Geodynamic evolution of the Rhenodanubian Flysch Zone – evidence from apatite and zircon fission-track geochronology and morphology studies on zircon

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Abstract: The geodynamic evolution of the East-Alpine Rhenodanubian flysch zone (RDFZ) is reconstructed by fission-track (FT) geochronology and the external habits of zircon. The samples are derived from Paleogene and Cretaceous formations of the RDFZ.

Ordovician, Carboniferous and Triassic zircon FT ages and the external morphology of the zircons of the Laab Formation are evidence for a European source area. The zircons of the Greifenstein Formation are derived from the Alpine orogen reflecting the Eoalpine orogeny. Due to the different provenance of these two Paleogene formations, two separate depositional areas are assumed, which are called the Main Flysch basin and the Laab basin. The Laab basin was positioned to the north of the Main Flysch basin. They were either separated by a submarine swell, or the Laab Formation was deposited in less deep water north of the Greifenstein Formation.

The thermal evolution of the RDFZ, which represents an accretionary wedge, is deduced from fission-track data. During the Paleogene, the differently buried stratigraphic units in the area between Salzburg and Ybbsitz experienced cooling due to exhumation after accretion of the European continental margin sediments.

Zusammenfassung: Die geodynamische Entwicklung der ostalpinen Rhenodanubischen Flyschzone (RDFZ) kann mit Hilfe von Spaltspurendatierungen und Zirkon-typologischen Studien rekonstruiert werden.

Ordovizische, karbonische und triassische Zirkon-Spaltspurenalter und die externe Morphologie der Zirkone der Laab-Formation beweisen ein europäisches Herkunftsgebiet der Siliziklastika. Die Zirkone der Greifenstein-Formation sind alpidischer Herkunft und reflektieren die eoalpidische Orogenese. Aufgrund der unterschiedlichen Provenienz der beiden paläogenen Formationen werden zwei Ablagerungsräume angenommen. Diese sind das Hauptflyschbecken und das Laaber Becken. Das Laaber Becken lag nördlich des Hauptflyschbeckens. Die beiden Ablagerungsräume waren entweder durch eine submarine Schwelle voneinander getrennt, oder die Laaber Formation wurde in geringerer Wassertiefe im Norden der Greifenstein-Formation abgelagert.

Die thermische Geschichte der RDFZ, die einen Akkretionskeil darstellt, kann aus Spaltspurendaten abgeleitet werden. Im Paläogen wurden durch Akkretion der europäischen Schelfsedimente die unterschiedlich tief versenkten Einheiten der RDFZ im Abschnitt Salzburg-Ybbsitz exhumiert.

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Keywords: Rhenodanubian Flysch Zone, Eastern Alps, Apatite and Zircon Fission-Track Geochronology, Pupin Method, Provenance, Thermal History

Contents

1. INTRODUCTION

The Rhenodanubian flysch zone (RDFZ) is of high geodynamic relevance for the reconstruction of the syn-collisional history of the East-Alpine area. Its sedimentary characteristics and clastic material contain information about the paleogeographic position, the internal basin structure and the source areas, which are still under discussion (e.g., HESSE, 1973; FRISCH, 1979; WINKLER et al., 1985; DECKER, 1990; FAUPL & WAGREICH, 1992; EGGER, 1992; HOMAYOUN & FAUPL, 1992; OBERHAUSER, 1995). In order to decipher the provenance of the detrital material the external and internal morphology of zircons were studied and the fission-track method on zircon and apatite was applied. The study provides new results and is a challenge to rethink the existing paleogeographic models. Another aim is to constrain the accretionary process by studying the thermal evolution of the RDFZ by apatite FT chronology.

2. GEOLOGICAL SETTING

The Rhenodanubian flysch zone forms a ~500 km long and narrow zone along the northern front of the Eastern Alps (Fig. 1). It contains mostly turbiditic sequences of Early Cretaceous to Middle/Late Eocene age (Fig. 2), deposited in a basin with partly oceanic and partly thinned continental crust (SCHNABEL, 1988, 1992; EGGER, 1992) at a convergent margin (TRAUTWEIN, 2000; TRAUTWEIN et al., 2001). Decoupled from its former basement (OBERHAUSER, 1980), the Rhenodanubian flysch is tectonically underlain by the Helvetic and Ultrahelvetic zones, which represent the shelf and the upper slope of the European margin to the north of the Rhenodanubian flysch.

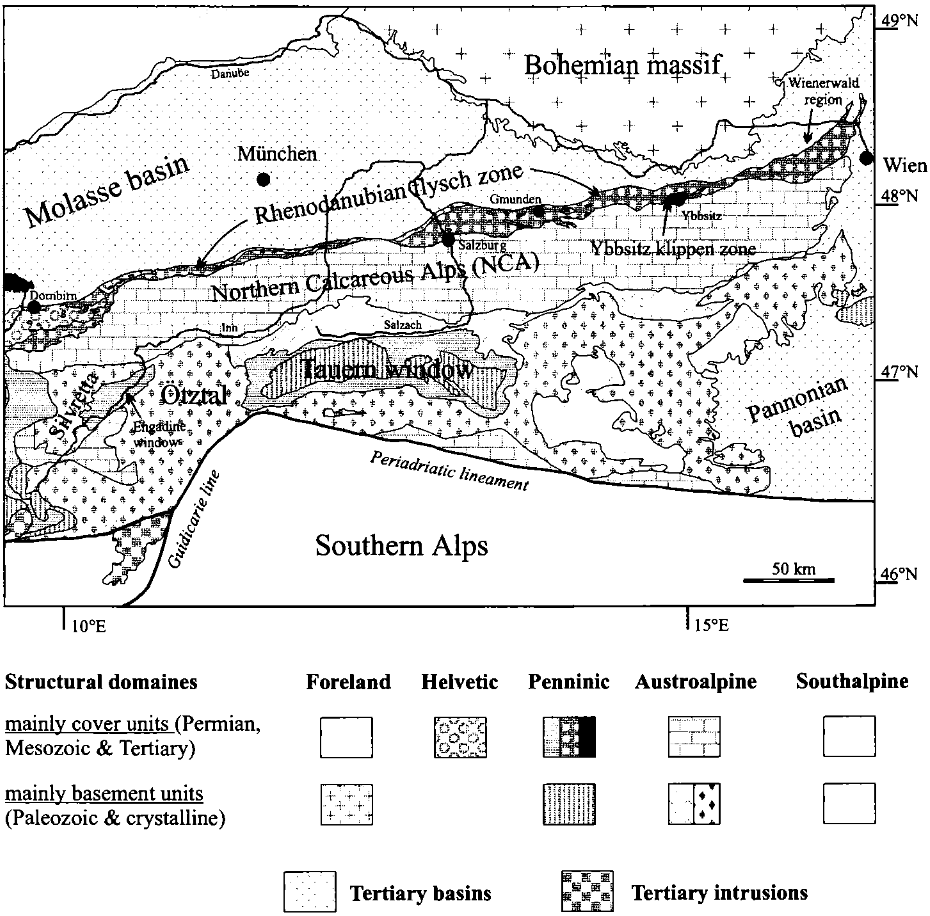


Fig. 1: Geological map of the Eastern Alps.

The Rhenodanubian flysch zone is strongly sliced and tectonically disrupted. The Main Flysch nappe stretches over the whole length of the RDFZ. In the Wienerwald, the RDFZ can be subdivided into three nappes. The Greifenstein nappe, which is the equivalent of the Main Flysch nappe (Schnabel, 1992), is overlain by the Laab nappe in the south and the Kahlenberg nappe in the south-east. The latter occupies the highest tectonic position (Prey, 1983).

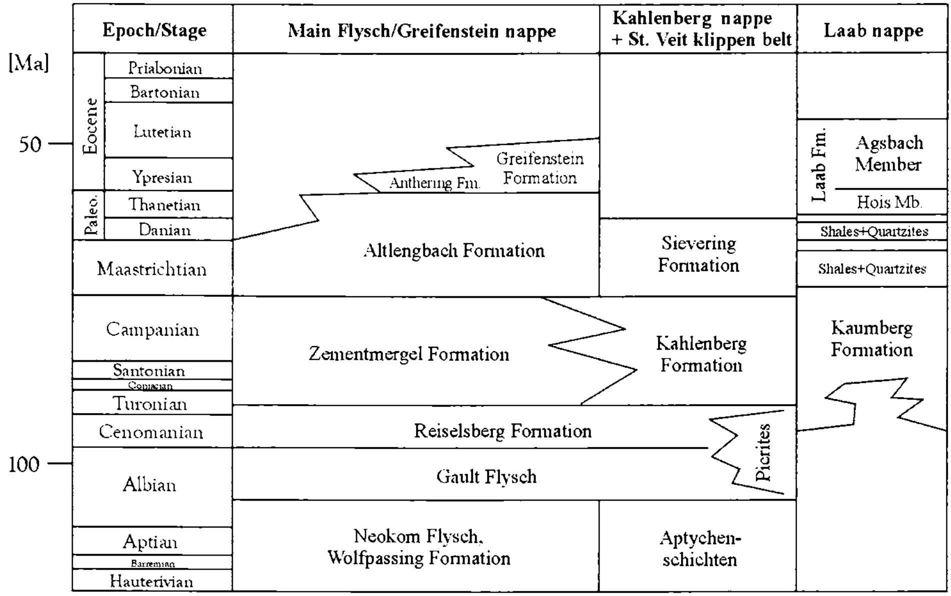


Fig. 2: Simplified stratigraphy of the Rhenodanubian flysch zone after EGGER (1995), FAUPL (1996), SCHNABEL (1980), PLÖCHINGER & PREY (1993).

3. METHODS

3.1. External and internal zircon morphology study

Zircons can be classified after their external morphology (Fig. 3) (PUPIN & TURCO, 1972; PUPIN, 1980, 1985). The typological method defines zircons on the basis of relative development of the prism and pyramid faces (PUPIN, 1980). The crystals show two different prism faces and three different pyramid faces, which occur in various combinations.

PUPIN & TURCO (1972) developed a petrogenetic classification of zircons in terms of three main magma types: (1) granites of crustal or mainly crustal origin related to regional anatexis, and/or melting by rising granitic bodies; (2) granites of both crustal and mantle origin (so called hybrid granites), which can be divided into calc-alkaline and subalkaline granites; (3) granites derived from the mantle or mainly from the mantle, comprising two subgroups: alkaline and tholeiitic granites. The three types are characterised by distinct zircon morphology.

Luminescence in zircons is caused by disturbance of the crystal lattice due to substitution of P, Hf, Y, HREE, U, Th, and OH in the crystal (SOMMERAUER, 1976). Different concentrations in crystals result in different intensity of luminescence. As their incorporation into a growing crystal is dependent on the crystal structure, availability of elements in the melt, growing velocity and thermodynamic conditions, cathodoluminescence can be used to reveal the internal growth history, and thus, gives information on the evolution of a magma. Characteristic growth paths of zircons can also be taken for provenance studies.

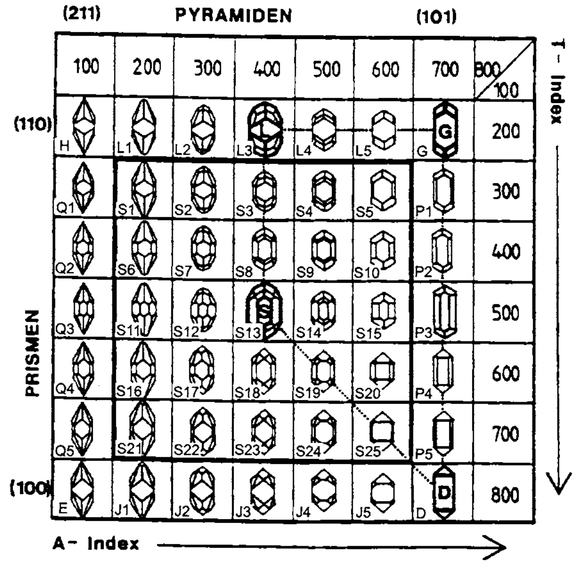


Fig. 3:
Zircon typologic classification of Pupin (1980) based on the ratio of the {101} and {211} pyramids (A-Index), and the ratio of the {100} and {110} prisms (T-Index).

3.2. Apatite and zircon fission-track dating method

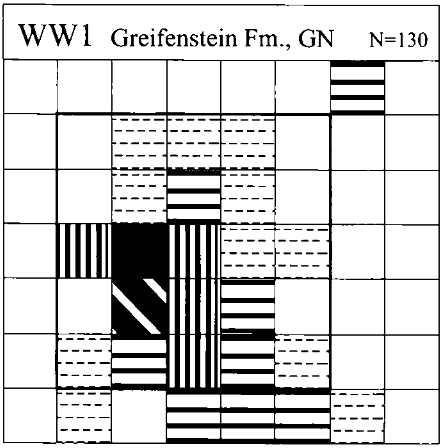
The fission-track dating method is widely used to date the low-temperature cooling history of rocks (e.g., Wagner & Van den haute, 1992). In case of sedimentary rocks, apatite and zircon fission-track geochronology provides information about the provenance of clastic material, and helps to reconstruct the exhumation history of their source area, if the sediment was not heated above ~70° C for apatite and ~220° C for zircon. Since apatites are sensitive to low temperatures (70–120° C), their provenance memory is often destroyed. In this case, the thermal evolution of the sediments can be constrained. In combination with fission-track length measurements, the meaning of an apparent apatite age and the basin evolution can be elucidated (Green, 1986).

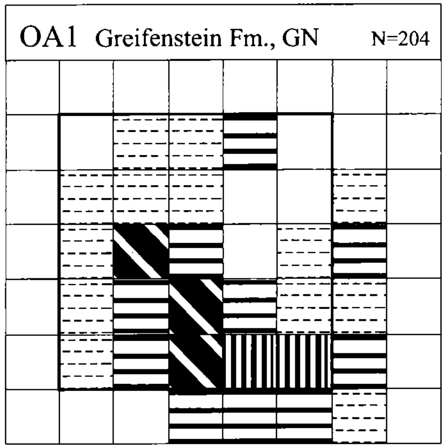
For the fission-track age determination the external-detector method is used (Gleadow, 1981). The details of sample preparation and laboratory procedures are described in Trautwein (2000). If the age population follows the rules of the Poisson statistics, the population is considered homogeneous and a pooled age is calculated (Galbraith, 1981). If the population is inhomogeneous, a mean age is calculated (Green, 1981).

The zircon and apatite fission-track grain-age spectra, which display more than one population, were decomposed using the program Binomfit (Brandon, 1992), which is based on the binomial peak-fitting method of Galbraith & Green (1990). This method decomposes the entire grain-age distribution into a finite set of component binomial distributions, each of them defined by a unique mean age, a relative standard deviation, and a number of grain ages in the component distribution.

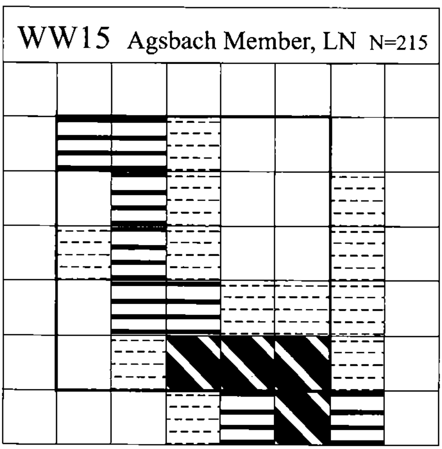
The study of fission-track length distributions in apatite constrains the time-temperature history of a rock under low-temperature conditions. Progressive annealing during

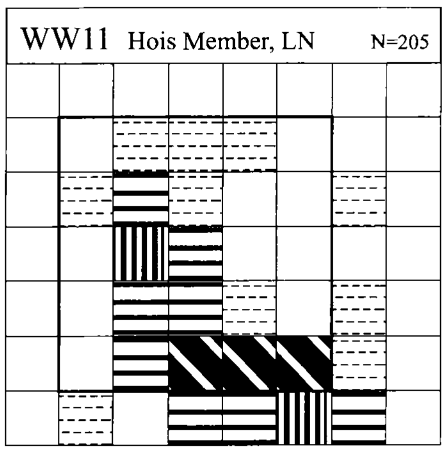
Greifenstein and Main Flysch nappe (GN)





Laab nappe (LN)





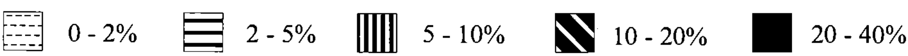


Fig. 4: External morphology of the zircons of the Greifenstein and Laab Formation.

Sample No.	Mineral	~ Sed. age formation	Locality N	Locality E	Alt. [m]	No. of crystals	spontaneous tracks ρ_s [10^5/cm²]	spontaneous tracks N_s	induced tracks ρ_i [10^5/cm²]	induced tracks N_i	dosimeter glass ρ_d [10^5/cm²]	dosimeter glass N_d	$P(\chi^2)$ (%)	ρ_s/ρ_i	U [ppm] (V.C. [%])	best-fit peaks: age ± 1s [Ma], N_f, W [%] 1	2	3	fit statistics	
Main flysch/Greifenstein nappe																				
WW1	apatite	Eo Greifen-stein F.	48°20'57''	15°15'34''	200	35	18,353	594	12,073	402	5,24	10395	<1	1,38	28 (±90)	**145.6 ± 10.1**	-	-	χ^2 = 63	
																N_f = 35	-	-	ν = 34	
																W = 45%	-	-		
WW1	zircon	Eo Greifen-stein F.	48°20'57''	15°15'34''	200	58	148,314	4170	26,995	759	5,49	10754	<1	7,99	177 (± 51%)	**59.9 ± 4.7**	**251.7 ± 13.4**	-	χ^2 = 62	-
																N_f = 8.0	N_f = 50.0	-	ν = 55	-
																W = 25%	W = 40%	-		
OA1	zircon	Pa-Eo Greifen-stein F.	48°04'16''	15°28'58''	360	60	303,629	8283	58,211	1588	6,67	13258	<1	6,2	326 (±38%)	**74.6 ± 8.1**	**168.7 ± 22.2**	**286.0 ± 25.0**	χ^2 = 63	P(F,1,ν) = 0%
																N_f = 4.2	N_f = 21.1	N_f = 34.6	ν = 55	F = 12.4
																W = 20%	W = 24%	W = 27%		
Laab nappe																				
WW15	zircon	Eo Laab F.	48°03'54''	15°50'52''	610	60	294,247	7093	47,458	1144	6,67	13258	<1	7,25	272 (± 42%)	**229.6 ± 11.5**	**460 ± 97**	-	χ^2 = 63	P(F,1,ν) = 0%
																N_f = 50.7	N_f = 9.3	-	ν = 57	F = 40.4
																W = 28%	W = 39%	-		
WW11	zircon	Pa Laab F.	48°01'45''	15°58'44''	420	60	338,62	8297	57,015	1397	6,67	13258	3,6	6,48	324 (± 34%)	**222.1 ± 16.0**	**304.6 ± 37.7**	-	χ^2 = 57	P(F,1,ν) = 0%
																N_f = 40.8	N_f = 19.2	-	ν = 57	F = 22.6
																W = 25%	W = 29%	-		

The zircon FT ages were calculated using a ζ-factor of 122.5±1.4 (CN2 glass). The ζ-value was calculated from thirteen different age standard measurements of Fish Canyon Tuff, Buluk Member, and Tardree Rhyolite zircons irradiated during seven different reactor runs. The apatite FT age was calculated using a ζ-factor of 380.4±6.5 (CN5 glass). The ζ-value was calculated from thirteen different age standard measurements of Fish Canyon Tuff and Durango apatites irradiated during six different reactor runs. ρ = track density, N = number of counted tracks, N_f = number of grains in the age population, W = relative standard deviation, n = degrees of freedom, N_f = number of grains in a population, χ2 = goodness-of-fit parameter, F = level of significance for peak 2 or 3, P(F,1,ν) = probability that the F-ratio value is due to chance alone, V.C. = variation coefficient; Pa = Paleocene, Eo = Eocene

Tab. 1: Zircon and apatite fission-track data and calculated age clusters using the computer program Binomfit (Brandon, 1982).

increasing temperature reduces the track-length until total erasure. Each T-t-path results in a certain track-length distribution. In thermally overprinted sedimentary basins, the ratio of inherited to newly formed tracks depends on the amount of annealing. Both track-length distributions and fission-track ages were used to model the thermal histories. Modelling was performed with the computer program AFTSolve (KETCHAM et al., 2000).

4. RESULTS

4.1. External and internal zircon morphology

The external morphology was determined for four zircon samples, which are derived from Paleogene formations of the Greifenstein and the Laab nappe in the Wienerwald area. A high portion of the zircons of the Greifenstein Formation has euhedral shape and is clear. The majority of the external habits cluster around the S_{12+13}, S_{17+18}, and S_{22+23} types in the Pupin classification, which is an indication for anatectic to calc-alkaline derivatives (Fig. 4). Zircons of mantle origin are not frequent. The zircons of the Laab Formation are predominantly S_{23-25} and J_5 types, which are of calc-alkaline origin (Fig. 4). Yellowish euhedral zircons are predominant.

The internal morphology analysis was performed on two zircon samples from different formations (WW1, WW11). The zircons of both formations are predominantly zoned and contain inherited cores. The cores are either of sedimentary or metamorphic origin (Fig. 5).

4.2. Fission-track ages of zircon and apatite samples

Fission-track age determination was carried out on nine apatite and four zircon samples of the eastern Rhenodanubian flysch zone (Salzburg–Wien). The determined ages are so-called apparent ages. Depending on the thermal evolution, they reflect cooling ages of reset sediments, mixed ages with an inherited history, or purely inherited ages without thermal overprint.

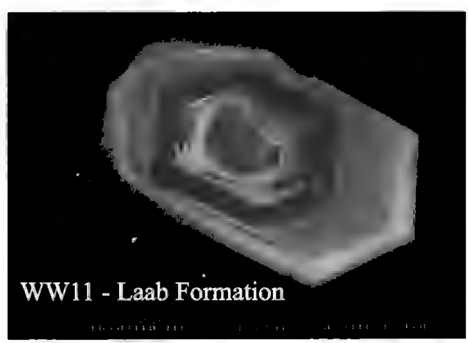


Fig. 5: Cathodoluminescence shows the internal morphology of zircons. Typical crystals of the Greifenstein and Laab Formation showing inherited cores.

Sample No.	~Sedimentation age	Locality N	Locality E	Alt. [m]	No. of crystals	spontaneous tracks ρ_s [10^5/cm²]	spontaneous tracks N_s	induced tracks ρ_i [10^5/cm²]	induced tracks N_i	dosimeter glass ρ_d [10^5/cm²]	dosimeter glass N_d	$P(\chi^2)$ (%)	ρ_s/ρ_i	Age ± 1σ [Ma]	U [ppm] (V.C. [%])	measurements of confined fission-track: No. of length	measurements of confined fission-track: mean track length [µm]	measurements of confined fission-track: Std. dev. [µm]
Rhenodanubian flysch zone																		
Main Flysch/Greifenstein nappe																		
Greifenstein Formation																		
17	Pa-Eo	48°04'16''	15°28'58''	360	60	4,22	822	14,828	2970	4,59	8938	<1	0,283	24.6 ± 0.6	39 (±73)	50	13,7	1,9
Altlengbach Formation																		
6	Ma	47°53'59''	13°23'15''	788	46	8,698	1213	11,909	1975	5,21	10345	<1	0,596	58.8 ± 1.7	27 (±73)	63	11,9	2,0
7	Ma	47°55'15''	13°45'55''	670	49	6,328	1011	9,927	1680	4,55	9175	<1	0,614	52.9 ± 1.5	26 (±85)	101	12,6	2,2
10	Ma	47°55'15''	13°45'55''	670	55	9,118	904	15,727	1673	4,863	9543	<1	0,581	53.5 ± 1.5	39 (±133)	74	12,1	2,5
18	Ma	47°59'06''	14°57'58''	760	60	8,01	623	15,134	1375	4,59	8938	<1	0,528	46.0 ± 1.2	40 (±68)	54	12,3	2,7
19	?Ca-Ma	47°59'49''	14°55'58''	490	60	4,098	546	10,619	1414	4,59	8938	<1	0,389	33.9 ± 0.9	28 (±67)	56	12,7	2,2
Reiselsberg Formation																		
15	Ce-Tu	47°51'53''	13°37'13''	750	45	2,795	617	8,425	1905	4,873	9543	2,6	0,31	28.7 ± 0.9	21 (±84)	31	14,0	1,2
20	Ce-Tu	47°58'22''	14°51'01''	455	31	2,125	151	7,304	471	5,24	10395	35,1	-	31.9 ± 3.0	16 (±101)	11	13,1	2,1

The ages were calculated as pooled ages if passing the χ^2-test (Galbraith 1981; Green 1981), if not the mean age was calculated. The ages were calculated using a z-factor of 380.4±6.5 (CN5 glass). The ζ-value was calculated from thirteen different age standard measurements of Fish Canyon Tuff and Durango apatites irradiated during six different reactor runs. ρ = track density, N = number of counted tracks, V.C. = variation coefficient; Ce = Cenomanian, Tu = Turonian, Ca = Campanian, Ma = Maastrichtian, Pa = Paleocene, Eo = Eocene

Tab. 2: Apatite fission-track ages and track-length parameters.

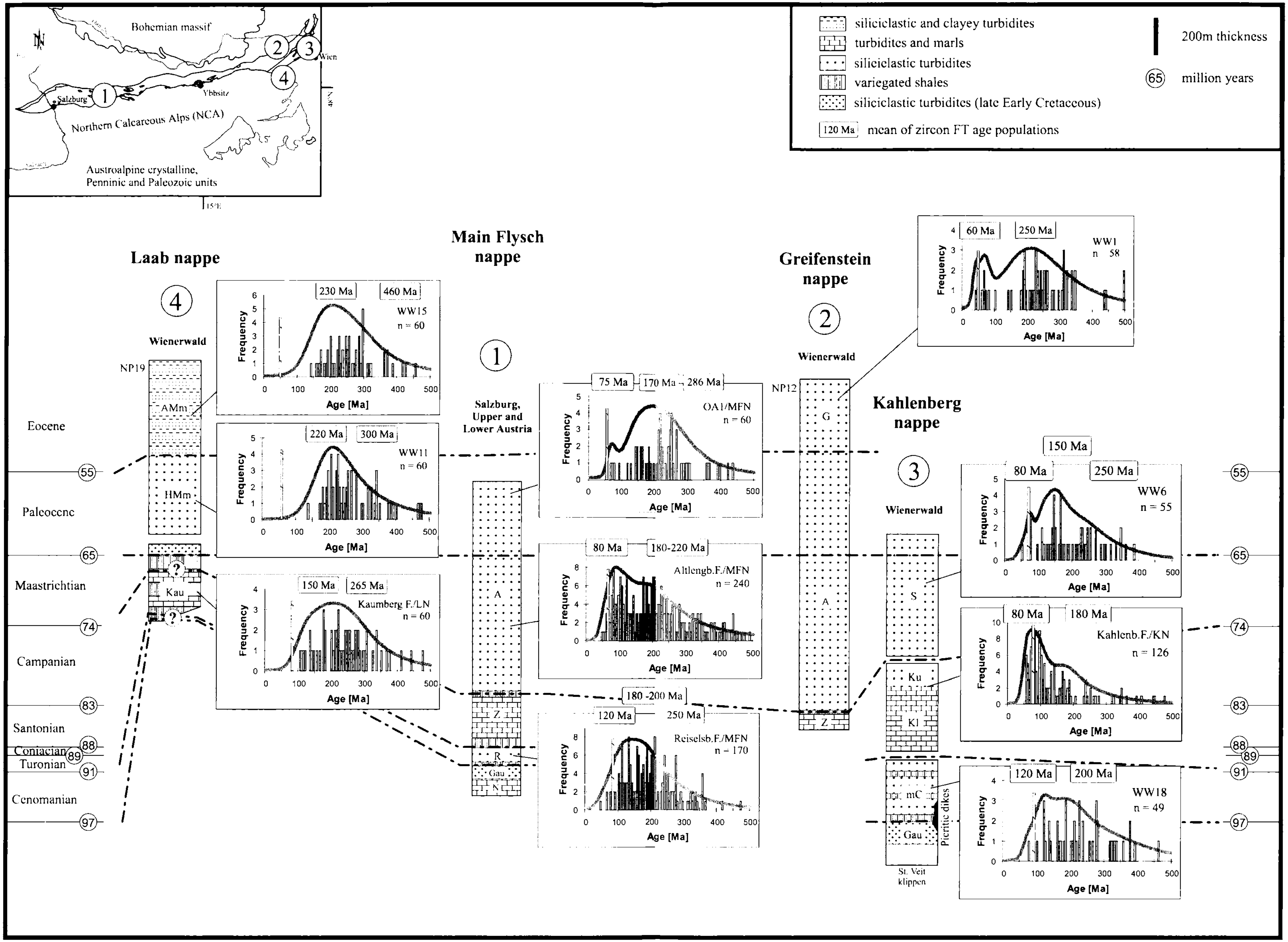


Fig. 6: Zircon fission-track age spectra of the different formations. Plots show the single zircon fission-track grain ages in a histogram and the probability density curve (HURFORD et al., 1984). The white bar indicates the sedimentation age of each sample. MFN = Main Flysch nappe, KN = Kahlenberg nappe, LN = Laab nappe. Facies development in the different nappes of the Rhenodanubian flysch zone (compilation after PREY, 1973; OBERHAUSER, 1995; SCHNABEL, 1992; FAUPL, 1996).
A = Altlengbach formation, AMm = Agsbach Member, Gau = Gault Flysch, G = Greifenstein Formation, HMm = Hois Member, Kau = Kaumberg Formation, Kl = lower Kahlenberg Formation, Ku = upper Kahlenberg Formation, mC = mid-Cretaceous formations (undifferentiated), N = Neocom Flysch, R = Reiselsberg Formation, S = Sievering Formation, Z = Zementmergel Formation; NP12, NP19 = nannoplankton zones.

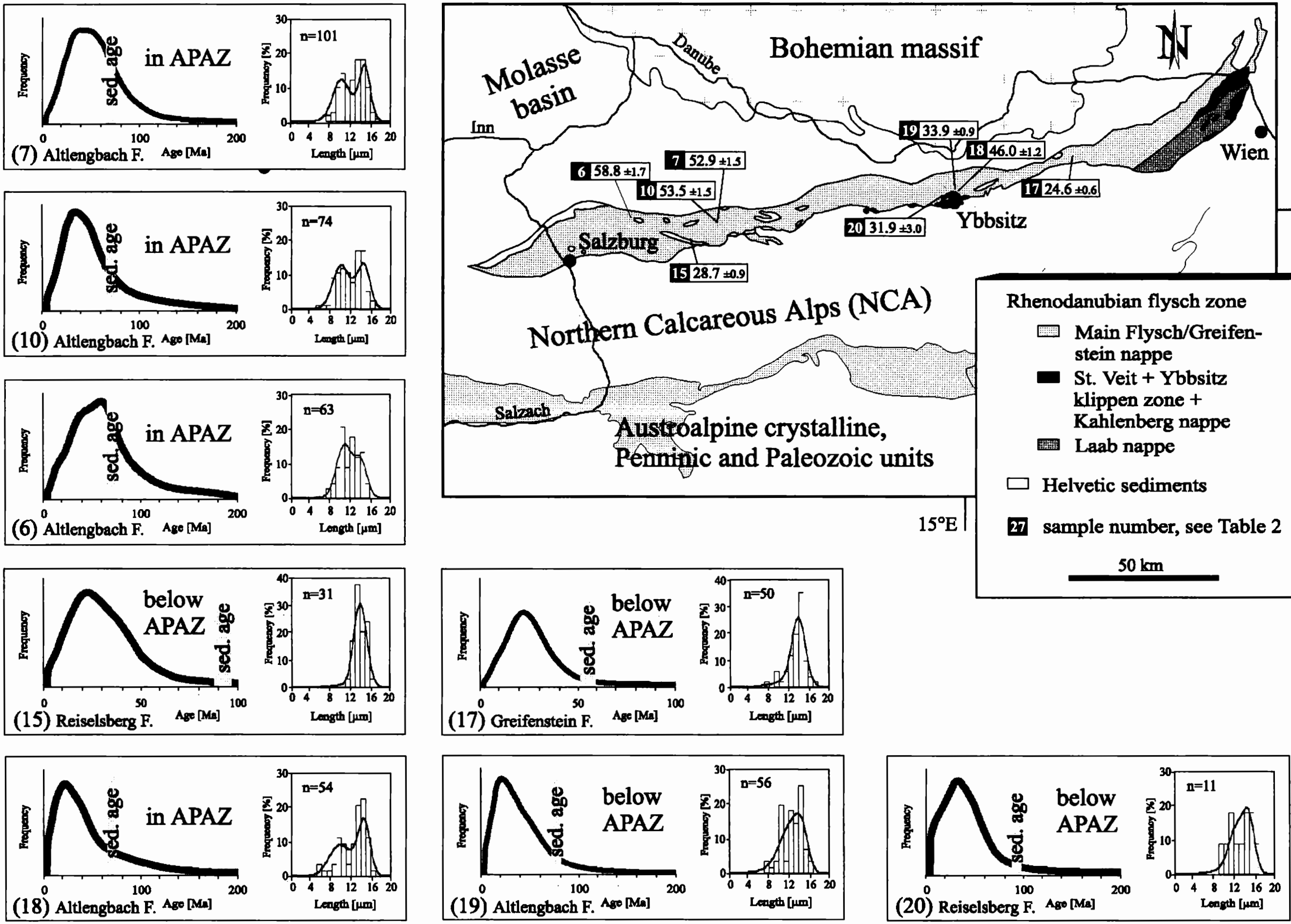


Fig. 7: Apatite fission-track ages and fission-track length distributions indicate the thermal history of the samples; APAZ = apatite partial annealing zone.

The FT age distributions of one apatite and the four zircon samples from Cenozoic formations indicate no overprint and the age spectra show several age clusters (Tab. 1, 2; Fig. 6). Therefore, these samples provide information about the provenance of the sediments and are useful in reconstructing the Paleogene paleogeography of the Wienerwald area. The Greifenstein Formation of the Greifenstein nappe shows zircon FT age clusters of Paleocene, Late Cretaceous, Jurassic, and Permian age (Fig. 6). The apatite sample displays an age cluster of Late Jurassic time (Tab. 2). The zircon FT age distributions of the Laab nappe contrast with those of the Greifenstein Formation. The Paleocene to Eocene samples show age clusters of Triassic, Carboniferous and Ordovician age (Fig. 6).

For better understanding of the provenance and paleogeography, zircon fission-track data of Late Cretaceous formations are included in this study. Zircon samples of the Cretaceous formations of the Rhenodanubian flysch zone are also not thermally overprinted and display several age populations. The Reiselsberg Formation of the Main Flysch/Greifenstein nappe and Kahlenberg nappe yield age populations of Early Cretaceous, Jurassic, Permian to Triassic and also Variscan ages. The Campanian to Maastrichtian formations of these nappes are characterized by age clusters of early Late Cretaceous, Jurassic to Permian, and Variscan ages. The time-equivalent Kaumberg Formation of the Laab nappe displays a different picture, the grain-age spectrum contains Late Jurassic and Permian age clusters but Cretaceous fission-track age populations are missing.

Eight apatite samples, derived from the Reiselsberg, the Altlengbach and the Greifenstein Formations, are thermally affected, and their provenance memory is erased (Fig. 7). In this case, ages and length distributions allow to quantify the thermal evolution of the RDFZ (Tab. 2). The apatite FT data of the Main Flysch/Greifenstein nappe vary along strike from Salzburg to Ybbsitz and show Paleocene to Oligocene ages.

5. DISCUSSION AND CONCLUSIONS

5.1. Provenance of the Paleogene and Cretaceous sediments

Laab Formation

The zircon FT age populations (225 Ma, 300 Ma and 460 Ma) of the Laab Formation are interpreted as follows. The pre-Variscan age of 460 Ma, represented only by a few grains and thus bearing a high error, is either a relic of the Caledonian cycle or, within its error (± 97 Ma), reflects the Early Variscan tectonometamorphic event. This old age could only survive in a zone, which was never buried to depths greater than ~7 km. The Variscan ages around 300 Ma point either to the Bohemian massif or to the westernmost part of the Austroalpine crystalline basement, or both. Such ages are known from whole rock analyses of Austroalpine rocks reflecting the Variscan tectonometamorphic event (FRANK et al., 1987; NEUBAUER et al., 1999), where Alpine thermal overprint was very weak.

The Triassic FT age group is an indication for Permo-Triassic rifting with increased heat flow, which affected Central Europe (ZIEGLER, 1988). HEJL et al. (1997) found such zircon fission-track ages in granites along the western border of the Bohemian massif.

However, they interpreted these ages as indicating post-Carboniferous unroofing during the Permian molasse stage and Early Triassic uplift. Zircon FT ages of the Moravicum in the eastern Bohemian massif also correspond to this age group.

In the Eastern Alps, such zircon FT ages are only preserved where the temperature of Cretaceous metamorphism did not exceed 250° C. These ages are known from deformed Permian sandstones along the southern margin of the NCA (Elias, 1998), Carboniferous sandstones of the Gurktal Alps (Dunkl et al., 1999), and the Southern Alps (Bertotti et al., 1999). Hunziker et al. (1992) reported zircon fission-track ages of 220 Ma in South Alpine blocks and the Silvretta nappe, which they interpreted as to reflect slow cooling after Variscan metamorphism.

Kaumberg Formation

A similar age spectrum (Late Jurassic, Permian) is representative for the Late Cretaceous Kaumberg Formation. The Permian age is interpreted as above. The Jurassic age is probably an indication for the thermal event due to the Penninic rifting. Comparing the data of the formations of the Laab nappe, the zircon age populations get older with decreasing sedimentation age. This can be explained by sediment-redeposition.

Greifenstein Formation

Permo-Triassic zircon FT ages can also be found in the Greifenstein Formation. Besides that, zircon FT ages of 60 Ma, 75 Ma, and 170 Ma are common. Middle to Late Jurassic ages were generally interpreted as meaningless mixed ages, as a result of partial overprint of Variscan units during the Alpine orogeny (Frank et al., 1987). Dunkl et al. (1999) assume that this age group records a given thermotectonic event and relate the Jurassic ages to the thermal effect of Penninic rifting starting in Central Europe during Early Jurassic times (Ziegler, 1988). In the Alps, such ages are reported from the Silvretta basement (Flisch, 1986) and the Gurktal Alps (Dunkl et al., 1999). Detrital zircons of these ages were also found by Eynatten (1996) in Cretaceous siliciclastic rocks of the NCA, and by Spiegel et al. (2000) in Tertiary siliciclastic rocks of the Swiss Molasse. Zircons from gneiss pebbles of the East-Alpine Molasse zone show similar ages which are interpreted as derivatives from the Silvretta and northwestern Ötztal basement (Brügel, 1998).

The 75 Ma zircon FT age reflects regional cooling after Cretaceous Eoalpine metamorphism (Frank et al., 1987). It is widespread in Austroalpine units (Neubauer et al., 1995; Fügenschuh et al., 1997; Elias, 1998; Hoinkes et al., 1999), in which Tertiary metamorphism generally did not exceed 250° C.

The zircons with ages around 60 Ma are colourless and of euhedral to subhedral shape. Since the lag time between zircon fission-track age and sedimentation age is very short, the ages are either evidence for volcanism or a fastly exhuming body in the source area. Similar zircon ages of ~58 Ma in Paleocene bentonites of the Schlieren flysch (Winkler et al., 1990), and the euhedral shapes or the crystals make a volcanic source most probable. Bentonite layers of similar age are also described in the Rhenodanubian flysch zone in the area of Salzburg and in the Northern Calcareous Alps (Egger, 1995; Egger et al., 1996). Winkler et al. (1985) suggested an origin of these ashes from a volcanic center situated south of the Alpine orogen. Since the dated zircons are collected from a sandstone and not from a distinct tuffitic layer, reworking of bentonites (EGGER et al., 1996) or airborne derivation are assumed.

Cretaceous formations of the Main Flysch/Greifenstein nappe and the Kahlenberg nappe
The Late Cretaceous formations of these nappes also display the Permian to Triassic thermotectonic event. The Jurassic age population points to the Penninic rifting. The Cretaceous fission-track age spectra are evidence for sediment supply from the Alpine orogen affected by Eoalpine metamorphism.

Comparison of the fission-track ages of the different formations
The Greifenstein and Laab Formations show completely different age spectra, only the Permo-Triassic event is characteristic for both formations. The same is true for the Late Cretaceous Kaumberg Formation, which differs from the other Late Cretaceous formations. The age spectra of the Laab Formation lack the young peaks. Besides, the zircons show a distinct external morphology, which emphasises their different source area from those of the Greifenstein Formation. The zircons of the Laab Formation are similar to the zircons of Variscan granitoids in the Bohemian massif, e.g., the Karlstift and Weinsberg granites (BARTAK et al., 1987; FINGER et al., 1987; FINGER & HAUNSCHMID, 1988).

The Late Jurassic apatite FT ages, as displayed by the apatite sample with provenance memory (WW1), support an Alpine provenance for the Greifenstein Formation as indicated also by the zircon FT data. Such ages are also reported from apatites of a Triassic sandstone and a Permian dolerite in the Northern Calcareous Alps, which were interpreted as cooling ages (HEJL & GRUNDMANN, 1989). In the Bohemian massif similar apatite ages were measured in the western crystalline basement (WAGNER, 1990). Nevertheless, due to slow cooling of this area (WAGNER, 1990), the according level was not on the surface in the Eocene and therefore could not have served as source area for the Eocene sediments of the Rhenodanubian flysch zone.

5.2. Paleogeography in Paleogene and Cretaceous times

Two sedimentation areas are deduced from zircon morphology and fission-track data, which are called the Main Flysch and the Laab basin (TRAUTWEIN, 2000). This basin configuration existed since Early Cretaceous times. The Main Flysch basin is characterised by receiving detritus from the Eoalpine orogen, which underwent Cretaceous cooling after metamorphism. The assumption of an Alpine source for the Greifenstein Formation is underlined by data of SACHSENHOFER (pers. comm.), who showed that the Paleocene part of the Altlengbach Formation in the Wienerwald contains reworked Triassic coal, which is known from the Northern Calcareous Alps.

The Laab basin, in contrast, did not receive sediments reflecting the Eoalpine cooling event. Due to the old zircon fission-track age populations (≤ Jurassic), a stable source area, which was not affected by Cretaceous metamorphism, is required for the Laab nappe. Therefore, an Alpine source area can be excluded, and the source area must be located north of the Alpine range. The Laab basin therefore has been situated north of the Main Flysch basin, an arrangement which was first proposed by OBERHAUSER (1995).

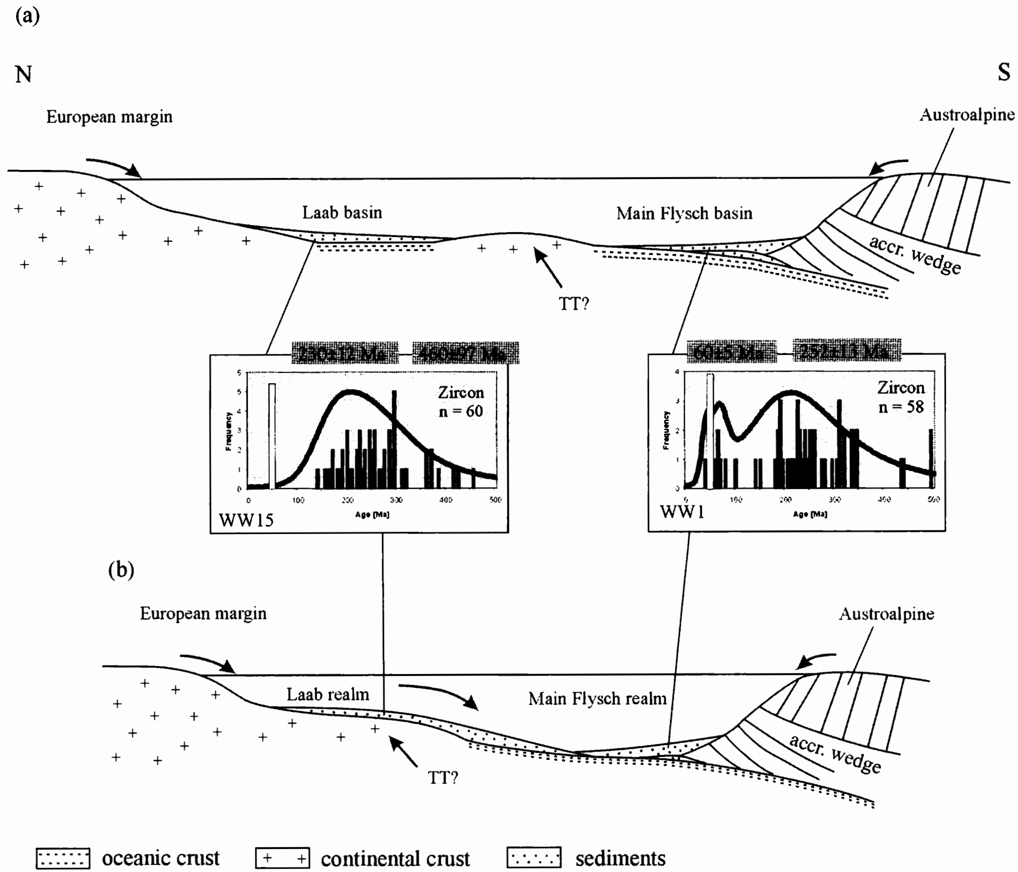


Fig. 8: Paleogeographic models of the Rhenodanubian flysch basin in Eocene times; (a) the two basins are separated by a submarine swell, (b) the Laab and Main Flysch depositional areas form a coherent depositional area but due to the higher position of the Laab realm, it does not receive detritus from the Alps. TT = Tauern terrane.

Undeformed coalified plant detritus from presumably Permo-Carbonifereous coals in the formations of the Laab nappe, which are similar to coals in the Bohemian massif (Boskowitzer trough, Perm von Zöbing) (SACHSENHOFER, pers. comm.), support these assumptions.

These conclusions contrast with others ideas, which, according to the three different nappes (Greifenstein, Kahlenberg and Laab nappe), assume three basins of flysch deposition in the Wienerwald area. The arguments for a subdivision into three basins are mainly based on paleocurrent and heavy mineral data (e.g., FAUPL, 1996). However, since the Rhenodanubian flysch zone was involved in nappe stacking and post-collisional tectonic extrusion, block rotations may have destroyed the information concerning the original paleocurrent pattern.

The complete lack of Eoalpine zircon FT ages in the Laab nappe shows that the depositional area of this nappe did not receive any Alpine material. This is explained as follows: (1) the Laab nappe had the northernmost position during sedimentation, closest to the Bohemian massif; (2a) the Laab basin was separated from the depositional area of the Main Flysch basin by a submarine swell preventing transport from Alpine sources into the Laab basin (Fig. 8a); or (2b) Laab and Main Flysch basin formed a coherent depositional area, but the Laab realm had a higher position with less deep water than the Main Flysch realm, thus preventing transport from the Main Flysch realm into the Laab realm (Fig. 8b). There are no reasons against a sediment exchange from the Laab to the Main Flysch sedimentation area. Possibility 2b is preferred by the authors, since it enables grains from the Bohemian massif to have been supplied into the Main Flysch basin.

5.3. Accretion and exhumation of the Rhenodanubian Flysch Zone

Successive and differential accretion and exhumation of the sediments evolved from Campanian to Miocene times (TRAUTWEIN, 2000; TRAUTWEIN et al., 2001). The sediments of different stratigraphic units were buried to different depth levels, and therefore heated up to different degrees before cooling started in Cretaceous and Paleogene times, respectivelly (Fig. 9). Since the Cretaceous evolution is beyond the scope of this paper, we refer the interested reader to the mentioned papers, which describe the beginning of the accretionary process in more detail.

In the area between Salzburg and Gmunden, one sample (no. 20) of the Reiselsberg Formation had been buried deep enough to reset the apatite FT age and track-length distribution totally. In contrast, the Maastrichtian Altlengbach Formation is characterized by burial into the apatite FT partial annealing zone (samples no. 6, 7, and 10). The fission-track ages and the length distributions reflect only partial reset. Near Ybbsitz, the sandstones of the Reiselsberg and Altlengbach Formations were buried into the total annealing zone and experienced total reset (samples no. 19 and 20). Another sample of the Altlengbach Formation (sample no. 18) did not suffer complete resetting, but stayed in the partial annealing zone. Sample 17 (Paleocene-Eocene) of the Greifenstein Formation shows cooling in Eocene to Oligocene times after complete reset.

In the area Salzburg-Gmunden cooling of Cenomanian to Early Paleocene rocks started in Middle Eocene times. Presumably, this age displays the timing of underplating of the RDFZ by the European continental margin incorporating Ultrahelvetic slices into the nappe stack. Cenomanian to Eocene sediments of the RDFZ in the area near Ybbsitz

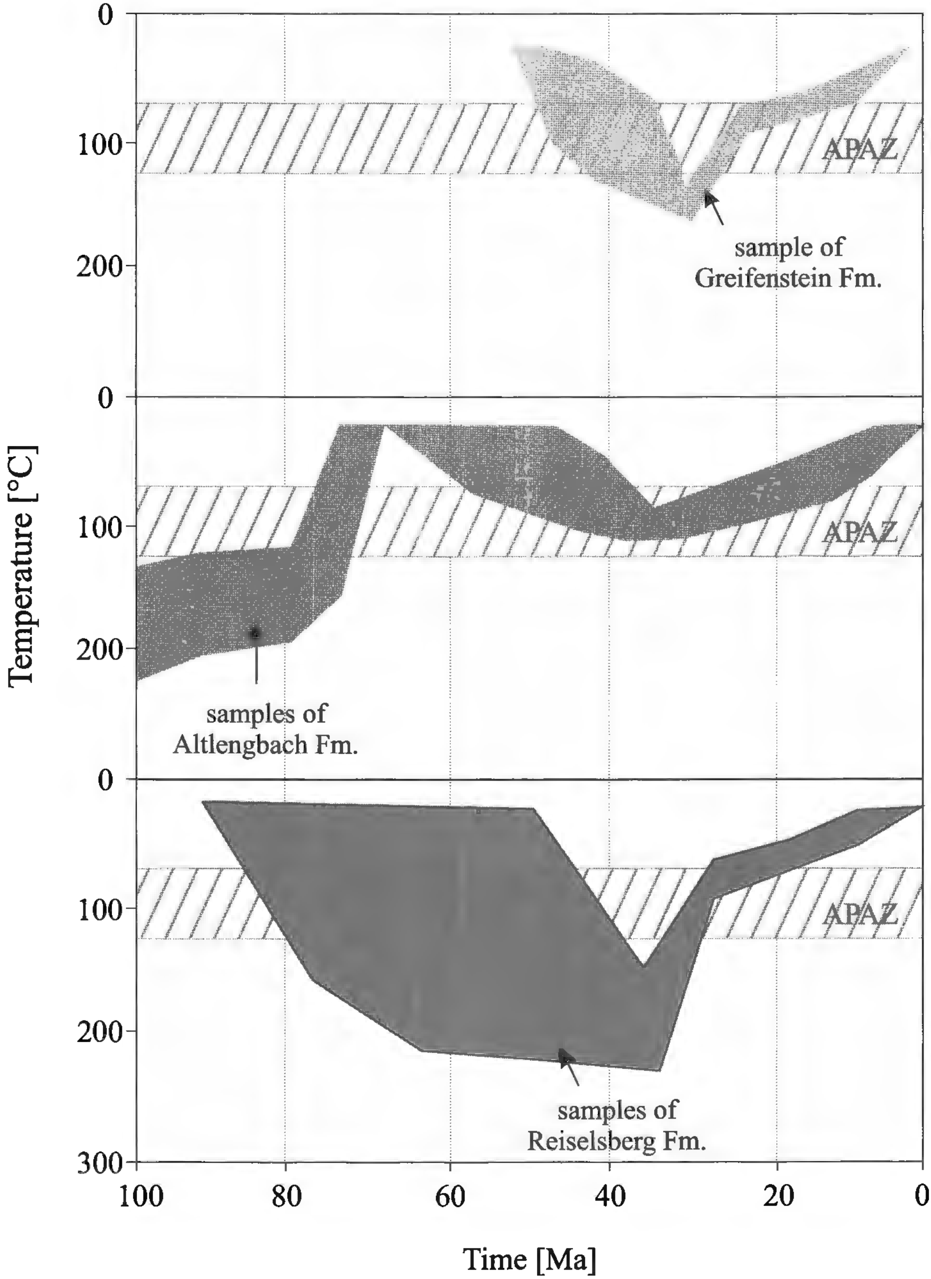


Fig. 9: Modelled T-t paths of samples from different formations; APAZ = apatite partial annealing zone. The grey areas are the envelopes of the better thermal paths.

show onset of cooling around Middle Eocene/Early Oligocene times. HEJL & GRUNDMANN (1989) measured an apatite fission-track age of ~31 Ma in the Ultrahelvetic sequences reflecting the involvement into the accretionary wedge. The different burial depths of the sediments and the diachronous cooling ages can be partly explained by the complexity of the accretionary process.

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