Pebble population dating as an additional tool for provenance studies – examples from the Eastern Alps

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Abstract: Detrital fission-track (FT) dating can be successfully used in provenance studies of siliciclastic sediments to define the characteristic cooling ages of the source regions during erosion and sedimentation. In order to obtain more specific information about potential source regions we have developed the pebble population dating (PPD) method in which pebbles of specific lithotype are merged and dated. Dating of both zircon and apatite crystals from such pebble populations yields age distributions, which reflect the cooling ages of the given lithotype in the source area at the time of sedimentation. By this technique it is possible to define 'FT litho-terrains' in the source regions and thus outline palaeogeological maps.

Two examples are presented from the Eastern Alps. (i) Comparison of FT ages from a sandstone sample and a gneiss PPD sample from an Oligocene conglomerate of the Molasse Basin shows that the youngest age cluster is present only in the sand fraction and derived from the Oligocene volcanic activity along the Periadriatic zone. The lack of the youngest ages in the gneiss pebble assemblage excludes the Oligocene exhumation of the crystalline basement from mid-crustal level. (ii) Pebble assemblages of red Bunter sandstone, gneiss and quartzite were collected from an Upper Miocene conglomerate of the Molasse Foreland Basin and merged as PPD samples. Apatite and zircon FT grain age distributions of these PPD samples, representing the largest ancient East Alpine catchment, allow generating a new combination of palaeogeological and palaeo-FT-age maps of the Eastern Alps for the Late Miocene.

The reconstruction of the palaeogeological and palaeogeographical setting of Alpine-type mountain chains is among the biggest challenges in the research of orogenic belts. Investigations of active, mountainous areas provide limited information, as erosion removed former higher tectonic units and only the most recently exhumed units can be studied. For this reason, interest has turned to peri-orogenic basins that may preserve a longer denudation history of the orogen. The petrography of pebbles, the mineralogical composition of the arenitic sediments and the geochemical signatures of the detritus reflect the former composition of the drainage areas of the orogen (e.g. von Eynatten 2007; Ruiz *et al.* 2007). Detrital fission-track dating, moreover, provides information on exhumation processes (e.g. McGoldrick & Gleadow 1978; Hurford *et al.* 1984; Hurford & Carter 1991; Garver & Brandon 1994; Thomson 1994; Carter 1999; Ruiz *et al.* 2004).

Fission-track (FT) analysis of pooled pebbles of a distinct lithotype combines the methodology of the widely used single-grain dating of sands and the petrographical analysis of single pebbles. Two examples from the Eastern Alps will be presented to illustrate applicability and potential of the pebble population dating method.

Pebble population dating

Besides structural and metamorphic studies there are three basic methods that are used to determine and quantify the exhumation history of a mountain range: (1) thermochronology of rocks exposed in the mountainous area itself; (2) evaluation of the sediment facies, petrography and accumulation rates in the basins adjacent to the mountain range; and (3) detrital FT dating of siliciclastic sediments.

The clusters of individual grain FT ages from a siliciclastic sediment reflect different erosional provinces with different cooling ages at the time of sedimentation. Brandon (1992) introduced the term '*FT source terrain*' to relate each age group to various eroding areas in the hinterland. We have developed a new technique for conglomeratic sediments, which implies FT dating of populations of pebbles with distinct lithologies. By selecting and merging 50–100 pebbles of the same distinct lithotype from the same outcrop we have obtained representative samples (pebble populations) for different lithologies (e.g. gneiss, quartzite, sandstone, granite). Fission-track analysis of individual apatite or zircon grains from these populations produces age distributions characteristic of the various

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lithological units (Fig. 1). The age clusters of the single-grain age distributions represent areas in the hinterland '*FT litho-terrains*' in which the given lithotype at the time of sedimentation was exposed. Several pebble populations can be studied from one outcrop, and the source area of the sediment may be reconstructed in terms of different lithologies with different exhumation histories. We have summarized in Appendix 1 some hints on the collection of PPD samples.

The (i) estimation of amounts of a given lithologies in the pebbles, (ii) the areal distribution of these lithologies in the present-day geological map, (iii) the present-day FT age distribution on the catchment area of the sediment and (iv) the identified apatite and zircon FT age components in the PPD samples allow the compilation of palaeogeological maps of the eroding areas.

Geological setting of the Eastern Alps

Crystalline units

The crystalline part of the Eastern Alps can be divided into two tectonic units distinguished by contrasting cooling histories (Fig. 2) (Frank *et al.* 1987). (a) The Austroalpine nappe complex forms the upper plate. It is composed of medium- to high-grade as well as low-grade Variscan basement slices, and weakly to non-metamorphosed Permo-Mesozoic volcano-sedimentary cover sequences. $^{40}Ar/^{39}Ar$ and Rb/Sr mica cooling ages between 140 and 70 Ma indicate a predominant Eoalpine metamorphic event, but there are 'patches' in which only the older Variscan metamorphism (*c.* 300 Ma) can be detected. (b) The lower unit is the Penninic domain, exposed in tectonic windows along the central axis of the orogen and in the narrow tectonic wedge of the Rhenodanubian flysch zone in front of the orogen. This unit contains both Variscan basement blocks with post-Variscan cover and Mesozoic ophiolites and oceanic metasediments. It has experienced high pressure (in part) and greenschist- to lower-amphibolite-facies metamorphism in Tertiary time. In completely reset areas mica $^{40}Ar/^{39}Ar$ cooling ages are usually around 20 Ma (see compilations of Frank *et al.* 1987; Thöni 1999).

During Palaeogene collision the Austroalpine nappe complex was thrust over the Penninic units. Nappe stacking was followed by lateral tectonic extrusion in Miocene times (Ratschbacher *et al.* 1991). The extrusion process created numerous brittle structures in the Austroalpine realm and

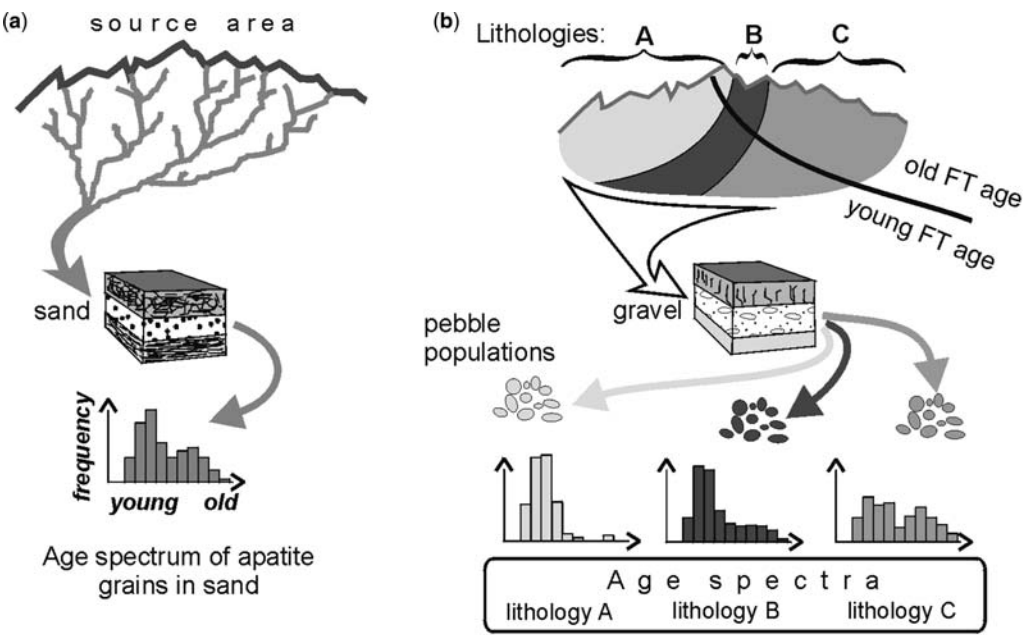

Fig. 1. Schematic cartoons presenting: (**a**) the capability of the detrital geochronology applied to a sandstone sample; and (**b**) the scheme of pebble population method applied to a gravel horizon. In the first case the age distribution characterizes the entire source area, while the PPD samples give litho-specific age information. For example: at the time of sedimentation 'lithology A' delivers pebbles mainly with young FT age, while 'lithology C' provides pebbles with old FT ages.

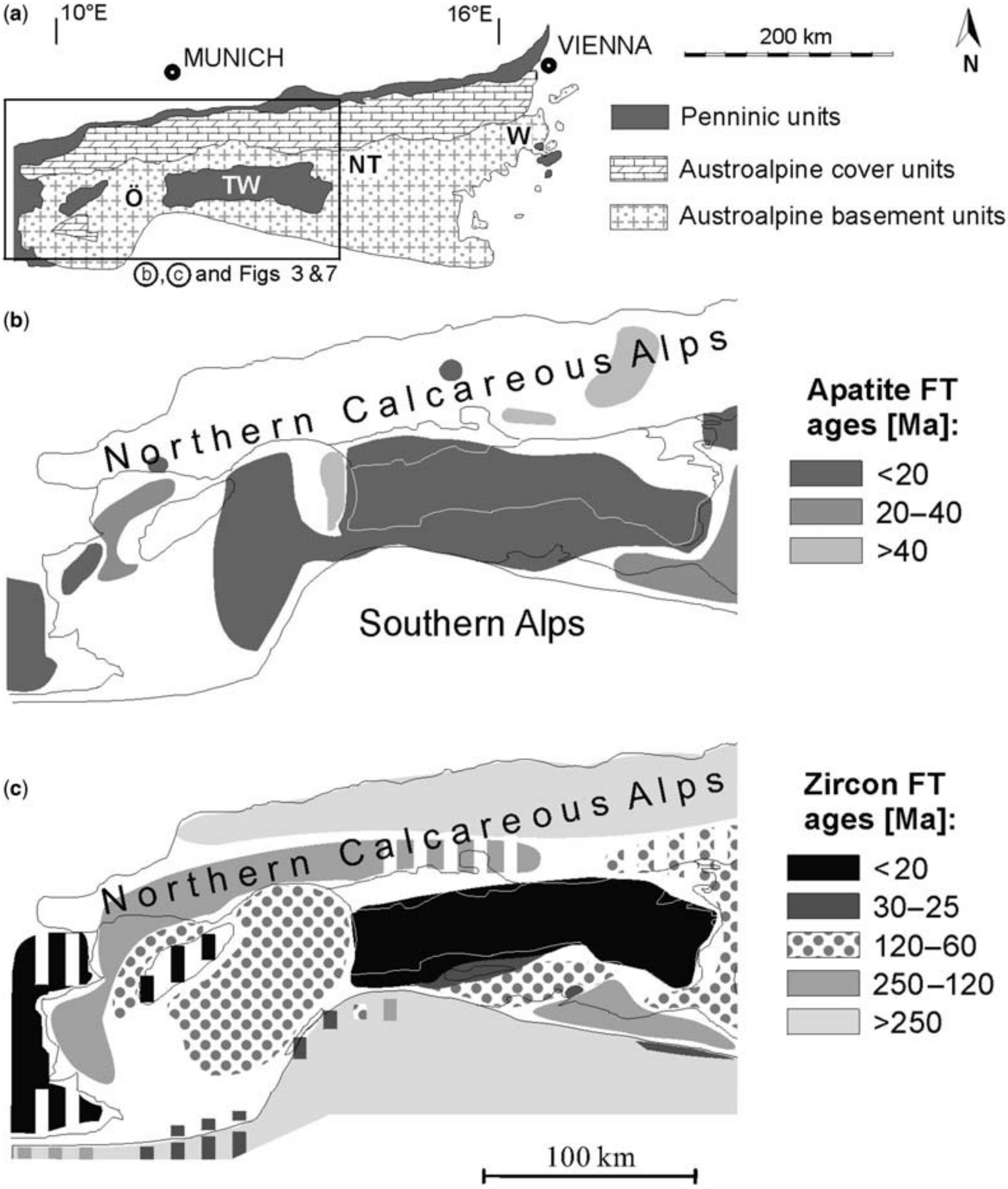

Fig. 2. (**a**) Simplified sketch showing Austroalpine and Penninic units of the Eastern Alps (Ö, Ötztal Alps; TW, Tauern Window; NT, Niedere Tauern; W, Wechsel). Map of fission track ages of the Eastern Alps: (**b**): apatite ages; and (**c**): zircon ages. The contours mark the envelope of the actual FT data coverage; vertical stripes indicate areas with sporadic data points or only an assumed characteristic FT age; white areas, no data. The maps were compiled from 311 apatite and 163 zircon FT ages of: Grundmann & Morteani (1985), Flisch (1986), Hurford (1986), Staufenberg (1987), Hejl & Grundmann (1989), Neubauer *et al.* (1995), Fügenschuh *et al.* (1997), Hejl (1997), Dunkl *et al.* (1998), Elias (1998), Sachsenhofer *et al.* (1998), Viola *et al.* (1999), Reinecker (2000), Stöckhert *et al.* (1999) and I. Dunkl (unpublished data).

exhumed the Penninic units in windows by orogen-parallel tectonic unroofing (Frisch *et al.* 1998, 2000). The margins of the windows are marked by highly contrasting mica ages (Late Tertiary ^{40}Ar/^{39}Ar and Rb/Sr ages inside, while mostly Mesozoic ages outside the windows) (Frank *et al.* 1987), which underlines the tectonic nature of unroofing of the lower plate terrains.

Present-day FT age distribution in the Eastern Alps

Zircon fission-track ages clearly show a sharp boundary between the Penninic (ages <20 Ma) and Austroalpine (ages usually >45 Ma) terrains (see compilation of FT ages in Fig. 2 and the citations in the figure caption). Only a slice of Austroalpine basement along the southern border of the Tauern Window shows Tertiary reset FT ages, and this slice is interpreted as the lower part of the upper unit. Contrary to the zircon ages, the tectonic boundary between the upper and lower plate units makes no recognizable change in the apatite FT age map of the Eastern Alps (Fig. 2b). Beyond the Penninic areas a significant part of the Austroalpine basement units yield Neogene apatite FT ages. The areas of Palaeogene apatite FT ages in the Austroalpine unit indicate minor Neogene erosion, and also mark the areas that could have supplied sand or pebbles with Cretaceous and Palaeogene apatite FT ages into the Molasse Basin during Miocene time. However, there are areas in the Austroalpine unit that experienced deep erosion in Neogene time, and the apatite FT chronometer shows Miocene ages (e.g. Ötztal Alps, Niedere Tauern, see Fig. 2). These intensely eroded tectonic blocks were the source regions for the large amount of siliciclastic sediments of the Neogene Molasse basins. As a consequence, the current apatite FT age map of the Eastern Alps does not reflect the distribution of ages in Miocene time.

Denudation history of the Eastern Alps

Beyond the above-listed thermochronometers, the temporal change of sediment volumes accumulated in the peri-Alpine basins provides further constraints on the erosional history of the Alps (see compilation of Kuhlemann 2000). The sudden increase in the amount of coarse conglomerates in molasse sediments in the late Early Oligocene indicates exhumation, surface uplift and relief enhancement as a consequence of collision between the European and Apulian continents and slab breakoff (von Blanckenburg & Davies 1995). In Oligocene and Miocene times the foreland basin was filled with alternating marine and fluviatile sediments (Lemcke 1988). Heavy mineral, petrographical and geochronological studies on sediments indicate that until the Middle Miocene only the Austroalpine upper plate supplied detrital material into the Molasse Basin (see the compilation in Brügel 1998). The first pebbles from the exhumed gneiss domes of the Tauern Window appeared at approximately 13 Ma (Frisch *et al.* 1999). By that time, all the currently exposed parts of the Eastern Alps were already subjected to erosion (Frisch *et al.* 1998).

The first study on the erosion of the Alps using detrital thermochronology was performed on the Gonfolite Lombarda Conglomerate by Gieger & Hurford (1989). The denudation of Eastern Alps was studied by the detrital thermochronological record of the sediments in the Veneto Basin by Zattin *et al.* (2003), and in the northern Molasse Basin and in the intramontane basin remnants by Brügel *et al.* (2003), Dunkl *et al.* (2005) and Kuhlemann *et al.* (2006). The age components identified in the siliciclastic sediments refer more to cooling–exhumation periods of the Eastern Alps. The oldest group of zircon FT ages indicate that a part of the Austroalpine unit was thermally overprinted in Jurassic time, but a Late Cretaceous, Eoalpine event is also documented in many samples. The metamorphic Penninic material – supposedly derived from the Tauern Window–appeared approximately 13 Ma ago and demonstrates the exhumation of the lower plate to the surface. The detrital AFT ages also record the cooling after the Eoalpine event and show a distinct, but probably less important, exhumation phase in Eocene time. The Miocene age components in the sediments show an increase in lag time (difference between the age of the youngest component and the age of sedimentation: Cerveny *et al.* 1988; Brandon & Vance 1992) from 3 to more than 6 Ma during the Late Miocene. This indicates a decrease in the exhumation rate after the Early–Middle Miocene thermo-tectonic climax.

In order to test the capability of the PPD method for detailed provenance studies, we have chosen two siliciclastic formations of the Alpine Molasse for case studies: (1) the 'Inntal Tertiary' of Oligocene age; and (2) the Late Miocene Hausruck Conglomerate.

Case study I – filtering out the volcanogenic contribution of a sandstone by gneiss PPD dating

Geology, samples and results

The sequence studied is part of the 'Inntal Tertiary', one of the oldest conglomerate members of the Molasse Basin. Distal turbidites of Rupelian age and polymict conglomerates of Chattian age (*c.* 28–26 Ma) were deposited both in the foreland and on top of the Northern Calcareous Alps (Fig. 3). The Inntal Tertiary is a basin remnant preserved in the Inntal strike-slip fault zone within the Northern Calcareous Alps (Ortner & Sachsenhofer 1996). The pebble composition is dominated by metamorphic material with some sedimentary lithologies (sandstone and limestone). Volcanic pebbles (andesites–dacites) occur rarely ($\ll 1\%$)

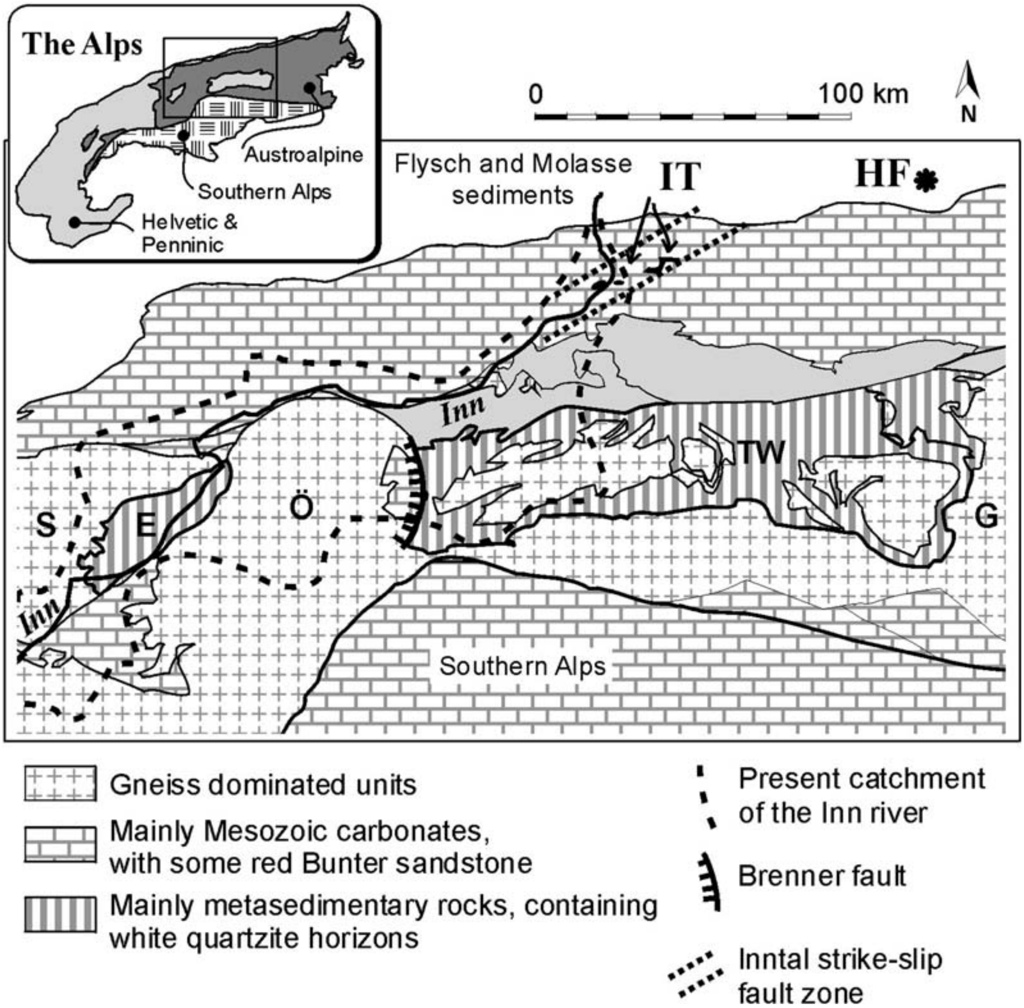

Fig. 3. Geological sketch map of the Eastern Alps with the sample localities and the present-day distribution of the dated lithologies. Ö, Ötztal Alps; S, Silvretta Alps; IT, Inntal Tertiary (within the Northern Calcareous Alps); HF, Hausruck fan; TW, Tauern Window; E, Engadin Window; G, Gurktal Alps. Units marked by a pale grey colour are composed of carbonate rocks and low-grade metapelites, and they do not produce apatite- or zircon-containing sediments during erosion.

(Mair *et al.* 1996; Brügel *et al.* 2000). During the Late Oligocene, the Penninic formations were still buried (Frisch *et al.* 2000), thus the sandy and pebbly material was derived from the uplifted western part of the Austroalpine realm and was transported by the fault-bounded palaeo-Inn River system to the NE (Brügel *et al.* 2003).

Samples were collected in an approximately 100 m-long, 2–3 m-high artificial outcrop of gravel, 400 m SSW of Mosen, 200 m east of Angerberg (Inn Valley, Austria; N47°27′40″/E11°54′38″). We have compiled a gneiss PPD sample, and the apatite and zircon crystals of the sandy matrix were also dated. The laboratory procedure is described in Appendix 2, and the results are in Table 1. The ranges and the means of single-grain apatite FT ages in the sandstone and conglomerate PPD samples are similar, but the fission-track age distributions show differences (Fig. 4). The values of dispersions and the results of Chi-square test indicate that the single-grain ages of the samples have composite distributions. The apatite and zircon FT ages in the sandstone sample form more clusters. The core of the apatite distribution (between 40 and 80 Ma) is identical to the range of the majority of the apatite ages in the gneiss

Table 1. *Apatite and zircon fission-track results obtained from sandstone and pebble population samples from the Alpine Molasse (left). Component analysis of the samples (right). The age components were determined by the 'Binomfit' computer program of Brandon (1996)*

Code	Petrography	Cryst.	Spont. ρ_s (N_s)	Ind. ρ_i (N_i)	Det. ρ_d (N_d)	Disp.	$P(\chi^2)$ (%)	Central age (Ma ± 1σ)	Component I			Component II			Component III		
									Mean (Ma)	CI (Ma)	*W* (%)	**Mean** (Ma)	CI (Ma)	*W* (%)	**Mean** (Ma)	CI (Ma)	*W* (%)
Inntal Tertiary (Late Oligocene, *c*. 27 Ma)																	
Apatite																	
NA-28/D	sand	60	4.03 (1309)	5.64 (1834)	4.08 (12045)	0.26	<1	55.9 ± 3.2	**33**	8	*15*	**59**	7	*79*	**105**	80	*6*
NA-28/B	gneiss PPD	80	6.27 (2912)	7.52 (3492)	4.08 (12045)	0.20	<1	62.7 ± 2.6	**54**	3	*64*	**80**	7	*36*			
Zircon																	
NA-28/D	sand	60	78.4 (5107)	58 (3777)	5.26 (10350)	0.53	<1	47.0 ± 3.5	**33**	2	*67*	**97**	9	*33*			
Hausruck Conglomerate (Late Miocene, *c*. 10 Ma)																	
Apatite																	
NA-40/C	w. qzte PPD	100	2.24 (1505)	12.3 (8259)	4.08 (12045)	0.09	5	13.9 ± 0.5									
NA-40/A	gneiss PPD	100	2.78 (1607)	10.5 (6084)	4.08 (12045)	0.49	<1	21.0 ± 1.3	**15**	1	*71*	**40**	5	*29*			
NA-40/B	red ss. PPD	100	9.61 (3419)	12.6 (4474)	4.08 (12045)	0.30	<1	57.4 ± 2.6	**39**	4	*40*	**74**	6	*60*			
Zircon																	
NA-40/C	w. Qzte PPD	100	33.3 (4701)	49.5 (6983)	5.26 (10350)	0.52	<1	23.2 ± 1.3	**16**	1	*70*	**52**	4	*30*			
NA-40/A	gneiss PPD	100	78 (6634)	61.6 (5230)	5.26 (10350)	0.51	<1	43.5 ± 2.5	**17**	2	*23*	**57**	3	*77*			
NA-40/B	red ss. PPD	100	168 (12005)	29.0 (2066)	5.26 (10350)	0.21	<1	193 ± 6.9	**127**	23	*14*	**209**	14	*86*			

Cryst: number of dated crystals.
Spont., Ind. and Det.: spontaneous, induced and detector track densities and track counts.
Track densities (ρ) are as measured ($\times 10^5$ tr cm^{-2}); number of tracks counted (N) shown in brackets.
Disp.: dispersion, according to Galbraith & Laslett (1993).
$P(\chi^2)$: probability obtaining Chi-square value for ν degree of freedom (where ν = number of crystals − 1).
Central ages calculated using dosimeter glass CN5 with $\zeta_{CN5} = 373.3 \pm 7.1$ (1 SE) for apatite and CN2 with $\zeta_{CN2} = 127.8 \pm 1.6$ (1 SE) for zircon.
CI, 95% confidence interval.
W, weight of the component.

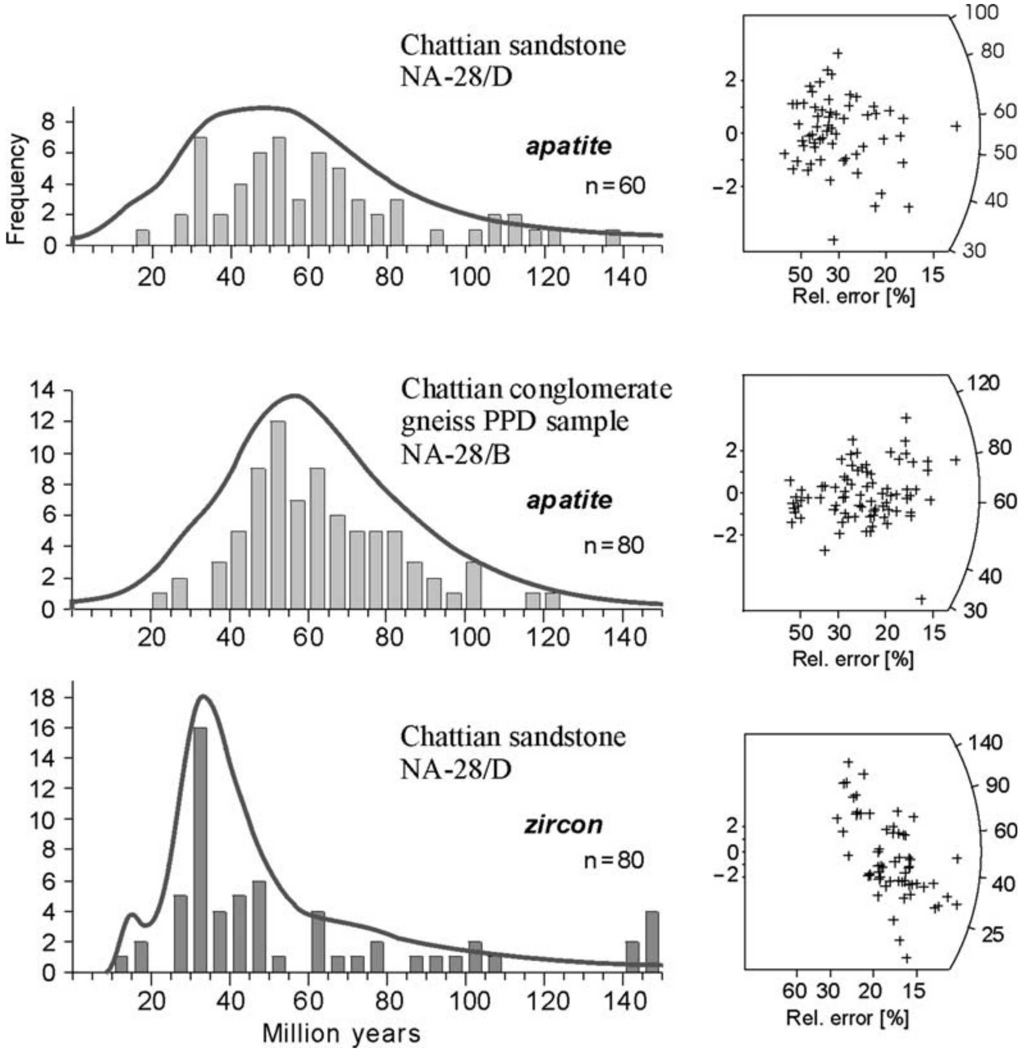

Fig. 4. Single-grain fission-track age distributions of the Inntal Tertiary samples. Age spectra (probability density plots) are computed according to Hurford *et al.* (1984).

PPD sample, but a younger and an older component are also present. Modelling of the age components with the program Binomfit (Galbraith & Green 1990; Brandon 1996) resulted in the following means for these age components: 33 ± 8, 59 ± 7 and 105 ± 80 Ma (Table 1). The poorly constrained oldest component is most probably derived from the 'Upper Austroalpine unit' (*sensu* Tollmann 1977), which is mainly composed of non-metamorphic and greenschist-facies rocks (without gneisses) with approximately 140–120 Ma mica K/Ar ages. This would explain why this age cluster does not appear in the gneiss PPD sample.

Discussion

The appearance of grains with a short lag time is especially important for the reconstruction of Alpine denudation history and palaeogeography in the Palaeogene time. The presence of zircon grains with an approximately 33 Ma FT age in a sediment of 27 ± 2 Ma depositional age can usually indicate a rapid exhumation in the catchment area. However, the youngest zircon age component identified in the sandstone is in apparent contradiction to the older apatite FT ages in the gneiss PPD sample (Fig. 4). Zircon should yield older ages than apatite due to its higher closing temperature. Even within the sandstone sample, the zircon FT ages tend to be younger than the apatite FT ages. Furthermore, apatite grains with ages of less than 40 Ma are rare in the gneiss PPD sample.

This apparent contradiction requires an alternative interpretation. The young zircon age cluster of the sandstone sample must be derived from a source other than the metamorphic basement that delivered the gneiss pebble association. The conglomerate sequence contains a small number of volcanic pebbles derived from the Periadriatic volcanic chain (Mair *et al.* 1996; Brügel *et al.* 2000). This mainly calc-alkaline volcanic–intrusive association (e.g. von Blanckenburg & Davies 1995) was active mainly around 33–28 Ma and formed an approximately 800 km-long belt along the Periadriatic lineament from the Western Alps to the Pannonian Basin. The euhedral shape of the crystals in the young zircon group also supports an origin from the Periadriatic suite (Fig. 5). These magmatic rocks were situated along the southern margin of the catchment of the palaeo-Inn River, some 150–250 km away today from the area of deposition (Brügel *et al.* 2000). Palaeogeographic reconstructions (Frisch *et al.* 1998) show that the transport distance of the volcanogenic pebbles was greater than for the gneissic material. The plagioclase-rich intrusive and volcanic pebbles and the syngenetic ashes were extremely sensitive to weathering, thus the major part of these rocks was decomposed during transport, enriching the accessory minerals, particularly the very durable zircons in the sediment. The low resistance to weathering and the large transport distance explain the scarcity of the volcanic pebbles in the conglomerate. Thus, we suppose that this source lithology supplied into the sandstone the zircon and apatite crystals with young FT ages. The contribution from the Periadriatic magmatic chain to the 'Inntal Tertiary' was much more significant than would be expected from the paucity of volcanogenic pebbles. The young apatite age cluster is very probably also volcanogenic in origin, although this is not evident from the shape

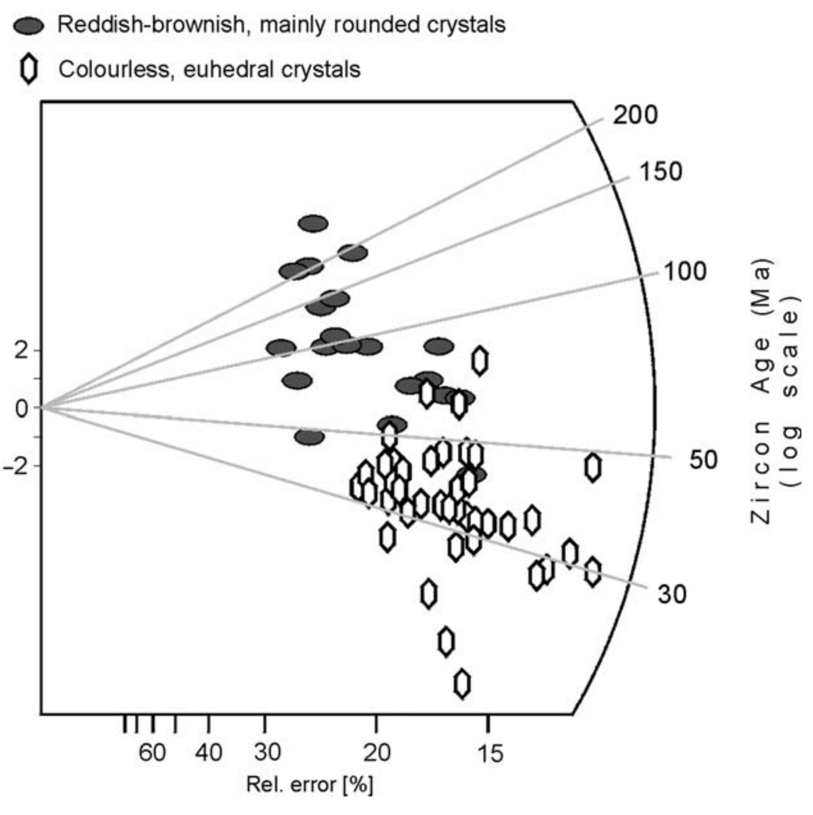

Fig. 5. The distribution of euhedral and rounded zircon crystals from the Oligocene sandstone of Inntal Tertiary on radial plot (Galbraith 1990). The majority of the euhedral crystals form a cluster around 30–35 Ma, which is interpreted as the weathering product derived from the Oligocene Periadriatic volcanic chain. The euhedral grains with an approximate 80 Ma FT age very probably came from the orthogneiss members of the Austroalpine unit.

of the grains, because apatite is much more sensitive to mechanical and chemical corrosion than zircon.

This case study shows that the apatite and zircon crystals were derived mainly from two source lithologies. Different lithologies can have significantly different yield and ratio of datable mineral species. FT analysis of just sandstone samples may provide zircon age distributions with components of short lag time that could be misinterpreted as active, contemporary exhumation of the basement, where in fact the zircons were derived from a volcanic source (see similar scenarios in Ruiz *et al.* 2004). The FT age distributions of PPD samples made from crystalline rocks show the typical cooling ages of the basement, and these cooling age distributions reflect the intensity and rate of the exhumation processes in the hinterland unbiased from the effect of volcanogenic contribution.

Case study II – FT litho-terrains of the Eastern Alps in the Late Miocene

Samples and present-day distribution of the dated lithotypes

The poorly cemented Hausruck Conglomerate is the youngest proximal fluviatile fan preserved in the foreland basin of the Eastern Alps. It was deposited during the Pannonian time (*c.* 10–8.5 Ma: Mackenbach 1984). The transport was directed NE, towards the modern course of the Danube (for the locality see the star in Fig. 3). Owing to the large catchment size and long transport, the pebble spectrum is polymict with a large proportion of polycrystalline quartz (55%). The other lithologies include various metamorphic rocks (32%), white quartzite (7%), sandstone (4%), and a small percentage of granite and limestone (Brügel 1998). Pebble composition, sedimentological data and palaeogeographic considerations suggest that this fan was deposited by the palaeo-Inn River where it entered the Molasse Basin (Brügel *et al.* 2003). We obtained pebble population samples from the most abundant zircon- and apatite-containing lithologies: gneisses, white quartzites and red Bunter sandstones. The studied PPD samples are derived from the lowermost part of the Hausruck Conglomerate sequence, from a gravel pit 300 m SW of Ditting (next to Haag am Hausruck, Austria; N48°10′44″/E13°37′29″).

Figure 3 shows the actual bedrock distribution of these lithologies in the Eastern Alps. Gneisses are the most widespread lithologies of the central zone of the Eastern Alps, and they occur both in the Austroalpine upper plate and Penninic lower plate units. White–light-greenish quartzite partly containing phengitic mica forms marker horizons in both the Austroalpine and the Penninic metamorphic cover sequences. Locally, slightly metamorphosed Lower Triassic (Bunter) sandstones are typical for the base of the western part of the Northern Calcareous Alps and occur only in a structurally high level of the Austroalpine unit.

Results

The fission-track data obtained from the various pebble populations are listed in Table 1 and are shown in Figure 6. Only the apatite age distribution of the white quartzite PPD sample passes the Chi-square test and this indicates the derivation from a single source (central age: 13.9 $\pm$ 0.5 Ma). The FT age distribution was decomposed using the Binomfit program for the component estimation (Galbraith & Green 1990; Brandon 1996). The apatite age distributions have two major components with mean ages of 15 $\pm$ 1 and 40 $\pm$ 5 Ma in the gneiss PPD sample, and with means of 39 $\pm$ 4 and 74 $\pm$ 6 Ma in the Bunter sandstone PPD sample (Table 1). The zircon probability density plots also show complex age distributions. The components are: 16 $\pm$ 1 and 52 $\pm$ 4 Ma in the white quartzite PPD sample (which does not show this bimodality for apatite ages); and 17 $\pm$ 2 and 57 $\pm$ 3 Ma in the gneiss PPD sample. The Bunter sandstone sample contains much older zircon grains than the gneiss PPD sample; it is noticeable that the age distributions have practically no overlapping (Fig. 6).

Discussion

Miocene age components. During the interpretation of the FT results the youngest age component has a prominent, sometimes diagnostic, function (Brandon 1992; Ruiz *et al.* 2004). The lag times of the detected youngest age components are rather short; they range from 4 to 6 Ma for apatite and from 6 to 7 Ma for zircon in both the white quartzite and gneiss PPD samples. The presence of young apatite and zircon ages in these lithologies, and the small difference between the means of the apatite and zircon age components, suggest rapid exhumation in a part of the hinterland.

We believe that the gneiss and white quartzite pebbles have a short lag time derived from the central and eastern Tauern Window, where the present-day zircon FT ages of the basement cluster around 18 Ma (Dunkl *et al.* 2003) and the apatite cooling ages are between 20 and 6 Ma (Staufenberg 1987). The western Tauern Window could not have had a role in the supply of gneiss and white quartzite pebbles because Fügenschuh *et al.* (1997) presented Late Miocene zircon FT ages (*c.* 10 Ma) from the western margin of the Tauern Window, close to the Brenner detachment fault. Hence, this westernmost part of the window was only exhumed later;

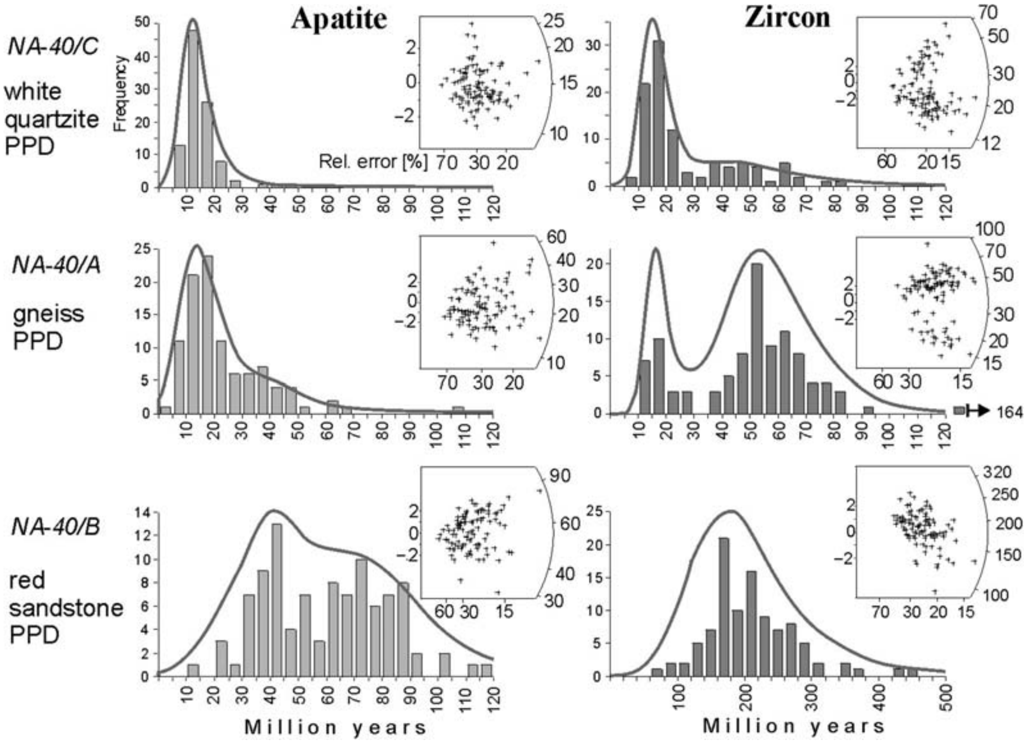

Fig. 6. Age distributions of the pebble population samples derived from the Late Miocene Hausruck Conglomerate (all samples contain 100 data; note the different age scale in the lower right-hand side diagram).

this segment of the lower plate was still covered by the Austroalpine hanging wall during sedimentation of the Hausruck Conglomerate at approximately 10 Ma.

Pre-Miocene age components. The mean values of the zircon age components of the gneiss PPD and the white quartzite samples are very similar, but the gneiss PPD sample contains a significantly higher amount of older grains (Table 1). The presence of Palaeogene apatite FT ages and the higher proportion and slightly older mean of the Palaeogene zircon age group in the gneisses indicate that:

- the gneiss pebbles were derived from both the Penninic and Austroalpine units;
- the Austroalpine source was dominant (a certain ambiguity arises from possible variations of the zircon/apatite ratio in the gneisses);
- high levels of the Austroalpine crystalline basement were not extensively eroded in the catchment area of the palaeo-Inn River during the sedimentation of the Hausruck Conglomerate because the proportion of >50 Ma old apatite ages is very small. This indicates that in the Late Miocene the Ötztal Alps and the Silvretta Alps had already lost the uppermost levels of the Austroalpine gneiss complexes.

The age distributions of the Lower Triassic Bunter sandstone PPD sample are fundamentally different from those of the other lithologies. The zircon ages show a wide scatter, partly due to the large uncertainties of old grains. Some of the zircon ages in the Bunter sandstone are older than the sedimentation age (250–240 Ma) of this rock and thus represent source areas that have not, or have only partly been, thermally overprinted during Alpine metamorphism. The FT age distribution in the red sandstone consists of two age components: a Triassic one (*c.* 209 Ma) and an Early Cretaceous one (*c.* 127 Ma). The older age component is related to cooling after the Permo-Triassic rifting processes (Bertotti *et al.* 1999), or the poorly defined Jurassic tectonothermal event in the Alps that caused partial resetting in certain tectonic blocks (Dunkl *et al.* 1999; Vance 1999). The younger age component of this lithology probably reflects the partial resetting generated by Eoalpine metamorphism in Cretaceous time (Thöni 1981). These Mesozoic thermal events have mainly affected the western part of the Austroalpine nappe pile (Elias 1998). In the eastern part of the presently exposed belt of red sandstones, these rocks generally do not show ductile deformation and the resetting of zircon FT ages.

The apatite age distribution in the Bunter sandstone PPD sample reflects two major source areas, one with Palaeogene and another with Cretaceous ages, which can be related to a western and an eastern source terrain. We suggest that Bunter sandstone pebbles with Palaeogene apatite FT ages originated from the west, where exhumation had been faster since the onset of Oligocene uplift. In this area, the deeper part of the pre-exhumation partial track annealing zone was exposed during the Late Miocene. However, in the east slower erosion had not yet incised into the Early Tertiary partial annealing zone within the Upper Austroalpine nappes. The pebbles of the Hausruck Conglomerate with Cretaceous FT apatite ages were derived from this eastern source terrain.

Palaeogeological implications

The reconstruction of the palaeo-drainage situation of the Inn River during the Late Miocene is based on the FT ages of the pebble population method, and on the recent distribution of the dated lithologies and of the FT ages in the drainage area. The following are the major palaeogeographical and palaeogeological features.

- The Inntal fault is an old and persistent strike-slip fault, repeatedly active since Oligocene times (Ortner & Sachsenhofer 1996). It is responsible for the formation of a longitudinal depression or valley system, which had canalized the runoff of the major part of the western Eastern Alps since Oligocene time (Frisch *et al.* 1998).
- The major rearrangement of tectonic blocks as a result of Early–Middle Miocene large-scale crustal extension and tectonic escape in the course of lateral extrusion was completed before the sedimentation of the Hausruck Conglomerate (Frisch *et al.* 1998, 2000). Thus, we consider the Austroalpine blocks in their present-day positions to be similar to their positions 10 Ma ago.
- The Tauern Window was only partly exhumed and was considerably smaller than today. Figure 7a integrates the lithological and geochronological data, and schematically presents the proportion of different lithologies of the pebbles and their FT ages at time of sedimentation (10 Ma). Figure 7b is an interpretation of the FT ages considering other observations (geology, pebble statistics, tectonics, etc.). The combination of the shading keys for the ages, the black patterns for the lithologies and tectonic units mark the FT litho-terrains.
- We infer that by the Late Miocene time on the exposed surface of the Silvretta Alps and Ötztal Alps the apatite FT ages were already different. Gneiss clasts with Palaeogene apatite FT age were probably derived from the Silvretta Alps (Flisch 1986), whereas Neogene ages were derived probably from the Ötztal Alps (Elias 1998).
- Gneiss pebbles with Miocene apatite and Palaeogene–Late Cretaceous zircon FT ages were mainly derived from the Ötztal Alps. Based on the lack of Cretaceous apatite FT ages in the gneiss PPD sample, we assume that the higher levels of the Ötztal Alps – dominated by the pre-Tertiary – was already eroded by about 10 Ma.
- At 10 Ma the orthogneiss cores within the embryonic Tauern Window were less extended than at present, and in the major part of the window the metasedimentary cover sequences were dominant (Brügel 1998). The western part of the Tauern Window was covered by an extensional allochton, composed of Austroalpine crystalline rocks. The apatite and zircon FT ages of around 10 Ma (Fügenschuh *et al.* 1997) along the western margin of the Tauern Window indicate a later exhumation of that part.
- The exposure of Miocene zircon FT ages during late Miocene time is mainly limited to the area of Penninic formations, but parts of the upper plate south of the Tauern Window and above the western Tauern Window also probably had Miocene zircon FT ages at the time of sedimentation of the Hausruck Conglomerate.

Conclusions

The PPD method is a valuable tool for discriminating the provenance of coarse clastic material. We draw the following conclusions from the two case studies of the pebble population dating method presented in this paper.

- In the case a of synsedimentary volcanic contribution, such a source appears as a young age cluster in the FT single-grain ages in the sandy matrix of the sediment. By dating PPD samples composed of metamorphic lithologies, a volcanogenic population in the sand fraction can be filtered out. Thus, a more reliable geodynamic reconstruction of the source area can be drawn from fission-track dating of pebble population samples than from the detrital thermochronology of sandstones. It is clear from these FT data that during the deposition of the Oligocene sediments of the Inntal Tertiary there was no rapidly cooling crystalline material exposed in the hinterland. The relatively long

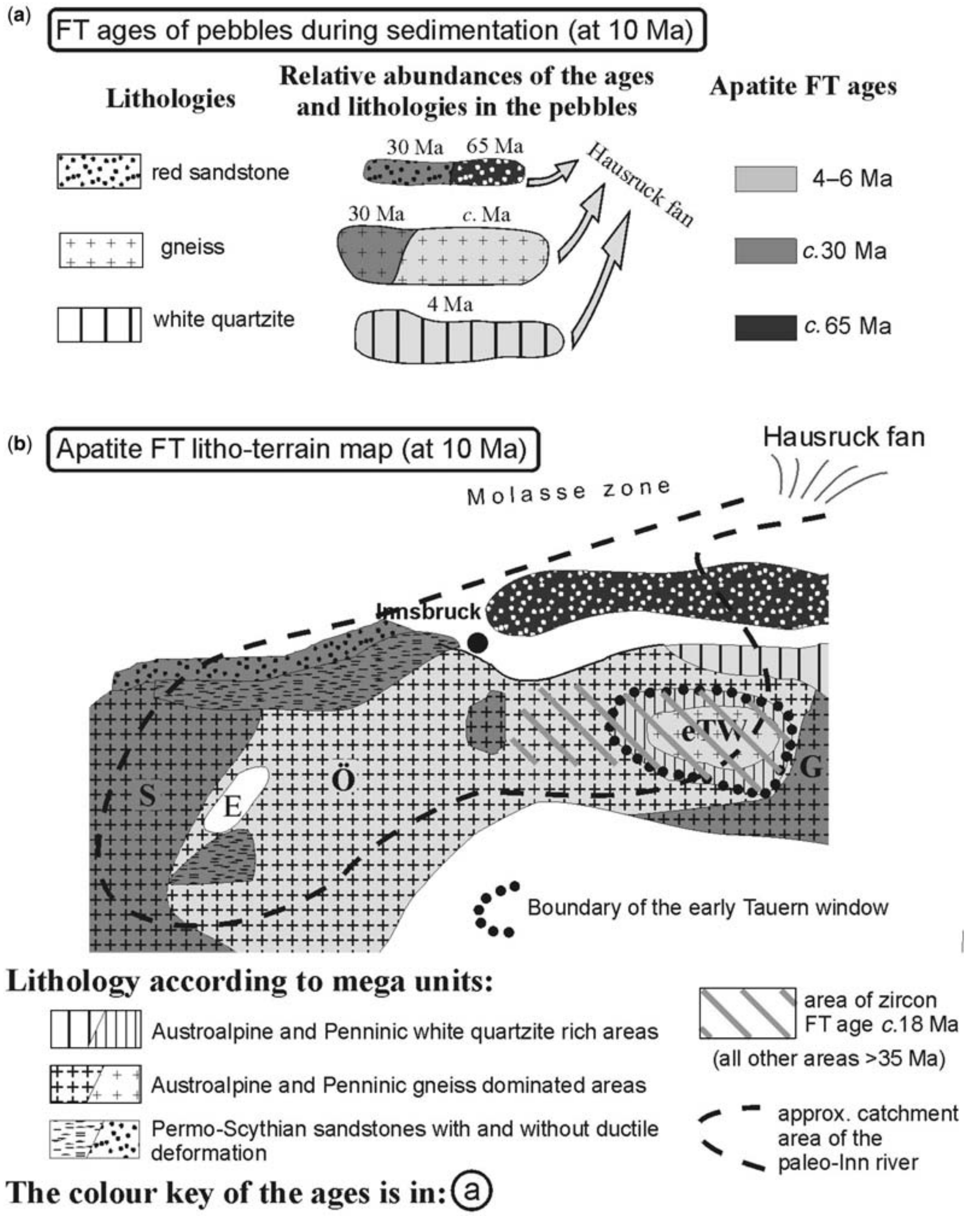

Fig. 7. (**a**) Simplified presentation of the total mass of pebbles in the sediments with their FT age during Hausruck fan sedimentation (average FT age of main clusters minus 10 Ma). (**b**) Palaeogeological map of the western Eastern Alps with the characteristic fission-track ages (10 Ma ago). The area corresponds approximately to the map of Figure 3. eTW, early stage of the Tauern Window; Ö, Ötztal Alps; S, Silvretta Alps; G, Gurktal Alps. The Engadin Window (E) in this early stage of exhumation supplies minor amounts of detrital apatites and zircons due to its dominantly metapelitic composition. Note the retro-deformed shape and position of the main units (cf. Fig. 3).

lag times (several tens of millions of years for both apatite and zircon FT ages) indicate moderate relief and slow exhumation in the western Eastern Alps during the Oligocene.

- PPD samples from different lithologies enable detailed palaeogeological reconstructions. The use of the PPD method on three lithologies from the same outcrop in the Late Miocene Alpine Molasse zone allows these rock types to be connected to distinct source units. The majority of the white quartzite was derived from the rapidly exhumed lower-plate units of the orogen, while the majority of the gneiss pebbles were derived from the upper plate. The gneisses and quartzites, however, show that the Penninic formations in the central and eastern parts of the Tauern Window had already been exhumed to the surface. The Lower Triassic weakly metamorphosed red Bunter sandstones have old apatite and zircon cooling ages, and were, therefore, derived exclusively from a high level of the upper-plate (Austroalpine) unit.
- The PPD method is a powerful tool for revealing the palaeogeodynamics in the catchment areas of river systems feeding syntectonic sedimentary basins. Because it is lithology-based, this technique is capable of providing detailed information about the exhumation history of different units of the source terrain. A combination of PPD results from different lithotypes reveals a detailed reconstruction of FT litho-terrain evolution, which serves as a basis for palaeogeological and palaeogeographical maps.

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Appendix 1: Sampling strategy for pebble population dating

- The pebbles or pebble fragments should be approximately similar in weight to avoid the dominance of apatite and zircon crystals from one or very few pebbles. In practice, we collected pebble (and pebble fragment) samples with a volume of 2–4 l. When the typical pebble size was small (2–3 cm), we split fragments of similar weights from the much larger pebbles. When the sediment was a fanglomerate and dominated by cobbles or boulders, fragments the size of a walnut were collected. Remains of the sandy matrix were carefully removed from the surface of the pebbles. Except for two–five typical rocks slabs (reserved for documentation and thin sections), all of the selected pebbles were crushed together. After homogenization, approximately one-third of the bulk amount was processed using standard mineral concentration techniques.
- An increasing number of pebbles decreases the biasing effect of few atypical pebbles, which may be extremely rich in datable apatite or zircon crystals. We suggest collecting a minimum of 50 pieces for a representative pebble population.
- FT dating of the sandy matrix can supply essential additional information. We recommend this technique, therefore, as a routine process accompanying PPD dating.

Appendix 2: Experimental procedure of fission-track chronology

The samples were treated using heavy liquid and magnetic separation processes; the apatite crystals were embedded in epoxy resin and the zircon crystals in PFA Teflon. For apatite, 1% nitric acid was used with 2.5–3 min etching time (Burchart 1972). In the case of zircon mounts, the eutectic melt of NaOH–KOH was used at a temperature of 210 °C (Gleadow *et al.* 1976). Couples or triplets of mounts were produced to gain enough, properly etched crystals. The etching time varied from 23 to 54 h. Neutron irradiations were made at the Risø reactor (Denmark). 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 30 min. Track counts were 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 using the classical procedure, that is by Poisson dispersion (Green 1981). Calculations and plots were made with the TRACKKEY program (Dunkl 2002).

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