ELSEVIER

Tectonophysics 272 (1997) 197–211

TECTONOPHYSICS

Exhumation of the Rechnitz Window at the border of the Eastern Alps and Pannonian Basin during Neogene extension

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Abstract

The Rechnitz Window is the easternmost Penninic window of the Alps and the only one that is partly covered by Neogene sediments. Zircon and apatite fission-track ages have been measured on the Penninic metasediments of the Rechnitz series to better understand the exhumation of the window at the Alpine–Pannonian border. The zircon FT ages range from 21.9 to 13.4 Ma, similar to the white mica K/Ar ages (19 and 23 Ma). The exhumation rate during the Early Miocene extension was high (~40°C/Ma). Apatite samples display FT ages of 7.3 and 9.7 Ma, thus the cooling rate was significantly less (7–11°C/Ma) during the post-rift uplift in Late Miocene–Pliocene than in the Early Miocene escape period. Zircon FT ages decrease eastward due to the gradual southeastward slide of the Austroalpine cover along low-angle normal faults. The exhumation of the Rechnitz metamorphic core complex is younger than the unroofing of the eastern Tauern Window.

Morphology of detrital zircon crystals of the Penninic metasediments was used for the differentiation of tectonic subunits and to trace the internal structure of the window. One population was probably derived from undifferentiated calc-alkaline granitoids and tholeiitic granitoid sources, while the other derived from evolved calc-alkaline granitoids and alkaline granitoids of anorogenic complexes. The areal distribution of zircon populations is in harmony with the eastward shift of zircon cooling ages. These data indicate the exhumation of deep levels of Penninic metasediments in the centre of the window.

Keywords: Eastern Alps; core complex; Penninic; fission-track; zircon morphology

1. Introduction

Since the fundamental paper of Schmidt (1956), it is well known that the Penninic unit extends to the eastern termination of the Alps, cropping out in four small windows between Rechnitz and Köszeg (referred to as Rechnitz Window) (Figs. 1 and 2). The polymetamorphic rocks in the windows belong to the Bündnerschiefer series and consist of ophiolite remnants, as well as various metasedimentary rocks. Although the geotectonic environment of the magmatites and the conditions of metamorphism have been thoroughly studied (Koller and Pahr, 1980; Lelkes-Felváry, 1982; Koller, 1985), there are only a few papers that have discussed the sedimentary rocks, and only sporadic data exist on the age of thermal evolution.

One of the aims of the present study is to constrain the exhumation of the window using fission-track

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PII S0040-1951(96)00258-2

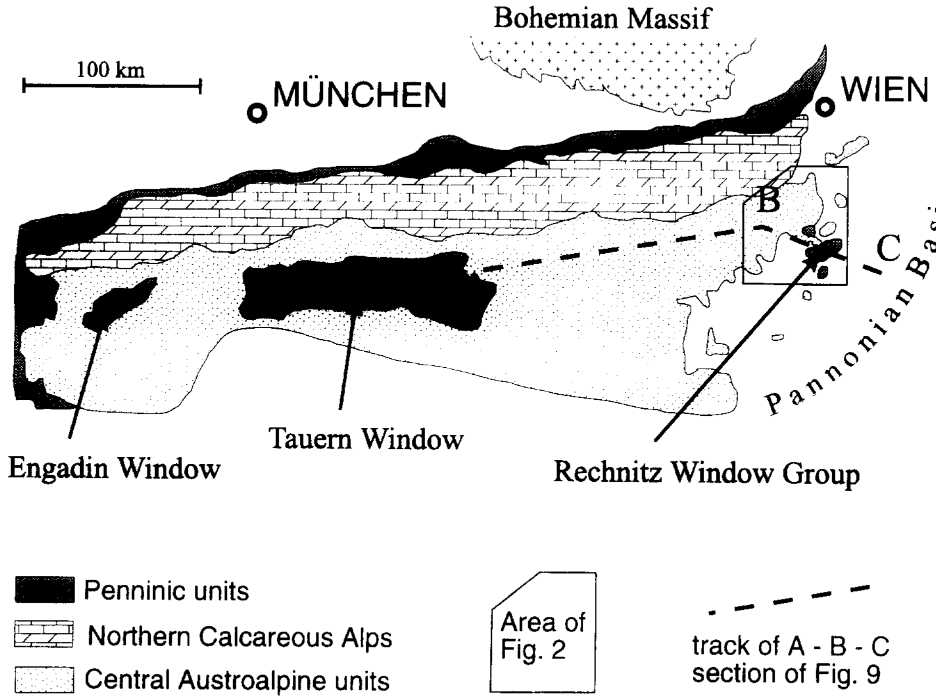

Fig. 1. Position of the Rechnitz Window Group at the eastern termination of the Eastern Alps (tectonic units after Ratschbacher et al., 1990).

age determinations. Another purpose is to reveal the internal structure of the window and its relationship to the exhumation history. We have used the morphology of detrital zircons as a mineralogical criterion for the distinction of quartz phyllite bodies of similar petrography, chemistry and metamorphic grade. The morphology of zircons also gave information on the provenance of Penninic sediments. Earlier papers on the detrital components of conglomerate bodies in the Bündnerschiefer dealt mainly with carbonate pebbles. Juhász (1965), Oravecz (1979) and Mostler and Pahr (1981) have described Permo–Carboniferous and Triassic microfossils in the carbonate pebbles of the Cák conglomerate. Zircon morphometry can provide information on the origin of siliciclastic components, the quartzites being rather mature and the spectrum of detrital heavy minerals being poor (Demény, 1988).

2. Geological background

The first detailed maps were made by Bandat (1928, 1932) and Földváry et al. (1948), the geology and petrology of the rocks were summarized by Pahr (1980) and Koller and Pahr (1980). The most up-to-date maps were compiled by Pahr (1984) and Ferencz et al. (1988). Structural analyses were published by Ratschbacher et al. (1990), Dudko and Younes (1990), Wiedemann and Younes (1990), and Neubauer et al. (1992). Koller (1985) has proved the ophiolitic origin of the mafic and ultramafic rocks; these are mainly serpentinites, gabbros and greenschists. Based on the geochemistry of these rocks, he correlated the metamagmatites with rocks from the Glockner nappe of the Tauern Window.

The metasediments are phyllites with variable amounts of quartz, white mica, carbonate, chlorite and albite. Graphite, zircon, rutile, tourmaline, apatite and opaque minerals are accessory phases. The organic matter was probably derived from marine organic material and from denuded carbonate rocks (Demény and Kreulen, 1993). The age of the sedimentation was determined by Schönlaub (1973) who found middle Cretaceous sponge spiculum in calcschists.

Three metamorphic events have been recorded in

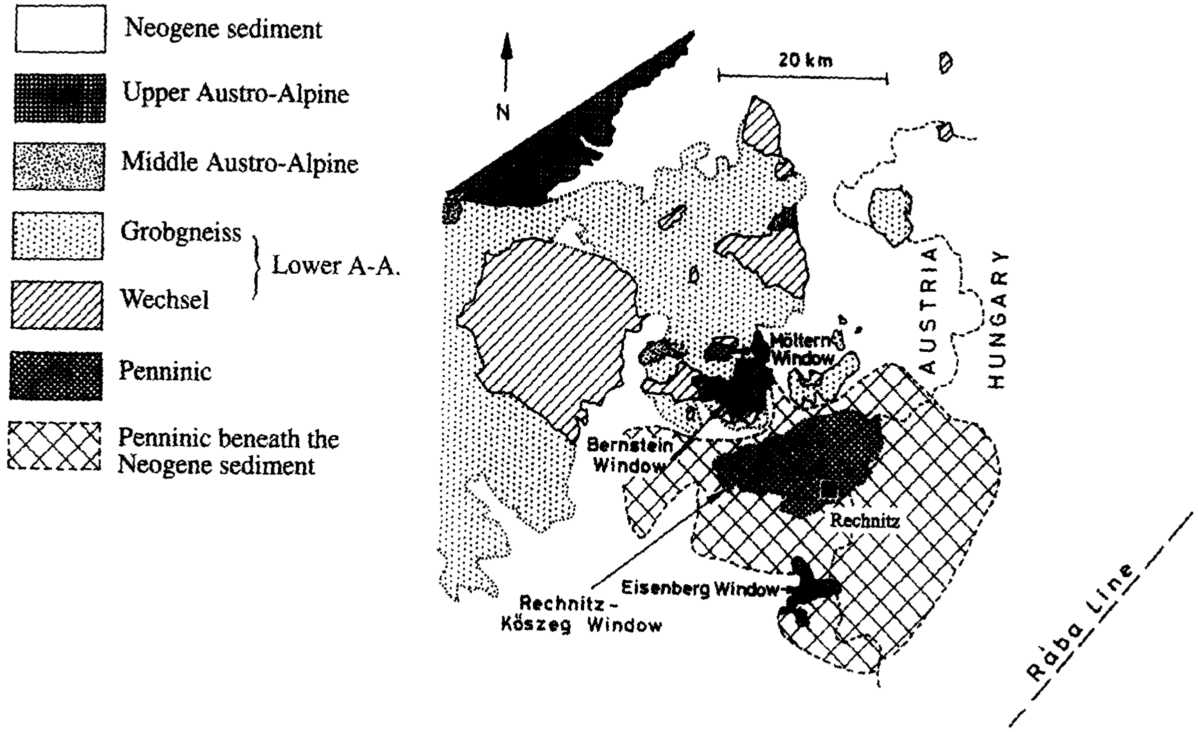

Fig. 2. Schematic tectonic map of the Rechnitz Window Group (after Ratschbacher et al., 1990 and Flügel, 1988).

the Rechnitz series: (1) oceanic hydrothermal activity; (2) subduction-related HP/LT metamorphism; and (3) late Alpine greenschist-facies metamorphism. Lelkes-Felváry (1982), Kubovics (1983) and Koller (1985) described sporadic remnants of the mineral assemblages of the oceanic hydrothermal influence and relics of the HP/LT metamorphism (blueschists, crossitites, and greenschists with lawsonite, glaucophane and pumpellyite). Koller (1985) determined temperature and pressure ranges with $T > 750°C$ for the first, and $T = 330–370°C$, $P = 6–8$ kbar for the second metamorphic event. The temperature during the late Alpine metamorphism ranged from 350°C to 430°C and the pressure reached 3 kbar.

Very few geochronological data have been published on the Rechnitz Penninic rocks. An early stage of the metamorphic evolution was registered in the K/Ar age of an amphibole sample of crossite–riebeckite composition by W. Frank (in Koller, 1985) who reported 65 ± 6 Ma and interpreted it as a mixed age. Whole-rock K/Ar data of K. Balogh (in Kubovics, 1985) measured on metagabbroic rocks from Eisenberg refer to neo-Alpine events (13.5 Ma on albite–epidote–sphene–crossitite; 12.0 Ma on sphene–crossitite). From the western part of the Rechnitz Window ages of 19 and 22 Ma have been determined on white mica by K/Ar measurements (W. Frank, pers. commun., 1992). Preliminary zircon fission-track results were presented by Demény and Dunkl (1991).

3. Fission-track ages

Table 1 contains the analytical results and the fission-track ages. Only two of the investigated twenty apatite samples (2–3000 grains) contained spontaneous tracks. Due to the young age and the uranium-poor geochemical milieu the spontaneous track densities are very low, which made measurement of the confined track length impossible. The average age of the apatite is 8.5 Ma.

The zircon ages range from 21.9 to 13.4 Ma. The oldest value was determined on the sample collected from the Bernstein Window in the north. All the other samples were collected from the Rechnitz

Table 1
Fission track results from the Penninic rocks of the Rechnitz Window

Code	Elevation (m)	Coordinates		Locality	No. cryst.	Spontaneous		Induced		$P(\chi^2)$ (%)	Dosimeter		FT age (Ma ± 2σ)
		North	East			Ps	(Ns)	Pi	(Ni)		Pd	(Nd)	
Apatite ages													
KR 3	440	47°18.7′	16°23.8′	Rechnitz	39	0.048	(32)	0.67	(429)	11	5.23	(9969)	7.3 ± 2.7
FE	300	47°12.5′	16°25.5′	Felsöcsatár	55	0.105	(97)	1.04	(971)	-	5.23	(9969)	9.7 ± 2.1
Zircon ages													
VE	380	47°20.9′	16°29.3′	Velem	4	21.9	(245)	35.6	(449)	10	1.48	(5826)	16.4 ± 2.8
Ve 9	450	47°21.4′	16°29.9′	Velem-9, 102 m	27	26.6	(1356)	26.4	(1353)	15	0.88	(4100)	16.5 ± 1.7
V 1/b	340	47°21.5′	16°31.1′	Cák N	18	25.0	(756)	28.5	(872)	12	1.17	(2918)	19.2 ± 2.3
Kö 6/6	580	47°23.4′	16°28.7′	Köszeg-6, 6.0 m	31	22.7	(3134)	26.5	(3937)	-	0.89	(4100)	13.4 ± 1.1
Kö 6/120	460	47°23.3′	16°28.8′	Köszeg-6, 120 m	33	23.9	(2050)	26.7	(2350)	15	0.88	(4100)	14.3 ± 1.3
Kö 7/40	260	47°23.3′	16°31.9′	Köszeg-7, 40 m	17	17.3	(1157)	20.3	(1411)	<1	0.87	(4100)	13.5 ± 1.4
K 1	460	47°23.8′	16°31.2′	Köszeg	20	20.5	(956)	28.0	(1294)	6	1.18	(2918)	16.0 ± 1.8
K 26	880	47°21.2′	16°26.2′	Írottkö	20	26.2	(1209)	30.9	(1408)	95	1.17	(2918)	18.6 ± 1.9
K 7	450	47°24.4′	16°27.8′	Hammer	20	24.6	(1231)	30.5	(1523)	56	1.18	(2918)	17.6 ± 1.8
KR 5	420	47°23.2′	16°23.2′	Glashütten N	20	26.8	(1296)	31.5	(1535)	3	1.19	(2918)	18.7 ± 1.9
KR 6	510	47°21.9′	16°23.3′	Glashütten S	20	21.1	(1057)	26.1	(1307)	6	1.19	(2918)	17.7 ± 1.9
KR 18	780	47°26.5′	16°16.7′	Bernstein	20	26.6	(1332)	27.1	(1354)	43	1.19	(2918)	21.9 ± 2.3
A 8	540	47°23.7′	16°24.7′	Lockenhaus S	20	21.6	(1060)	28.0	(1348)	2	1.17	(2918)	17.0 ± 1.8
A 94	620	47°22.0′	16°20.6′	Oberkohlstetten	20	21.0	(1052)	27.0	(1349)	32	1.17	(2918)	17.2 ± 1.9
A 97	800	47°20.8′	16°23.4′	Hirschstein	15	25.4	(789)	30.5	(953)	81	1.18	(2918)	18.3 ± 2.2
A 103	540	47°22.1′	16°24.2′	Glashütten E	20	24.8	(1238)	29.1	(1453)	40	1.18	(2918)	18.8 ± 1.9
A 87	460	47°23.1′	16°21.5′	Weissenbachl	20	23.8	(974)	27.5	(1117)	<1	1.18	(2918)	19.3 ± 2.2

Track densities (P) are as measured and are ($\times 10^5$ tr/cm^2); number of tracks counted (N) shown in brackets, P(?^{2}) is probability of obtaining ?^{2} value for n degrees of freedom (where n is no. crystals — 1); apatite ages calculated using dosimeter glass SRM 612 and zeta = 373 ± 8; zircon ages calculated using zeta = 370 ± 11.

Window and gave a narrow range with an average of 17.0 ± 1.9 Ma.

The interpretation of the FT results as cooling ages is evident, because the temperature reached during metamorphism annealed all pre-existing tracks both in detrital zircon and apatite. The apatite closure temperature is well established to be at around 110°C (Naeser and Faul, 1969; Haack, 1976; Wagner et al., 1977; Zeitler et al., 1982; James and Durrani, 1986). The published zircon FT closure temperatures scatter slightly. The results of the laboratory annealing experiments extrapolated to geological time intervals carry an unavoidable error, because of the effect of the α-recoil track accumulation (the metamictization). Such experiments resulted in unrealistically high closure temperatures of 300–380°C (Fleischer et al., 1965; Krishnaswami et al., 1974; Lal et al., 1980; Nagpaul, 1982; Bal et al., 1983; Carpéna, 1992). Therefore, as suggested by Kasuya and Naeser (1988), the preferable references for zircon FT closure temperatures were based on natural, steadily cooled terrains by interpolation to other isotopic systems (Harrison et al., 1979; Gleadow and Brooks, 1979; Zaun and Wagner, 1985; Hurford, 1986; Shibata et al., 1990; Carter, 1990). Their considerations on the zircon stability threshold range was between 175 ± 20°C and 240 ± 50°C. We use the value of 200 ± 30°C (e.g., Kohn et al., 1990) for a fast-uplifted terrain such as the Penninic unit.

The zircon ages of Rechnitz Windows show a slight younging from northwest to southeast (Fig. 3). For proper evaluation of this trend the comparison to a model and an understanding of the structure is necessary.

4. Differences in the exhumation patterns of the Rechnitz and Tauern Windows

The comparison of the cooling paths of the Tauern and Rechnitz Windows is limited owing to technical reasons, as the datum sets are incomplete. Only mica and apatite data were published from the Tauern

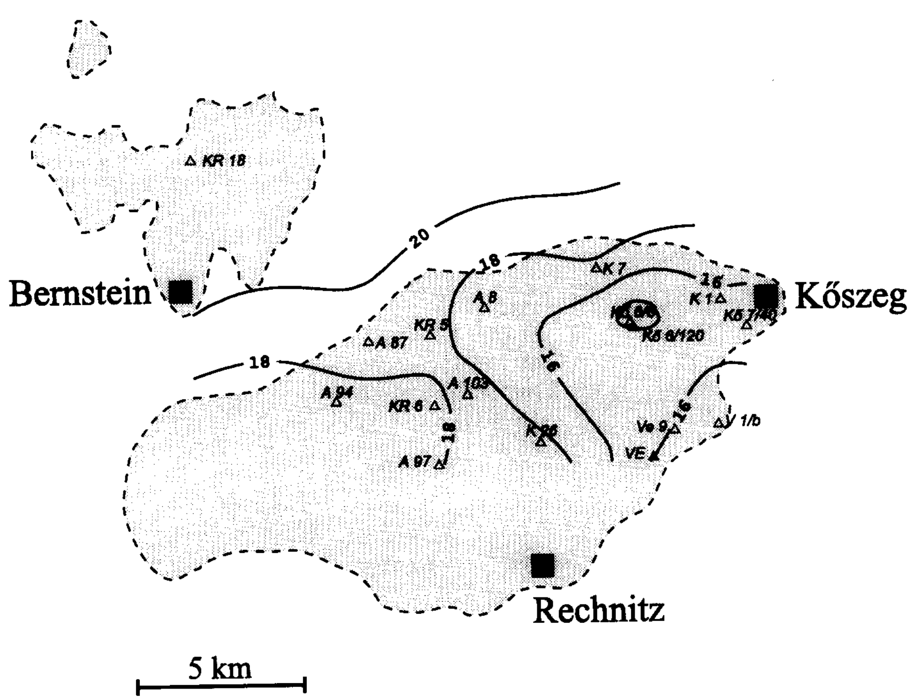

Fig. 3. Distribution of zircon fission track ages in the Rechnitz Window. Contour values are in million years, sample locations are indicated by open triangles.

Window, while mainly zircon FT ages with a few data on mica and apatite have been determined in the Rechnitz Window. The Tertiary thermal evolution of the Tauern Window is well dated by biotite and white mica Rb/Sr and K/Ar results (see the compilation of Frank et al., 1987; Table 2). Apatite fission-track studies from the western part (Grundmann and Morteani, 1985; Fügenschuh and Seward, 1995) and eastern part (Staufenberg, 1987) of the Tauern Window complete the data base.

Inside the Tauern Window the trends are complicated. The mica Rb/Sr, K/Ar and the apatite fission-track results along the E–W section of the Tauern Window show a reverse trend to the Neogene dome formation observed by Cliff et al. (1985) in a N–S section. Both in the western and the eastern termination of the window the mica ages are younger than in the inner part (Raith et al., 1978; Staufenberg, 1987). The contradiction can be resolved by postulating a difference in the kinematics and time relations of the N–S and E–W movements. The main compressional stress was perpendicular to the axis of the Tauern Window, and the extensional forces were subparallel to it (Ratschbacher et al., 1991a,b). So the temporal crossing of the closure temperature horizons in the N–S and E–W sections must be different from each other (u- and n-shapes, see Fig. 4). Calling this structure a dome may be a little misleading, as its isochronal surface is saddle-shaped. Thus we cannot apply the trends inside the Tauern Window as a model for the interpretation of the areal pattern of the Rechnitz data, because the Rechnitz Window was formed in a purely extensional regime (Ratschbacher et al., 1989; Tari, 1994).

Prior to the discussion on the chronological data the results of zircon morphometry will be presented because such data are necessary for the final conclusions.

5. Morphology of the detrital zircon crystals

The morphometrical classification of the zircon crystals were done mainly on the same monomineralic fractions as those dated by the fission-track method. The morphology of the zircons shows a clustering in some fields of the diagram of Pupin

Table 2
Compilation of mica isotope geochronological results of the Tauern Window and the surrounding area

Source	Rb/Sr		K/Ar	
	Biotite	White mica	Biotite	White mica
Oxburgh et al. (1966)			18–26	
Besang et al. (1968)			19–30	
Jäger et al. (1969)	17.7–22	ph. 24.5–29		
Lambert (1970)			26.7	27–34 (42)
Cliff et al. (1971)	14–16	15–17	16–25 (49)	17.5–23.5
Borsi et al. (1973)	16–23	51–65		
Satir (1974)	~15	ph. 25–70 [a]		
Satir (1976)	12–18 [b]	ph. ~30 [b]		
Hawkesworth (1976)	21–25	31–36 (41)		
Satir and Morteani (1982)	14	ph. 21		
Peer and Zimmer (1980)				29.6–36.8 [c]
Roddick et al. (1980)			17.5–20 (22) 18.6–20 A	16.5–18.5
Hammerschmidt (1981)	20–26	25–30 [d]	22 [d]	30 [d]
Cliff et al. (1985)	16.5		18–19.5	16.5–22
Blanckenburg et al. (1989)	13.3	ph. 20	13.3	ph. 15
Zimmermann et al. (1994)				ph. 32–36 A

A = $^{40}Ar/^{39}Ar$ dating; ph. = phengitic composition.
[a] Cooling age probably 25 Ma.
[b] Compilation.
[c] Whole-rock analyses (mica-rich samples).
[d] Youngest results of the mixed ages.

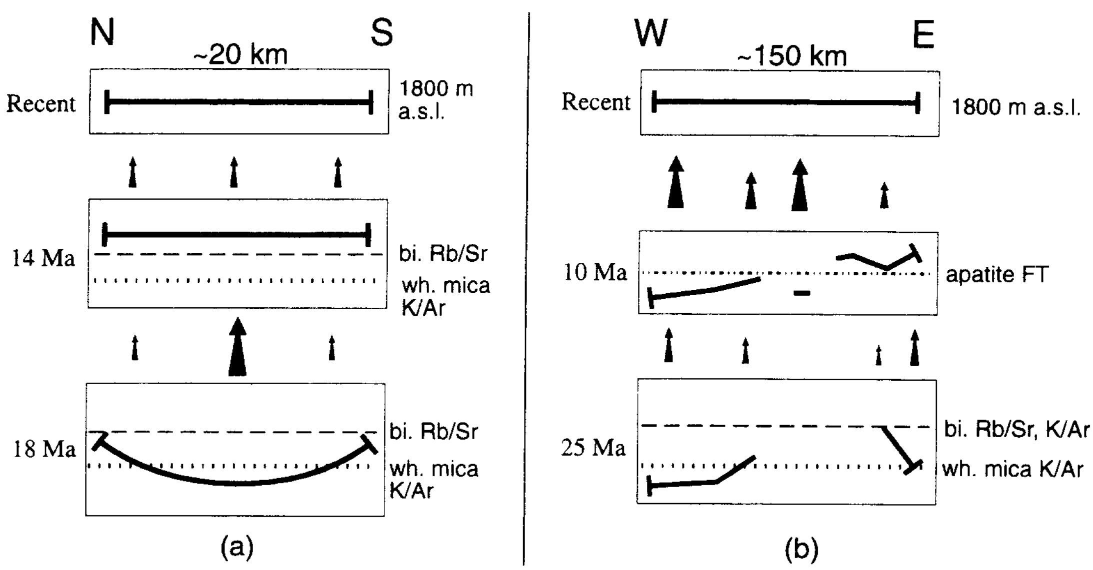

Fig. 4. (a) In the N–S section across the Tauern Window the present horizontal section was nearly horizontal 14 Ma ago in the temperature range of 300–350°C (Cliff et al., 1985). (b) However, according to the compilation of Staufenberg (1987) in the E–W direction the vertical arrangement continued during the last 10 Ma; the wings had some delay in cooling. The solid line represents the position of the recent horizon of 1800 m altitude. Broken lines mark the closure temperature levels of selected mineral-isotope systems during the exhumation. Sizes of the arrows express the relative exhumation rates along the sections.

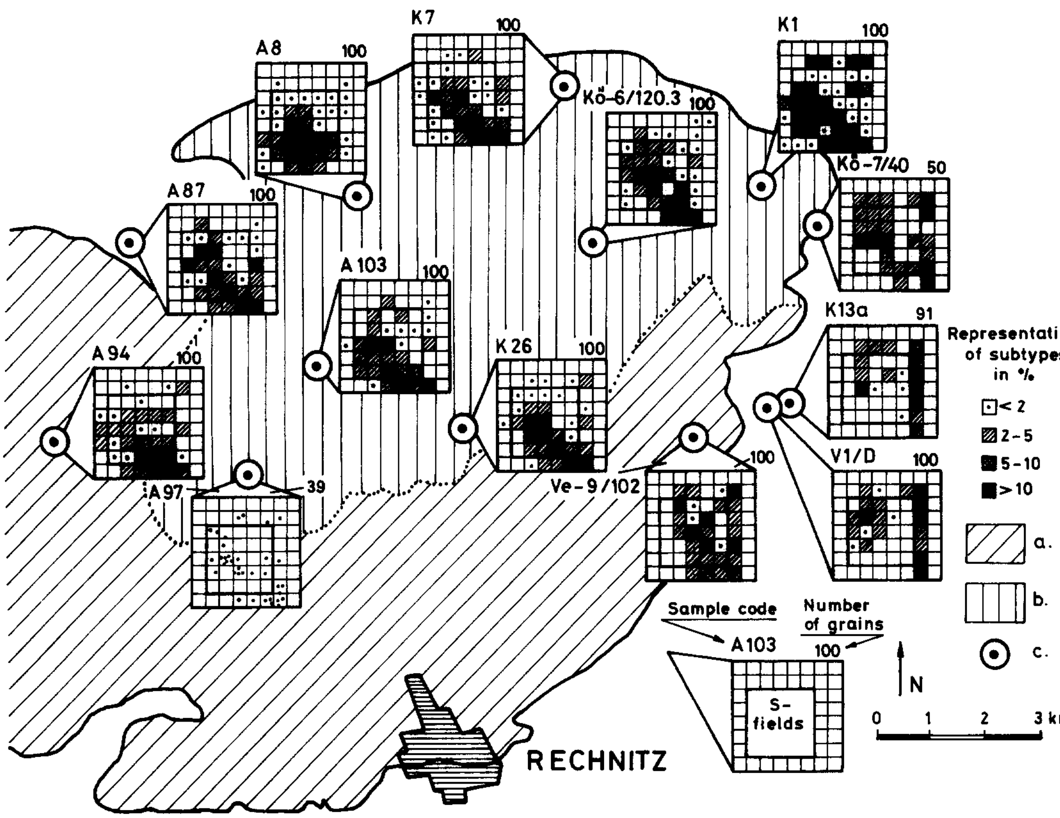

Fig. 5. Typological diagrams of the euhedral detrital zircons in the Rechnitz Penninic window. Legend: *a* = mainly calcareous phyllite and greenschist; *b* = mainly quartz phyllites; *c* = sample location.

(1980), but crystals occurred in nearly each field. Two main crystal assemblages are distinguished in frequency diagrams (Fig. 5). The first one is represented by sample A 94 and consists of zircons that belong to the S12-S14-S22-S24 field giving I.T. and I.A. index ranges of 500–700 and 300–500, respectively. According to the classification of Pupin (1980), this field is related to calc-alkaline granitoid formation. The relatively high I.T. and I.A. indices could mean higher crystallization temperatures (750–850°C) than are usual for this granitoid group, and would point to the undifferentiated character of the source granitoid. Besides this morphological field, another significant zircon population appears in the assemblage with a frequency maximum at the J5-D types. This field gives unusually high I.T. and I.A. indices (800 and 600–700, respectively), which is characteristic for zircons of tholeiitic granites (Pupin, 1980).

The other zircon assemblage appears most significantly in sample V1/D and consists also of two main crystal populations. The first one has a frequency maximum in the S1–S3–S11–S13 field with I.T. and I.A. indices of 300–600 and 200–400, respectively. This field belongs to the zircon types of evolved calc-alkaline granites and is interpreted to represent lower crystallization temperatures of the source granite from 800°C down to 650°C (Pupin, 1980). The morphological types of the other population fall into the field of G1 to D having a more pronounced frequency maximum. This distribution is characteristic for zircons of alkaline granites of anorogenic complexes. The even distribution of the crystal types along the G1–D field hints at the existence of a whole differentiation sequence in the source complex of this zircon population.

Although the observed zircon populations are characteristic mainly for the granite types listed above, Pupin (1980) mentions other rocks that may contain such morphological populations. Thus the zircons of undifferentiated calc-alkaline granites are similar to those of tonalites, while the morphological field of zircons of tholeiitic granitoids is equivalent to that of the alkaline series rhyolites or hypersolvus granites of anorogenic complexes. The latter similarity points to the relationship between sources of zircons of the J5–D field and those of the G1–D field.

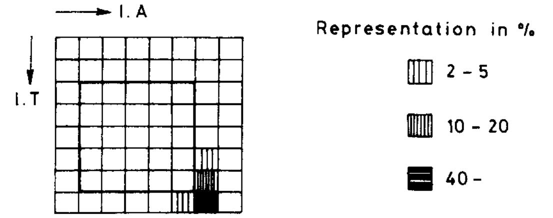

Fig. 6. Typological diagram of zircons of the blueschist transformed from plagiogranite.

6. Provenance of the zircons

As described by Tollmann (1980) and Frisch (1984) the majority of the detrital material of the Bündnerschiefer sediments probably originated from the south. This affinity to the Austroalpine series (situated to the southeast during Jurassic–Cretaceous times) is also reflected in the carbonate pebbles of the Cák conglomerate in the Rechnitz series (Oravecz, 1979). For the zircon provenance we consider mainly granitoid complexes, as parametamorphic rocks usually contain few zircon grains and predominantly rounded crystals. More than 20% of the basement of the Eastern Alps is built up by metagranitoids (Schermaier et al., 1992). The typological diagram reported by Finger and Neumayr (1990) from a leucogranitic member of Zentralgneis contains zircon crystals of the 'L' field. Such grains are missing from the investigated Penninic samples, so it is thought that this type of leucogranites was not present in the eroded area. Vavra (1989) showed the variability of zircon morphology in the different lithotypes of Zentralgneis. A major part of his samples contains 'G–P–D' type crystals. Similar zircons are also present in the studied Penninic metasediments.

Only few zircon typological data have been presented from the Austroalpine crystalline bodies, so the direct comparison to them is limited. Intrusion bodies of the Ötztal and Silvretta Mass (Böhm et al., 1991; Haiß, 1992; Müller et al., 1995) show a similar distribution to the samples from the eastern side of the Rechnitz Window.

Besides the fourteen quartz phyllite samples, one blueschist occurrence close to Oberkohlstätten was also studied. The origin of this rock has been discussed by Koller (1985) who, on basis of the geochemical data, presumed that the protolith was plagiogranite. As zircons of plagiogranites usually show restricted morphological variability (Pupin, 1985), the zircons of the blueschist can provide a check of the presumed origin. Most of the zircon grains from the blueschist belong to type D which confirms the plagiogranitic character of the rock (Fig. 6).

7. Areal variability of typological populations

The frequency distributions differ in the western and in the eastern parts of the Rechnitz Window (Fig. 5). In the western part the detrital zircons of the quartz phyllites may originate from undifferentiated calc-alkaline granites and from granites of tholeiitic character, while the zircons of quartz phyllites found in the eastern part were derived from more evolved calc-alkaline granites and from anorogenic alkaline complexes.

If we accept the dome structure of the Rechnitz Window (Demény and Kreulen, 1993), the lower quartz phyllites are in the central part of the window, while the higher ones are at the margins. This arrangement means that the source rocks of the zircon populations changed during sedimentation. If a direct relationship between the presumed source rocks really existed, it means that an evolved granitoid series eroded first, followed by undifferentiated granitoids.

8. Discussion of the exhumation history

The range of zircon FT data and the two white mica K/Ar ages of W. Frank (19 and 23 Ma; pers. commun., 1992) form a narrow range. This suggests that cooling was much faster in the 350–200°C temperature interval than in the lower temperature range, between the zircon and apatite temperature

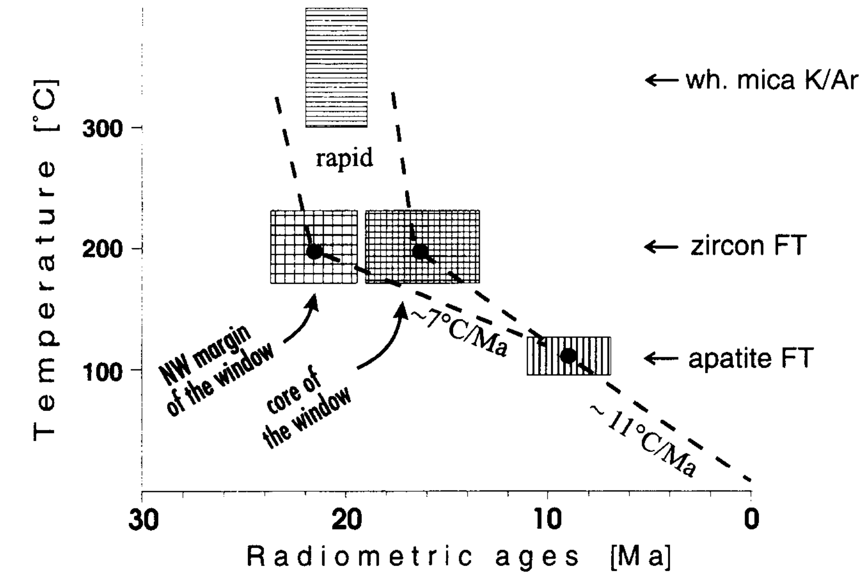

Fig. 7. Cooling curve of the Penninic unit of the Rechnitz Window. Width of boxes corresponds to the standard deviation.

thresholds (~40°C/Ma and 7–11°C/Ma, respectively, see Fig. 7). The rapid initial exhumation corresponds to the main rifting stage of crustal extension in the Alpine/Pannonian border zone. The unroofing of the Rechnitz Window was connected to the E–W extension at the eastern margin of the Tauern Window (Genser and Neubauer, 1989; Ratschbacher et al., 1989, 1990; Neubauer and Genser, 1990). The last of the three-stage plastic shear deformation of the Penninic formations in the Rechnitz Window was related to Miocene events (Dudko and Younes, 1990), while the youngest extension formed low-angle normal faults (Neubauer et al., 1992; R. Wiedemann, pers. commun., 1992).

The Rechnitz Window has been interpreted as a metamorphic core complex (Tari and Bally, 1990; Tari and Horváth, 1992). This Penninic window is the most exhumed part of the 'Rába River extensional corridor' (Tari, 1994) which includes the Wechsel Window, the small Austroalpine windows north to the Rechnitz Window (see Fig. 2) and a great part of the basement of the western Pannonian Basin. This whole Wechsel–Rechnitz Window System formed during the same extensional event (Neubauer et al., 1992). The apatite cooling ages around 10 Ma from the Wechsel structure are evidence for this relationship (Dunkl, 1992). On the other hand, the hangingwall unit of the Rechnitz detachment has not suffered thermal overprint higher than 200–240°C in Miocene time (Dunkl et al., 1993). The zircon FT ages range between 57 and 53 Ma in the lower Austroalpine Wechsel series which is the immediate structural cover of the Penninic unit. This jump of ages across the nappe borders of the Penninic window emphasizes the magnitude of the displacement along the Rechnitz detachment surface.

Tari (1994) presented a regional interpretation for the Rechnitz extensional structure. He suggested, that the breakaway of the main detachment fault was in the Koralpe, some 90 km to the west of the Rechnitz Window.

Tari and Bally (1990) and Tari et al. (1992) pointed out the large amount of extension at the boundary of the Eastern Alps and the Pannonian Basin during the Middle Miocene. They considered the low-angle normal faults at the margin of the windows are of the same magnitude as the major detachment faults of the metamorphic core complexes in the Basin and Range Province of the western U.S. The kinematic model presented for the interpretation of the fission-track and other thermochronologic data of the Basin and Range Province uses tilted blocks (Dokka et al., 1986; Fitzgerald et al., 1991; Foster et al., 1991). The tilting of the Rechnitz Penninic unit has been proved by palaeomagnetic studies. The results of Mauritsch et al. (1991) showed that the

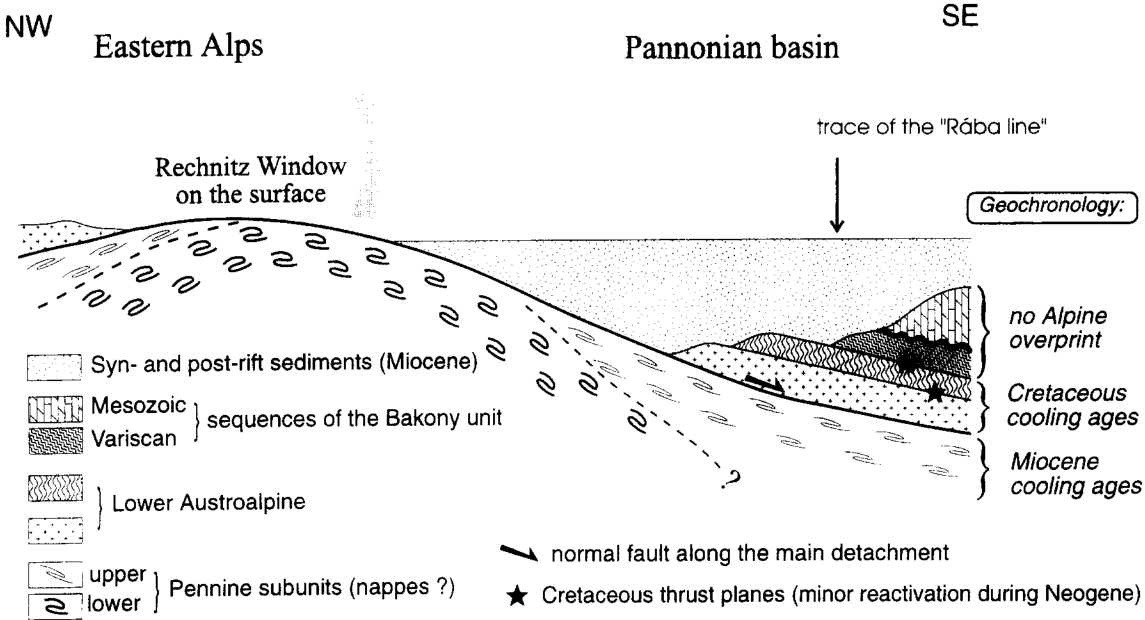

Fig. 8. Schematic cross-section through the Rechnitz core complex (strongly simplified after Horváth, 1993). More than half of the window is covered by Miocene sediments. Arrow indicates the maximum uplift of the central part of the window during extension and the location of the youngest zircon FT ages. Dashed lines separate the lower and upper Penninic subunits.

highest level of the Penninic unit of the Rechnitz Window rotated counterclockwise, together with the Middle Miocene sedimentary cover. They concluded that the Mid-Miocene tectonic movements postdated the deposition of the sediments.

Most of the Rechnitz Window is covered by a thick (up to 1.5 km) sediment pile of Miocene–Pliocene age (Fig. 2). Thus the eastern part of the outcropping Penninic rocks is the central part of the entire window area, where younger cooling ages exist due to gradual eastward unroofing of the Austroalpine cover (Fig. 8). The observed morphological variations of the detrital zircons and the areal distribution of carbon isotope ratios of graphite (Demény and Kreulen, 1993) indicate a lower Penninic (tectonic) subunit exhumed at the central part. Similar concentric arrangements of the different Penninic horizons are well documented in the Engadine and Tauern Windows (see e.g., Bigi et al., 1990). The exhumation of deeper levels in the central part of the window fits to the core complex model of Tari (1994).

The Neogene zircon cooling ages and the low-angle normal faults observed in the Rechnitz Window throw light on the debated mechanism of the final activity of the 'Rába Line'. This tectonic border of the western Pannonian Basin separates the northwestern and the southeastern part of the pre-Neogene basement, respectively, with and without Alpine metamorphic overprint (Árkai and Balogh, 1989). This displacement zone was interpreted as a strike-slip fault (Kázmér, 1984). However, the FT ages and the seismic studies (Tari and Horváth, 1992) together prove that the Rába Line is a low-angle normal fault. It is the border between two pre-Miocene nappes — one metamorphic, the other not — within the hangingwall (Fig. 8), thus it has less importance than the main detachment at the top of the Penninic unit.

9. Different cooling paths of the East Alpine Penninic windows

The difference between the cooling curves of the Tauern and Rechnitz areas emphasizes the decoupling of the Tauern and the eastern blocks during and after the escape. The major differences are the following.

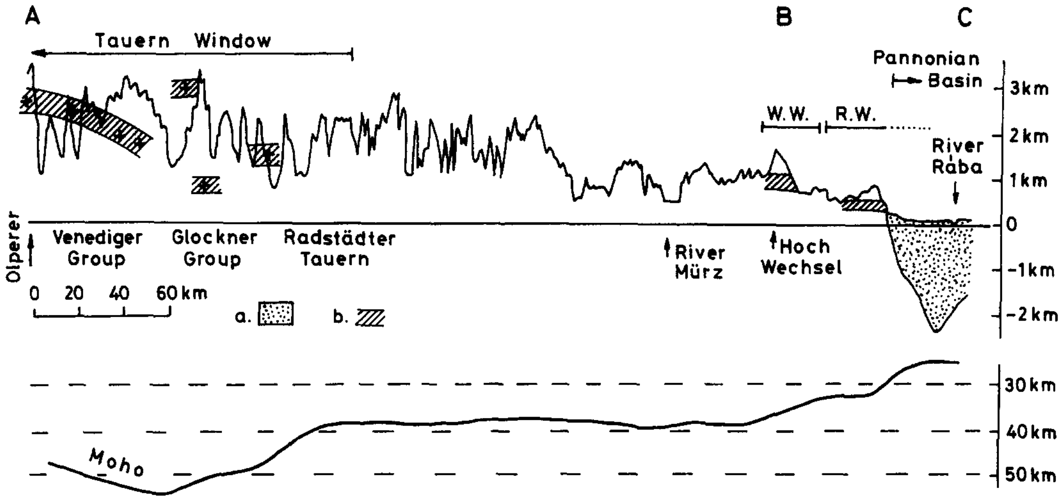

Fig. 9. E–W section of the Eastern Alps showing topography and the depth of the Mohorovicic surface (after the map of Posgay et al., 1991). Position of the section is on Fig. 1. *W.W.* = Wechsel Window; *R.W.* = Rechnitz Window; *a* = Neogene sediment of the Pannonian Basin; *b* = zone of apatite cooling ages of 9 Ma (Tauern data from Grundmann and Morteani, 1985 and Staufenberg, 1987).

(A) The cooling rate changed in time from rapid to 'normal' orogenic cooling in the Rechnitz Window (see Fig. 7); however, the mica K/Ar–zircon FT–apatite FT cooling trends do not show a break in the Tauern (Fügenschuh and Seward, 1995).

(B) The most elevated Penninic rocks in the eastern Tauern Window show significantly older cooling ages than the ages in the Rechnitz Window (20 Ma apatite ages at Reißeck, see Staufenberg, 1987).

(C) The late Alpine metamorphic overprint reached the conditions of eclogite–amphibolite facies in the Tauern, but only greenschist facies in the Rechnitz area.

(D) At the Rechnitz Window the basement nappes are missing.

(E) The continental crust between the Tauern area and the Pannonian Basin thins from >50 km to <30 km (Fig. 9).

These differences in the radiometric ages show the end of the rapid exhumation period of the Rechnitz Window. This exhumation began later than the exhumation of the eastern Tauern Window, but 'became frozen' in Middle Miocene. The early, fast uplift was a result of the vertical component of the E–W extension. Later, when the lateral extrusion slowed down, the main agent of uplift was the continuing N–S contraction after continent–continent collision in the central part of the Eastern Alps, but this 'engine' has no effect on the escaped blocks to the east.

10. Conclusions

(1) The fission-track data of Penninic formations of the Rechnitz Window are interpreted as cooling ages. The cooling was faster during the Early Miocene (~40°C/Ma) than in the Late Miocene. The mean zircon age of 17.3 Ma and mean apatite age of 8.5 Ma provide a cooling rate around 7–11°C/Ma in the sub-200°C range. The fast uplift terminated after the active extension and the subsequent isostatic emergence is insignificant as the thick continental root is missing in the Rechnitz area.

(2) The zircon FT ages inside the Rechnitz Window are decreasing towards the southeast. The drift in the values reflects the gradual eastward unroofing of the metamorphic dome.

(3) The uplift of the Rechnitz and the Tauern Windows are related to the same Neogene E–W extension. The unroofing of the Penninic horizon in the east took place later.

(4) The morphology of the detrital zircon crystals is a useful tool to distinguish the subunits of a monotonous siliciclastic metasedimentary complex. The euhedral populations of the detrital zircons in Penninic metasediments cluster into two

main groups. The source rocks of the detrital zircon populations have the characteristics of calc-alkaline granitic and undifferentiated alkaline granitic rocks.

(5) The main clusters of these groups show an areal change inside the window. If the inner structure of the Penninic window has preserved the original stratigraphic sequence, this difference refers to a change in the composition of the detritus and thus a change in the exhumed igneous terrains in the late Mesozoic. Different Penninic nappes of similar quartz–phyllitic petrography may also cause the heterogeneity of zircon typology. In this case the differences can relate not only to temporal, but areal changes of the Mesozoic detritus provenance.

(6) The main tectonic border of the western Pannonian Basin is the detachment at the top of the Penninic unit; the Rába Line is a low-angle normal fault in the hangingwall, it has much less importance.

Acknowledgements

The assistance of A. Pahr (Oberschützen) and F. Koller (Wien) during the field work is gratefully acknowledged. The age standards were made available as a favour from J. Král' (Bratislava), C.W. Naeser (Denver) and A.J. Hurford (London). The paper was improved by F. Neubauer, G. Tari, P. Árkai, L. Csontos, F. Horváth, W. Frisch, M. Kázmér and two anonymous reviewers. Thanks for their valuable aid. The German Science Foundation financed this study in the frframe of the Collaborative Research Centre 275. Support from the Hungarian National Scientific Research Fund (OTKA Project No. 232/91) is also acknowledged.

Appendix A. Analytical methods

Hand specimens were crushed and sieved, the 0.063–0.125 mm fractions were used for the further procedure. The zircon and apatite grains were separated using bromoform and magnetic separator, then were hand-picked under a stereo-microscope. For typological analysis the zircon crystals were placed on sticky paper tapes so that they could be rotated and the faces and edges could be perfectly seen. One hundred grains were selected where possible, but some samples did not contain this quantity.

For fission-track age determinations the apatite crystals were embedded in epoxy resin, the zircons in FEP-teflon. For apatite 1% nitric acid was used with 2.5–3 min etching time at 23°C (Burchart, 1972). In the case of zircon crystals, the eutectic melt of NaOH–KOH–LiOH was used at somewhat lower temperature (190°C) than suggested by the recommendations of Zaun and Wagner (1985). Neutron irradiations were made at the nuclear reactor of the Technical University of Budapest. The external detector method was used (Gleadow, 1981); after irradiation the induced fission-tracks in the mica detectors were etched by 40% HF for 40 min. Spontaneous track counts were made in oil immersion under a Zeiss NU 2 microscope, with magnification of 1600×; for mica external detectors dry optics of 800× magnification were used.

The FT ages were determined by the zeta method (Hurford and Green, 1983) using zircon from the Fish Canyon Tuff, Buluk Member Tuff and Tardree Rhyolite and apatite from Durango and Fish Canyon Tuff. Reference ages of 27.8 ± 0.2 Ma for the Fish Canyon Tuff, 31.4 ± 0.5 Ma for Durango apatite, 16.2 ± 0.6 Ma for Buluk Member Tuff and 58.7 ± 1.1 Ma for Tardree Rhyolite have been adopted according to Hurford and Hammerschmidt (1985), Green (1985), Hurford and Watkins (1987) and Hurford and Green (1983). The zeta values (9 and 16 measurements for apatite and zircon, respectively) were determined in the same manner as the FT age of the samples. The error was calculated by using the classical procedure, i.e., by the double Poisson dispersion (Green, 1981).

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