Originally published as:

Gemignani, L., Sun, X., Braun, J., van Gerve, T. D., Wijbrans, J. R. (2017): A new detrital mica $^{40}\text{Ar}/^{39}\text{Ar}$ dating approach for provenance and exhumation of the Eastern Alps. - *Tectonics*, 36, 8, pp. 1521—1537.

DOI: <http://doi.org/10.1002/2017TC004483>

RESEARCH ARTICLE

10.1002/2017TC004483

Lorenzo Gemignani and Xilin Sun contributed equally to this work.

Key Points:

- New $^{40}\text{Ar}/^{39}\text{Ar}$ detrital thermochronology data from 19 modern river sand samples were compared with existing in situ thermochronology data
- A new quantitative mixing model approach of the detrital age distributions to map the present-day erosion from river's catchments
- The exhumation rates were calculated using classic lag time and age-elevation methods

Supporting Information:

- Supporting Information S1

Correspondence to:

L. Gemignani,
l.gemignani@vu.nl

Citation:

Gemignani, L., X. Sun, J. Braun, T. D. van Gerve, and J. R. Wijbrans (2017), A new detrital mica $^{40}\text{Ar}/^{39}\text{Ar}$ dating approach for provenance and exhumation of the Eastern Alps, *Tectonics*, 36, 1521–1537, doi:10.1002/2017TC004483.

Received 17 JAN 2017

Accepted 19 JUL 2017

Accepted article online 27 JUL 2017

Published online 11 AUG 2017

A new detrital mica $^{40}\text{Ar}/^{39}\text{Ar}$ dating approach for provenance and exhumation of the Eastern Alps

L. Gemignani¹ , Xilin Sun¹ , J. Braun^{2,3}, T. D. van Gerve¹, and J. R. Wijbrans¹
¹Department of Earth Sciences, Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, Amsterdam, Netherlands, ²GFZ Deutsches GeoForschungszentrum, Potsdam, Germany, ³ISTerre, Université Grenoble Alpes and CNRS, Grenoble, France

Abstract Detrital thermochronology can be used as a tool to quantitatively constrain exhumation rates and its spatial variability from active mountain belts. Commonly used methods for this purpose assume a steady state relationship between tectonic uplift and erosion. However, this assumption does not account for the transitory response of a dynamic orogenic system to changes in the boundary conditions. We propose a different approach that uses the observed detrital age distributions as “markers” of the past exhumation and of the present-day erosion and mixing occurring in a river system. In this paper, we present new $^{40}\text{Ar}/^{39}\text{Ar}$ biotite and white mica age distributions for 19 modern river sands from the Eastern Alps north of the Periadriatic line. The results present three main clusters of ages at ~0.5–50, ~60–120, and ~250–350 Ma that record the main orogenic phases in this sector of the Alps. We have applied two numerical methods to the cooling ages to (a) linearly compute the spatial variability of the relative present-day erosion of a set of four detrital mineral samples from drainage basins along the Inn River and (b) quantify the rates of the cooling and erosion in the Tauern Window during Paleocene-Miocene time of the Alpine orogeny. Our results suggest a 0.34–0.84 mm/yr range of exhumation rates for the Tauern Window since the Miocene. Our estimates of exhumation rates of the western Tauern Window are higher than those for the eastern Tauern Window, which is consistent with the previous studies.

1. Introduction

Topography in orogenic belts is the result of surface uplift of the rocks caused by the competition of internal tectonic forces and external surface processes, weathering and erosion, both acting to drive tectonic exhumation. The rate of erosion can be constrained by thermochronology on detritus in the sediment record in modern rivers, the foreland basin, or of minerals obtained from the bedrock as exposed in crystalline cores of mountain belts. Each of these different approaches has been applied to various sectors of the Alps to constrain exhumation and present-day erosion [Garver *et al.*, 1998; Carrapa *et al.*, 2004; Carrapa, 2009; Von Eynatten and Wijbrans, 2003; Wölfler *et al.*, 2016; Bertrand *et al.*, 2017]. Applications of detrital thermochronology on both retrowedge and prowedge basin sedimentary rocks have been applied on the Western Alps [Bernet *et al.*, 2004; Carrapa, 2009; Carrapa *et al.*, 2016; Garver *et al.*, 1998], Central Alps [Spiegel *et al.*, 2000, 2004; Von Eynatten and Wijbrans, 2003], and Eastern Alps [Kuhlemann *et al.*, 2006].

Rivers in the Alpine domain transport sediment from the high mountains to the foreland, and thus, their sediment load contains key information on sediment provenance, on the age range of rocks contributing to the sediment load, and on exhumation in the source area. However, so far, only relatively few studies have focused on the link between foreland basin record and mountain surface processes from Alpine river sediments [Bernet *et al.*, 2004, 2009; Carrapa *et al.*, 2004; Glotzbach *et al.*, 2011; Reiter *et al.*, 2013].

In the present study, we use $^{40}\text{Ar}/^{39}\text{Ar}$ dating of white mica and biotite single crystals using a laser fusion technique. White mica and biotite have limited resistance to physical abrasion and chemical weathering and relatively low closure temperatures (350–425°C and 300–350°C, respectively) [Harrison *et al.*, 2009; McDougall and Harrison, 2000] and therefore are well suited to reveal information concerning recent tectonic events in their source areas. White mica and biotite age signals record cooling and exhumation from crustal depths of ~10–12 km in the orogen, assuming a normal geothermal gradient of 25°C/km and commonly adopted values for the closure temperature for the two target minerals.

In recent years, detrital mineral data sets have been collected from the modern river sediments worldwide in several studies, and new numerical methods have been proposed to extract quantitative information about

the history and the lateral variation of the erosion/exhumation of active regions [e.g., *Ruhl and Hodges*, 2005]. *Brewer et al.* [2006], for example, used a new approach to a set of detrital samples from the Marsyandi River (Nepal) and its tributaries to derive, by mixing, the theoretical and observed detrital cooling age, and the variation of erosion rates from confined neighboring catchments. *Enkelmann and Ehlers* [2015] coupled detrital age distributions of low-temperature thermochronometers from river sand samples and from sedimentary basins to reconstruct the thermokinetic evolution of a glaciated landscape. Using a thermal model, *Bracciali et al.* [2016] compared their multithermochronometer data set with the computed heat flow solutions to infer the thermal evolution of the “pop-up” of the Namche Barwasyntaxis (Eastern Himalaya) coupled with the Siang-Brahmaputra River capture. However, most of such methods rely on the assumption of a steady state between tectonic uplift and erosion over known geological time intervals. This assumption precludes a test of the transitory response of the orogeny to changes in tectonic and climate forcing.

In this paper, we applied a new linear inversion approach (Mixing model) to the “raw” detrital age distributions from river sand samples to extrapolate information about the relative spatial-variability of the present-day erosion from catchments along the river trunk and from in-between tributaries. We use detrital cooling age peaks (bins), as a set of “colors” or “passive markers” that, without relying on any thermal parameters or steady state assumption, allow to infer the present-day mixing of different eroding sources in the river drainage system. The model is based on a limited number of important and measurable parameters that describe the lateral variation of lithologies among different exclusive catchments and on the binned raw age distributions. The bins are arbitrarily chosen to represent known tectonic events in the area under consideration. The method is highly dependent on the cooling-age distributions, and to test whether 20–40–60 single grains are representative of an entire catchment, we compared our age distributions with surface in situ dates from literature.

The Alps form an appropriate test case for such an approach, as there is a substantial database of ages obtained from minerals in the crystalline source rocks [i.e., *Hunziker et al.*, 1992; *Luth and Willingshofer*, 2008; *Scharf et al.*, 2013]. In the first part of the paper, we compare our new single grain river sand biotite and white mica age data from modern rivers with in situ thermochronology to test for consistency with the patterns found in crystalline basement rocks. In the second part of the paper, we apply our new numerical approach to three Inn River trunk catchments and to one of its lateral tributaries to predict the relative present-day erosion rates of the catchment areas. Finally, the detrital white mica and biotite cooling ages of five samples collected from three rivers draining the Tauern Window are used to constrain the relatively young (Miocene) exhumation of the area. Using this simple approach, we derive first-order exhumation rates of ~ 0.10 – 0.65 mm/yr for the ~ 45 – 7 Ma period.

2. Geological Summary of the Eastern Alps

The Alpine orogen is the result of the convergence, subduction and collision between the Adria and Eurasian plates since the Cretaceous [*Frisch et al.*, 1998; *Stampfli et al.*, 1998; *Berger and Bousquet*, 2008]. The current configuration of the Alps is caused by a complex geodynamic evolution characterized by three major orogenic phases known as Pre-Alpine or Variscan, Eo-Alpine, and Alpine. The Late Paleozoic Variscan orogeny affected the Austroalpine basement nappes (Figure 1) and was followed, in the Late Paleozoic–Mesozoic, by the breakup of Pangea leading to the rifting of the ocean basins of the Neothetys [*Handy et al.*, 2010]. The northern branch of the Neothetys refers to the opening during the Middle-Jurassic of the Meliata–Maliac–Vardar (Meliata) ocean and is kinematically linked to the rifting of the Atlantic Ocean [*Handy et al.*, 2010]. During the Early Cretaceous, the inversion of the Mesozoic basin-related extensional phase resulted in a new pulse of contractional deformation that closed the Meliata Ocean. During the Cretaceous orogenic phase, the Austroalpine acted as lower plate and was affected by the Eo-Alpine metamorphic overprinting [*Frisch and Gawlick*, 2003] (Figure 1). The Early Cretaceous orogeny that caused the stacking of the Austroalpine units in a pro-and-retro wedge position was followed by a prolonged period of extension during the Late Cretaceous. This extensional phase was accompanied by topography development and erosion, causing sediment deposition in intraorogenic sedimentary basins [*Dal Piaz et al.*, 2003; *Froitzheim et al.*, 1994]. A new stage of contractional deformation led during the Tertiary to the “Alpine” orogeny characterized by crustal-scale folding coupled with orogen-parallel extension and lateral-extrusion processes. Lateral extrusion, in turn, led to the exhumation and overthrusting of the high-grade rocks of

Figure 1. Simplified tectonic map of the Eastern Alps modified after Schmid *et al.* [2004]. The main litho-tectonic units are indicated in the legend together with the major tectonic discontinuities (red lines). The white stars indicate the samples location and the dotted blue lines the major river paths.

the Penninic units during the Cenozoic, whereas the upper plate Austroalpine units remained unaffected by tectonic overprinting because they were located in the upper crust [Schmid *et al.*, 2004, 2013; Stampfli *et al.*, 1998]. Alpine overprinting can be found in the metamorphic domes of the Eastern Alps located in the Tauern Window. Such domes formed due to the exhumation of deeply buried units during the Neogene [Neubauer *et al.*, 1999].

Our work is focused on the north verging sector of the Eastern Alps, north of the Periadriatic line. In this sector, the main tectonic terranes are from the internal to the external side of the Austroalpine nappe system (Adriatic passive continental margin), the Penninic metamorphic nappes system and the Helvetic zone that was thrust on top of the Molasse foreland (Figure 1). The Austroalpine nappes are made of sedimentary cover units and basement that underwent Early-mid Cretaceous (Eo-Alpine) metamorphism and that overthrust the Mesozoic Penninic units that bound the Tauern Window and the Engadin Window [Dal Piaz *et al.*, 2003; Schmid *et al.*, 2008]. The Austroalpine nappe complex includes the Northern Calcareous Alps (NCA), situated at the northern margin of the European accretionary wedge [Frisch and Gawlick, 2003], and crystalline units including ortho-gneisses, para-gneisses, and mafic intrusives, dykes, and gabbros of Permian age (reference to Mohn, Petri, Manatschal). The Austroalpine domains consist of pre-Alpine crystalline basement rocks, low-grade Paleozoic blocks (phyllitic and grauwacke rocks) and post-Variscan sedimentary sequences (calcareous rocks) [Frisch *et al.*, 1998]. The stacking in the Austroalpine nappe complex is classically related to the subduction of the Piedmont-Liguria Ocean during Cretaceous and to the collision, during the Tertiary, with the Penninic basement [Liu *et al.*, 2001; Pfiffner and Ellis, 2001].

2.1. The Tauern Window

In the Eastern Alps, the most recent exhumation associated with crustal-scale extension is localized along the axial zone of the belt, where the Penninic units of the Tauern Window show the youngest cooling ages as recorded by different thermochronometric systems in the region [Bertrand *et al.*, 2017; Frisch *et al.*, 1998;

Fodor *et al.*, 2008; Luth and Willingshofer, 2008; Rosenberg and Berger, 2009; Viola *et al.*, 2001; Wölfler *et al.*, 2011] (Figure 2). The Penninic units were overprinted during the burial and exhumed due to the gravitational collapse of the Eastern Alps coupled with substantial lateral extrusion toward the east along a conjugate system of shear zones during the Miocene [Frisch *et al.*, 1998; Ratschbacher *et al.*, 1991]. The Tauern Window and the Engadin Window have been described as a crustal-scale antiformal stack bounded by Austroalpine basement rocks [Liu *et al.*, 2001; Schmid *et al.*, 2013]. The present-day surface rock units and cooling ages of the Tauern Window present a contrasting cooling history when compared with the adjacent Austroalpine surrounding units. The exhumation of the Tauern Window, associated with localized deformation, occurred from early to late-Miocene [Rosenberg and Berger, 2009]. Lateral extrusion starting from the mid-Miocene was associated with an N-S contractional phase defined by the displacement at high angles to the strike of the mountain range [Neubauer *et al.*, 1999; Ratschbacher *et al.*, 1991; Robl *et al.*, 2008].

In situ thermochronology iso-age contours are subparallel to the axial plane of the large-scale folding, suggesting that folding coupled with erosion was the mechanism controlling the exhumation of the Tauern Window during Miocene [Bertrand *et al.*, 2017, and reference therein]. This interpretation is an alternative to models that emphasize the role of the eastward lateral extrusion associated with lateral extension components and subordinate N-S normal faulting [Frisch *et al.*, 1998; Neubauer *et al.*, 1999; Robl *et al.*, 2008] and argues for a more complex exhumation history where the steady state assumption may have been fulfilled only for limited periods of time starting from Late Oligocene [Neubauer *et al.*, 1999; Kuhlemann *et al.*, 2006]. In the Penninic units of the Tauern Window, a diachronous character of the cooling has been described in cooling maps displaying the results of different thermochronometers [e.g., Luth and Willingshofer, 2008]. Contrasting rates of Miocene exhumation from high to low between western and eastern sectors of the Tauern are derived from numerical inversion of low-temperature cooling ages [Bertrand *et al.*, 2017, and reference therein]. In the western Tauern Window, younger cooling ages postdate by ~5 Ma the age patterns found in the eastern sector of the window.

3. Detrital $^{40}\text{Ar}/^{39}\text{Ar}$ Analytical Method

Nineteen modern river sand samples were collected from rivers in the Eastern Alps between eastern Switzerland and Liechtenstein in the west, Austria in the center, and northeast Slovenia in the southeast of the study area (Figure 1 and Table 1). The sampling sites were chosen at least 1 km away from tributary junctions to the main trunk of the river and any landslides to avoid bias toward one particular source in the main river stream. Approximately 2 kg of medium-grained sand was collected from the top 10 cm sediment at each sampling location from the edge of the active river channel.

Biotite and muscovite were separated for radio-isotopic $^{40}\text{Ar}/^{39}\text{Ar}$ analysis. Mineral separation was performed using standard procedures in the mineral separation laboratory at the Vrije Universiteit of Amsterdam. Organic material was removed by density separation. The samples were sieved to obtain 400–200 μm grain size fractions. A Faul vibration table was used to separate the flat micas from the nonflat minerals. Biotite and muscovite were separated from each other by heavy liquid separation ($\rho_{\text{muscovite}} = 2.77\text{--}2.9 \text{ g cm}^{-3}$, $\rho_{\text{biotite}} = 2.9\text{--}3.3 \text{ g cm}^{-3}$) and by making use of the higher magnetic susceptibility of biotite in a Franz isodynamic magnetic separator. Finally, all samples were handpicked under a binocular microscope to remove any significant weathering variation or inclusions and to obtain 200–250 grains of pure muscovite and biotite.

After separation, the samples were wrapped in Al foil and loaded in 9 mm ID quartz tubes together with the monitor standard Drachenfelsanidine dated at $25.43 \pm 0.03 \text{ Ma}$. This value is compatible with the set of Kuiper *et al.* [2008]. Samples were irradiated at the Oregon State University TRIGA reactor in the CLICIT facility for 12 h. Muscovite and biotite ages determinations were conducted at the argon geochronology laboratory of the Vrije Universiteit of Amsterdam. Single white mica or biotite grains were loaded into a copper disk with 185 holes of 2 mm diameter and 3 mm depth. The copper disk was heated overnight at 150°C in an ultrahigh vacuum sample house fitted with a multispectral ZnS externally pumped double vacuum seal window. Single mica grains were fused under a 25 W Synrad CO_2 laser instrument. The gas was cleaned in a sample purification system by exposure to SAES St707 (Fe-V-Zr alloy) getters and a SAES NP50 getter device (Hiden based system) or a SAES NP10 getter (Helix system) each fitted with ST101 cartridges. The Ar isotope spectrum was analyzed on Thermo Fisher Helix MC+ multicollector noble gas mass

Table 1. Samples Locations^a

River	Lab-ID	Longitude	Latitude	Minerals
Rhein	EA1	9°39'39"	47°26'58"	Ms and Bt
Rhein	EA2	9°35'53"	47°13'59"	Ms and Bt
Inn	EA3	10° 4'45"	46°44'52"	Ms and Bt
Inn	EA4	10° 4'23"	46°44'58"	Ms and Bt
Inn	EA5	10° 38'14"	47° 6'50"	Ms and Bt
Inn	EA6	11° 4'27"	47°18'4"	Ms and Bt
Inn(Sill)	EA7	11°27'27"	47° 6'29"	Ms and Bt
Inn(Ziller)	EA8	11°51'51"	47°20'51"	Ms and Bt
Salzach	EA9	12°21'14"	47°16'18"	Ms and Bt
Salzach	EA10	13°11'47"	47°20'21"	Ms and Bt
Salzach	EA11	12°56'21"	47°56'32"	Ms and Bt
Tiroler	EA12	12°30'19"	47°49'10"	Ms
Enns	EA13	14° 5'15"	47°30'58"	Ms and Bt
Mur	EA14	15°13'50"	47°24'6"	Ms and Bt
Mur	EA15	15°31'27"	46°53'1"	Ms and Bt
Drau	EA16	15°29'51"	46°32'37"	Ms and Bt
Raab	EA17	15°45'5"	47° 3'44"	Ms and Bt
Raab	EA18	16° 9'57"	46°59'52"	Ms
Leitha	EA19	16°10'13"	47°43'44"	Ms

^aSummary of sample number, rivers, and locations expressed as longitude and latitude. Minerals indicate the type of target analysis (Ms = muscovite; Bt = biotite).

spectrometer (Helix) and Hiden HAL 3F Series 1000 Pulse Ion Counting Triple Filter quadrupole mass spectrometer.

A system blank was measured before every fifth sample measurement, and three blanks and two gas pipette air aliquots were analyzed at the start and the end of the tray measurement, respectively. Total system blank levels were approximately $2-6 \times 10^{-17}$ moles for ^{40}Ar and $0.5-6 \times 10^{-18}$ moles for ^{39}Ar , ^{38}Ar , and ^{36}Ar , and $1-2 \times 10^{-17}$ moles for ^{37}Ar . The data reduction software ArArCALC2.5 was used for data reduction and age calculation [Koppers, 2002]. Corrections were applied for ^{37}Ar and ^{39}Ar decay following sample irradiation and for procedure blanks.

4. Age Distributions and Comparison to Existing In Situ Ages

The analysis of detrital modern river sand samples has produced a remarkably representative fingerprint of the bedrock ages drained into the basin by erosional and tectonic (i.e., exhumation along faults zones) processes as demonstrated by several studies over the past decades [Bernet *et al.*, 2004; Brewer *et al.*, 2006; Garver *et al.*, 1998]. Three major exhumation pulses (Permo-Carboniferous, Late-Cretaceous, and Eocene-Miocene) are recorded for both biotite and white mica as shown in the composite total age probability density plots (PDPs) (Figure 2). The relative peaks of muscovite ages are generally higher for the Variscan and Eo-Alpine events in comparison with biotite ages that record mostly Alpine Cenozoic exhumation.

Figure 2. Composite probability density plots for the biotite distributions (continuous line) and for the muscovite (dotted line); On the x axis, the ages are expressed in million years and as a relative probability on the y axis. The number of single grain analysis is indicated for both the target minerals.

We compared the consistency of our detrital signal with existing in situ bedrock ages (references are shown in Figure 3). The contribution of the source to the drainage basins is tracked in the detrital age distribution by an age-related color code (Figure 3). The overall detrital mineral ages were plotted together as histograms and Kernel Density Estimator (KDEs) [Vermeesch, 2012]. Comparison of the detrital distributions with the in situ thermochronological data allows deriving multiple pieces of information. The first piece of information comes from the observed cooling-age distributions from the river samples, which give an insight into how much a cooling

Figure 3. Tectonic map and in situ bed rocks ages of the Eastern Alps. The major river network is indicated by the pale blue paths. The samples are indicated by the yellow stars. The square represents the muscovite data, the circle the biotite, and they are associated with a color code as explained in the legend. On the side, the boxes display the new $^{40}\text{Ar}/^{39}\text{Ar}$ plotted as Kernel Density Estimator (KDE) and as histograms with the same color code of the bed rock ages. The age range from 0 to 500 million years. The histograms and the KDEs for the biotite are mirrored and reflected on the upper side of the box, whereas white mica dates are on the bottom of the box. The numbers associated with the in situ cooling ages describe the references of the work as explained in the legend of the map. In each box, the number of analysis per target mineral is indicated.

event has imprinted the source surface unit rocks, under the assumption that it is representative of the entire catchment area. The second piece of information comes from the present-day mixing of the signal in the river, which gives an insight into the present-day erosion in the regional-scale geology. In this section, we will describe the river sand sample cooling age distributions and how they compare to the available in situ thermochronological data and which additional information they bring to our understanding of the regional scale tectonics.

Samples from the Rhine EA1 and EA2 sites and from the Inn EA3–EA5 sites contain minerals that originate in the internal Penninic and Austroalpine basement nappes and Northern Calcareous Alps. The bedrocks ages available for those basins area are varied and range from 400 Ma to ~10 Ma [Handy et al., 1996; Von Eynatten et al., 1996; Challandes et al., 2003; Wiederkehr et al., 2009]. Detrital mineral ages from the Rhine and Inn samples are consistent and homogeneous for the two target minerals, as 70% of the total distributions are in the range 298 ± 2 to 290 ± 2 Ma. Downstream from the Inn River, sample EA6 presents a more scattered distribution with muscovite peaks at ages 80 ± 20 Ma (40%), 300 ± 20 Ma (50%), and 250 Ma. The biotite ages of EA6 concentrate on a peak at 80 ± 20 Ma that includes 70% of the total distribution with the other 30% of measurements showing a broad scattering of older ages (Figure 3).

The Sill (EA7), Ziller (EA08), and the Salzach (EA9 and EA10) samples contain minerals from catchments draining the Penninic nappes of the Tauern Window. These samples yield muscovite and biotite grains younger than 50 Ma and are consistent with a major cluster of published in situ ages around Paleogene ages [Kurz et al., 2008; Liu et al., 2001; Ratschbacher et al., 2004; Scharf et al., 2013; Warren et al., 2012; Zimmermann et al., 1994]. Downstream, the Salzach sample (EA11) contains minerals coming from the external Austroalpine units toward the north. This sample displays a bimodal distribution in the biotite age population with two narrow peaks at 40 ± 5 and 300 ± 20 Ma. In the muscovite data set, the <50 Ma peak is dominant and represent 95% of the distribution, with one statistically unrepresentative single grain of 300 ± 20 Ma. The sample downstream of the Salzach basin (EA11) contains mostly muscovite and biotite grains that are derived from the Tauern Window.

Sample EA12 from the Tiroler Achen River received minerals from the Northern Calcareous Alps units; the detrital white mica ages distribution is made of a narrow peak at 300 Ma. The Enns (EA13) sample was collected in the middle of the Northern Calcareous Alps unit that is characterized by a range of muscovite bedrocks ages of 300–200 and 100–50 Ma [Liu *et al.*, 2001]. This sample yields a heterogeneous set of ages from 450 to 60 Ma in the biotite distribution, whereas the white mica ages from the same samples form a 90–60 Ma peak.

The Mur River where samples EA14 and EA15 were collected originates in the metamorphic internal zone of the Penninic nappes (Tauern Window) which has characteristic in situ ages of 0–50, 100–200, and 200–300 Ma and flows east toward the Austroalpine Nappe units [Liu *et al.*, 2001; Neubauer *et al.*, 1995; Scharf *et al.*, 2013]. Downstream from sample EA14 site located in the Northern Calcareous Alps units, the river bends southward and flows across the Austroalpine Nappes units and Cenozoic cover. The Mur detrital age distribution presents a narrow peak at 80 ± 20 Ma. The young (Miocene) age signal of the Tauern Window is not found in the distributions observed in the Mur river.

The Drau river (EA16) originates in the Penninic units of the Tauern Window south of the main ranges and drains along a west-to-east section of the internal units of the Austroalpine basement nappes. Published bedrocks ages are comprised of several intervals, i.e., 50–5 Ma, 100–50 Ma, 300–200 Ma, and 400–300 Ma [Ratschbacher *et al.*, 2004; Wiederkehr *et al.*, 2009] for the muscovite and 100–50 Ma for the biotite [Wiederkehr *et al.*, 2009]. This wide range of ages is recorded in our detrital muscovite data also, which display peaks clustering around 80 ± 3 Ma (70%), 300 ± 2 Ma (10%), 180 ± 2 Ma (5%), 140 ± 2 Ma (5%), and 47 ± 10 Ma (10%). A minor 10–30 Ma peak, related to the internal metamorphic core of the Tauern Window, is present in the biotite age distribution.

Samples EA17 and EA18 from the Raab river receive mineral grains from Austroalpine nappe, and Tertiary cover units that yield mostly pre-Variscan and Variscan age signatures and not Alpine overprinting as observed from several in situ age analyses [Dallmeyer *et al.*, 1998]. Our detrital muscovite age distribution shows peaks at 240–310 Ma, 310–300 Ma, and 200–80 Ma which is consistent with observed in situ ages. Sample EA19 (for which we only have a muscovite age distribution) is derived from a location draining the Northern Calcareous Alps and the Austroalpine basement nappes and present circa 70% of the muscovite ages ranging within 298 ± 2 Ma and 290 ± 2 reflecting a univocal Variscan range of ages.

As described above our detrital basin-related age distributions are generally comparable with the bedrocks ages, although information on in situ bed rock ages is by necessity more fragmentary. Interestingly, the most recent Alpine (<50 Ma) pulse of exhumation and metamorphism is spatially confined to the Tauern Window and Engadin Window and within the catchments draining those units (Figure 3). As pointed out earlier, these areas have experienced exhumation since the Oligocene along major normal faults during episodic lateral (E-W) extension in a convergent (N-S) steady regime [Ratschbacher *et al.*, 1991]. The < 50 Ma cooling signal is recorded in the tributaries draining the Tauern Window and is transported downstream in the Salzach river; but is not seen in the catchments of the Mur, Drau, and Enns rivers.

Those rivers mostly record pre-Alpine and Variscan exhumation of the Austroalpine units. The Variscan signal is pervasive and constitutes the major peak in all basins draining toward the northwest and in the rivers draining the Northern Calcareous Alps units.

5. Inversion of Age Distributions to Estimate Relative Present-Day Erosion

5.1. A New Approach to Extract Relative Present-Day Erosion Estimates From Detrital Age Data

In the study area, the detrital record yields a consistent picture of cooling ages in the downstream sediments of the Eastern Alps Rivers. To assess the spatial variability of the present-day erosion for each exclusive source draining into the Inn River basin, we use the age distributions of three samples along the Inn River trunk and one tributary draining into it.

We have developed a method based on the linear inversion of the raw binned age data points without involving any thermal calculation. Previous methods where a thermal model was used [i.e., Brewer *et al.*, 2006] tried to compare their data to theoretical density age distributions that rely on thermal model predictions. The use of the “raw” binned detrital ages allows us to avoid any complication or bias that may arise from assumptions about the past geothermal gradient or rock thermal conductivity and heat production. Such assumptions can

Table 2. Input Parameters Used for the Inversion of the Detrital Age Distributions^a

Sample	Position	Area (km ²)	α Value	Mineral
EA3	1	1345	0.75	Bt
EA4	-2	72	0.7	Bt
EA5	3	1571	0.35	Bt
EA6	4	2975	0.65	Bt
EA3	1	1345	0.7	Ms
EA4	-2	72	0.75	Ms
EA5	3	1571	0.4	Ms
EA6	4	2975	0.7	Ms

^aFitted parameters used for the inversion of the Inn basins age distributions. See equation (S1) in the supporting information.

lead to unnecessary uncertainty in interpreting the data. Due to the simplicity of its basic assumptions, our method is, however, highly limited by the number of samples in the age distribution (whether 10, 30, or 100) as each distribution/sample needs to contain a sufficient number of analyses to provide a robust interpretation that can be applied to an entire catchment area.

The method regards the ages as passive markers that define a characteristic signature of a given catch-

ment. The age distributions observed at different sites along the river are the results of mixing of these signatures that depend, among other things, on the mean present-day erosion in each catchment, i.e., with contributing areas to the sections of the river between successive sites. The relative size of these individual catchments also influences the mixing process as well as the relative concentration in surface rocks of the mineral used for the linear inversion. Recently, evidence of bias related to so-called mineral fertility or concentration (defined as the target mineral abundance in the source rocks) has been explored [Malusà *et al.*, 2016] within the Western Alps. In their work, Malusà *et al.* [2016] argue that any geological interpretation obtained from a detrital record in modern and ancient settings can be significantly improved when mineral fertility is properly considered. The importance of the estimation of mineral abundance in the source rocks (concentration factor α), to correctly interpret signal dilution over the length of a river convinced us that we should also take into account this factor.

Our approach was to give to each site along the river a position number that corresponds to the relative location of the site in the river network, and that is expressed as a progressively increasing (downstream) numerical value. The position is defined by a positive value for samples located in the main river trunk and by a negative value for the samples located in a tributary (second column in Table 2). The areas of the exclusive catchment corresponding to each site has been calculated from a DEM and is expressed in square kilometer (third column in Table 2). We call α (fourth column in Table 2) a semiquantitative estimate of the relative concentration of the dated mineral in the surface rocks of the corresponding catchment. To compute it, we make the simplifying assumption that rocks have an average mineral composition that can be estimated from the lithology as indicated on a geological map of the region for each exclusive area [Bigi *et al.*, 1990]. To do this, we overlapped the catchment areas on top of the geological map. We then estimated the number of surface units in the area assuming that, i.e., carbonate rocks of 40% of the total area would have produced nil concentration of white mica and biotite, although the 60% of medium- to high-grade metamorphic rocks would have contributed 60% of the total area. Because the concentration α is expressed as a relative number ($0 < \alpha_i < 1$), we derive a concentration of 0.6 of white mica and biotite.

In the supporting information, we give a detailed description of the method we have designed to retrieve this information from the data. The method yields estimates of present-day erosion, as well as estimates of the present-day distribution of ages in surface rocks for each catchment. The method works best when successive age distributions are markedly different from each other, implying that each successive exclusive catchment has a distinct signature that can be used to infer the mean erosion characterizing it. We also show how the method needs to be slightly modified to obtain independent relative erosion estimates from detrital age distributions measured in tributaries.

One drawback of our simple approach is that it cannot provide estimates of the confidence we should attach to our estimates of relative present-day erosion and surface rock age distributions in each catchment. In order to derive such an estimate, we used a bootstrapping method that relies on computing the relative present-day erosion and surface age distribution estimates from a large number of subsamples of the original data set by arbitrarily and randomly removing a set number of data points. Simple statistics are then applied to a large number of erosion estimates and surface rock age distributions.

Table 3. Results of the the Present-Day Erosion as Computed from the Mixing Model and Bootstrapping Approach^a

Locations	Mean Value	St. Deviation	Modal Value	Mineral
EA-03	0.957	0	0.672	Bt
EA-05	0.561	0.206	1.235	Bt
EA-06	1.481	0.825	1.032	Bt
EA-04	0.488	0.297	1.231	Bt
EA-03	0.411	0	0.314	Ms
EA-05	0.213	0.118	0.471	Ms
EA-06	2.376	1.346	1.629	Ms
EA-04	0.208	0.125	0.471	Ms

^aHere we show the computed relative present-day erosion for the two target minerals, standard deviation, and modal values obtained from the mixing model and bootstrapping procedure. Locations refer to the sample sites of Figure 5. Note that the numbers are relative.

5.2. Application of the Mixing Model to the Inn River Detrital Age Distributions

Mean present-day erosion estimates, their standard deviation, and modal values obtained by the inversion of the age distributions as described above are shown in Table 3. The observed age distributions and predicted concentrations of surface ages are displayed as normalized histograms in Figures 4a and 4b (from the biotite and white mica data, respectively). Predicted relative modal erosion together with the relative surface

age concentration for the muscovite and biotite are summarized in map form in Figure 5. The raw age data are available in the data repository.

Looking at the relative present-day erosion distributions obtained by using the bootstrapping technique (Table 3), we can see that the standard deviations are commonly large, i.e., of the order of 35–55% of the mean predicted erosion estimates for both the muscovite and the biotite age samples. We note also that,

Figure 4. Results of the computation of the age distribution. In the x axis, each double box represent one bin range expressed in Ma. From the origin of the x axis the bins are (1) 0–50 Ma, (2) 50–100 Ma, (3) 100–200 Ma, (4) 200–300 Ma, and (5) 300–500 Ma. In the y axis is expressed the normalized height of the bins (i.e., the number of grains in the bin range). (a) Observed surface distributions of ages (light grey) for the samples collected at locations showed in Figure 5 and (b) predicted surface age distributions (dark grey) in corresponding catchment areas for the biotite ages and for the muscovite.

Figure 5. (a) Topographic map, catchments area (light gray), and sample locations (red dots) used for the inversion. The Inn River and the flowing direction are indicated by the white arrow, and the main trunk river profile is displayed from A to B. Predicted modal present-day erosions and relative (normalized as the sum of the five bins is 1) concentrations of surface age distributions for the (b) biotite and (c) muscovite.

for both systems, the modal value is significantly smaller than the mean value where present-day erosion values are highest.

In each panel of Figure 4, the light gray bars represent, for each site, the observed age distributions in the detrital sample. The dark gray bars represent the distribution among the different age bins of the mean of the predicted relative surface concentrations obtained at each site from the bootstrapping procedure. Figure 4a is for the biotite ages, while Figure 4b is for the muscovite ages.

We note that, in general, the observed distributions substantially vary from one station to the next. This implies that the method should yield meaningful estimates of the relative present-day erosions in all catchments. Indeed, the data set does not suffer from the uncertainty that we describe above and results from the difficulty in interpreting two consecutive age distributions that are very similar.

We note that the distribution of predicted surface concentrations in the first catchment is not exactly equal to the observed distribution in the river sample, despite the method requiring that it be the case. This is because, at each step of the bootstrapping procedure, we generate a subsample that is different from the original data set, therefore, generating a mean set of surface concentrations that is similar but not identical to the observed, complete data set.

We also note that where the distribution of predicted surface concentrations (dark grey bars) are very similar to the observed distributions (light grey bars), such as for the white mica data at site EA6, it implies that the signal coming from the corresponding catchment dominates the signal in the river; in other words, this means that the local contribution strongly overprints the signal coming from upstream. This must mean that the erosion rate in the catchment must be high or that the catchment area is markedly larger than the cumulative upstream catchment area, which in the case of site EA6, is not true. This explains why the method predicts that, according to the white mica data, relative present-day erosion in catchment area EA6 is very large (Figure 5).

Figure 5 contains the same information as Figure 4 but displayed in a geographical manner to help interpret the results of the mixing model. For ease of interpretation, we have also normalized the estimated media values of erosion rate by their modal. Importantly, these remain relative values that should only be interpreted as giving us information about the spatial variability or gradient in relative present-day erosion, not its absolute value. We see that both data sets suggest an increase in relative present-day erosion downstream but that the biotite data favor the highest relative present-day erosion in the central section (catchment EA5) and the white mica in the lowest catchment (EA6). In view of the substantially larger number of ages in the muscovite data set, compared to the biotite data set, the conclusion arising from the white mica data should be preferred. Interestingly, both data sets predict a similar relative present-day erosion in the tributary (EA4) compared to its “parent” catchment (EA5), despite the fact that the observed distribution in the tributary is markedly different from that observed for the entire parent catchment. This demonstrates the strength of our method and the fact that its prediction in terms of erosion rate is independent of the absolute value of the ages in the observed distributions.

Finally, we note that the predicted surface concentrations of the youngest ages (0–200 Ma) are, in general, larger in the downstream catchments, while higher relative concentrations of older ages (200–400 Ma) are found in the upstream catchments.

5.3. Estimating Long-Term Exhumation Rate

5.3.1. Classic Lag Time Method

The exhumation rate can be roughly estimated using the cooling age and closure depth of closure temperature of mineral from river system

$$E_{\text{lag}} = Z_c / t_c = [(T_c - T_s) / D] / L \quad (1)$$

Where E_{lag} is the exhumation rate, Z_c is the closure depth of mineral, and t_o is the time for bringing mineral from closure depth to the surface which is approximately equal to L when the transport time is short in the maintains. T_s (20°C) is surface temperature and T_c is the closure temperature of mineral. The geothermal gradient of the Alps spans from 20°C/km to 45°C/km based on various methods. We chose the medium value ($D = 32.5^\circ\text{C}/\text{km}$) as geothermal gradient for this study. We assume that the closure temperature of muscovite and biotite are 350–425°C and 280–345°C, respectively [Hames and Bowring, 1994; Harrison et al., 2009]. Samples EA7–EA11 were collected from rivers originating in the Tauern Window (Figure 6). We chose the youngest age peak center of each sample as the cooling age (L). The detrital muscovite and biotite age distributions of these samples are used to constrain the average exhumation rate of the Tauern Window. Because surface rocks of the Tauern Window form only part of the catchment area of sample EA11 (Figure 6), we infer that the muscovite and biotite grains that form the young age peak of this sample

Figure 6. Results of the exhumation rates calculated from the Tauern Window using the lag-time (E_l) and age-elevation profile (E_e) methods. The shaded area is the Tauern Window. The dashed lines represent the sample catchment, and white lines represent the current river.

were derived from the Tauern Window, whereas the older muscovite grains originated from other areas (e.g., Austroalpine units). Based on equation (1) and detrital muscovite and biotite ages (Figure 3), the approximate exhumation rate for each sample was calculated. The results are shown in Figure 6. EA7 yield highest exhumation rate (Ms: 0.68–0.84 mm/yr and Bt: 0.52–0.65 mm/yr) among five samples compared with EA11 has lowest exhumation rate (Ms: 0.37–0.46 mm/yr and Bt: 0.34–0.42 mm/yr). In general, the exhumation rates calculated from muscovite are higher than those of biotite in all five samples.

5.3.2. Detrital Age-Elevation Method

Comparing detrital ages and bedrock ages suggests that almost all young micas (<50 Ma) were derived from the Tauern Window (section 3). These young mica ages are therefore likely to mostly provide information about the exhumation rate in the Tauern Window. The white mica and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages record the time taken for each mineral to be exhumed from the depth of its closure temperature to the surface (assuming that the surface transport time, i.e., of the order of thousands of years is short compared to the time necessary for exhumation, i.e., of the order of millions of years). Consequently, a cooling age can be used to calculate a first-order approximation of the exhumation rate, E , according to

$$E = R_{\text{range}}/t_{\text{range}} = (Z_{\text{max}} - Z_{\text{min}})/(t_{\text{max}} - t_{\text{min}}) \quad (2)$$

where Z_{max} and Z_{min} are the highest and lowest elevations, respectively, and t_{max} and t_{min} are the oldest and youngest ages in a given catchment/sample, respectively. We make the simplifying assumption that the

difference between highest elevation ($Z_{\max}$) and lowest elevation ($Z_{\min}$) is the main cause for the difference between the oldest ($t_{\max}$) and youngest ($t_{\min}$) ages observed in a given distribution. The youngest, respectively oldest, detrital muscovite or biotite ages in a river sample are expected to originate from the lowest, respectively highest, elevation. The validity of this assumption can be evaluated by comparing the hypso-metric curve computed in the catchment and the observed cooling age cumulative curve (Figure 6). If the two curves are similar, our assumption is valid and we can derive from it the first-order estimation of exhumation rate, E .

Based on the detrital age and elevation data, we calculated an approximate value for the exhumation rate for every sample catchment (EA7–EA11) over the time range (~5–47 Ma) (Figure 6), by using equation (2). The results are shown in Figure 6. They confirm that the exhumation rate of samples from the western Tauern Window is higher than east, in general, which is consistent with the younger muscovite and biotite ages in the western Tauern Window. The exhumation rates based on biotite data of samples EA7 (0.28 mm/yr) and EA8 (0.30 mm/yr) are similar but are lower than those of EA7 (0.52 mm/yr) and EA8 (0.64 mm/yr) calculated from white mica data of same sample for the period that ranges from ~8 to 25 Ma. However, muscovite and biotite ages of samples (EA9–EA11) from the eastern Tauern Window yield similar exhumation rate. Note that for samples EA09–EA11 that contain surficial rocks from an area that drains also Austroalpine units, we only use the young (<50 Ma) ages to calculate the exhumation rates. The discrepancies in exhumation rate between samples as well as between target mineral's estimates (i.e., EA7 and EA8) are also insignificant.

6. Discussion

6.1. Relative Present-Day Erosion

The Inn River originates in the pre-Alpine basement of the Grisons-Bernina units (Austroalpine) and crosses the Cenozoic Penninic nappes of the Engadin Window in the upper reaches of the river (Figures 1 and 2). The observed detrital age distributions of this area record mostly pre-Alpine metamorphism and exhumation (compare gray histogram bars in Figure 4). From the inversion of the detrital ages the highest present-day erosion estimates are predicted to occur in the lower part of the main trunk (sample EA06). Interestingly, there is a good correlation between catchments where high concentrations of young surface ages (0–50 Ma and 50–100 Ma) are seen and catchments where higher present-day erosions are predicted by the inversion. Similarly, in the inversion predictions, there is a good correspondence between the predicted lower present-day erosion estimates and the size of older age bins generated by the algorithm (compare the central panel displaying the predicted relative present-day erosion with the top/bottom panels showing the relative age concentrations of Figures 5b and 5c). Note that the relative erosion estimates inferred with the new method are obtained by considering the ages as passive markers. The predicted surface concentrations are also independent of what the ages mean (i.e., whether they are old or young). The fact that younger surface ages are found in the fastest-eroding catchment (and vice versa) must be regarded as an independent confirmation of the predicted relative present-day erosions and that this gradient in erosion rate has existed for some time. There could be situations where surface ages in the fastest-eroding catchments are older than those in the slower-eroding catchments. This would indicate that the present-day erosion is relatively recent and have not been sustained for sufficiently long periods of time to reset the ages set by a previous tectonic event to younger values [Braun, 2016].

We describe an increase of the predicted values of relative erosion downstream in the Inn trunk river (Figure 5). This is associated with the relative change in the age distributions between EA3 and EA6, which shows an increase of younger bin ages (5–100 Ma) ages in the downstream catchments. This contribution is probably related to the inset in the river system of sediments eroded from the younger Penninic units of the Engadin Window. For example, from the inversion of the white mica ages, the large difference in the predicted concentration of ages of the 50–100 Ma bin between EA6 and its upstream catchments (EA4 and EA5), only can be explained by one step increase of the erosion of the younger surface rocks units contributing to the downstream.

As observed earlier, the new method works well with our data set because the age distributions are very different from one site along the river to the next and the information they contain can be used to derive relative present-day erosion, independently of the absolute age values. Because the absolute ages are very old, in

part because the closure temperature of the systems being considered is relatively high, they contain relatively little information concerning the present-day erosion rate.

In summary, the inversion of the binned detrital age distributions has allowed us to quantitatively constrain the spatial variability of the relative present-day erosion along the Inn River.

6.2. Late-Oligocene-Miocene Exhumation Rates

The rapid exhumation of the Tauern Window commenced from the late Oligocene-early Miocene [Luth and Willingshofer, 2008; Schneider *et al.*, 2013]. This is supported by the younger muscovite and biotite ages for samples (EA7 and EA8) from the western Tauern Window when compared with samples (EA9–EA11) from the eastern Tauern Window (Figure 3). Both samples EA7 and EA8 come from points where the sediment load in the river drains from a relatively small part of the total drainage area covered by the Tauern Window. The classic lag time method and age-elevation method both show that the exhumation rates of EA7 and EA8 from the western Tauern Window are higher than those of EA9–EA11 from the east, which is consistent with the previous studies based on the thermochronological data [Bertrand *et al.*, 2017; Wölfler *et al.*, 2011, 2016]. This could be caused by a westward increase of shortening, leading to a westward increasing of vertical thickening and exhumation rate [Bertrand *et al.*, 2017]. The exhumation rates calculated from the classic lag-time method are higher than those of the corresponding sample estimated from age-elevation method (Figure 6). Moreover, the exhumation rates are about 0.5–0.9 mm/yr during 20–10 Ma in the western Tauern Window based on various thermochronometric data [Bertrand *et al.*, 2017; Fox *et al.*, 2016, and references therein] and are generally in agreement with those derived from the classic lag-time method. Therefore, the exhumation rates estimated from age-elevation method could be to some extent underestimated due to a limited number of analyzed grains. The exhumation rates calculated from muscovite and biotite using classic lag-time method are generally consistent when compared to those using age-elevation method (Figure 6). The exhumation rates derived from biotite using age-elevation method is significantly lower than those estimated from classic lag-time method and bedrock ages. The hypsometric curve and cooling age cumulative curve of sample EA7 and EA8 are more similar than in any other sample except biotite in EA7 (Figure 6), implying that the exhumation rates obtained for these two samples are the more reliable. The lower exhumation rates estimate for EA10 and EA11 might be due to their larger river catchment which provided older mica to these two samples from Austroalpine units.

7. Conclusions

We have demonstrated here that using detrital age data obtained from modern river sands in the Eastern Alps, we were able to derive first-order information on the spatial variability in exhumation rate averaged over large segments of the belt. We also predicted the distribution of in situ bedrock ages exposed in each drainage basin that was assessed. The age distributions were compared with published in situ ages and used to refine the existing information on the relative contribution of different units to the erosion and consequently to river sediment load. Three main exhumation pulses, classically described within the Alps as Variscan (~350–300 Ma), Pre-Alpine (~100–50 Ma), and Alpine (~50–5 Ma) are clearly recorded in our data set.

We applied a new numerical approach to the detrital age distributions, in order to get first-order magnitude about the relative present-day erosion and the mixing of the different sources in the main river trunk. This relatively simple method has the advantage of looking at the raw age distribution as reliable markers of the amount, extent, and lateral variability of the erosional processes happening in adjacent catchments. We constrained, using a bootstrapping approach the uncertainties (σ) of our estimates that are generally high. Despite large errors, we can infer the downstream evolution of the present-day erosion in the Inn River.

Our model shows that low erosion characterizes the catchments that drain the Austroalpine units (EA3–EA5) for both target minerals. A twofold increase of the present-day erosion estimates is recorded in the downstream EA06 sample where a clear input of younger surface ages from the Penninic units of the western Tauern Window and Engadin Window is added to the signal derived from erosion of Austroalpine units.

Based on the white mica and biotite age distributions derived from the Tauern Window, we compared catchment age-elevation relationship to estimate exhumation rates over the ~5–47 Ma interval. We derived the

higher estimates of the exhumation rates from smaller-size catchments draining the western sector of the Tauern Window (sample EA8 from the Ziller River). The exhumation rates calculated from the classic lag-time method and bedrock ages are generally comparable, which is higher than those from the age-elevation method. The lowest exhumation rate estimates (0.11 mm/yr and 0.34 mm/yr) are found in the eastern parts of the Tauern Window (EA11, Salzach River). Our estimates are consistent with previous studies, and highlight the asymmetric cooling evolution of the western and eastern sector of the Tauern Window during Miocene. This work also demonstrates the strength of single grain Ar-dating of detrital mica minerals, to constrain the past and present exhumation history of a given tectonic area. From the analysis of modern detritus, in addition, we derive a reliable picture of the provenance of the contributing sources in the Eastern Alps as previously done using ZFT dating, or $^{40}\text{Ar}/^{39}\text{Ar}$ dating in the southern Alps and Himalayas [Bernet *et al.*, 2001; Brewer *et al.*, 2006; Carrapa *et al.*, 2004]. We also demonstrate that modern river catchment-related thermochronology is sufficiently precise to characterize the tectonic history of middle- to high-grade rocks within an actively deforming mountain orogen. However, further improvements are needed to precisely unravel the dynamics of transport and comminution of the target minerals from the source to the basin and the bias that could result from differences in the so-called mineral abundance (concentration factor) within the source rocks.

Acknowledgments

We much appreciated the useful discussions with Marco Malusà and Franz Neubauer. We are grateful to Barbara Carrapa and an anonymous reviewer as well as the Editor who improved the quality of this manuscript. Roel van Elsas is acknowledged for his strategic help and support in the mineral separation laboratory at the VU Amsterdam. We want to thank Christel Bontje and Bertram Uunk for their support during total fusion analysis at Ar-Laboratory of the VU, Amsterdam. The results and analysis presented here were supported by the FP7/People/2012/ITN, grant 316966. The data for this paper are included in the 706-page manuscript and associated with the Data Repository Eastern Alps at the following URL: https://figshare.com/articles/Data_Repository_Eastern_Alps_xlsx/5031410. This work is dedicated to the memory of our extraordinary colleague, Gwladys Govin.

References

- Berger, A., and R. Bousquet (2008), Subduction-related metamorphism in the Alps: Review of isotopic ages based on petrology and their geodynamic consequences, in *Tectonic Aspects of the Alpine-Dinaride-Carpathian System*, edited by S. Siegesmund, B. Fugenschuh, and N. Froitzheim, *Geol. Soc. Spec. Publ.*, 298, 117–144, doi:10.1144/SP298.7.
- Bernet, M., M. Zattin, J. I. Garver, M. T. Brandon, and J. A. Vance (2001), Steady-state exhumation of the European Alps, *Geology*, 29(1), 35–38, doi:10.1130/0091-7613.
- Bernet, M., M. T. Brandon, J. I. Garver, and B. Molitor (2004), Downstream changes of Alpine zircon fission-track ages in the Rhône and Rhine Rivers, *J. Sediment. Res.*, 74(1), 82–94, doi:10.1306/041003740082.
- Bernet, M., M. Brandon, J. Garver, M. L. Balestrieri, B. Ventura, and M. Zattin (2009), Exhuming the Alps through time: Clues from detrital zircon fission-track thermochronology, *Basin Res.*, 21(6), 781–798, doi:10.1111/j.1365-2117.2009.00400.x.
- Bertrand, A., C. Rosenberg, A. Rabaute, F. Herman, and B. Fugenschuh (2017), Exhumation mechanisms of the Tauern Window (Eastern Alps) inferred from apatite and zircon fission track thermochronology, *Tectonics*, 36, 207–228, doi:10.1002/2016TC004133.
- Bigi, G., A. Castellarin, M. Coli, G. V. Dal Piaz, R. Sartori, P. Scandone, and G. B. Vai (1990), Structural model of Italy, sheets 1–2: CNR, Progetto Fin. Geodinamica, SELCA Firenze.
- Bracciali, L., R. R. Parrish, Y. Najman, A. Smye, A. Carter, and J. R. Wijbrans (2016), Plio-Pleistocene exhumation of the eastern Himalayan syntaxis and its domal “pop-up,” *Earth Sci. Rev.*, 160, 350–385, doi:10.1016/j.earscirev.2016.07.010.
- Braun, J. (2016), Strong imprint of past orogenic events on the thermochronological record, *Tectonophysics*, 683(2016), 325–332, doi:10.1016/j.tecto.2016.05.046.
- Brewer, I. D., D. W. Burbank, and K. V. Hodges (2006), Downstream development of a detrital cooling-age signal: Insights from $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite thermochronology in the Nepalese Himalaya, *Geol. Soc. Am. Spec. Pap.*, 2398(20), 321–338, doi:10.1130/2006.2398(20).
- Carrapa, B. (2009), Tracing exhumation and orogenic wedge dynamics in the European Alps with detrital thermochronology, *Geology*, 37(12), 1127–1130, doi:10.1130/G30065A.1.
- Carrapa, B., A. Di Giulio, and J. Wijbrans (2004), The early stages of the Alpine collision: An image derived from the upper Eocene-lower Oligocene record in the Alps-Apennines junction area, *Sediment. Geol.*, 181, doi:10.1016/j.sedgeo.2004.05.015.
- Carrapa, B., A. Di Giulio, N. Mancin, D. Stockli, R. Fantoni, A. Hughes, and S. Gupta (2016), Tectonic significance of Cenozoic exhumation and foreland basin evolution in the Western Alps, *Tectonics*, 35, 1892–1912, doi:10.1002/2016TC004132.
- Challandes, N., D. Marquer, and I. M. Villa (2003), Dating the evolution of C-S microstructures: A combined $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating and UV laser probe analysis of the Alpine Rofna shear zone, *Chem. Geol.*, 197(1–4), 3–19, doi:10.1016/S0009-2541(02)00354-6.
- Dal Piaz, G. V., A. Bistacchi, and M. Massironi (2003), Geological outline of the Alps, *Episodes*, 26(3), 175–180, doi:10.18814/epiugs/2003/v26i3/62456.
- Dallmeyer, R. D., R. Handler, F. Neubauer, and H. Fritz (1998), Sequence of thrusting within a thick-skinned tectonic wedge: Evidence from $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb-Sr ages from the Austroalpine Nappe Complex of the Eastern Alps, *J. Geol.*, 106(1), doi:10.1086/516008.
- Enkelmann, E., and T. A. Ehlers (2015), Evaluation of detrital thermochronology for quantification of glacial catchment denudation and sediment mixing, *Chem. Geol.*, 411(C), 299–309.
- Fodor, L. I., et al. (2008), Miocene emplacement and rapid cooling of the Pohorje pluton at the Alpine-Pannonian-Dinaridic junction, Slovenia, *Swiss J. Geosci.*, 101, 255–271, doi:10.1007/s00015-008-1286-9.
- Fox, M., F. Herman, S. D. Willett, and S. M. Schmid (2016), The exhumation history of the European alps inferred from linear inversion of thermochronometric data, *Am. J. Sci.*, 316(6), 505–541, doi:10.2475/06.2016.01.
- Frisch, W., and H.-J. Gawlick (2003), The nappe structure of the central Northern Calcareous Alps and its disintegration during Miocene tectonic extrusion—A contribution to understanding the orogenic evolution of the Eastern Alps, *Int. J. Earth Sci. (Geologische Rundschau)*, 92(5), 712–727, doi:10.1007/s00531-003-0357-4.
- Frisch, W., J. Kuhlemann, I. Dunkl, and A. Brügel (1998), Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion, *Tectonophysics*, 297, 1–15, doi:10.1016/S0040-1951(98)00160-7.
- Froitzheim, N., S. M. Schmid, and P. Conti (1994), Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden, *Eclogae Geol. Helv.*, 87(2), 561–607, doi:10.5169/seals-167471.
- Garver, J. I., M. T. Brandon, M. Roden-Tice, and P. J. J. Kamp (1998), Exhumation history of orogenic highlands determined by detrital fission-track thermochronology, *Geol. Soc. Spec. Publ.*, 154, 283–304.

- Glottzbach, C., M. Bernet, and P. van der Beek (2011), Detrital thermochronology records changing source areas and steady exhumation in the Western European Alps, *Geology*, 39(3), 239–242, doi:10.1130/G31757.1.
- Hames, W. E., and S. A. Bowring (1994), An empirical evaluation of the argon diffusion geometry in muscovite, *Earth Planet. Sci. Lett.*, 124, 161–169.
- Handy, M. R., M. Herwegh, B. S. Kamber, R. Tietz, and I. M. Villa (1996), Geochronologic, petrologic and kinematic constraints on the evolution of the Err-Platta boundary, part of fossil continent-ocean suture in the Alps (Eastern Switzerland), *Schweiz. Mineral. Petrogr. Mitt.*, 76, 453–474.
- Handy, M. R., S. M. Schmid, R. Bousquet, E. Kissling, and D. Bernoulli (2010), Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps, *Earth-Sci. Rev.*, 102, 121–158, doi:10.1016/j.earscirev.2010.06.002.
- Harrison, T. M., J. Clerier, A. B. Aikman, J. Hermann, and M. T. Heizler (2009), Diffusion of ^{40}Ar in muscovite, *Geochim. Cosmochim. Acta*, 73(4), 1039–1051, doi:10.1016/j.gca.2008.09.038.
- Hunziker, J. C., J. Desmons, and A. J. Hurford (1992), Thirty-two years of geochronological work in Central and Western Alps: A review on seven maps, *Memor. de Geol.*, (Lausanne), No. 13.
- Koppers, A. A. P. (2002), ArArCALC-software for $^{40}\text{Ar}/^{39}\text{Ar}$ age calculations, *Comput. Geosci.*, 28(5), 605–619, doi:10.1016/S0098-3004(01)00095-4.
- Kuhlemann, J., I. Dunkl, A. Brugel, C. Spiegel, and W. Frisch (2006), From source terrains of the Eastern Alps to the Molasse Basin: Detrital record of non-steady-state exhumation, *Tectonophysics*, 413(3–4), 301–316, doi:10.1016/j.tecto.2005.11.007.
- Kuiper, K. F., A. Deino, F. J. Hilgen, W. Krijgsman, P. R. Renne, and J. R. Wijbrans (2008), Synchronizing rock clocks of Earth history, *Science*, 320(5875), 500–504, doi:10.1126/science.1154339.
- Kurz, W., R. Handler, and C. Bertoldi (2008), Tracing the exhumation of the eclogite zone (Tauern window, Eastern Alps) by $^{40}\text{Ar}/^{39}\text{Ar}$ dating of white mica in eclogites, *Swiss J. Geosci.*, 101(S1), 191–206, doi:10.1007/s00015-008-1281-1.
- Liu, Y., J. Genser, R. Handler, G. Friedl, and F. N. (2001), $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite ages from the Penninic-Austroalpine plate boundary, Eastern Alps, *Tectonics*, 20, 526–547, doi:10.1029/2001TC900011.
- Luth, S. W., and E. Willingshofer (2008), Mapping of the post-collisional cooling history of the Eastern Alps, *Swiss J. Geosci.*, 101(S1), 207–223, doi:10.1007/s00015-008-1294-9.
- Malus, M. G., A. Resentini, and E. Garzanti (2016), Hydraulic sorting and mineral fertility bias in detrital geochronology, *Gondwana Res.*, 31, 1–19, doi:10.1016/j.gr.2015.09.002.
- McDougall, I., and T. M. Harrison (2000), *Geochronology and thermochronology by the $^{40}\text{Ar}/^{39}\text{Ar}$ method*, 2nd ed., Oxford Univ. Press, New York, doi:10.1093/petrology/41.12.1823.
- Neubauer, F., R. D. Dallmeyer, I. Dunkl, and D. Schirnik (1995), Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: Kinematics, cooling history and sedimentary response in a sinistral wrench corridor, *Tectonophysics*, 242, 79–98, doi:10.1016/0040-1951(94)00154-2.
- Neubauer, F., J. Genser, W. Kurz, and X. Wang (1999), Exhumation of the Tauern window, Eastern Alps, *Phys. Chem. Earth Part A*, 24(8), 675–680.
- Pfiffner, O. A., and S. Ellis (2001), Collision tectonics in the Swiss Alps: Insight from geodynamic modeling, *Tectonics*, 19, 1065–1094.
- Ratschbacher, L., W. Frisch, H.-G. Linzer, and O. Merle (1991), Lateral Extrusion in the Eastern Alps, Part 2: Structural analysis, *Tectonics*, 10(2), 257–271.
- Ratschbacher, L., C. Dingeldey, C. Miller, B. R. Hacker, and M. O. McWilliams (2004), Formation, subduction, and exhumation of Penninic oceanic crust in the Eastern Alps: Time constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, *Tectonophysics*, 394(3–4), 155–170, doi:10.1016/j.tecto.2004.08.003.
- Reiter, W., S. Elfert, C. Glottzbach, M. Bernet, and C. Spiegel (2013), Relations between denudation, glaciation, and sediment deposition: Implications from the Plio-Pleistocene Central Alps, *Basin Res.*, 25, 659–674, doi:10.1111/bre.12023.
- Robl, J., K. Stwe, S. Hergarten, and L. Evans (2008), Extension during continental convergence in the Eastern Alps: The influence of orogen-scale strike slip faults, *Geology*, 36(12), 963–966, doi:10.1130/G25294A.1.
- Rosenberg, C. L., and A. Berger (2009), On the causes and modes of exhumation and lateral growth of the Alps, *Tectonics*, 28, TC6001, doi:10.1029/2008TC002442.
- Ruhl, K. W., and K. V. Hodges (2005), The use of detrital mineral cooling ages to evaluate steady state assumptions in active orogens: An example from the central Nepalese Himalaya, *Tectonics*, 24, TC4015, doi:10.1029/2004TC001712.
- Scharf, A., M. R. Handy, S. Favaro, S. M. Schmid, and A. Bertrand (2013), Modes of orogen-parallel stretching and extensional exhumation in response to microplate indentation and roll-back subduction (Tauern Window, Eastern Alps), *Int. J. Earth Sci.*, 102(6), 1627–1654, doi:10.1007/s00531-013-0894-4.
- Schmid, S. M., B. Fgenschu, E. Kissling, and R. Schuster (2004), Tectonic map and overall architecture of the Alpine orogen, *Eclogae Geol. Helv.*, 97(1), 93–117, doi:10.1007/s00015-004-1113-x.
- Schmid, S. M., D. Bernoulli, B. Fgenschu, L. Matenco, S. Schefer, R. Schuster, M. Tischler, and K. Ustaszewski (2008), The Alpine-Carpathian-Dinaridic orogenic system: Correlation and evolution of tectonic units, *Swiss J. Geosci.*, 101, 139–183, doi:10.1007/s00015-008-1247-3.
- Schmid, S. M., A. Scharf, M. R. Handy, and C. L. Rosenberg (2013), The Tauern window (Eastern Alps, Austria): A new tectonic map, with cross-sections and a tectonometamorphic synthesis, *Swiss J. Geosci.*, 106(1), 1–32, doi:10.1007/s00015-013-0123-y.
- Schneider, S., K. Hammerschmidt, and C. L. Rosenberg (2013), Dating the longevity of ductile shear zones: Insight from $^{40}\text{Ar}/^{39}\text{Ar}$ in situ analyses, *Earth and Planetary Sci. Lett.*, 369–370, 43–58, doi:10.1016/j.epsl.2013.03.002i.
- Spiegel, C., J. Kuhlemann, I. Dunkl, W. Frisch, H. Von Eynatten, and K. Balogh (2000), The erosion history of the Central Alps: Evidence from zircon fission track data of the foreland basin sediments, *Terra Nova*, 12(4), 163–170, doi:10.1046/j.1365-3121.2000.00289.x.
- Spiegel, C., W. Siebel, J. Kuhlemann, and W. Frisch (2004), Toward a comprehensive provenance analysis: A multi-method approach and its implications for the evolution of the Central Alps, *Geol. Soc. of Am.*, 378, 37–50, doi:10.1130/0-8137-2378-7.37.
- Stampfli, G. M., J. Mosar, D. Marquer, R. Marchant, T. Baudin, and G. Borel (1998), Subduction and obduction processes in the Swiss Alps, *Tectonophysics*, 296, 159–204, doi:10.1016/S0040-1951(98)00142-5.
- Vermeech, P. (2012), On the visualisation of detrital age distributions, *Chem. Geol.*, 312–313, 190–194, doi:10.1016/j.chemgeo.2012.04.021.
- Viola, G., N. S. Mancktelow, and D. Seward (2001), Late Oligocene-Neogene evolution of Europe-Adria collision: New structural and geochronological evidence from the Giudicarie fault system (Italian Eastern Alps), *Tectonics*, 20, 999–1020, doi:10.1029/2001TC900021.
- Von Eynatten, H., R. Gaupp, and J. R. Wijbrans (1996), $^{40}\text{Ar}/^{39}\text{Ar}$ laser-probe dating of detrital white micas from Cretaceous sedimentary rocks of the Eastern Alps: Evidence for Variscan high-pressure metamorphism and implications for Alpine orogeny, *Geology*, 24(8), 691–694, doi:10.1130/0091-7613(1996)024<0691:AALPDO>2.3.CO;2.

- Von Eynatten, H., and J. R. Wijbrans (2003), Precise tracing of exhumation and provenance using $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of detrital white mica: The example of the Central Alps, *Geol. Soc. Spec. Publ.*, 208(1), 289–305, doi:10.1144/GSL.SP.2003.208.01.14.
- Warren, C. J., A. J. Smye, S. P. Kelley, and S. C. Sherlock (2012), Using white mica $^{40}\text{Ar}/^{39}\text{Ar}$ data as a tracer for fluid flow and permeability under high-P conditions: Tauern Window, Eastern Alps, *J. Metamorph. Geol.*, 30(1), 63–80, doi:10.1111/j.1525-1314.2011.00956.x.
- Wiederkehr, M., M. Sudo, R. Bousquet, A. Berger, and S. M. Schmid (2009), Alpine orogenic evolution from subduction to collisional thermal overprint: The $^{40}\text{Ar}/^{39}\text{Ar}$ age constraints from the Valaisan Ocean, central Alps, *Tectonics* 28, TC6009, doi:10.1029/2009TC002496.
- Wölfler, A., W. Kurz, H. Fritz, and K. Stüwe, (2011), Lateral extrusion in the Eastern Alps revisited: Refining the model by thermochronological, sedimentary, and seismic data, *Tectonics*, 30, TC4006, doi:10.1029/2010TC002782.
- Wölfler, A., W. Kurz, H. Fritz, C. Glotzbach, and M. Danišík (2016), Late Miocene increasing exhumation rates in the eastern part of the Alps—Implications from low temperature thermochronology, *Terra Nova*, 28(5), 297–305, doi:10.1111/ter.12221.
- Zimmermann, R., K. Hammerschmidt, and G. Franz (1994), Eocene high pressure metamorphism in the Penninic units of the Tauern Window (Eastern Alps): Evidence from ^{40}Ar – ^{39}Ar dating and petrological investigations, *Contrib. Mineral. Petrol.*, 117(2), 175–186, doi:10.1007/BF00286841.