and in Benedek et al., 2001, respectively). On the other hand it is obvious that during Paleogene times there were important events in the evolution of the Alps:

-Western and Central Alps: Numerous geochronological data indicate overthrusting and metamorphism during Paleogene times (see. e.g. compilation in Hunziker et al., 1992, Gebauer, 1999).

- Westernmost Eastern Alps: Paleogene strata in the Penninic metamorphic assemblage of the Engadine Window constrain a maximum age for the overthrusting of the Austroalpine lid (Waibel and Frisch, 1989; Bousquet et al., 1998).

- Argon and fission track cooling ages of the Tauern window and its surrounding show displacement, metamorphism and rapid cooling in Eocene times (Dunkl et al., 2003; Ratschbacher et al., 2004).

- The Cretaceous-Paleogene Gosau beds suffered deformation during Middle Eocene (Tollmann, 1986; Wagreich, 2001).

We can summarize that in the Eastern Alps the knowledge of the significance of the Eocene "post-Gosau" orogenic phase and its surface response and paleogeographical consequences is rather incomplete.

The Neogene clastic sediments in the intramontane basins have preserved the paleogeologic setting of the Eastern Alps before Miocene. The Miocene orogeny caused major changes in the Alps with respect to the former arrangements of the structural blocks and exhumed the metamorphosed Penninic and Helvetic rocks. Pebble petrography and heavy mineral spectra are archives of the surface lithologies, whereas facies and transport directions provide essential information for the restoration of basin sedimentation and paleogeographic reconstruction. Furthermore, the cooling ages in the detrital minerals reflect the cooling ages of the exhumed basement during the sedimentation - prior to the Miocene orogeny. In our study we have used the apatite single grain fission track age distributions of intramontane sediments in order to reconstruct the surface distribution of FT cooling ages in Early-Middle Miocene times and thus to quantify the pre-Neogene cooling and exhumation phases. By the combination of the new age data, the provenance indicators of the sedimentary basins and the apatite fission track ages in the presently exposed basement of the study area we have compiled a paleogeographic sketch-map for the time of the formation of intramontane basins and provide an estimate of Cenozoic relief evolution for the eastern part of Eastern Alps.

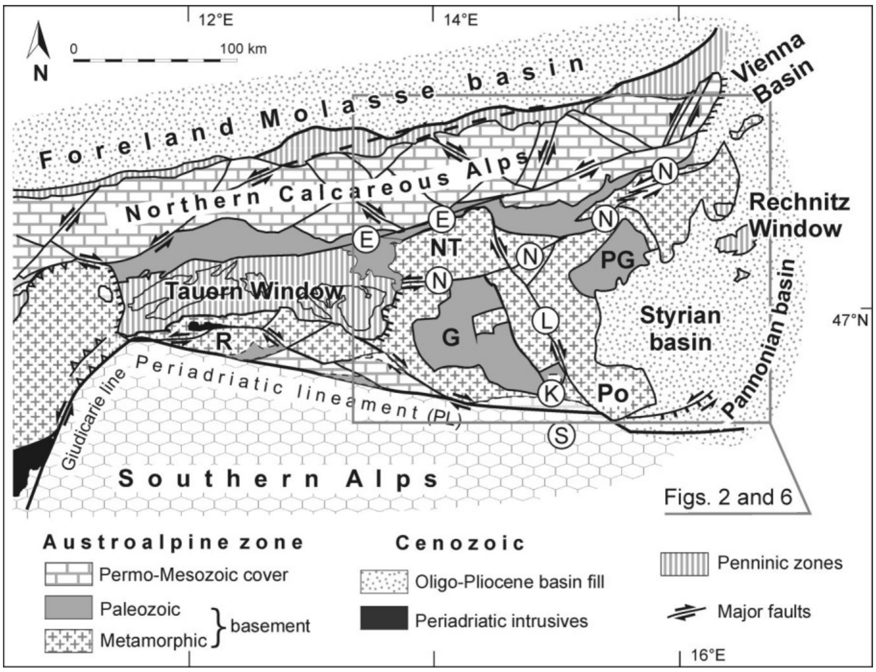

Figure 1: Tectonic framework of the Eastern Alps. E: Enns valley; N: Noric depression; L: Lavanttal; K: Klagenfurt basin; S: Slovenian basin; Po: Pohorje (Bachern) mountains; G: Gurktal Alps; NT: Niedere Tauern; PG: Paleozoic of Graz; R: Rieserferner intrusion. The remnants of the Noric depression are arranged along the sinistral, WSW-ENE oriented Mur-Mürz fault system (map after Bigi et al., 1990).

2. Regional geological setting

The most characteristic feature of the Eastern Alps is the Austroalpine mega-unit (Fig. 1), which represents the rigidly behaving upper plate during Paleogene continental collision. The Austroalpine unit acts as an orogenic lid above the Penninic mega-unit, which experienced metamorphism and hence behaved ductilely during collision (Lammerer and Weger, 1998). The Penninic domain contains remnants of the 'Alpine' ocean separating the Austroalpine unit, a former part of the Africa-derived Adriatic plate, and the European plate (e.g., Frisch, 1979; Dercourt et al., 1985; Stampfli et al., 1998). In the Tauern Window (Fig. 1), an oceanic sequence including ophiolites is underlain by a fragment of Variscan basement (largely occupied by Zentralgneis) and post-Variscan cover rocks that split off from the European continent in late Mesozoic times (Lammerer and Weger, 1998). The Zentralgneis masses, Variscan granitoids transformed into gneisses during Cenozoic metamorphism, were rapidly exhumed in Miocene times and form a complex metamorphic dome structure in the Tauern Window (Frisch et al., 2000b). In the Rechnitz Window Group at the eastern margin of the Alps (Fig. 1) only parts of the oceanic sequence with ophiolites are exposed (Koller, 1985). The area east of the Tauern Window, which is the object of this study, is occupied by Austroalpine metamorphic basement, weakly metamorphosed Paleozoic rocks, and subordinate Permo-Mesozoic cover. The Penninic windows to the east (Rechnitz Window Group) and west (Tauern Window) of the study area indicate that the Austroalpine domain overlie on Penninic substratum. Seismic measurements suggest that the Austroalpine/Penninic boundary reaches a depth of about 5 to 10 km between these windows (Aric et al., 1987; Graßl et al., 2004).

Paleogene continental collision was responsible for the formation of the crustal stack. Slab breakoff in Early Oligocene time (Blanckenburg and Davies, 1995; Sinclair, 1997) caused surface uplift of the Alps west of the later Tauern Window (Frisch et al., 1998). Thermal weakening in the course of metamorphism (thermal peak around 30 Ma; Christensen et al., 1994), continued N-S convergence, and free space for escape due to subduction in the Intracarpathian Basin formed the prerequisites for lateral tectonic extrusion in Early and Middle Miocene times (Ratschbacher et al., 1991). Around 17 Ma, when the Zentralgneis units of the Tauern Window experienced updoming and rapid exhumation (Cliff et al., 1985), the Austroalpine lid disintegrated into a number of tectonic blocks that moved eastward on top of the softened Penninic substratum and along large-scale strike-slip faults. Lateral tectonic extrusion is defined as the combination of orogen-parallel collapse and block escape (Ratschbacher et al., 1991).

2.1 Intramontane basins

Transtensional movement along large-scale conjugate strike-slip fault zones of the escape pattern created a number of short-lived intramontane basins filled with mostly Ottnangian or Karpatian through Badenian (Early/Middle Miocene) sediments. Most of the basins represent pull-apart or negative flower structures lined up along the dextral Lavanttal and the sinistral Ennstal and Mur-Mürztal ("Noric depression") fault systems (Figs. 1 and 2).

In most cases, the age of the sediment fill of the basins is poorly constrained by paleontological data (see overviews by Weber and Weiss, 1983; Kuhlemann, 2000). However, it is generally accepted that the climax of subsidence and sedimentation occurred in the Karpatian and Early Badenian (ca. 18-15 Ma; Fig. 3), synchronously in all basins. In the Lavanttal basin the sedimentation continued until Pannonian times (ca. 10 Ma). In the Klagenfurt basin, which is a relatively large basin with an asymmetric geometry, sedimentation started in Sarmatian times (ca. 12 Ma).

The intramontane basins of the study area contain conglomerates, sandstones, siltstones, claystones, and marls (Weber and Weiss, 1983; Tollmann, 1985). Conglomerates are generally dominant in the basal parts of the sequences. Their material derived from local sources, mostly from the Austroalpine metamorphic basement and the weakly metamorphosed Paleozoic units. The Penninic units were still buried and not at disposal for erosion (Exner, 1949). Coal seams, several of which have been exploited in former days, occur in most basins. In early Badenian time, a marine ingression affected the Lavanttal basin (Beck-Mannagetta, 1952) and brackish equivalents invaded the Fohnsdorf basin and its eastward continuation in the Noric depression (e.g. Sachsenhofer et al., 2003). Since the intramontane basins formed as fault-bounded structures during W-E extension, their remnants are lined up along valley-like depressions today. The basins were probably much more extended during Miocene than today and the basin remnants arranged along the major W-E depressions were probably interconnected.

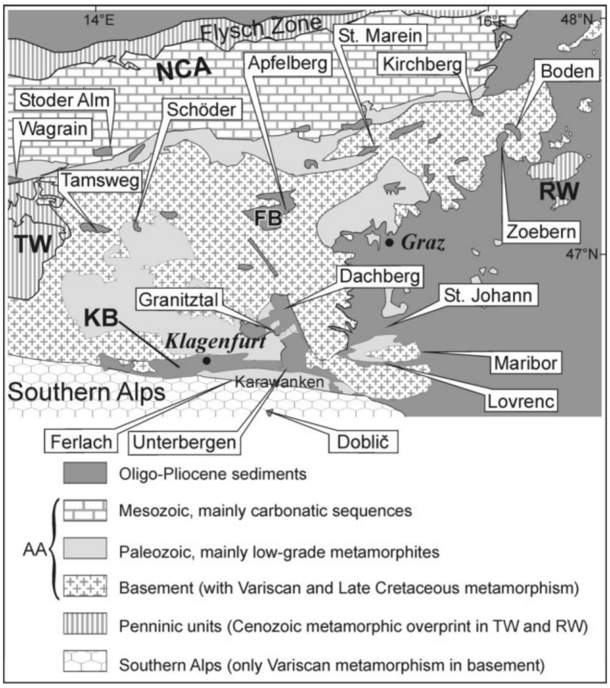

Figure 2: Distribution of the intramontane basins east of the Tauern Window and the sample sites. AA: Austroalpine, TW: Tauern Window, RW: Rechnitz Window, NCA: Northern Calcareous Alps, KB: Klagenfurt basin, FB: Fohnsdorf basin.

2.1.1 Ennstal depression

The westernmost occurrence of the intramontane sediments is known from the *Wagrain basin* situated north of the Tauern Window. In local fans of the Wagrain basin conglomerates, mica-rich sandstones, claystones and coal seams are exposed (Sachsenhofer, 1988). The *Stoder Alm* succession is situated 1000 m above the valley floor in the eastern Dachstein massif, but is considered to have formed a continuous deposit with the Gröbming-Stainach basin remnant in the valley floor of the Ennstal depression (see in Fig. 2 the elongated basin remnant east of Stoder). The latter is only represented by scarce outcrops of bad quality, consisting of brown pebbly siltstones and marls. In the Hieflau basin the Miocene (probably Ottnangian-Karpatian) coarsening-upward siliciclastic cycle was deposited on remnants of bauxite lenses (Wagreich et al., 1997). The depositional ages of the sediments in the basin remnants aligned along the Ennstal depression are badly constrained. Tollmann and Kristan-Tollmann (1963) attributed a Middle Oligocene to Early Miocene age to the coal-bearing sandstones, claystones and marls of Stoder Alm (Fig. 2). Imbrication of pebbles indicates transport from the south in the Wagrain basin. We find that in the axial fluvial system of this depression the orientation of leaves and silt pseudomorphs after log pieces indicate transport of sandy material from the SW.

2.1.2 Noric (Murtal-Mürztal) depression

The major and sampled basin remnants of the Noric depression are the *Tamsweg basin*, the Schöder creek, the Fohnsdorf basin (sampled at Apfelberg), St. Marein and Kirchberg (from west to east). In the Tamsweg basin, at a distance of 4 km from the actual eastern margin of the Tauern Window (Fig. 2), exclusively Austroalpine debris, mainly from the metamorphic basement but also the Paleozoic units, was deposited (Winkler-Hermaden, 1957; Exner, 1949; Heinrich, 1977; Zeilinger et al., 1999). Sediment supply from western directions dominated. This indicates that the Penninic rocks of the Tauern Window were still covered by Austroalpine units. The *Fohnsdorf basin* is the largest and deepest basin of the Noric depression, located at the intersection of the conjugate sinistral Mur-Mürz and the dextral Pöls-Lavanttal fault systems. Above local basal breccias and conglomerates, 500 m of mainly sandy to clayey sediments of probably Karpatian age, dated by land and freshwater molluscs, were deposited (Mottl, 1970; Polesny, 1970). A tuff layer near the top is dated by the zircon fission track method at 14.9 Ma (Ebner et al., 2000), suggesting a Badenian depositional age for the major part of the succession (Sachsenhofer et al., 2000; 2003; Strauss et al, 2001; 2003). A coal layer up to 15 m thick, which was mined until recent times, and an over 1000 m thick, mainly marly sequence deposited in lacustrine environment, follow. Towards the top, sandstones and fine-grained conglomerates are intercalated. Finally, a thick sequence of conglomerates has been deposited. In contrast to the former view of a compressional event forming an asymmetric syncline with an overturned southern limb between a Karpatian and a Badenian sedimentary cycle (see Weber and Weiss, 1983, and references therein), seismic data favour a syn- and post-depositionally formed positive flower structure (Sachsenhofer et al., 1998). The Fohnsdorf basin is the most spectacular example of a pull-apart hole in the Eastern Alps (see Ratschbacher et al. 1991). Sediment provenance from north was documented at the northern margin by Hölzel and Wagreich (2004), whereas sediments in the Apfelberg area derived from the South (Strauss et al., 2003). In the *St. Marein basin*, a waste pit 2 km SW of St. Marein temporarily exposed conglomerate channels in greenish, immature sandstones, which grade into fine-grained, variegated sandstones upsection. Ripple marks, oriented leaves and coalified log pieces indicate dominant current directions from the SE to E.

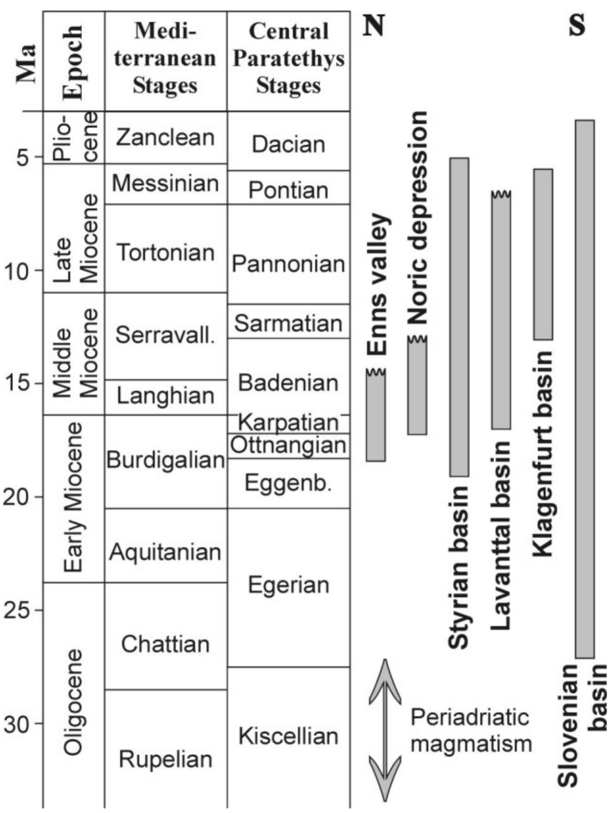

Figure 3: Time scale with Mediterranean and local, Paratethyan stages (Steininger et al., 1988), and the sedimentary record of the intramontane basins (modified after Sachsenhofer, 1992; Blanckenburg and Davies, 1995; Tari and Horváth, 1995; Frisch et al., 1998).

2.1.3 Lavanttal basin

This elongated basin developed by subsidence in pull-apart and halfgraben structures following the NNW-SSE trending dextral Lavanttal fault (Fig. 1). The Granitztal subbasin, located south-west of and oriented perpendicularly to the main basin, started with a fluvial cycle dominated by relief-filling fanglomeratic local debris in the Ottnangian (Beck-Mannagetta, 1952; Klaus, 1956). In Early Badenian time, an ingression from the southern Styrian basin established fully marine conditions in the Lavanttal basin. The basal Mühldorf beds contain a marine fauna with molluscs, corals, and foraminifera (Schmid, 1974). In the Middle to Late Badenian, the sequence graded into brackish, then freshwater deposits with conglomerates, sandstones, claystones, marls and coal seams. A Late Badenian conglomerate fan prograded from the west (Beck-Mannagetta, 1952). In Early Sarmatian times, a final ingression of the Paratethys from the southeast established a brackish environment, passing into freshwater deposits with coal seams in the northern part of the basin. Fault-controlled differential subsidence enabled local lacustrine and fluvial deposition in Pannonian time (Beck-Mannagetta, 1952).

2.1.4 Klagenfurt basin

The Klagenfurt basin forms a 75 km long, asymmetric structure, along in E-W direction, bounded in the south by a reverse fault along the Karawanken Mts. Sedimentation of fossiliferous lacustrine clayey and sandy material accompanied by coal seams, started in Sarmatian times (Kahler, 1935; Klaus, 1956; Papp, 1957). Similar deposits locally also cover the southward-tilted Karawanken chain. Some intercalated, quartz-rich, fine-grained conglomerates in the main basin derived from low-grade metamorphic Paleozoic sequences of the Gurktal nappe to the north. In slightly younger beds of this succession pebbles were supplied from the south. Late Sarmatian to Early Pannonian conglomerates deposited from north-directed rivers are found in tectonic slices of the Karawanken chain (Nemes et al., 1997). Upsection, olistoliths up to 2 km long have glided from the rapidly uplifting Karawanken chain into the conglomerate fans of the Klagenfurt basin (van Husen, 1976).

2.1.5 Slovenian basin

There is hardly any literature available for the northern margin of the Slovenian basin in the area of the Kamnik (Steiner) Alps. We have collected at Doblic arenitic samples from the molasse sequence of Burdigalian age (pers. comm. U. Herlec 1995; Fig. 2). Presence of volcanic debris and calc-arenitic components of bryozoans, red algae, and shells indicate a near-shore marine environment.

3. METHODS

Our study is based on the fission track ages of apatite grains in sandstone samples from the Neogene intramontane basins in the eastern part of the Eastern Alps. The detrital thermochronology or age provenance method is successfully used to reconstruct the cooling ages of the source areas of a clastic sediment at the time of sedimentation (Hurford, 1984;

Carter, 1999; Garver et al., 1999; Ruiz et al., 2004). The fission track detrital thermochronology is usually applied on zircon crystals due to their mechanical and chemical stability. Because of their high uranium content a high number of tracks (often >100) can be counted in a single zircon crystal. Thus the individual crystal data have relatively high precision. Technically, apatite is less ideal and its usage is less widespread, because (i) it is softer and chemically less stable than zircon, (ii) the uranium content in the apatite crystals is usually two order of magnitude less than in zircon crystals and (iii) the apatite has a high sensitivity to post-sedimentary thermal overprint. However, in our case the magnitude of post-Cretaceous exhumation was much less than the depth of the reset temperature of zircon fission tracks. The Austoalpine areas contain mainly pre-Cenozoic zircon FT ages. Thus only apatite FT dating can yield relevant results for the Cenozoic exhumation history of the study area.

3.1 Field work

We have studied all intramontane basins of the Eastern Alps in several field campaigns. During the detailed mapping of some occurrences (Zeilinger et al., 1999; Márton et al., 2000) and during sampling of selected sites we have registered provenance indicators with special care. Pebble composition, imbrication, bedding style and flow indicators in the arenitic sedimentary rocks and orientation of plant fragments in the pelites have been registered. For a proper understanding of the pebble composition of the Neogene sedimentary formations we have visited the creeks in the neighbourhood and compared the ancient and recent pebble spectra.

3.2 Laboratory procedure

In total 26 medium grained sandstone samples were processed with the usual heavy mineral concentrating techniques (crushing, sieving, Wilfley-table, acetic acid treatment, polytungstate gravity separation, isodynamic magnetic separation and di-iodmethane gravity separation). No handpicking was applied to avoid man-made fractionation of some apatite population with special properties. 16 samples were rich enough in apatites, these were dated by the external detector method (Gleadow, 1981). After imbedding in epoxy and a five step polishing procedure the crystals were etched by nitric acid (Donelick et al., 1999). Neutron irradiations were made at the RISØ reactor (Denmark) and the reactor of the Oregon State University (USA). After irradiation the induced fission tracks in the mica detectors were revealed by etching in 40% HF for 30 min at 21°C. Track counting was made with a Zeiss-Axioskop microscope – computer-controlled stage system (Dumitru, 1993), with magnification of 1000. The FT ages were determined by the zeta method (Hurford and Green, 1983) using age standards listed in Hurford (1998). The error was calculated by using double Poisson dispersion (Green, 1981). Usually sixty grains were dated per sample to create a proper database for the component analysis (Copeland and Peters, 1997; Vermeesch, 2004).

Some useful additional age-independent information can be obtained by the optical characterisation of the apatite crystals. The shape, surface, colour, zoning, and inclusions of the dated apatite grains can carry information on the lithologies of the source rocks and partly also on the transport mode and distance (e.g. Sachsenhofer et al., 1998). These features were registered for all dated grains during the microscopic work.

3.3 Data processing - identification of age populations

By the dating of single grain ages in clastic sediments the result can not be expressed by a single number, thus neither the pooled, nor the mean or central age (Galbraith and Laslett, 1993) can represent a composite sample. Only *the whole distribution of single grain ages* refers to the character of a sample and the age distribution in the source areas. The characteristic age populations of a distribution can be identified by 'component search'

Basin	Locality	Code	Strat. Age	Cryst.	Spontaneous ρs (Ns)	Induced ρi (Ni)	Dosimeter ρi (Ni)	$P(\chi^2)$ [%]	Disp.	FT age [Ma ± 1s]
Enns valley	Wagrain	B-6	Karpatian	59	3.01 (735)	5.09 (1242)	4.42 (8607)	99	0.00	50.0 ± 2,6
Enns valley	Stoder Alm	EN-11	Ottnangian	60	10.0 (2648)	13.3 (3529)	5.01 (12211)	36	0.08	70.1 ± 2,5
Noric depr.	Schöder	EN-17	Ottnangian	50	2.59 (1013)	5.86 (2294)	5.15 (10041)	0	0.22	43.4 ± 2,4
Noric depr.	Apfelberg	EN-21/A	Badenian	60	2.64 (1218)	6.15 (2845)	5.17 (10168)	39	0.09	41.4 ± 1,8
Noric depr.	St. Marein	EN-19/C	Badenian	52	2.98 (1172)	6.74 (2646)	4.44 (10915)	53	0.08	36.7 ± 1,6
Noric depr.	Kirchberg	GP-23	Badenian	42	3.67 (819)	7.59 (1695)	4.97 (12211)	95	0.05	44.6 ± 2,2
Styrian B.	Boden	GP-20	Badenian	50	4.79 (1274)	8.74 (2322)	4.56 (4486)	35	0.10	46.6 ± 2,1
Styrian B.	Zoebern	GP-19	Badenian	60	7.31 (2732)	15.1 (5653)	4.66 (9076)	3	0.12	42.0 ± 1,5
Styrian B.	St. Johann	GP-44	Karpatian	55	3.77 (1310)	11.5 (4004)	5.11 (10041)	4	0.14	31.4 ± 1,4
Lavanttal	Dachberg	GP-50	Badenian	60	3.55 (1593)	11.0 (4936)	5.17 (10168)	0	0.27	31.8 ± 1,6
Lavanttal	Granitztal	GP-49	Ottn.-Karp.	60	5.45 (1444)	10.7 (2852)	5.08 (6232)	0	0.41	47.2 ± 3,2
Klagenfurt B.	Unterbergen	GP-47	Sarmatian	60	3.58 (1207)	11.5 (3898)	5.17 (10168)	61	0.05	29.8 ± 1,2
Klagenfurt B.	Ferlach	GP-30	Sarmatian	60	2.69 (1208)	8.32 (3725)	4.44 (4486)	0	0.35	28.2 ± 1,8
Slovenian B.	Doblic	GP-58	Egg.-Ottn.	60	4.47 (1717)	9.04 (3473)	4.97 (12211)	0	0.47	43.1 ± 3,1
Pohorje	Tunnel	SLO-11	Karpatian	60	2.60 (1383)	11.3 (6279)	4.66 (9076)	0	0.34	18.7 ± 1,1
Pohorje	Maribor	SLO-59	Ottn.-Karp.	60	2.36 (1016)	10.4 (4650)	4.66 (9076)	1	0.14	19.3 ± 0,9

Table 1: Apatite fission track results obtained on samples from the intramontane basins. The indicated mean ages have no definite meaning because the samples contain more than one apatite population. For their evaluation, see text and Table 2. Cryst: number of dated apatite crystals. Track densities (ρ) are as measured ($\times 10^5$ tr/cm^2); number of tracks counted (N) shown in brackets. $P(\chi^2)$: probability obtaining Chi-square value for n degrees of freedom (where n = no. crystals-1). Disp.: Dispersion, according to Galbraith and Laslett (1993). Central ages calculated using dosimeter glass: CN 5 with $\zeta_{CN5} = 373 \pm 7$.

methods. We have used the PopShare software (Dunkl and Székely, 2002) and SIMPLEX algorithm (Cserepes, 1989) in order to identify the age populations within the single grain age distributions of our samples. The fittings were performed to search two populations by minimizing the root mean square value.

4. Results

The fission track results are summarised in Table 1 and the age distributions are presented in Fig. 4. The single grain age distributions show a very variable picture. In some samples the youngest ages are around 50 Ma (e.g. Stoder), while in other samples the oldest ages of the dominant population is around 30 Ma. The distributions are also variable according to their spread and shape. Sometimes mixing from more sources is obvious, but in case of more samples the symmetry and narrow distribution suggest that only one age component is present. The central ages of the samples usually do not have any meaning, because the apatite crystals usually derived from diffe-rent sources and display a complex distribution. Seven samples did not pass the chi-square test (Galbraith, 1981). These and some others were treated for component analysis. The frequently low numbers of spontaneous track counts results in a rather broad scatter, which did not allow separating more than two components with proper reproducibility. The results are pre-sented in Table 2.

4.1 The meaning of detrital apatite ages

We conclude that the measured age spectra are representing the apatite FT ages of Austroalpine areas in Early-Middle Miocene

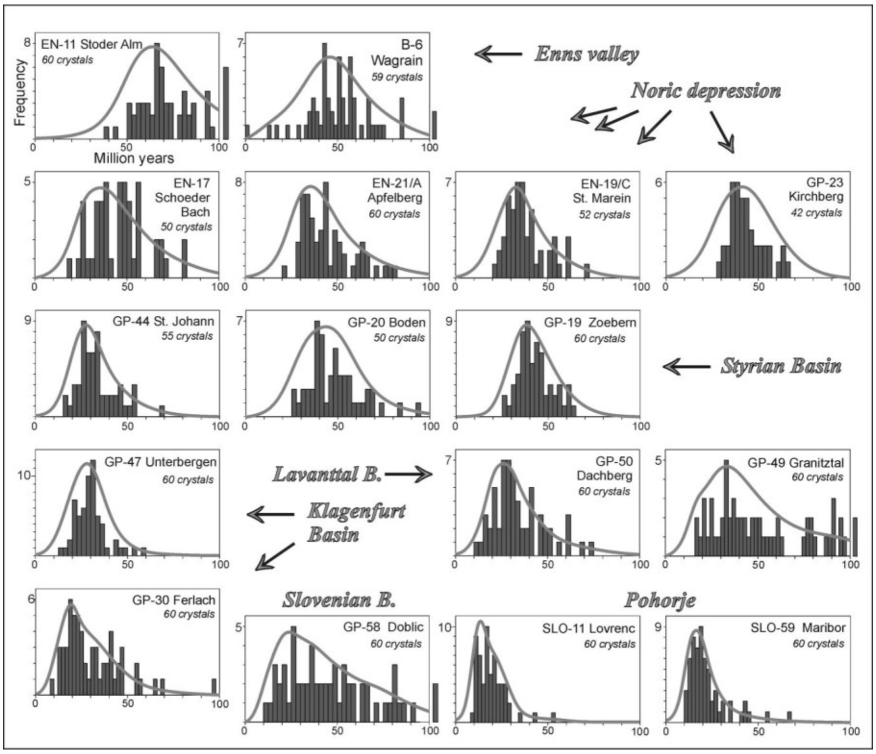

Figure 4: Apatite fission track single grain age distributions in the Miocene intramontane sediments. The arrangement of the diagrams follows the geographic position of the sample localities (northern samples at top, western ones at left). The gray lines represent age spectra (probability density plots) and they were computed for all crystals according to Hurford et al. (1984).

time (ca. 15 Ma). Our assumption is based on the following:

- The samples were mainly collected from Karpatian and Badenian strata. The Unterbergen and Ferlach samples of the Klagenfurt basin are slightly younger (Sarmatian) and the Doblic sample in the Slovenian basin is older (probably Eggenburgian). In the evaluation of the age-provenance data we do not consider the minor and rather poorly constrained differences in the sedimentation age. The samples are in general considered to have Early to Middle Miocene depositional ages of 15 ± 2 Ma.

- There is no indication of sediment recycling. The pebble spectra of the intramontane sedimentary basins do not contain sandstone pebbles from older sedimentary successions, only metamorphic material and some non-metamorphosed carbonate pebbles from the Northern Calcareous Alps can be found.

- The characters of the apatite grains correspond to the apatites found in the heavy mineral concentrates made from the metamorphic rocks of the region. We found traces of the Cenozoic magmatic activity only in one sandstone sample (Unterbergen, Klagenfurt basin; Fig. 2). From this sample 60 apatite grains were dated. Roughly one half of the crystals are euhedral with very well preserved prismatic faces and edges. The other half consists of irregular crystal fragments or rounded grains. The inclusions also show a consistent difference: in the euhedral apatites the inclusions are mainly needle-shaped zircons, while in the irregular and rounded crystals tiny opaque flakes predominate, probably graphite and/or Fe-Ti-oxides. The central ages of the two different populations are practically indistinguishable (Fig. 5). However, the chi-square test shows a considerably tighter distribution of the euhedral grains as compared to the anhedral population. The uranium content has also a much smaller relative error, which is a characteristic of magmatic, especially volcanic rocks with simple geochemical evolution (Král' and Burchart, 1983). The broad scatter in the U content of the anhedral population is typical for (para-)metamorphic rocks. As the sedimentation age of the sandstone is considerably younger than the central age of the euhedral apatite population (lag time: ~17 Ma; see Brandon and Vance, 1992), we can not relate the euhedral population directly to an ash-fall. It probably derived from volcanic edifices and shallow intrusions by very short transport. The very similar average cooling ages of the two apatite populations (Fig. 5) indicates that the rounded grains were reset in the thermally affected zone around the intrusions. The broader scatter of the individual grain ages of the rounded population can be explained by the lower number of tracks in some grains (higher variation in the U content of the grains) and by the complex cooling histories in the contact zones around the intrusions.

- The vitrinite reflectance data measured on the sampled sites indicate only very mild, practically negligible post-depositional thermal overprint (Sachsenhofer, 1988; 1992; Sachsenhofer et al., 1998). The only exception is the Tamsweg basin (Fig. 2), where the burial temperature was high and the apatite FT chronometers suffered significant reset. Therefore, the FT data of this locality are not evaluated in this work. All other sites are considered as unreset and therefore the apatite FT ages trapped in the sediments are considered to reflect the surface distribution of cooling ages in the Middle Miocene across the study area.

5. Age-provenance of the intramontane sediments and paleogeographic reconstruction of major river systems in Miocene

The apatite age components of these Miocene sediments are mainly Paleogene, only few age components fall into the latest Cretaceous or into the Miocene (Table 2; Fig. 6A). In the samples from the northern part of the study area (Enns valley and Noric depression), the characteristic means of the age components are Cretaceous-Paleocene, and Eocene. The arrangement of these old ages at the north allows concluding that:

a) The post-Cretaceous (more precisely post-Eoalpine) exhumation in the northern belt of the Austroalpine basement was very low. The preservation of pre-Eocene ages indicate that the erosional removal just touched the topmost part of the post-Eoalpine partial annealing zone and the apatite ages on the surface had not modified significantly since Late Cretaceous. The depth of total pre-Miocene erosion was probably less than ca. 1.5 km (considering normal geothermal gradient of ca. 30 °C/km).

b) Even in the immediate surroundings of the present Tauern Window, the Austroalpine metamorphic basement supplied apatite grains with old, pre-Neogene FT ages (localities Wagrain and Schöder; Fig. 6A). This

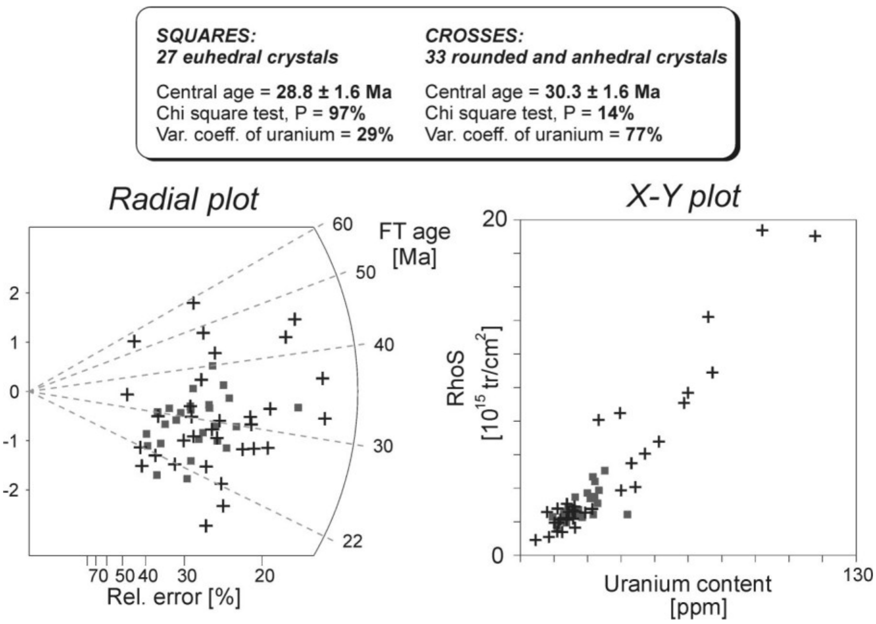

Figure 5: Identification of the magmatic component in a sandstone sample (Unterbergen, Klagenfurt basin, Sarmatian sandstone).

means that at the time of deposition, the erosion in the Austroalpine basement had not yet incised into the zone of young apatite cooling ages of the exhuming crust even above the contemporaneously forming Penninic windows - although the Middle Miocene exhumation was fast in this region (Cliff et al., 1985; Kuhlemann et al. 2001).

c) There was no sediment import from the south and southeast, because no Oligocene and Miocene age components (typical for the southern areas, see below) were identified in the northern samples.

It is possible to sketch a paleogeographic map on the position of the major rivers and sediment transport trends for Middle Miocene. According to the array of the sediment remnants, provenance indicators and the pre-Oligocene apatite FT ages in the north we suppose that the two roughly west-east trending depressions (see Fig. 1) were filled by an east-draining river network: Paleo-Enns and Paleo-Mur-Mürz rivers (Fig. 6B). These supposed rivers occupied the valley system created by Early Miocene strike-slip tectonics between the rotating and displacing structural blocks (Ratschbacher et al., 1989; Márton et al., 2000). The marginal facies debris cones indicate small side rivers as presented in Fig. 6B by small arrows. These side rivers prove the existence of an eroding area (and a watershed) between Paleo-Enns and Paleo-Mur-Mürz river valleys. The Niedere Tauern were already a barrier between the valleys at that time, because apatite fission track ages indicate its cooling and exhumation for Early Miocene (Hejl, 1997; Reinecker, 2000). However we suppose a connection and sediment transport from the north to the Mur-Mürz river valley NE of the Fohnsdorf basin. Southwest of Leoben the sediments of the Noric depression contain conglomerates with fossiliferous Mesozoic limestone pebbles typical for the Northern Calcareous Alps. Toward east the reconstruction contains more uncertainties, the sediments of the Kirchberg basin (see Fig. 2) are badly exposed and only very few provenance indicators are available.

In the *southern part of the study area* the picture is more complex (Fig. 6A). Here we found age components from the Cretaceous to the Miocene. The mean values of the Oligocene age components give a rather tight cluster between 30 Ma and 27 Ma (Table 2). These ages match well with the final and dominant peak of Periadriatic magmatic activity (Dal Piaz et al., 1988; see Fig. 3). The thermal effect of the intrusions created a characteristic reset in many isotope chronometer systems along the Periadriatic Lineament (Hejl, 1997; Elias, 1998; Steenken et al., 2002; Most, 2003). We conclude that the apatites having Oligocene FT age and thus a significant part of the siliciclastic sediments are derived from the immediate neighbourhood of the Periadriatic magmatic bodies.

Basin	Locality	M1	SD1	%c1	M2	SD2
Enns valley	Wagrain	**50**	3	*100*		
Enns valley	Stoder Alm	**70**	3	*100*		
Noric depr.	Schöder	**43**	13	*93*	**80**	6
Noric depr.	Apfelberg	**37**	7	*69*	**60**	12
Noric depr.	St. Marein	**34**	7	*83*	**56**	5
Noric depr.	Kirchberg	**45**	2	*100*		
Styrian B.	Boden	**40**	8	*43*	**53**	14
Styrian B.	Zoebern	**39**	6	*78*	**56**	5
Styrian B.	St. Johann	**28**	4	*41*	**36**	12
Lavanttal	Dachberg	**27**	6	*42*	**38**	17
Lavanttal	Granitztal	**36**	13	*70*	**85**	13
Klagenfurt B.	Unterbergen	**30**	1	*100*		
Klagenfurt B.	Ferlach	**20**	4	*37*	**36**	14
Slovenian B.	Doblic	**29**	12	*42*	**58**	23
Pohorje	Lovrenc	**19**	1	*100*		
Pohorje	Maribor	**17**	4	*73*	**33**	11

TABLE 2: Age components of the apatite single-grain distributions (M1 and M2: mean values of the components (Million years); S1 and S2: standard deviations of the components; *%c1*: fraction of the younger component). The components were identified by the SIMPLEX procedure (Cserepes, 1989) using PopShare program (Dunkl and Székely, 2002). Gray records indicate age distribution with single component.

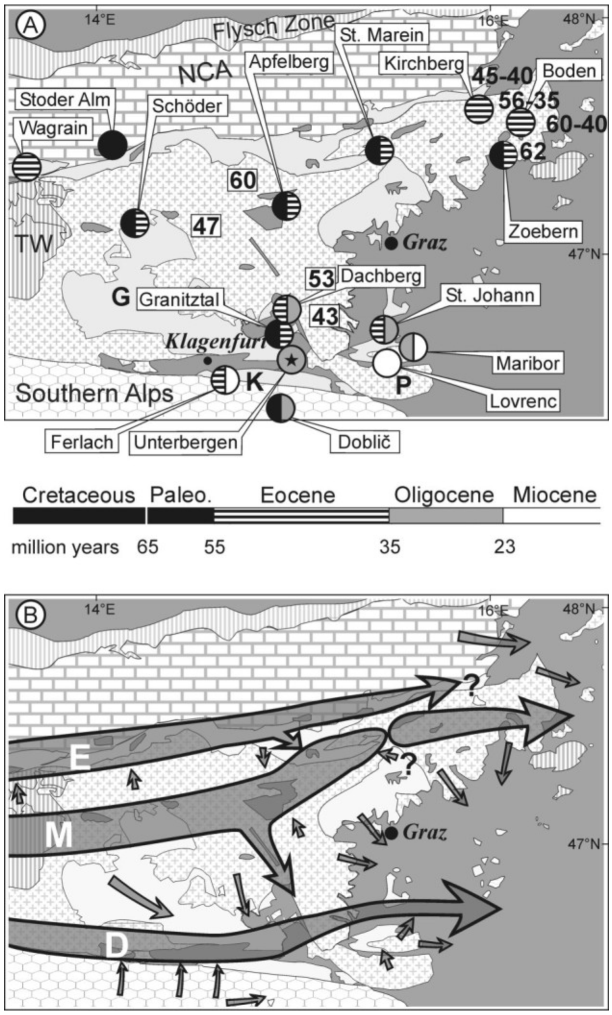

FIGURE 6: (A): Apatite FT age components in the sediments of the intramontane basins (for legend see Fig. 2). Star represents magmatic component (Fig. 5). Ages of the stage boundaries at the time scale from Harland et al., 1989. Numbers show apatite apparent FT ages measured on crests and other elevated localities of the metamorphic basement (in frame: Hejl, 1997; no frame: Frank et al., 1996; Balogh and Dunkl, 2005; Dunkl unpublished data). NCA: Northern Calcareous Alps, P: Pohorje, K: Karawanken, G: Gurktal Alps.
(B): Major provenance systems of the eastern Eastern Alps in the Middle Miocene. Long broad arrows represent the principal dewatering features, the Paleo-Enns, Paleo-Mur-Mürz and Paleo-Drau rivers (E, M and D, respectively). Small arrows indicate local sediment suppliers (along the margin of Styrian basin: Ebner and Sachsenhofer, 1991).

In this southern area, the drainage system of the Paleo-Drau river was dominating and transported sediments towards east, into the Pannonian basin (Benedek et al., 2001; Frisch et al., 2001). The Periadriatic magmatogenic clasts of the Unterbergen sample and the metamorphic apatites of Oligocene age could be derived from the contact zone of intrusives to the west, e.g., from the roof zone of the Rieserferner intrusion (Fig. 1). However, sedimentological observations indicate that short N-S directed rivers were also transporting material into the major drainage system of the Paleo-Drau river (Kuhlemann, 2000). We relate the Cretaceous age component of the Granitztal locality to such a side river from the north (Fig. 6B). However, there was most likely an additional source area in the south. We can suppose a southerly origin, because the Karawanken Mountains were not uplifted before the latest Middle Miocene and have not formed a barrier for north-directed sediment transport prior to the early 2001). The Periadriatic magmatogenic clasts of the Unterbergen sample and the metamorphic apatites of Oligocene age could be derived from the contact zone of intrusives to the west, e.g., from the roof zone of the Rieserferner intrusion (Fig. 1). However, sedimentological observations indicate that short N-S directed rivers were also transporting material into the major drainage system of the Paleo-Drau river (Kuhlemann, 2000). We relate the Cretaceous age component of the Granitztal locality to such a side river from the north (Fig. 6B). However, there was most likely an additional source area in the south. We can suppose a southerly origin, because the Karawanken Mountains were not uplifted before the latest Middle Miocene and have not formed a barrier for north-directed sediment transport prior to the early Late Miocene (van Husen, 1976). Thus we consider for the Doblic sample a southern provenance from the Southern Alps. The apatite FT thermochronometer shows rather young, mainly Miocene ages in the metamorphic basement exhumed along the presently exposed northern margin of the Southern Alps (see compilation in Most, 2003). However, prior to intense Miocene exhumation the South Alpine basement could have delivered apatites of pre-Cenozoic FT age (see locality Doblic; Figs. 6A and 6B).

The sediments of the Maribor and Lovrenc samples (see details in Sachsenhofer et al., 2000) mainly derived from the adjacent Pohorje (Bachern) Mountains. Local debris cones were dominating (indicated by small arrows around Pohorje in Fig. 6B). Contribution from distant sources transported by the Paleo-Drau river played a subordinate role. The Pohorje underwent extremely rapid Miocene exhumation (Fodor et al., 2002), which led to the supply of apatite grains with nearly synsedimentary FT ages with lag times of only 2-3 Ma.

6. Relief evolution of the Alps east of the Tauern window

We aim to compile a relief evolution trend for the study area. For this trial the principal input data are the cooling histories and sediment yields of the metamorphic areas. Additionally, we made following assumptions: (i) After the Late Cretaceous (Eoalpine) orogeny there was no tectonic denudation in the Austroalpine realm during the Paleogene, only erosional removal of the Austroalpine material. (ii) The climatic factor was subordinate relative to tectonic forces in the sediment production during Paleogene and Miocene (see Kuhlemann et al., 2002). (iii) In times of tectonic activity, applying to most of the Cenozoic, the rate of exhumation detected by thermochronology and the sediment yield display a positive correlation with the relief. For the reconstruction of paleo-relief the known structural events, basin formation histories, sediment yield as well as the FT data from the basement units and the clastic sediments were considered (Fig. 7).

(a) The Austroalpine basement underwent different grades of Cretaceous metamorphism and cooled with variable rates in Late Cretaceous (and Paleocene) times. Parts of the Austroalpine mega-unit were deeply buried in lower plate position (e.g. eclogite facies metamorphism in Koralpe; Miller and Thöni, 1996), and these blocks show very rapid cooling in Late Cretaceous. The Eastern Alps at that time had a mountainous relief with a high erosion rate supplying considerable amounts of siliciclastic sediment into the north Alpine Rhenodanubian flysch basin (Trautwein et al., 2001). An orogenic collapse was proposed by Ratschbacher et al. (1989) for the period around 80 Ma. This means that in some parts of the Austroalpine realm the decay of the mountainous relief was probably rapid (represented by curve α in Fig. 7). In other regions, e. g. near the western margin of the Eastern Alps, a mountainous relief was maintained for longer time. These areas supplied the Rhenodanubian flysch basin with Alpine-derived siliciclastic sediments until Paleocene time (Trautwein et al., 2001; curve β in Fig. 7). The Austroalpine relief evolution in Late Cretaceous and Paleocene times is thus represented by two trends indicating different exhumation modes.

(b) For the Paleocene - Early Eocene time we have only few direct information concerning relief and sedimentation in the Austroalpine realm. In the Northern Calcareous Alps, which formed the cover sequence of large parts of the metamorphic basement and the Paleozoic low-grade terrains until Eocene times, both marine sedimentation (Gosau Group sediments and reef limestones) and continental red clay deposition are characteristic (Wagreich and Faupl, 1994; Kázmér et al., 2003). We therefore conclude that the Paleocene and the Early Eocene was partly a period of stagnating uplift or subsidence and paleo-elevations of large areas were close to sea level. The Austro-alpine metamorphic basement was partly covered by shallow marine and lateritic sediments.

(c) The Gosau sedimentation was terminated by a compressional period that resulted in folding and thrusting in Middle Eocene times (Tollmann, 1986; Wagreich, 2001). During this compression the relief increased and we suppose mountainous relief for a short period in Middle Eocene. The basement areas were nearly completely exposed to erosion and a major part of the apatite FT ages were reset at that time. We therefore calculate widespread erosion to the depth of the partial stability zone of fission track in apatite. Considering a geothermal gradient of ca. 30 °C/km the depth of material being eroded was at least 2 km. On the other hand it was clearly less than ca. 6 km, because rather few Eocene mica argon or zircon FT ages are known from the Austroalpine unit (Liu et al., 2001). We have to distinguish the very northern part of the central Eastern Alpine metamorphic belt, where the Eocene erosion has

has removed only a thin layer and Cretaceous apatite cooling ages were preserved until Middle Miocene (see in Fig. 7 the dotted line during Eocene time).

(d) During Late Eocene - Early Oligocene the erosion was slow, and fine-grained sediments are characteristic in the foreland Molasse basin (Lemcke, 1988). We therefore assume a low relief and widespread peneplainization until ca. 30 Ma (see a similar scenario in the Northern Calcareous Alps; Frisch et al., 2001).

(e) Coarse clastic sedimentation in the Molasse Zone started ca. 30 Ma ago (Lemcke, 1988; Kuhlemann and Kempf, 2002). The Periadriatic magmatism reached its climax at the same time, which is considered as a consequence of slab breakoff (Blanckenburg and Davies, 1995). These processes indicate an increase of the relief in certain parts of the Eastern Alps, probably in the south (along the Periadriatic zone) and above the later Tauern Window, although its magnitude is not constrained properly (see Fig. 7).

(f) Before the beginning of the late Early Miocene we observe local subsidence and sediment filling of some intramontane basins, the relief east of the Tauern Window was probably moderate to low (Frisch et al., 2000a). In some basins the basal clastic sediments are mature with high amounts of quartz and depletion in heavy minerals except in the extremely resistant zircon-rutile-tourmaline group (Sachsenhofer et al., 2001). This chemically strongly leached material derived from slowly eroding areas with low relief. In contrast, the subsequently deposited main mass of the intramontane sediments is badly sorted and highly immature, which indicates short transport and rapid erosion. The basins subsided while the surrounding metamorphic highs exhumed and supplied siliciclastic debris (that is why this time period is represented by diverging lines in Fig. 7).

(g) During and after the Middle Miocene there was a decrease in relief. The preserved Eocene and Paleocene apatite FT ages at the highest levels of the metamorphic units (Hejl, 1997; Balogh and Dunkl, 2005; see numbers in Fig. 6A) and the existence of Cenozoic paleosurface remnants in this region (e.g. Nock paleosurface: Exner, 1949; Frisch et al., 2000a) exclude high erosion rates after Middle Miocene. Further the mass of molasse sediment derived from the Eastern Alps shows a significant drop during Middle Miocene and this indicates also a general decay of the relief (Kuhlemann, 2000). We suppose for Late Miocene low relief and extensive sediment coverage.

(h) The Pliocene to present compressional field of the Pannonian realm (Becker, 1993) is responsible for an increasing relief in the eastern Eastern Alps. The time constraints of the inversion of the intramontane basins are badly known, because the sedimentary sequences are all truncated and often deeply eroded. Using analogies from the Pannonian basin, a Late Sarmatian (~12 Ma; curve γ in Fig. 7) and/or a Pliocene inversion event (~5 Ma; curve δ) appear to be plausible as the major engine of the formation of the present relief (Royden et al., 1983 and Horváth and Cloething, 1996, respectively).

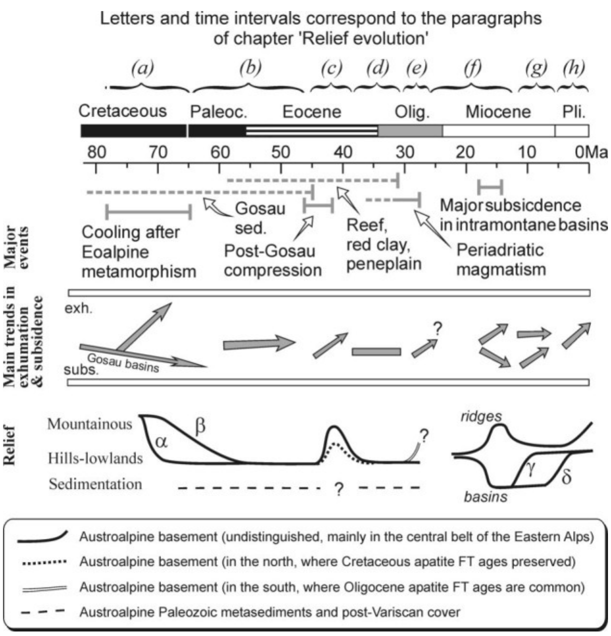

Figure 7: Summary of the major structural events, sedimentation periods, dominant trends in exhumation or subsidence, and the deduced relief evolution of the eastern part of Eastern Alps. Explanation of relief evolution paths α, β, γ and δ is in the text.

7. Conclusions

The alignment of Neogene intramontane sediment basin occurrences in three west-east belts mark major paleo-river systems (Paleo-Enns, Paleo-Mur-Mürz and Paleo-Drau) dewatering the Austroalpine area towards east. There was minor, probably only north to south directed sediment transport between the river valleys. The apatite FT age spectra in these sedimentary basins are very variable, the age components of the distributions are older in the northern than in the southern occurrences. The Cretaceous and Paleocene apatite FT age components indicate minor erosion of the Austroalpine metamorphites between Late Cretaceous and Middle Miocene in the north. In the south Oligocene apatite FT ages indicate the significance of exhumation and thermal reset generated by volcanism and magma emplacement along the Periadriatic lineament. The occurrence of Miocene apatite ages in the Miocene siliciclastic deposits at the Pohorje Mountains refers to a local, very rapid exhumation triggered probably by transpressional forces along the Periadriatic lineament.

The exhumation of the Austroalpine metamorphic basement occurred in several pulses. The post-Gosau compressional phase in Middle Eocene time generated a certain but limited increase in the relief of the eastern part of the Eastern Alps. It was sufficient to exhume metamorphic blocks, thus Eocene apatite FT ages became dominant on the surface of Austroalpine areas before Miocene. The post-Eocene exhumation was not able to completely destroy the Eocene peneplains, thus remnants of this paleosurface with Cretaceous to Eocene apatite FT ages at high elevations are still preserved.

We conclude also that a part of the eastern Eastern Alps (mainly along the east-trending river valleys) was covered by sediments in Middle and Late Miocene times. This area can be considered as (an already inverted) western prolongation of the Pannonian basin system.

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