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Autor(en): **Dunkl, István / Frisch, Wolfgang / Grundmann, Günter**

Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **96 (2003)**

Heft 2

PDF erstellt am: **20.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-169016

0012-9402/03/020209-9
DOI 10.1007/s00015-003-1092-3
Birkhäuser Verlag, Basel, 2003

Eclogae geol. Helv. 96 (2003) 209–217

Zircon fission track thermochronology of the southeastern part of the Tauern Window and the adjacent Austroalpine margin, Eastern Alps

ISTVÁN DUNKL[1,2], WOLFGANG FRISCH[1] & GÜNTER GRUNDMANN[3]

Key words: Eastern Alps, Tauern Window, Penninic, Austroalpine, zircon, fission track, thermochronology

ABSTRACT

New zircon fission track data establish that the eastern Tauern Window and the Rechnitz Window, both belonging to the Penninic mega-unit, cooled synchronously below the track annealing temperature of zircon during Early to Middle Miocene times. There is an E-W shift in the age of the exhumation process within the Tauern Window. The exhumation from the zircon partial annealing conditions by normal faulting terminated around 18-16 Ma at the eastern margin of the window, while at the western margin the zircon fission track ages give an average around 12 Ma. The Austroalpine basement south of the eastern Tauern Window has not suffered Neogene thermal overprint reaching the zircon track annealing temperature. It displays a N-S gradient with Paleogene zircon ages close to the Penninic Tauern Window to the north and Cretaceous and Jurassic ages to the south.

ZUSAMMENFASSUNG

Neue Zirkon-Spaltspurendaten zeigen, daß das östliche Tauernfenster und das Rechnitzer Fenster beide zur penninischen Grosseinheit gehörig gleichzeitig im Unter- bis Mittelmiozän unter die Verheilungstemperatur von Zirkon-Spaltspuren abkühlten. Im Tauernfenster ist aus den Altern eine E-W Verschiebung des Exhumierungsprozesses ableitbar. Die auf Abschiebungsvorgänge zurückgehende Exhumierung endete am Ostrand des Tauernfensters um 18-16 Ma, während an dessen Westrand die Zirkon-Spaltspurenalter im Mittel um 12 Ma liegen. Das ostalpine Kristallin südlich des östlichen Tauernfensters erfuhr im Neogen keine thermische Überprägung, die die Spaltspuren-Verheilungszone für Zirkon erreichte. Hier ist eine N-S Zonierung mit paläogenen Zirkon-Spaltspurenaltern nahe der Grenze zum Penninikum im N und kretazischen und jurassischen Altern weiter im S festzustellen.

Introduction

The Tauern Window is a major structural feature of the Eastern Alps that also represents an important milestone in the history of geological knowledge: "window" as a structural term was first used here to describe this elongate dome (Termier 1904, see Fig. 1A). Several studies on structural geology, thermobarometry and geochronology have emphasized the contrast in evolution of the Penninic footwall and the Austroalpine hanging wall (see e.g. compilation of Genser et al. 1996). The hanging wall is mainly composed of amphibolite facies metamorphic rocks with Cretaceous or pre-Alpine muscovite and biotite K/Ar or Rb/Sr ages. In contrast, the footwall underwent Tertiary regional metamorphism and the geochronometers indicate a rapid Miocene cooling event. This rapid cooling has been related to normal faulting (Behrmann, 1988; Selverstone, 1988; Genser & Neubauer 1989) and large-scale, orogen-parallel extrusion and tectonic exhumation of the window (Ratschbacher et al. 1991; Frisch et al. 1998).

There are some uncertainties with regard to the mica ages due to incomplete resetting of the Ar and Sr chronometres. A part of the orthogneiss bodies within the Penninic suites of the Tauern Window has suffered only minor Alpine deformation and still shows well-preserved Variscan structures (Lammerer 1986). The temperatures attained during Tertiary metamorphism were largely those of the greenschist facies and thus not sufficient for complete resetting of the Rb/Sr ages of the old white mica generation by thermal diffusion (Reddy et al. 1993). On the other hand, the amount of newly formed micas is variable and sometimes rather small. That is why an important part of the mica Rb/Sr data is considered as "mixed ages". Papers dealing with Ar chronology emphasize the role of excess argon in a part of the dated mineral fractions (e.g. von Blanckenburg et al. 1989). Unfortunately, K/Ar ages are more common than Ar/Ar ages in the published literature on the region and thus the amount of excess argon is not controllable (Oxburgh et al. 1966; Cliff et al. 1985).

[1] Institut für Geowissenschaften, Universität Tübingen, Sigwartstrasse 10, D-72076 Tübingen, Germany. E-mail: istvan.dunkl@uni-tuebingen.de
[2] Laboratory for Geochemical Research, Hungarian Academy of Sciences, H-1112 Budapest, Hungary
[3] Lehrstuhl für Allgemeine, Angewandte und Ingenieur-Geologie, Technische Universität München, Arcisstrasse 21, D-80290 München, Germany

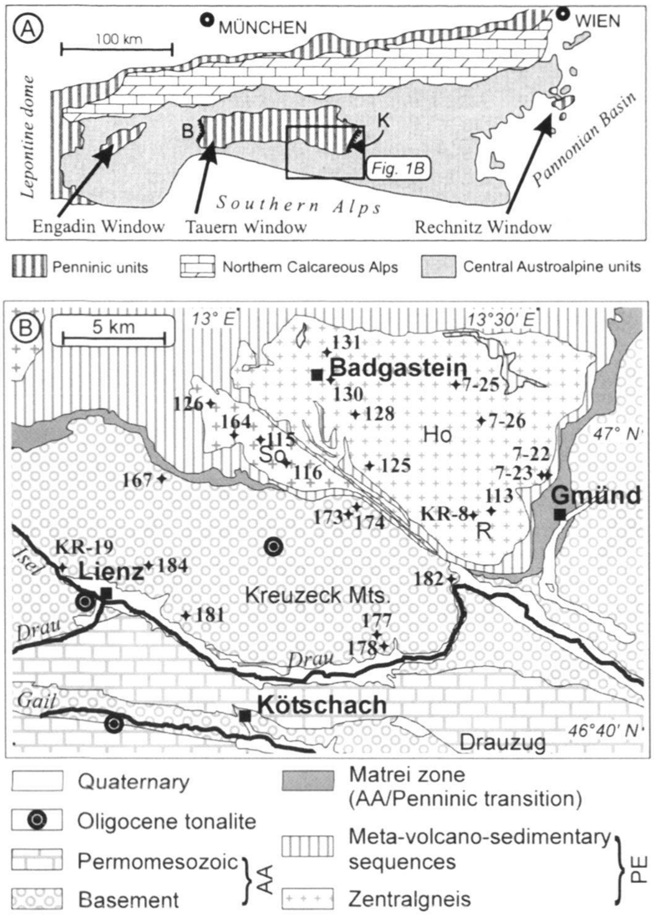

Fig. 1A. Main tectonometamorphic units of the Eastern Alps. B and K: Brenner and Katchberg low-angle extensional shear zones. B). Geological sketch map of the SE corner of the Tauern Window and adjacent Austroalpine areas with localities of the dated samples; numbers refer to samples collected by Staufenberg (1987); "KR-" and "7-" are the code of the additional samples. So and Ho: Sonnblick and Hochalm granite-gneiss cores; R: Reisseck peak; AA: Austroalpine; PE: Penninic. Base map according to Bigi et al. (1990).

The resetting mechanism in fission track (FT) thermochronology is completely different from that of the above-mentioned methods. Annealing of fission tracks is only controlled by the effective heating time, the temperature and mineral chemistry (Fleischer et al. 1965; Green et al. 1985). It is not sensitive to the activity of fluids, deformation or mineral reactions. Fission track thermochronology is a useful method to reveal the lower temperature thermal history, especially when the higher-temperature chronometers are biased by the effects discussed above.

The works of Grundmann & Morteani (1985), Staufenberg (1987) and Fügenschuh et al. (1997) already contain large data sets of apatite FT ages from the Tauern window and its frame. These results outline the final stage of the cooling history. Apatite ages are sensitive to the effect of temperatures even below 100°C, their distribution therefore often shows altitude dependence (Grundmann & Morteani 1985). The apatite age pattern reflects the rate and depth of erosion for the time after the tectonic exhumation. Thus, the apatite FT method cannot solve the question of the timing of large-scale crustal extension and tectonic exhumation of the Penninic unit.

Zircon fission track thermochronology, on the other hand is the most promising tool to date the tectonic exhumation. Although the closure temperature is debated, it is generally accepted to be in the range of 240-280 °C (Hurford 1986; Foster et al. 1996; Tagami et al. 1998). Thus, zircon FT ages register the passage though a slightly lower temperature than the mica K/Ar and Rb/Sr thermochronometers (ca. 300-330 °C – see compilation of von Blanckenburg et al. 1989). Prior to this study there was a major gap between the mica ages and the apatite ages in the eastern part of the Tauern Window, since zircon FT ages were only published from the western margin of the window (Fügenschuh et al. 1997).

Although the main character of the thermotectonic evolution is known, there are several problems in the accurate timing of the cooling process. The youngest mica ages are around 15 Ma, but there is a diffuse group of mica ages ranging between 20 and 40 Ma (see compilations of Frank et al. 1987; Genser et al. 1996). This age distribution raises crucial questions: (1) Was the exhumation and cooling of the Penninic footwall a single, short-lived process or did extension take place over a longer period during Tertiary time? (2) The Tauern window is elongated in shape and composed of three mega-boudins (Frisch et al. 2000). Were these structural elements exhumed synchronously, or did their exhumation occur in discrete steps and at which time? (3) Were the Penninic windows of the Eastern Alps (Tauern and Rechnitz) and the Lepontine dome of the Cental Alps exhumed within the same time brackets, or was there a systematic E-W migration of the extensional process?

The aim of this study is to refine the Neogene cooling history of the southeastern Tauern Window and its Austroalpine frame. The zircon FT ages measured on crystalline rocks also yield essential information for provenance studies of Peri-Alpine molasse sediments using the FT age distribution of detrital zircon crystals.

Geology

The research area is situated in the central zone of the Eastern Alps. It comprises parts of the Penninic mega-unit exposed in the southeastern Tauern Window, together with parts of the overlying Austroalpine mega-unit (Fig. 1A).

On a broad scale, the Penninic units in the Tauern Window consist of two nappe groups, the lower Venediger nappe and the higher Glockner nappe (Frisch 1980). The Venediger nappe consist of pre-Alpine basement intruded by Variscan granitoids, which were deformed to gneisses (Zentralgneis) during Tertiary metamorphism. In the study area, the Variscan basement is exposed in the Sonnblick and Hochalm gneiss domes (Fig. 1B). This Variscan basement carries a relatively thin Permomesozoic cover sequence. The Glockner nappe consist of a Jurassic ophiolitic basement present in scarce slices, now folded and imbricated with largely turbiditic deep-water sediments (Frisch 1980). The entire pile underwent Tertiary greenschist to amphibolite facies metamorphism of the Barrow type with its peak in Oligocene time around 30-26 Ma (Inger & Cliff 1994; Reddy et al. 1993). Probably large parts of the Venediger nappe and basal slices of the Glockner nappe experienced an earlier high-pressure metamorphism, which passed into the Barrow type metamorphism. The pressure peak was probably attained in Eocene times (ca. 45 Ma; Zimmermann et al. 1994; Christensen et al. 1994), although Cretaceous eclogites are also reported from the western part of the window (Frey et al. 1999).

Exhumation of the Penninic units of the Tauern Window occurred in Miocene times. A rapid exhumation pulse is inferred from geochronologic data (von Blanckenburg et al. 1989, Fügenschuh et al. 1997) and also from the sediment mass balance of the Peri-Alpine basins (Cliff et al. 1985; Frisch et al. 1999; Kuhlemann, 2000). Exhumation occurred largely by tectonic removal of the Austroalpine lid, which was block segmented and pulled apart during a large-scale extensional event affecting the Eastern and Central Alps ("lateral tectonic extrusion"; Ratschbacher et al. 1991; Frisch et al. 2000). During exhumation, the Zentralgneis body was boudinaged on a dekakilometric scale and formed three distinct cores. Apatite fission track ages suggest slightly earlier exhumation of the eastern core than the western core (Grundmann & Morteani 1985; Staufenberg 1987).

The Austroalpine crystalline basement in the study area, i.e., south of the eastern Tauern Window, mainly consists of paragneisses, orthogneisses and micaschists, which experienced Variscan amphibolite facies metamorphism. Cretaceous (Eo-Alpine) metamorphic overprint attained amphibolite and locally even eclogite facies in the lower structural levels close to the margin of the Tauern Window, and greenschist facies further south (Hoke 1990; Frey et al. 1999). This crystalline unit is tectonically overlain by an Early Paleozoic volcano-sedimentary unit metamorphosed to greenschist facies in Variscan and in some areas also during Eoalpine times. This basement unit carries the Permomesozoic cover sequence of the Drau Range, which was not affected by Alpine metamorphism.

A large part of the border between the Penninic and the Austroalpine unit in the study area is marked by the SE trending dextral Mölltal strike-slip fault, which was active during lateral tectonic extrusion in Early to Middle Miocene time. Conjugate, ENE-trending sinistral and SE-trending dextral faults of the same event characterise the Austroalpine zone of the study area.

Results and discussion

Details on the analytical procedure are described in Appendix I. Zircon fission track analysis was performed on a sample set from Staufenberg (1987) and a number of additional samples.

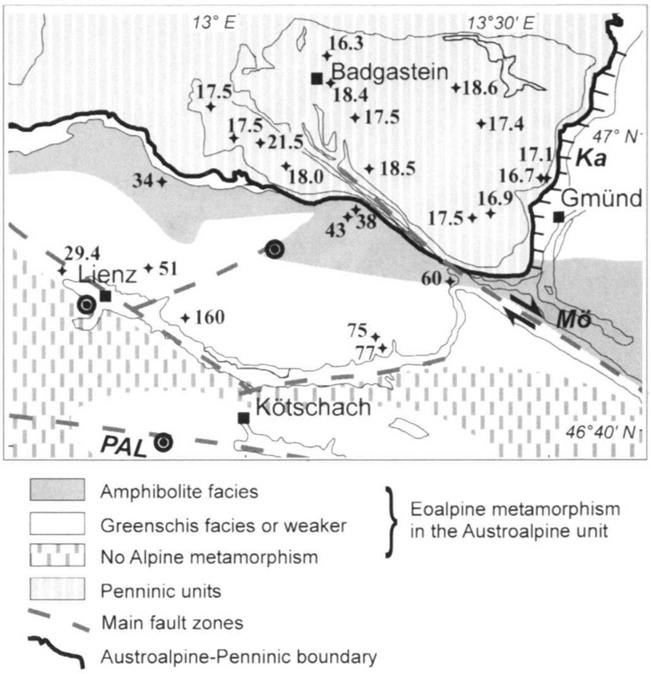

Fig. 2. Structural sketch of the eastern Tauern Window with the zircon FT ages. Ka: Katschberg shear zone, Mö: Mölltal fault, PAL: Periadriatic lineament. Metamorphic facies distribution after Frey et al. 1999.

From the 74 heavy mineral concentrates only 17 contained zircon crystals of proper amount and quality. The dated Penninic rocks are mainly derived from the 'Zentralgneis cores', the Austroalpine samples are mainly derived from different paragneisses (Fig. 1B). The fission track results are listed in Table 1. All Penninic samples have Early and Middle Miocene cooling ages, while the zircon FT ages of the Austroalpine samples are older than Oligocene (Fig. 2).

Penninic rocks

The zircon fission track ages are rather uniform and range between 21.5 and 16.3 Ma. The areal distribution of ages does not show any systematics and there is no pronounced correlation with elevation (Fig. 3). The interpretation of these results, however, poses some problems. The mean of the FT ages (17.8 ± 1.3 Ma) are in line with the published mica ages, but not with the apatite FT ages of Staufenberg (1987). His data set from the Reisseck block contains apatite FT ages 3-6 Ma older than the zircon ages of this study. This is in contradiction to the higher track annealing temperature of zircon relative to apatite. We have performed an apatite FT dating on this problematic sample by external detector method. Using this technique the new apatite age is younger than the zircon one. The possible sources of the disagreement between the ages and the details of the different FT techniques are discussed in Appendix II.

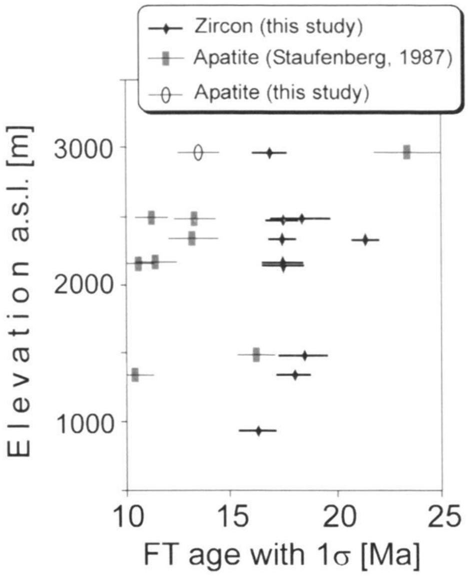

Fig. 3. Fission track age versus elevation plot for the Penninic samples. No obvious correlation can be detected for the zircon FT ages. Note the significant difference between the two apatite FT ages measured on the same sample from the highest elevation (Reisseck peak). The possible reason comes from the unequal system calibrations (see detailed discussion in Appendix II).

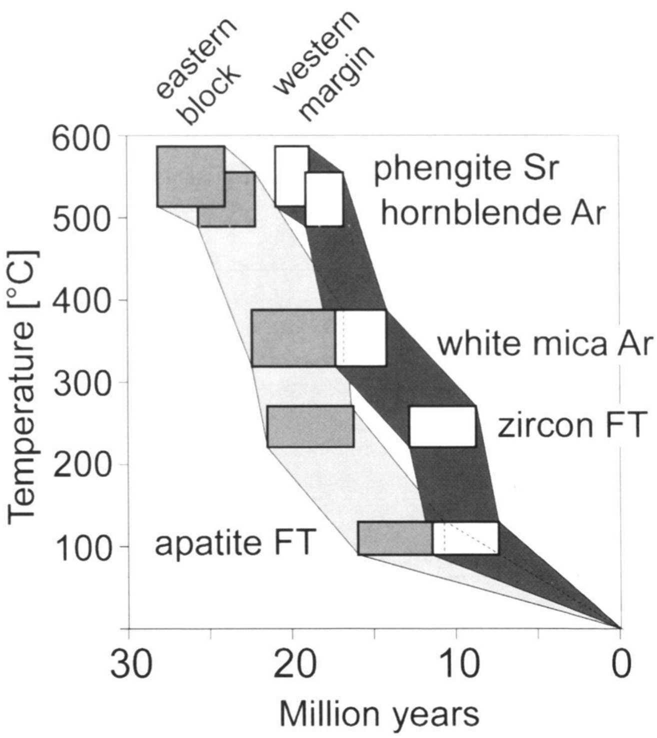

Fig. 4. Temperature-time plot of the thermochronologic data from the western and eastern parts of the Tauern Window. Data from western margin: Grundmann & Morteani (1985), von Blanckenburg et al. (1989), Fügenschuh et al. (1997) and Stöckhert et al. (1999); data from the eastern part of the window: Oxburgh et al. (1966), Cliff et al. (1985), Staufenberg (1987), Reddy et al. (1993) and this study. For apatite, the ages calculated for the 1800 m level. The horizontal sizes of the boxes represent the range from the youngest to the oldest ages.

We interpret the tight grouping of the zircon FT ages from the Penninic units as a sign of the homogeneity of the thermal history of the southeastern Tauern Window. The tectonic exhumation and cooling by downward movement of the isotherms relative to the gneiss masses occurred rather rapidly. The zircon FT ages do not reflect the difference of the thermal evolution between the Sonnblick and Hochalm domes as it was detected by higher temperature chronometers by Reddy et al. (1994).

The zircon FT ages of this study are older than the zircon results from the western margin of the Tauern Window (Fügenschuh et al. 1997). The difference is significant by t-test at the level of α=0.05 (means: 17.8 ± 1.3 Ma and 11.4 ± 2.9 Ma, east and west, respectively). It is an indication for different ages of the normal faulting activity of the Brenner and Katchberg low-angle extensional shear zones (Fig. 1A). The areal distribution and the young cluster of mica K/Ar and Rb/Sr ages also support the proposal that the eastern 'Zentralgneis' cores exhumed first and that the western part of the window followed with a delay of ~3 Ma (Fig. 4). This trend is similar to the internal age pattern of the Lepontine Alps, where the mica Ar and zircon FT ages are older close to the eastern margin than at the western margin (data compiled in Hunziker et al. 1992; see Fig. 5). The Rechnitz window group has a tendency to the opposite sense, with the older zircon FT ages situated in the west (Dunkl & Demény 1997). However, the range of ages is much narrower in the small Rechnitz window and the contrast between age groups consequently smaller than at the western and eastern margins of the Lepontine and Tauern structures.

Austroalpine samples

There is a jump between the zircon FT ages of the Penninic and Austroalpine samples (ca. 18 Ma versus 30 to 160 Ma). The youngest age from the immediate hanging wall of the Tauern Window falls in Oligocene times. There is no evidence for Neogene resetting of zircon ages in the Austroalpine hanging wall along the southern margin of the eastern Tauern Window. West of our study area, close to the southwestern corner of the window, thermally overprinted Austroalpine units from deeper structural levels are exposed (Stöckhert et al. 1999). That profile is situated close to the tip of the Adriatic indenter, and the pronounced compressional forces resulted in the exhumation of a slice from the deepest levels of the Austroalpine pile.

The zircon FT ages increase to the south, with the younger ages situated close to the margin of the window and the older ones around the Drau valley (Table 1, Fig. 2). We consider the Paleogene ages as cooling ages. Similar radiometric ages can be found in the Tauern window and in the Austroalpine nappe pile (Zimmermann et al. 1994; Handler et al. 2000) as well as in

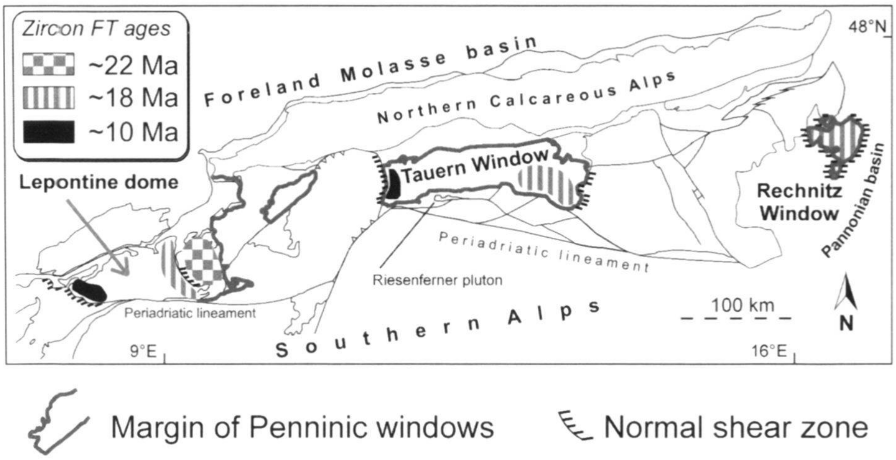

Fig. 5. Sketch map of Central and Eastern Alps with the zircon fission track ages of the Penninic windows (references in the text).

the Lepontine dome (the so-called 'Lepontine phase', see Hunziker et al. 1992). Apatite FT ages in the Austroalpine realm also register an Eocene cooling phase (Grasemann & Dunkl submitted).

The Late Cretaceous zircon FT ages of the western Kreuzeck Mountains belong to the most characteristic age cluster of the Austroalpine rocks. A Jurassic age in the eastern Kreuzeck Mts. (sample #181) indicates that there is also evidence for thermal overprint during Mesozoic extension (Triassic and Jurassic rifting) in the Austroalpine complex south of the Tauern Window. This Jurassic thermal phase was also recognised by K/Ar dating of white mica fractions of < 2 µm in the Drauzug Mountains south of our study area (Hepp 1999). Similarly to the southeastern margin, the zircon FT ages southwest of the Tauern Window also show zoning in the Austroalpine belt (Stöckhert et al. 1999), as also evidenced by zircon FT data by Fügenschuh (1995) and Mancktelow et al. (2001). The zircon FT ages increase from north (Miocene) to south (Paleogene and Early Cretaceous). The fault pattern in the west is mainly determined by E-W trending faults (Schulz 1989). In contrast, in our study area NW-SE trending faults determine the age distribution pattern (Hoke 1990; Sprenger 1996, see Fig. 2).

Conclusions

The new zircon fission track ages allow an important refinement of the thermal history of the eastern Tauern Window and lead to the following conclusions.

1) The recently exhumed Penninic rocks were in the thermal level of zircon track instability before Neogene tectonic exhumation since no Pre-Miocene FT ages are preserved in the Tauern Penninic rocks.
2) The samples passed through the zircon partial stability zone around 19-18 Ma ago; we consider this time as the major period of tectonic exhumation.
3) The southeastern part of the window shows uniform age distribution, the exhumation process was rapid and affected the whole eastern granite-gneiss cores at the same time.
4) The mean of zircon FT ages of this study is the same within 1σ error as the mean of zircon ages obtained from the Penninic formations of the Rechnitz window (17.8 ± 1.3 Ma and 17.1 ± 2.0 Ma, respectively). The tectonic exhumation of the eastern Tauern Window and the Rechnitz Window can be considered as synchronous.
5) The easternmost granite-gneiss core of the Tauern Window experienced earlier cooling than the westernmost parts of the window, which was exhumed along the Brenner shear zone. This indicates the diachronous exhumation of the Zentralgneiss cores during the Neogene tectonic exhumation.
6) A similar trend of westward migration of the exhumation process is found in the Lepontine gneiss dome of the Central Alps.
7) The Austroalpine belt south of the eastern Tauern Window shows N-S zoning of the zircon ages. No Neogene resetting was found in the hanging wall. This implies that the displacement was dominated by lateral movements and that there is no exhumation of the lower but only of the middle part of the upper-plate Austroalpine sequence. This is different from the Austroalpine zone to the south of the western Tauern Window.

Appendix I. – *Experimental procedure*

The samples were treated by the common heavy liquid and magnetic separation processes. The zircon crystals were embedded in FEP and PFA teflon; the apatites in epoxy resin. For etching, the eutectic melt of NaOH-KOH-LiOH was used at a temperature of 200°C (Zaun & Wagner 1985) for zircons. For apatite 1% nitric acid was used with 2.5-3 min etching time (Burchart, 1972). Neutron irradiations were made at the RISØ reactor (Denmark) and the reactor of the Oregon State Uni-

Tab. 1. Fission track ages obtained on Penninic and Austroalpine samples.

Code	Latitude	Longitude	Elevation [m, a.s.l.]	Cryst.	Spontaneous ρs (Ns)	Induced ρi (Ni)	Dosimeter ρd (Nd)	$P(\chi^2)$ [%]	Disp.	FT age * [Ma ± 1s]
Zircon FT data of Penninic samples										
11 ST81 - 113	13° 21' 54"	46° 56' 59"	2963	15	26.4 (815)	54.7 (1688)	5.48 (10787)	87	0.00	16.9 ± 0.8
13 ST 81-115	13° 01' 04"	47° 00' 44"	2340	20	105 (2052)	171 (3342)	5.48 (10787)	26	0.05	21.5 ± 0.7
14-St-81 116	13° 03' 12"	46° 59' 04"	1350	12	85.4 (890)	166 (1730)	5.48 (10787)	58	0.01	18.0 ± 0.8
23 ST 81-125	13° 13' 01"	46° 59' 00"	1490	13	23.8 (663)	45.1 (1255)	5.48 (10787)	14	0.12	18.5 ± 1.2
74 St81 - 126	12° 55' 35"	47° 03' 16"	2480	16	70.5 (935)	126 (1671)	4.90 (4899)	58	0.00	17.5 ± 0.8
26 ST81 - 128	13° 10' 32"	47° 02' 53"	2150	13	50.5 (1037)	101 (2077)	5.48 (10787)	2	0.13	17.5 ± 1.0
28St81 - 130	13° 10' 21"	47° 05' 52"	2490	17	41.7 (730)	81.4 (1425)	5.48 (10787)	< 1	0.27	18.4 ± 1.5
29 St 81 - 131	13° 08' 33"	47° 08' 00"	940	10	98.4 (590)	190 (1139)	4.94 (4899)	38	0.06	16.3 ± 0.9
62 St81 - 164	12° 58' 37"	47° 00' 29"	2170	16	84.7 (1133)	153 (2052)	4.92 (4899)	< 1	0.15	17.5 ± 1.0
KR-8	13° 22' 31"	46° 55' 00"	2345	20	78.9 (1467)	139.7 (2596)	4.85 (4899)	52	0.01	17.5 ± 0.7
7-22	13° 30' 25"	46° 57' 34"	990	20	8.75 (271)	21.8 (674)	6.57 (4543)	77	0.10	17.1 ± 1.3
7-23	13° 30' 17"	46° 57' 34"	950	20	18.8 (588)	47.4 (1483)	6.60 (4543)	28	0.11	16.7 ± 1.0
7-25	13° 21' 46"	47° 03' 41"	1650	20	62.5 (989)	150 (2382)	7.02 (4543)	56	0.02	18.6 ± 0.8
7-26	13° 24' 40"	47° 01' 14"	1110	20	35.8 (658)	92.3 (1698)	7.05 (4543)	27	0.08	17.4 ± 0.9
Zircon FT data of Austroalpine samples										
65 St81 - 167	12° 54' 00"	46° 56' 54"	1000	20	45.5 (1091)	41.7 (1001)	4.92 (4899)	77	0.01	34.2 ± 1.6
71 St81 - 173	13° 11' 00"	46° 54' 33"	1910	20	62.7 (1337)	45.5 (970)	4.91 (4899)	23	0.09	43.2 ± 2.2
72 St81 - 174	13° 11' 39"	46° 55' 00"	1280	20	54.4 (1311)	43.8 (1054)	4.90 (4899)	25	0.08	38.7 ± 1.9
75 St81 - 177	13° 14' 41"	46° 46' 09"	985	20	86.0 (1615)	35.8 (673)	4.92 (4899)	76	0.00	75.0 ± 3.7
76 St81 - 178	13° 15' 00"	46° 45' 43"	640	16	108 (1438)	43.3 (579)	4.90 (4899)	93	0.00	77.3 ± 4.1
79 St81 - 181	12° 54' 25"	46° 47' 36"	950	20	129 (1659)	24.8 (320)	4.89 (4899)	47	0.03	160 ± 10
82 St81 - 184	12° 52' 04"	46° 52' 00"	1100	15	224 (1651)	137 (1013)	4.93 (4899)	70	0.00	51.1 ± 2.3
85 St81 - 187	13° 22' 08"	46° 50' 00"	570	17	63.7 (958)	33.0 (497)	4.93 (4899)	54	0.04	60.3 ± 3.6
KR-19	12° 42' 27"	46° 51' 10"	700	20	39.3 (1264)	41.7 (1339)	4.89 (4899)	21	0.09	29.4 ± 1.4
Apatite FT age of the Reisseck peak										
11 ST81 - 113	13° 21' 54"	46° 56' 59"	2963	20	1.35 (246)	8.64 (1575)	4.62 (9076)	91	0.00	13.5 ± 1.0

Localities of 'St' samples are indicated in Staufenberg (1987).
Cryst: number of dated zircon crystals.
Track densities (ρ) are as measured (x10^5 tr/cm^2); number of tracks counted (N) shown in brackets.
$P(\chi^2)$: probability obtaining Chi-square value for n degree of freedom (where n = no. crystals-1).
Disp.: Dispersion, according to Galbraith and Laslett (1993).
*: Central ages calculated using dosimeter glass: CN 2 with ζ_{CN2} = 127.8 ± 1.6 for zircon and CN 5 with ζ_{CN5} = 373.3 ± 7.1 for apatite.

versity (USA). The external detector method was used (Gleadow 1981). After irradiation the induced fission tracks in the mica detectors were revealed by etching in 40% HF for 40 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 & Green 1983) using age standards listed in Hurford (1998). The error was calculated by using the classical procedure, i.e., by double Poisson dispersion (Green 1981). Calculations and plots were made with the TRACKKEY program (Dunkl 2002).

Appendix II. – *Remarks on the system calibration and comparison of apatite and zircon FT data*

The basic aim of our study was to create a data set by zircon fission track thermochronology that can be used for the dating of cooling in deeper crustal environment, roughly between 240 and 280 °C and the apatite chronology was not our original target. However, the serious contradiction between the published apatite ages (determined by the population method) and zircon ages of the Reisseck peak sample motivated us to date an apatite using the external detector method, i. e. the same methods as used for zircon FT datings. The new apatite FT age is 10 Ma younger than that published by Staufenberg (1987), and it is younger than our zircon FT age (Table 1 and Fig. 3). The basic contradiction and the new dating asks for a discussion of the details of the system calibrations used by the different fission track techniques.

The FT age determinations performed on the two minerals were made by different techniques by two investigators. The apatite samples were dated by the population technique with calibration by the activation method (Staufenberg, 1987), while the zircon samples of our study were dated by the external detector method (EDM) with zeta calibration (see technical details in Hurford & Green 1982 and Wagner & Van den haute 1992). There is no consensus about the rating of these methods and no absolute criterion exists to argue for one or the other.

Summary of different fission track methods

Population method	*External detector method*
- Tracks detection geometry:	**- Tracks detection geometry:**
apatite 4π / apatite 4π	apatite 4π / muscovite detector 2π
- System calibration:	**- System calibration:**
Neutron fluence measured by metal activation using Au, Co, Cu, In...	Nominal value of neutron fluence is not considered (only used indirectly).
Decay constant of natural fission is considered; published values have a broad scatter: $\lambda = 6.85 — 8.46 \times 10^{-17}$ / year	No decay constant is used, the FT age is calculated using age standards.

Fig. 6. The population and external detector methods are the most widely used techniques of fission track geochronology. This short compilation presents the major differences.

The population method & activation process were widely used in the seventies and eighties, while the EDM & zeta calibration are more and more the rule in the nineties. It is probably better to discuss separately the observation geometry (population vs. EDM) and the neutron fluence monitoring (see Fig. 6). We can exclude that the population method and EDM can give significantly different track counting results. Parallel measurements of the same samples usually yield coherent ages with these techniques (Miller et al. 1990; Balestrieri, pers. comm. 1998), but Andriessen (1990) mentioned that the population method resulted in ages that were slightly older than the external detector technique. We suppose that the neutron fluence calibration can be the source of the unexpected deviation. The activation method is based on measurement of gamma activity of irradiated metals like Cu, Co, Au. The cross section of the (n, γ) reactions of these metals strongly depend on neutron energy, and these distributions are basically different from each other and from the energy-dependence of the ^{235}U(n, f) reaction (Green & Hurford 1984). The problem of the badly constrained fission decay constant (λ_F) introduces another source of uncertainty into the age calculation (see review of Bigazzi 1981). This additional error can reach 35 relative % in the most extreme cases by using various metals for neutron monitoring and performing the age calculation by different values of the decay constant. To overcome these problems, Arias et al. (1981) suggested that the mean of fluences determined by two different metals (Au and Cu) should be applied. Hurford & Green (1982) proposed the application of different decay constants for different metals, for example to use the value of $6.85 \pm 0.2 \times 10^{-17}$/year for calibration performed with cobalt. The irradiations of Staufenberg (1987) were calibrated with Co and the ages were calculated by the decay constant of 8.46×10^{-17}/year. Recalculation by using the λ_F value mentioned above would result in even older apatite FT ages, and this kind of re-calibration is therefore not a feasible way to eliminate the contradiction between the apatite and zircon ages.

There is another possible source of the anomalous behaviour of the Reisseck samples. The Tauern Window contains a number of ore deposits, and the zircon samples from this region are unusually rich in uranium. A possible enrichment in rare earth elements in the apatites can have a self-shielding effect during the neutron irradiation. In such an extreme case, this could result in a (virtual) older FT age.

It is difficult to give an exact reason for the difference of the apatite ages measured on the same sample, and a single remeasured apatite FT age does not mean a general and constant shift between the two methods. But, the facts and speculations listed above warn about the necessity of the check of the details of the ages when a regional compilation is made from results generated by different system calibrations.

Acknowledgement

The German Science Foundation financed this study. The final version of the manuscript benefited from the helpful comments of G. Morteani (München) and the reviewers B. Fügenschuh (Basel) and N. Mancktelow (Zürich). The authors are thankful for the careful sample preparation made by Dagmar Kost, Gerlinde Höckh and Dorothea Mühlbayer-Renner (Tübingen) and for the precise work of the staffs of the RISØ and Oregon nuclear reactors.

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Manuscript received January 15, 2001
Revision accepted April 26, 2003