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Toward a comprehensive provenance analysis: A multi-method approach and its implications for the evolution of the Central Alps

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ABSTRACT

In this study, we discuss potential problems connected with using geochronological data from foreland basins to unravel exhumation histories of the hinterland. In particular, we compare the results of a provenance analysis solely based on zircon fission-track ages from the foreland basin with a multi-method approach based on (i) the aforementioned zircon fission-track data, (ii) Nd isotope ratios of detrital epidote, and (iii) sediment accumulation rates in the foreland basins. For the example of the Central European Alps, we demonstrate that the multi-method approach can lead to highly different interpretations in terms of hinterland exhumation and geodynamic evolution. This is due to the fact that fission-track dating on detrital zircons alone only monitors the exhumation and erosion of zircon-containing lithologies and therefore only of restricted areas of the hinterland while the combination with Nd isotope ratios on detrital epidote also includes the erosion of zircon-free or -poor units such as basic magmatic rocks. A comparison of zircon fission-track and epidote Nd data with the sediment accumulation curve shows whether hinterland exhumation was predominantly caused by tectonic or by erosional denudation. Furthermore, we discuss some problems that may arise from using geochronological data from foreland basins to assess the maturity of a mountain belt in the hinterland. Applied to the Central Alps, our combined approach shows that the metamorphic core became exposed simultaneously over large areas by one sudden pulse of exhumation between 21 and 20 Ma. The main trigger for that exhumation event was tectonic denudation which is consistent with a geodynamic setting of large-scale extension. The Central Alps did not achieve exhumational steady-state conditions before 14 Ma.

Keywords: zircon fission-track dating, Nd isotopic signature, sediment budget, Swiss Molasse Basin, steady-state exhumation.

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INTRODUCTION

Dating detrital minerals from synorogenic sediments has turned out to be a powerful tool for the reconstruction of long-term thermal and denudation histories of mountain belts (e.g., von Eynatten et al., 1999; Köppen and Carter, 2000; Krapez et al., 2000). For this approach, the most frequently dated minerals are white mica ($^{40}Ar/^{39}Ar$ dating) and zircon (U/Pb, fission-track, and (U-Th)/He dating), because both minerals are relatively stable against chemical alteration by weathering and mechanical destruction during sediment transport. Zircon especially can survive several cycles of redeposition. With closure temperatures of 420–350 °C for $^{40}Ar/^{39}Ar$ white mica dating (McDougall and Harrison, 1988; Kirschner et al., 1996) and ~240 °C for zircon fission-track dating (Hurford, 1986) the minerals give information on the thermal evolution of the upper crust during mountain building processes and are likely to retain their provenance signal during burial in most sedimentary settings. However, reconstructions of orogenic evolutions based exclusively on dating detrital zircon and/or white mica bear the following problems.

1. Both minerals are absent or occur only in very small amounts in basic magmatic lithologies. Therefore, the erosion of ophiolitic units, for example, will not be monitored. Metabasic rocks in general and ophiolitic rocks in particular are important components of orogens and are often associated with suture zones. Neglecting them may lead to incomplete or even wrong interpretations in terms of geodynamics.

2. Dating detrital minerals from foreland basin sediments basically yields average cooling rates integrated over a certain drainage area and cooling period in the hinterland. If the paleo-geothermal gradient is known, these cooling rates can be transformed into exhumation rates. However, exhumation rates are not necessarily equivalent to erosion rates. Therefore, the detrital age record does not allow estimating how much exhumation is due to erosional denudation and how much has to be attributed to tectonic denudation.

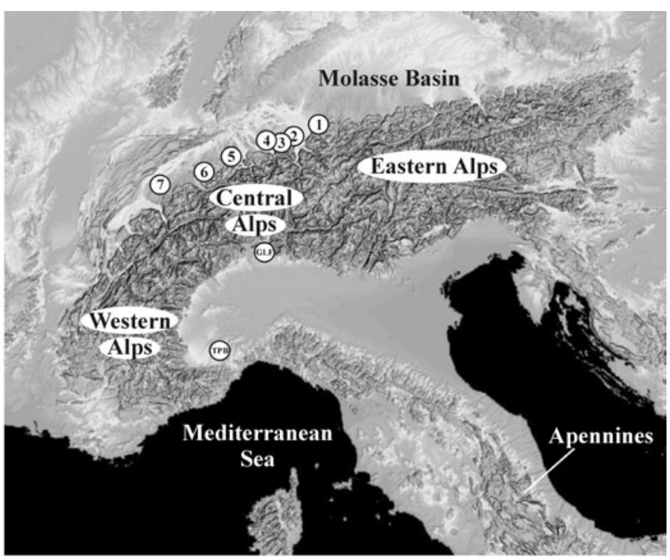


Figure 1. Digital elevation model of the Alps and the adjacent regions (Székely, 2001). Numbers refer to the different studied sections of the foreland basin. See also captions of Figure 2. GLF—Gonfolite Lombarda Formation; TPB—Tertiary Piedmont Basin.

This study aims to meet these problems by combining fission-track data of detrital zircons with Nd isotope analyses of detrital epidotes and sediment accumulation data from the foreland basins. The Nd data allow specifying the provenance of epidote and thus give evidence for the erosion of epidote-bearing ophiolitic rocks in the hinterland, while the sediment accumulation data provide an estimate for the amount of material removed from the source area by erosion alone. For the example of the Central Alps and their northern foreland basin, we will discuss advantages and disadvantages of each method and highlight the different interpretations resulting from a single-method approach compared to a multi-method approach.

GEOLOGICAL SETTING

Central Alps

The Central Alps (Figs. 1 and 2) basically consist of three different tectonic mega-units: the Austroalpine units at the top, thrust over Penninic units, which in turn overlie the Helvetic units (Figs. 2 and 3). Austroalpine units represent the former margin of the African continent. Penninic units comprise continental crust as well as oceanic remnants. Ophiolitic rocks are frequent (Fig. 3), especially at the top of the Penninic sequence. These ophiolites are remnants of the South-Penninic ocean, which was situated between the European and the African continent. The Helvetic units belong to the former southern margin of the European continent. Each of these units experienced an individual metamorphic and tectonic history. In this study, we present only a short, simplified outline and refer to Steck and Hunziker (1994) and Schmid et al. (1996), for example, for more detailed information.

Only the Austroalpine units, which are widely exposed in the Eastern Alps but only sparsely preserved in the Central Alps, experienced an early orogenic phase in Cretaceous times, which culminated in metamorphism up to eclogite and amphibolite facies at ca. 100 Ma in parts of the eastern Alpine crystalline basement (e.g., Thöni, 1981; Frank et al., 1987). During the Tertiary orogeny of the Alps, the Austroalpine unit acted as a rigid orogenic lid (Laubscher, 1983) and remained largely undeformed. Therefore, zircon fission-track cooling ages of Austroalpine units mainly cluster between ~90–60 Ma (Frank et al., 1987; Hunziker et al., 1992). In contrast to the Eastern Alps, Cretaceous metamorphism of Austroalpine units in the Central Alps only reached temperatures around or slightly below the zircon fission-track closure temperature (Spiegel et al., 2001). Therefore, many older fission-track cooling ages (Variscan, Triassic, Jurassic, and Early Cretaceous) are also preserved.

The Tertiary orogeny involved ~500 km of north-south convergence between Africa and Europe and is characterized by

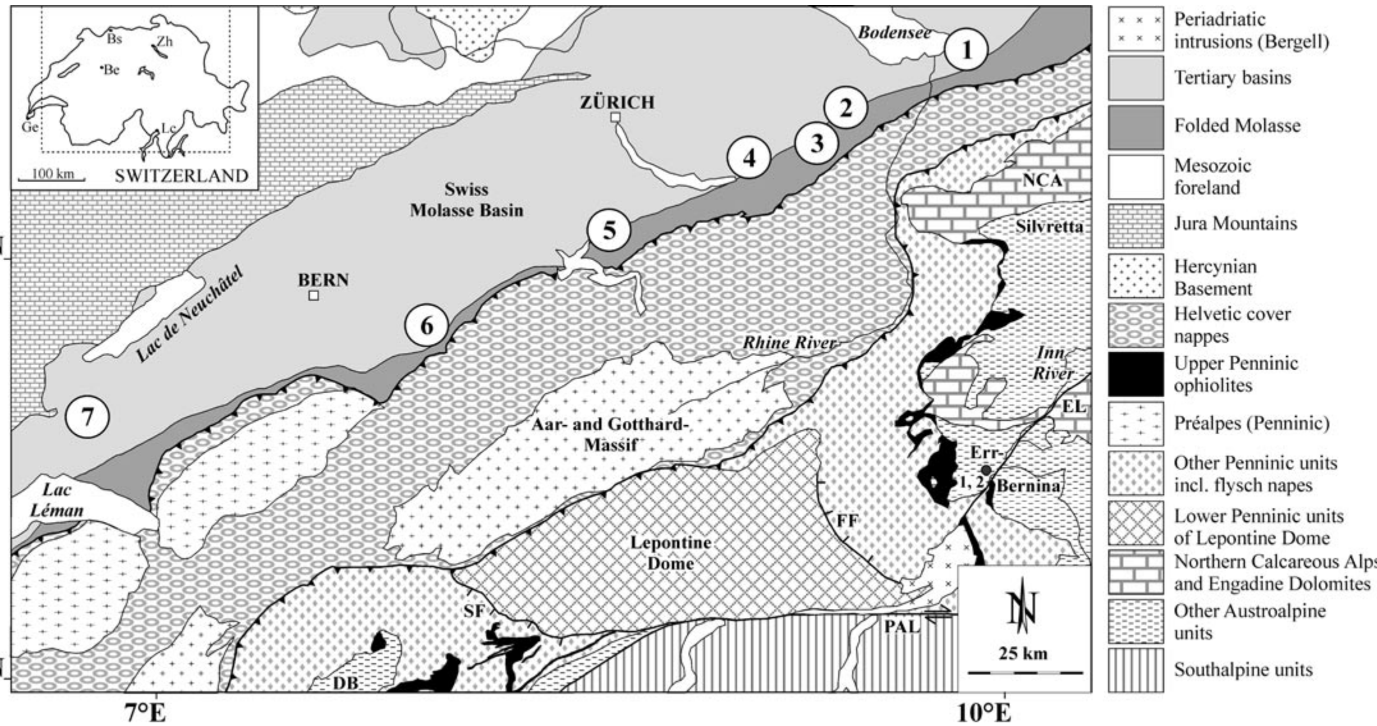


Figure 2. Geological map of the Central Alps and the Swiss Molasse Basin. Numbers refer to the different studied sections. 1—Pfänder system; 2—Kronberg-Gäbris system; 3—Speer system; 4—Hörnli system; 5—Rigi-Höhrone system; 6—Honegg-Napf system; 7—axial drainage system. NCA—Northern Calcareous Alps; DB—Dent Blanche unit; SF—Simplon normal fault; FF—Forcola normal fault (Meyre et al., 1998); PAL—Periadriatic lineament; EL—Engadine line. Inset: Bs—Basel; Be—Berne; Zh—Zurich; Ge—Geneva; Lc—Locarno.

top-to-the-north and north-northwest movements (Schmid et al., 1996). Between ~65 and 35 Ma, convergence, subduction, and finally, continent-continent collision took place with the Austroalpine units acting as overriding upper plate and the Penninic units as downgoing lower plate (see Figure 4). At ca. 45 Ma, the subducting slab is assumed to break off, resulting in an upwelling of the asthenospheric mantle (Davies and von Blanckenburg, 1995). The subsequently upward migrating heat front caused melting in the lithospheric mantle. Magmatic activity first took place in Eocene times (Villa, 1983; Dunkl, 1990) and culminated between 32 and 30 Ma (von Blanckenburg, 1992). During this time, the Bergell plutonic body intruded, and volcanic activity was widespread in the area of the Periadriatic lineament (Fig. 2; Ruffini et al., 1997; Brügel et al., 2000). Magmatic activity was accompanied by enhanced heat flow (Davies and von Blanckenburg, 1995), affecting large areas of the present-day Central and Western Alps and resetting parts of the Austroalpine basement of the Western Alps (Hurford et al., 1991; Dunkl et al., 2001).

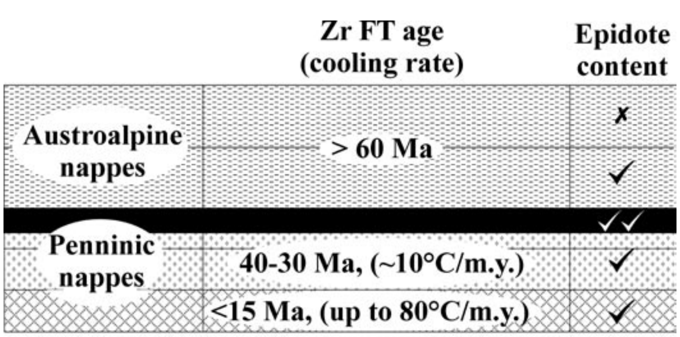


Figure 3. Highly schematic sketch of the Austroalpine-Penninic nappe system and some of its important characteristics concerning zircon fission-track (Zr FT) ages, mid-Tertiary cooling rate, and epidote content. For legend see Figure 2.

Between 40 and 30 Ma, the Penninic units of the Central Alps underwent greenschist to amphibolite-facies metamorphism (Steck and Hunziker, 1994; Gebauer, 1999), resulting in Oligocene or younger cooling ages (Hunziker et al., 1992). The lower Penninic units form the Lepontine structural dome (Fig. 2), which yields zircon fission-track cooling ages mainly younger than 15 Ma, and experienced fast cooling during mid-Tertiary times with rates up to 80 °C/m.y. (Hurford, 1986). In contrast, the cooling rates of the upper to middle Penninic hanging wall of the dome are only in the range of 10 °C/m.y. for the same time (Markley et al., 1998; Fig. 3). Our study focuses on timing and processes that led to the successive removal of the Austroalpine upper plate and the exposure of the Penninic lower plate

Swiss Molasse Basin

The Swiss Molasse Basin is a flexural basin formed due to tectonic loading of the evolving Alps. Coarse molasse sedimentation started in late Rupelian times (ca. 31 Ma) and lasted until at

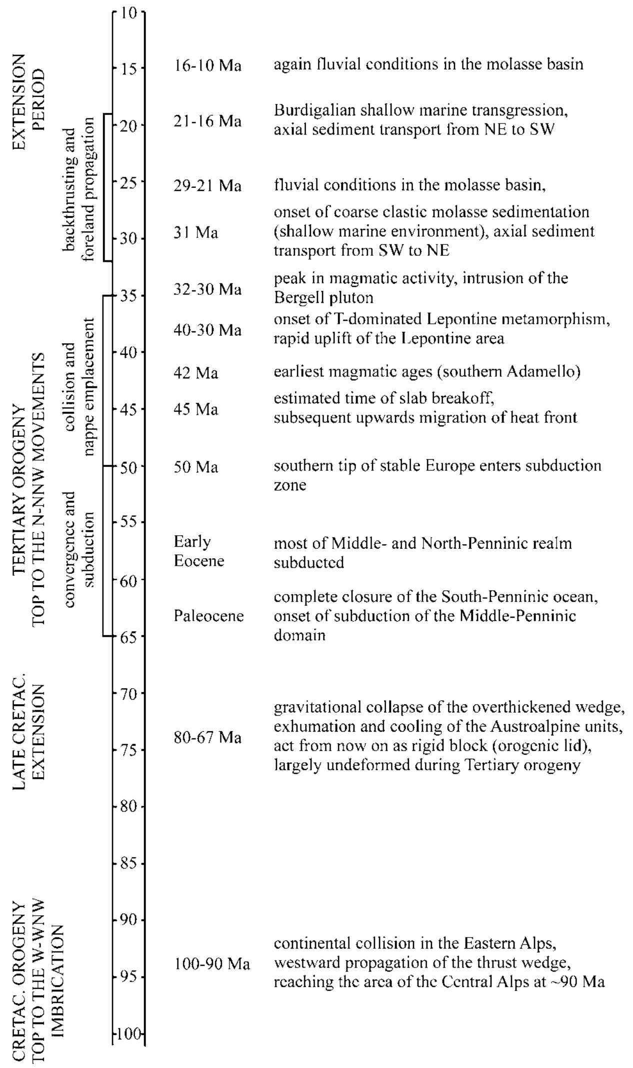


Figure 4. Simplified evolution of the Central Alps and the Swiss Molasse Basin after Schmid et al. (1996, Cretaceous and Tertiary orogeny), Davies and von Blanckenburg (1995, slab breakoff and magmatism), Steck and Hunziker (1994, Lepontine metamorphism), Gebauer (1999, Lepontine metamorphism), Frisch et al. (2000, Tertiary extension), Matter and Weidmann (1992, molasse evolution).

least Langhian to Serravallian times (Pfiffner, 1986; Matter and Weidmann, 1992). The sedimentary succession is characterized by two coarsening and shallowing upward sequences reflecting changes from shallow marine to fluvial environments. During the first sequence (Rupelian and Chattian times), the axial sediment transport was directed from southwest to northeast (e.g., Berger, 1996). During that early shallow marine stage, the molasse basin was connected to the Rhine graben in the north (Kuhlemann et al., 1999). The second sedimentary cycle (Burdigalian to Langhian/Serravallian) was associated with northeast-southwest directed currents along the axis of the basin (e.g., Berger 1996).

The proximal part of the molasse basin consists of large alluvial fan systems (Figs. 1 and 2) which are composed of conglomerates, sandstones, and mudstones (for more detailed descriptions, see, e.g., Tanner, 1944; Matter, 1964; Schiemenz, 1960; Schlunegger et al., 1998; Kempf, 1998). Major components of these conglomerates are flysch and limestone pebbles, but crystalline clasts (mainly granites, granitic gneisses, and quartzites) are also present in most of the fan systems. The most striking feature of the molasse sandstones is their heavy mineral compositions. While the older molasse sandstones mainly contain garnet, apatite, zircon, tourmaline and rutile, the younger sandstones show a pronounced change toward epidote dominance with up to 90% epidote of the total amount of heavy minerals (Füchtbauer, 1964, Schlunegger et al., 1997). This change happened diachronously in the molasse basin (i.e., several million years earlier in the western part of the basin than in the eastern part [Fig. 5; Schlunegger et al., 1997; Kempf et al., 1999; Strunck, 2001]). The provenance of the epidote is a long-standing problem in the literature. Most researchers attribute its occurrence to the onset of erosion of the upper Penninic ophiolites in the hinterland (e.g., Renz, 1937; Dietrich, 1969). Another possible source is greenschist-facies metagranites, which are common in the lower Austroalpine units (Füchtbauer, 1964).

In this study, we mainly focus on samples from the alluvial fan systems (sections 1–6 in Figure 2), because sediment input from sources other than the direct Alpine hinterland can be excluded, due to the proximity of the fans to the Alpine front. In the following, we refer to sections 1 to 3 as eastern fans, sections 4 and 5 as central fans, and section 6 as western fan. For local names, see caption of Figure 2. Only section 7 is situated in a more distal position within the axial drainage system of the basin.

THE MULTI-METHOD APPROACH

Zircon Fission-Track Dating

Method

The fission-track method is based on the spontaneous decay of uranium which causes defects in the zircon crystal lattice. At temperatures above ~240 °C (zircon fission-track closure temperature; Hurford, 1986) these defects or spontaneous fission tracks anneal after their formation while at temperatures below ~240 °C they are retained. Tracks are made visible by etching and are counted under an optical microscope at high magnification (>1000×). To determine their U-content, zircons are irradiated by thermal neutrons, which induces the fissioning of ^{235}U. The induced tracks are monitored and counted on a low-uranium mica detector, which is attached to the zircon mount during irradiation (external detector method; see Gleadow [1981] for more detailed description). From the ratio between spontaneous and induced track density, the time which has passed since the sample cooled below ~240 °C is calculated. The external detector method allows the dating of single detrital zircon grains. About 60 grains per sample are dated. From the attained age distributions, single age populations are derived by fitting to a set of Gaussian distribution functions (Brandon, 1992).

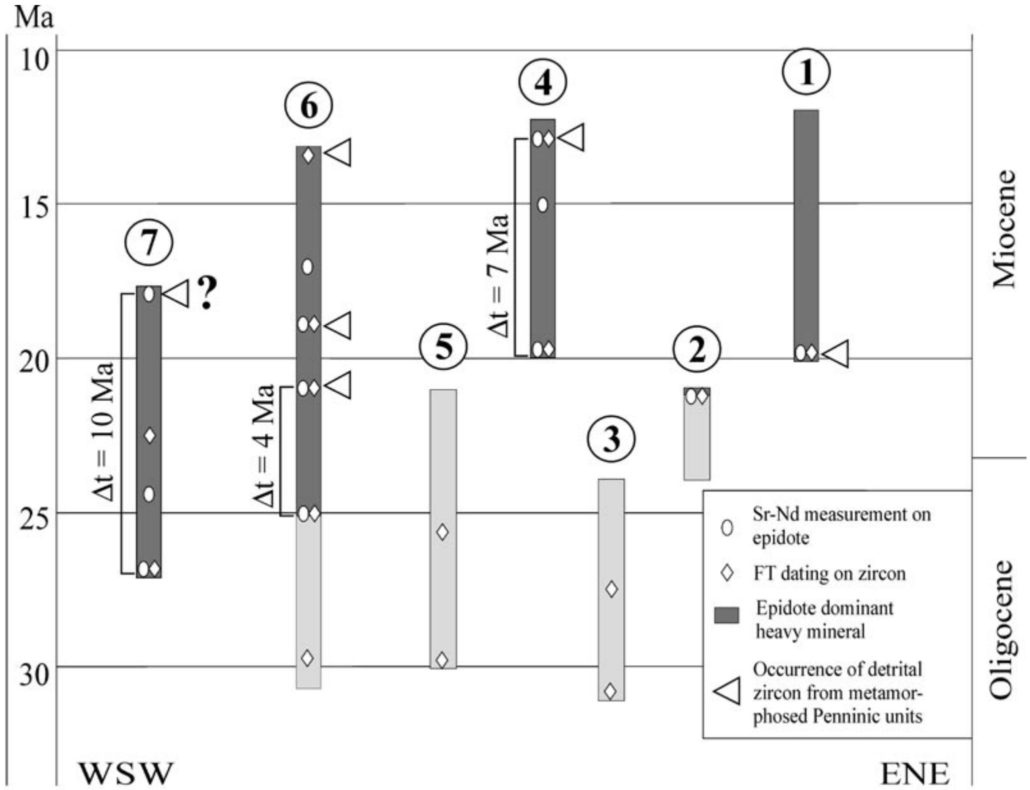


Figure 5. Temporal relationship of the different stratigraphic profiles from the Swiss Molasse Basin and the investigated samples therein. The columns symbolize the drainage systems of the Swiss Molasse Basin according to their east-west position and their time of activity. Stratigraphic positions of samples used for fission-track (FT) and Nd analyses are indicated, as well as the change of the heavy mineral composition and the first occurrence of zircons from the Penninic lower plate and the time difference between the two latter events (Δt). The youngest sample from section 7 is not dated by the fission-track method, but cooling ages of detrital white mica (von Eynatten and Wijbrans, 2003) suggest the presence of zircons derived from metamorphosed Penninic units.

To use zircon fission-track dating in provenance studies, the following requirements should be met. (1) The different tectonic units exposed in the hinterland should have contrasting age patterns. (2) For a precise timing of exhumation processes in the hinterland, a good stratigraphic control of the foreland basin sediments is important. (3) The postdepositional thermal history of the foreland basin sediments should be known to make sure that heating during burial did not reach the closure temperature of the dated mineral. (4) For samples from distal basin positions, information on paleocurrents and directions of sediment transport is needed for a correct interpretation of the sediment provenance.

For the Central Alps–Swiss Molasse Basin system all these prerequisites are fulfilled: With zircon fission-track ages <30 Ma and >60 Ma for Penninic and most of the Austroalpine units, respectively, cooling patterns in the hinterland are highly contrasting (Frank et al., 1987, Hunziker et al., 1992). Stratigraphic control is excellent due to biostratigraphic and magnetostratigraphic calibrations, except for section 1, which is only dated by biostratigraphy (Berger, 1992; Bolliger, 1992; Schlunegger et al., 1997; Kempf et al., 1997; Strunck, 2001). Errors for most of the stratigraphic ages are only in the range of a few hundred thousand years. Vitrinite reflection data (Schegg, 1992; Schegg et al., 1997; Erdelbrock, 1994) show that postdepositional temperatures were well below the zircon fission-track closure temperature. The foreland basin evolution in terms of sedimentology and paleogeography has been extensively studied (e.g., Pfiffner, 1986; Homewood et al., 1986; Berger, 1996; Kuhlemann and Kempf, 2002).

Results

Figure 6 shows the modeled fission-track age populations from the Swiss Molasse Basin (after Spiegel et al., 2000, 2001, 2002). The majority of the populations are of Triassic, Jurassic, and Cretaceous age. The relation of the pre-Cenozoic cooling ages to thermal events in the Alpine hinterland are discussed by von Eynatten et al. (1999), Spiegel et al. (2000), and Dunkl et al. (2001). They reflect the erosion of Austroalpine basement units and to a large part the recycling of sedimentary units in the hinterland. In this study, we focus on the Cenozoic cooling ages. They can be subdivided into (i) Eocene and (ii) Oligo-Miocene cooling ages.

(i) Eocene age groups in the molasse sediments cluster between 55 and 40 Ma (Fig. 6 and Table 1). Most of them contain only two to three grains, resulting in ill-constrained mean ages with large errors. Only in section 3 and 5 do Eocene age groups contain a significant number of grains (Fig. 6). Their

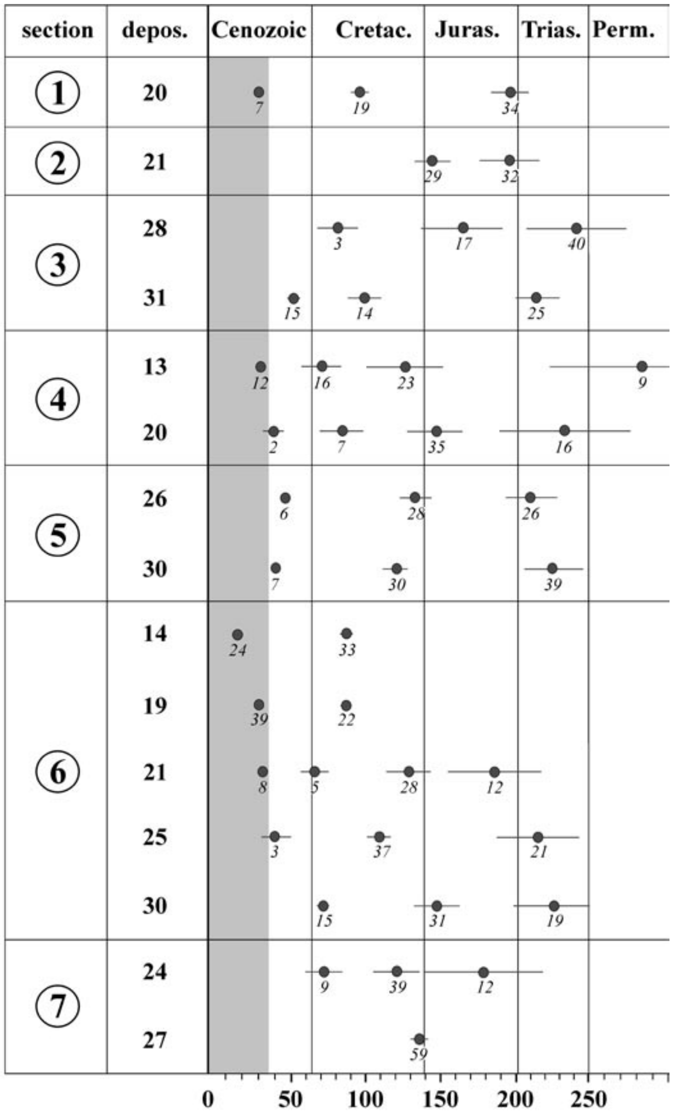


Figure 6. Modeled fission-track age groups of detrital zircons (given in Ma ±1σ) from the Swiss Molasse Basin listed according to section number and deposition age. The numbers in italics refer to the number of dated grains per modeled age group. The grey-shaded area shows the range of ages expected for zircons derived from the metamorphosed Penninic lower plate (= Oligo-Miocene ages). Modeling was performed by BinomFit (Brandon, 1992), based on the binomial model of Galbraith and Green (1990). For location of the dated sections, see Figures 1 and 2. Data is compiled after Spiegel et al. (2000, 2001, 2002).

interpretation is difficult because Eocene ages are scarce in the hinterland today. They could be related to an Eocene exhumation period (Dunkl et al., 2002) or to volcanic activity (Winkler et al., 1990; Dunkl, 1990). However, we suggest that the Eocene ages of the molasse sediments do not directly result from incision into a crystalline basement in the hinterland but are recycled ages due to the erosion of flysch nappes. This assumption is based on the following. (1) Incision into basement rocks should result in a detrital record with cooling ages becoming continuously younger upsection. Section 5 shows the opposite trend with the youngest age population becoming older upsection, while in section 3, the Eocene age group completely disappears upsection. (2) Dating of flysch pebble populations from the molasse basin showed that the flysch contains some zircon grains with ages between 50 and 40 Ma (Spiegel et al., 2000), similar to what is contained in the Oligocene molasse sandstone. Furthermore, flysch nappes from the present-day exposures of the Central Alps also contain an Eocene (volcanic) age component (Winkler et al., 1990). Therefore, we assume that the Eocene ages are recycled ages and do not give evidence on hinterland exhumation processes during the time of molasse sedimentation.

(ii) The first Oligocene fission-track cooling ages (32 Ma) are found in the easternmost and western fan (sections 1 and 6) with deposition ages of 21–20 Ma (Fig. 6). From the difference between fission-track age and deposition age, an average hinterland cooling rate of ~20 °C/m.y. is calculated. These young zircons are interpreted to be derived from the metamorphosed upper to middle Penninic units of the Central Alps and therefore reflect the exposure of the Penninic lower plate in the Central Alps. At the same time, the other sections (2 and 4, eastern and central fans) did not receive any Oligocene zircon grains. In a Middle Miocene sandstone of section 6 (14 Ma deposition age), zircons with fission-track ages of 20 Ma suggest an average cooling rate in the range of 40 °C/m.y. in the hinterland (Fig. 6). This cooling rate is too high to be derived from the erosion of the upper to middle Penninic hanging wall of the Lepontine Dome. Therefore, we assume that the lower Penninic Lepontine Dome became exposed in Middle Miocene times in the hinterland of the western molasse fan. At the same time the central fan system (4) did not receive zircons from the Lepontine Dome but from its hanging wall, as suggested by a fission-track age group of 32 Ma in the sandstones of this fan.

Discussion

As outlined in the introduction of this paper, exhumation histories solely based on age-provenance studies bear the risk of neglecting the erosion of lithologies, which are devoid of the dated mineral phase. In the following, we summarize an exhumation history of the Central Alps as suggested by the fission-track data; later, we compare this to an interpretation based on a combination of different methods. According to our fission-track data, the Penninic lower plate was exposed at 21–20 Ma in the hinterland of the easternmost and western fan and only several millions years later in the hinterland of the central fan. Exhumation leading to its exposure was apparently a process which took place diachronously over a long period of time. This would fit to a setting where moderate erosion is the driving force for exhumation.

If we compare the fission-track data with the heavy mineral compositions of the molasse sandstones, we find a considerable time gap of 4–10 m.y. between the first occurrence of large amounts of epidote and the occurrence of young zircons with Penninic provenance (Fig. 5). If the epidote is in fact derived from the erosion of upper Penninic ophiolites, then the exposure

TABLE 1: MODELED AGE GROUPS FROM FISSION-TRACK DATING ON DETRITAL ZIRCONS

Section no.	Sample code	Sediment age (Ma)	Modeled age groups (Ma ± 1s)			
			P1	P2	P3	P4
Swiss Molasse Basin						
1	212	20	32 ± 2 *n* = 7	99 ± –6 *n* = 19	— —	197 ± 12 *n* = 34
2	ZC 18	21	— —	— —	144 ± 12 *n* = 29	195 ± 18 *n* = 32
3	ZC 23	28	— —	81 ± 14 *n* = 3	165 ± 27 *n* = 17	240 ± 17 *n* = 40
	ZC 15	31	54 ± 4 *n* = 15	— —	100 ± 11 *n* = 14	213 ± 14 *n* = 25
4	ZC 12	13	32 ± 2 *n* = 12	73 ± 12 *n* = 16	126 ± 27 *n* = 23	282 ± 60 *n* = 9
	ZC 10	20	40 ± 6 *n* = 2	86 ± 15 *n* = 7	148 ± 16 *n* = 35	238 ± 42 *n* = 16
5	ZC 22	26	47 ± 3 *n* = 6	— —	137 ± 10 *n* = 28	213 ± 17 *n* = 26
	ZC 5	30	41 ± 3 *n* = 7	— —	121 ± 9 *n* = 30	224 ± 19 *n* = 39
6	ZC 3	14	20 ± 1 *n* = 24	87 ± 4 *n* = 33	— —	— —
	ZC 4	19	28 ± 1.2 *n* = 39	81 ± 5 *n* = 22	— —	— —
	ZC 6	21	32 ± 3 *n* = 8	67 ± 8 *n* = 5	129 ± 13 *n* = 28	187 ± 33 *n* = 12
	ZC 1	25	41 ± 9 *n* = 3	— —	112 ± 9 *n* = 37	215 ± 26, *n* = 21
	ZC 24	30	— —	75 ± 4 *n* = 15	152 ± 10 *n* = 31	275 ± 26 *n* = 19
7	ZC 37	23	— —	74 ± 12 *n* = 9	121 ± 16 *n* = 39	178 ± 37 *n* = 12
	ZC 36	27	— —	— —	137 ± 5 *n* = 59	— —
Gonfolite Lombarda Formation						
	ZC 17	ca. 15	31 ± 1 *n* = 50	48 ± 4 *n* = 9	— —	
	ZC 8	ca. 20	29 ± 1 *n* = 45	44 ± 4 *n* = 14	95 ± 29 *n* = 1	
	ZC 20	ca. 24	31 ± 4 *n* = 17	38 ± 2.5 *n* = 32	135 ± 15 *n* = 4	

of the lower plate would accordingly have taken place several million years earlier than recorded by the fission-track data. For the Central Alps, this would mean that conventional heavy mineral analysis give a much better clue about timing of exhumation processes in the hinterland than the geochronological approach. If, in contrast, the epidote is derived from greenschist facies lower Austroalpine metagranites, as suggested by Füchtbauer (1964), no contradiction between heavy mineral and fission-track data would result.

Nd Isotope Ratios on Detrital Epidote

Method

Nd isotopic ratios give evidence on a crustal or mantle origin of rocks and permit calculation of crustal residence ages. Nd isotope studies on sediments have been successfully used for provenance analysis (e.g., Richard et al., 1976; Miller and O'Nions, 1984; Basu et al., 1990; Henry et al., 1997; and, more recently, Najman et al., 2000; Clift et al., 2001; and Robinson et al., 2001). In most of the provenance studies, whole-rock data are used, but Nd ratios of pebbles or single mineral phases also turned out to be useful in attaining more specific information on distinct lithologies of the hinterland (see, e.g., Henry et al., 1997). In the Central Alps, we measured Nd ratios of detrital epidote because of the dominance of epidote in the heavy mineral spectra of the molasse sandstones (see Spiegel et al. [2002] for base data). However, in other orogen-sedimentary basin systems, it may make sense to combine geochronological data with isotopic signatures of other heavy mineral phases and/or whole-rock data.

In the hinterland of the Swiss Molasse Basins, two lithologies are potentially able to supply the huge amount of epidote: Austroalpine metagranites and Penninic ophiolites (Fig. 3). The different chemical compositions and origins of these potential source rocks should be reflected by their Nd isotopic signature. Because Nd isotope ratios had not been used before to specify the provenance of detrital epidote, we first tested how far this approach is suitable for our purpose (Spiegel et al., 2002). We sampled Penninic metabasitic and Austroalpine metagranitic rocks from the present-day exposures as well as metabasitic and metagranitic pebbles from the molasse basin, separated the epidote and measured the Nd ratios. In addition, we measured Sr isotopic ratios and a variety of trace elements. We found that the Nd data allow a very good distinction between the two different lithologies (Fig. 7), while the Sr ratios largely overlap. The contents of Ba, U, Rb, Nb, and Th correlate well with the εNd data (Spiegel et al., 2002). The good discrimination by Nd ratios was used to define a "crustal source" and a "mantle source" range.

Results

The results of the Nd measurements of the detrital epidote are plotted in Figure 7. Epidotes from Lower Miocene sandstones of sections 2 and 4 (eastern and central) clearly show a provenance from a metabasic source rock. Although these sandstones do not contain young zircons of Penninic provenance, the isotopic signature of the epidote points to an exposure of Penninic ophiolites in the hinterland. The western and the easternmost fan (sections 6 and 1—those which received "Penninic zircons" during Lower Miocene times) yield a more complex picture. The oldest epidotes (25 Ma deposition age) clearly plot within the crust-derived field and are therefore interpreted to be derived from lower Austroalpine metagranitic lithologies. This means that even though the first large amounts of epidote appeared in the molasse in Oligocene times (Fig. 5), the Penninic lower plate did not become exposed before the end of Oligocene times in the Central Alps. Epidote from the western fan (6), deposited at around 20 Ma, plots in an intermediate position. We interpret this to reflect a mechanical mixture of epidote derived from both Austroalpine metagranites and Penninic ophiolites. Although the detrital epidote looks basically homogeneous, we tried to verify this assumption by separating two different epidote populations from the sample of the easternmost fan (1). These two populations were distinguished due to slight differences in color, shape, and zonation (Spiegel et al., 2002). One population plots in the crustal source field while the other plots close to the mantle source field. This seems to corroborate the assumption of a mechanical mixture from two different sources. Epidote from the oldest sandstones from section 7 also plots in an intermediate position, which means that this part of the Swiss Molasse Basin received a mixture of granitic and ophiolitic detritus as early as 27 Ma. For the interpretation of this data, we have to consider that section 7 is situated in the axial drainage system of the basin with southwest to northeast directed currents. In the Western Alps, Penninic ophiolitic rocks were already exposed during Chattian to Aquitanian times (Mange-Rajetzky and Oberhänsli, 1982). Due to the currents prevailing in the molasse basin, we suggest that the epidote from section 7 was derived from the Western Alps, and was transported toward the east and redeposited in the foreland basin of the Central Alps.

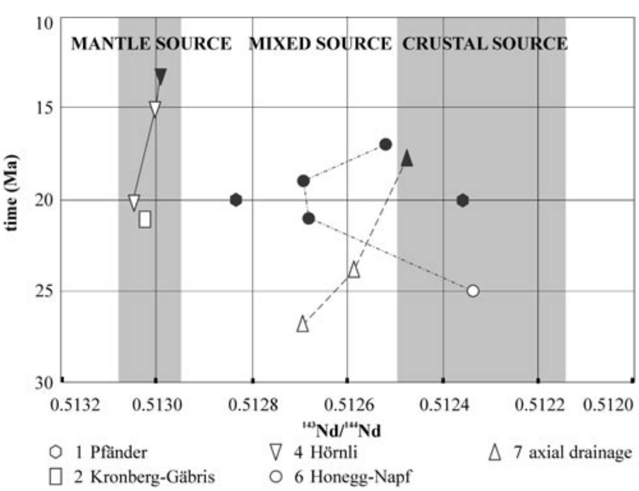


Figure 7. Variations of Nd isotopic ratios of epidote from the different molasse fans through time. Ranges of Nd ratios for the "mantle source" and "crustal source" fields are derived from measuring epidote from the present-day Penninic and Austroalpine hinterland as well as from ophiolitic and metagranitic pebbles from the Swiss Molasse Basin. Filled symbols indicate sandstones with reset zircon grains from the Penninic lower plate. Note that sandstones from section 3, 5, and 8 do not contain significant amounts of epidote. For base data, see Spiegel et al. (2002).

Discussion

The Nd data show that the molasse epidote is derived from two different sources—Austroalpine metagranitoids and Penninic ophiolites—belonging to the upper and lower plates, respectively. Because conventional heavy mineral analysis alone cannot distinguish between different types of epidote, it is not suited for timing exhumation processes in the hinterland. For the hinterland of the eastern and central sections (2 and 4) Nd isotope ratios suggest that the Penninic lower plate became exposed 7 m.y. earlier than indicated by the fission-track data. For epidote plotting in an intermediate position (section 1 and 6), an admixture from ophiolitic source rocks seems likely but cannot ultimately be proven by the Nd data alone, at least if we do not measure Nd ratios on single epidote grains.

The combination of Nd and fission-track data shows that, at 21–20 Ma, each molasse fan received detritus from Penninic units, either zircon or epidote. This leads to an entirely different picture of the Oligo-Miocene Central Alps. Instead of a relatively slow unroofing over several million years, the lower plate was exhumed to the surface by a single pulse of exhumation which caused the simultaneous exposure of Penninic units over large areas of the Central Alps. This simultaneous exposure can be bracketed between 21 and 20 Ma. However, we still cannot answer the question of the geodynamic framework. In other words, was the sudden pulse of exhumation caused by tectonic denudation or by a phase of enhanced erosional denudation?

Sediment Budget of the Foreland Basins

Method

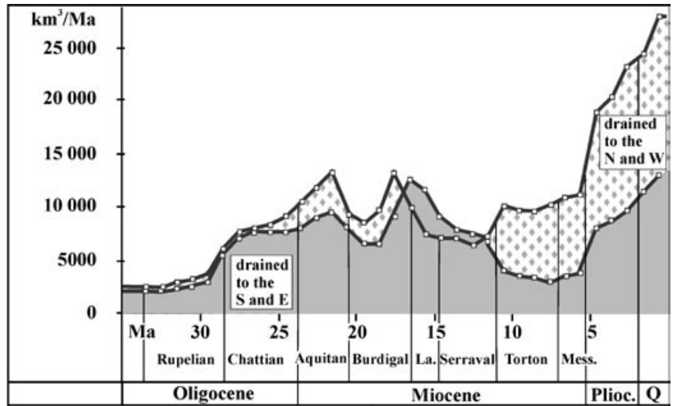
The calculation of sediment accumulation rates provides a direct estimate of the surface erosion in the source area and an indirect measure of the topographic evolution of the hinterland (Kuhlemann, 2000). It is based on the calculation of sediment volumes of the circum-Alpine basins by digitizing the available thickness maps of strata and base contour lines of sedimentary basins, as well as planimetry of geological profiles. The export of dissolved material is estimated on the basis of recent catchment settings and includes areal estimates of recent and ancient rocks exposed at the surface to account for highly variable ratios of solid versus dissolved rock (e.g., quartzite vs. limestone). The calculated sediment volumes were recompacted to a porosity equivalent to the solid rock of the source area and plotted for 1 m.y. steps (Kuhlemann et al., 2001). The 1 m.y. steps provide a good time resolution but are also large enough to exclude disturbances by local short-term events like storms or landslides. Therefore, calculation of the sediment budget monitors the long-term erosional flux (see also Willett and Brandon, 2002). The calculation is corrected for recycling of orogenic sediments due to cannibalism in thrust sheets of the subalpine molasse but did not take into account the different erodibilities of the bedrock lithologies (Kuhlemann, 2000). The disadvantages of this approach are the relatively high uncertainties and the poor spatial resolution, which means that erosion rates c annot be specified for smaller catchment areas.

Results

Figure 8 shows the sediment accumulation data in the foreland basins of the Central and Western Alps, separated for south/east and north/west directed catchments (after Kuhlemann, 2000). Between 30 and 21 Ma, sediment accumulation rates were continuously rising. This is interpreted to reflect the buildup of relief in the hinterland and is in line with the onset of coarse clastic sedimentation in the foreland basins at ca. 30 Ma. At 21 Ma, sediment discharge rates decreased dramatically, which suggests the collapse of the relief. This drop is not restricted to the Central Alps, but is independently calculated for the entire Alps (Hay et al., 1992; Kuhlemann, 2000). After a short period of enhanced sediment accumulation rates between 18 and 15 Ma, discharge rates dropped again. Between 5 Ma and the Quaternary, sediment accumulation rates were again strongly increasing. This is in line with the up to ten times enhanced erosion rates estimated for the Alps during late Pleistocene times (Hinderer, 2001).

Discussion

The most striking and, for our study, most important feature of the sediment accumulation curve is the sharp drop at 21 Ma (i.e., exactly contemporaneous with the exposure of the Penninic lower plate over large areas of the Central Alps). Combining fission-track, Nd, and sedimentary data reveals the following.



convergence rate (cm/y)	≥0.55	0.45	0.3**
amount of convergence	45 km*	58 km	61 km

Figure 8. Sediment accumulation rates in Alpine foreland basins between Oligocene times and the Quaternary (Kuhlemann, 2000) compared to estimated north-south convergence (Schmid et al., 1996). *—convergence since Late Eocene times (40 Ma); **—0.5 cm/yr if deformation stopped at 7 Ma.

1. Keeping in mind that the erodibilities of the bedrock lithologies were not taken into account for the sediment budget calculation, the decrease of the sediment supply could be at least partly caused by a change of the bedrock lithology to rocks with low erodibility. However, the Nd data indicate the exposure of upper Penninic ophiolitic rocks over significant hinterland areas. These upper Penninic ophiolites are generally associated with fine-grained schist (Bündnerschiefer), which is characterized as "highly erodable" due to its lithology and pervasive cleavage (Kühni and Pfiffner, 2001). In this context, the drop of the sediment supply seems to be even more dramatic.

2. The combination of enhanced hinterland exhumation and reduced erosion rates suggests that exhumation and unroofing of the Alpine metamorphosed lower plate was triggered by tectonic denudation rather than by erosion. This would fit well to a geodynamic setting of large-scale lateral extension processes affecting the Eastern and also the Central Alps in Oligocene-Miocene times, as suggested by Frisch et al. (2000).

IMPLICATIONS FOR THE ALPINE EVOLUTION

Combining all our data as well as data from the literature, we propose the following evolution for the postcollisional Central Alps. At ca. 30 Ma, the Central Alps started to develop significant relief, which caused enhanced erosion and therefore the onset of coarse clastic molasse sedimentation in the foreland basin. During upper Oligocene times, mainly sedimentary cover units and increasingly Austroalpine basement units were eroded and subsequently deposited in the molasse basin. At 25 Ma, erosion of epidote-rich greenschist-facies metagranitoids belonging to the lower Austroalpine units caused the influx of large amounts of

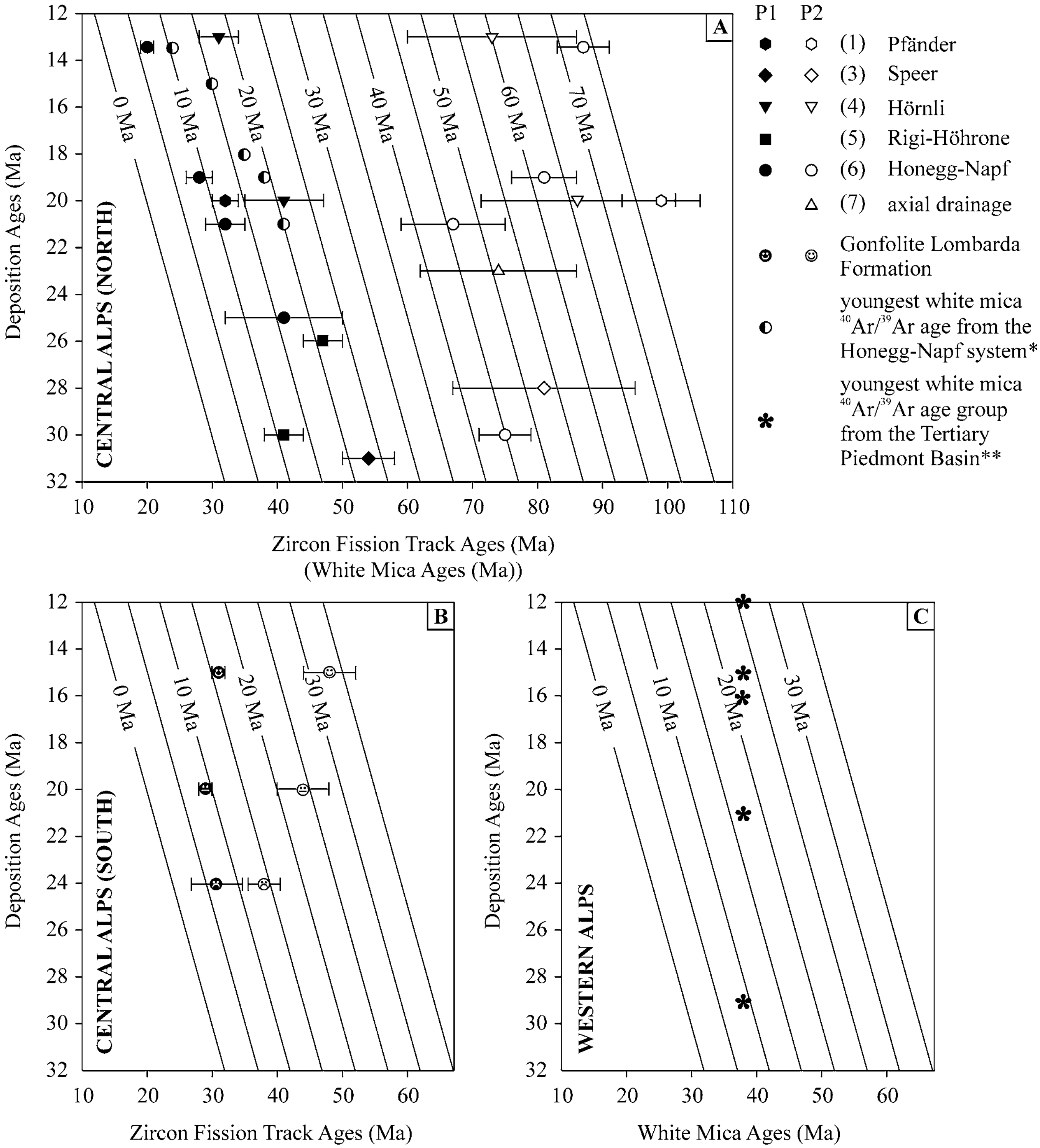


Figure 9. Relationship between population ages, sedimentation ages, and derived lag times. A: The two youngest modeled age groups of zircon fission-track age distributions from sandstones of the Swiss Molasse Basin, plotted against their deposition ages. Oblique lines mark contours of constant lag times. For comparison, the youngest $^{40}Ar/^{39}Ar$ ages of white mica from the same sandstones were also plotted (*—after von Eynatten and Wijbrans, 2003). B: Youngest modeled zircon fission-track age groups from sandstones of the Oligo-Miocene Gonfolite Lombarda Formation south of the Central Alps. Modeled age groups are previously unpublished; for the base data, see Spiegel et al. (2001). C: Youngest modeled $^{40}Ar/^{39}Ar$ age groups of detrital white mica from the Tertiary Piedmont Basin, which drained the internal retro wedge of the Western Alps. The same 38 Ma age group also persists in sediment younger than 12 Ma and even in recent river sediments (**—after Carrapa, 2002).

epidote into the molasse basin. Around the Oligocene-Miocene boundary, large-scale orogen-parallel extension started in the Eastern and Central Alps as a result of ongoing north-south convergence, tectonic escape toward the unconstrained margin in the east (Pannonian basin), and a topographic west-east gradient (Ratschbacher et al., 1991; Frisch et al., 1998, 2000). This extension caused (i) an east-west stretching of more than 200 km in the Eastern Alps and ~100 km in the Central Alps (Frisch et al., 2000), (ii) the collapse of the relief, as indicated by the strong decrease of the sediment discharge (Kuhlemann, 2000), and (iii) a pulse of enhanced exhumation in the Central Alps, which led to the simultaneous exposure of Penninic units over large areas of the hinterland at 21–20 Ma, as indicated by the occurrence of zircon and epidote from the Penninic lower plate in molasse sandstones. Extension processes and normal faulting continued until ca. 13 Ma, causing the contemporaneous exposure of the Tauern window in the Eastern Alps (Brügel, 1998; Frisch et al., 1998, 2000) and the Lepontine Dome in the Central Alps between 14 and 13 Ma. The exhumation of the Lepontine Dome is reflected by zircon fission-track ages in the foreland basin, showing a sharp increase in the average cooling rates of the hinterland from ~20 °C/m.y. in Lower Miocene times to ~40 °C/m.y. in Middle Miocene times (Spiegel et al., 2000). The same is observed for detrital white micas from the molasse basin, which indicate a continuous rise of the hinterland cooling rate from ~20 °C/m.y. to ~28 °C/m.y. between 21 and 15 Ma, and a sharp increase of the cooling rate to ~40 °C/m.y. between 15 and 14 Ma (von Eynatten and Wijbrans, 2003). At 5 Ma, erosion rates in the Alps strongly increased. The reason for this increase is unknown, but it may have been caused by the increasing importance of orographic precipitation in the course of Pliocene southward migration and intensification of the westerlies (Kuhlemann, 2000). Since ca. 2.7 Ma, late Neogene climatic changes caused glaciations in the northern hemisphere, which resulted in an increase of valley erosion, relief formation, and isostatically forced mountain top uplift. These processes eventually shaped the Alps into the mountain chain we know today.

Toward Steady State?

The reconstruction of the postcollisional Alpine history leads to the question whether the Central Alps reached steady-state conditions at any point of their postcollisional evolution, as proposed by Bernet et al. (2001). Steady state of orogenic systems has been the subject of many studies in recent times because it is considered to provide a measure for the maturity of a mountain belt (Willett and Brandon, 2002). In theory, convergent orogens experience three different stages during their lifetimes: a constructional phase, a steady state, and a decay phase (Howard, 1965; Jamieson and Beaumont, 1989). Willett and Brandon (2002) defined four different forms of steady state: topographic, thermal, exhumational, and flux. For this study, only the latter two are relevant. Flux steady state is characterized by a dynamic equilibrium between accretional flux into the orogenic system and erosional flux out of the system (i.e., erosion balances accretion). Exhumational steady state refers to constant hinterland exhumation rates, which are thought to be reflected by constant lag times of detrital minerals from synorogenic sediments (Garver et al., 1999). "Lag time" means the time difference between cooling age and depositional age, i.e., the time a certain mineral takes to be exhumed from the depth of its closure temperature to the surface plus the time of erosion, transport and deposition in the foreland basin. The latter term is assumed to be negligible compared to the time required for the exhumation to the surface (Brandon and Vance, 1992). Orogens in a constructional phase should yield sediments with decreasing lag times upsection, while steady state is expected to result in constant lag times. The decay phase is associated with increasing lag times upsection (Brandon and Vance, 1992; Garver et al., 1999).

Figure 9A shows a plot of the two youngest modeled age populations from the molasse basin against their deposition ages. For comparison, we also show detrital white mica ages from the same molasse sandstones (von Eynatten and Wijbrans, 2003), zircon fission-track data from the southern foreland of the Central Alps (Fig. 9B and Table 1; Gonfolite Lombarda Formation), and detrital white mica ages from the foreland of the Western Alps (Fig. 9C; Tertiary Piedmont Basin; Carrapa, 2002). For steady-state conditions, the respective modeled ages should plot on the same contour line of constant lag time (e.g., Bernet et al., 2001). Before we discuss the data in terms of potential steady-state conditions, we will first discuss the problems which may arise from the choice of the age groups in this kind of plot.

For population 1 (P1), we chose all Cenozoic cooling ages, while population 2 (P2) was assigned to Late Cretaceous cooling ages (Fig. 9A). These Late Cretaceous ages are interpreted as to be initially derived from the erosion of Austroalpine nappes. However, we cannot assess how many of these Cretaceous zircons were directly derived from incision into the Austroalpine basement rocks and how many were stored in unmetamorphosed flysch nappes in an intermediate stage. The latter zircons do not provide any information in terms of hinterland exhumation during the time of molasse sedimentation. Furthermore, Cretaceous metamorphism of the eroded Austroalpine units of the Central Alps only reached temperatures in the range of the zircon fission-track closure temperature (Spiegel et al., 2001). Therefore, we cannot be sure whether the fission-track ages are fully reset cooling ages or if we are dealing with partly reset mixed ages. In that respect, measuring the track length distribution would be helpful. The P1 age groups contain Eocene and Oligo-Miocene cooling ages. As discussed before, for the Eocene ages, again the problem of recycling arises so they cannot be used to assess hinterland exhumation.

In the southern foreland of the Central Alps, we found Oligocene (P1) and Eocene (P2) component ages (Fig. 9B). This is in line with the data of Dunkl et al. (2001) from the Chattian to Aquitanian Macigno formation, which is also situated south of the Central Alps. For the southern flank of the Central Alps, the problem of recycled ages is less pronounced because there were fewer sedimentary cover units exposed than on the northern flank (Longo, 1968; Giger, 1991). The problem of cooling age distributions from the southern foreland basin is that the modeled age groups cannot be clearly attributed to a special source area. In the southern Central Alps, a variety of potential sources with roughly the same age but entirely different thermal histories were exposed: (i) the Bergell plutonic body with an intrusion age of ca. 32 Ma (von Blanckenburg, 1992); (ii) reworked volcanic detritus from Periadriatic Oligocene volcanism and its Eocene precursors (Giger and Hurford, 1989; Dunkl, 1990; Ruffini et al., 1997, Brügel et al., 2000); (iii) the Austroalpine orogenic lid, which was largely thermally overprinted by enhanced Mid-Oligocene heat flow (Hurford et al., 1991); (iv) Penninic units from the Lepontine area which experienced Tertiary metamorphism and exhumation (e.g., Schmid et al., 1996); and (v) the South-Alpine Ivrea zone, which yields in the present-day exposures Eocene zircon fission-track cooling ages (Hurford, 1986). Because we are not able to define the provenance of the age groups from the Gonfolite Lombarda Formation more precisely, an interpretation of this data in terms of a potential steady state is impossible.

After a closer examination, most of the fission-track data seem to be insufficient for applying the lag-time concept because of mixed ages, recycled ages, or uncertainties in terms of the provenance of the age groups. What remains are the Oligocene cooling ages from the Swiss Molasse Basin, in combination with detrital white mica ages from the same samples (Fig. 9A). Their provenance is well defined: Between 21 and 15 Ma, P1 was derived from the upper to middle Penninic hanging wall; after 15 Ma, P1 was derived from the lower Penninic footwall of the Lepontine Dome. The source area should have remained roughly the same during lower to middle Miocene times, although we assume some changes of the main drainage divide at 17 Ma (Kuhlemann et al., 2001). Therefore, testing a potential steady state on the base of these zircon and white mica ages seems reasonable. Between 21 and 19 Ma, lag times deduced from the zircon fission-track data seem to be more or less constant at ca. 10 Ma, while between 19 and 14 Ma, the lag time decreases to ca. 6 Ma. For the same period of time (21 to 14 Ma), the lag time deduced from $^{40}Ar/^{39}Ar$ ages continuously decreases from 21 to 10 Ma. Hence, the geochronological data is in line with a constructional orogenic state. Therefore, we can clearly exclude exhumational steady-state conditions in the Central Alps before 14 Ma. For the time after 14 Ma until the present, Bernet et al. (2001) proposed exhumational steady state based on zircon fission-track data from the southern foreland of the Central Alps that show a constant exhumation of the footwall of the Lepontine Dome. However, the Central Alps did not achieve a flux steady state in postcollisional times, because this would require constant erosion rates (Willett and Brandon, 2002), which is clearly not the case for the Central Alps (see Figure 8). Instead, the orogenic wedge was still growing between ca. 9 and 4 Ma (thrusting of the Jura mountains; Becker, 2000), corresponding to a constructional state.

In the Tertiary Piedmont Basin, the foreland of the adjacent Western Alps, detrital white mica yield a youngest modeled age group of 38 Ma (Fig. 9C; Carrapa, 2002). This youngest age group is persistent from Late Oligocene times until the present. It is interpreted to reflect very fast post-Eocene exhumation and subsequently slow and continuous erosion for more than 25 m.y. (Carrapa, 2002). According to the lag-time concept, the detrital white mica ages are consistent with a decay phase for the internal zone of the Western Alps. A comparison of the Central and Western Alps shows that the Alps as a whole did not reach steady-state conditions at a certain time but that the different parts of the Alps may have attained regional equilibria at different points in time.

CONCLUSIONS

From this study, we can draw two main conclusions for the use of age data from detrital minerals.

1. The sole use of age provenance studies for reconstructions of hinterland denudation histories can result in misleading interpretations. Instead, geochronological data should be combined with other methods that are able to add information on the erosion of basic magmatic lithologies and on the geodynamic framework, such as geochemical or isotopic fingerprints of heavy mineral phases and the sediment budget of the foreland basins. The importance of a combined approach is demonstrated for the example of the Central Alps, where we tried to reconstruct timing and processes leading to the exposure of the Alpine metamorphosed lower plate by the sedimentary record. According to the fission-track data alone, the lower plate became exposed by relatively slow erosion processes over several million years. In contrast, the combined approach showed that it became exposed by one fast exhumation pulse mainly triggered by tectonic denudation. Similar combined approaches may be transferred to foreland studies on other orogenic systems.

2. Using the lag-time concept to recognize steady-state conditions of an orogen requires detailed knowledge on the provenance of the single modeled age groups. For the example of the Central Alps, we had to deal with the following problems. (i) Recycling of zircon grains from sedimentary cover units. "Recycled" age groups do not give direct evidence on hinterland exhumation. (ii) Partial resetting of cooling ages. These ages are geologically meaningless mixed ages that, again, cannot be used to decipher hinterland exhumation rates. (iii) Different provenances of similar age groups. In the southern Central Alps, similar age groups were derived from different tectonic units and thermal settings (magmatic ages, thermally reset ages due to enhanced heat flow and metamorphic cooling ages). They cannot be combined with each other for the lag-time concept. From our fission-track data of sandstones from the Swiss Molasse Basin, we can conclude that the Central Alps did not reach exhumational steady state before 14 Ma.

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