Revealing exhumation of the central Alps during the Early Oligocene by detrital zircon U–Pb age and fission-track double dating in the Taveyannaz Formation

Gang Lu^{1,2} · Maria Giuditta Fellin¹ · Wilfried Winkler¹ · Meinert Rahn³ · Marcel Guillong¹ · Albrecht von Quadt¹ · Sean D. Willett¹

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Abstract

The late Eocene-to-early Oligocene Taveyannaz Formation is a turbidite series deposited in the Northern Alpine Foreland Basin (close to the Alpine orogenic front). Double dating of zircons with the fission-track and the U–Pb methods is applied on samples from the Taveyannaz Formation to reconstruct the exhumation history of the Central-Western Alps and to understand the syn-collisional magmatism along the Periadriatic lineament. Three samples from this unit show similar detrital zircon fission-track age populations that center at: 33–40 Ma (20%); 69–92 Ma (30–40%); and 138–239 Ma (40–50%). The youngest population contains both syn-volcanic and basement grains. Combined with zircon U–Pb data, it suggests that the basement rocks of Apulian-affinity nappes (Magna Sesia, Austroalpine) were the major sources of detritus, together with the Ivrea Zone and recycled Prealpine flysch, that contributed debris to the Northern Alpine Foreland Basin. Furthermore, the rocks of the Sesia–Lanzo Zone or of equivalent units exposed at that time presumably provided the youngest basement zircon fission-track ages to the basin. The Biella volcanic suite was the source of volcanogenic zircons. Oligocene sediment pathways from source to sink crossed further crystalline basement units and sedimentary covers before entering the basin from the southeast. The lag times of the youngest basement age populations (volcanic zircons excluded) are about 11 Myr. This constrains average moderate-to-high exhumation rate of 0.5–0.6 km/Myr in the pro-side of the orogenic wedge of the Central Alps during the late Eocene to early Oligocene.

Keywords Alpine magmatism · Detrital zircons · U–Pb/fission-track dating · Exhumation

Introduction

Provenance analysis is a useful tool to understand the paleogeographic position and exhumation histories of ancient tectonic units and to unravel ancient sediment pathways (e.g., Haughton et al. 1991). The composition of clastic sediments is mainly controlled by the eroded lithologies and tectonics in the source area, and by sediment transport and weathering processes. The foreland basins of the European Alps preserve a stratigraphic record starting from Paleogene collision to ongoing Neogene convergence between the European and the African/Apulian plates (Sinclair 1992). From the late Eocene to the Early Oligocene, the Northern Alpine Foreland Basin (NAFB) was mainly fed by the pre-Alpine sedimentary cover and basement units (e.g., Spiegel et al. 2000, 2001, 2004; von Eynatten 2007; Bernet et al. 2009; Jourdan et al. 2013), as well as syn-collisional magmatic rocks along the Periadriatic lineament (e.g., Rahn et al.

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✉ Maria Giuditta Fellin
giuditta.fellin@erdw.ethz.ch

¹ Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

² State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu, China

³ Swiss Federal Nuclear Safety Inspectorate, Brugg, Switzerland

1995; Ruffini et al. 1997; Bruegel et al. 2000; Boyet et al. 2001; Di Capua and Groppeoli 2015; Lu et al. 2018). However, the reconstruction of the source-to-sink routes during that time is complicated by the major topographic changes associated with the deformation and exhumation that have affected the Alps since Early Oligocene time.

In this study, we investigate the turbiditic deposits of the Taveyannaz Formation (Taveyannaz Fm, lower Oligocene). The deposits contain a syn-tectonic volcanic signature, as indicated by volcanic fragments within the sandstones (Pfiffner 2014). Previous studies based on sedimentology, sandstone petrography (Vuagnat 1944; Lateltin 1988; Sinclair 1992; Boyet et al. 2001; Di Capua and Groppeoli 2015), as well as geochemistry and geochronology (Rahn et al. 1995; Ruffini et al. 1997; Lu et al. 2018) indicate that the Taveyannaz Fm also contains abundant detritus from non-volcanic sources eroded from the early Alps. Thus, this study aims at identifying the Alpine units that provided the non-volcanic detritus to the NAFB at the time of deposition of the Taveyannaz Fm. To this goal, different sources of detrital zircons from the Alpe de Taveyenne and Haute-Savoie occurrences are identified by dating detrital zircons with both the U–Pb and the fission-track method. Detrital zircon fission-track analysis of synorogenic sediments is a tool to examine the exhumation history of orogenic belts. In addition, U–Pb age dating of detrital zircon is helpful in provenance analysis, especially for documenting syn-sedimentary volcanoclastic influx. The expectation is that if the provenance of the Taveyannaz sandstone was dominated by non-volcanic sources, then its age spectra should be very wide and reflect varied source rocks with different cooling ages (Garver et al. 1999). If the age spectra contained a population of syn-depositional volcanic zircons, then the fission-track ages of these zircons should be identical to their U–Pb ages. Our results are compared to a compilation of all previous detrital zircon fission-track data from the Alpine foreland basins, because altogether these data should provide useful information on the large-scale erosional evolution of the Alps, which in turn could be essential to understand the provenance of the Taveyannaz Fm zircons.

Geological setting

The northern Alpine foreland basin (NAFB)

The late Paleogene-to-Neogene sediment sequence of the NAFB developed in the course of the continent–continent collision during the Alpine orogeny. The NAFB is supposed to be a ‘underfilled’ flysch period between late Eocene and early Oligocene (e.g., Sinclair 1992). The syncollisional sediments were deposited at the proximal deformed margin of the NAFB in a wedge-top position. The deposits spread in a

narrow, discontinuous area (width > 10 km, length > 200 km) from the Haute-Savoie (France, Ruffini et al. 1997) to the Glarus area (east of Switzerland, Rahn et al. 1995) along the Subalpine chain (Fig. 1).

In the different sections of the NAFB (Glarus, Alpe de Taveyenne, Haute-Savoie) a similar stratigraphic subdivision (Fig. 2) is observed comprising the underlying deepening-upward series of the Einsiedeln and Stad formations, informally also known as Nummulitic limestones and Globigerina marls, respectively. They are overlain by the Taveyannaz Fm, for which a diachronous succession is suggested (Lateltin 1988; Sinclair 1992). Scarce nannoplankton data indicating nannofossil zones NP 21–23 correlate the formation with the uppermost Eocene (Priabonian: 38.0–33.9 Ma; Ogg et al. 2016) and lower Oligocene (Rupelian: 33.9–28.1; Ogg et al. 2016) in western Switzerland and France. Their detrital zircon U–Pb age data (Lu et al. 2018) confirm the biostratigraphic correlation of Lateltin (1988).

Composition and provenance of the Taveyannaz Fm

The composition of the Taveyannaz Fm has been systematically studied by previous researches (Lateltin 1988; Rahn et al. 1995; Ruffini et al. 1997; Di Capua and Groppeoli 2015). The types of sandstone samples in the Haute-Savoie and Alpe de Taveyenne area are from subarkosic to lithoarenitic (Di Capua and Groppeoli 2015). Based on the classification of arenites of Dickinson (1985), its modal composition reflects a magmatic arc provenance straddling the boundary between transitional and dissected arcs (Ruffini et al. 1997). Modal composition, mineral chemistry, whole-rock minor and trace elements indicate that it originated essentially from volcanic source rocks with a basaltic to basaltic–andesitic composition and subordinately from plutonic and sedimentary sources (Lateltin 1988; Rahn et al. 1995; Ruffini et al. 1997; Di Capua and Groppeoli 2015). It also contains 15% by volume of acid volcanic fragments that could be linked either to andesitic collisional magmatism or to volcano-sedimentary cover of the Hercynian basement (Ruffini et al. 1997). In the Haute-Savoie and Alpe de Taveyenne, the Taveyannaz Fm features three facies (Di Capua and Groppeoli 2015) comprising: (1) dark-grey to dark-brown pelite and marl layers with strong basement, minor sedimentary and rare volcanic supplies, (2) greenish to light-brown meter-thick sandstones with volcanic and/or basement supplies with ephemeral sedimentary covers and (3) green to spotted green and beige meter-thick sandstones with major volcanic and minor terrigenous supplies. These three facies have been interpreted as representing two different sediment sources, the growing Alpine belt and syn-sedimentary volcanic centers, which were mixed in variable proportions during cycles with different mechanisms

Fig. 1 Simplified tectonic map of the Alps and Apennines with sample locations (adapted from Schmid et al. 2004; Bigi et al. 1983). NAFB Northern Alpine foreland basin, SAFB Southern Alpine foreland basin, A Adamello, AT Alp de Taveyanne, B Bergell, BVS Biella

Volcanic suite, DB Dent Blanche, GA Glarus Alps, GP Gran Paradiso, HS Haute-Savoie, PL Periadriatic Lineament, SL Sesia Lanzo Zone, SCZ Strona-Ceneri Zone

of sediment transports to and within the foreland basin. The foreland was deforming by thrust propagation liberating metamorphic and sedimentary detritus (Di Capua and Groppe 2015). Despite the large volcanic component in the Taveyanne Fm, detrital U–Pb zircon age distributions include only 10% of Neo-Alpine zircons and 90% of pre-Alpine zircons: the Neo-Alpine zircons in the Haute-Savoie and Alpe de Taveyanne range between 31 and 34 Ma; the pre-Alpine zircons feature three major populations linked to the Cadomian, Caledonian, Variscan orogenic events (Lu et al. 2018, 2019).

Syn-tectonic volcanic activity

The Cenozoic Alpine orogeny involved about 500 km of north–south convergence between Africa and Europe and is characterized by top-to-the-north and north-northwest movements (Schmid et al. 2004). During the Paleogene, convergence, subduction, and finally, continent–continent collision took place within the Austroalpine units acting as the overriding upper plate and the Penninic units as the down-going lower plate. Volcanic and magmatic activities are recorded mostly in the central Alps, where they started

Fig. 2 Left (**a**) Composite stratigraphy of the Paleogene section studied in the Alpe de Taveyanne and Haute-Savoie areas modified after Lateltin (1988) and Lu et al. (2018). The red star indicates the sampled interval. Numerical ages for the stage boundaries and for the calcareous nannoplankton zones after Ogg et al. (2016). Right (**b**, **c**) U–Pb ages of volcanic zircons from the Taveyannaz Fm exposed at Alpe de Taveyanne and Haute Savoie from Lu et al. (2018) and from this study. Ages range between 33.9 and 30.2 Ma. The grey areas indi-

cate the 2 s range for the three concordant youngest ages in the samples here investigated (dark grey) and for all ages (light grey). Panel **b** shows $^{206}\text{Pb}/^{238}\text{U}$ ages from this study with a relative uncertainty (2 s) < 5% and that are < 10% discordant relative to $^{207}\text{Pb}/^{235}\text{U}$ ages. **c** Shows $^{206}\text{Pb}/^{238}\text{U}$ ages from this study with a relative uncertainty (2 s) > 5% and/or with discordancy > 10% relative to $^{207}\text{Pb}/^{235}\text{U}$ ages. DISC: discordancy

with the emplacement of the Adamello magmatic system during the Eocene (Tiepolo et al. 2014) and culminated in the area of the Periadriatic lineament in the Early Oligocene (Bergell and Biella; e.g., Waibel 1993; Berger et al. 2012b; Lu et al. 2018). For the studied area (Haute-Savoie and Alpe de Taveyanne), detrital zircon U–Pb data and initial Hf ratios indicate the Biella area as source of the volcanic detritus (Lu et al. 2018). At present, the Biella Volcanic Suite (BVS) occurs in a narrow belt of about 20 km between the Periadriatic lineament and the Sesia–Lanzo Zone (Fig. 1). The composition of the volcanic rocks ranges from basalt to andesite within a high-K calc-alkaline suite and from trachyandesite to trachydacite in a shoshonitic suite (Callegeri et al. 2004). The BVS represents a complex volcanic sequence of porphyrites, coarse-grained conglomerates, volcanic breccias and thin tuffitic layers. According to published dating results, the Biella intrusion and volcanos were active during the Early Oligocene (Kapferer et al. 2012).

Potential source areas

The magmatic zircons of the Taveyannaz Fm are of Rupelian age (30–34 Ma) and were likely derived from the Biella volcanic suite (Lu et al. 2018) that today partly covers the high-pressure metamorphic rocks of the Sesia Lanzo zone in proximity of the Periadriatic lineament (Kapferer et al. 2012). The Sesia Lanzo zone, together with the Dent Blanche, are part of the uppermost tectonic unit of the Western Alps and are remnants of a larger unit of Apulian affinity defined as Margna Sesia fragment (Schmid et al. 2004) (Fig. 1). During the late Eocene to early Oligocene, the Margna Sesia fragment was exposed at surface in the Western Central Alps. Today, the Sesia Lanzo zone is incised by rivers that drain to the southeast, but the presence of volcanic material from the Biella region in the Taveyannaz Fm indicates that during the Rupelian not only the Biella volcanic products, but also

other rocks in their proximity were eroded and transported to the NAFB. Moreover, the proximity between the Biella province and the basement rocks of the Southern Alps raises the question whether part of the detritus in the Taveyanaz Fm of Rupelian age could have come also from regions that today are located to the south of the Periadriatic lineament. Tectonic reconstructions indicate that the Southern Alps were not exposed at that time and that likely only units north of the Periadriatic lineament like the Margna Sesia and the Austroalpine units were at surface (Schmid et al. 2004; Handy et al. 2010). These reconstructions are largely based on the ages of Alpine metamorphism, subsequent exhumation and cooling, and partly also on the synorogenic sedimentary record (e.g., Di Giulio et al. 2001). These data altogether indicate that the units with an Alpine high-grade metamorphic overprint now exposed in the Central Alps, as, e.g., the Penninic nappes, underwent metamorphic burial during the late Eocene and early Oligocene (Pfiffner 2014) and, therefore, were not exposed at that time. Instead, the units with Apulian affinity exposed today at surface north of

the Periadriatic lineament show zircon fission-track (ZFT) cooling ages that range from 35 to 44 to the west of the Bergell intrusion (Margna Sesia units) and between 58 and 129 Ma to the east of it (Austroalpine units) (Hurford et al. 1989; Fügenschuh et al. 1997) (Fig. 3, Table S1 in supplementary Material). The Southern Alps, which are largely unaffected by Alpine metamorphism, are not likely a potential source area of detritus as stratigraphic and detrital data indicate that they were first exposed at surface in the Miocene (Di Giulio et al. 2001). However, Paleogene cooling ages are today exposed locally in the western Southern Alps and specifically in the Ivrea Zone (Figs. 1, 3). This zone exposes basement rocks composed of the Ivrea–Verbano Zone (IVZ) and the adjacent Strona–Ceneri Zone (SCZ), which are interpreted as representing a cross section of the entire continental crust (Zingg 1990). They show ZFT ages older than 30 Ma close to the Periadriatic lineament and older than 100 Ma far away from this fault (Siegesmund et al. 2008). In the rest of the Southern Alps, ZFT ages are commonly older than 100 Ma (Fig. 3).

Fig. 3 Bedrock and detrital zircon fission-track ages from previous studies (Tables S1 and S2 in Supplementary Material). *NAFB* Northern Alpine foreland basin, *WNAFB* Western Northern Alpine foreland basin, *CNAFB* Central Northern Alpine foreland basin, *ENAFB* Eastern Northern Alpine foreland basin, *SAFB* Southern Alpine foreland basin. *WNAFB*, *CNAFB* and *ENAFB* correspond to an approximate division into three geographic regions. West, center and east refer to the approximate geographic divisions of the Alps and to the

main provenance from these regions of the sediments in the foreland basins: e.g., the main provenance of the foreland sediments **e**, **f** and **h** located in the Apennines is from the central Alps. TH: Torino Hill. Data sources: **a** modern river sediments of Bernet et al. (2001, 2004a, b); **b** Spiegel et al. (2000); **c** Bernet et al. (2009); **d** WNAFB ages of Bernet et al. (2009); **e** SAFB ages of Bernet et al. (2001, 2009); **f** Dunkl et al. (2001); **g** Jourdan et al. (2013); **h** Stalder et al. (2017)

Among the remaining units of the Western-Central Alps, the only ones that could have been potential sources for ZFT ages older than 30 Ma are located in the Swiss and French Prealps. The Swiss Prealps, in particular, represent a major tectonic depression containing the following structural units: Simme, Brèche, Niesen and Ultrahelvetic nappes (e.g., Cosca et al. 1992; Mosar et al. 1996). The Niesen nappe consists of 2 km of Niesen Flysch, mainly of Late Cretaceous age, with provenance from the North Penninic (Ackermann 1986) and it has a non-reset ZFT age of 181 ± 25 Ma (Soom 1990). Along the northern front of the Central Alps, several additional synorogenic turbiditic deposits are locally still preserved as, for instance, the Schlieren Flysch (Winkler 1983) and the Gurnigel Flysch Nappes (van Stuijvenberg 1979). Their depositional ages range from Late Cretaceous to early Eocene and since early on they were progressively accreted at the top of the Alpine wedge so that they have largely escaped deep burial conditions (van Stuijvenberg 1979; Winkler 1983). They carry a provenance signature from the South Penninic as attested by Permian and Early Triassic detrital zircon U–Pb age populations and by the sandstone composition (Bütler et al. 2011; Beltrán-Triviño et al. 2013).

Previous detrital zircon fission-track data from the Alpine foreland basin

Numerous previous studies provided detrital ZFT data from synorogenic clastic sediments of the southern Alpine foreland basin (SAFB) and NAFB, and these data were compared to detrital data from modern river sands (Spiegel et al. 2000, 2001, 2004; Bernet et al. 2001, 2004a, b, 2009; Dunkl et al. 2001; Jourdan et al. 2013; Stalder et al. 2017; Fig. 3, Table S2 in Supplementary Material). These studies aimed at determining the paleo-erosion rates of the Alps using the lag time between the detrital age populations and the depositional age of the sampled sediment. Here, we provide an overview of the existing detrital ZFT data (Figs. 3, 4) and discuss the implications of these data relative to our new data and the tectonic evolution of the Alps in “Detrital zircon fission-track record of the Alpine foreland basin”.

The existing large detrital ZFT dataset has to be interpreted cautiously in terms of provenance as detrital data are inevitably influenced by biases related to sampling, to the combination of variable zircon fertilities and erosion rates of the source rocks (Andersen 2005; Sláma and Košler 2012; Malusà et al. 2013) and also to analytical procedures like possible differences in the fission-track etch techniques (Rahn et al. 2019). Altogether the existing data show major differences from west to east along the Alpine strike and through time in both the NAFB and SAFB (Fig. 4).

One of the notable prominent features of the northern Alpine detrital record in relation to our data is the presence

of Triassic to Jurassic, or even older, age populations. These are regularly found in the central sector of the NAFB, but in the western sector they only appear with very large uncertainty in one of the modern rivers and in one of the 30 Ma old sediments. Furthermore, such populations are absent in the eastern sector of the NAFB. In the SAFB, age populations > 150 Ma are found only in the west (Torino Hill, Fig. 3), whereas elsewhere the oldest age populations are Early Cretaceous in age. These ages characterize one of the sampled modern river draining the Southern Alps (Figs. 3, 4) (Bernet et al. 2001). Notably, they appear as sizeable populations in the middle Miocene in the central SAFB and they might reflect unroofing of the basement of the Southern Alps given that extensive exposure of the basement of the Southern Alps has occurred since the Miocene (Di Giulio et al. 2001).

Samples and methods

Sample material

We collected samples from Early Oligocene Taveyannaz Fm. sandstones in the Haute-Savoie and Alpe de Taveyanne area from outcrops with typical turbidites, greenish to brownish in color. Limitations to the number of datable samples were imposed by the low zircon yield of some of the collected samples and the restriction to areas of burial conditions below temperatures of ZFT partial annealing. Sample MRP006 is from the Alpe de Taveyanne type locality and samples 16GL02/16GL17 are from the Haute-Savoie (Table 1). Grain size varies from medium to coarse sand, with occasional out-size pebbles. With regard to lithic clasts, volcanic and continental basement fragments are largely dominating, together with sedimentary lithoclasts. Single grains of plagioclase are abundant, with volcanogenic clinopyroxene, amphibole and biotite occurring in minor proportions in most samples. Detrital quartz grains occur in variable amounts from 10 to 50%, and detrital white mica implies substantial basement erosion in the hinterland.

Zircon fission-track dating

Zircons were separated from the crushed rocks with standard magnetic and heavy liquid separation techniques. Zircons were mounted into Teflon pads, which were polished to expose grain-internal surfaces. Prior to analysis, all zircon grains were inspected by cathodoluminescence imaging to check for homogeneous composition and their magmatic growth pattern. Adopting the multiple-etch technique of Naeser et al. (1987), five mounts per sample were etched in a eutectic melt of NaOH and KOH at 228 °C for either 14 or 21 h. Mica laminae were attached to the

Fig. 4 Detrital zircon fission-track age populations of Alpine and Apenninic sediments. Data locations are shown in Fig. 3. As shown in Fig. 3, west, center and east correspond to an approximate division into three geographic regions within the Alps and to the main provenance from these regions of the sediments in the Alpine foreland.

Circles with yellow, red and blue filling color are data from Spiegel et al. (2000), Dunkl et al. (2001), Berner et al. (2001, 2004a, b, 2009), Jourdan et al. (2013) and Stalder et al. (2017). Purple circles are data from this study. The circle size is proportional to the fraction of grains forming the detrital age population

Table 1 Location of samples in the Taveyannaz Formation

Sample	Area	Locality	Latitude	Longitude	Altitude (m)
MRP006	Alpe de Taveyanne	Gryonne	46° 18' 4" N	7° 07' 33" E	1780
16GL02	Haute-Savoie	Flaine	46° 0' 36" N	6° 40' 40" E	1840
16GL17	Haute-Savoie	Chalêt des Juments	45° 53' 22" N	6° 26' 53" E	1740

samples as external detectors. The mounts were irradiated at the Radiation Center of Oregon State University, using a nominal neutron fluence of $1 \times 10^{15} \text{ ncm}^{-2}$. Induced tracks in mica were revealed by etching in 40% HF at 21 °C for 45 min. Fission tracks were analyzed at ETH Zurich on grains from both etch times, using the Fish Canyon tuff as a standard for the zeta calibration (Hurford and Green 1983). We dated about 100 grains per sample to obtain grain-age distributions that can be decomposed into major, statistically robust age populations (Bernet et al. 2006). Age distributions were decomposed into dominant age peaks using the BinomFit program of Brandon (2002). This method was chosen to compare our data with those from previous studies that also used Binomfit (Spiegel et al. 2000, 2001, 2004; Bernet et al. 2001, 2004a, b, 2009; Dunkl et al. 2001; Jourdan et al. 2013; Stalder et al. 2017).

Zircon U–Pb age dating

Laser ablation ICP-MS U–Pb dating of detrital zircon was performed in a spot mode of 30 µm diameter using an Excimer laser (ArF 193 nm, Resonetics resolution 155) coupled to a Thermo Element XR sector-field ICP-MS in the Institute of Isotope Geochemistry and Petrology (IGP), ETH Zurich (Guillong et al. 2014). Analysis spots were located within the same area, where fission tracks were counted as shown in Fig. 5 and where possible, on large grains, multiple spots were analyzed (Fig. 6s in the supplementary material). A gas-stream was used to transport the ablated material (He, flux rate 1, 0.5 l/min). The laser pulse repetition rate was 5 Hz and the energy density/fluence was $\sim 2.0 \text{ J/cm}^2$. Backgrounds were measured for 30 s and ablation duration was about 40 s. The accuracy and reproducibility of U–Pb zircon analyses were monitored by periodic measurement on external standards (AUSZ7-5, Plesovice, Temora2, 91500, NIST610; von Quadt et al. 2014). GJ-1 is used as a primary reference standard for the dating and NIST 610 to calculate the trace element composition using Si (15.2 wt%) as internal standard. Ratios, ages and element concentrations were calculated using IOLITE 2.5 (Petrus and Kamber 2012). Calculated isotopic ratios and ages were processed with ISOPLOT 4.0 (Ludwig 2012) to constrain concordia plots and frequency U–Pb age distribution diagrams.

Results

Zircon U–Pb ages

Cathodoluminescence pictures (Fig. 5) of zircon grains from the Taveyannaz Fm. show mainly prismatic euhedral crystals or fragments of it. Only a few sub-rounded and unzoned grains were observed. Part of the detrital zircons show well-developed oscillatory zoning, sometimes containing inherited cores recording older zircon growth phases. These features indicate a magmatic origin (Rubatto et al. 1999). The age distributions of detrital zircons reveal a large dominance ($\sim 90\%$, of totally 281 dated zircons) of pre-Tertiary ages as commonly observed in the same formation in the Glarus area (Lu et al. 2018). The age clusters are consistent with older orogenic cycles comprised in the Alpine basement (Fig. 6) including (1) a Cadomian (650–540 Ma) age population amounting to $\sim 25\%$ of the grains, (with a major peak at 580 Ma), (2) a Caledonian (497–393 Ma) age population including $\sim 25\%$ of the grains (with a major peak at 450 Ma), and (3) Variscan and post-Variscan (393–252 Ma) zircons, which represent about 20% of the grains (with a major peak at around 290 Ma and 270 Ma). All three samples yielded a total of 29 ages in the range of 30–34 Ma. All U–Pb ages for the double-dated zircons are within uncertainty equal to or older than the ZFT ages (Table 3).

Zircon fission-track ages

All samples fail the χ^2 test, indicating that their mean ages contain multiple zircon age populations (Fig. 7). All samples contain a cluster of grains with ZFT ages close to the depositional age and some of these grains have ZFT ages similar to their U–Pb age (Table 3, Fig. 8). The Alpe de Taveyanne sample MRP006 contains 18 grains with single grain ZFT ages of 30–39 Ma; 14 of these grains have U–Pb ages of 30–34 Ma, but another 4 grains show U–Pb ages from 449 to 678 Ma. The Haute-Savoie sample 16GL02 contains 19 grains with ZFT ages from 30 to 37 Ma; among these, 8 grains have U–Pb ages between 32 and 34 Ma, 5 grains have U–Pb ages from 314 to 590 Ma and the remaining ones have discordant U–Pb ages. Similarly,

Fig. 5 Cathodoluminescence images of zircon grains from sample MRP006, Taveyannaz Fm, showing the areas of $^{206}\text{Pb}/^{238}\text{U}$ LA-dating (red labels and dashed circles) and fission-track dating (yellow labels and dashed polygons). Age uncertainties are given as 2 s

16GL17 contains 10 grains with ZFT ages from 30 to 40 Ma; 7 have U–Pb ages between 32 and 34 Ma and 3 other grains have U–Pb ages between 305 and 462 Ma. Those grains with young and identical ZFT and U–Pb ages are identified as volcanic zircons; those with old U–Pb ages, however, represent basement zircons, coming from exhumed units in the hinterland.

Detrital age populations were calculated in different ways: including only the volcanic zircons (Table 2: P1-volcanic), including all zircons (Table 2: *N* all., P1-All; Fig. 7), and, finally, excluding the volcanic zircons (Table 2: *N* bas., P1-basement to P4-basement; Fig. 7). The P1-volcanic was derived from the mean of the volcanic zircon ages: this varies between 30 and 31 Ma with standard deviations in the range from 1 to 2 Ma. The youngest detrital ZFT age populations, derived using Binomfit (Brandon 2002) and by excluding the volcanic zircons, center at 38–47 Ma (P1-basement), consist of small fractions of zircons between 7 and 16% and

are slightly older than the youngest populations including the volcanic zircons that center at 35–40 Ma (P1-All). The rest of the populations (P2-Basement to P4-Basement), also derived using Binomfit (Brandon 2002), vary in number and also in age among the three samples (Table 2; Fig. 7); the P2-Basement populations are Late Cretaceous in age (69–92 Ma), the older populations (P3- and P4-Basement) are Triassic to Early Cretaceous in age (239–138 Ma).

Discussion

Post-depositional thermal overprint and counting bias

The ZFT partial annealing zone may extend to distinctly different temperatures depending on whether the zircons under investigation are characterized by substantial accumulated

Fig. 6 Histogram and probability U–Pb age curves of detrital zircon ages from sandstones of the Haute-Savoie and Alpe de Taveyenne areas. The $^{206}\text{Pb}/^{238}\text{U}$ ages have been corrected according to the

method of Sliwinski et al. (2018), see Supplementary Material. Only concordant ages (> 90%) are considered and also small error ellipses situated close and only below the concordant age curve

radiation damage or not and depending on the duration and rate of the thermal event that causes annealing (Reiners and Brandon 2006). For instance, for a thermal event lasting 1 Ma the partial annealing zone extends from about 200 to > 350 °C and these temperature boundaries decrease with

increasing duration of the heating event (Reiners and Brandon 2006). However, annealing data based on field studies commonly suggest a transition between partially and fully annealed zircons at the transition between prehnite–pumpellyite and greenschist facies (Liu et al. 2001). These findings

Fig. 7 Probability density plots and histograms of detrital zircon fission-track (ZFT) ages from the Taveyannaz Fm. in the Haute-Savoie and Alpe de Taveyenne areas. The binomial best fit solution to the observed distribution is indicated with a grey line. The binomial populations and their ages are reported with colored lines and numbers (Brandon 2002). The diagrams on the left show the distributions of all the counted grains within each sample; for these diagrams P1 includes the youngest basement zircons and the volcanic zircons (P1-All in Table 2). The mean age of the volcanic population is also reported in black (P1-volcanic). The diagrams on the right show the distribution of the basement zircons (P1- to P4-basement), which are obtained by excluding the volcanic grains. The number of grains for each diagram is reported next to the sample name

are in line also with a recent study (Rahn et al. 2019) on the long-lasting thermal overprint of detrital zircons that concluded that areas with diagenetic to lower anchizonal overprint (≤ 270 °C) are likely to still contain the original detrital ZFT signal. The reason for the discrepancy between field and laboratory studies may be a methodical bias related to counting on grains of suitable track density and good track etching, which are commonly of relatively low U content, and, therefore, relatively high temperature annealing properties.

For the Alpe de Taveyenne locality, Schmidt et al. (1997) reported maximum burial temperatures of 210–250 °C (zeolite facies, vitrinite reflectance ($R_{\max}$) value of 2.7%). Our sample MRP006 from Alpe de Taveyenne was collected in close proximity of their sampling locality, so that equal maximum temperature conditions can be assumed. The samples from the Haute-Savoie (16GL02/16GL17) are from a region, in which the Taveyannaz Fm. has faced an even lower degree of diagenetic/metamorphic overprint, as illustrated by a vitrinite reflectance (R_o) value $\leq 0.9\%$ (Kübler

Fig. 8 Double-dating results of combined fission-track (FT, vertical axis) and U/Pb (horizontal axis) analysis on 281 single grains from samples MRP006, 16GL02 and 16GL17 (grey lines indicate corresponding 1σ uncertainties). Lower and right diagrams are Kernel density plots (KDE) of the U–Pb data and of the ZFT data based on DensityPlotter by Vermeesch (2012). Zircon U–Pb ages related to the Variscan orogenic magmatic activity typically range within the Car-

boniferous–Early Permian time and those related to post-Variscan magmatism due to extension within Pangaea range within the middle–late Permian time (e.g., Rubatto and Hermann 2003; von Raumer et al. 2013; Letsch et al. 2015). Cambrian–Ordovician and Precambrian zircon U–Pb ages correlate with the Caledonian (Frisch et al. 1984) and Cadomian magmatic activities (e.g., Stern et al. 2004), respectively

et al. 1979) corresponding to maximum burial temperatures ≤ 160 °C (Mullis et al. 2017). The ZFT age distributions of our samples from both localities show no significant difference: in fact, their age spectra (Figs. 7, 9; Fig. S1 in Supplementary Material) and age populations are similar within analytical error (Table 2). Similarly, ZFT data from the Flysch sandstones (including the Taveyannaz Fm.) in the Glarus Alps show no shift in age populations up to temperatures of 270 °C (Rahn 2001). Therefore, we infer that the post-sedimentation maximum temperatures of all three samples under investigations show no partial annealing of their ZFT data.

The U concentration in the zircons investigated with both the ZFT and U–Pb methods by this study varies within a tight range around a mean of 204 ppm, whereas

in the zircons from the Taveyannaz Fm. dated by the U–Pb method in Lu et al. (2018) and in those from Oligocene–early Miocene sandstones and modern sands of the SAFB dated by Malusà et al. (2016), the U concentration varies over a much larger range from ≤ 10 ppm to over > 2000 ppm around a mean of 450 ppm and 550 ppm, respectively (Fig. 9). Thus, the ZFT dating technique we used for our samples results in a distribution of U biased towards low concentrations, similar to other ZFT studies (e.g., Bernet et al. 2004a). This leads to the question as to whether the counting bias may also result in an age bias. The comparison between the U–Pb age distributions of our double-dated zircons with the single-dated zircons from the Taveyannaz Fm. of Lu et al. (2018) fails the Kolmogorov–Smirnov test that assesses whether two

Table 2 Detrital zircon fission-track data of the Taveyannaz Formation

Sample	<i>N</i> all	P1-all (Ma)		P1-volcanic (Ma)		<i>N</i> bas	P1-basement (Ma)		P2-basement (Ma)		P3-basement (Ma)		P4-basement (Ma)	
MRP06	100	34.5	− 4.3	30.2	1.4	86	41.7	− 10.4	69.2	− 8.4	138.2	− 21.8	238.8	− 30.7
		18%	5	14%			7%	13.9	27%	9.6	30%	25.8	35%	35.1
16GL02	104	35.8	− 4.8	30.8	1.8	96	37.7	− 6.8	72.4	− 7.8	179.8	− 15.2		
		20%	5.6	8%			14%	8.3	38%	8.7	48%	16.6		
16GL17	84	40.4	− 4.8	30.3	1.3	77	47.3	− 7.9	92.4	− 11.2	203.8	− 19.8		
		22.9%	5.4	8%			16%	9.5	37%	12.7	47%	21.9		
Pooled	288	54	− 1.9	30.4	1.6	259	40.8	− 4.8	68.9	− 6.9	123.4	− 17.3	217.5	− 17.7
		40.4%	1.9	10%			11%	5.4	26%	7.7	26%	20.1	37%	19.2

N all, total number of counted grains, *N* bas, number of basement-derived grains calculated as the difference between the *N* all and the number of volcanic grains, *P1*-all youngest binomial peak age of the zircon fission-track age distributions including the volcanic zircons, *P1*-volcanic mean zircon fission-track age of the volcanic zircons; the standard deviation is given next to the mean age, *P1*-basement to *P4*-basement binomial peak-fitted ages of the zircon fission-track age distributions without the volcanic zircons, including corresponding $\pm 95\%$ confidential interval and percentage of grains to specific peak, *Pooled* binomial peak ages of all the zircon ages grouped together

Fig. 9 Upper panel: comparison among the U concentration in the double-dated zircons from this study, the single (U–Pb) dated zircons of the Taveyannaz Fm (Lu et al. 2018) and the single (U–Pb) dated zircons of Oligocene–early Miocene sandstones and modern sands in the southern Alpine foreland (Malusà et al. 2013, 2016). Lower panel: comparison between the U–Pb age distributions of double-

dated and single-dated zircons from the Taveyannaz Fm: the plot to the left shows Kernel density plots (KDE) of the U–Pb data based on DensityPlotter by Vermeesch (2012); the plot to the right shows cumulative curves derived not including the age uncertainty. *KS* Kolmogorov–Smirnov test

samples are drawn from the same distribution ($KS < 5\%$; Fig. 9). The peaks in the U–Pb distributions of our samples correspond in age to the peaks of the U–Pb age distributions of Lu et al. 2018 (Fig. 9); however, they differ in relative proportion; the double dated zircons have higher fractions of ~30 Ma old zircons and of zircons older than 1000 Ma (Fig. 9). Such differences may result from the counting bias and from differences in the sample preparation. The zircons of Lu et al. (2018) were hand-picked, those of this study were poured above glass plates and then directly pressed into Teflon discs. For the purpose of this study, it is important to note that the double-dated samples are biased towards low U-concentrations, their U–Pb age distributions are geologically not significantly different from those dated with the U–Pb method only and finally the counting bias may explain why our samples are unaffected by post-depositional burial.

Significance of the zircon U–Pb age

The U–Pb ages of detrital zircons show a wide age range from Cenozoic to Precambrian, with several composite peaks (Fig. 6). The age distribution of detrital zircons reveals a dominance (~90%) of pre-Alpine ages as observed in a previous study (Lu et al. 2018): the Cadomian ages (~30%) correlate with the orogenic activity roughly in the Precambrian (e.g., Stern et al. 2004); the Caledonian ages (~20%) possibly come from the magmatic activity during Cambrian–Ordovician rifting along the northern Gondwana margin (Frisch et al. 1984); the Variscan (Carboniferous–Early Permian) indicate orogenic magmatic activity and post-Variscan (middle–late Permian) magmatism due to extension within Pangaea (e.g., Rubatto and Hermann 2003; von Raumer et al. 2013; Letsch et al. 2015). Among the Variscan zircons, Carboniferous ages are dominant and this feature is characteristic of detrital supplies from the passive paleo-European margin that recorded Variscan magmatism and metamorphism prominently during the Late Devonian to late Carboniferous (e.g., Beltrán-Triviño et al. 2013; Müller et al. 2020). Instead, detrital contributions from the Apulian margin feature large post-Variscan (middle–late Permian) populations in agreement with the minor geochronologic constraints of Carboniferous magmatism recorded along the southern passive margin of the Tethys.

For the young volcanogenic zircons (population P1-volcanic), the three samples from the Haute-Savoie and Alpe de Taveyanne area yielded around 10% ages ranging from 34 to 30 Ma (Fig. 6), which are similar in age but higher in percentages than those found in the same sandstones by a former study (5%, Lu et al. 2018). There is no quantitative age difference among these three samples (Fig. 9).

Pre-Alpine and Alpine thermal events in the detrital ZFT record

The cluster of the oldest detrital ZFT ages forms large age populations in all our samples (populations P3- and P4-Basement, $\geq 47\%$) and covers a wide time range from the Triassic to the Early Cretaceous (Fig. 7, from 239 to 138 Ma). P3- and P4-basement can broadly be related to the thermal effect of rifting during the opening of the Penninic Ocean (e.g., Frisch et al. 2000), which is recorded on both the European (e.g., in the Ligurian Alps, Decarlis et al. 2017) and the Apulian rifted margin (e.g., in the Southern Alps, Bertotti et al. 1999; Siegesmund et al. 2008; Berger et al. 2012a).

The second largest population (P2-basement, 27–38%) of our detrital ZFT age spectra falls into the Late Cretaceous and forms well separated populations between 92 and 69 Ma. These ages are interpreted as reflecting a cooling period that followed the Eo-Alpine metamorphic event (Dunkl et al. 2001). Late Cretaceous cooling is also preserved in other detrital records of the SAFB and NAFB: in the SAFB (Macigno Fm., late Oligocene) ZFT data show age populations of 80–60 Ma (Dunkl et al. 2001); in the NAFB (Swiss Molasse units, Oligocene to Miocene) ZFT data show age populations of 99–67 Ma (Spiegel et al. 2004).

Zircons with Eocene/Oligocene ZFT ages and old U–Pb ages represent a small percentage of the age spectra (P1-Basement, 7–16%). They form distinct populations clustering around 38–47 Ma. We interpret these ages as representing the initial stage of cooling and erosion of Alpine metamorphic rocks since the beginning of Alpine collision. Those zircons with ZFT and U–Pb ages around 30 Ma (P1-volcanic, Fig. 10) are zircons that cooled extremely rapidly and reached the NAFB shortly after crystallization and rapid cooling. These zircons are euhedral and colorless, and these features together with their ages clearly indicate a magmatic origin (Fig. 5). These observations confirm the findings of previous studies that the abundant volcanoclastic detritus in our samples are likely volcanic zircons from the Biella region (Lu et al. 2018).

Depositional age

Detrital volcanic zircons are commonly used to constrain the maximum depositional age of strata and in the case of the samples here investigated, they can provide tighter constraints on the time of deposition than those available based on biostratigraphic data. Biostratigraphic data from the Taveyanne Fm. correlate with the nannofossil zones NP 21–23 that indicate uppermost Eocene and lower Oligocene as time of deposition. Detrital U–Pb ages (Lu et al. 2018) of nine volcanic zircons out of ten samples from the Haute-Savoie and Alpe de Taveyanne range between 31.6 and 33.7 Ma (Fig. 2).

Fig. 10 Left: mineral ages expected at different levels of an unroofing volcano–plutonic complex, showing the idea of the lag-time concept: a rock is exhumed from deeper crustal levels. The rock cools while exhuming across the closure isotherm of the ZFT system up to the surface (adapted from Bernet et al. 2009). Right: lag-time plot for the divided youngest age population of the pooled samples from the

Additional volcanic grains from two of the same samples as in Lu et al (2018; MRP06 and 16GL02) and from a new sample (16GL17) were dated by this study (Fig. 2b, c; Table 4S in the supplementary material). Both rims and cores were analyzed on several of these grains resulting in forty (40) data with rim age or single age < 40 Ma and much younger than the core age (Fig. 6S in the supplementary materials).

Eleven (11) of these data have high relative analytical uncertainty (2s and/or age discordance > 10% discordance; Fig. 2c). However, the range of these data, from 29.8 to 34.2 Ma, is similar to the range of the remaining concordant ages that is from 30.2 to 33.9 Ma (Fig. 2b, c). It is unclear whether the scatter of the ages reflects analytical uncertainty or different volcanic ages. In sample MRP06 the three oldest ages do not overlap within 2s with the rest of the ages. Notably, the oldest volcanic ages in the samples here investigated are about 34 Ma old, which is close to the age of the base of the nannofossil zone NP21 (Fig. 2). Finally, the three youngest concordant ages from our samples (one from each sample; Table 3: MRP06-1-94-1; 16GL02D-74-1, 16GL17D-32-1) are very similar and have a mean of 30.4 ± 0.4 Ma (2s), which we consider the maximum depositional age of our samples based on that previous studies demonstrated this approach as valid (Dickinson and Gehrels 2009).

Provenance of the detrital zircons

Triassic–Jurassic cooling ages

Triassic-to-Jurassic ZFT ages are present in the basement rocks of the Southern Alps and are interpreted as related

Haute-Savoie and Alpe de Taveyanne samples: P1-B: youngest basement population age; P1-V: youngest volcanic population age. Error bars refer to 2s uncertainty for the age populations. The grey bars represent the samples depositional age as constrained by the U–Pb ages of the volcanic zircons

to Tethyan rifting (Fig. 3; Bertotti et al. 1999; Siegesmund et al. 2008; Berger et al. 2012a). Similar ages have been reported from an Austroalpine context (e.g., Silvretta unit and eastern Austroalpine units; Hurford et al. 1989; Dunkl et al. 2001) and from the Swiss Prealps (Soom 1990). The pre-Alpine ZFT ages in the Austroalpine units have so far been interpreted as partially reset and they have not been attributed to any tectonic event. Alternatively, they may indicate that in the Austroalpine units, or in other units of Apulian affinity north of the Periadritic lineament, pre-Alpine rifting-related ZFT ages could be locally preserved despite the common early Alpine metamorphic overprint. The same interpretation has been suggested by a previous study on the thermochronologic record related to the Permo-Triassic extension in the Austroalpine nappes (Schuster et al. 2001). Thus, it is not possible to unequivocally attribute the provenance of our detrital Triassic-to-Jurassic ZFT ages to rocks with Apulian affinity located either to the north or to the south of the Periadritic lineament. The U–Pb ages associated to these Jurassic–Triassic ZFT ages are with one exception all older than the Triassic (Figs. 6, 8) and they do not allow any further discrimination, because the basement rocks of Apulian affinity share a similar, pre-Triassic, U–Pb age spectra (e.g., Beltrán-Triviño et al. 2013).

The Triassic volcanic zirconogenic event at about 230–250 Ma (Beltrán-Triviño et al. 2013; Furrer et al. 2008) is characteristic for the detrital U–Pb age record of the Apulian rift margin and this could allow discriminating between either the European (no Triassic) or Apulian (with Triassic) provenance of detrital zircons. Another significant difference between the European and Apulian passive

Table 3 Zircon fission-track and U–Pb ages of Tertiary volcanic zircons

Double date <i>n</i>	ZFT						U–Pb				
	Sample	Seq. <i>n</i>	Age	Lower 95%CI	Upper 95%CI	1s	ID	U–Pb age	2s		Age disc 207/235 versus 206/238
									Ma	%	%
1	MRP06	1	29.4	21.54	47.55	6.12	MRP06-1-28-1	29.76	0.95	3.19	13.58
							MRP06-1-28-2	32.70	1.80	5.5	12.76
2	MRP06	3	31.34	18.88	51.86	7.5	MRP06-1-36-1	33.90	1.60	4.72	1.77
3	MRP06	16	29.49	20.13	43.08	5.43	MRP06-1-94-1	30.20	1.40	4.65	7.62
							MRP06-1-94-2	34.20	4.00	11.69	28.65
4	MRP06	24	30.82	13.34	70.44	11.45	MRP06-2-36-1	30.2	3.3	10.93	9.27
5	MRP06	33	30.43	12.16	75.02	12.18	MRP06-2-78-1	31.20	2.40	7.69	5.77
6	MRP06	50	29.32	17.48	48.89	7.13	MRP06-3-84-1	30.50	0.86	12.46	8.20
7	MRP06	51	30.65	17.06	54.76	8.35	MRP06-3-88-1	31.33	0.94	2.74	9.67
							MRP06-3-88-2	30.38	0.94	3.09	7.64
8	MRP06	64	29.7	18.26	48.07	6.83	MRP06-4-24-1	30.20	0.79	2.62	5.30
9	MRP06	65	31.47	19.77	49.98	6.96	MRP06-4-28-1	129.10	4.60	3.56	2.79
							MRP06-4-28-2	33.70	1.80	5.34	12.76
10	MRP06	73	29.78	21.34	41.47	4.82	MRP06-4-102-1	30.45	1.00	3.28	4.28
							MRP06-4-102-2	30.42	0.83	2.73	5.98
11	MRP06	76	30.23	15.91	57	8.93	MRP06-4-132-1	33.80	1.60	4.73	6.21
12	MRP06	79	29.79	18.44	47.89	6.77	MRP06-4-144-1	30.05	0.79	2.64	14.48
13	MRP06	80	29.68	16.79	52.12	7.88	MRP06-4-174-1	30.75	1.10	3.58	0.98
							MRP06-4-174-2	30.81	0.99	3.21	8.08
14	MRP06	85	30.41	18.51	49.75	7.13	MRP06-4-204-1	30.50	1.30	4.26	14.10
							MRP06-4-204-2	31.07	0.84	2.70	4.09
15	16GL02	2	30.29	20.81	43.95	5.48	16GL02A-34-1	31.91	0.50	1.57	1.54
16	16GL02	31	32.7	22.52	49.14	6.27	16GL02B-64-1	32.38	0.62	1.91	0.86
17	16GL02	36	30.04	17.91	50.07	7.3	16GL02B-106-1	31.24	0.57	1.82	2.43
18	16GL02	56	30.49	15.21	60.53	9.66	16GL02C-48-1	32.22	0.54	1.68	1.92
19	16GL02	67	31.44	17.71	55.52	8.41	16GL02C-104-1	32.85	1.06	3.42	3.42
20	16GL02	78	30.38	16.59	68.62	10.96	16GL02D-74-1	30.99	0.64	2.10	3.64
21	16GL02	97	31.08	16.86	56.95	8.8	16GL02D-190-1	31.65	0.57	1.80	1.11
22	16GL02	101	30.08	10.09	87.29	13.8	16GL02D-222-1	31.05	0.76	2.45	0.48
23	16GL17	1	29.54	15.88	54.46	8.46	16GL17A-24-1	32.02	0.55	1.84	3.80
24	16GL17	4	30.7	19.82	47.39	6.41	16GL17A-36-1	32.15	0.44	1.37	1.09
							16GL17A-36-2	31.86	0.32	1.00	1.13
25	16GL17	22	29.66	17.68	49.44	7.21	16GL17B-70-1	33.6	1.2	3.57	67.86
							16GL17B-70-2	32.11	0.52	1.56	6.20
26	16GL17	26	29.99	19.4	46.18	6.24	16GL17B-86-1	31.87	0.43	1.35	0.72
							16GL17B-86-2	32.42	0.37	1.14	0.68
27	16GL17	27	30.92	12.9	73.21	11.91	16GL17B-98-1	32.4	1.70	5.25	5.25
28	16GL17	31	31.25	13.98	69.22	11.23	16GL17B-150-1	32.75	0.66	2.02	0.46
29	16GL17	75	30.03	10.79	81.79	13.11	16GL17E-178-1	32.32	0.86	2.66	7.36
							16GL17E-178-2	32.01	0.85	2.66	1.22

Seq. *n*. is the sequence number of the zircon fission-track analysis within each sample as also reported in Table 5S of the supplementary material. ID is the U–Pb analysis label number as also listed in Table 4S of the supplementary material. The last number in the U–Pb label indicates the sequence number within individual grain; some grains have two U–Pb analysis

paleomargins is their different Variscan record that results into prominent Late Devonian to late Carboniferous detrital populations from the European margin, but large Permian populations from the Apulian margin, where the geochronologic constraints document mostly the late Variscan cycle (Beltrán-Triviño et al. 2013; Müller et al. 2020). The U–Pb age spectra of our samples only contains few early Triassic zircons, a minor Permian component and a prominent Carboniferous component. This distribution does not exclude Apulian supplies but points towards a significant European provenance signature. An indirect provenance from Europe for some of the Taveyannaz zircons could be explained by recycling of early Alpine or pre-Alpine sediments that were deposited on or near the European margin and then included into the growing Alpine accretionary prism. This inference is supported by compositional data of the Taveyannaz sandstones that, besides the volcanic fragment, also include significant amounts of basement and sedimentary lithics (Ruffini et al. 1997; Di Capua and Groppe 2015). In particular, metamorphic and sedimentary lithics could have been liberated by the activity of thrusts propagating into the foreland and then discharged by turbiditic currents into the Taveyannaz depocenter (Di Capua and Groppe 2015). Thus, sedimentologic observations points towards sediment recycling as a significant contributor to the detrital record. Sources of recycled zircons at the time of deposition of the Taveyannaz Fm could be, e.g., the Niesen Flysch (Ackermann 1986; Beltrán-Triviño et al. 2013) or any other early Alpine flysch units of the Prealps and Chablais klippen as the Schlieren Flysch and the Gurnigel Flysch. The few available ZFT data in the Swiss Prealps are older than 100 Ma (Soom 1990) (Fig. 3) and metamorphic proxies such as illite crystallinity, coal rank and fluid inclusion data record high diagenetic to maximum anchizonal conditions (Frey et al. 1980). Provenance of the Niesen Flysch is from the North Penninic paleogeographic realm (Ackermann 1986) and along the European margin Triassic-to-Jurassic ZFT cooling ages related to the Tethyan rift have also been documented (Decarlis et al. 2017). The Schlieren Flysch and Gurnigel Flysch record very little burial (van Stuijvenberg 1979; Winkler 1983) and are characterized by a South Penninic (Apulian margin) provenance, i.e., typified by Permian and Triassic detrital zircon age populations (Bütler et al. 2011; Beltrán-Triviño et al. 2013). Currently the Prealps and Chablais klippen are located to the north of the Taveyannaz Fm due to tectonic transport after Taveyannaz Fm. deposition. During the late Eocene–early Oligocene, the units exposed today in the Prealps and Chablais klippen were detached from their substratum and deformed at the front of the active Alpine accretionary prism in a position that was situated to the south of the Alpine foreland (Mosar et al. 1996). Within the active prism, some of these units were placed underneath the Nappe Supérieure (Mosar et al. 1996

and references therein) and were, therefore, partly covered but other units remained uncovered at shallow levels, and therefore, their zircons could have been eroded and recycled into the NAFB basin. For the time being, the available data are not sufficient to fully assess a possible recycling of early Alpine detrital sediments into the Taveyannaz depocenter, but our data point towards this possibility indicating especially synorogenic sediments of North Penninic provenance as most likely candidates.

Late Cretaceous and Eocene/Oligocene cooling ages

Zircons with Late Cretaceous fission-track ages derive likely from rocks that were affected by the Eo-Alpine metamorphic overprint. At present, cooling ages belonging to this metamorphic overprint are mainly preserved in two sub-units of the Austroalpine nappes: the Oetzal–Stubai complex (71–63 Ma, Fügenschuh et al. 1997) and the Silvretta unit (106–68 Ma, Hurford et al. 1989). Zircon crystallization ages in the Oetzal–Stubai nappe date back to the Carboniferous (i.e., Variscan; Hoinkes and Thöni 1993; Fügenschuh et al. 1997) and in the Silvretta units to the Ordovician/Cambrian (Hurford et al. 1989; Müller et al. 1996). Both U–Pb age groups are found for the Late Cretaceous and Paleogene ZFT data (Figs. 7, 8). Currently, these Austroalpine units are exposed too far to the east with respect to the here investigated Taveyannaz Fm depocenter. Unless the topography of the NAFB and/or drift currents allowed far-reaching westward detritus transport, it is possible that, instead, a closer source of zircons with Late Cretaceous cooling ages was at surface and actively eroding. This source could have also been of Apulian affinity, such as the Margna Sesia nappe. The remnants of this nappe today show Paleogene cooling ages (Fig. 3) (Hurford et al. 1991; Vance 1999; Wolff et al. 2012) but, speculatively, shallower levels of the same nappe may have preserved earlier cooling and could have been eroded during the Rupelian.

Zircons with Oligocene/Eocene fission-track ages are today exposed largely in the Western Alps (Fig. 3). Oligocene ZFT ages are common in the Penninic Gran Paradiso massif and in the Dent Blanche, which is part of the Margna Sesia nappe (Hurford and Hunziker 1989; Hurford et al. 1991; Vance 1999; Wolff et al. 2012) (Figs. 1, 3). Oligocene and Eocene ZFT occur mostly in the Sesia–Lanzo zone, which is also part of the Margna Sesia nappe, and in a narrow belt in the Ivrea–Verbano Zone, close to where this unit is juxtaposed to the Sesia–Lanzo zone along the Periadriatic lineament (Fig. 1; Siegesmund et al. 2008).

The Gran Paradiso massif is a fragment of Variscan basement that includes a large body of metagranites with Middle Permian U–Pb ages (~270 Ma; Ring et al. 2005; Bertrand et al. 2000). Only three Middle Permian U–Pb ages appear in the age spectra of our sample and only one of those has

a Paleogene ZFT age. Moreover, peak high-pressure metamorphism in the Gran Paradiso Massif is as young as 33 Ma (e.g., Radulescu et al. 2009). Therefore, we can consider the Gran Paradiso Massif as an unlikely source area for the NAFB at the time of the Taveyannaz Fm. In contrast to the Gran Paradiso Massif, the Dent Blanche and Sesia Lanzo zone are typified by magmatic rocks of late Carboniferous–early Permian age (Paquette et al. 1989; Bussy et al. 1998; Rubatto et al. 1999; Monjoie et al. 2007; Zucali et al. 2011). Moreover, the Sesia Lanzo zone was at least partly already at the surface when the Biella volcano-sedimentary suite was deposited (Kapferer et al. 2012), i.e., at the same time of deposition of the Taveyannaz Fm (see above). Thus, the Margna Sesia units are the most likely source of the Paleogene ZFT of our samples.

Finally, an additional potential source area is the Ivrea-Verbano Zone that was exhumed to a near-surface position already in Jurassic times (Berger et al. 2012a) and during the Miocene it was tilted to its current position and exposed at surface (Wolff et al. 2012). It recorded a minor cooling event in the Eocene and thus it is possible that small portions of this unit were already eroding and, therefore, exposed at the same time of Taveyannaz Fm deposition. However, the Ivrea-Verbano zone is characterized by Permian to Triassic (e.g., Zanetti et al. 2013) and locally even Jurassic (Galli et al. 2018) magmatic events and these ages are either absent or only a minor fraction of the age distributions in the samples here investigated (Fig. 8).

Detrital zircon fission-track record of the Alpine foreland basin

As discussed in “Triassic–Jurassic cooling ages”, based on the basement cooling record, the Triassic–Jurassic ages could come from any basement sliver with Apulian affinity that include the basement of the Southern Alps, the Austroalpine and the Margna Sesia nappes or from recycled early- to pre-Alpine sediments carrying a provenance signal from the passive European margin. If the Triassic–Jurassic detrital signal came from the Austroalpine or Southern Alps basements, this signal would persist into the eastern sector of the NAFB and into the central SAFB, because these sectors of the Alpine foreland collect sediments from the Austroalpine and Southern Alps units at present and likely collected them also during the Oligocene (Garzanti and Malusà 2008). However, the detrital records of the eastern NAFB and the central SAFB show no Triassic–Jurassic ages (Fig. 4), and therefore, neither the Austroalpine nor the Southern Alps basements are likely the source rocks of these detrital ages.

The fact that the detrital Triassic–Jurassic signal characterizes not only the Oligocene–Miocene sediments of the central NAFB but also those of the western SAFB (Fig. 4), and possibly those of the western NAFB, might be a further

indication that the provenance of this signal could be indeed from recycling of early- to pre-Alpine sediments like those now exposed in the Prealps and Chablais klippen. The Prealps and Chablais klippen are in fact small remnants of a larger decollement nappe pile derived from the Piedmont–Ligurian basin and from the paleo-European margin and the only other remnants of these units are present in the Western Alps. However, besides the Prealps and Chablais klippen or similar units, the Margna Sesia nappe remains a potential source area, if the eroded portion was unaffected by the Alpine overprint.

The fact that there is no detrital record of the Triassic–Jurassic signal in both the central SAFB and the eastern NAFB (Fig. 4) is partly surprising. In the eastern NAFB, this may be explained by the thermal overprint related to Tethyan rifting in the Austroalpine units leading to annealing by subsequent Alpine events. Moreover, if the Triassic–Jurassic thermal overprint is preserved in the Austroalpine units, these units may have had low erosion rates and/or low zircon fertility or may have drained south- and eastwards.

The absence of this signal in the central SAFB is even more surprising, because Triassic–Jurassic ZFT ages certainly characterize the basement of the Southern Alps (Bertotti et al. 1999), where the Alpine overprint is limited to temperatures within or below ZFT annealing. Possible explanations relate to low zircon fertility and to the present-day limited exposure of the basement of the Southern Alps, which may have reached surface only after removal of a thick Mesozoic–Tertiary cover. Thus, the detrital signal of the central SAFB is dominated by zircons coming from fast eroding and zircon-rich rocks to the north of the Periadriatic lineament and of the Periadriatic magmatism, which can dilute and obscure any signal from the Southern Alps. These interpretations partly could explain also the observation that the oldest detrital ZFT ages in the central SAFB with significant populations only appear from the Middle Miocene onwards (Fig. 4).

Exhumation rate of basement units

The difference between the age of deposition of a zircon and its detrital cooling age is defined as the lag time (Bernet et al. 2009). This time represents the travel time of a zircon from its closure depth to the surface and then to the sedimentary basin (Fig. 10). The source-to-sink travel time (kyr time scale) is commonly much shorter than the time needed for exhumation (Myr-time scale). Accordingly, the lag time is directly proportional to the exhumation rate of the source area. The evolution of lag times in the foreland deposits through time provides insight into the exhumational history of the basement units. The volcanic zircons (P1-volcanic, Fig. 10) are of no relevance for the calculation of a lag time, as the ZFT and U–Pb ages overlap within error. Given a

depositional age of 30 Ma based on the youngest detrital zircon U–Pb ages, the average lag time of P1-basement is about 12 Myr or of 11 Ma for the pooled zircons (P1-basement of pooled in Table 2; Fig. 10). To convert the ZFT ages into exhumation rates, we used a one-dimensional thermal model (Age2edot program; Willett and Brandon 2013). This model assumes constant cooling and steady-state topography. The kinetic parameters for zircon fission-track formation are taken from Brandon et al. (1998). To calculate an exhumation rate from a basement age with this model, estimates of the modern geothermal gradient, time of initiation of exhumation, and surface temperature are required. In our case, we assume that significant erosion started at about 50 Ma with the beginning of continual collision, that the rocks reached the surface at 30 Ma (i.e., roughly at the time of Taveyannaz Fm. deposition) after cooling below closure at 41 Ma (i.e., the time of deposition plus the average lag time), that at the time of rock surface exposure the geothermal gradient was 45 °C/km and the surface temperature was 10 °C. With these parameters, we obtain a geothermal gradient at the onset of erosion of 30 °C/km, a closure temperature of 235 °C and a moderate-to-high average exhumation rate of 0.5–0.6 km/Ma.

Lag times of 11–12 Myr are comparable to the longest lag times found for the NAFB during the late Oligocene–Miocene (Bernet et al. 2009; Spiegel et al. 2000). In the late Oligocene–Miocene sandstones of the NAFB, those ZFT population with the shortest lag time constitutes in most cases the largest populations ($\geq 30\%$), whereas in our samples the 11-to-12 Myr lag times encompasses a small fraction of zircons only ($\leq 16\%$). Thus, our data indicate paleo-erosion rates that are very low for most of the source areas in the Alps draining towards the Taveyannaz Fm depocenter and only locally as high as 0.5–0.6 km/Myr. Sedimentologic data from the NAFB indicate that this depocenter was underfilled during the Rupelian (Sinclair 1992). The underfilling of the foredeep together with the low erosion rates during the Rupelian may reflect a slow erosional response of the pro side of the orogen to the major tectonic processes related to continental collision that were ongoing and that could have just started to generate rapid rock and surface uplift.

Conclusions

Based on the combination of detrital zircon U–Pb and fission-track dating, we derive that:

1. A large detrital ZFT age population in the range from 138 to 238 Ma (P3- and P4-Basement: $\geq 47\%$) is similar to detrital populations common only in the Miocene and older foreland record of the Western Alps (western and central NAFB) and of the Torino Hill. These zircon

populations could be sourced directly from basement rocks not-affected by Alpine metamorphism or from the European margin possibly through recycling of early Alpine foreland sediments.

2. The Late Cretaceous detrital ZFT age populations, in the range of 69–92 Ma (P2-Basement: 27–38%) are likely from rocks of the Margna Sesia and Austroalpine nappes that represent the uppermost Alpine units, where the record of the earliest metamorphic and cooling Alpine events is preserved. Most likely the predominant source for these group of ages in the studied samples is the Margna Sesia unit based on its proximity to the here investigated Taveyannaz depocenter.
3. The basement units of the Sesia Lanzo zone and possibly locally also of the Ivrea-Verbano zone are the likely source of the young ZFT zircon basement ages (P1-basement) in the range of 38–47 Ma. The neighboring Biella volcanic suite provided volcanic detritus and fission-track ages of ~ 30 –31 Ma (P1-volcanic) (Fig. 10).
4. The lag times for the young basement peak (P1-basement: 7–16%) of 11–12 Myr long during the early Oligocene only encompasses a small fraction of zircons. This lag time can be translated into a moderate-to-high average exhumation rate of approximately 0.5–0.6 km/Myr, suggesting a relatively slow erosional response of the pro side of the orogen to the major tectonic events active during the Rupelian in the Alps.

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