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Article

Detrital Zircon Fission-Track Thermochronology of the Present-Day Isère River Drainage System in the Western Alps: No Evidence for Increasing Erosion Rates at 5 Ma

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Abstract: The Isère River system drains parts of the Western Alps in south-eastern France. Zircon fission-track data of the Isère River and its tributaries show a range of apparent cooling ages from about 7 to 150 Ma. Zircons with Jurassic to early Tertiary cooling ages are derived from partially reset or non-reset sedimentary cover units of the internal and external Alps, while grains belonging to the minimum age fraction are derived from areas of active river incision in the external crystalline massifs or from the Penninic front. With the absence of major normal faults, upper crustal exhumation in the Western Alps is driven by erosion. First-order long-term exhumation rate estimates based on minimum ages are about 0.5–0.6 km/Myr for the fastest exhuming areas, while drainage basin average rates based on central ages are about 0.2–0.4 km/Myr. These rates are slower than published short-term erosion rates determined from detrital quartz ^{10}Be analyses in the Pelvoux massif. While present-day erosion is faster than the long-term average exhumation rates, the Isère River drainage zircon fission-track data do not show evidence for increasing erosion rates at 5 Ma. Exhumation has not been sufficient in this area to expose rocks with <5 Ma cooling ages today. The increase in erosion may have happened only in glaciated areas between 1 and 2 Ma.

Keywords: fission-track thermochronology; exhumation; erosion; Western Alps

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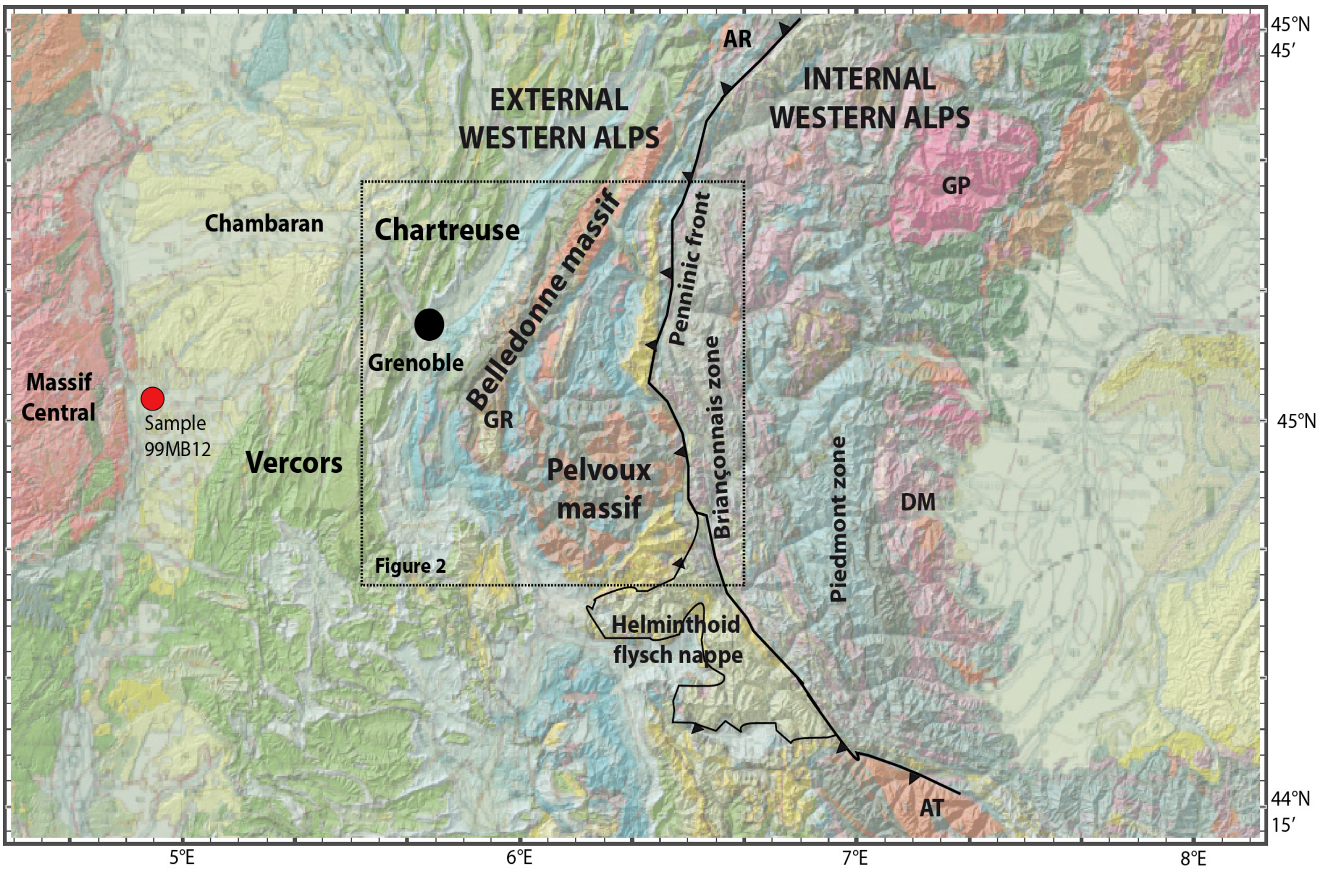
1. Introduction

The exhumation history of the Western Alps has been a matter of discussion for many years, (e.g., [1–3]). While some authors presented evidence on the basis of thermochronologic data for rapid exhumation in the Western Alps during the Eocene to early Oligocene, (e.g., [4–7]), and fairly steady exhumation since [8], others argue for an increase in erosion at 5 Ma [9,10], based on sediment budget calculations from surrounding basins. The question is if the proposed increase in erosion rate at 5 Ma is real or not, as this has important implications for developing scenarios of the tectonic evolution and the possible feedback to climatic change in the Alps, as proposed elsewhere [11–13]. In this study, new detrital zircon fission-track (ZFT) data and published detrital and bedrock apatite fission-track (AFT) and ZFT data of the Isère River drainage system in the central Western Alps (Figure 1) are used to evaluate the present-day signal of exhumation in this part of the Alps.

Figure 1. Overview geologic map of the Western Alps. AT = Argentera massif, AR = Aguilles Rouges massif, DM = Dora Maira massif, GP = Gran Paradiso massif, GR = Grandes Rousses. The map was created with GeoMapApp version 3.3.6 [14] using the BRGM geological Map of France 1:1,000,000 overlay.

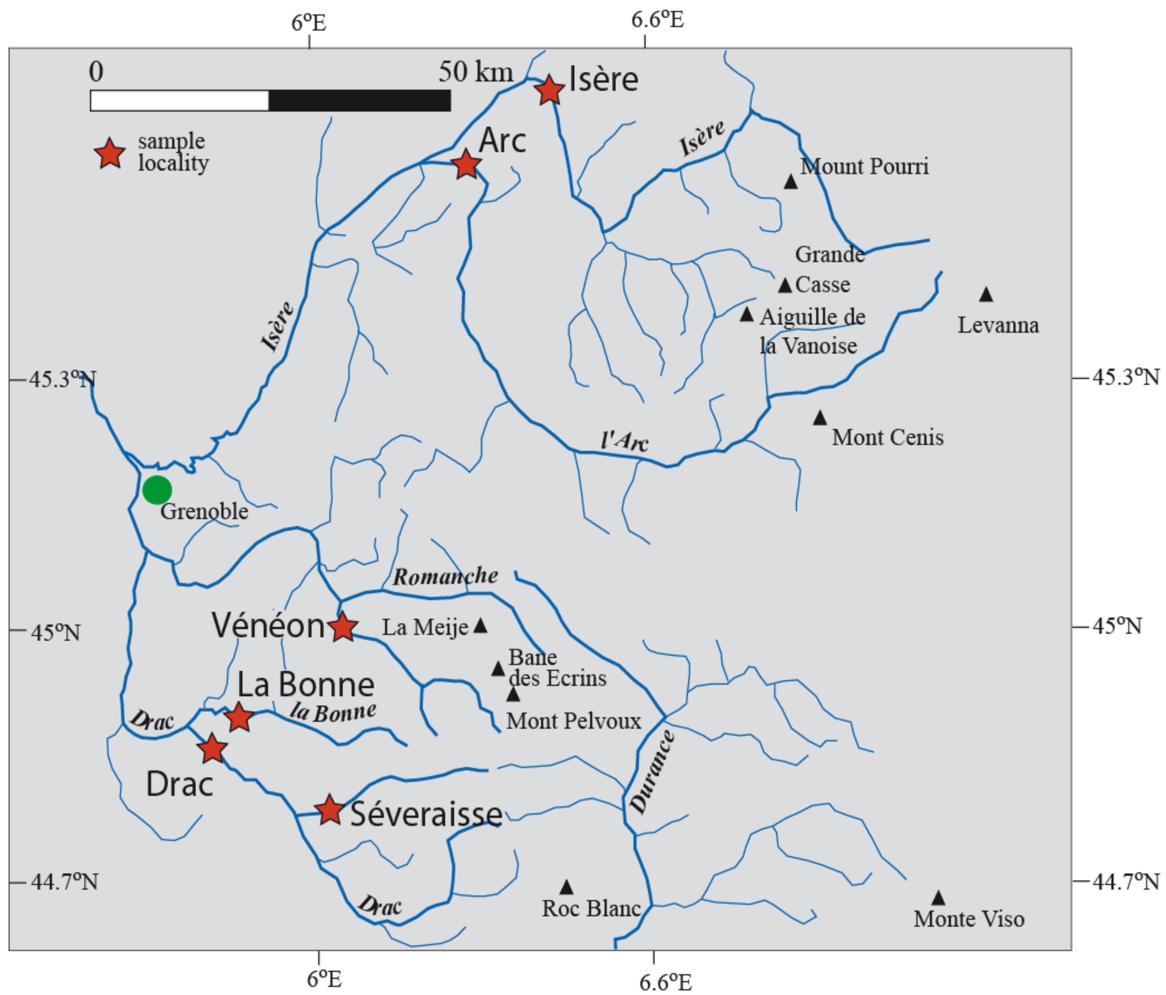


2. Geological Setting

Convergence between the European and African plates since the Late Cretaceous caused closure of the Ligurian Ocean and deformation of the southern European margin. The Oligocene European-Apulian continent-continent collision caused the growth of the Western Alpine arc ([15,16] or see [17] for a comprehensive overview). The Western Alps are separated by the Penninic front, which is a major thrust fault, into two different zones, the internal and external Western Alps (Figure 1). The internal Western Alps consist from east to west of high-pressure/low-temperature metamorphic rocks of the internal crystalline massifs (Dora-Maira, Grand Paradiso, *etc.*), the Piedmont zone and Briançonnais zone medium to low-grade metamorphic nappes and the non-metamorphic Helminthoid flysch nappes (Figure 1). The external Western Alps, to the west of the Penninic front, consist of the external crystalline massifs, which are the Hercynian basement rocks of, for example, the Aiguilles Rouges, Pelvoux, Belledonne and Argentera massifs, in addition to Permo-Triassic sedimentary rocks and the Jurassic to Cretaceous sedimentary cover rocks of the former European passive margin. The latter form, to some part, the so-called subalpine chains (e.g., Vercors or Chartreuse massifs) in south-eastern France (Figure 1). The western part of the external Western Alps experienced only very low-grade Alpine metamorphism, while most of the sedimentary rocks are non-metamorphic, e.g., [17]. The subalpine chains were deformed during Alpine shortening after the mid-Miocene [18,19].

In the northern Isère River drainage, the Isère and Arc rivers drain part of the internal Western Alps before cutting across the Penninic front and into the crystalline rocks of the external Belledonne massif and Mesozoic sedimentary cover rocks. The southern Isère drainage drains the external Pelvoux massifs and part of the subalpine chains, such as the Vercors massifs (Figures 1 and 2).

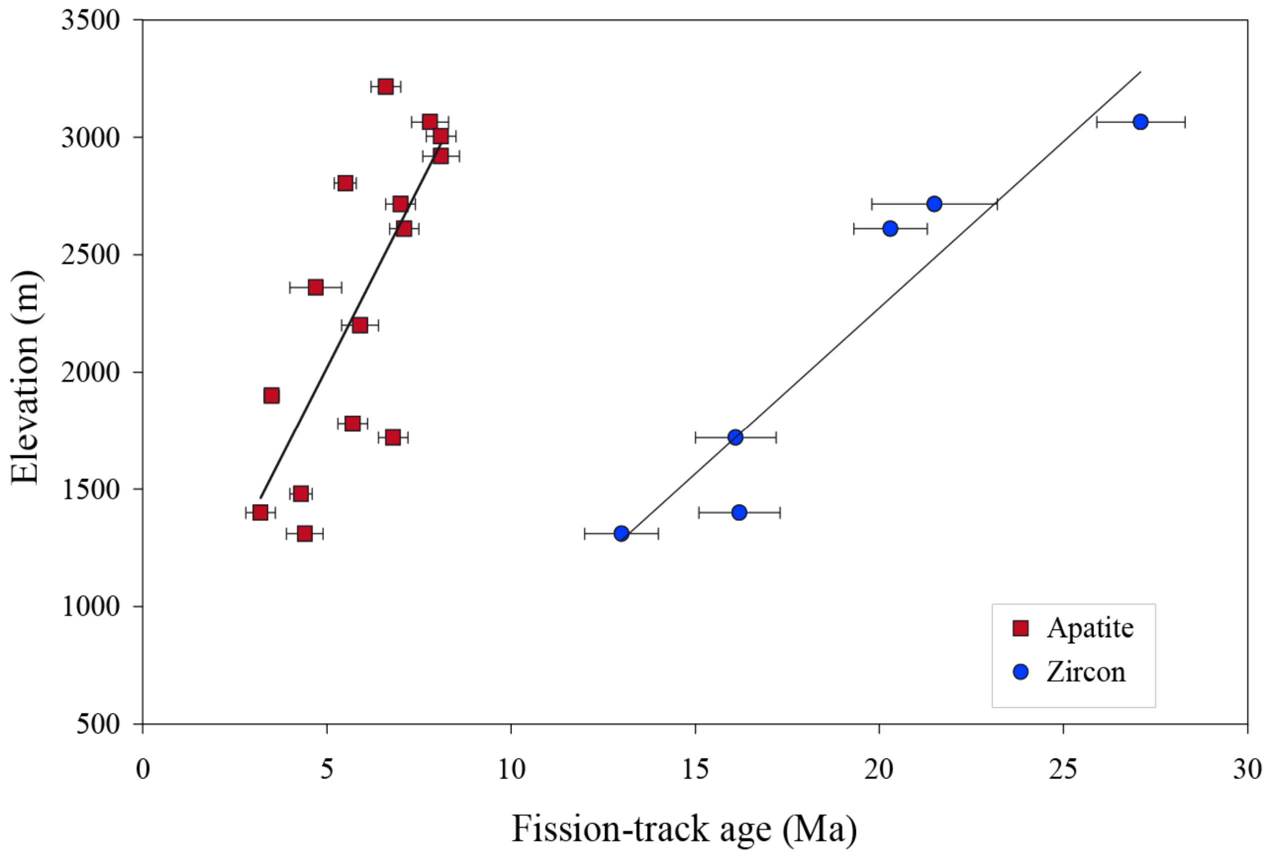
Figure 2. Isère River drainage network. Sampling locations of this study are marked with stars.



3. Previous Thermochronologic Work in the Isère River Drainage Area

Part of the southern Belledonne and the Pelvoux massifs were analyzed with the apatite and zircon fission-track methods in the past. Here, only the age information is of interest and not the interpretations of the different studies. For example, Fügenschuh and Schmid [20] presented AFT and ZFT data for the upper reaches of the Isère and Arc rivers to both sides of the Penninic front (internal and external Western Alps), with apatite ages ranging from 2 to 18 Ma and zircon ages from 8 to 92 Ma. A study by van der Beek *et al.* [21] presented AFT and ZFT data from the La Meije "vertical" profile (Figure 3) in the Pelvoux massif. AFT ages are between 3.2 and 8 Ma and ZFT ages between 13 and 27 Ma. Seward *et al.* [22] presented AFT ages between 3 and 14 Ma from the southern Pelvoux area and Sabil [23] AFT ages between from 4 and 14 Ma for the southern Belledonne/Grandes Rousses massif.

Figure 3. La Meije bedrock apatite and zircon fission-track age-elevation plot. Data from [21].



Detrital apatite data exists for the Drac and Isère rivers upstream of their confluence near Grenoble, showing main age peaks for the Drac River at 6.4, 11.6 and 26.8 Ma and for the Isère River (which covers, here, the northern part of the Isère drainage system) at 6.7 and 24.3 Ma [24]. Detrital ZFT ages have been determined for the Isère River just upstream of its confluence with the Rhône River, near Chateauneuf sur Isère (sample 99MB12 in Figure 1), with age peaks at 14.1, 35.6 and 87.7 Ma [25].

4. Methods

New detrital zircon fission-track data of six samples from different rivers in the Isère River drainage system are presented in this study. These rivers include, from north to south, the upper Isère

River, the Arc River, the Vénéon River, the La Bonne River, the Drac River and the Séveraisse River (Figure 2, Table 1).

Table 1. Isère drainage system river sample locations for zircon fission-track analysis.

Sample No.	River	Latitude	Longitude	Altitude	Locality
04MB129	La Bonne	N 44.89758°	E 5.92480°	745 m	near Valbonne
04MB130	Drac	N 44.79351°	E 5.97391°	764 m	near Ambel
04MB131	Arc	N 45.55579°	E 6.25442°	303 m	near Aiton
04MB132	(upper) Isère	N 45.65057°	E 6.43442°	363 m	near Tour en Savoie
04MB145	Vénéon	N 45.01297°	E 6.06382°	750 m	near Venosc
04MB146	La Séveraisse	N 44.78396°	E 6.06249°	888 m	near Le Séchier

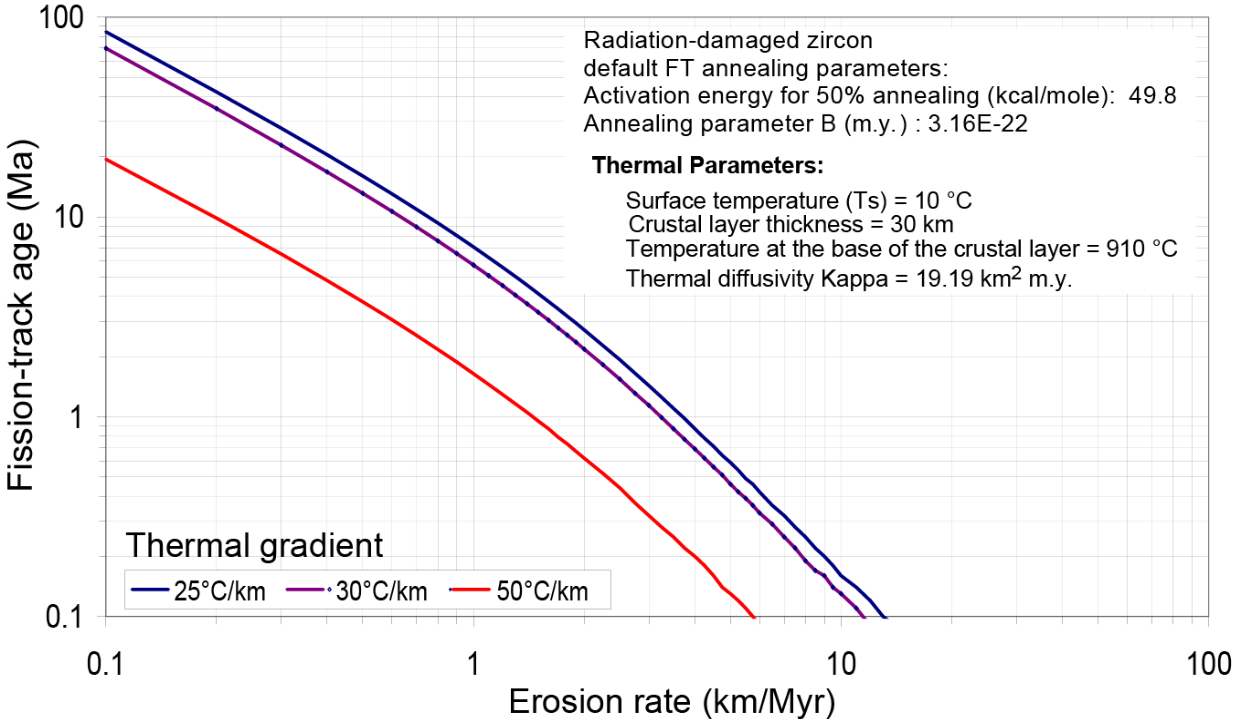
All six samples were collected in the field from sand or gravel bars. About 10 kg of sand-sized river sediments were processed for each sample in the field by panning the sediments directly in the rivers for increasing the heavy mineral concentration of the samples. In the lab, the samples were sieved, and the 160–80 µm fraction was further separated with standard magnetic and heavy liquid separation techniques. Zircon aliquots were mounted in Teflon® sheets, polished and etched in a eutectic NaOH-KOH melt at 228 °C in a laboratory oven. Two mounts were prepared for each sample and etched for different lengths of time between 10 and 35 h [26–28]. After etching, the Teflon mounts were covered with muscovite sheets as external detectors and irradiated together with Fish Canyon Tuff and Buluk Tuff age standards and CN1 dosimeter glasses at the well-thermalized ORPHEE reactor in Gif-sur-Yvette, France. After irradiation, the mica detectors were etched at 20 °C for 18 min in 48% HF for revealing induced fission-tracks. All samples were analyzed dry at 1250× magnification with an Olympus BH2 microscope (Olympus Corp., Tokyo, Japan) at the fission-track laboratory in Grenoble, using the FTStage 4.04 system of T. Dumitru (Jasper Canyon Research Inc., Palo Alto, CA, USA).

Central and minimum ages for all samples were determined and plotted with the RadialPlotter program of Vermeesch [29,30]. The central age is an estimate of a mean age of an over-dispersed discordant age distribution, while the minimum age is basically a pooled age of the largest concordant fraction of grains with the youngest cooling ages in a sample [31]. Both ages are used in this study for estimating drainage basin average and maximum long-term exhumation rates.

All grain-ages of the six new samples were also merged into an Isère drainage ZFT dataset simply by adding and without any weighting. The merged dataset of this study and previously published ZFT data of the downstream Isère River [25] were compared using Kolmogorov-Smirnov (KS) statistics [32]. A KS probability value of P(KS) <5% indicates that the difference between the age distributions of two samples is significant and systematic. If the P(KS) value is much larger than 5%, the difference is most likely due to random chance alone.

Exhumation rates from thermochronologic data can be estimated/calculated with different approaches [33]. In this study, a first-order estimate is applied, using the Age2edot program of Brandon [34,35]. This program provides a one-dimensional thermal advection solution for transferring thermochronologic ages into erosion/exhumation rate estimates (Figure 4).

Figure 4. Relationship between zircon fission-track age and erosion rate, depending on initial thermal gradient and steady-state conditions. Calculations based on the Age2edot program of Brandon [34,35]).



5. Results

It was the objective to date at least 50–100 zircon grains per sample with the fission-track method, but because of metamict grains, grains with strong U-zoning and fractures and grains lost during polishing and etching, only between 16 and 55 grains were analyzed per sample. Radial plots of all six samples are presented in Figure 5, while the raw data is available in the supplementary data to this article. Despite these small datasets with few analyzed grains, some observations can be made. The calculated minimum and central ages (Table 2) and the observed range of grain ages do reflect mid-Miocene, Early Miocene, Late Oligocene and older ZFT ages in the Isère River drainage area (Figure 5, Table 2). To overcome the limitation of the small individual datasets per sample, all new samples were merged into one dataset (Table 2).

Comparison of the merged Isère River drainage ZFT data of this study with the Isère River ZFT data of [25] shows that the two age distributions are very similar. A P(KS) value of 16.4% indicates no statistically significant difference between the two distributions (Figure 6), even if the central ages are not the same (Table 2).

Figure 5. Radial plots of zircon fission-track (ZFT) data of all six samples of the Isère drainage. Plots were made with the RadialPlotter of Vermeesch [29,30].

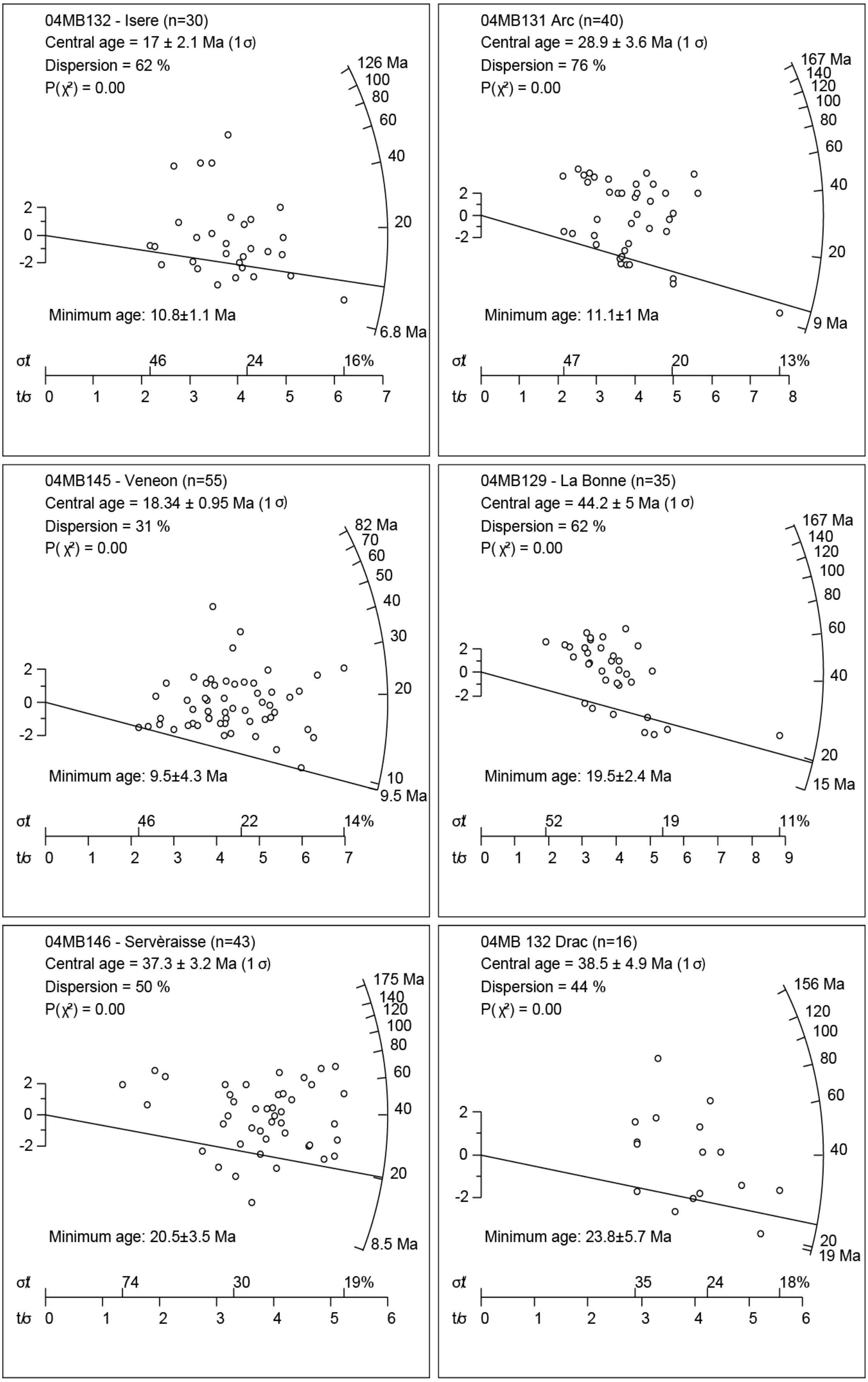
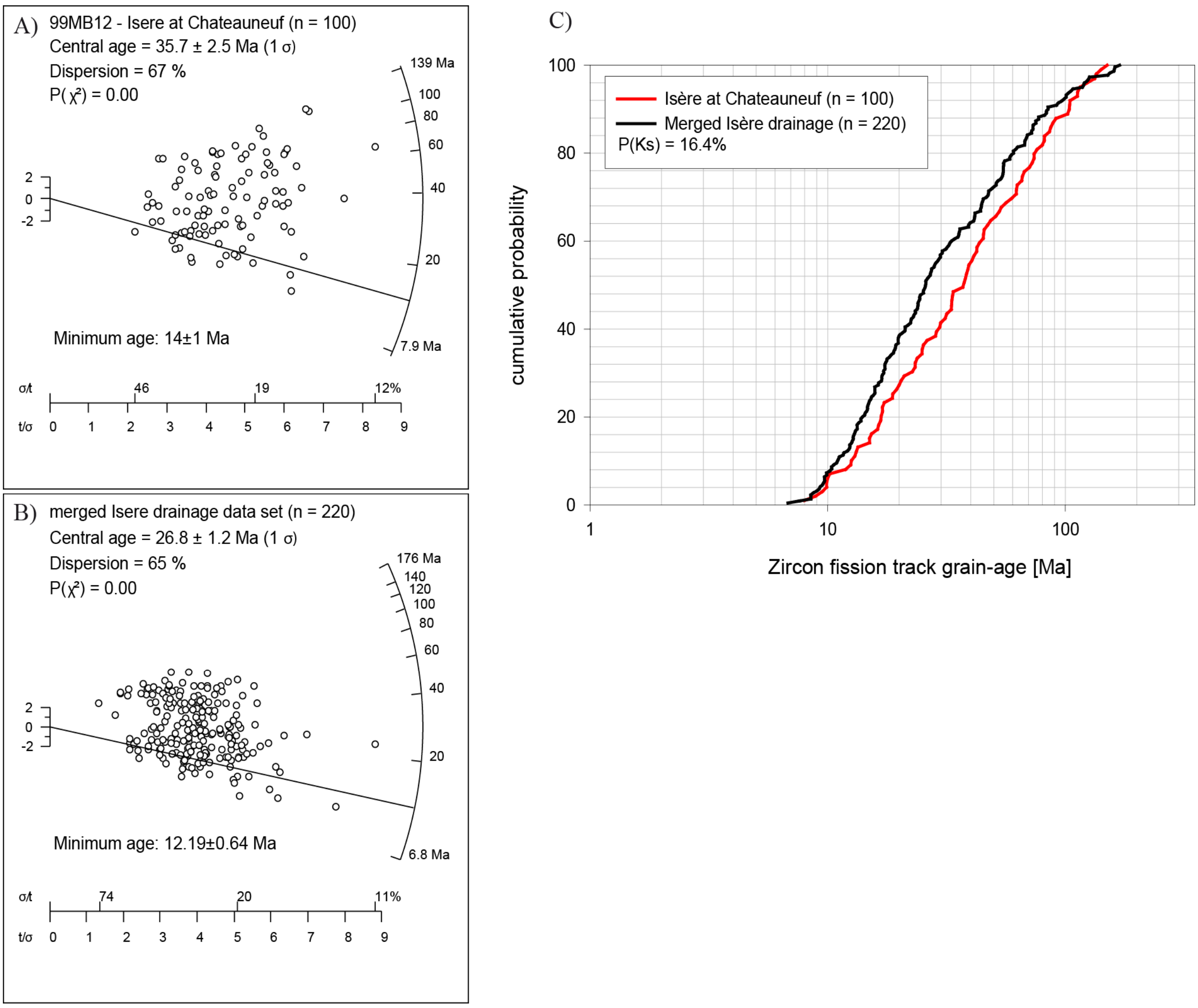


Table 2. Detrital zircon fission-track data of the Isère River drainage.

Sample	N	ρ_s (t/cm^{-2})	N_s	ρ_i (t/cm^{-2})	N_i	ρ_d (t/cm^{-2})	$P(\chi^2)$	Grain age range (Ma)	Central age (Ma)	±1σ	Minimum age (Ma)	±1σ
Isére	30	3.36×10^6	1,224	2.58×10^6	941	2.25×10^5	0.0	6.9–122.9	17.0	2.1	10.8	1.1
Arc	40	4.31×10^6	2,409	1.99×10^6	1,113	2.26×10^5	0.0	9.1–153.5	28.9	3.6	11.1	1.0
Vénéon	55	3.82×10^6	2,661	2.89×10^6	2,010	2.25×10^5	0.0	9.7–80.9	18.3	1.0	9.5	4.3
La Bonne	36	5.41×10^6	2,564	1.78×10^6	846	2.27×10^5	0.0	14.9–149.8	44.8	5.0	19.5	2.4
La Sevèraisse	43	4.41×10^6	2,708	1.56×10^6	955	2.24×10^5	0.0	8.6–157.5	37.3	3.2	20.5	3.5
Drac	16	4.87×10^6	1,031	1.73×10^6	366	2.26×10^5	0.0	19.2–150.1	38.5	4.9	23.8	5.7
Merged samples *	220	4.32×10^6	12,597	2.15×10^6	6,269	2.25×10^5	0.0	6.9–157.7	26.8	1.2	12.19	0.64
Isére at Chateauneuf **	100	5.19×10^6	5,059	5.13×10^6	5,007	2.34×10^5	0.0	8.1–145.9	35.7	2.5	14.1	1

Notes: All samples were analyzed dry at 1250× using a BH2 Olympus microscope and a CN1 zeta of 126.71 ± 5.36; * The merged samples are all six new samples analyzed together; ** The "Isère at Chateauneuf" sample is the "99MB12" sample of [25]. Central and minimum ages calculated using RadialPlotter by Vermeesch [29,30].

Figure 6. Radial plots of (**A**) the Isère at Chateauneuf with ZFT data of [25]; (**B**) the merged Isère River ZFT dataset of this study; and (**C**) comparison of grain age distributions of the two Isère River ZFT datasets using Kolmogorov-Smirnov (KS) statistics. A P(KS) value of 16.4% indicates that the two age distributions are not significantly different.

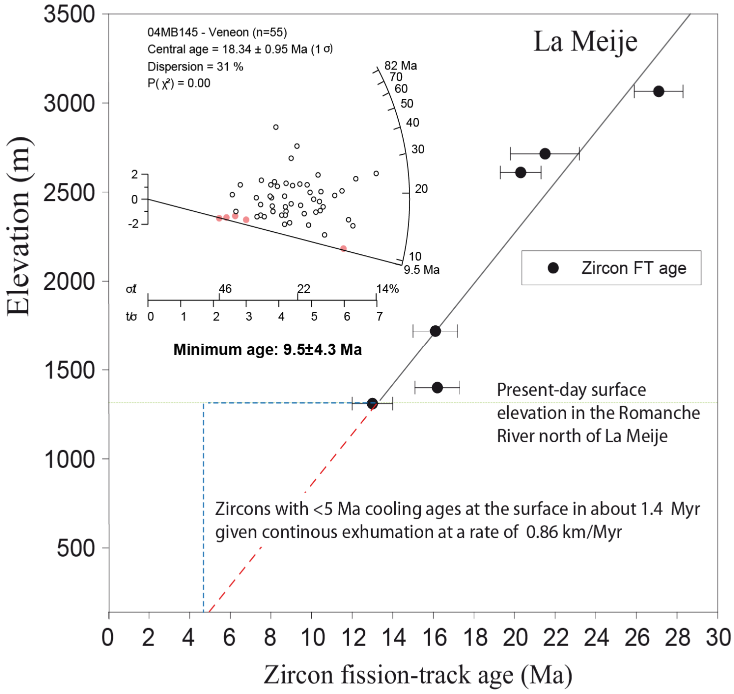


6. Discussion

6.1. Comparison with Published Detrital and Bedrock AFT and ZFT Data

When comparing the new and previously published detrital and bedrock thermochronologic data, it is apparent that the detrital data provide a reliable estimate of the bedrock AFT and ZFT ages in the Isère drainage area. As the bedrock of this drainage area mainly consists of apatite and zircon bearing rocks, no major lithologic bias is to be expected. The exceptions are the subalpine chains, which mainly consist of carbonate, and marly sedimentary rocks that contain basically no apatites or zircons. The available bedrock fission-track data come from individual studies and were not collected in a systematic fashion across the drainage area. The rivers, on the other hand, sample the landscape systematically, and the further downstream the detrital samples are taken, the better mixed is the age signal. Therefore, the spatially limited bedrock samples may miss part of the bedrock fission-track age signal in the drainage area, which is detected in detrital river samples. Using the ZFT data from the Vénéon River, which drains the southern flank of the La Meije Mountain, allows for such a comparison on a local scale between a detrital ZFT age signal and the bedrock ZFT age-elevation profile of [21] (Figure 7). The Vénéon River sample contains a minimum age of 9.5 ± 4.3 Ma and a central age of 18.3 ± 1 Ma, while the ZFT ages of the La Meije age-elevation profile range between 13.0 ± 2.0 and 27.1 ± 2.4 Ma [21]. This indicates that the zircons that belong to the minimum age of the Vénéon sample come from the valley bottom, where river incision occurs. The zircons with up to Oligocene cooling ages were derived from rocks exposed towards the top of the mountain. Clearly, the Eocene and older ZFT bedrock ages in the Vénéon drainage were not detected in the age-elevation profile. However, the surface area of rocks with such ZFT cooling ages in the Vénéon drainage is probably limited, as this fraction is small in the detrital sample.

Figure 7. Vénéon River radial plot with minimum age estimate in comparison to the La Meije bedrock zircon fission-track data of [21].



6.2. Exhumation Rate Estimates

The detrital ZFT central ages of the river samples can be used to estimate drainage basin long-term (over millions of years) average exhumation rates. Upper crustal exhumation, which is defined as the unroofing history of rock towards the Earth's surface [36], can be driven by erosion or normal faulting in convergent mountain belts. In the absence of major normal faults in the Isère River drainage area, exhumation is considered here to be driven by the most part by erosion. Using the above mentioned relationship between fission-track age and exhumation rate (Figure 3), first-order exhumation rates can be estimated for the minimum and central ages. Obviously, zircons belonging to the minimum age come from areas with the fastest and most recent exhumation, e.g., the valley bottoms in the Pelvoux massif (Figure 7), or, in the case of the Arc and upper Isère rivers, from near the Penninic front [20]. The estimated maximum rate of exhumation of these fastest exhuming areas is on the order of 0.5–0.6 km/Myr (for an assumed thermal gradient of 30 °C/km). By calculating a central age of the detrital age distributions, one can also estimate that drainage basin mean exhumation rates derived from central ages are on the order of 0.2–0.4 km/Myr for the rivers in the Isère drainage network. The same exercise can be done for the available detrital AFT data [24], which provides very similar exhumation rate estimates.

6.3. Short-Term versus *Long-Term Exhumation Signal*

The exhumation rates determined here are long-term estimates, averaged out over millions of years, neglecting short-term changes in exhumation rates or changes in the thermal structure of the mountain belt. Van der Beek *et al.* [21] performed inverse and forward modeling of their age-elevation data for retrieving local exhumation histories. They concluded that the La Meije experienced a three phase exhumation history with a short-lived phase of rapid exhumation at a rate of 2.5 km/Myr between 6–5.5 Ma and slower exhumation on the order of 0.3 to 0.4 km/Myr before and after the short-lived fast exhumation event. The signal of the short-lived phase of rapid exhumation is smoothed out in the detrital signal and is not detectable. The phases of slower exhumation before and after 6–5.5 Ma have rates compatible to the long-term average rates presented above when using the central age of the present day Vénéon River sample for estimating an exhumation rate.

The question is: how do long-term exhumation rates compare to short-term (over thousands of years) erosion rates? To answer this question, it is useful to compare the data of this study with erosion rates determined from detrital quartz ^{10}Be analyses by Delunel *et al.* [37]. These authors analyzed detrital quartz from river drainages in the Pelvoux massif to some part the same drainages analyzed in this study (Vénéon, La Bonne, La Séveraisse and Drac rivers; see Table 3). The detrital quartz ^{10}Be erosion rates are regarded as river drainage average erosion rates. One interesting result of the Delunel *et al.* [37] study is that the different river drainages of the Pelvoux massif show almost a factor of six difference in erosion rates, from 0.29 ± 0.06 km/Myr (La Bonne River) to 1.69 ± 0.31 km/Myr (Gyronde River in the eastern Pelvoux massif). Delunel *et al.* [37] demonstrated a positive relationship between average erosion rate and mean elevation of these river drainages, and they concluded that erosion rates were controlled by frost-cracking.

Table 3. Pelvoux massif short-term *versus* long-term erosion rate estimates.

River	Short-term estimate (km/Myr) from ^{10}Be analyses *	Long-term estimate (km/Myr) from ZFT central age	Long-term estimate (km/Myr) from ZFT minimum age
Vénéon	0.86 ± 0.16	0.39 ± 0.08	0.65 ± 0.14
La Bonne	0.29 ± 0.06	0.18 ± 0.04	0.39 ± 0.08
Séveraisse	0.65 ± 0.12	0.19 ± 0.04	0.27 ± 0.06
Drac	0.67 ± 0.13	0.19 ± 0.04	0.30 ± 0.06

Note: * Detrital quartz ^{10}Be erosion rate estimates from [35]. ZFT-derived erosion rate estimates are based on data of this study and given with an estimated 20% error envelope.

The comparison shown in Table 3 demonstrates that the short-term ^{10}Be erosion rates are faster than the maximum long-term ZFT exhumation rates in the Vénéon, La Bonne, Séveraisse and Drac river drainages, based on minimum ages. The 1D-thermal model exhumation rate estimates are relatively conservative and robust [34,35], so the question arises if this difference is due to a new long-term erosion rate trend or just a short-term variation on the scale of Milankovitch cycles. To answer this question, more detailed research is needed on Pliocene and Quaternary erosion rates in the Alps.

6.4. Increasing Erosion Rates at 5 Ma?

On a regional scale, long-term exhumation rates of the Western and Central Alps, derived from detrital thermochronologic data, have been fairly constant since at least 15 Ma [24,38] or, possibly, since about 27 Ma [8]. Orogen-scale average erosion rates for the Alps have been estimated to be on the order of 0.2–0.3 km/Myr [39] since the Oligocene, with the fastest areas exhuming at about 0.7 km/Myr [38,39].

An increase in erosion rates at 5 Ma has been proposed for orogenic systems world-wide [40]. However, it is possible that this is simply an artifact of reading an incomplete stratigraphic record from tectonically active areas, as long-term stability of global erosion rates are documented by geochemical ^{10}Be/^{9}Be analyses of ocean sediments [41]. Kuhlemann [9] proposed an increase in erosion rates in the Alps at 5 Ma, on the basis of sediment yield data from circum-alpine basins. Sediment yield data estimates from foreland basins can be problematic, depending on the preserved sedimentary record. In the circum-alpine basins, the more recent sedimentary record (Pliocene and younger) tends to be more complete, and sediment volumes can be more or less correctly calculated. However, the more ancient sedimentary record has, in many areas, been overthrusted and subducted or was lost to erosion and sediment recycling. Estimating sediment volumes from an incomplete and dissected record of older sedimentary rocks is difficult and prone to error. This is also true for the Alps. Sediment yield estimate errors of 100%–200% are reasonable in many basins for mid-Miocene and older deposits [9], which means that the sediment volumes and the derived erosion rates may be severely underestimated for the older deposits. Alternatively, increasing sediment yield could also be explained by eroding larger areas without changing the erosion rate.

Assuming that the increase in erosion rates at 5 Ma is real, Willett [13] presented an interesting evaluation of the question if the apparent increase in Neogene sediment yield in the Alps is linked to climate change. After discussing published sediment yield, detrital and bedrock thermochronologic and cosmogenic data on the scale of the Western and Central Alps, he concluded that erosion rates accelerated since the latest Miocene until today, and given the slowing of tectonic processes in the Alps, the climate needs to be regarded as the main driver for increasing erosion.

However, the proposed increase in erosion rates at 5 Ma remains elusive. As shown in this study, a significant increase in exhumation rates at 5 Ma cannot be detected with detrital ZFT age data in the Isère River drainage system of the Western Alps today. Even the local short-lived exhumation event at 6–5.5 Ma, as proposed by van der Beek *et al.* [21], remains undetected in the present-day ZFT river data. This is not a surprise, because the youngest zircon grain dated in the Isère drainage has a cooling older than this short-lived exhumation event. Given the present-day short-term ^{10}Be erosion rate estimate for the Vénéon River of 0.86 km/Myr, it would take at least another 1.4 Myr before zircons with <5 Ma cooling ages are exposed at the surface at La Meije (Figure 7).

Therefore, if the ZFT data do not reflect increasing exhumation rates since 5 Ma, what about other dating techniques? AFT analysis is much more sensitive to changes in upper crustal exhumation rates than ZFT analysis, because of the much lower closure temperature of the AFT system and the integration of exhumation rates over only 2–3 km of crustal depths. Using detrital AFT data from the Western Alps, Glotzbach *et al.* [24] demonstrated by PeCube [42] modeling that if erosion rates really significantly increased at 5 Ma, as proposed by Kuhlemann [9], then this should be detectable in the detrital apatite thermochronologic record with apatite AFT ages much younger than 5 Ma. However, the detrital AFT data from the Isère and Drac rivers do not reflect fast exhumation since 5 Ma, as the youngest age components are about 6 Ma for both rivers [24]. Therefore, the difference between short-term erosion rates and long-term exhumation rates observed in the Isère River drainage today are most likely caused by a much younger increase in overall erosion rates, which did not yet allow for sufficient exhumation to produce significant apatite and zircon grains with fission-track ages that reflect this increase, or the short-term erosion rates vary on a temporal scale that is not detectable (within the error-range) in the detrital thermochronologic record. Work by Valla *et al.* [43] using ^{4}He/^{3}He analyses on apatite from the external Alpine Aar and Aiguilles Rouges massifs indicates that relief formation and, therefore, more rapid erosion (at least on a local scale) is linked to enhanced glaciations starting at about 1–2 Ma.

7. Conclusions

Bedrock and detrital apatite and zircon fission-track thermochronologic data from the Isère River drainage in the Western Alps show no evidence for increasing erosion rates at 5 Ma. Detrital ZFT data of the Isère River and its tributaries have a range of apparent cooling ages from about 7 to 150 Ma. The fastest exhumation areas, the valley bottoms of the mountainous river drainages, are exhuming at long-term rates of about 0.5–0.6 km/Myr, with drainage basin average long-term exhumation rates on the order of 0.2–0.4 km/Myr. These first-order long-term exhumation rate estimates are slower than short-term erosion rates based on cosmogenic ^{10}Be analyses of Pelvoux massif river drainages. The increase in overall erosion rates, if real, is either much younger than 5 Ma (<2 Ma) and has been insufficient to exhume apatite and zircon with fission-track ages that reflect increasing erosion rates, or the short-term variations are insignificant on a million years' time-scale and within the error-range of detrital and bedrock fission-track thermochronology.

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Conflict of Interest

The author declares no conflict of interest.

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