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Late stage differential exhumation of crustal blocks in the central Eastern Alps: evidence from fission track and (U–Th)/He thermochronology

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ABSTRACT

Thermal history modelling based on zircon- and apatite fission track and apatite (U–Th)/He data constrain and refine the near-surface exhumation of the south-eastern Tauern Window (Penninic units) and neighbouring Austroalpine basement units in the Eastern Alps. Fast exhumation on both sides of the Penninic/Austroalpine boundary coincides with a period of lateral extrusion and tectonic denudation of the Penninic units in Miocene time (22–12 Ma). The jump to older ages occurs within the Austroalpine unit along the Polinik fault, which therefore defines the boundary between the tectonically denuded units and the hangingwall at that time. According to the different (U–Th)/He ages between the Penninic Hochalm- and Sonnblick Domes we demonstrate a differential cooling history of these two domes in the latest Miocene and early Pliocene.

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Introduction

The Tauern Window in the Eastern Alps exposes Penninic units framed by the superimposed Austroalpine units (Fig. 1). Thermochronological data indicate only little differences in cooling ages across the Penninic/Austroalpine boundary along the south-western border of the Tauern Window (Borsi *et al*., 1973, 1978; Grundmann and Morteani, 1985; Fügenschuh *et al*., 1997; Most, 2003). The cooling histories document that a substantial part of vertical displacement during exhumation occurred along the Defreggen-Antholz-Vals (DAV) fault (Fig. 1b). Hence, the Austroalpine unit north of the DAV was exhumed together with the Tauern Window (Frisch *et al*., 2000). The continuation of this boundary to the east is yet unknown and its knowledge may provide important contributions to the exhumation history of the Tauern Window.

In this study, we reconstructed the tectono-thermal evolution of the south-eastern Tauern Window and the adjacent Austroalpine units by means of low-temperature thermochronometry and thermal modelling. We used the zircon fission track (ZFT), apatite fission track (AFT), and apatite (U–Th)/He dating methods, the sensitivity intervals of which, often referred to as partial annealing or retention zones (ZPAZ, APAZ, HePRZ), are ca. 300 to 200 °C, 120 to 60 °C, 80 to 40 °C, respectively (Green *et al*., 1986; Wagner and Van den haute, 1992; Wolf *et al*., 1996). The combination of these methods allows to reconstruct the exhumation paths of different tectonic blocks in detail and to correlate them with the well-documented lateral extrusion scenario of the Eastern Alps in Miocene time (Ratschbacher *et al*., 1991; Frisch *et al*., 1998) and local post-extrusion events. Our new results underline the importance of using multiple low-temperature thermochronometers in elucidating details of the near-surface history of orogens which have previously remained undetected.

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Geology

During the Miocene orogen-parallel extrusion the Tauern Window was exhumed by pull-apart of the Austroalpine upper plate (Frisch *et al*., 2000). Removal of the Austroalpine lid was partly achieved by large-scale displacement along low-angle normal shear zones, i.e. the Brenner shear zone in the west (Selverstone, 1988) and the Katschberg shear zone in the east (Genser and Neubauer, 1989) (Fig. 1b). In the study area, Variscan granites that transformed to the Sonnblick and Hochalm gneiss domes during the Alpine orogeny are exposed within the Tauern Window. Cooling ages of white mica based on the Rb/Sr system document significant earlier cooling of the Sonnblick (27 Ma) than of the Hochalm Dome (22–16.5 Ma) (Reddy *et al*., 1993). AFT and ZFT ages record a homogeneous cooling history for both domes in Early Miocene time (Staufenberg, 1987; Dunkl *et al*., 2003).

The Austroalpine units to the south-east of the Tauern Window largely consist of pre-Variscan rocks that were affected by Variscan and Cretaceous metamorphism (e.g. Thöni, 2006). The southern boundary of the eastern Tauern Window is marked by the Mölltal fault (Figs 1 and 2), which was active in Early to Middle Miocene time. The Polinik fault in the Austroalpine unit (Fig. 2) separates a block characterized by Cretaceous mica cooling ages to the north (in this study referred to as Polinik Block) from a block showing mostly

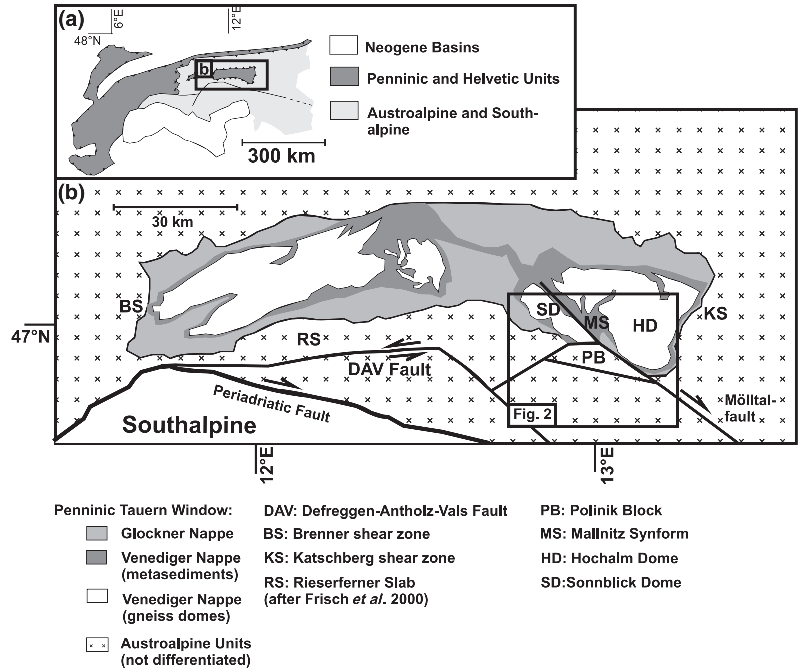

Fig. 1 (a) Simplified tectonic sketch map of the Alps. (b) Sketch map of the Tauern Window with study area (rectangle).

Variscan ages to the south (referred to as Kreuzeck Block) (Hoke, 1990). The Polinik fault is characterized by both ductile strike slip and brittle dip slip displacement (Hoke, 1990).

Methods

Spontaneous tracks in apatites and zircons were revealed according to methods described by Donelick *et al.* (1999) and Zaun and Wagner (1985), respectively. We used the external detector method (Gleadow, 1981) with low-uranium muscovite sheets (Goodfellow mica^{TM}; Goodfellow GmbH, Badnauheim, Germany) as external detector. The IUGS-recommended zeta calibration approach (Hurford and Green, 1983) was used to determine the ages. FT ages were calculated with the program TRACKKEY version 4.1 (Dunkl, 2002). Modelling of the low-temperature thermal history based on AFT data was carried out using the HeFTy modelling program (Ketcham, 2005). All track lengths are projected to c-axis (Donelick *et al.*, 1999).

For (U–Th)/He analysis, apatite crystals were hand-picked following the selection criteria of Farley (2002), degassed in vacuum by laser and analysed for He by a Pfeiffer Prisma QMS-200 mass spectrometer in the thermochronological Laboratory at University of Tübingen. At least one duplicate of every sample was measured. Following the He measurements, the crystals were analysed for U–Th at the Scottish Universities Environmental Research Centre (SUERC) in East Kilbride (Scotland) using a VG PlasmaQuad 2 ICP-MS. The total analytical uncertainty (TAU) was computed as a square root of the sum of squares of weighted uncertainties on U, Th and He measurements. The raw (U–Th)/He ages were corrected by Ft correction following Farley *et al.* (1996). The value of 5% was adopted as the uncertainty of the Ft correction, and was used together with TAU to calculate the errors of corrected (U–Th)/He ages. Replicate analyses of Durango apatite over the period of this study (42 analyses) yielded a mean (U–Th)/He age of 30.8 with standard deviation of 2.5 Ma, which is in good agreement with the reference (U–Th)/He age of 31.13 ± 1.01 Ma (McDowell *et al.*, 2005). For more details on analytical procedures the reader is referred to Danišík (2005).

Results

Four steep elevation profiles were investigated, two in the Austroalpine unit and one each in the Penninic Hochalm and Sonnblick Dome (Fig. 2). Apatite (U–Th)/He ages were obtained from eight samples. All (U–Th)/He single grain ages are younger or overlap within their one sigma errors with their corresponding AFT age (Tables 2 and 3). Single grain ages that do not meet these criteria are not reported.

Austroalpine basement units: The Kreuzeck Block yields systematically higher ages than the Polinik Block (Fig. 2). According to the chi-squared statistical test, all ZFT ages were totally reset during the Cretaceous metamorphic overprint (Table 1). The ZFT ages do not show any age-elevation relationship. Two micaschist samples derived from the southernmost part of the Kreuzeck Block yield higher ZFT ages (106.7 ± 8.5 and 103.1 ± 7.7 Ma) than previously recognized in this area. In the northern part the ZFT age is 64.8 ± 3.5 Ma (Fig. 2, Table 1). AFT ages range from 27.4 ± 2.7 to 19.6 ± 1.6 Ma with a positive correlation between age and elevation (Fig. 3a). The mean track lengths for two apatite samples are 13.3 and 13.6 μm (Fig. 2, Table 2). Cooling rates determined from zircon/apatite pairs and thermal history modelling indicate slow cooling in the order of $\sim$4 °C Ma^{-1} between Late Cretaceous and Early Miocene time (Fig. 4a). No apatite grains from the Kreuzeck Block were suitable for (U–Th)/He measurements.

The two ZFT ages from the Polinik Block are 39.1 ± 2.3 and 30 ± 1.8 Ma. AFT ages are systematically younger than those from the Kreuzeck Block (between 19.4 ± 1.3 and 7.3 ± 0.9 Ma). One unimodal track length distribution indicates a single period of rapid cooling (Fig. 2). Apatite (U–Th)/He ages are younger than the AFT ages and increase similarly with elevation (Table 3, Fig. 3b).

Tauern Window: ZFT ages from the south-eastern Tauern Window are rather uniform and range between 21.5 and 16.3 Ma (Dunkl *et al.*, 2003). AFT ages of both domes show positive age-elevation correlations (Fig. 3c,d) between 10.6 ± 0.9 and 7.8 ± 0.6 for the Sonnblick Dome and 15.2 ± 1.3 and 7.4 ± 0.5 for the

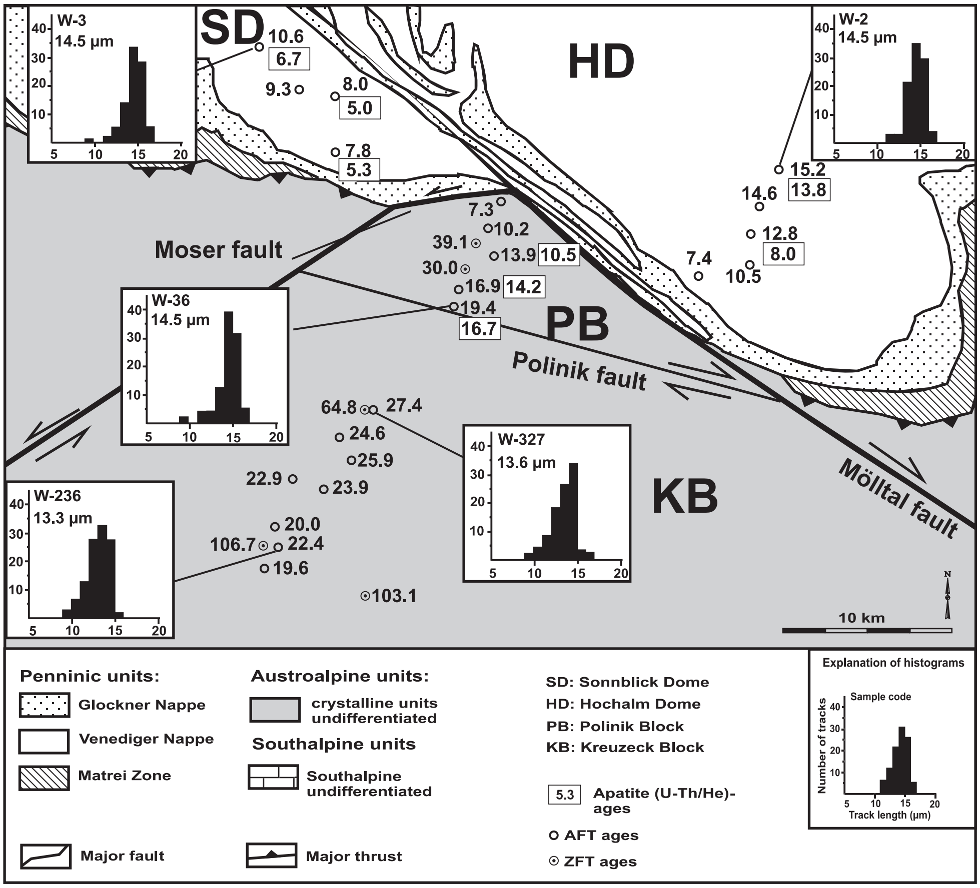

Fig. 2 Fission track (zircon, apatite) and apatite (U–Th)/He ages together with track length distributions of confined horizontal tracks in apatite.

Hochalm Dome. Both mean track lengths are 14.5 µm indicating rapid cooling through the entire APAZ. Apatite (U–Th)/He ages of the Sonnblick Dome range from 6.7 ± 0.5 to 5.0 ± 0.4 and are systematically younger than those from the Hochalm Dome (13.8 ± 0.8 and 8.0 ± 0.6 Ma) (Table 3). Both He age sets show a positive age-elevation relationship (Fig. 3c,d).

Mean Dpar values of all analysed samples range from 1.62 to 1.99 µm (Table 2). They show no variation between different tectonic units and thus indicate uniform chemical composition of the apatite grains. Therefore, variations either in age or track length distribution are only related to differences in their thermal history.

Thermal history

The mean length of tracks induced by thermal neutron irradiation is 16.3 µm (Laslett *et al.*, 1987). To adjust the modelling results to the observed amount of annealing, the model requires an artificial, late cooling event (Kohn *et al.*, 2002; Gunnell *et al.*, 2003). Naturally occurring spontaneous tracks, however, do not exceed this length (Gleadow *et al.*, 1986a,b). Gunnell *et al.* (2003) demonstrated that reducing the initial track length yields thermal histories, which do not show the pronounced artificial cooling event. According to our laboratory calibration of the initial track length

Table 1 Zircon fission Track data from the south-eastern Tauern Window and adjacent Austroalpine units.

Sample code	Longitude	Latitude	Elevation (m)	Tect. block	n	ρ_s	N_s	ρ_i	N_i	ρ_d	N_d	$P(\chi^2)$ (%)	Age (Ma)	±1σ (Ma)
W 207	46°54′54″	13°11′21″	1460	PB	20	70.096	613	97.540	853	6.774	3089	67.0	30.0	1.8
W 124	46°55′45″	13°10′57″	860	PB	20	55.244	653	58.713	694	6.743	3089	99.8	39.1	2.3
W 327	46°47′45″	13°08′06″	2490	KB	20	100.590	1131	64.569	726	6.764	3089	100.0	64.8	3.5
W 202	46°45′55″	13°08′48″	1350	KB	20	71.488	687	29.240	281	6.876	3089	100.0	103.1	7.7
W 204	46°45′10″	13°09′51″	740	KB	20	88.305	611	34.831	241	6.866	3089	100.0	106.7	8.5

PB, Polinik Block; KB, Kreuzeck Block; n, number of dated zircon crystals; ρ_s/ρ_i, spontaneous/induced track densities ($\times 10^5$ tracks cm^{-2}); N_s/N_i, the number of counted spontaneous/induced tracks; N_d, number of tracks counted on dosimeter; $P(\chi^2)$: probability obtaining chi-squared value (χ^2) for n degrees of freedom (where n is number of crystals − 1); age ± 1σ, central age ± 1 standard error (Galbraith and Laslett, 1993); ages were calculated using zeta calibration method (Hurford and Green, 1983); glass dosimeter CN-2, and a zeta value of 123.92 ± 2.53 yr cm^{-2}.

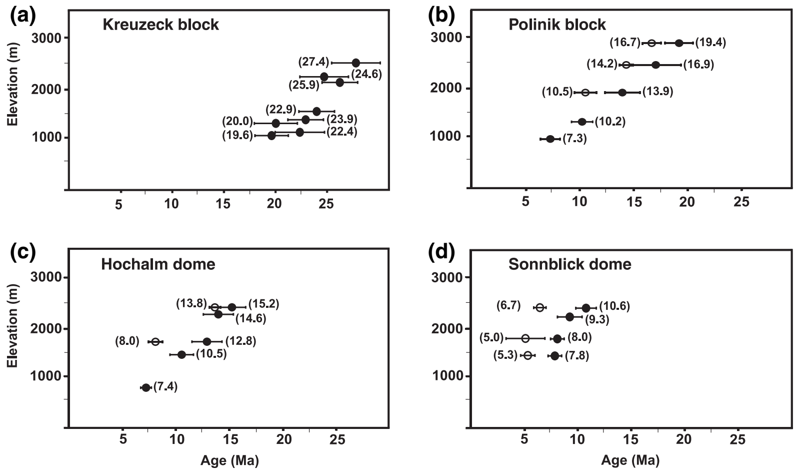

Fig. 3 Age-elevation relationship of apatite fission track (black dots) and (U–Th)/He ages (white circles). Indicated age errors are 1σ for both datasets. The numbers in brackets are the corresponding AFT/He ages (for detailed information, see Tables 2 and 3).

in the Durango apatite, we adopted an initial track length of 15.5 μm for thermal history modelling. We undertook forward modelling of AFT and (U–Th)/He data, following the approach of Ketcham (2005). To amplify the range of solutions, the forward modelled time-temperature history was inversely modelled with the following constraints: (1) the beginning of the time-temperature path was constrained by the ZFT data and (2) the end of the time–temperature paths was set at 5 °C according to present-day mean surface temperatures above 2000 m elevation. Rocks that experienced fast cooling (> 10 °C Ma^{-1}) display ages, which increase with elevation; the slope of this relationship is equivalent to the denudation rate (e.g. Gallagher *et al.*, 1998). Such assumption is met when the isotherms are spatially and temporally constant. However, Foeken *et al.* (2007) demonstrated that the isotherms beneath the Hochalm Dome were warped sufficiently to affect at least the 60–40 °C isotherms. Furthermore, our profiles were not directly vertical. Therefore, we abstain from calculating denudation rates from these profiles.

Austroalpine units

Thermal history modelling of the Kreuzeck Block reveals tT paths characterized by slow cooling through Late Crateceous and Palaeogene time until the Early Miocene, when the region was already near the surface (Fig. 4a). In contrast, thermal modelling of the Polinik Block demonstrates onset of rapid cooling at around 22 Ma, followed by modest cooling from 12 Ma onwards (Fig. 4b).

Table 2 Apatite fission track data from the south-eastern Tauern Window and adjacent Austroalpine units.

Sample code	Longitude	Latitude	Elevation (m)	Tect. block	n	ρ_s	N_s	ρ_i	N_i	ρ_d	N_d	$P(\chi^2)$ (%)	Age (Ma)	±1σ (Ma)	MTL (μm)	SD (μm)	N (L)	Dpar (μm)
W1	46°56′18″	13°15′11″	1660	HD	25	0.509	98	2.818	727	5.904	11328	99.3	12.8	1.4				1.93
W2	46°57′00″	13°15′43″	2350	HD	25	0.675	144	4.094	1022	7.643	15118	99.9	15.2	1.3	14.53	1.3	90	1.86
W3	46°58′22″	13°08′20″	2340	SD	27	0.785	209	7.597	2022	7.654	15118	98.2	10.6	0.9	14.49	1.1	102	1.72
W4	46°57′57″	13°08′11″	2170	SD	25	0.709	189	8.093	2156	7.758	15118	85.1	9.3	1.1				1.78
W6	46°55′48″	13°14′58″	1360	HD	25	0.477	115	3.966	1023	5.774	11328	69.1	10.5	1.1				1.88
W7	46°56′59″	13°15′28″	2240	HD	25	0.833	208	4.522	1129	5.783	11328	98.2	14.6	1.4				1.77
W8	46°57′32″	13°09′04″	1800	SD	25	0.343	85	4.372	1083	7.761	15118	100.0	8.0	0.6				1.74
W9	46°57′08″	13°09′31″	1350	SD	25	0.953	238	10.125	2528	5.187	11328	99.9	7.8	0.6				1.99
W10	46°54′50″	13°14′46″	710	HD	25	0.921	201	9.672	2412	5.194	11328	99.9	7.4	0.5				1.72
W12	46°55′28″	13°11′21″	950	PB	25	1.280	312	8.901	2170	5.861	11328	88.9	7.3	0.9				1.62
W21	46°54′18″	13°10′46″	1915	PB	25	0.902	218	4.789	1158	4.539	8636	99.9	13.9	1.6				1.95
W28	46°54′54″	13°11′27″	1400	PB	25	0.789	197	4.998	1248	4.555	8636	75.5	10.2	1.0				1.72
W35	46°53′58″	13°09′52″	2400	PB	25	0.891	219	4.090	1005	4.527	8636	93.5	16.9	2.3				1.82
W36	46°53′45″	13°09′24″	2784	PB	25	1.054	258	4.257	1042	4.508	4688	100.0	19.4	1.3	14.51	1.0	84	1.81
W194	46°47′12″	13°08′02″	2210	KB	27	1.298	342	6.290	1657	7.408	14233	99.8	24.6	1.6				1.97
W199	46°47′39″	13°08′03″	2400	KB	25	1.278	304	6.104	1452	7.052	12503	98.1	23.9	2.5				1.86
W236	46°45′33″	13°09′32″	1080	KB	25	1.496	394	7.079	1865	6.583	12503	99.9	27.3	1.7	13.28	1.9	92	1.72
W251	46°45′29″	13°09′21″	1020	KB	25	1.201	307	8.033	2053	8.018	15118	100.0	19.6	1.6				1.83
W252	46°46′04″	13°90′39″	1515	KB	25	0.842	202	3.984	947	6.624	12503	89.8	22.9	1.7				1.67
W253	46°45′56″	13°09′10″	1420	KB	30	1.232	367	7.856	2340	7.894	15118	92.7	20.0	2.0				1.93
W327	46°47′45″	13°08′06″	2490	KB	25	1.432	366	6.671	1705	7.866	15118	90.0	27.4	2.7	13.58	1.9	84	1.77
W417	46°47′02″	13°08′40″	2180	KB	27	1.627	451	5.476	1518	5.476	11328	96.7	25.9	1.6				1.86

PB, Polinik Block; KB, Kreuzeck Block; n, number of dated apatite crystals; ρ_s/ρ_i, spontaneous/induced track densities (×10^5 tracks cm^{-2}); N_s/N_i, number of counted spontaneous/induced tracks; N_d, number of tracks counted on dosimeter; $P(\chi^2)$, probability obtaining chi-squared value (χ^2) for n degree of freedom (where n is number of crystals – 1); age ± 1σ is central age ± 1 standard error (Galbraith and Laslett, 1993); ages were calculated using zeta calibration method (Hurford and Green, 1983); glass dosimeter CN-5, and zeta value of 325.11 ± 6.65 yr cm^{-2}.

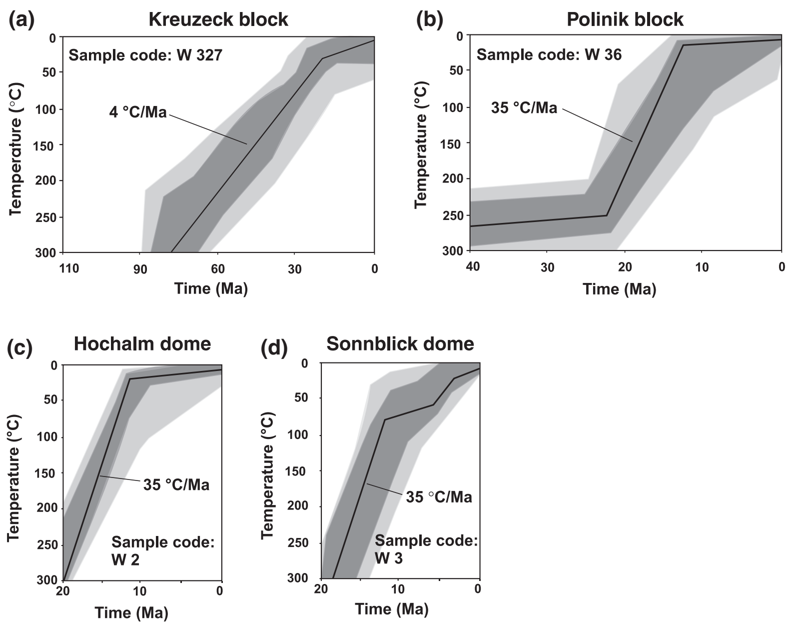

Fig. 4 Apatite fission track and (U–Th)/He thermal history modelling results using HeFTy (Ketcham, 2005). Zircon fission track ages of Hochalm Dome and Sonnblick Dome after Dunkl *et al.* (2003); light grey paths: acceptable fit; dark grey paths: good fit; thick black line: best fit; note different scale for Kreuzeck Block.

Tauern Window

The combination of AFT and (U–Th)/He data with ZFT ages from Dunkl *et al.* (2003) reveals a rapid cooling history (35 °C Ma^{-1}) between 20 and 12 Ma, followed by modest cooling until present (Fig. 4c,d). Assuming an increased geothermal gradient between 35 and 40 °C for the Tauern Window (Genser *et al.*, 1996; Sachsenhofer, 2001) during the Early and Middle Miocene, exhumation rates in the range of 0.9–1.0 mm yr^{-1} are derived. This is valid for both the Hochalm and Sonnblick Dome. However, during the latest Miocene and early Pliocene, a different exhumation history of these two domes can be inferred from the (U–Th)/He data (Fig. 2a, Table 3).

Discussion and conclusions

Our data combined with published cooling ages (Cliff *et al.*, 1985; Hoke, 1990; Reddy *et al.*, 1993; Dunkl *et al.*, 2003; Foeken *et al.*, 2007) result in an exhumation phase in the Miocene, which corresponds to the period of lateral extrusion and tectonic denudation of the Tauern Window (22–12 Ma) as defined earlier (Ratschbacher *et al.*, 1991; Frisch *et al.*, 1998, 2000). Assuming that cooling at low-temperature conditions corresponds to vertical movements within the upper crust, this evolution provides the reconstruction of episodic activity along distinct fault segments with two main phases:

Table 3 Apatite (U–Th)/He data from the south-eastern Tauern Window and adjacent Austroalpine units.

Sample code		Elevation (m)	Tect. block	n.c.	U (n.g.)	Th (n.g.)	^{4}He ncc	TAE %	Grain Dimension (MWAR)	unc. Age (Ma)	Ft	corr. Age (Ma)	Average age (Ma)	±1σ error (Ma)
W-1	#1	1660	HD	1	0.131	0.189	0.105	8.1	61.0	5.0	0.69	7.2	8.0	0.6
	#2			1	0.075	0.119	0.166	6.6	80.3	6.9	0.78	8.8		
W-2	#1	2350	HD	1	0.214	0.029	0.273	6.8	103.2	10.2	0.80	12.8	13.8	0.7
	#2			1	0.131	0.024	0.171	5.4	99.7	10.4	0.79	13.2		
	#3			1	0.257	0.041	0.399	3.2	118.4	12.4	0.80	15.5		
W-3	#1	2340	SD	1	0.322	0.443	0.266	2.5	72.6	5.2	0.79	6.6	6.7	0.5
	#2			1	0.125	0.161	0.096	15.8	54.5	4.9	0.68	7.2		
	#3			1	0.271	0.391	0.217	5.6	76.5	5.0	0.79	6.3		
	#4			1	0.441	0.553	0.346	4.1	72.6	5.0	0.76	6.6		
W-8	#1	1800	SD	1	0.145	0.118	0.069	2.9	55.9	3.3	0.70	4.7	5.0	1.6
	#2			1	0.025	0.018	0.014	6.7	79.7	4.1	0.78	5.3		
W-9	#1	1350	SD	1	0.111	0.203	0.084	14.6	80.1	4.4	0.76	5.8	5.3	6.0
	#2			1	0.086	0.149	0.059	4.1	65.2	4.0	0.72	5.6		
	#3			1	0.028	0.062	0.019	4.5	96.8	3.6	0.79	4.6		
W-21	#1	1915	PB	1	0.123	0.026	0.088	9.9	65.5	5.6	0.69	8.1	10.5	1.0
	#2		PB	1	0.054	0.022	0.071	8.8	76.5	9.9	0.77	12.9		
W-35	#1	2400	PB	1	0.283	0.049	0.514	4.7	85.8	14.4	0.78	18.5	14.2	0.6
	#2			1	0.073	0.023	0.099	5.3	83.5	10.5	0.76	13.8		
	#3			1	0.125	0.057	0.136	5.6	88.9	8.1	0.78	10.4		
W-36	#1	2784	PB	1	0.159	0.201	0.369	3.1	78.1	15.0	0.73	19.5	16.7	0.9
	#2			1	0.076	0.039	0.114	8.3	84.7	11.0	0.79	13.9		

HD, Hochalm Dome; SD, Sonnblick Dome; PB, Polinik Block; KB, Kreuzeck Block; n.c., number of dated apatite crystals; U, amount of $^{238}U + ^{235}U$; ^{4}He, amount of in nano-cubic centimetres at standard pressure and temperature; TAE, total analytical error; MWAR, mass weighted average grain radius; unc. age, uncorrected age; Ft, correction factor calculated after Farley *et al.* (1996); corr. age, corrected age.

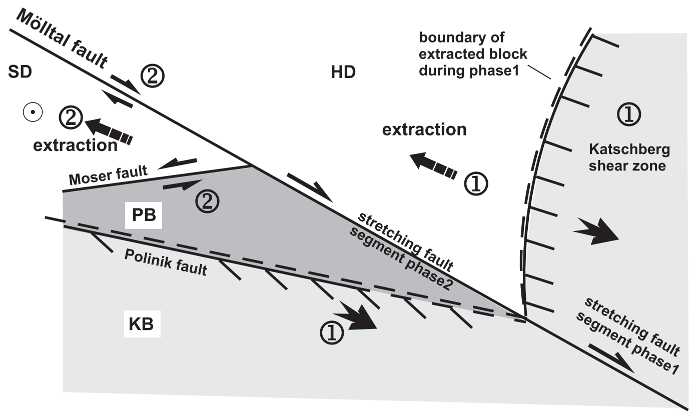

Fig. 5 Kinematic evolution along the south-eastern margin of the Tauern Window. Phase 1: Katschberg- and Polinik normal faults merge together in the Mölltal fault; exhumation of Hochalm Dome and Polinik Block started at around 20 Ma. Phase 2: at around 6 Ma the Sonnblick Dome was denuded between the Mölltal and the Moser fault. HD, Hochalm Dome; SD, Sonnblick Dome; PB, Polinik Block; KB, Kreuzeck Block.

Phase 1: Vertical movement of the Hochalm Dome is accommodated by normal faulting along the Katschberg shear zone (Fig. 5) at around 20 Ma (Fig. 4c). To the south, this normal displacement is transferred into the Mölltal fault resulting in dextral displacement of the Austroalpine units east of the Katschberg shear zone (Frisch *et al.*, 2000) (Fig. 5). Nearly at the same time, a structurally similar evolution may be reconstructed for the Polinik fault, accommodating vertical movement of the Polinik Block from *c.* 22 Ma onwards (Fig. 4b). Displacement along the Polinik fault is transferred into the Mölltal fault too. The main jump in mineral cooling ages occurs along the Polinik fault and not along the boundary of the Penninic and the Austroalpine unit. Therefore, we consider the Austroalpine basement to the south of the Penninic units and north of the Polinik fault as part of the footwall during exhumation (Polinik Block; Fig. 1b).

Phase 2: During the latest Miocene, early Pliocene, only the samples from the Sonnblick Dome were still in the apatite HePRZ, whereas the Hochalm Dome and Polinik Block had already passed through it (Fig. 2, Table 3). Vertical movement of the Sonnblick Dome was accommodated by oblique normal displacement along its northeastern and southern margins (Kurz, 1993; Kurz and Neubauer, 1996). Again, displacement along the southern margin of the Sonnblick Dome was transferred into the Mölltal fault. Accordingly, the Sonnblick Dome was extracted between two faults with opposite sense of displacement (Fig. 5). These two faults (Mölltal- and Moser fault) merge together at the trailing edge of the extracted Sonnblick Dome. This shows that the Mölltal fault acted as a stretching fault in terms of Means (1990) as described by Kurz and Neubauer (1996).

The early to middle Miocene exhumation derived from these data fits well with palinspastic and morphological reconstructions (Frisch *et al.*, 1998), which demonstrated that the Eastern Alps developed a mountainous relief at that time. An important constraint on the exhumation history of the Hochalm Dome was provided by Foeken *et al.* (2007). On the basis of different age components in their AFT samples, they proposed rapid cooling between 22 and 16 Ma followed by slow cooling between 16 and 6 Ma and accelerated cooling after 6 Ma.

The thermal model based on our data derives a cooling history over two periods (Fig. 4c). The disagreement may be because of the lack of track length data in the study of Foeken *et al.* (2007) and the different chi-squared statistics.

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