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From source terrains of the Eastern Alps to the Molasse Basin: Detrital record of non-steady-state exhumation

J. Kuhlemann *, I. Dunkl, A. Brügel, C. Spiegel, W. Frisch

University of Tübingen, Institute for Geosciences, Sigwartstrasse 10, D-72076, Tübingen, Germany

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Abstract

Fission-track cooling ages of detrital apatite (AFT) in the East Alpine Molasse Basin display age groups corresponding to geodynamic events in the orogen since Jurassic times. These age groups are typical of certain thermotectonic units, which formed a patchwork in the Swiss and Eastern Alps. By a combination of petrographic and thermochronologic data, progressive erosion of source terrains is monitored in different catchments since the Oligocene. The AFT cooling ages show a decrease in lag time until when rapidly cooled debris derived from tectonically exhumed core complexes became exposed. After termination of tectonic exhumation, lag times of debris derived from the core complexes increased. Neither on the scale of the entire Eastern Alps, or on the scale of individual catchments, steady-state exhumation is observed, due to the highly dynamic changes of exhumation rates since Late Eocene collision.

Keywords: Detrital thermochronology; Apatite fission track; Eastern Alps; Foreland basin; Provenance

1. Introduction

Exhumation rates in collisional orogens such as the Alps are recorded in the cooling history of orogenic debris in adjacent basins (Einsele et al., 1996). The cooling history in the depositional record monitors timing and rates of exhumation processes more effectively and regionally than local cooling paths deduced from surface samples of an orogen (Brandon and Vance, 1992). Exhumation processes in active orogens may operate at different rates throughout their evolution, depending on, e.g., varying rates of convergence, varying thickness of subducted continental crust and varying lithospheric strength along strike of the orogen (Schmid et al., 1997; Pfiffner et al., 1997). Such temporal and spatial variability is typical in the Alps, and several studies have shown discontinuous exhumation in the Western Alps (Dunkl et al., 2001; Carrapa et al., 2003; Fügenschuh and Schmid, 2003) and the Swiss Alps (Von Eynatten et al., 1999; Spiegel et al., 2000, 2001). Nevertheless, the Swiss Alps have recently been quoted as an example of a steady-state exhuming orogen since Oligocene times (Bernet et al., 2001). Detailed knowledge of provenance, however, is crucial for the interpretation of thermochronologic data of distal detrital material. If rapidly cooled detritus is shed from varying fastly exhuming source terrains in migrating catchments, and also from volcanic sources, apparent steady-state exhumation may be misleading. Rapid cooling of exhuming rocks causes a very short lag time, which expresses the time span between the age of mineral cooling below its closure temperature at

* Corresponding author. Tel.: +49 7071 2974701; fax: +49 7071 5059.
E-mail address: kuhlemann@uni-tuebingen.de (J. Kuhlemann).

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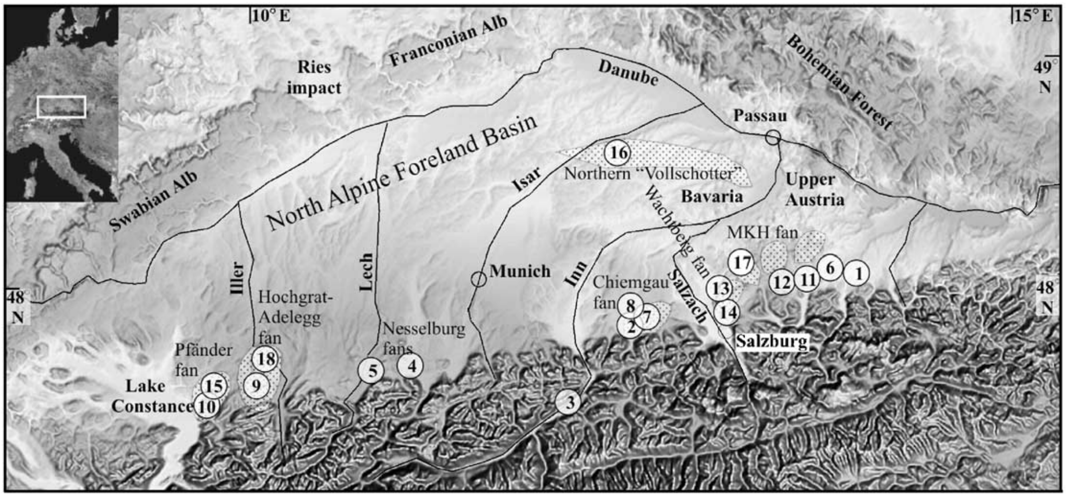


Fig. 1. Digital elevation model (shaded relief) of the eastern part of the Molasse Basin, showing major fan deposits and sample locations. The Chiemgau-, Wachtberg- and Munderfing-Kobernausser-Hausruck (MKH) fans represent fan delta deposits of the Paleo-Inn river. The sample numbers follow stratigraphic order (for localities see Table 1).

some kilometer depth (F-apatite: around 110 °C; Gleadow and Duddy, 1981) and its surface exposure, subsequent detrital tranport and deposition (Brandon and Vance, 1992). In the light of the recent discussion, data from the Eastern Alps provide evidence for a better understanding of the entire orogen.

In this study, we present thermochronologic data from the eastern part of the Molasse Basin (Fig. 1), which we partly relate to well-defined feeder systems and catchments with distinct source terrains. The Eastern Alps are characterised by erosion rates that are about half as high as those detected in the Swiss and Western Alps (Kuhlemann et al., 2002). The purpose of this study is to provide details on the exhumation of the Eastern Alps in space and time. The Oligocene to Early Miocene period is of special interest, since it monitors the erosion of upper plate Austroalpine units which had already been removed from the Swiss Alps during this period (Pfiffner et al., 1997).

2. Tectono-thermal setting of the Eastern and Swiss Alps

The Alps are composed of three mega-units representing the northern tip of African/Adriatic continental crust in upper plate position (Austroalpine mega-unit), the southern margin of Europe in lower plate position (Helvetic mega-unit), and the complex terrane of the Penninic mega-unit sandwiched in between (Fig. 1c; Frisch, 1979; Schmid et al., 1997). The Austroalpine mega-unit is exposed over large parts of the Eastern Alps whereas it is largely eroded in the Swiss Alps. It consists of crystalline basement characterised by Variscan amphibolite-facies metamorphism and Cretaceous (Eoalpine) metamorphic overprint, as well as of low-grade metamorphic Paleozoic terrains and post-Variscan (Permian to Eocene) cover sequences (Ratschbacher et al., 1989). The Penninic mega-unit is composed of Variscan basement fragments with Mesozoic cover sequences, and relics of Mesozoic oceanic crust and its sedimentary cover. Metamorphosed Penninic units are exposed in the tectonic windows of the Swiss and Eastern Alps, whereas an unmetamorphosed flysch belt crops out at the northern front of the Alps. Penninic units exposed in the windows experienced Early Tertiary metamorphism up to amphibolite facies grade. Temperature maximum was attained in Oligocene times around 30 Ma (Von Blanckenburg et al., 1989; Christensen et al., 1994; Inger and Cliff, 1994). The Helvetic mega-unit is subordinately exposed in the Eastern Alps but abundant in the Swiss Alps. It is composed of a granite-rich Variscan basement with Miocene low-grade metamorphic overprint, and post-Variscan (Permian to Eocene) cover sequences (Schmid et al., 1997).

Presently exposed litho-terrains of the Alps show highly contrasting cooling histories. Core complexes experienced Miocene tectonic exhumation during lateral extension (Fig. 1b; Hunziker et al., 1992; Frisch et al., 2000a). Differential erosional exhumation also caused contrasting cooling paths in the Austroalpine units of the Eastern Alps with AFT cooling ages spanning from Cretaceous to Miocene times (Hejl, 1997; Elias, 1998). Moreover, Early Oligocene magmatic ac-

Table 1
Apatite fission track results from the East Alpine basin

Code	Location	Depo. period	Fan	Latitude	Longitude	n	Spontaneous		Induced		Dosimeter		$P(\chi^2)$	Disp.	FT central age
							ρ_s	(N_s)	ρ_i	(N_i)	ρ_d	(N_d)			
1	Aistwald	Eocene	Bohemian massif			50	53.89	(4768)	31.23	(2763)	5.15	(10,041)	20	0.08	164 ± 5.7
2	Osterbuchberg	E. Chattian	Inn/Chiemgau	47° 48′ 32″	12° 30′ 25″	60	4.69	(1167)	7.41	(1843)	4.44	(10,915)	<1	0.28	52.1 ± 3.1
3	Angarth	Up. Rupel	Inn/Inntal	47° 30′ 00″	12° 03′ 28″	60	4.81	(1410)	6.32	(1853)	4.08	(12,045)	58	0.09	57.4 ± 2.5
4	Lechbruck	E. Chattian	Nesselburg	47° 41′ 00″	10° 45′ 00″	60	5.50	(1661)	11.22	(3386)	4.12	(12,045)	<1	0.27	36.6 ± 1.9
5	Murnau	E. Chattian	Nesselburg	47° 40′ 13″	11° 11′ 53″	60	2.76	(994)	4.42	(1591)	4.42	(6454)	<1	0.35	50.1 ± 3.5
6	Bergern	L. Egerian	Submarine Inn fan	47° 47′ 47″	12° 35′ 45″	60	4.52	(2092)	9.05	(4192)	5.01	(12,211)	<1	0.35	49.9 ± 2.9
7	Traunstein	Aquitanian	Inn/Traunprofile	47° 50′ 44″	12° 38′ 30″	60	3.63	(1395)	8.92	(3431)	5.11	(10,041)	<1	0.53	38.2 ± 3.1
8	Traunstein	Aquitanian	Inn/Traunprofile	47° 50′ 45″	12° 38′ 33″	60	3.41	(1646)	9.74	(4702)	4.44	(10,915)	<1	0.30	28.4 ± 1.6
9	Hochgrat	Aquitanian	Hochgrat	47° 34′ 00″	10° 10′ 46″	65	10.68	(5221)	20.33	(9938)	4.38	(6454)	<1	0.31	39.6 ± 2.0
10	Langen	Burdigalian	Pfaender	47° 30′ 11″	09° 47′ 36″	20	2.57	(515)	9.25	(1852)	4.38	(6454)	<1	0.29	22.4 ± 2.0
11	Bergern	Burdigalian	Submarine Inn fan	47° 47′ 47″	12° 35′ 45″	60	5.88	(1610)	13.27	(3632)	5.22	(10,168)	<1	0.51	42.8 ± 3.3
12	Lochen	Burdigalian	Submarine Inn fan	48° 00′ 32″	13° 11′ 03″	60	4.20	(1503)	10.95	(3924)	4.97	(12,211)	<1	0.31	35.5 ± 2.0
13	Wachtberg	Burdigalian	Submarine Inn fan	47° 57′ 15″	12° 58′ 40″	80	5.16	(1952)	10.42	(3940)	4.62	(9076)	<1	0.54	42.8 ± 3.1
14	Nuβdorf	Ottnangian	Inn/Wachtberg	47° 57′ 20″	13° 01′ 05″	60	3.42	(1842)	9.40	(5062)	4.62	(9076)	<1	0.31	32.4 ± 1.7
15	Langen	Ottnangian	Pfaender	47° 37′ 31″	09° 53′ 39″	60	2.89	(1475)	10.76	(5497)	4.08	(12,045)	<1	0.23	20.9 ± 1.0
16	Niederaichbach	L. Badenian	Inn/Vollschotter	48° 35′ 20″	12° 19′ 10″	80	3.98	(1752)	8.33	(3666)	4.62	(9076)	<1	0.44	43.6 ± 2.8
17	Munderfing	Sarmatian	Inn/Munderfing	48° 03′ 52″	13° 12′ 22″	65	1.90	(1120)	7.11	(4197)	4.08	(12,045)	<1	0.52	21.9 ± 1.7
18	Adelegg	Sarmatian	Hochgrat/Adelegg	47° 42′ 25″	10° 09′ 50″	60	4.54	(2035)	13.29	(5954)	4.62	(9076)	17	0.09	29.2 ± 1.0

The indicated central ages of the samples have limited meaning, because the majority of the samples is composite in character (indicated by the low chi-square values and by the high dispersion values). The age components are evaluated in the text and listed in Table 2. n: number of dated apatite grains. Track densities (ρ) are measured as ($\times 10^5$ tr/cm^2); number of tracks counted (N) shown in brackets. $P(\chi^2)$: probability of obtaining chi-square value for n degrees of freedom (where n = no. crystals-1). Disp.: Dispersion, according to Galbraith and Laslett (1993). Ages were calculated using $\zeta_{CN5} = 373 \pm 7$.

tivity along the Periadriatic line exposed volcanic material and tonalite bodies with surrounding contact zones became subsequently exposed (Frisch et al., 1999). A discrimination between exhumation rates, as reflected by thermochronology, and erosion rates, as reflected by sediment budget calculations, provides an estimate of tectonic denudation of the upper crust (Kuhlemann et al., 2001a).

3. Regional setting of the Molasse Basin and adjacent Alpine catchments

The detrital record of the Molasse Basin largely monitors the exhumation history of the northern flank of the Swiss and Eastern Alps. Alpine dispersal systems in the Molasse Basin (Fig. 2) partly remained in a stable position, like the Oligocene to Early Miocene deposits of the Hochgrat fan and the succeeding Middle Miocene Adelegg fan (Brügel, 1998). Other Alpine dispersal systems were shifted eastward in the course of lateral extension of the Alps, like the deposits of the Paleo-Inn which moved from the Chiemgau in the Oligocene towards the east to the region N and NE of Salzburg (Wachtberg fan, late Early Miocene), and further to the east (Northern Vollschotter, ~14 Ma; Munderfing-Hausruck-Kerbernausser fan, 13–8 Ma; Fig. 2). The size of this northward-drained flank of the orogen (Fig. 2a) underwent gradual changes since the Oligocene as well as a drastic decrease around 17 Ma and an increase around 11 Ma, due to shifts of the main drainage divide (Kuhlemann, 2000; Kuhlemann et al., 2001b).

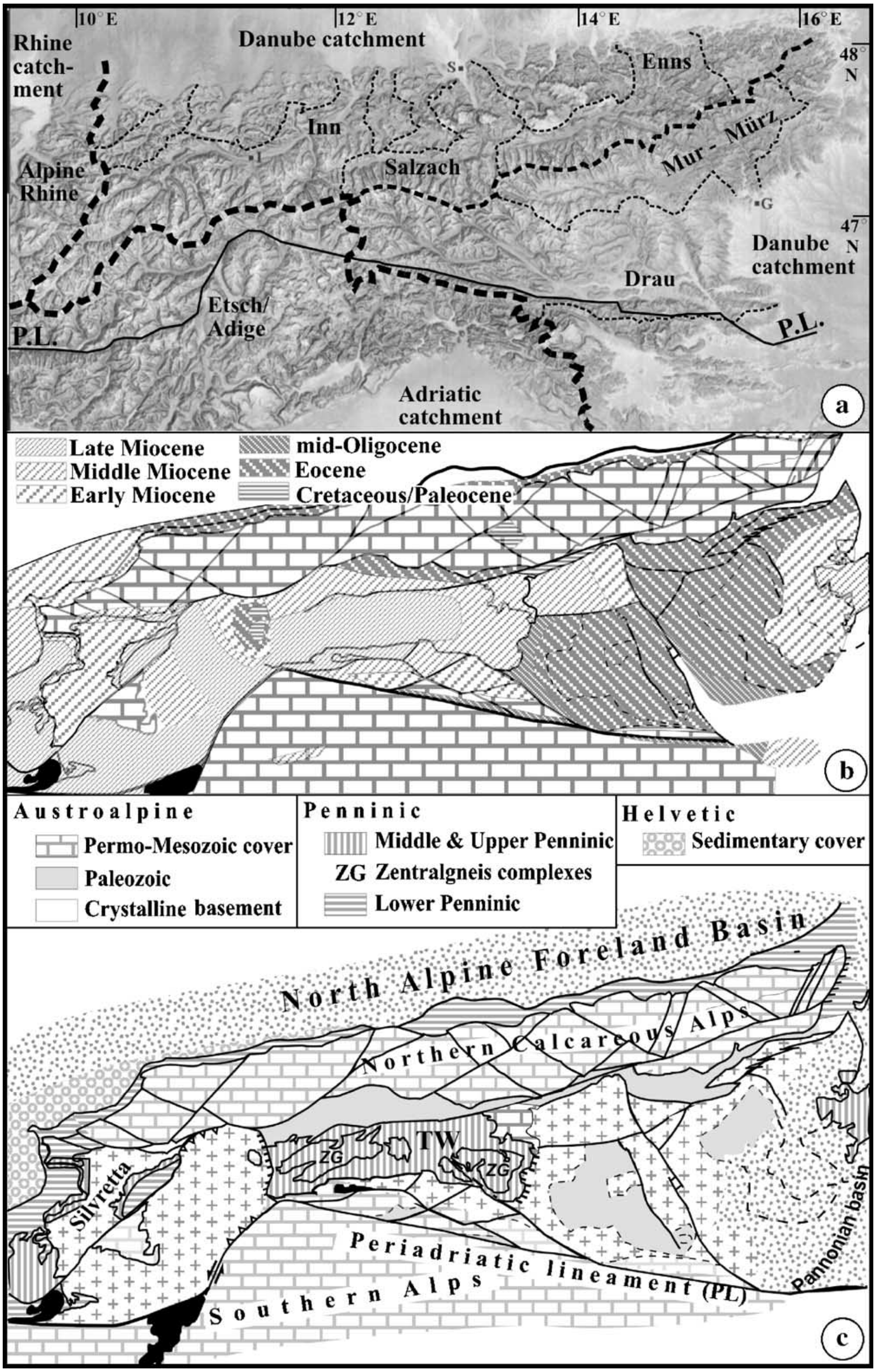
Heavy mineral associations and petrographic composition of pebbles in these Alpine dispersal systems reveal major reorganisations of individual catchments in the Swiss sector (Matter, 1964; Schlunegger, 1999) and the East Alpine sector (Skeries and Troll, 1991; Brügel et al., 2000). In the Eastern Alps, ophiolite and gneiss pebbles derived from Penninic units of Tauern window were deposited by around 13 Ma and testify the first exposure of this core complex (Fig. 2c; Brügel, 1998). In contrast, Penninic ophiolite material was shed from the Swiss Alps to the eastern Molasse Basin by axial transport already around 20 Ma (Spiegel et al., 2002, 2004). Thus, thermochronologic information retrieved from distal sandy material requires supplementary provenance data in order to be able to properly relate such data to their original sources.

In the Eastern Alps, major reorganisations of the north-draining river network occurred in the catchment of the Paleo-Inn (Frisch et al., 1999). This includes Early Miocene acquisition of headwaters in the SW of the Eastern Alps and later loss of high mountainous hinterland to south-draining rivers (Kuhlemann, 2000). The Paleo-Inn represents the largest individual drainage system in the Alps. It followed a prominent ENE-running fault which has been stable since the Late Oligocene (Frisch et al., 1998). Nevertheless, reorganisations of the Paleo-Inn catchment include also eastward shifts of the outlet into the Molasse Basin, as a consequence of the eastward extension of the Eastern Alps (Frisch et al., 1999). Thus, sediments shed from the Paleo-Inn river are found in regions scattered over eastern Bavaria and Upper Austria (Fig. 1). Oligocene to Early Miocene deposits have been related to deep marine fluxo-turbidites (Puchkirchen formation; Robinson and Zimmer, 1989; Wagner, 1996). Middle and Late Miocene deposits comprise shallow marine deltas and fluvial deposits, recording overfilling of the basin (Kuhlemann and Kempf, 2002).

Fan delta deposition and facies distribution in the North Alpine Foreland Basin (NAFB) is largely controlled by subsidence. The subsidence evolution comprised two episodes (megacycles), both starting with fast subsidence and low sediment supply (Kuhlemann and Kempf, 2002). Between ~35 and 21 Ma, subsidence of the Molasse Basin was forced by N-propagating tectonic loading, and supported by the load of sediment deposition (Sinclair, 1997). This first depositional megacycle was characterised by an early marine phase in the underfilled Molasse Basin, and terrestrial environment W of the Chiemgau area from 30 Ma on. Shift of facies belts and facies change were caused by rapidly increased sediment supply from the Swiss Alps and the western section of the Eastern Alps as a consequence of continental collision and slab breakoff (Kuhlemann and Kempf, 2002; Fig. 3). The eastern part of the Molasse Basin, however, remained underfilled with deep marine depositional conditions throughout the entire first sedimentary megacycle until ~18 Ma (Robinson and Zimmer, 1989). From 21

Fig. 2. Geomorphic (a), thermochronologic (b), and structural (c) setting of the Eastern Alps. (a) Displays a shaded relief generated from a DEM with location of larger catchments, separated by drainage divides. For orientation, the Periadriatic Lineament (P.L.) is indicated. (b) Shows the simplified interpretative distribution of apatite fission track age groups of surface samples according to Grundmann and Morteani (1985); Flisch (1986), Staufenberg (1987); Hunziker et al. (1992), Fügenschuh et al. (1997), Dunkl and Demény (1997), Hejl (1997), Elias (1998), Stöckhert et al. (1999), Reinecker (2000), Steenken et al. (2002), Trautwein et al. (2001), Most (2003), Balogh and Dunkl (2005). (c) Shows major tectonic units of the Alps. Periadriatic intrusives are marked in black. In the center of the Eastern Alps, the core complex of the Tauern window (TW) is exposed (ZG: Zentralgneiss domes).

to 11 Ma, the Molasse Basin experienced differential and generally decreasing subsidence (Zweigel et al., 1998). During the 2nd depositional megacycle, the short-lived Burdigalian Seaway (~21 to 18 Ma), connecting the Paratethys in the E with the western Mediterranean basin, developed in the course of lateral east–



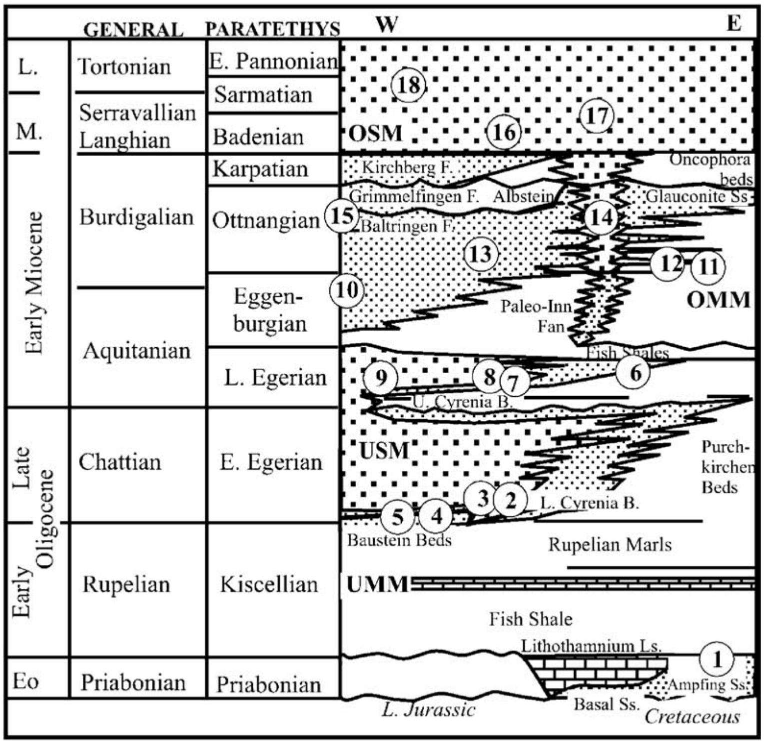


Fig. 3. Wheeler diagram of the along-strike facies distribution in the eastern Molasse Basin with approximate stratigraphic positions of samples. Stratigraphy displays both Mediterranean (international) and Paratethys timescales. The order of sample numbers is the same as in Figs. 1, 4, and Table 1. The classic abbrevations UMM, USM, OMM, OSM denote the Lower Marine Molasse, Lower Freshwater Molasse, Upper Marine Molasse, and Upper Freshwater Molasse, respectively.

west extension in the Alps. By the end of the Burdigalian, the seaway became rapidly filled due to accelerated sediment supply from the rapidly uplifting Alps (Kuhlemann and Kempf, 2002).

4. Materials and methods

In fan systems of the Molasse Basin, both sand and pebbles from distal and proximal settings of fan systems were sampled (Fig. 1). Sand samples from distal settings cannot be related to a specific feeder system and provide evidence of the more general cooling pattern in the orogen. Gneiss pebbles of similar lithologic phenotype (>50 pebble pieces) were processed together in order to specify the cooling pattern of distinct lithologies (Frisch et al., 1999). Fission track dating of individual apatite or zircon grains from such pebble populations yields age clusters characteristic of specific litho-terrains (Dunkl et al., 1998). This technique allows to exclude a potential volcanic contribution in detrital sands, which may bias the cooling age distribution resulting from exhumation in the hinterland (see Frisch et al., 2001; Kuhlemann et al., 2001a,b). Furthermore, core material from oil wells in the deep marine basin center of the Upper Austrian foreland trough was kindly provided by the oil company RAG (Vienna).

Heavy minerals were extracted by standard magnetic and heavy liquid separation. Detrital apatites were dated by the fission track (FT) dating method, which is sensitive to cooling of source rocks in the temperature range between 60 and 110 °C (Gleadow and Duddy, 1981). FT dating was performed by the external detector method (Gleadow, 1981) and the zeta calibration approach (Hurford and Green, 1983). Between 25 and 80 individual apatite grains in each sample were dated. The resulting FT age spectra have been modeled with the PopShare computer program (Dunkl and Székely, 2002). The age components, calculated lag times, and statistical parameters are listed in Table 2.

5. Results

The cooling age spectra from the Molasse Basin provide two lines of evidence: (i) a temporal change of exhumation rates in fan deposits covering about 15 Ma, and (ii) spatial variations at certain periods of time. The cooling age spectra shown as histograms of age

Table 2
Result of component identification using PopShare program (Dunkl and Székely, 2002)

		Sedi.	Unc.	M1	M2	M3	sd1	sd2	sd3	%c1	Lag time to M1
		Million years									
1 Aistwald	Eocene	35	1	164			6			100	129
2 Osterbuchberg	E. Chattian	28	1	48.6	86.2		15	11		82	20.6
3 Angarth	Up. Rupel	29	1	57.4			3			100	28.4
4 Lechbruck	E. Chattian	28	1	23.9	46.7		7	8		44	−4.1*
5 Murnau	E. Chattian	28	1	45.1	112.2		21	27		86	17.1
6 Bergern	L. Egerian	22	1	39.1	54.2		2	21		14	17.1
7 Traunstein	Aquitanian	22	1	25.8	58.3		8	19		88	3.8
8 Traunstein	Aquitanian	22	1	23.8	55.1		4	27		46	1.8
9 Hochgrat	Aquitanian	22	1	34.2	44.1	68.3	12	3	*4*	66	12.2
10 Langen	Burdigalian	19	1	22.4			2			100	3.4
11 Bergern	Burdigalian	19	1	34.1	73.2		12	9		80	15.1
12 Lochen	Burdigalian	19	1	35.5			2			100	16.5
13 Wachtberg	Burdigalian	18	1	23.8	37.9		3	13		34	5.8
14 Nußdorf	Ottnangian	19	1	26.9	63		7	32		45	7.9
15 Langen	Ottnangian	18	1	18.4	36.6		5	8		78	0.4
16 Niederaichbach	L. Badenian	13	1	14.3	51.8		4	19		13	1.3
17 Munderfing	Sarmatian	12	1	11.8	27.6		2	15		31	−0.2
18 Adelegg	Sarmatian	12	1	29.2			1			100	17.2

Sedi.: age of sedimentation; Unc.: uncertainty of sedimentation age; M1–M3: mean values of the age components; sd1–sd3: standard deviations of the components; %c1: fraction of the youngest component; *: the sample underwent a mild thermal overprint.

classes display some random scatter of few grains with ages apparently younger than the age of deposition. This, however, is no indication for partial resetting. As an exception, sample no. 5 requires a special treatment, because it derived from the imbricated "folded molasse" along the Alpine front. Teichmüller and Teichmüller (1975) and Kuckelkorn et al. (1990) reported a weak thermal overprint of these strata. The vitrinite reflectance data up to 0.55 VR_0 % indicate a mild post-sedimentary thermal event which may have caused minor rejuvenation and thus partial resetting of the detrital apatite ages. All other surface and borehole samples have not been thermally overprinted, due to extremely low heat flow in the Molasse Basin (Malzer et al., 1993; Sachsenhofer, 2001).

5.1. Detrital cooling ages from the Paleo-Inn deposits

The Alpine depositional record in the eastern Molasse Basin covers the time from ~33 to ~8 Ma. Our samples span the time from 28 to 12 Ma depositional age. Most important thermochronological information is deduced from fan delta deposits of the Paleo-Inn river, which drained the most rapidly exhuming western interior parts of the Eastern Alps. For reference of a non-Alpine AFT age spectrum, an Eocene sandstone recovered from a drill core has been studied (Fig. 4, sample 1). Facies distribution in the Eocene suggests a derivation of this detritus from the north, from the Bohemian Massiv (Malzer et al., 1993). A derivation from the Bohemian Massiv is also supported by Variscan to Permian zircon FT ages. The low dispersion, the passing of the chi-square test, and the compact apatite FT age distribution reflect a single source with a cooling age of c. 160 Ma. This age matches with the onset of formation of the South Penninic ocean floor and probably this rifting process was responsible for the reset of the apatite FT chronometer in the Bohemian Massif.

A distal Chattian sandstone of the Inn fan reflects a complex age provenance (Fig. 4, sample 2). The component analysis indicated two age clusters (49 and 86 Ma; see Table 2). The dominant age component reflects Eocene cooling in the source region, but Late Cretaceous AFT cooling ages typical of metamorphic Austroalpine units are also present (Hejl, 1997). Such ages are found also in Early Oligocene relics of siliciclastic cover sequences in the Northern Calcareous Alps (Augenstein deposits; Frisch et al., 2001) and the so-called intramontane deposits of the lower Inn valley (Kuhlemann and Kempf, 2002; Dunkl et al., in press).

The apatite single grain ages in proximal Paleo-Inn fan deposits of the lower Inn valley (~27 Ma depositional age; Fig. 4, sample 3) form a single age cluster according to the chi-square test, thus we suppose a geodynamically homogeneous source region is dominated by Paleocene apatite FT ages. The Paleocene and Eocene ages are typical of the topmost layer of Austroalpine crystalline units in the eastern part of the Eastern Alps (Hejl, 1997; Balogh and Dunkl, 2005),

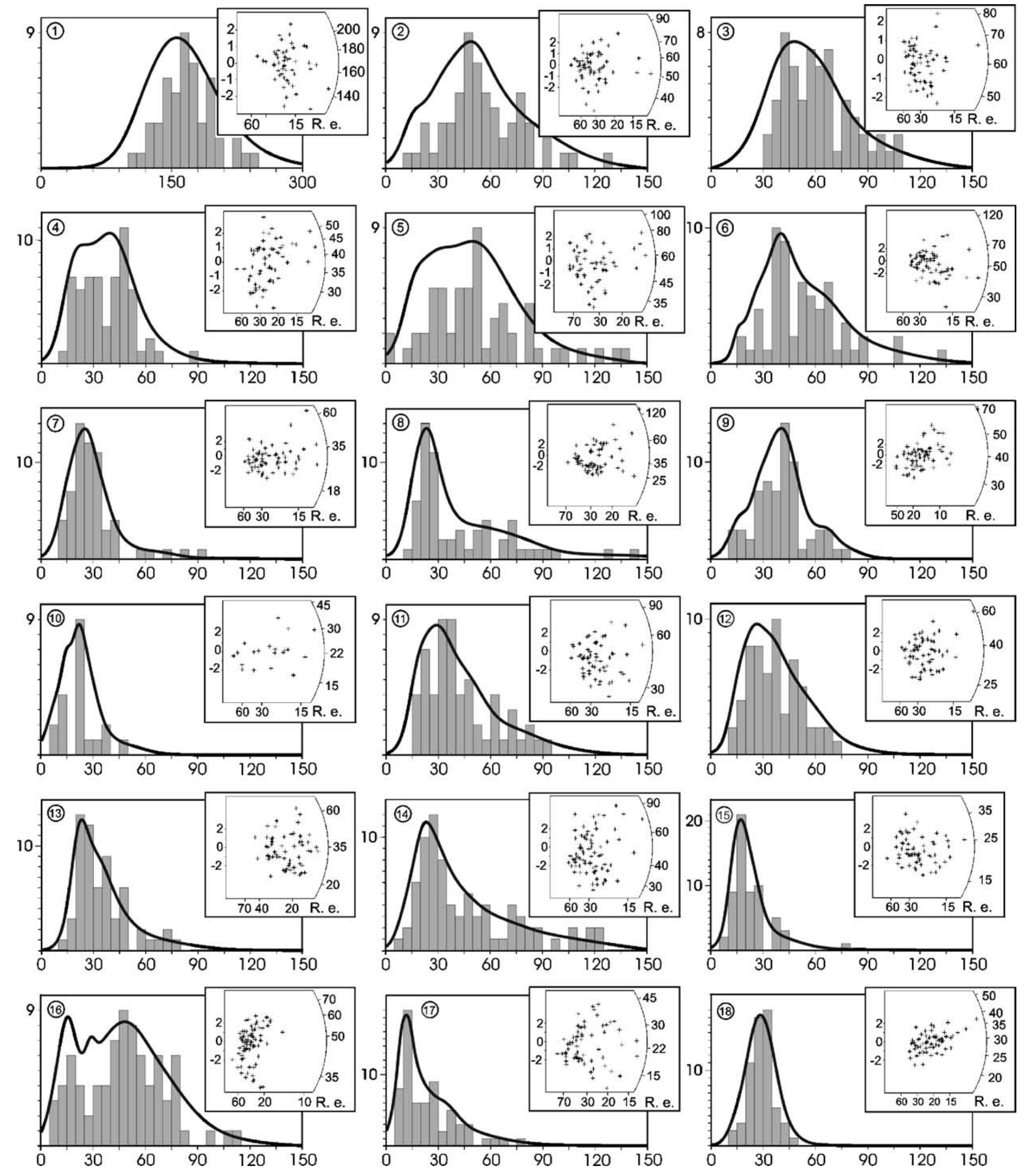


Fig. 4. Single grain apatite FT age distributions of the molasse samples presented in age spectra and radial plots. Age spectra (black lines) were created according to Hurford et al. (1984).

and is a widely spread signal also in the Western Alps (Carrapa et al., 2004).

Aquitanian sandstone samples and gneiss pebbles of the Paleo-Inn (~22 Ma depositional age; Fig. 4, samples 7 and 8) uniformly display mean apatite cooling ages slightly older than the age of deposition, and thus a supply from a fastly cooling crystalline source. Marker pebbles in this occurrence, e.g., of greenish granite from an Austroalpine massiv in the SW, indicate that the Paleo-Inn captured Austroalpine crystalline source regions in the immediate vicinity of the Oligocene intrusives lined up along the Periadriatic lineament (Brügel, 1998). The aforementioned older AFT age groups (Cretaceous, Eocene) are still present. Their subordinate presence reflects an ongoing destruction of the highest erosional level which was not affected by Noegene thermal overprint.

Early Burdigalian distal sand samples from the deep marine Puchkirchen formation (Fig. 4, samples 11–13) show variable mixtures of younger and older age components (c. 22 and 35 Ma, respectively, see Table 2). The samples still show a subordinate cluster of Late Cretaceous and some randomly scattered older ages. According to recent cooling age pattern in the orogen (Fig. 2b) and former source terrains of the Oligocene Augenstein formation in the central Northern Calcareous Alps (Frisch et al., 2001), the pre-Tertiary ages probably derived from the eastern parts of the Paleo-Inn catchment. Gneiss pebbles of the Inn deposited in the late Burdigalian (~17.5 Ma; Fig. 4, sample 14) reflect a similar, but slightly younger age cluster as the Aquitanian gneiss sample (sample 8). These gneisses represent typical lithologies of the western Austroalpine basement present also in the modern Inn river bed, and the marker pebbles from the Bernina massiv are also present (Brügel, 1998).

By late Langhian time (~14 Ma depositional age) the youngest age component is only ~3 Ma older than the depositional age in distal foreland sands of the W-directed Paleo-Inn river (Fig. 4, sample 16), which according to marker pebbles (Brügel, 1998) included the catchment of the modern Salzach river (for location, see Fig. 1). The pebble assemblage includes the same phenotypes of gneisses as found in older fan deposits. Metasediments or ophiolites of Penninic sequences are not yet present in the pebble spectrum (Frisch et al., 1998). The AFT age spectrum of theses pebbles is dominated by a cluster of Oligocene and Eocene ages, and also subordinate Late Cretaceous ages. The older ages may represent the eastern parts of the Paleo-Inn catchment, since source terrains of this cooling age are still preserved at present whereas they are totally eroded in the western part. The young age component probably derived from thermally reset Austroalpine crystalline slices still covering the footwall of the Tauern window.

By late Serravallian time (~12 Ma depositional age), AFT age spectra of Paleo-Inn pebbles are dominated by cooling ages ~3 Ma older than the time of deposition. Ongoing erosion of above mentioned Austroalpine source terrains is indicated by a subordinate age component at 30 Ma, which is a common AFT cooling age in the presently exposed Austroalpine basement. The young age component is in line with rapid exhumation in the Tauern window (Fig. 4, sample 17). The presence of gneisses from the Tauern window has been demonstrated by Miocene K–Ar ages of pebbles, and characteristic petrography and geochemistry (Brügel, 1998).

In summary, the cooling history in a distinct catchment reflects the exposure of certain age clusters formed during large-scale thermotectonic events. Cooling age groups are explained by 4 major events: (1) a Late Cretaceous nappe stacking in Austroalpine units, (2) an Eocene short-lived thermotectonic event, (3) an Early Oligocene heating in the vicinity of Periadratic intrusives, and (4) Miocene tectonic unroofing of Penninic rocks of the Tauern window, which became exposed around 13 Ma.

5.2. Spatial variation and temporal evolution of East Alpine catchments

Comparison of spatial variations requires samples of roughly similar depositional age. In 4 selected time slices, we integrate data from sediments whose depositional ages are less than 3 Ma apart. These time slices comprise: (a) Early Chattian, (b) Aquitanian, (c) early Burdigalian, (d) late Langhian to Serravallian.

(a) *Early Chattian (~28 Ma):* Two AFT age spectra from the western study area (Fig. 4, samples 4, 5) represent the coastal facies of the so-called "Baustein" beds, which were deposited immediately before a strong global regression at the Rupelian/Chattian boundary. Both AFT age spectra display a dominant Eocene age component and a subordinate synsedimentary age component probably related to Periadriatic volcanics. Although detrital apatites of these age components are likely derived from the Paleo-Inn, the signal is found in up to 100 km distance to the fan delta. A poorly constrained Late Cretaceous age cluster is also present, reflecting input from the highest Austroalpine units widely present in the eastern parts of the Alps by this time.

The age spectrum is quite similar to those found in apatite samples further to the east.

A basin-scale mixture of sand by shore-parallel transport reasonably explains this homogeneity. Hummocky cross stratification typical of the Baustein beds testifies for intense redeposition in a high-energy environment. Only sample 4 exclusively reflects age-provenance, since sample 5 suffered a mild thermal overprint.

(b) *Aquitanian (~22 Ma):* Sample no. 9 (Fig. 4) from the western study area is constituted of gneiss pebbles from the Silvretta massiv (Fig. 6b). The northern part of the Silvretta catchment had been captured by the Hochgrat feeder system by this time (Brügel, 1998). The fan delta of the Hochgrat catchment remained in the same location for the entire depositional history of the Molasse Basin (Brügel, 1998). Despite of the small size of the catchment within the Silvretta basement, three age groups can be distinguished. These comprise a minor Cretaceous age component, a dominant Eocene age component, and a subordinate Oligocene age component which probably derived from the northern boundary fault of the Silvretta massiv.

(c) *Early Burdigalian (~20 Ma):* Sample no. 10 records the first establishment of the Alpine Rhine in the Pfänder fan with an almost synsedimentary age component of rapidly exhuming fine-grained Penninic metasediments and unmetamorphic cover units (Brügel, 1998, with further references). Sample no. 15 from the same fan delta reflects further younging of the age component with younging depositional age of ~18 Ma. The lag time of about 3 Myr remains constant.

(d) *Late Langhian to Serravallian (~12 Ma):* Gneiss pebbles from the Hochgrat fan (Fig. 4, sample no. 18) displayed a uniform 30 Ma AFT age component, matching with a similar age component in the Paleo-Inn deposits in the east.

In summary, the spatial variation displays minor differences along strike since Early Miocene times. From 20 Ma on, synsedimentary AFT cooling ages are shed from tectonically unroofed Penninic footwall rocks of the Swiss Alps by the newly established Alpine Rhine river. Although Penninic rocks in the Eastern Alps were not exposed before 13 Ma, almost synsedimentary AFT cooling ages were shed from rugged Austroalpine source terrains in the vicinity of the Periadriatic plutons since 22 Ma. Minor spatial variation of AFT age components in sand samples from the Molasse Basin reflects variable, but generally strong amalgamation, due to basin-scale mixture of sand. In contrast, samples of pebbles of uniform phenotype enable a detection of distinct litho-terrains in the hinterland, e.g. by separation of Penninic gneisses of the Tauern window from Austroalpine source terrains with short lag time.

If AFT component ages are plotted versus time of deposition (Fig. 5A), accelerating denudation with time is nicely recorded. Around 22 Ma, rapidly enhanced denudation rates are reflected by a sharp decrease of the lag time of the youngest age component time to only 3 Myr (Fig. 5B). Around 18 Ma synsedimentary AFT ages reflect exposure of tectonically exhumed Penninic units in the Swiss Alpine core complex, which were incised by the newly established Alpine Rhine river along active faults (Frisch et al., 2001). Around 14 Ma, synsedimentary AFT ages were also shed from

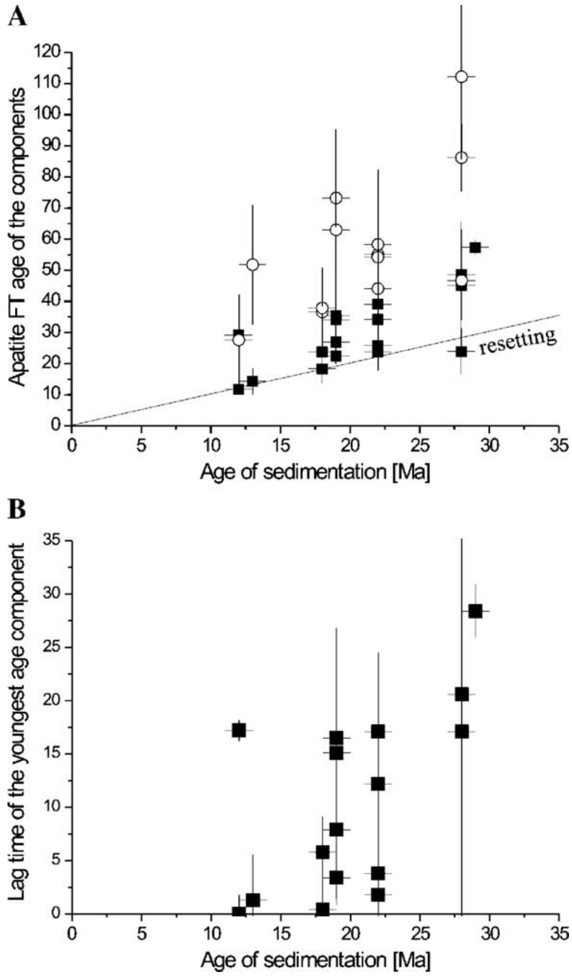


Fig. 5. (A) Relation of the age components and sedimentation age. (Black square: mean of the youngest age component, white circle: second and third age components.), (B) Drift of lag time with the sedimentation age.

the thin Austroalpine cover of the Tauern window into the Paleo-Inn river.

5.3. Spatial model of East Alpine catchment and source terrain evolution: a tentative synthesis

If available thermochronologic data from the Eastern Alps (Staufenberg, 1987; Hunziker et al., 1992; Axen et al., 1995; Hejl, 1997; Elias, 1998; Reinecker, 2000; Steenken et al., 2002) are combined with provenance data (Brügel, 1998; Brügel et al., 2000) and detrital thermochronology (Hejl and Wagner, 1989; Frisch et al., 2000a,b; Spiegel et al., 2000, 2001, 2004; Dunkl et al., in press; this study), erosion of distinct thermotectonic units of the Eastern Alps can be monitored from Early Oligocene until present. For a localisation of AFT age terrains and a full cover of the entire Eastern Alps, some interpretative assumptions have to be made. Our sketch maps of 4 time slices (Fig. 6a–d) integrate the palinspastic and paleogeographic reconstruction of Frisch et al. (1998, 2000a,b), basin evolution of Kuhlemann and Kempf (2002), and the aforementioned references. The reconstruction shows only gradual erosion of Cretaceous AFT age terrains and increasing exposure of rocks with Eocene and Oligocene AFT ages in the Eastern Alps from 28 to 20 Ma, whereas in the Swiss Alps more rapid erosion exposed Penninic rocks of the Lepontine dome already between 21 and 20 Ma (Spiegel et al., 2004). Extremely rapid changes of exposed AFT source terrains affected the Eastern Alps between 20 and 13 Ma: The distribution reflects a minimum in lag time and an age pattern which largely matches the modern one (Fig. 2b). Source terrains of very short lag times are not restricted to the core complexes, but also occur along the Periadriatic intrusives, where rivers draining southward with steep gradients captured the former headwaters of the Paleo-Inn, facilitating rapid incision (Kuhlemann, 2000). Local crustal extension, regionally high heat flow and uplift also caused very short lag times at the southeastern corner of the Eastern Alps. The period between 20 and 13 Ma includes the most rapid palinspastic, geomorphic and thermochronologic changes in the younger history of the Eastern Alps. Since 12 Ma, gradual changes driven by moderate but increasing erosion rates slightly modified the pattern acquired in the Early and Middle Miocene.

6. Discussion

Late Cretaceous cooling ages were generated during thermal relaxation after the climax of the Eoalpine orogeny, exhumation of core complexes (Frank et al., 1987) and local extension (Wagreich, 1993). The Eocene cooling age component is poorly understood

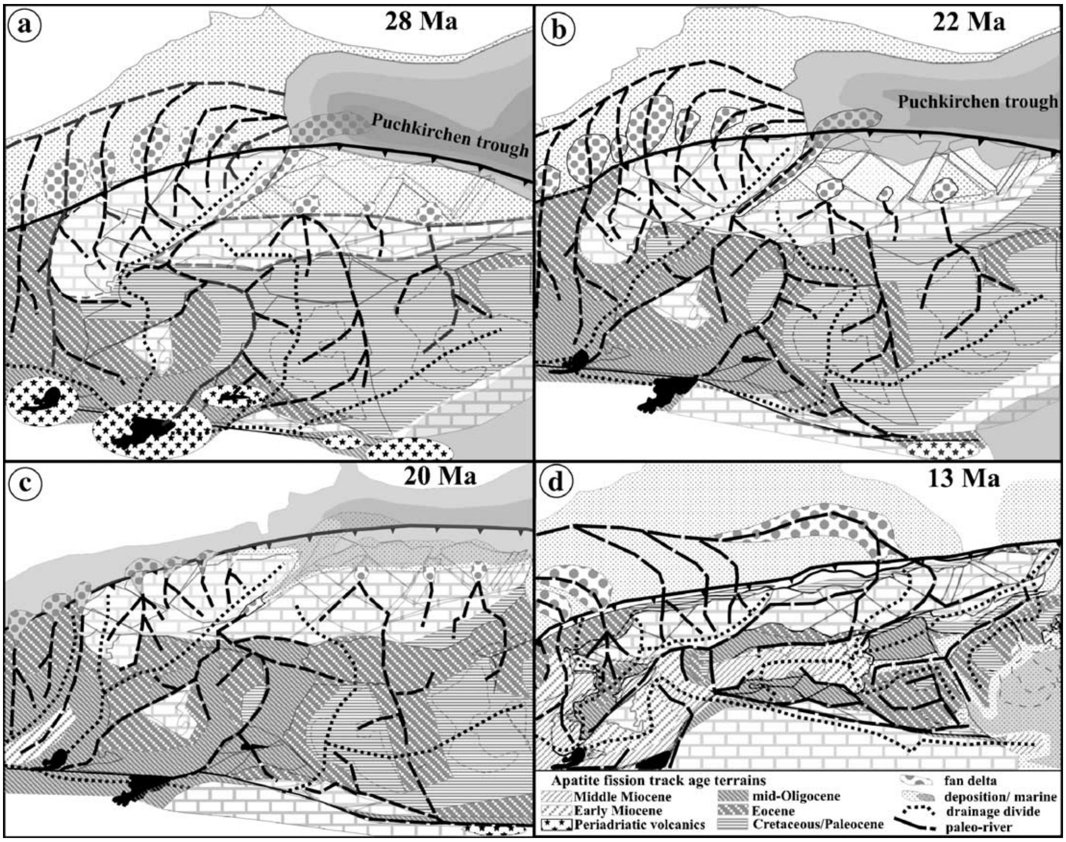


Fig. 6. Paleogeographic maps of the Eastern Alps with simplified interpretative distribution of apatite fission track age groups during the: (a) Chattian, (b) Aquitanian, (c) early Burdigalian, (d) Serravallian. For orientation, some tectonic lines and recent margins of carbonate and low-grade metamorphic terrains are outlined (see Fig. 2). Dashed lines show inferred drainage divides and major paleo-rivers. Regions of terrestrial and marine deposition in the Eastern Alps and the central-eastern Molasse Basin are outlined according to Kuhlemann and Kempf (2002). The shapes of the Alps and internal tectonic blocks are based on palinspastic restorations of Frisch et al. (1998, 2000a,b). Note that the arrangement of tectonic blocks changes with time.

(Dunkl et al., in press), but it is most likely related to the Eocene orogenic event, which is well recorded in large parts of the Eastern Alps.

Early Oligocene cooling ages are related to a combination of substantial exhumation in the course of Alpine collision and mantle upwelling related to slab breakoff (Frisch et al., 1998). Early Oligocene slab breakoff perturbated isotherms up to the topmost crustal layer along the Periadriatic Lineament (Von Blanckenburg and Davies, 1995). As a result of this short-lived pulse of heatflow, a small but thick upper crustal layer supplied detritus of similar cooling age from the Late Oligocene until present times (Dunkl et al., 2001). Average erosion rates since Late Eocene collision, ranging between 100 and 300 m/Myr (Kuhlemann, 2000), were too low to explain AFT age clusters. Miocene cooling ages reflect rapid crustal extension along strike and lower-plate tectonic exhumation (Frisch et al., 2000a).

By c. 14 Ma, footwall rocks from the Tauern metamorphic core complex and covering basal Austroalpine tectonic slices became exposed. Although the core complex was progressively deeper incised, it yielded constant AFT cooling ages of ~17 Ma for several million years. This thermal signature was created by rapid exhumation of hot footwall rock (Cliff et al., 1985). Exhumation decelerated in the final phase of E–W extension around 13 Ma (Frisch et al., 2000a). This deceleration of exhumation supported thermal relaxation. As a result, lag times of AFT cooling ages increased from 3 Myr to more than 6 Myr during the Late Miocene. At present, AFT cooling ages of 6 Ma are exposed in the western Tauern window (Grundmann and Morteani, 1985; Axen et al., 1995; Most, 2003), indicating that the trend towards increasing lag time has stopped. This is in line with accelerated surface erosion since about 4 Ma before present in the entire Eastern Alps and especially in the Tauern window (Kuhlemann, 2000). The increase of erosion rates since the Late Pliocene is coeval with a global trend, governed by increasingly rapid climate oscillations (Peizhen et al., 2001).

In contrast to the Tauern window, Penninic cover of the Lepontine core complex in the Swiss Alps became already exposed by 21 to 20 Ma and contributed to the Paleo-Rhine river (Spiegel et al., 2000, 2001). This earlier exposure is facilitated by stronger surface uplift and erosion of the Swiss Alps in the Oligocene and Early Miocene (Schlunegger, 1999; Kuhlemann, 2003), which caused almost complete erosion of the Austroalpine cover units on the northern flank (Pfiffner et al., 1997). Oligocene low-angle normal faulting of the Turba mylonite zone at the top of the Penninic megaunit also contributed to exhumation (Nievergelt et al., 1996). By c. 14 Ma, low-angle normal faulting of the Simplon fault exposed deeper Penninic footwall rock (Frisch et al., 2000a,b).

Before 14 Ma, AFT ages in foreland deposits largely reflect erosion rates in the Eastern Alps. Nevertheless, exhumation of the Tauern window started already in the earliest Miocene (Grundmann and Morteani, 1985), but Penninic rocks from the window remained covered until 14 Ma (Frisch et al., 2000a,b). On the other hand, short lag times of AFT ages by ~22 Ma deceive rapid exhumation. The decrease in lag time in this case reflects erosion of crustal material affected by thermal perturbation in the vicinity of Periadriatic intrusives. Incidentally, erosion rates increased between 24 and 21 Ma (Kuhlemann et al., 2001b), but the small thermal perturbation created by the short-lived acceleration of erosion would require more than 10 Myr to reach the surface of the Eastern Alps at average erosion rates of less than 300 m/Myr. In case of zircon fission track dating of orogenic detritus, very high erosion rates exceeding 1 km/Myr over several Myr are required to monitor meaningful changes in lag time. Such high erosion rates are not present in the Alps (Kuhlemann, 2000). For a detection of thermal perturbations in the eroding crustal profile, two thermochronometers of different closure temperature are required.

7. Steady-state exhumation in the Alps?

Interpretations in terms of exhumational steady state of an orogen require independent evidence of provenance, in order to ensure that the observed cooling pattern is related to a single source region and to rule out volcanic contribution.

In the Alps, evidence of catchment reorganisations, fan delta migrations, spatially and temporally restricted thermal perturbations, and volcanic input enable to select well-documented catchments and related feeder systems to test assumptions of steady-state exhumation. In the Eastern Alps, periods of possible post-collisional steady-state exhumation may have occurred in the Early and the Late Miocene for a few million years (Fig. 7). This is, however, not reflected by thermochronology, but by the faster-responding sediment budget. In the latter period, the Western Alps may have been in an exhumational steady state as well.

In the most rapidly exhuming cross section of the Swiss Alps, between western Aar massiv, Simplon fault, and western Lepontine dome, steady-state exhumation may have operated since ~15 Ma (Bernet et al., 2001).

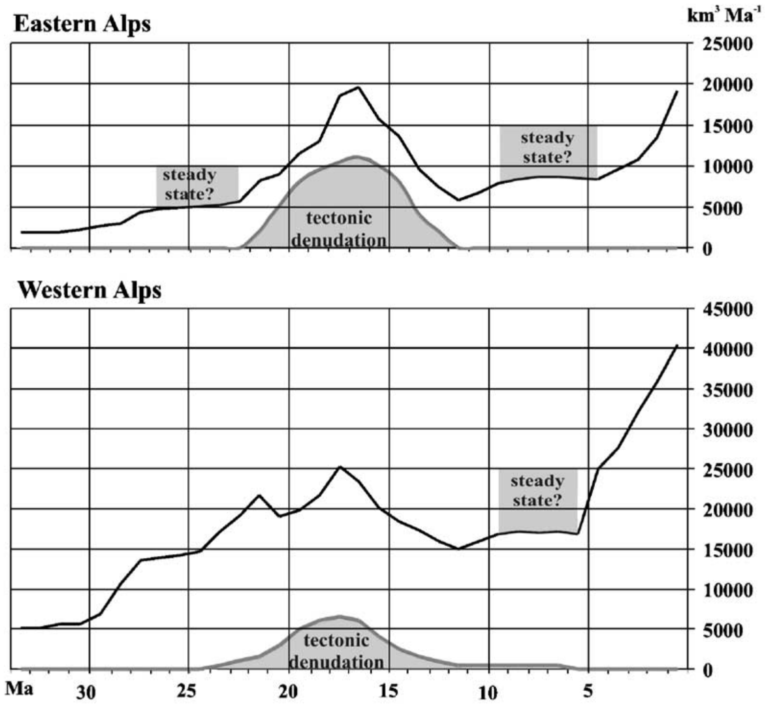


Fig. 7. Bulk denudation rates (in volumes of solid rock of $\delta = 2.7$ g/cm^3 in km^3/Ma) of the Eastern and Western Alps, separated for erosion and tectonic denudation. Periods of potential steady-state denudation are marked in grey.

However, this results from incidentally decreasing rates of tectonic exhumation and coevally increasing rates of erosion in terminal Miocene time (Kuhlemann et al., 2001b). Before 15 Ma, even in this cross section a change in lag time is documented (Spiegel et al., 2004).

In order to trace steady-state exhumation, it is more feasible to combine thermochronologic data both from recent exposures and from the detrital record in the foreland basin with sediment budget data (Kuhlemann et al., 2001b). Bulk erosion in the Alps tentatively adjusts within a few million years for geodynamic changes, much faster than the related thermochronologic response formed at depth is exhumed to the surface. If sediment budget data from the Alps are combined with thermochronologic data from the core complexes to differentiate for erosional and tectonic denudation (Fig. 7), short periods with fairly stable exhumation rates, approaching steady-state exhumation, are detectable. In the beginning of the Late Miocene, the youngest AFT cooling ages are hardly decernable from the age of sedimentation, whereas recently exposed rocks in the western Tauern window yield a minimum age of 5 Ma (Most, 2003). In the case of zircon fission-track cooling ages, lag times of 6 to 8 Myr at the beginning of the Late Miocene (Frisch et al., 1999) are lower than recently exposed minimum cooling ages of 11 Ma (Most, 2003). Thus, increasing lag times of apatite and zircon fission-track cooling ages in the last 11 Myr deceive decreasing rates of exhumation, whereas in fact erosion rates increase rapidly around 4 Ma after ~6 Myr of stagnation.

In the Eastern Alps, the decreasing lag time reflects fairly slow exhumation of rocks affected by a thermal perturbation created by Early to Middle Miocene tectonic exhumation. In the central cross section of the Swiss Alps, a similar trend is camouflaged by the incidental decrease of tectonic exhumation and increasing rates of erosion in terminal Miocene time at a much higher level than in the Eastern Alps. This local coincidence in the central Swiss Alps is not representative of the entire Alps. The Alps, similar to many other orogens, probably adjusts to internal and external forcing within a lag time of few million years and approaches steady-state exhumation, but important reorganisations of several forcing mechanisms during tens of million years of orogen evolution disturb steady-state conditions.

8. Conclusions

Detrital thermochronology in the eastern Molasse Basin mirrors erosion of terrains which are characterised by distinct apatite fission track age groups.

These age groups formed during geodynamic events which caused high heat flows for varying periods of time. Source terrains characterised by distinct AFT age patterns formed a patchwork in the Swiss and Eastern Alps, which was generated during a complex history of thrusting, faulting, and differential uplift and erosion. This complex history does not fit into a simplified concept of steady-state exhumation, as proposed by Bernet et al. (2001). Tectonic exhumation of core complexes is recorded by detrital thermochronology, but a differentiation of such material from other fastly cooled terrains requires additional geochemical and petrographic evidence. Samples from fan deposits record a sudden decrease in lag time when lower plate rocks became exposed. A subsequent increase in lag time thereafter results from the termination of extension and tectonic exhumation.

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